Evaluating CO_2 Sequestration Enhancement Through Silvicultural Practices: A Simulation Analysis

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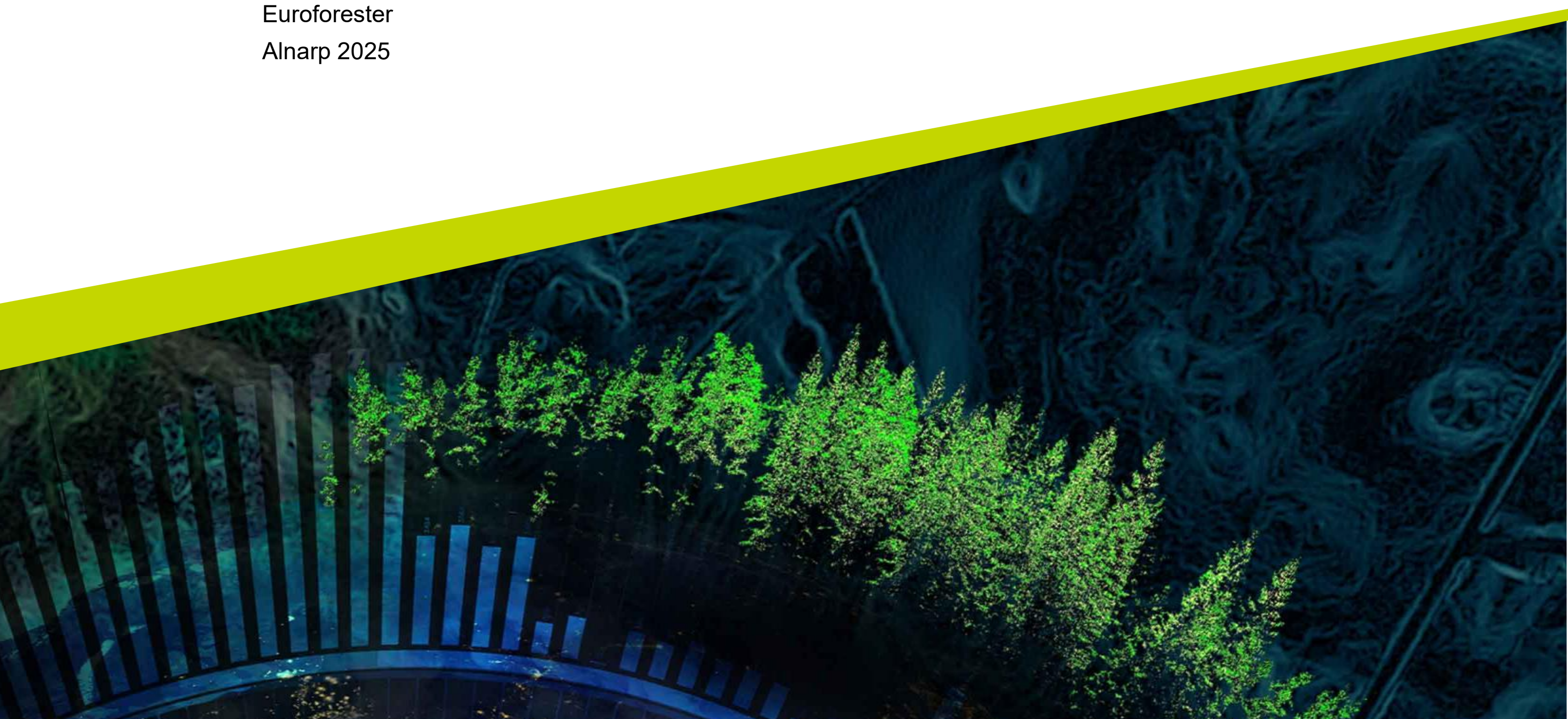

Evaluating CO_2 Sequestration Enhancement Through Silvicultural Practices: A Simulation Analysis

Utvärdering av förbättrad koldioxidinlagring genom skötselåtgärder: En simuleringsanalys

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Abstract

Forests in reserves are often left untouched to preserve biodiversity, allowing nature to shape their structure over time. Consequently, natural forests in nature reserves and national parks tend to be denser than managed forests under similar conditions, which can impact their ability to sequester carbon. This study examines the effects of low-intensity forest management on carbon sequestration in temperate broadleaf forests. Simulations were performed using Heureka's RegWise tool with forest data from Söderåsen National Park in southern Sweden, predominantly featuring beech trees. The management scenarios examined included no treatment, selective fellings that removed 5–10 % of the basal area per intervention, and lower-intensity fellings that removed 2–5 % of the basal area. The results showed that even minor interventions significantly increased net carbon sequestration over the 100-year simulation period, all while preserving forest structure and avoiding drastic disturbance to natural systems conditions. Among the three main species dominant in any plot, Fagus sylvatica (European beech) and Picea abies (Norway spruce) showed significant improvement in carbon sequestration after minimal intervention. In contrast, Betula pendula (silver birch) did not exhibit significant improvement after minimal intervention when compared to an unmanaged forest. The findings indicate that tailored management strategies, both species-specific and site-specific, can enhance carbon sequestration. Simulation tools, such as Heureka, provide a user-friendly, site-focused strategy that can guide national park management as well as private forest owners, particularly as the importance of carbon farming and credits increases in European forestry policy. Through systematic data gathering and focused actions, managed forests can play a significant role in mitigating climate change. This topic still requires additional research for a complete understanding of how other site characteristics, or species, can influence carbon sequestration.

Keywords: Heureka, simulations, carbon sequestration, selective fellings.

Sammanfattning

Skogar i reservat lämnas ofta orörda för att bevara biologisk mångfald, vilket gör att naturen formar deras struktur över tid. Därför tenderar naturliga skogar i naturreservat och nationalparker att vara tätare än brukade skogar under liknande förhållanden, vilket kan påverka deras förmåga att lagra kol. Denna studie undersöker effekterna av lågintensiv skogsskötsel på kolinlagring i tempererade lövskogar. Simuleringar utfördes med hjälp av Heurekas RegWise-verktyg med skogsdata från Söderåsen National Park i södra Sverige, där bokträd dominerar. De analyserade skötselscenarierna inkluderade ingen åtgärd, selektiva uttag på 5–10 %, och uttag med lägre intensitet på 2–5 %. Resultaten visade att även små ingrepp förbättrade kolinlagringen avsevärt, allt medan skogens struktur och biologiska mångfald bevarades. Bland de tre huvudarter som dominerade någon provyta visade *Fagus sylvatica* och *Picea abies* signifikant förbättring i kolinlagring efter minimal åtgärd. I kontrast visade *Betula pendula* ingen signifikant förbättring efter minimal åtgärd jämfört med en oskött skog. Resultaten visar att skräddarsydda skötselstrategier, både art- och platsanpassade, kan förbättra kolinlagringen. Simuleringsverktyg som Heureka tillhandahåller användarvänliga, platsspecifika strategier som kan vägleda förvaltningen av nationalparker såväl som privata skogsägare, särskilt när betydelsen av kolodling och krediter växer i europeisk skogspolitik. Genom systematisk datainsamling och fokuserade åtgärder kan brukade skogar spela en betydande roll i att mildra klimatförändringarna. Detta ämne kräver fortsatt forskning för full anpassning och för att förstå hur andra ståndortsfaktorer eller arter kan påverka kolinlagringen.

Nyckelord: Heureka, simuleringar, kolinlagring, selektiva uttag.

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1. Introduction

1.1 Carbon and forests

Forests in reserves are often left untouched to preserve biodiversity and can remain undisturbed for a long time, allowing nature to shape the forest's structure. Therefore, natural forests in nature reserves and national parks are generally denser than managed forests under the same conditions, which can impact their ability to sequester carbon, since denser forests tend to have lower single tree growth and vitality (Kadavý *et al.*, 2025). While forests in nature reserves are valued for their roles in biodiversity conservation, recreation, cultural heritage, and as a source of valuable scientific research data, their function as carbon stores is becoming increasingly important in the context of climate change (Sexton, 2023). It is also believed that such forests stop being carbon sinks and begin releasing more carbon at an earlier age than managed forests would. The carbon sequestration capacity of trees reduces with age, thus old forest turns into a carbon source instead of a carbon sink (Leng *et al.*, 2024). There are still considerable uncertainties about how forests sequester and emit carbon, particularly under varying management practices. Forest carbon sequestration has received increasing scientific attention, particularly regarding how forests of different ages store carbon and how management practices influence their sequestration potential. There is no doubt that temperate forests play an essential role in storing carbon in both trees and soil. According to Musselman et al. (1991), harvesting plays a pivotal role in releasing carbon back into the atmosphere. During the study period, harvesting was estimated to contribute up to 3 gigatons of carbon emissions annually. These changes in carbon release can enhance photosynthesis by 30 to 40 % in optimal conditions and contribute to global warming. While forests are carbon sinks, absorbing carbon, they can also be carbon sources when deforestation happens and through respiration. Especially when forests become old or suffer from disturbances, like wind, pests, or diseases, they can emit more carbon than they sequester. Due to rising CO2 levels, temperate forests will experience changes. In some regions, forest growth is expected to increase, while in others, significant declines may occur. Temperate forests do play a pivotal role in absorbing carbon. However, the carbon sequestration potential of temperate forests, while substantial, remains limited in duration and capacity (Musselman et al., 1991). In Sweden, forests, as everywhere, do their part in carbon sequestration. Research in specific forests that serve as a representative of the region in Uppsala County examines many differences in sequestration and other related factors (Eriksson *et al.*, 2007). Research in Uppsala County additionally indicates that the rotation periods of forests and their species composition have a significant impact on carbon storage. For instance, pure stands of Norway spruce can store as much as 85 tons C/ha over a span of 120 years, while mixed stands reach comparable levels. However, the rate of storage increase drops significantly after 60 years, and economic viability also declines beyond this point frame. These insights imply that determining the optimal rotation period is essential to enhance both carbon sequestration and financial return.

Jörgensen *et al.* (2021) found that forest management methods such as thinning and fertilization may produce varying impacts on CO_2 absorption in Scots pine forests. Thinning typically lowers the carbon storage in trees, while the soil carbon levels tend to stay constant. Fertilization can boost tree carbon reserves, but this effect doesn't consistently occur alongside thinning.

Lazdiņš (2013) highlights that silvicultural methods like afforestation and drainage enhance CO_2 storage in trees and soil. Forests hold more carbon than meadows, particularly in deeper soil layers (40–80 cm). Additionally, drainage boosts tree growth, notably in Norway spruce. Even following clear-cutting, CO_2 is retained in roots and stumps for years.

Lorenz *et al.* (2010) emphasize that mature forests are effective in storing carbon, but their ability to sequester it decreases as they age because of slower growth. Although old forests can serve as carbon reservoirs, they are not as efficient at absorbing more CO_2. Effective forest management can sustain a favourable carbon balance by encouraging growth and utilizing harvested wood in durable products.

To improve forest carbon balance, the following strategies are recommended Lorenz *et al.* (2010):

- Conservation strategies for soil
- Increase the age at which trees are cut (since older trees store more CO_2)
- Preferring to use selective cuttings instead of clear-cuttings (since clear-cuttings are damaging to the soil and are significant forest disturbances)
- Reduction of harvest intensities
- Managing natural disturbances (fire management, managing pests, diseases, etc.)
- Using trees as timber products instead of firewood

It is crucial to notice how many research opinions are divided on whether management is good for CO_2 sequestration or if we cannot stop managing forests. We should at least reduce it.

The debated fact is about when trees stop sequestering CO_2 and when their carbon balance becomes negative. This was also the main topic in research by Jansons *et al.* (2016). The research concluded that even at the age of 250, the Norway spruce forest stands are still sequestering more carbon than emitting, even in quite dense forests, as the Basal area in these forests was from 27 to 36 m^2 per ha. Although there is a considerable variation between same-age forests, in some cases, the forests emit more carbon than they sequester. Scots pines' balance was quite neutral in old age, with few stands emitting more than sequestering. The basal area for pine in this research was from 17 to 27 m^2 per ha. For silver birch in the old age from 80 to 100 years, the study points out that sequestration is not as positive anymore because of its rapid decomposition cycle (Jansons *et al.*, 2016). More studies have showcased that old forests are still actively sequestering carbon. In an article by (Carey *et al.*, 2001), it is showcased how older models often miss the importance of how effective trees can be in carbon sequestration even after 100 years. Emphasizing the value of keeping forests even after 475 years, they still provide more benefits related to carbon sequestration than drawbacks.

As many researchers emphasize that trees should be left even in old age due to their continued ability to sequester carbon, many sources argue the opposite. Greenfield (2025) states that one-third of Arctic tundra forests face the opposite effect. According to the article, these forests have become a source of carbon emissions. The leading cause in this case is the climate warming, which leads to permafrost melting as the soil becomes warmer. Another thing is the mortality of trees, with old-age trees becoming more susceptible to pests, diseases, and natural hazards. At that point, trees can again become carbon emission sources. According to (Woods *et al.*, 2021), the stand tree mortality rate has grown compared to the past in temperate forests. The difference is as big as 0,7 to 2,5 % per year on average. The most significant difference is in unlogged forests, as trees may have been left in more significant densities, and their individual tree health and vitality have not been increased with thinning (Woods *et al.*, 2021). There is much more evidence pointing to similar things. Research by (Petit-Cailleux *et al.*, 2021) has modeled the future scenarios for Europe, pointing out that more extreme climate scenarios may cause high mortality rates for tree species. In worst-case scenarios, by 2100, up to 90 % of Europe's protected forest gene pools could be at risk of extinction. Even in best-case scenarios, 38 % of these forests could be lost, threatening the carbon balance of forests, as one of many things caused by these changes (Petit Cailleux *et al.*, 2021). The old tree's carbon balance and mortality in the future are very controversial subjects, even among scientists, and need more research in the future.

1.2 Technologies and models in forestry

Fewer people choose to work in the forestry sector, and there is a decline in the number of people working there, so there is a need for work to be automated (VMD, 2021). Nowadays, thanks to technology, many things can be done precisely with technology's help, such as models and simulations to help with forest data calculations, and drones to gather data. Nonetheless, several questions come to mind: is it sufficiently accurate, and do these factors cause people to lose money over time? A study tested the accuracy of photogrammetric models for counting trees in Scots pine stands. The main conclusion is that these models can achieve over 90% accuracy, but issues still arise (Dzenis, 2023).

For a long time, to get forest models to work, and to be precise, they were used in the stands where one species was dominant, and not in mixed forests. Now that technologies, modelling, and simulations have come a long way, they are also expected to deliver precise results in mixed stands.(Porté *et al.*, 2002). Most commercial forest areas may grow in the same-age monocultures, as it is easier to establish and tend. In Sweden, 83 % of forests are coniferous forests, 5 % are pure broadleaf, and only 12 % are mixed forests (Ågren, 2025). Even in those forests, some mixture is inevitable, as some mixture between conifers or some broadleaves growing in the middle of a conifer forest is entirely usual. Between the broadleaves, a mixture is also widespread and tends to happen. These things also point to the need for advanced models and simulations in the case of mixtures. Many models are very precise with standards in monoculture. Still, in mixed species stands they may need human invention and changes in some things to give accurate results and reliable data that can be used in the future (Dzenis, 2023). So, for many different models and simulation tools, it is crucial to understand what they excel at and what they are not as good at. For example, the experiment analyzed many differences to see their weaknesses and strengths. Distance-dependent models struggled with modeling 3D stands over longer times and areas. Gap models were better in such regions, mainly including the ecosystems' ecological functions. Mechanistic models were not as precise as empirical models, but empirical models were more dependent on parameterization data (Porté *et al.*, 2002). It only further proves the need to know in which situation which model should be used, and to be flexible and knowledgeable. It has been tested by Ekuzis (2024) that only processing of data using models can be 30 % faster than manually calculating everything, saving a lot of crucial time. Also, using drones and models with DTM (Digital Terrain Model) and DSM (Digital Surface Model), it is possible to get forest inventory data with an accuracy of 97 % (Ekuzis, 2024).

In another research, the Heureka system was analyzed. Heureka is a forest planning and analysis tool that can help balance the goals of profit-making and including biodiversity. Heureka works at the stand and regional levels and uses simulation, optimization, and multi-criteria decision-making, which can be set with the user's desired settings. Heureka is still under development and requires further tests and research to become better (Lämås *et al.*, 2023). Modern technologies, models, and simulations can significantly improve the efficiency of forest work and reduce its labor intensity. So, assessing the accuracy of Heureka simulations would significantly improve how forest management practices are planned in the future.

1.3 Objectives of the thesis

This thesis aims to assess if low-intensity forest management can boost carbon sequestration in protected forest areas while minimizing disruption to natural ecological processes. The research employs simulations using the Heureka RegWise model to analyze the impact of limited interventions, like selective felling, on carbon uptake across various tree species, particularly emphasizing European beech, Norway spruce, and silver birch. This thesis aims to address some of these questions. Simulation models provide one of the most efficient ways, in terms of both time and accuracy, to predict how forest management can impact carbon sequestration and gather all other essential data about the forest. It is possible to simulate various scenarios and determine which can help achieve all the owners' goals (Ekuzis, 2024). Simulation tools like Heureka can simulate long-term forest dynamics by incorporating management interventions at the owners' specified times and illustrating changes in carbon dynamics. Heureka is an advanced forest management tool developed by SLU. It is extensively utilized in both research and forestry companies for forest management planning (Lämås *et al.*, 2023). Thus, accurately evaluating the accuracy of Heureka simulations would substantially enhance the planning of future forest management practices.

Hence, the main research questions are:

- Can minimal intervention in nature reserves extend the duration of carbon sequestration and prolong its capacity to act as a carbon sink?
- Compare the carbon dynamics of different tree species under various management scenarios.

The aims of this study are:

1. Analyze how management scenarios can influence the future forest carbon sequestration ability of nature reserves.
2. Analyze how varying management scenarios and tree densities influence the carbon dynamics of different tree species in Söderåsen National Park.

A central hypothesis is proposed to guide the research. With minimal interventions, such as selective tree felling, it is possible to prolong the period during which these forests maintain a positive annual carbon balance and enhance their carbon sequestration. The main trends in carbon dynamics and responses to low-intensity management are consistent across various species, showing similar characteristics.

2. Materials and methods.

2.1 Study Area

Established in 2001, Söderåsen National Park is situated in southern Sweden and spans 1,625 hectares of continuous ridge terrain (Länsstyrelsen Skåne, 2024). Söderåsens National Park experiences an average temperature of 7 to 8 °C, with the warmest month being July, with an average of 18 °C, and the coldest month being January, with an average of 0 °C. The average annual precipitation is 800 to 1000 mm per year. In Söderåsen National Park, the elevation varies significantly due to its ridge and valley landscape, with the highest point being 212 m above sea level and the lowest point being 60 m above sea level. Söderåsen National Park is recognized as the largest continuous deciduous forest in Northern Europe. The majority of its area is designated under the NATURA 2000 network. The park represents southern Sweden's characteristic flora, fauna, and climate. It holds ecological and economic importance, serving as a habitat for numerous endangered species while attracting approximately 500,000 visitors annually. The dominant natural habitats include the *Fagus sylvatica (*European beech) forest, covering 856 hectares, followed by the *Alnus glutinosa* (black alder*)* forest, with 148 hectares, and the birch forest occupying 133 hectares. The dominant age for beech forests is 90 to 120 years (Schröder, 2024). Before the establishment of the national park, the area now comprising Söderåsen National Park was used for agriculture and forestry. The presence of pastures, clearings, single-layered forest stands, and the introduced species, such as thuja, evidences this historical land use in this area. The current management plan aims to preserve native vegetation types, support their natural development, and gradually restore the landscape by converting coniferous stands into deciduous forests to eliminate traces of past forestry activities (Schröder, 2024).

From all gathered data in the Söderåsen National Park, the most dominant tree was beech, followed by oak and birch, as shown in Figure 1. There is a wide age distribution, with the dominant tree age mainly between 105 and 120 years (Figure 2). Beech tends to live for about 150 to 300 years, depending on conditions, and sometimes reaches even 500 years (Packham *et al.*, 2012).

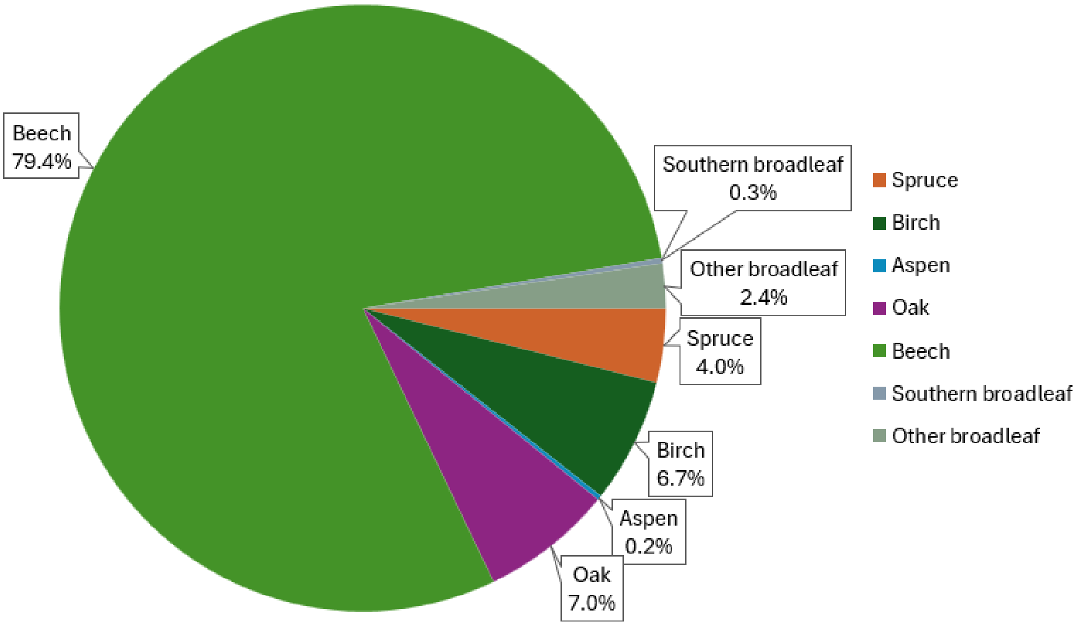

Figure 1. Tree species distribution by volume. (Dzenis, J. (2025) [Chart] RegWise).

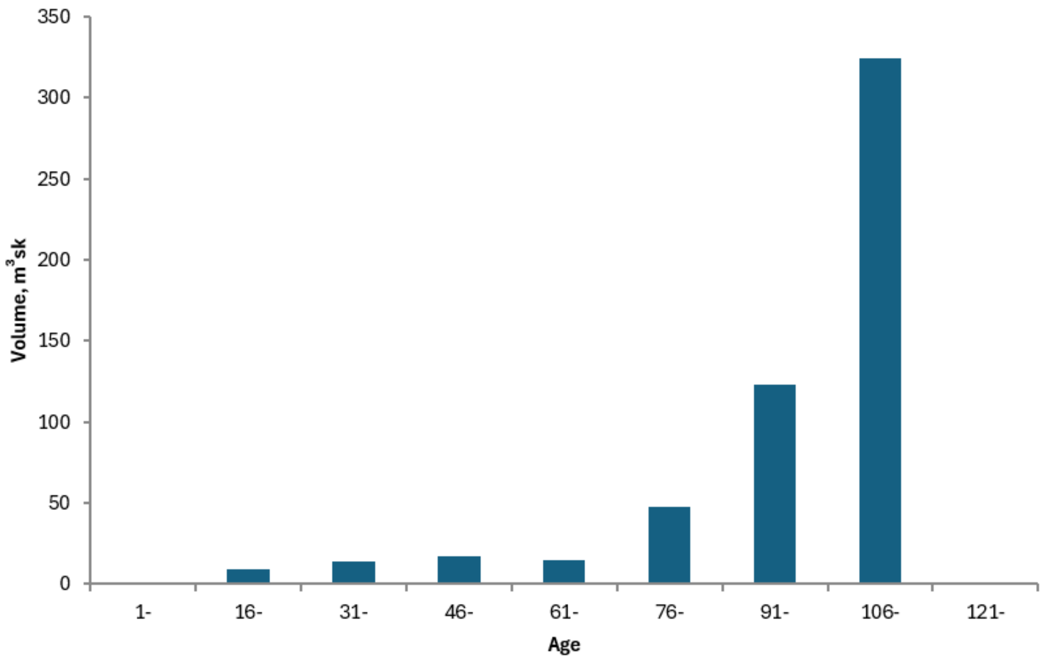

Figure 2. Volume Distribution by Tree Age Class. (Dzenis, J. (2025) [Chart] RegWise).

In Söderåsen National Park, the most frequent age was from 90 to 120 years old, as seen in Figure 2, and almost 80 % of all tree species were beech. The age of this tree species is still not reaching its peak, but if it lives for 100 years more without any interventions, the beech tree ages will start to become old.

2.2 Data Collection Methodology

This study collected data from 64 randomly generated points within Söderåsen National Park using Python, as illustrated in Figure 3. Due to the randomization process, the distribution of points may not proportionally represent all forest types, as some may be over- or underrepresented by chance.

Figure 3. Map of Söderåsen National Park with randomly generated sampling points. (Dzenis, J. (2025)[Screenshot] Apple Maps).

For data collection, circular plots with a radius of 9 meters were used, corresponding to a 0.1% sampling intensity. This approach resulted in the selection of 64 plots, representing a total area of 1625 hectares. The plot locations were randomly generated using Python, based on the provided map of Söderåsen National Park. Each plot was georeferenced, and the coordinates were used for field navigation via mobile GPS. At each plot, the following data were collected:

- Species name of each tree
- Diameter at breast height (DBH) 1.3m for each tree above 2m
- Height of the 3 dominant trees of each species

- Soil moisture determination
- Basal area
- Representative area picture

Out of the total of sixty-four plots, in six plots, data collection was impossible due to reasons like high slope, fence around the area, or location being in the middle of a meadow. In a total of 58 sample plots, data were gathered and further used in Heureka simulations.

For data collection tools used were a tree caliper for DBH measurements, a measuring tape for distance measurements, colorful paper ribbons for tree marking, Haglöf Vertex 5 (Vertex further in the text), and a Transponder T3 for tree height measurements, and for basal area measurements, an angle gauge.

Figure 4. Transponder T3 (on the left) and Vertex 5 (on the right). (Haglöf. (N/A) Vertex 5. [Screenshot] https://haglofsweden.com/project/vertex-5/ [01.04.2025]).

The first step in collecting data was to find a place for the sample plot coordinates in the field. For this step, a mobile phone with Google Maps was used. Once the coordinates' center was reached, the middle tree was taped with the colorful paper ribbon. From the center, 9 m was measured in each direction, and borders were marked with a ribbon. Then, in the plot, each tree's DBH was measured with a caliper at 1.3 m height or breast height, and its species was noted down. Each measured tree was marked with a colorful ribbon to ensure no tree was skipped or counted twice. From the center of the plot, the basal area was measured using an angle gauge. The next step was to measure each species' top three tree heights. For this step, Vertex was used. With the on button, the Vertex was turned on, and in settings, the distance from the tree was set to 15 meters. Using the hook that the Transponder T3 was equipped with, Transponder T3 was put on a tree at a height of 1.3 m. Then, with a measuring tape, 15 meters were measured from the tree, and the Vertex was turned on the measuring mode. First, the height of Transponder T3 was calibrated to see the angle and check if the height was correct. After that, Vertex is aimed at the top of the tree, and its height is measured. This process repeats for each species' 3 tallest trees, and all measurements are noted on a mobile phone. The next step is to determine how wet the area is, which was determined with a number from 1 to 5, with 1 being completely dry and 5 areas with standing water and damp. The last step was to represent the area to see the ground vegetation and the area's characteristics, and to take a screenshot of the area coordinates to remember when the data gets processed. From all the coordinates gathered, the NATURA 2000 website is accessed, and it checks what kind of vegetation type grows at each coordinate location.

2.2.1 Heureka Model

Once the data is gathered from the Heureka official website, Excel templates for RegWise are downloaded. RegWise is a large-scale forestry scenario simulation and analysis tool. Heureka is an advanced Decision Support System (Lämås *et al.*, 2023), used by many large forest companies in Sweden. The growth simulator includes a set of empirical models for tree growth and establishment, in-growth, and mortality of the commercially important tree species. All these are regression models fitted to data from the National Forest Inventory (Fahlvik *et al.*, 2014). In these templates, the necessary fields are filled with data from sample plots, and other essential fields like volume, tree number per hectare, and quadratic mean diameter get calculated from the data.

InventoryYe	OwnerType	EvenAged(	DGV	DG	H	MeanAge	N	G	V	CAI	PropPine	PropSpruc	PropBirch	PropAsper	PropOak	PropBeec
2025				34.1	32	120	511	18.5	325.6							1
2025				46.47	28	120	314	13	200.2							1
2025				25.73	25	80	747	25	343.75							1
2025				19.47	28	100	1375	16.5	254.1							1
2025				15.61	23	80	1022	18	227.7				0.308			0.423
2025				60.86	34	120	157	15	280.5							1
2025				50.31	27	110	236	16	237.6							1
2025				16.83	19	60	1965	31	323.95				0.14			0.86
2025				24.13	26	100	1179	22	314.6							0.966
2025				23.41	29	120	747	17	271.15						0.028	0.972
2025				30.18	27	110	1415	25	371.25							1
2025				19.64	22	70	552	19	229.9							1
2025				30.19	19	100	629	21	219.45				0.125			0.688
2025				15.75	20	70	1729	25	275				0.227			0.75
2025				35.88	28	120	432	17	261.8							1
2025				11.85	16	60	2083	15	132			0.019	0.472			
2025				33.29	26	100	550	28	400.4				0.214		0.071	0.571

Figure 5. Example of a part in the RegWise Excel template for stand data. (Dzenis, J. (2025) [Screenshot] Excel template).

Once the data was all transferred to Excel templates, these templates were imported into Heureka RegWise to see the data and to be able to do simulations for all regions and specific stands. For the primary research, RegWise version 2.23.0.2 will be used, where forest inventory data will be uploaded as "Tree List". For the "Tree List", individual tree-level data, such as individual tree DBH and height, was used.

2.2.2 Management Scenarios

Data were analyzed over 100 years, and simulations will be conducted using scenario settings with Uneven-aged (CCF) forestry. To determine if minimal interventions can increase carbon levels in the park, simulations will be conducted for the entire area. There was a test using the Nature Conservation Forest as scenario settings, but since mainly all trees are big and of too much conservation value, with this scenario, no interventions were done. There were three different management methods in the simulations, one with no interventions (unmanaged) and two management scenarios with varying intensity of selective felling. Both low intensities, where the basal area removed during each selective felling was around 5 to 10 % and 2 to 5 %, respectively. Further in results, selective fellings with 5 to 10 % intensity will be called "Treatment 1" and selective fellings with 2 to 5 % intensity will be called

"Treatment 2", while "No Treatment" is an unmanaged forest. First, the tree age and the things that can be done, and the max height is extended to match the tree ages of trees in the national park, and how much they would change, and the max height is increased to match the highest trees in the park. Therefore, the selective fellings were accurately simulated to see if they would have any positive changes. It varied how many selective fellings were done in each plot-designed area, as it could be zero or multiple. For analysis, "Total carbon in living trees (above and below ground) in ton C/ha" was selected. From this, the average carbon sequestration for all forests in each period could be calculated.

The other thing to compare is carbon sequestration changes between species in Söderåsen National Park. While there are many different species, as shown in Figure 1, such as beech, oak, aspen, birch, and spruce, not all were dominant in any plots, as they may have had an occasional appearance. Like oak, which accounts for 7 % of all trees collected, its prevalence was largely due to the appearance of a few trees in many plots, while spruce was 4 %, but it was the most dominant tree in the plots. This comparison applies to tree species identified and predominant in one or more sample plots, including beech, spruce, and birch. The same simulation parameters were applied, and the dominant species—European beech, Norway spruce, and silver birch—were analyzed individually to assess their unique responses to light selective thinning treatment. This allowed for a comparison of species-level differences in carbon sequestration over the full 100-year duration.

2.2.3 Variables and Calculations

The difficulty was with stand age as tools like increment borer could affect the health of trees in the national park, the age class of 90 to 120 years was given for mature forests. Judging from the forest soil fertility, from the NATURE 2000 website, soil moisture, tree height, mixture, and DBH, the age estimations were done for trees in each plot. In each sample plot, the three highest trees of each species were measured, so the rest were calculated. A tree's height (measured in decimeters) is estimated using a multiple regression model, which connects tree height to multiple stand and site variables according to the height function developed by Söderberg (1992).

$$ln(h) = c + b_1 * \frac{1}{d + 50} + b_2 \cdot Akl + b_3 * Akl^2 + b_4 * (lat * alt) + b_5 * gp + b_6 * sost + b_7 * reg5 + b_8 * delyta \quad (1)$$

Where:

- h: Estimated tree height, in decimeters (dm). Converted to meters after calculation.
- ln(h): Natural logarithm of the tree height.
- d: Diameter at breast height (DBH), in centimeters (cm).
- Akl: Tree age, typically measured in years.

- lat·alt: Product of latitude and altitude, used to capture geographic effects.
- gp: Proportion of conifers in the stand (ranges from 0 to 1). For pure beech stands, this is 0.
- sost: Dummy variable for Southeastern Sweden (1 if true, 0 otherwise).
- reg5: Dummy variable for Region 5 (1 if applicable, 0 otherwise).
- delyta: Dummy variable indicating shared stand type (1 if shared, 0 if single species).
- c: Intercept (constant term), set to 5.2974 in this model.
- b_1 to b_8: Regression coefficients derived from empirical data.

Exponentiate to get the height in decimeters:

$$h\_dm = e^{ln(h)} \tag{2}$$

Where:

- h_dm = estimated tree height in decimeters (dm)
- ln(h) = log-transformed height value derived from the regression model
- e = Euler's number (the base of the natural logarithm, approximately 2.71828)

Carbon sequestration will be calculated for each time period based on the total carbon to see the differences.

$$CS_t = C_t - C_{t-1} \tag{3}$$

Where:

- CS_t = Carbon sequestration during period t (tons C/ha)
- C_t = Total carbon stored at the end of period t in living trees (tons C/ha)
- C_{t-1} = Total carbon stored at the end of the previous period in living trees (tons C/ha)

Furthermore, there will be three specific tree simulations with tree species that have dominated any plot, being the main species in it. The remaining settings in the simulations will be the same. Carbon sequestration was assessed as the net change in total carbon stored in living trees over successive periods. For each plot, the change in carbon sequestration for each period was calculated by subtracting the total carbon value of the previous period from that of the current period, such as Period 1 - Period 0, Period 2 – Period 1, up to Period 20 – Period 19. This approach yielded estimated carbon fluxes for each period, facilitating the analysis of both short-term and long-term sequestration trends under different management alternatives. Data for this calculation was derived directly from the "Total Carbon in Living Trees ton C/ha" column in the Heureka RegWise simulation output. One period spans 5 years, and with a total of 21 periods (from Period 0 to Period 20), these periods collectively represent 100 years. To evaluate the similarity in carbon stock levels between treatment and unmanaged (no treatment) scenarios, the Percent Similarity (%) was calculated for each period using this formula:

$$Percent\ Similarity = \left(\frac{C_{treatment}}{C_{no\ treatment}}\right) * 100 \tag{4}$$

Where:

- $C_{treatment}$ = Total carbon stock in the managed scenario (Treatment 1), (tons C/ha)
- $C_{no\ treatment}$ = Total carbon stock in the unmanaged scenario (No Treatment), (tons C/ha)

To maintain consistency in species age structures, a filtered dataset was developed specifically for beech-dominated plots. In this version, known as "updated beech", only mature beech stands (around 90–120 years old) are included, while plots with significantly younger beech trees are omitted. This modification allows for a more equitable comparison of carbon sequestration trends among similarly aged stands of birch, spruce, and beech.

3. Results and analysis

3.1 Forest-Wide Carbon Sequestration Simulations Under Different Management Intensities

The simulations are conducted for all parks, including all sample plots, which produce results that illustrate the difference between No Treatment and Treatment 1, characterized by selective fellings of 5 to 10% of the intestines. This shows the differences between the two treatments in Table 1.

Table 1. *Comparison of total carbon stock among all living trees.*

Year	10	20	30	40	50	60	70	80	90	100
No Treatment, ton C/ha	137	149	158	167	173	178	181	184	186	187
Treatment 1, ton C/ha	133	139	145	149	154	157	159	162	165	166
Numeral deviation, ton C/ha	4	10	13	18	19	21	22	22	21	21
Percent Similarity, %	97	93	92	89	89	88	88	88	89	89

It can be seen that the differences are not very big in Table 1, considering that a lot of harvested wood would still store carbon from selective felling, and since harvested wood's carbon stock is not included, showing just living trees and not considering trees that are harvested to see actual forest carbon storage. Furthermore, to see more effects, the thinning and selective felling grade was reduced by 5 % at max and 2 % min. With a lower thinning grade, the interventions would be less harmful, especially in national parks; yet, they might be performed more frequently in simulations.

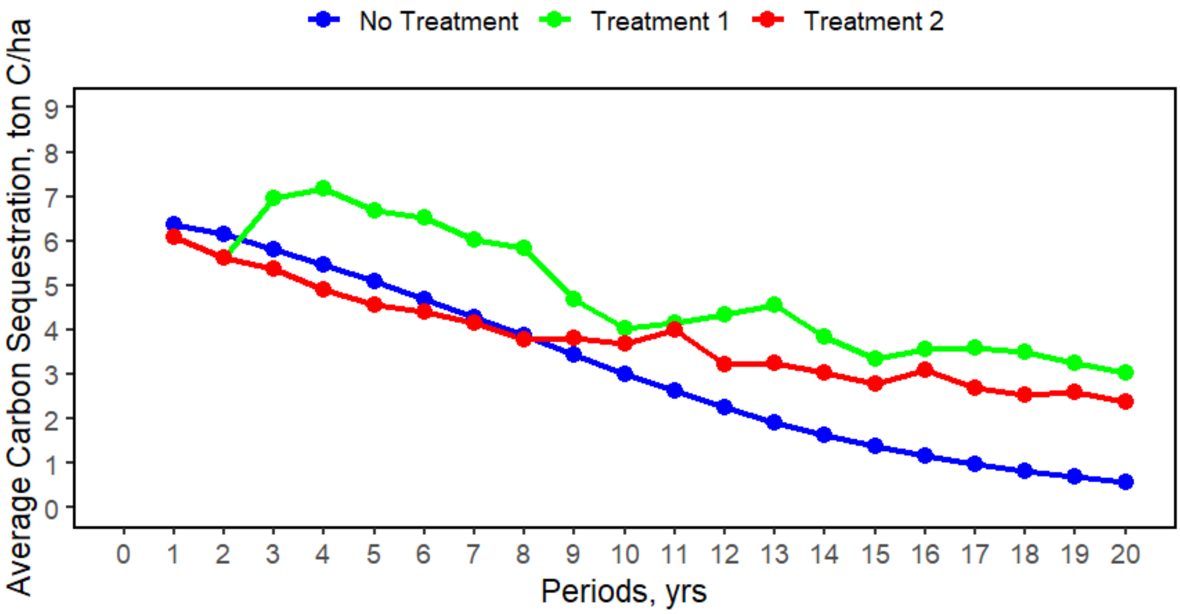

Figure 6. Average carbon sequestration (ton C/ha) per 5-year period over a 100-year simulation, under different forest management intensities. "No Treatment" signifies unmanaged forest conditions. "Treatment 1" implements low-intensity selective felling at a rate of 5–10%, while "Treatment 2" applies this practice at a lower rate of 2–5%. (Dzenis, J. (2025) [Chart] RStudio).

While examining average carbon sequestration throughout the park, it becomes apparent that it does not drop below zero, even over 100 years, but instead approaches zero. Therefore, it is plausible that the trend will continue, and the park will eventually begin to emit carbon. Figure 6 illustrates that intervention through selective felling, even at low intensities, can alter the amount of carbon sequestered. From the figure, it is evident that without interventions, the average sequestered carbon from all sampled areas at period 10 was already below 3. The line with Treatment 1 remains higher at period 20, which is 50 years later. Additionally, both methods exhibit lower carbon sequestration compared to the No Treatment method, but they subsequently show positive differences. The average carbon sequestration for no interventions was 2.38 tons C/ha lower than that of the selective felling intervention. Lastly, the mean difference ranged from -2.25 to -2.52 tons C/ha, indicating that the intervention of selective fellings consistently leads to higher estimates of carbon sequestration across all periods. A very important aspect is not only how much carbon is sequestered in the forest each period, but also how much carbon is stored in each period compared to the no-treatment method and Treatment 1 with selective fellings at intensities ranging from 5 to 10 %. With lower intensity rates of selective fellings (2 to 5%), the average carbon sequestration remains higher than in the case where no action is taken. Still, it is slightly lower than in the case of selective felling intensities of 5 to 10 %. For the minimal-intensity selective felling method (2-5%), the average carbon sequestration per 5-year period, calculated over 20 periods (100 years), was 4.63 tons C/ha for low-intensity selective felling, while without any treatment it was 3.11 tons C/ha. While the difference ranged from 0.47 to 2.58 tons C/ha. This further supports the notion that improvement in carbon sequestration is statistically significant and practically meaningful. It can be concluded that minimal selective fellings significantly increase carbon sequestration compared to unmanaged forests. Comparing the differences between the two methods of selective fellings of 2 to 5% (very light selective thinning) and selective fellings with the intensity of 5 to 10% (light selective thinning) also showed differences. For very light selective thinning, the mean carbon sequestration per period was 4.63 tons C/ha, which was -0.86 tons C/ha lower than the mean carbon sequestration light selective thinning had. The results indicate that light-selective thinning has a slightly higher carbon sequestration rate.

3.2 Species-Specific Responses to Low-Intensity Forest Management

The management method used in simulations is selective fellings with an intensity of 5 to 10 %, as it showed the best results. In comparison, intensity-selective fellings with a 3 to 5 % intensity won't be tested since there is no significant difference; therefore, the method with the highest increase will be tested, allowing for the study of trends. They all will be tested in RegWise to see if there is any trend of differences between species and if there is a statistically significant difference in how species react to management regarding carbon sequestration.

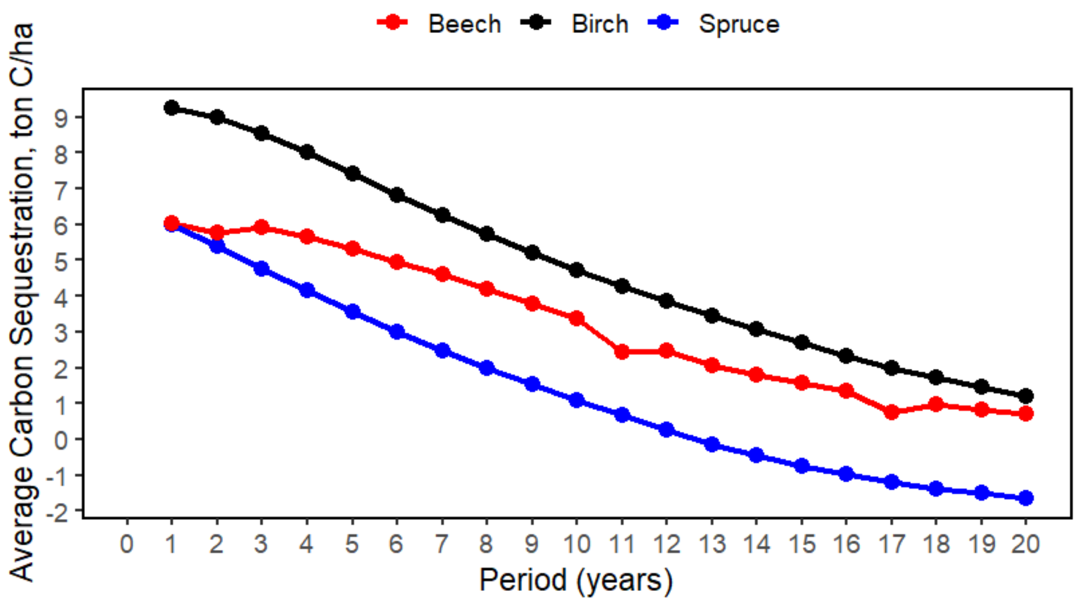

Figure 7. Average carbon sequestration (ton C/ha) per 5-year period over a 100-year simulation of unmanaged forests characterized by various tree species. The graph illustrates the carbon uptake of European beech (Fagus sylvatica), silver birch (Betula pendula), and Norway spruce (Picea abies) as they develop naturally without management interventions. (Dzenis, J. (2025) [Chart] RStudio).

As shown in Figure 7, the average carbon sequestration for spruce is consistently below 0 per period. In contrast, while spruce stands were old, a variety of younger and older stands were present for beech. To do an accurate comparison, the young beech stands will be removed, allowing us to compare full-growth stands with other full-growth stands. Since the average difference is 0.93 ton C/ha, from old beech stands and all beech stands, and the interval ranges from 0.64 to 1.23 ton C/ha. This shows that in 20 periods, or approximately 100 years, younger beech stands help sequester significantly more carbon, whereas in older stands, carbon sequestration decreases, and therefore older stands are chosen in the future.

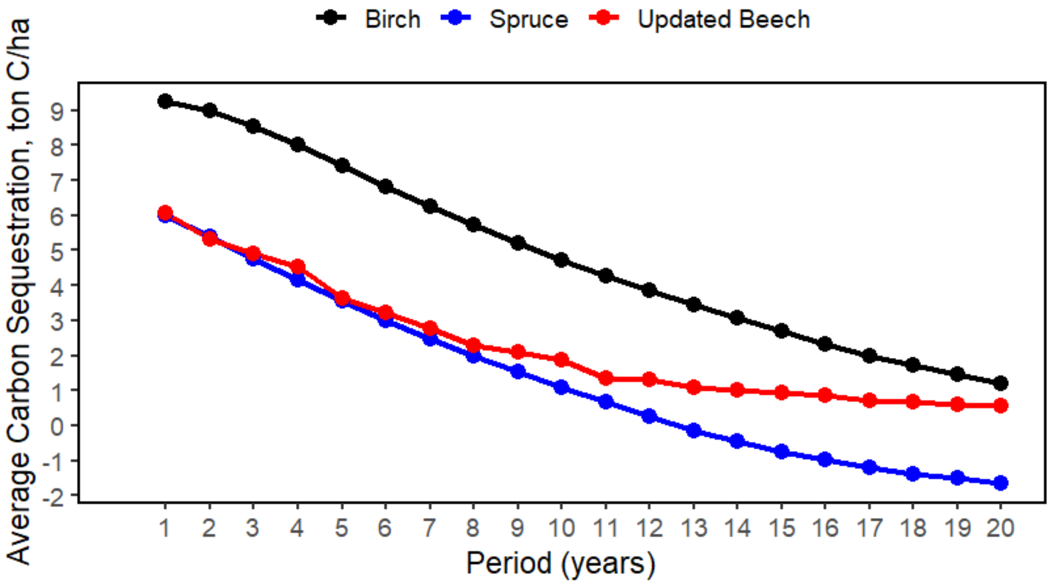

Figure 8. Average carbon sequestration (ton C/ha) per 5-year period over a 100-year simulation for unmanaged birch, spruce, and updated beech data. The updated beech curve includes only mature, fully-grown stands, omitting younger beech sample plots. This analysis ensures consistency across species age structure when assessing long-term carbon dynamics. (Dzenis, J. (2025) [Chart] RStudio).

Still, even with older stands, carbon sequestration remains positive, never reaching the point of emitting more carbon than sequestering (Figure 8). Initially, it can be observed that while spruce and beech are approximately 100 to 120 years old, they exhibit the same sequestration. However, as both stand age and spruce sequestration decrease, they go very low, to the point where they emit carbon. Beech, on the other hand, remains positive, but also at a very low level. Birch has the most positive carbon sequestration early on, but over 100 years, it drops the most.

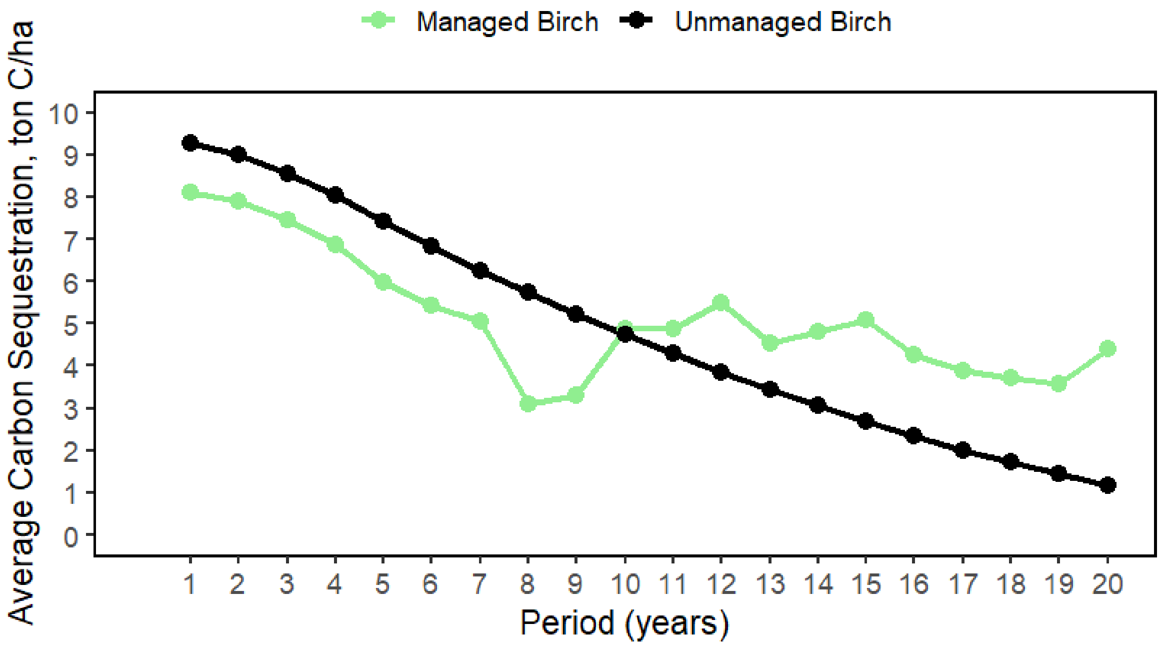

Figure 9. Average carbon sequestration (ton C/ha) per 5-year period over a 100-year simulation for birch-dominated stands under managed versus unmanaged conditions. "Managed Birch" refers to areas undergoing low-intensity selective felling (5–10%), while "Unmanaged Birch" indicates areas allowed to grow naturally without interventions (Dzenis, J. (2025) [Chart] RStudio).

For birch, it can be seen in Figure 9 that, with management at the beginning, the impact is negative, as it sequesters less carbon when left unmanaged. Still, as it reaches older age and its sequestration rates drop, with selective felling rates of 5 to 10 % in intensity, the carbon sequestration rates remain higher. The mean difference between these two treatments is approximately 0.28 ton C/ha. The difference interval ranged from -0.54 to 1.10 tons C/ha. These results indicate that managing birch stands does not result in a significant difference compared to unmanaged birch stands.

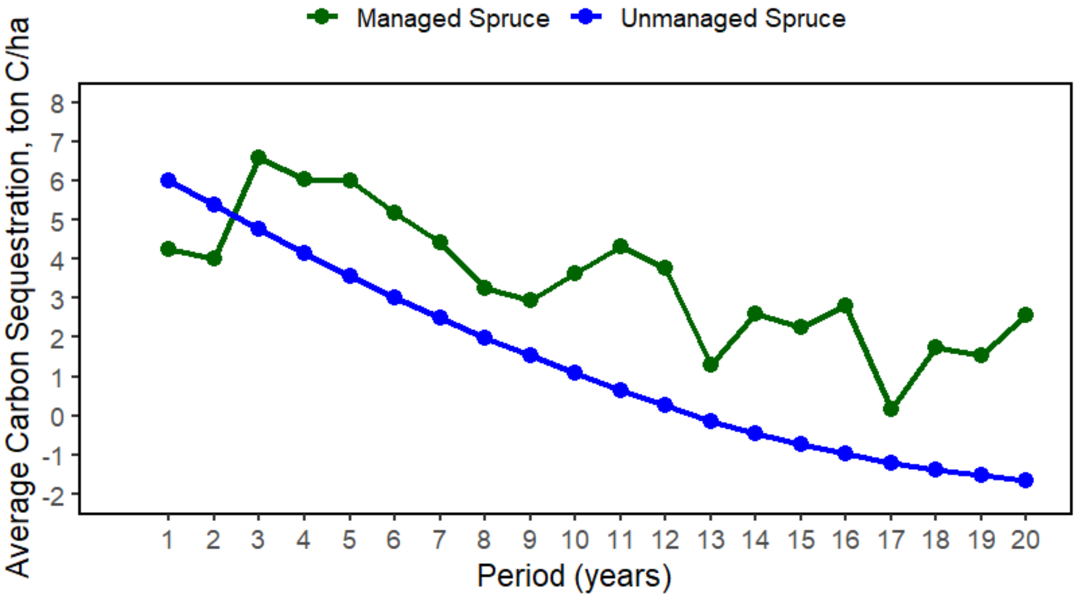

Figure 10. Average carbon sequestration (ton C/ha) per 5-year period over a 100-year simulation for spruce-dominated regions under both managed and unmanaged conditions. "Managed Spruce" denotes areas exposed to low-intensity selective felling (5–10%), while "Unmanaged Spruce" pertains to regions that are allowed to grow naturally without any interventions (Dzenis, J. (2025) [Chart] RStudio).

For spruce, it can be seen in Figure 10 that management of selective felling with an intensity of 5 to 10 % yields more positive results, as the average carbon sequestration is higher. Big drops could be explained if selective felling is done during these periods, so carbon sequestration would decrease as trees in the forest are removed. Ultimately, even if an unmanaged spruce forest emits carbon, if these areas are managed, carbon sequestration remains positive. The average carbon sequestration increase for managed spruce was approximately 2.12 tons C/ha, with a difference interval of 1.40 to 2.85 tons C/ha. These results further indicate that managing spruce stands through low-intensity selective felling of 5 to 10% can significantly enhance carbon sequestration compared to unmanaged spruce stands.

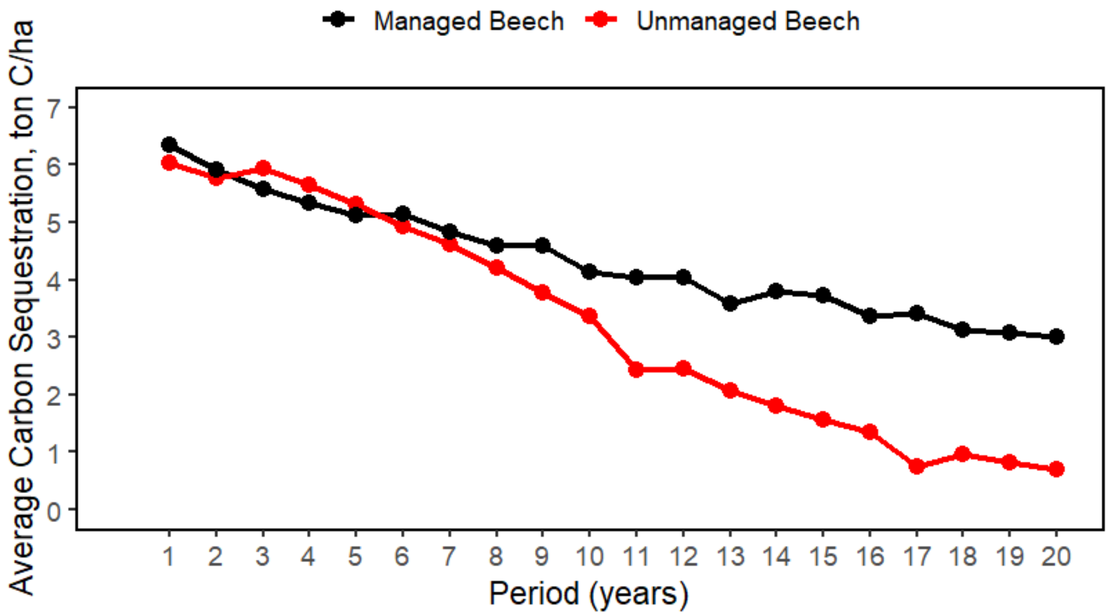

Figure 11. Average carbon sequestration (ton C/ha) per 5-year period over a 100-year simulation in beech-dominated regions, both managed and unmanaged. "Managed Beech" indicates areas undergoing low-intensity selective felling (5–10%), whereas "Unmanaged Beech" signifies regions allowed to evolve naturally without any interventions (Dzenis, J. (2025) [Chart] RStudio).

Beech is similar at the beginning; however, as it ages, there is a clear difference in the amount of carbon sequestered through selective felling at intensities of 5 to 10% compared to doing nothing, and it grows larger with each subsequent period Figure 11. Still, in both cases, the graph indicates a downward trend, but with management, carbon sequestration is both prolonged and enhanced. The mean difference in carbon was 1.11 tons C/ha, indicating that managed beech sequesters more carbon than unmanaged beech, while the difference interval ranged from 0.64 to 1.59 tons C/ha. These results demonstrate that managing beech through selective felling at low intensity significantly increases carbon sequestration in beech stands. After comparing all three species that dominated each plot, two out of three species showed statistically significant differences between treatments, and all species secreted more carbon with low-intensity selective fellings.

Table 2. Forest management impact on different species.

Species	Cumulative carbon sequestered (living + harvested), ton C/ha		Numeral deviation, ton C/ha	Percentage deviation, %
	Unmanaged	Managed		
Birch	96.93	104.22	7.29	7.52

Continuation of Table 2.

Species	Cumulative carbon sequestered (living + harvested), ton C/ha		Numeral deviation, ton C/ha	Percentage deviation, %
	Unmanaged	Managed		
Spruce	26.77	172.24	145.47	543.37
Beech	64.46	114.08	49.62	76.98

This further demonstrates the significant impact of low-intensity forest management on the carbon sequestration of different species. For birch (Table 2), it changes by only 7.52 %, while for beech, the difference between unmanaged and managed forests' carbon sequestration is already 76.98 %, and for spruce, the difference is quite substantial at 543.37 %. This indicates that spruce responded more robustly to low-intensity management than birch, whereas the differences with beech were less distinct. This reinforces the necessity for species-specific management to optimize carbon sequestration. The heightened response noted in spruce may be due to its quicker growth dynamics and increased sensitivity to competitive release after thinning. At the same time, birch and beech might need different structural or intensity thresholds to achieve similar carbon gains.

4. Discussion

4.1 Enhancing Carbon Sequestration: Forest Management and Modelling Approaches

The results clearly showed that with minimal interventions, it is possible to enhance the carbon sequestration of forests (Figure 6). While carbon sequestration is enhanced, a downward trend persists as the amount being sequestered declines each period for the forest, raising the question of how long it will last before it starts emitting carbon. The primary reason more carbon is sequestered with minimal interventions is that new space becomes available for trees, even with minimal actions, thereby enhancing the growth of existing trees. (Peng *et al.*, 2022).

Minimal interventions, such as low-intensity selective felling, strike a balance between passive conservation and active management. They primarily aim to enhance carbon sequestration without significantly altering the forest's natural makeup, structure, or biodiversity (Lindenmayer *et al.*, 2006). In protected areas like Söderåsen National Park, maintaining ecological integrity is crucial, making low-impact approaches preferable to intensive forestry. Research shows that high-intensity logging can negatively affect species diversity, soil health, and ecosystem functions (Paillet *et al.*, 2010). On the other hand, minimal interventions help conserve old-growth features and enable forests to serve as carbon sinks, avoiding the ecological costs of large-scale disturbances (Bauhus *et al.*, 2009). The objective is therefore not just to maximize carbon capture but to enhance sequestration with minimal impact on biodiversity and ecosystem resilience.

Harvested wood can still serve as a carbon sink, unless used as firewood, enhancing also the total carbon stored (Lorenz *et al.*, 2010). Simulations can aid decision-making by guiding forest management strategies that focus on maximizing carbon sequestration and enhancing long-term carbon stocks. Simulations and models can be quite accessible and help simplify complex concepts for people without a deeper knowledge of the subject. If there is a possibility of simulating how to manage their forest while still generating income, it could become a desirable option even for private owners. Currently, models and simulations are making significant advancements, becoming more precise and accessible to a broader audience. If, with a single forest visit and brief simulated data processing, it is possible to obtain 97 % accurate forest data regarding tree DBH, then, of course, the aim should also be to apply this to other inventory data, such as vitality, height, and carbon, making it easier as well. (Ekuzis, 2024). Data gathering remains the most significant challenge for simulations, due to its time-consuming and expensive/cost-inefficient nature. With Heureka, simulations can be run for the entire forest or divided into sample plots, and mean stand variables can be calculated using tree-level data. Furthermore, choosing appropriate management methods can help understand how various scenarios affect forests, the processes within them, and the income that can be generated. If people have an easy way to calculate their expenses and see a steady income, they are also likely to show interest in ecological factors like carbon sequestration and enhancing their forest in a nature-friendly way. Research shows that people are willing to pay more for certified or nature-friendly wood products (Cai *et al.*, 2013).

4.2 Impacts of Management Intensity on Forest-Wide Carbon Sequestration

Heureka simulation results with RegWise indicate a notable rise in carbon sequestration when comparing unmanaged forests to those managed through low-intensity selective felling. However, decreasing the selective felling intensity from 5–10% to 2–5% led to only a minor reduction in average carbon sequestration, suggesting diminishing benefits at lower thinning levels. Table 1 and Figure 6 illustrate two interconnected yet distinct aspects of forest carbon dynamics. Table 1 presents the total carbon stored in living trees at specific time points (e.g., 10, 20, ..., 100 years), representing the cumulative above-ground biomass carbon. This accounts for both gains through growth and losses from activities such as harvesting and natural mortality under various management practices. Conversely, Figure 6 illustrates the average carbon sequestration over 5-year intervals, with each period corresponding to a simulation span of five years (e.g., Periods 1–2 for Year 10, Periods 3–4 for Year 20, and so on). This figure highlights only the incremental gains—how much new carbon was captured during each period, averaged across all plots. The difference between the two arises because:

• The graph focuses only on growth, without subtracting carbon removed by harvest or lost to mortality.

• The table includes both accumulation and reductions, offering a more complete view of the net carbon stock.

• The graph reflects averages per plot, while the table shows totals at a landscape level at decadal intervals.

These two visuals combined offer a clearer picture: the graph shows short-term carbon accumulation trends, while the table displays the long-term net effects of forest dynamics and management practices. Utilizing low intensities is crucial in cases of national parks, where strict rules dictate the types of management allowed, typically permitting low-intensity management to a certain extent. Significant improvements in carbon sequestration models and simulations could influence future national park management, especially as the world seeks methods to reduce atmospheric carbon. Furthermore, an essential aspect revealed by these results is that with low-intensity interventions, it is possible to maintain forests with great age and biodiversity while simultaneously achieving substantial carbon sequestration. This could transform our perspective of national parks in the future, viewing them not only as areas for recreation, nature, and science but also as significant carbon sinks that contribute to carbon sequestration, while still sequestering carbon (Lemelin, 2020). While nature reserves are already seen as places that store carbon, no interventions have been done to increase their capacities and sequestration. To make it happen, it is crucial to have simulation tools like Heureka that can simulate and demonstrate which methods would be most beneficial for each species to achieve the goals of all involved parties. Of course, there are difficulties in managing many parts of the national park since they are often left to natural processes through views that these areas should be left to minimal to no interventions (Gissibl, 2014). Still, it is possible to change long-held beliefs and views by presenting new research and data that support the idea that minimal interventions, at least in some areas, can be beneficial. With the changing global situation, sequestration and storing carbon may sooner or later become priorities, prompting the search for new solutions that could address many of these questions. This data is useful not only for national parks but also for other forest owners, demonstrating how management can aid in carbon sequestration and that managing forests is not necessarily detrimental to the carbon balance. As the new popular topic of carbon farming and carbon credits in European forestry (Naumann *et al.*, 2021) suggests, simulation tools like Heureka could become crucial in assessing carbon in forests and determining how forest owners can enhance carbon stocks in their forests. Moreover, carbon sequestration should be considered an essential factor, as harvested wood often stores carbon (Lorenz *et al.*, 2010). By increasing the sequestration potential of remaining forests, the total carbon stored in forests and harvested wood can be greater, and these aspects should be considered.

4.3 Species-Specific Reactions to Low-Intensity Management

The other crucial part is assessing how different species react to management and how the effect of management changes over time. One of the aspects that is often examined is the increase in species DBH after management; however, the change in carbon sequestration is also of great importance, particularly in national parks or when aiming to increase carbon credits. The results showed that there can be three completely different outcomes from minimal management of three different species (Figures 9, 10, 11, and Table 2). While birch seemed not to be welcoming towards management in earlier stages and became more welcoming later on, for spruce, management changed the amount of carbon sequestered by 145.47 tons C/ha. Two of the three species exhibited a noticeable rise in carbon sequestration when comparing the simulations without management to those with low-intensity management, such as selective tree removals at rates of 5 to 10%. This also suggests that not all species should be treated with a single method and model, and species-specific approaches may be necessary. This is not the only thing that should be considered, as species growth can also change in different places (Umaña *et al.*, 2019). Depending on the site, several factors can change, like vitality, height, DBH, crown, and leaf thickness, which impact how trees sequester and store carbon. Models like Heureka can simulate site-specific scenarios and how each management change impacts the reactions of specific trees and their capacity to sequester carbon at different ages and levels. This could also help determine which parts of national parks can be left unaltered and which parts can be left with minimal intervention, thereby providing the best benefit for nature and the fight against increasing carbon emissions. This would require further research to determine how different site conditions affect tree carbon sequestration and how mixing tree species alters the carbon sequestration dynamics compared to pure stands. So far, the conclusion is that low-intensity management has a statistically significant increase in carbon sequestration for spruce and beech-dominated stands, and management should be considered for them if carbon storage and sequestration are prioritized. This would also require intensive inventories to gather accurate data about trees and sites for the best simulations. Data gathering can be time-consuming and requires specific knowledge, making it challenging for individuals without prior knowledge in the forestry field (Ma *et al.*, 2021). This could be facilitated by using drones and prebuilt models, which can help gather forest inventory data much faster and with great accuracy. Still, this process is also very dependent on weather, such as fog, wind, and rain, which can crucially decrease accuracy and lead to a loss of foliage for broadleaf trees (Ekuzis, 2024), (Dzenis, 2023).

4.4 Generalisability of Findings to Other Protected Forests

The results of this study, based on simulations in Söderåsen National Park, suggest that low-intensity management, which is more environmentally friendly than larger-scale management, can enhance carbon sequestration. These results also demonstrate that using species-specific management can benefit all species. However, when considering how well these findings can be applied to other protected areas, several factors must be taken into account. Some of these factors are species composition, site productivity, disturbance regimes, and existing management policies, and these factors are usually very place-specific, like, for example, Söderåsen National Park being on continuous rocky and ridge terrain. Protected forests in similar temperate regions, with species such as beech, spruce, and birch, as well as comparable stand structures, could react similarly to low-intensity interventions. However, in areas with different ecological features or conservation goals—such as maintaining pristine wilderness or protecting rare habitats—the use of such interventions might be more restricted or need adjustments. Furthermore, site productivity has a significant influence on tree growth. Söderåsen National Park typically has soil that is not highly productive, and applying the same management practices to different soils can yield very different results.

The findings can be applied to other protected areas that share similar ecological characteristics and have a similar species composition and age. This includes temperate forests with moderate productivity, featuring mixed-species stands—mainly beech, spruce, or birch—and shaped by past management practices that have affected their current structure. Notably, protected areas that permit some active intervention, such as those managed with close-to-nature silviculture principles, could benefit from light selective fellings. These practices can help maintain or enhance carbon sequestration while protecting biodiversity. Areas that are interested in preserving their old-looking forests while showing a wish to increase global factors of higher carbon sequestration, for sure, can find this method to be very beneficial. While these results are directly applicable to Söderåsen National Park, they can still serve as a helpful starting point for understanding how low-intensity management affects carbon in forests and for planning management in specific areas.

4.5 Possible Errors and Further Recommendations

Forest inventory can be a time-consuming process and requires prior knowledge. The accuracy of inventory data can significantly impact subsequent simulation results. There may be errors in accessing tree height and DBH, as well as in ensuring that the plot is exactly 9 m in radius. The data management process is quite time-consuming, as each Heureka simulation requires a template to be filled out, regardless of the simulation's specificity level. Human error can significantly reduce accuracy, as highlighted by research showing that, on average, there is a 1% error in manual input (Thompson, 2025). Furthermore, a significant learning curve is associated with simulations like RegWise. Simulations are still a developing subject, so the results should not be taken as 100 % accurate and immediately applied; instead, they should be analyzed and then utilized. Furthermore, the age provided for each place was approximate. While it was specified that the main age in a particular location was, for example, 120, determining the age of each tree can introduce an error.

It is recommended that future studies of this nature be conducted to assess how different tree species respond to minimal interventions aimed at enhancing carbon sequestration. Additionally, research should focus on how site conditions influence results and how these variables may change over time. It would be beneficial to evaluate the accuracy of Heureka simulations by comparing them with manually collected data and analyzing the evolution of this data over the years. A comparison of Heureka simulations using historical management methods should also be performed to determine whether the outcomes are consistent or vary significantly. Furthermore, it is crucial to investigate how low-intensity interventions impact forests in terms of species composition. Providing accurate results regarding species, age, and density will help clarify how changes in carbon sequestration and other factors affect these variables.

5. Conclusions

In conclusion, it is clear that low-intensity forest management can improve carbon sequestration in Söderåsen National Park. The simulations run with Heureka RegWise indicate that low-intensity management through selective felling, at levels of 2 to 5% and 5 to 10%, can raise carbon sequestration by an average of 1.52 and 2.38 tons C/ha, respectively, compared to unmanaged forests. In both scenarios, the results were consistent across different simulation periods. Additionally, although the 5 to 10% selective felling intensity led to higher carbon sequestration, the difference compared to the 2 to 5% scenario was relatively small.

The research indicates that low-intensity management affects carbon sequestration differently depending on tree species, highlighting the importance of tailored approaches. Results show a significant impact on beech and spruce forests, with these areas sequestering more carbon than unmanaged ones. The research confirms the hypothesis that minimal interventions, such as selective tree felling, can enhance carbon sequestration and prolong the period during which these forests maintain a positive annual carbon balance. The results also refute the hypothesis that the main trends in carbon dynamics and responses to low-intensity management are consistent across various species, as they exhibit different patterns. Notably, birch displayed a markedly different response to low-intensity forest management regarding carbon sequestration compared to spruce.

The findings indicate that even in protected forest areas, well-planned and minimal silvicultural practices can significantly boost carbon sequestration while still achieving conservation objectives. The varied responses among species underscore the importance of developing species-specific management strategies rather than adopting universal solutions. This study proposes that forest carbon storage can be enhanced in production forests and within nature reserves by using a light-touch, scientifically grounded method. Future studies should investigate the effectiveness of these techniques under climate change conditions and their potential integration into national carbon offset initiatives or EU biodiversity goals.

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Popular science summary

Forests in nature reserves often develop through natural processes, permitting nature to determine how the forest will grow and which species will inhabit it. Unmanaged forests tend to be denser than those managed under similar conditions. This research seeks to address the question of whether, with minimal management that would not significantly disrupt nature, it is possible to enhance the amount of carbon trees absorb and extend the period before they begin releasing carbon. To observe these changes, simulations are conducted to model different scenarios.

Results indicated that with minimal tree removals, it is possible to increase the forest's carbon absorption over a century. This could help address atmospheric carbon issues more effectively. Results also revealed that minimal tree removals in the park impact different species in varying ways. Birch did not experience much benefit from minimal tree removals, as its carbon intake initially declined, showing only at a later stage a higher intake than if the forest had been left to its natural processes. In contrast, the improvement was significant for beech and spruce, with a rapid increase in carbon intake following minimal tree removals. This illustrates that each species should be managed individually and that distinct management plans are necessary.

These findings demonstrate that it is possible to enhance carbon absorption in nature reserves without disturbing nature much by removing just a few trees and allowing more space for the remaining ones, achieving both high conservation values and increased carbon intake simultaneously. Additionally, removed trees can be utilized in ways that allow them to continue storing carbon for an extended period.

Can simply removing a few trees aid in our fight against climate change? These results suggest — yes.

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