UNIVERSITY OF COPENHAGEN
FACULTY OF SCIENCE

DEPARTMENT OF GEOSCIENCES AND NATURAL RESOURCE MANAGEMENT
SECTION FOR FOREST, NATURE AND BIOMASS

Modeling of Carbon Balance using Conifer and Broadleaf Marteloscope Sites in Denmark

Andrew David Harold Stratton – qmj244
Prescott Huntley Brownell II – dvt574

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Supervisor: Thomas Nord-Larsen

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Abbreviation	Description
C	Carbon
CBH	Crown base height
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
CPT	Carbon parity time
DBH	Diameter at breast height
DKK	Danish kroner
EFI	European Forest Institute
ESL	Estimated service life
FOD	First-order decay
GHG	Greenhouse gases
HL	Half-life
HWP	Harvested wood products
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land-use change and forestry
MACI	Mean annual carbon increment
MAI	Mean annual increment
MAP	Mean annual production
NFI	National Forest Inventory
PPM	Parts per million
TreM	Tree-related Microhabitat

Abstract

The ability of trees to mitigate the threat of anthropogenic climate change caused by carbon emissions has received prominent attention. Trees have the potential to remove large amounts of carbon from the atmosphere and store it in forests and wood products and be used to prevent fossil carbon emissions by substituting wood products for fossil fuel derived products or energy production. However, there is a knowledge gap in forest management about how to best manage a stand for climate impact. One potential means to address this gap is the marteloscope - a learning tool that enables comparison of management actions. However, they have not yet been used to evaluate carbon impacts, and none have been established in Denmark. We set out to establish two marteloscopes and develop a model estimating carbon impact under different thinning scenarios. The model developed takes into account carbon remaining in standing trees, harvested wood products (HWP), the substitution effect, and stand regrowth after harvesting. We have shown that the carbon storage and substitution potential of a forest stand can be estimated and when combined with microhabitat biodiversity scores and economic values, tradeoffs and synergies between all three can be discussed. Under default Tier 2 IPCC assumptions, we found all single-thinning scenarios applied had a net positive carbon impact over the unharvested scenario when the substitution effect was included. The magnitude of this effect two years after harvesting ranged from approximately 6-27 tons C/ha in the broadleaf plot to 26-50 tons C/ha in the mixed conifer plot. When re-growth over time is included, in 2050 net positive carbon benefit from a single thinning ranged from 28-55 tons C/ha in the broadleaf plot to 35-64 tons C/ha in the conifer plot. Finally, we applied HWP assumptions we postulate to be more accurate than Tier 2 IPCC defaults and identified potentially significant differences in future carbon balances.

1 Introduction

It is widely accepted that anthropogenic climate change represents a significant threat to many aspects of current life on Earth. Rising concentrations of CO_2 in the atmosphere amplify the so-called greenhouse effect, trapping heat in the atmosphere at increasing levels and altering ecosystems worldwide. As of February 2020, the global mean CO_2 concentration in the atmosphere was 413.2 parts per million (US Department of Commerce 2020). This is an increase over the pre-industrial levels of 280 ppm (Lindsey 2020). Driving this change is human activity, including deforestation and land use change, but especially the burning of fossil fuels. Total anthropogenic emissions of carbon to the present time have been estimated at approx. 600 gigatons (Bastin, Finegold et al. 2019, in Waring, Neumann et al. 2020). Given the scope of carbon emissions to date, it is clear that a variety of solutions are urgently needed to remove carbon from the atmosphere. One solution in particular has received popular attention in recent years - that of using the natural carbon- fixing properties of trees and forests to confront the climate crisis. See for example (Bastin, Finegold et al. 2019).

1.1 Trees and carbon storage

Through the process of photosynthesis, trees remove carbon dioxide from the atmosphere, combining it with water to construct complex polysaccharides that are a major component of wood and other plant matter. This growth is an accumulation of biomass which effectively stores carbon in wood (and also in leaves, roots, and bark) until it decays, when the stored carbon is again released. As a rule of thumb, carbon is about half of above-ground dry biomass.

The annual growth of trees in forests worldwide has been estimated to store 2 gigatons of carbon each year (Pugh, Lindeskog et al. 2019, in Waring, Neumann et al. 2020). This is a significant mechanism; further, forests are understood to represent about 45% of the above-ground terrestrial carbon pool (Sabine and al. 2004, in Bonan 2008). Given the size of the forest carbon pool and the mechanism of tree growth, it follows that appropriate management of this carbon pool will be crucial in the effort to reduce levels of carbon in the atmosphere.

While the storage of carbon in forests is important for mitigating climate change, there is a limit to the amount of land that can be forested. If it is accepted that natural forests at a landscape scale eventually reach a semi-steady equilibrium where biomass creation is balanced by decay, then there must accordingly be an upper limit to the amount of carbon that may be stored in forests; see (Pugh, Lindeskog et al. 2019). A recent study in Denmark indicated that Suserup, a forest with a 200-year history of almost no management, was likely near a steady state in terms of carbon storage, including above and below-ground biomass, deadwood, and soil carbon. Of the total carbon per hectare, 47% was estimated to be in above-ground biomass, 11% in below-ground biomass, 9% in dead wood, 2% on the forest floor, and 31% in the top 75 cm of the mineral soil (Nord-Larsen, Vesterdal et al. 2019). The above-ground biomass (consisting largely of wood) therefore represents the largest reservoir of carbon in mature forest.

Passive forest storage of carbon, however, is not the only means by which trees and forests might play a role in mitigating anthropogenic climate change. Carbon stored in wood also exists outside of the forest when wood is used for construction or to make products such as furniture. These harvested wood products (HWP) represent an important additional pool of carbon.

1.2 Trees and carbon substitution

In addition to the HWP pool of storage, carbon-containing wood and wood products may also substitute for the use of fossil fuels in a variety of applications which can reduce fossil fuel-origin carbon emissions. This is known as the substitution effect and occurs both when wood is used directly in place of fossil fuel-derived products, and when wood products require less fossil fuel-derived energy to produce. A recent review of 51 studies examining substitution found an average effect of 1.2 across all categories and uses – indicating that for each kg of C in wood that substitutes for the use of other materials in products, there occurs an average emission reduction of roughly 1.2 kg C (Leskinen, Cardellini et al. 2018).

1.3 The importance of forest management

If the global potential of trees and forests to store carbon and substitute for fossil fuels is well established, there is much poorer understanding of how this might translate to management of individual forests or stands in a way that most effectively contributes to climate mitigation. As society increasingly expects forests to be managed for the benefit of the climate, there is a need for forest managers to have tools available to them to understand the climate implications of forest management actions.

1.4 What is a marteloscope?

Marteloscopes are silvicultural training tools originally developed to train foresters in tree selection for conducting thinnings in stands. Within a fixed plot, every tree is measured, graded, and positioned, allowing users to simulate thinning selections in a computer program. The program then outputs results of the thinning exercises in terms of economic return, volume of wood removed, characteristics of the remaining stand, etc. With this information, group simulation exercises can be conducted in the field which allow for comparison of results between groups and their management implications (Schuck, Kraus et al. 2015).

1.4.1 EFI marteloscope program and integrated forest management

As concerns about biodiversity in general and biodiversity in managed forests have spread in recent years, the European Forest Institute (EFI) has adapted the marteloscope idea in the hope that it would assist practitioners to integrate management for biodiversity into management of production forest. The area of forest available to set aside as protected reserves is limited, so forests outside of protected areas are also needed by society to provide ecosystem services like biodiversity conservation (Kraus 2013). How then, to train practical techniques in this "integrated forest management" to those who must practice it in the field? This has been addressed by introducing an additional dimension of data to the marteloscope: a tree-level biodiversity score based on a tree microhabitat index, thus enabling users to evaluate consequences of management decisions at the stand and individual tree level, and explore ways to ensure a sustainable supply of wood and conserve biodiversity. Through their Integrate+ and INFORMAR projects, the EFI has established a network of 98 marteloscopes across 15 countries in Europe as of May 2020 (European Forest Institute 2020), though until now, none have been established in Denmark.

1.4.2 The need for a carbon perspective in marteloscopes

While the EFI program has been focused on integrating considerations of biodiversity into forest management, those concerned with the management of trees and forests have another dimension of management on their minds today: that of the carbon cycle and the potential role of trees and forests in combating climate change. It is yet another ecosystem service that forests are expected to provide. How might we best manage forests to benefit the climate? Is it better to leave the forest untouched, to continue to grow and store carbon in situ, or is it better to harvest trees to produce wood products, storing carbon outside the forest while the forest regenerates anew, storing more carbon within? And what if wood products from harvested trees are displacing fossil fuel alternatives? How can we manage a forest for the climate while conserving biodiversity? Considering these pertinent questions, including carbon considerations in marteloscope exercises would be highly relevant. It would enable learning groups to explore what the potential carbon implications of forest management decisions might be and to discuss those implications in relation to economic and biodiversity values.

Having visited a marteloscope site in Germany during the course of their studies at the University of Copenhagen in 2018, the authors realized there was an opportunity for a two-fold project. First, there was a desire on the part of the University, the Danish Nature Agency (*Naturstyrelsen*) and EFI to establish at least one marteloscope in Denmark. Second, a model could be developed that would use marteloscope data to estimate both carbon stored in standing forest volume and the carbon outcomes if trees were to be harvested. It would therefore be necessary to review the fate of harvested wood and of the carbon stored in that wood outside of the forest, as well as so-called substitution effects, where the use of harvested wood products (HWP) instead of other materials would result in reduced carbon emissions from fossil fuel.

The final aim would be to take the developed model and simulate management actions in the marteloscope (thinnings) to evaluate the effect of management on the above-ground carbon pool – both in and outside of the forest. Different thinning scenarios could then be compared against each other and against a baseline unharvested scenario to gain better understanding of how one might best manage a stand (and by extension, a forest) for climate impact. This would ultimately enable comparison between thinning scenarios on three fronts: carbon, biodiversity, and economy.

2 Carbon Accounting/Harvested Wood Products

2.1 Carbon accounting – forests

A natural starting point for developing a model to consider carbon effects of management actions was to understand how forests, as carbon sinks and sources, are accounted for globally. To navigate the nuances involved in carbon accounting, the Intergovernmental Panel on Climate Change

(IPCC), a body established by the United Nations Environment Programme, structured guidelines for reporting anthropocentric greenhouse gas emissions (GHG) and removals within the umbrella of land use, land-use change and forestry (LULUCF) activities. Originally, these guidelines covered carbon stock and stock changes in five carbon pools constituting above-ground biomass, below-ground biomass, dead wood, litter and soil organic carbon; the HWP pool is also accounted for separately until all the pools are combined to determine a net CO_2 removal or emission (IPCC 2014).

2.2 IPCC accounting methods for Harvested Wood Products

Once woody biomass is converted into HWP, the carbon within begins a journey with many probable pathways but in the end, oxidation is inevitable. Crucially, the nature of these pathways determines the longevity of the wood and carbon outside the forest and thus, the mitigation potential of these products. The existing framework and assumptions used by researchers to calculate carbon stored in HWP aim to measure, disclose, and easily compare data on carbon emissions from sources and removals by sinks globally.

The approach used in the *Revised IPCC 1996 Guidelines* (IPCC 1997) was based on an instantaneous oxidation of carbon after harvesting due to the prevailing thought that the new stock replaced the old stock in an equivalent manner. More recently, a three tier system was set in place with the *IPCC 2006 Guidelines* (IPCC 2006) and then was further modified by the *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol* (IPCC 2014). At present, Tier 1 stipulates that countries register an immediate oxidation of carbon when insufficient HWP data is available; when such data is adequate, countries must then apply the Tier 2 method (IPCC 2014). This consists of dividing HWPs into three categories of semi-finished products: sawnwood, wood-based panels, and paper; default first-order decay functions with their respective half-lives are then applied accordingly (IPCC 2014).

In Tier 3, the IPCC encourages the use of more detailed data, custom HWP categories, and country-specific half-life information where national data exists, but it is apparent that there is often a shortage of such data. Recent studies in the Czech Republic and Lithuania have shown that there can be significant differences in carbon stock in HWP when country specific data is used (Aleinikovas, Jasinevicius et al. 2018, Jasinevičius, Lindner et al. 2018). As per the Danish National Forest Accounting Plan, Denmark uses IPCC Tier 2 default half-lives as they currently do not have country-specific data to create custom half-lives (Johannsen, Nord-Larsen et al. 2019).

2.3 Carbon parity, carbon debt, and carbon balance

Since removals from the forest are currently accounted for as CO_2 emissions at the time of harvest, it is relevant to model the development of carbon accumulation and substitution associated with these removals. In this way, the cumulative impact of harvesting decisions on the climate can be analyzed. In order to measure and assess this climate change mitigation potential of forests, carbon parity time (CPT) and carbon debt repayment are commonly employed. The CPT is defined as "the time between biomass harvest and when the overall carbon balance offsets the loss of carbon that would have been stored if the biomass were not harvested" (Mitchell, Harmon et al. 2012, in Ter-Mikaelian, Colombo et al. 2015). The carbon debt repayment is the amount of time that it takes for the harvested forest to return to the initial carbon stock before harvest (Mitchell, Harmon et al. 2012). This metric is essentially a measure of stand growth potential and is useful when comparing monocultures used in biomass production for energy. CPT is helpful in some cases to see when benefits occur but a recent study by Tærø, Mustapha et al., found that CPT is not always the most robust measure to use as it is often zero when considering substitution effects (2017).

Given that singular focus of carbon debt and carbon parity, we suggest it is more useful to consider the holistic measure of carbon balances (total amounts of carbon) in the different pools over time when comparing harvesting decisions. Such pools include carbon in HWP, re-growth, and carbon offset from carbon substitution.

3 Materials

3.1 Site selection and establishment criteria

As any marteloscope would be incorporated into the EFI program and the University of Copenhagen's system of permanent research plots, requirements for both were considered in the site selection and establishment processes. Criteria used to select the sites were developed by drawing from the existing protocol in the Integrate+ Marteloscope guidance document (Schuck, Krumm et al. 2015) with some further considerations by the authors (Table 1). It was desired that the sites be considered "interesting" from a silvicultural and learning perspective; i.e., that the sites would provide multiple themes of discussion to enable them to be useful for the broadest possible range of didactic uses.

The following criteria were sent to forest managers to curate a list of sites to be visited by the establishment team:

Table 1: Marteloscope criteria directly sourced from Integrate+ Marteloscopes (Schuck, Krumm et al. 2015) with additional criteria developed by the authors.

Integrate+ Marteloscope Establishment Criteria
1. Representativeness should be given attention (forest type, stand characteristics and management applied)
2. The selected forest stand needs to show a certain "need" for management action and be suitable for virtual tree selection exercises
3. Ownership and future expectations towards the forest stand need to be clarified
4. The Integrate+ project strives to have a representative set of Marteloscopes covering a wide range of different forest types; this aspect should be considered during the selection process
5. The continuance/life time of a Marteloscope needs to be guaranteed; management operations should be renounced for a time-span of at least 5- 15 years so that the expenses of set-up are justified and the usability for training exercises ensured in case management operations take place soon after Marteloscope establishment the suitability for training may be lost (at least for some years).
6. Preferred terrain is such that allows effective set-up of a Marteloscope; flat terrain is thus favoured but it is not a requirement (e.g. mountain forests)
7. Ease of accessibility
8. Safety issues (e.g. rock fall in mountainous forests)

Additional Criteria
9. Structural diversity and variation of species desirable in the stand
10. Interest in evaluating both conifer-dominated and broadleaf-dominated stands
11. One site to be established on Zealand and one site on Jutland
12. Site owner willing to set up marteloscope site as a permanent research plot
13. Presence of interesting tree related microhabitats visible from the ground
14. Preferred presence of natural regeneration
15. Preferred presence of dying/dead trees or deadwood
16. Presence of wet areas or other interesting non-tree ecological features a plus

3.2 Field visits and site selection

In Jutland, field visits were conducted to the privately managed Løvenholm Estate and Salten Langsø Skovadministration and to publicly owned Rold Skov. Potential stands were evaluated based on the criteria specified; all three forest estates have had multiple stands that are suitable for the establishment of a marteloscope. A mixed conifer stand in Salten Langsø was selected after a walk-through of 25 stands listed as potential candidates by the three estates. After the selection of the Salten Langsø site in Jutland, it was decided to also select a broadleaf stand near Copenhagen that would be easily accessible to students and others in the capital region. Several dozen stands were visited and a mixed oak and beech stand in Stenholtvang was selected.

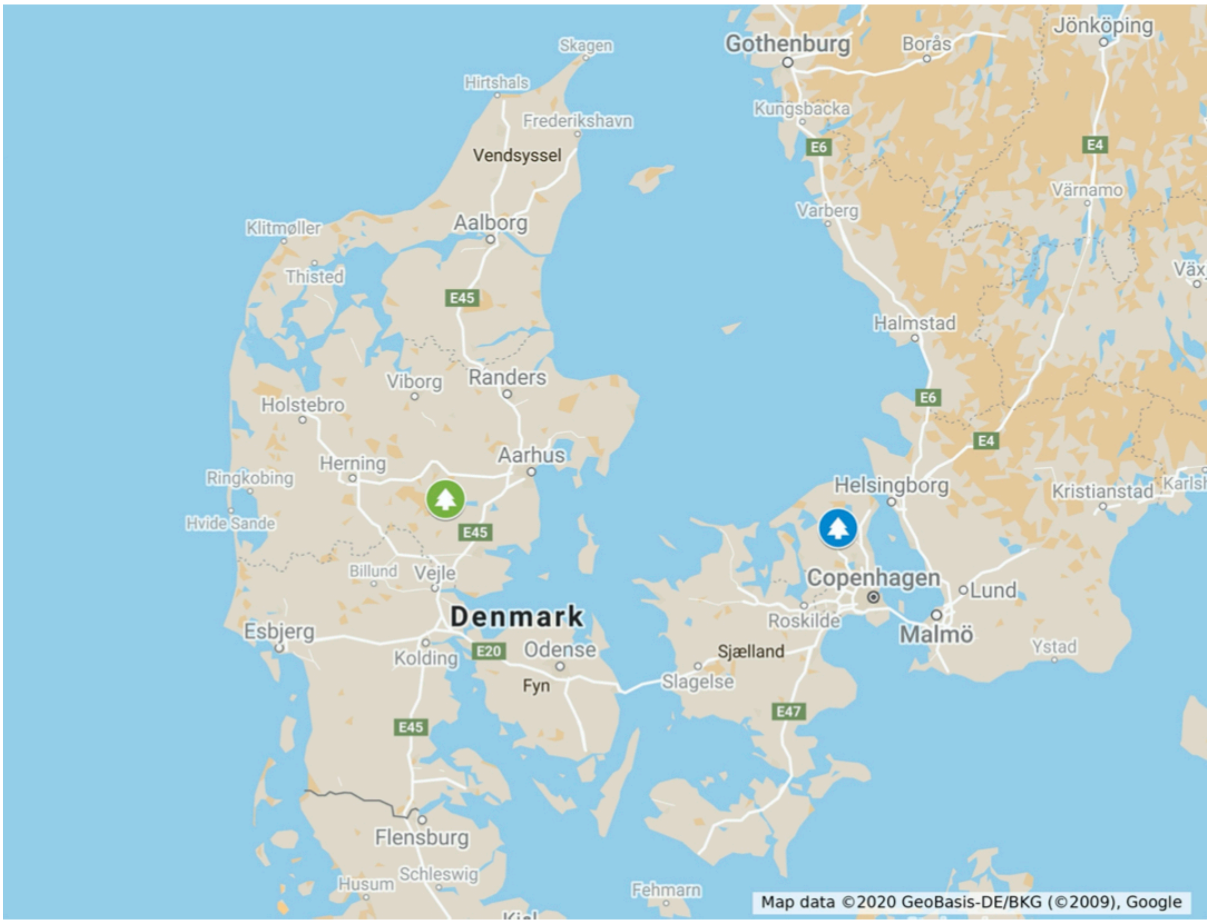

Figure 1: Map of Denmark showing location of marteloscopes established by the project. The green icon represents the approximate location of Salten Langsø while the blue represents Stenholtvang.

3.2.1 Site description - Salten Langsø

The Salten Langsø marteloscope site is located in central Jutland near the village of Addit in an area with steep, moraine hills and sandy soil. Annual mean temperature at the nearest weather station for which data is available (Silkeborg) is 7.5°C with around 720mm annual rainfall (climate-data.org). This site was largely chosen because of its unique (for northern Europe) mix of conifer species of varying age and diameter in addition to having particularly old *Fagus sylvatica* with a number of notable microhabitats. The size and economic value of mature *Abies grandis* and *Pseudotsuga menziesii* also present immediate harvesting tradeoffs between biodiversity, economy, and carbon that would enable rich discussion during marteloscope training exercises.

In many ways this site could be considered a model for continuous cover/close-to-nature forestry. These forestry practices are relatively new in modern Denmark and there are few examples of conifer stands under this type of management with mature trees for students to observe. Another rationale for the selection of this site was that a portion of the stand has a remnant of even-aged *Picea sitchensis* and *Picea abies* which is representative of many stands in Denmark. It thus has the potential to prompt a discussion about conversion from even aged monoculture to more diverse mixtures, for example how to introduce more species diversity from the surrounding stands. This is also a very relevant topic in Danish forestry today. In addition to the aforementioned species, *Tsuga heterophylla*, *Betula sp.*, *Pinus spp.*, and *Larix sp.* are present in smaller numbers.

Figure 2: Portion of Salten Langsø marteloscope with mixture of even aged Sitka and Norway spruce.

Figure 3: Large grand fir (up to 40m in height and 95cm dbh) seen in the background at Salten Langsø with regeneration of grand fir, Douglas fir, Sitka and Norway spruce.

The site classes for the various species were determined by plotting the ages, derived from the stand list provided by Salten Langsø Skovadministration A/S, against measured heights. This was compared with yield tables procured from the Danish *Skovbrugstabeller*, or Forestry Tables (Forsøgsvæsen 1990). Site class I was indicated for most species except *P. menziesii* which indicated site class III.

3.2.2 Site description – Stenholtvang

Stenholtvang is located in northern Zealand on undulating terrain with loamy, fertile Hapludalf soil, a mean annual temperature of 8°C and annual precipitation of about 650 mm (Hansen 2003, in Röser, Asikainen et al. eds 2008). In addition to being accessible by public transport, this site offers marteloscope users the opportunity to discuss several typical broadleaf management challenges in Denmark. The canopy consists of approx. 110-year-old *Quercus sp.* that is being grown into by *Fagus sylvatica*, so marteloscope users could explore managing for either oak or beech in the future. The large oak trees might provoke interesting discussion with potential inherent conflict between high ecological value and high economic value. There are also remnants of previous management including ditching and adjacent wet areas, as well as the presence of *P. abies* that provide opportunities for discussing past and future management. *Betula sp.* and *Sorbus sp.* are also present in small numbers. It was determined that both oak and beech were growing on site class I, using the same method as in Salten Langsø.

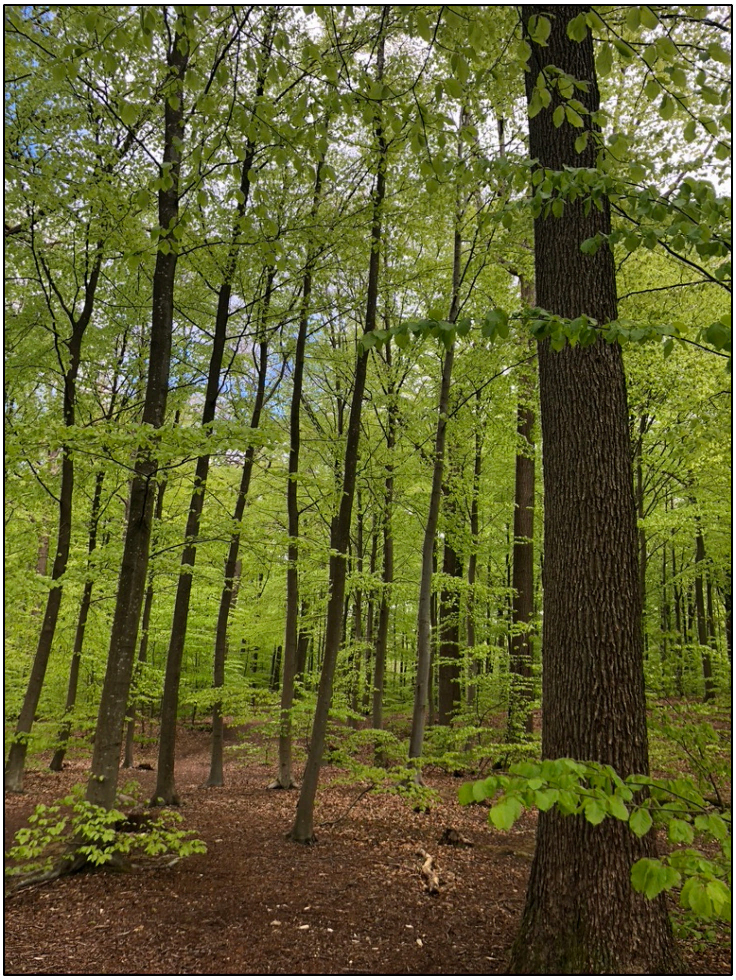

Figure 4: Overall stand picture of Stenholtvang where large oaks can be seen with smaller beech trees surrounding.

Figure 5: Oak being overgrown by beech in Stenholtvang. This particular tree has a broken crown and dead branches providing additional habitat value.

3.3 Measuring devices and materials

The following table denotes which tools were used in the establishment of the marteloscope and their respective purpose:

Table 2: Measuring devices and materials used in marteloscope establishment

Device/Material(s)	Purpose
Binoculars	Identification of tree-related microhabitats in the stem and crown.
Chainsaw/Axe	Removal of regeneration impeding the sight lines of the Theodolite.
Hammer	Placement of aluminum tree number tags in the stem.
Handheld transceivers	Facilitation of communication between members of the measurement team within the stand.
Field Computer – *Juniper systems Allegro CX, Allegro 2*	Field data entry
Line poles	Alignment of marteloscope quadrants measuring points.
Measuring tape, 50m	Measurement of distance between plot points, DBH for trees larger than calipers at hand, and calibration of the Vertex IV.

Device/Material(s)	Purpose
Numbered aluminum tree tags and nails	Marking of individual trees.
Spray paint	Marking of trees as needed during the measurement process.
String	Demarcation of plot edges to determine which trees were within the plot.
Theodolite – *VEB Carl Zeiss JENA Theo 020*	Measurement of angles on a horizontal plane to survey plot boundaries and position individual trees.
Tree caliper, *Mantax Blue, Haglöf, Sweden*	Measurement of DBH.
Digital Hypsometer – *Vertex IV and Transponder T3, Haglöf, Sweden*	Measurement of tree height, crown base height, and distance of trees to known points in the plot.
Wooden/metal stakes and sledge	Permanent placement of stakes at the marteloscope edges, center point, and quadrant center points

4 Methods

The methods section consists of three parts: field measurements and assessments carried out during marteloscope establishment, calculations of stand attributes, and modeling of carbon balances.

4.1 Field measurements and assessments

Marteloscope plots in the EFI program are typically one square hectare having four sides of 100 meters in length. The plot is further divided into four quadrants (see Figure 7). Before tree measurements can begin the plot must first be surveyed and marked. A theodolite was used for this purpose.

4.1.1 Plot establishment – Salten Langsø

The first point in this plot was established with a stake in the ground at SE (see Figure 7); from this point, the theodolite was used to sight to S and SW. The theodolite was moved to SW and SW was used as a reference point to W and NW. It was moved again to NW in order to sight to N and NE. The center point of the marteloscope, C, was sighted from W. Quadrant I center point was sighted from NE and quadrant II center point was sighted from C. Quadrant III center point was sighted from SW and quadrant IV center point was sighted from SE. Dense regeneration meant it was necessary to clear lines of sight with a chainsaw (See Figure 6).

Figure 6: Clearing regeneration at Salten Langsø in order to create a sight line during the establishment of the marteloscope.

4.1.2 Plot establishment – Stenholtvang

The first point in this plot was staked at NE (see Figure 7); from this point, the theodolite was used to sight to N and NW. From N, the center point of the marteloscope, C, was sighted but no permanent stake was placed as the point was in a footpath. NE was also used to sight E and SE and SE was then used to sight S. Quadrant I center point and quadrant IV center point were sighted from C. Quadrant II center point was sighted from NW with II then being used to sight quadrant III center point and W. SW was sighted from III.

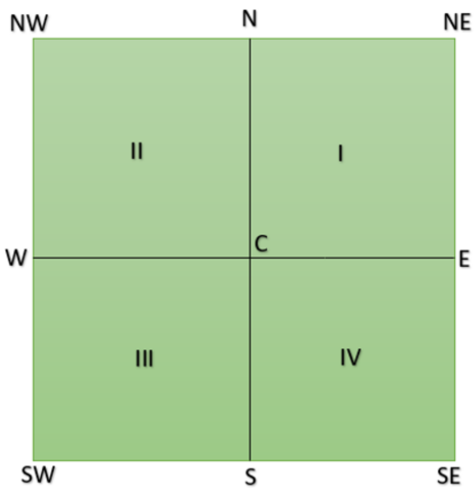

Figure 7: Diagram of marteloscope with points I, II, III, and IV denoting the center of each respective quadrant with C marking the marteloscope center. NW, NE, SW, and SE denote the corner points spaced 100 meters apart with W, N, E, S marking the respective 50-meter midway points.

4.1.3 Tree mensuration

At each reference point listed in Table 3, the theodolite was set onto the tripod and approximately leveled over the stake set during the plot establishment and centered by adjusting the vertical axis of the theodolite over the stake. A built-in air bubble level was used to ensure proper levelling. Rather than "zeroing" the theodolite to North, the theodolite was most often "zeroed" to a visible known point, generally one of the quadrant corners. It was initially attempted to zero to magnetic north, but lack of an appropriate compass made it impractical; it was also unnecessary for positioning the trees relative to each other.

Table 3: Salten Langsø list of where the theodolite was set up; where the theodolite was zeroed to; which trees were measured from each point; and which point the theodolite was facing to start the measurements.

Theodolite Location	Theodolite Zeroing Point	Trees Measured	Theodolite Observation Starting Point
IV	Magnetic North	1-137	SE clockwise
III	SW	138-257	S clockwise
II	C	258-335, 337-338, 342, 344-371	C clockwise
N	NE	336, 339-341, 343,372-389	NE counterclockwise
NE	E	390-405	E counterclockwise
E	NE	406-416	C clockwise
C	W	417-429	N clockwise

Table 4: Stenholtvang list of where the theodolite was set up; where the theodolite was zeroed to; which trees were measured from each point; and which point the theodolite was facing to start the measurements

Theodolite Location	Theodolite Zeroing Point	Trees Measured	Theodolite Observation Starting Point
I	E	1-116	NE clockwise
II	NW	117-183	NW clockwise
III	W	184-244, 313-315	W clockwise
IV	SE	245-308	SE clockwise
SE	NE	309-312	NE counterclockwise

All parameters collected for each tree are listed in Table 4. The theodolite's telescope was rotated horizontally with the relative angle (azimuth) observed from the zeroing point to the apparent center of the stem of each tree. Once the relative angle of the tree was recorded, a numbered aluminum tree tag was placed on the north facing side of the tree above breast height. The T3 transponder was placed such that it rested on the center of the theodolite under the telescope. To measure the distance from the tree to the T3 transponder, the digital hypsometer was held next to the tree at breast height with the scope lined up with the edge of the tree facing the theodolite.

The DBH was measured with two caliper measurements, with the main axis of the caliper pointing to the theodolite for the first measurement, and the caliper perpendicular to the theodolite for the second measurement; the average of these two measurements was recorded as the DBH. For trees that were leaning, the caliper was shifted to be perpendicular with the trunk and for trees with knots, measuring was done just above and below the knot according to standard practice. Tree heights were measured from a distance up to 40 meters away corresponding to tree height using the digital hypsometer and the T3 transponder attached to the stem at breast height. Crown base heights, measured as height to lowest living branch, were measured simultaneously with overall height.

Only trees over 7.5 centimeters in DBH were recorded. All values were recorded using an Allegra field computer.

Table 5: List of parameters collected during the data collection process and their respective unit of measurement.

Type	Unit
Tree number	ordinal number
Tree species	latin name
Diameter at breast height	dbh [cm] (>7.5 cm)
Tree height	h [m]
Crown base height	h_{cb} [m]
Quadrant measuring point	quadrant measuring point (I, II, III, IV, NE, NW, W, E, C)
Status	bit [Alive=1, Dead=0]
Tree location	distance [m], azimuth from measuring point [gon]
Timber quality	class (A, B, C, D/IT, F) and section length [m]
TreMs	abundance [n] and type [index code]

4.1.4 Tree-related microhabitat assessment

A survey of tree related microhabitats (TrEMs) was the basis for deriving an ecological value for each tree. The 64 saproxylic and epixylic microhabitat types, characterized under the broader categories of cavities, injuries and wounds, deadwood, bark, deformations, epiphytes, nests, and other, are described in an index catalogue developed for assessing TrEMs in marteloscopes (Kraus, Bütler et al. 2016). A visual assessment was conducted by two individuals with at least two passes being made around each tree; attempts were further made to observe each tree crown from multiple vantage points to improve chances of identifying TrEMs. A line gauge and binoculars were used to verify the size of microhabitats around the base of the tree and identify microhabitats in the crown, respectively.

4.1.5 Timber quality assessment

Assigning a quality grade to sections of tree bole was necessary to calculate current economic value for each tree. Much of the merchantable wood lies in the lower part of the stem and the value is often determined by local market conditions. Buyers typically come to a negotiated price with stand owners after stems have been felled which allows for an appraisal to be conducted in close proximity. This means external defects or damages are easily visible and internal flaws can be observed where cuts through the stem have been made. However, in this case, all evaluations were made from the ground while observing standing trees.

In Stenholtvang, quality sections for each stem with merchantable value were expertly assessed by a local forester. Quality assortments for broadleaf species were determined based on the degree of stem curvature; magnitude of twist; presence of knots, overgrowths, or bark damages; epicormic branching; and length of the bole. The classification criteria are outlined in more detail in *Råtræhæftet*, or Raw Timber Catalogue (Danske Skoves Handelsudvalg 2008). To save time, trees that clearly had no timber potential were marked as fuelwood by the authors prior to the forester's assessment. This included trees with less than 14 cm DBH, and suppressed trees with poor form or excessive branching.

In Salten Langsø, while there was some assistance from a local forester in grading, the assessment was largely conducted by the authors of this paper. Quality was allocated in section lengths of 2.5 to 5 meters as stems were sold mostly as short timber. 'A' quality was assigned when there was no branching or defects. Even though Salten Langsø Skovadministration did not differentiate between 'B' and 'C' quality, the authors assigned 'B' quality where minor branching occurred and the branch diameter did not exceed 10% of the bole and 'C' quality where the branch diameter was, at its largest, 20% of the bole. If any section of the stem was judged to be a sufficient diameter to still produce sawnwood after any 'A', 'B', or 'C' quality was assigned, 'D' quality was assigned. Otherwise, it was designated as fuel wood.

4.2 Calculations

Microsoft Excel was used to process marteloscope data and make all calculations. These calculations were necessary to obtain stand attributes, microhabitat scores, economic value, and spatial distribution of trees.

4.2.1 Diameter, basal area, and volume

Individual tree diameter at breast height (DBH) was calculated by averaging the two caliper measurements taken for each tree; where circumferences were measured, a diameter was calculated from this single measurement. Basal area was then further calculated for each tree.

Single tree volumes were estimated for the authors by Danish National Forest Inventory staff using individual species volume functions as described in (Nord-Larsen and Johannsen 2016). The volumes of individual tree sections of the different quality grades and fuelwood were calculated with the formula below (Kraus, Schuck et al. 2018):

$$V_x = (dm_1/100)^2 * \frac{\pi}{4} * L_x \tag{1}$$

Where:

V_x = volume of section x [m^3]

dm_x = diameter of section x at the midpoint [cm]

L_x = length of section x [m]

Individual section diameters for sections graded A, B, or C were calculated depending on whether or not the section contained part of the crown as defined by the measured crown base height (CBH). The formulas were adapted from (Kraus, Schuck et al. 2018) and are as follows, moving from the base of the tree upward:

Sec. 1: $$dm_1 = d_{1.3} - L_1/f_T + 0.8 \tag{2}$$

Sec. 2 (below CBH): $$dm_2 = dm_1 - L_1 * f_t/2 - L_2 * f_t/2 \tag{3}$$

Sec. 2 (with crown): $$dm_2 = dm_1 - L_1 * f_t/2 - (L_2 * f_t/2) * d_{1.3}/h - 1.3 \tag{4}$$

Sec. 3 (below CBH): $$dm_3 = dm_2 - L_2 * f_t/2 - L_3 * f_t/2 \tag{5}$$

Sec. 3 (with crown): $$dm_2 = dm_1 - L_1 * f_t/2 - (L_2 * f_t/2) * d_{1.3}/h \tag{6}$$

Where:

dm_x = diameter at midpoint of section x

L_x = length of section x

f_t = tree or tree type specific tapering factor

$d_{1.3}$ = DBH

h = tree height

Diameters for sections with a quality grade of D, also known as industrial roundwood, was calculated using the same formula as Sec. 3 (with crown).

The general trend for these equations is to increase the taper and decrease the section diameter moving toward the top of the tree. The volumes for up to four quality sections (A-D) were calculated in this way while fuelwood volume was calculated as the sum of all the quality sections subtracted from total tree volume. A tree tapering factor of 1 cm/m was used for conifer species and a factor of 0.5 cm/m was used for broadleaf species.

4.2.2 Microhabitat values

The ecological value of each tree, with units denoted as 'habitat points', is based on the number of TrEMs, their respective rarity gradient, and the time span needed for the TrEM to develop (Kraus, Schuck et al. 2018). It is expressed as follows:

$$H_i = \sum_{j=1}^{n} N_j * s_j * (R_j + D_j) \quad (7)$$

Where:

H_i = habitat value of the tree

N_j = number of microhabitat type

s_j = size score

R_j = value for the rarity of a microhabitat

D_j = value for the time needed for a microhabitat to develop

4.2.3 Economic value

The economic value for each tree was calculated in Danish kroner (DKK) by multiplying the volume in cubic meters of each graded section by a price per cubic meter specified for each species, quality grade, and diameter class. The individual sections were then added together for a total price.

The price list used to calculate economic values of the section lengths in the Salten Langsø plot adapts pricing information received from Salten Langsø Skovadministration A/S at the time of data collection; these prices were averages based on price sheets from the first quarter of 2020. As most timber from the estate is sold as "short timber", prices were provided for the entirety of a quality grade with no distinction between diameter classes. For the purposes of modeling, the same price was assigned to the diameter classes in intervals of 5 cm. Prices for fuel wood were used in higher quality grades for the 10 cm diameter class which includes 14.99 cm to 10 cm wide trees. 2019 price statistics (Dansk Skovforening 2020) were used to calculate timber values in Stenholtvang; these prices are based on average sale prices for each assortment as self-reported from private forests in Denmark. It should be noted that prices for timber sales fluctuate so the price list should be updated to approximate economic value in future modeling.

Due to a significant learning curve in developing a consistent grading process across all species present in Salten Langsø, there was some disparity between trees graded at the beginning of the process and those in the latter stages. All trees in the plot that had merchantable wood were plotted with crown base height (CBH) against total usable length in the tree, meaning all trees that were designated as fuel wood in the assessment were removed from the analysis. Linear regression was used to reflect the relationship between the two parameters; with the resulting function, predicted usable lengths were set against actual usable lengths graded to determine the standard deviation. All trees that were above two standard deviations were deemed to have too much usable wood assigned to the quality evaluation and were thus downgraded to better reflect the entire grading process and a quality distribution more consistent with the overall trend. In total, 40 trees were adjusted in this manner, and they were all trees that had been assessed early in the process – early on the learning curve.

4.2.4 Polar *x, y* coordinates

In order to obtain polar coordinates and permit mapping of trees, it was necessary to convert measured azimuths and distances from theodolite to tree into an *x, y* format in meter units. Limited visibility owing to dense regeneration and the outright size of the plot meant several different measuring points were used.

As the distance measured to each tree was from the tripod center to the point on the stem nearest the tripod, a length in centimeters equivalent to half the diameter was added to the distance measurement, roughly establishing the center of the tree for mapping purposes.

As described, a variety of tripod positions were used to measure azimuths, and the instrument was not always zeroed in the same direction (toward the northern edge). This required that a correction factor be applied to the observed azimuth; the factor was calculated as 400 (total number of gradians in a circle) minus the number of degrees in a counterclockwise direction to the initial zeroing point of the theodolite as observed from each measuring point. This correction factor was then subtracted from each observed azimuth; if the result was positive it was corrected, if it was negative, 400 was added. The resulting number was then the corrected azimuth to each tree, as if the azimuth to each tree had been observed with the theodolite calibrated perpendicular to the northern edge of the marteloscope at each measuring point.

The observed azimuth in gradians (with 400° in a circle) was then converted to an angle of bearing (with 360° in a circle) by multiplying it with 0.9.

As gradians and angles of bearing are measured in a clockwise direction, with 0° oriented north, it was necessary to convert them to "standard angles" as used in mathematics and a polar system. Standard angles are measured counter-clockwise, with 0° being to the right or "east" – along the *x* axis. To convert to a standard angle, the bearing angle is subtracted from 90°. If the result is negative, 360° is added. As Microsoft Excel uses radians, the angle is converted to radians and the corrected distance is multiplied by the cosine of the angle for the *x*-coordinate and the sine of the angle for the y-coordinate.

The final step is to apply a correction factor for *x*- and *y*-coordinates to compensate for the different measuring points; this correction factor makes it possible to plot all trees at *x, y* coordinates as if they had been measured from the center point of the marteloscope (i.e., where the *x*- and *y*-axis converge). This was done by simply adding the *x, y* coordinate of the measuring point in each case, easily determined since the marteloscope is a 100 m x 100 m grid and the measuring points were always at defined points within the grid.

This completed the initial marteloscope establishment.

4.3 Introduction to modeling of carbon balance

Marteloscope data was used as a foundation to develop a model in Microsoft Excel that would follow the fate of carbon stored in individual trees and stand carbon balances after thinning over time. The following subsections detail the various processes, equations, assumptions, and simulations employed.

4.3.1 Tree biomass and carbon

As a first step toward estimating individual tree carbon content, it was necessary to estimate dry biomass. It was decided that only above-ground biomass would be considered in the modeling as this is the part of the tree that would be harvested—it is only the carbon stored in this part of the tree that is removed from the stand. The contribution of tree roots constituting below-ground biomass to the overall carbon content of the stand is acknowledged; however, with the assumption that it would decay and re-grow at rates proportional to the rest of tree biomass, it could be excluded from modeling. Other carbon present in the stand and not incorporated in our modeling could include, for example, soil organic carbon and carbon in other living terrestrial organisms such as insects and vertebrates. It is assumed that these would remain relatively stable over time, given that both sites host mature forest indicating continuity of land use, and that we expect continuous cover management to continue in the future. In temperate regions there is evidence that soil carbon remains stable over time with continuity in land use; see for example (Smith 2005) and (Poeplau, Don et al. 2011).

The dry biomass of each tree was estimated using species specific parameters and biomass formulas and parameters used in the Danish National Forest Inventory. The formula is shown below while the parameters for each species are listed in a study that constructed biomass models for 13 species in Denmark (Nord-Larsen, Meilby et al. 2017). Stem and crown biomass are calculated separately and summed together.

$$B_{stem} = \alpha_0(\text{dbh} * 1000)^{\alpha_1} * (h - 0.3)^{\alpha_2} + \varepsilon_{stem} \quad (8)$$

$$B_{crown} = \beta_0(\text{dbh} * 1000)^{\beta_1} * (h - 0.3)^{\beta_2} + \varepsilon_{crown} \quad (9)$$

Where:

$B_{stem,crown}$ = biomass of individual tree section (stem or crown)

α_x, β_x = species and section specific parameter

$\varepsilon_{stem,crown}$ = species and section specific constant

dbh = diameter at breast height of individual tree

h = height of individual tree

The estimation of carbon stored in an individual tree is simply derived by multiplying biomass by a carbon conversion factor, as follows:

$$C_i = B_i * f \quad (10)$$

Where:

C_i = carbon stored in tree i, kg

B_i = above-ground biomass in tree i calculated as oven dry weight, kg

f = specified carbon conversion factor

A widely used factor to determine carbon content of dry biomass is 0.5; however, a meta-analysis in 2012 found carbon content in temperate and boreal tree species varied between 43.4% – 55.6% with “conifer species overall exhibiting greater wood C content than angiosperm species 50.8 ± 0.7% (95% C.I.) and 47.7 ± 0.3%, respectively” (Thomas and Martin 2012). In order to avoid additional model complexity, carbon was assumed to compose 50% of dry biomass for all species modeled.

4.3.2 Modeling of potential storage in Harvested Wood Products of individual trees

To provide a basis for estimating the fate of harvested wood, it was first necessary to assign the graded quality distributions in the marteloscope data (i.e., A,B,C,D, and F) to semi-finished HWP categories - i.e., for each species and quality grade, what sort of HWP would it become? In the model, for each species a percentage of a particular quality grade can be split among multiple semi-finished HWP categories depending on local market conditions. In addition to the default IPCC categories of sawnwood, wood-based panels, and paper products, a custom category was added to enable modeling alternatives to the default, and a fuelwood category was also added. For both stands, the default distribution was set as follows: A-quality assortments are categorized as wood-based panels, as these assortments were assumed to be used for veneer in the case of broadleaves and specialized products such as wood wool in conifers. B, C, and D/IT quality assortments for all species were set to 100% sawnwood, while F was set 100% to fuelwood.

4.3.2.1 IPCC semi-finished HWP categories

The definitions for the semi-finished product categories found in the IPCC guidelines are derived from the FAO Joint Forest Sector Questionnaire and are set out as follows:

> [Sawnwood includes] wood that has been produced from both domestic and imported roundwood, either by sawing lengthways or by a profile-chipping process and that exceeds 6 mm in thickness. It includes planks, beams, joists, boards, rafters, scantlings, laths, boxboards and "lumber", etc., in the following forms: unplaned, planed, end-jointed, etc. It excludes sleepers,

wooden flooring, mouldings (sawnwood continuously shaped along any of its edges or faces, like tongued, grooved, rebated, V-jointed, beaded, moulded, rounded or the like) and sawnwood produced by resawing previously sawn pieces. It is reported in cubic meters solid volume.

[Wood-based panels] is a product category [that] is an aggregate comprising veneer sheets, plywood, particle board, and fibreboard. It is reported in cubic meters solid volume.

The paper and paperboard category is an aggregate category. In the production and trade statistics, it represents the sum of graphic papers; sanitary and household papers; packaging materials and other paper and paperboard. It excludes manufactured paper products such as boxes, cartons, books and magazines, etc. It is reported in cubic metric tonnes (IPCC 2014).

4.3.2.2 Custom category

The custom category was created to enable exploring the effect of HWP assumptions differing from IPCC tier 2 defaults. This would allow the model to reflect more locally accurate end use (and therefore climate impact) of a significant amount of volume within the two marteloscopes.

Emballage, from French, is a word used in Denmark to describe packaging materials and would normally be considered sawnwood under IPCC guidelines, though it may have a much shorter half-life than the default of 35 years in this category. For the alternate scenarios explored at Salten Langsø the custom category was used to model emballage, with the ability for the user to change the half-life to an alternate, potentially more appropriate one. At Stenholtvang the custom category was used to model alternative longer half-lives for broadleaf assortments.

4.3.2.3 Decay/Half-lives

As the semi-finished HWP categories feed into finished products in different end uses, they encompass a wide range of commodities with varying estimated service lives (ESL). The rate at which carbon is removed from the pool is determined by a decay rate and an associated half-life, defined as “the number of years it takes to lose one-half of the material currently in the pool” (IPCC 2014). Products are removed from service and carbon is released in a variety of ways including through burning or decomposition. Default half-lives reflect the aggregation of ESLs of all commodities falling within a particular HWP category. For default modeling scenarios, IPCC default first order decay functions and half-lives (listed in Table 6) were used to align with how Denmark currently conducts carbon accounting (Nielsen, Plejdrup et al. 2016).

Table 6: Semi-finished harvested wood product categories and their respective half-lives (IPCC 2014).

Semi-finished Harvested Wood Product categories	Tier 2 default half-lives (years)
Sawnwood	35
Wood-based panels	25
Paper and Paperboard	2

Applying default standards from the *2013 Revised Supplementary Methods*, HWP carbon is assumed to decay with a first-order decay function, using a constant calculated as follows:

$$k = \frac{\ln(2)}{HL} \tag{11}$$

Where:

k = decay constant of first-order decay, yr^{-1}

HL= half-life of HWP pool, years

Using (10) and (11), (12) was formulated to estimate the amount of carbon remaining in the HWPs made from a single tree at a given year from harvest:

$$C_{i,t} = e^{-k_{sw}*t} * C_{i,sw} + e^{-k_{wp}*t} * C_{i,wp} + e^{-k_p*t} * C_{i,p} + e^{-k_f*t} * C_{i,f} \ldots \tag{12}$$

Where:

$C_{i,t}$ = carbon stored in tree i at t years from the present time

k_{type} =first order decay constant, yr^{-1}, for the three IPCC default categories: sawnwood (*sw*), wood-based panels (*wp*), and paper (*p*), a fuelwood category (*f*), plus any additional custom categories for alternative scenarios

The 2050 scenario was modeled to be consistent with the global response to impacts of climate change as used in the Special Report on Global Warming of 1.5° (Masson-Delmotte, A. Pirani et al. 2018).

4.3.2.4 Harvested wood loss during processing

It is recognized that not all biomass from a harvested tree makes its way into semi-finished HWPs. A processing efficiency factor was applied to account for the fact that much biomass is lost in processing, including leaves/needles, bark, branches, and stem wood. Some of this biomass remains in the forest itself, and some of it is even burned to provide energy for processing. After the processing efficiency factor is applied, the biomass remaining is allocated to HWP categories while the biomass removed by the factor is considered as waste. Knowing that some of this waste is reused or recycled into HWP categories (for example, sawdust made into panels or burned for energy) a waste distribution percentage is applied to the removed biomass which distributes the waste back into the HWP categories, including fuelwood. Given the lack of data available, a provisional assumption was made to redistribute 50% of total waste into the wood-based panel category, leaving 50% of waste as fuelwood. It is noted that with this method of distributing the waste among categories, the fuelwood category includes residues left behind in the forest. Given our assumed short half -life in the fuelwood category of ½ year (Nielsen, Bentsen et al. 2020), we also assume that forest residues will be oxidized relatively quickly.

4.3.3 Modeling of carbon substitution effect of individual trees

The tree-level carbon substitution potential was calculated by applying a substitution factor to the carbon contained in each post-harvest category (including IPCC defaults, and custom categories including fuelwood) and summing the totals for each tree. The substitution is assumed to occur within a year of harvesting. This is expressed as follows:

$$C\mathrm{SUB}_i = C\mathrm{SUB}_{i,sw} * z_{sw} + C\mathrm{SUB}_{i,wp} * z_{wp} + C\mathrm{SUB}_{i,p} * z_{wp} + C\mathrm{SUB}_{i,f} \ldots \qquad (13)$$

Where:

$C\mathrm{SUB}_i$ = total carbon substituted by tree i

$C\mathrm{SUB}_{i,type}$ = carbon substituted by tree *i*, for the three IPCC default categories: sawnwood (*sw*), wood- based panels (*wp*), and paper (*p*), a fuelwood category (*f*), plus any additional custom categories for sensitivity analysis.

z_{type} = carbon substitution factors for the three IPCC default categories: sawnwood (*sw*), wood-based panels (*wp*), and paper (*p*), a fuelwood category (*f*), plus any additional custom categories for alternative scenarios or sensitivity analysis.

For the sawnwood HWP category, a substitution factor of 1.4 was used, while 1.2 was used for panels as described in (Leskinen, Cardellini et al. 2018, in Nielsen, Bentsen et al. 2020). As none of the assortments were assigned to the paper and paperboard category, no substitution factor was assumed. Fuelwood was assigned a substitution factor of 0.9 kg C / kg C, assuming that it would substitute for coal (Anders Tærø Nielsen, 2020, Personal Communication). In order to not credit waste left in the forest with a substitution value, the overall fuelwood substitution factor is reduced by a user-defined percentage. This was set to 10% (Nielsen, Bentsen et al. 2020).

4.3.4 CO_2 expansion factor and CO_2 equivalents

There is often confusion when discussing carbon emissions about whether tons of carbon or carbon dioxide are being discussed. As emissions of various greenhouse gasses need to be aggregated in order to realize the full effect of a particular activity, the unit of "carbon dioxide equivalent" (CO_2-eq) was created. In order to convert the carbon stock into CO_2-eq, the amount of C in a given tree is multiplied by 44/12, namely the stochiometric ratio of CO_2 to C.

4.3.5 Modeling of growth

Comparison of future scenarios based on current management actions and the calculation of carbon parity time and carbon balance in the future required that growth in the stand be modeled. While it would be desirable, it was deemed impractical to attempt to use a single-tree growth model. In the first attempt to simulate the projected stand growth, the total expected volume production for each species was calculated from site class specific yield tables from the Danish Forestry Tables (Forsøgsvæsen 1990). Mean annual increments (MAI) were calculated using the species-specific rotation ages which were subsequently converted into mean annual production (MAP) and mean annual carbon increments (MACI).

However, the rotation ages in the various yield tables led to MAIs reflective of widely different ranges of time. It was therefore decided to model growth using MAP from a Danish common garden experiment spanning 48 growing seasons and including most of the species needed (Nord-Larsen and Pretzsch 2017). This allowed for a better picture of the biomass production potential of the different species at the same point in time on different sites.

For Salten Langsø, mean MAP across all sites in the study were used; this mean across all sites was deemed a conservative but fair estimate given that we derived a site class III for Douglas fir and site class I for most other species in this stand. In the case of Stenholtvang, an average of the MAP values from site 1010 and 1011 for oak, beech, and Norway spruce were used. Birch was modeled as beech and rowan was modeled as oak. The mean of these sites was chosen as both sites are on rich soils on the island of Zealand and are assumed to better reflect similar growing conditions to Stenholtvang then the mean values across all sites. For both stands, the species mix percentages, calculated for every species by taking the total volume of each species over the stand volume, were then applied to the respective MAPs and summed to achieve a stand level weighted MAP.

It was further necessary to set an upper limit to stand above-ground carbon accumulation to reflect limitations in biomass accumulation per hectare. The two stands have entirely different species composition necessitating different upper limits. A meta-analysis of studies examining forest biomass in different biome types found a mean value of 334 Mg C ha^{-1} for "cool temperate moist forest" and noted that the range of values for forests of similar species composition to Salten Langsø in North America was between 224 and 587 Mg ha^{-1}. (Keith, Mackey et al. 2009). As there is no data available for long term accumulations with such a species mix in Denmark and the mean value for temperate moist forest was on the lower end of the figures for a similar species mixture, 334 Mg C ha^{-1} was assumed for Salten Langsø. For Stenholtvang, Suserup was used as a reference point. Like Stenholtvang, it is a fertile site on the island of Zealand and is considered site class I. The forest consists of three compartments, one of which is very wet with a different species composition, so the mean above-ground biomass carbon of the other two compartments (183.7 Mg ha^{-1} and 208.5 Mg ha^{-1}) was calculated to be 196.1 Mg ha^{-1} and this figure was used to represent maximum accumulation potential.

A model developed by Tærø, Mustapha et al. depicting the development of carbon accumulation in an unharvested and harvested stand scenario was used to estimate growth curves using the weighted MACI and carbon accumulation carrying capacity listed above for the respective stands (2017). The model uses a version of the Gompertz function; this is a type of sigmoid function that operates with a short phase of growth initially which is then followed by an exponential period of growth that decreases gradually until the growth rate is zero (Pödör, Manninger et al. 2014).

4.3.6 Modeling of thinning

Two thinning exercises for each stand were simulated using the marteloscope computer program and incorporated into the model to determine the climate mitigation potential from a particular harvest.

4.3.7 Salten Langsø thinnings

The first thinning exercise focused on removing overholders of grand fir to promote growth in existing natural regeneration. To promote further regeneration, a section of the stand in Quadrants III and IV comprised mostly of even-aged Sitka and Norway spruce was thinned to allow for a wider range of species to begin to regenerate. Stems were selected for removal by looking at the proportion of fuel wood and low-quality timber relative to the trees in competition; if they were of low quality but had habitat values higher than 10, they were left in the stand.

With the same management goals listed above, a second thinning was conducted. This thinning was designed to reflect a heavier thinning of the stand with more of the stand opened up and most of the overholders removed. Stems were selected for removal by focusing on their relative size compared to the smaller trees with future potential. Additionally, all pines were removed as they were considered to have reached maturity, and the larger Douglas fir and larch were removed except for several seed trees. As in the first thinning, quadrant III and IV were opened in a similar way though with an increase in the number of trees removed; overall the second thinning was a heavier thinning.

4.3.8 Stenholtvang thinnings

The first thinning in this stand was focused on maintaining the light-demanding oak by reducing the pressure from the neighboring shade-tolerant beech; currently, many branches lower in the crown of the oak are dying off from the lack of adequate sunlight. Over time, the oak will be outcompeted by the beech and its inability to regenerate naturally under shade will likely result in its disappearance. Smaller beech were retained around the oak as they served to prevent epicormic branching and resulting reduced bole quality. This thinning is attempting to maintain the ecological diversity by creating structural heterogeneity.

As significant silvicultural considerations and repeated interventions are needed to manage the inter-species competition within the stand, it was decided that the second thinning focus on harvesting the oak that have higher economic values and remove the low-quality beech. The idea here is to salvage the value that is present now and focus on developing a good crop of beech. Future trees were selected by looking at quality of neighboring trees and removing trees with lower quality boles.

4.3.9 Modeling of alternate scenarios

As our assumptions are rooted in the default half-lives from IPCC Tier 2 accounting protocols, it was of interest to change these to reflect potentially more accurate half-life values; these half-lives represent the reality of the HWP given our knowledge of the end use of the timber in these two particular stands.

Two points in time, 2022 and 2050, were chosen to examine how changes in the assumptions would affect the carbon balances. In both stands, the default scenario in the model was set according to IPCC defaults as previously described. In the alternate scenarios, the custom category was used and set with a specific half-life.

In the first alternate scenario (Custom Half-life Scenario) for Salten Langsø, D/IT assortment quality for all species was categorized as emballage, reflecting past sales from this forest district. Assortment quality B and C of grand fir was also categorized as emballage - this was done because even higher-quality grand fir is sold to be made into packaging material in the Danish market because of its poor local reputation for strength (Jan Østergaard, 2020, Personal communication). While packaging made from sawnwood is part of the aggregate sawnwood category under IPCC defaults, it is unlikely to have a half-life of 35 years. This presents the issue of overrepresenting carbon stored over time if inaccurate half-lives are used. We therefore set the half-life of emballage to three years, reflecting country specific half-lives used for EURO pallets in Lithuania (Aleinikovas, Jasinevicius et al. 2018).

In the second alternate scenario (Grand fir Scenario), we recategorized B and C grades of grand fir back to sawnwood to reflect it being more optimally utilized as construction timber while keeping D/IT assortments for all species in the emballage category with a three year half-life. It was hoped that this would highlight the potential of better utilization of this species were it not all going to short-lived packaging.

In the alternate scenario (Custom Half-life Scenario) for Stenholtvang, the half-life was set to 67 years for the sawnwood category. This is an estimated half-life for nonresidential construction based on historical data on wood harvest and end use found in USDA Forest Surveys (Skog and Nicholson 1998). The idea here was to explore the effect of lengthening the half-life in an effort to reflect the potential use of broadleaf timber in this stand being used in longer lasting products. For example, some of the oak sold in this forest district is used for the keel, frames, and planking of traditional ships (Jan Erik Løvgren, 2020, Personal Communication).

5 Results

5.1 Initial stand characteristics

After the measurements and calculations described above, the stands were found to have the summary characteristics presented in Table 7. Volume, economic value, habitat value, and carbon content are further separated out by species in order to examine the distribution of these values by species and how these relationships impact tradeoffs and synergies within both stands.

Table 7: Initial stand characteristics for Salten Langsø and Stenholtvang

Initial Stand Characteristics

Attributes	Salten Langsø	Stenholtvang
Stem number [n]	429	315
Basal area [m²]	30.06	36.29
Volume [m³]	540.96	486.18
Economic Value [DKK]	174,437	359,253
Habitat Value	1363	1829
Carbon [Mg]	120.10	135.40
CO_2-eq [Mg]	440.35	496.45
Carbon Substitution Potential [Mg C]	132.22	128.28

A further breakdown of the volume by quality assortment is given in Table 8; the concentration of volume in fuel wood in Stenholtvang is particularly notable.

Table 8: Volume distributions by quality assortment for Salten Langsø and Stenholtvang.

Volume Distributions by Quality		
Quality Assortment	Volume in Salten Langsø [m³]	Volume in Stenholtvang [m³]
A	22.40	20.11
B	119.84	48.12
C	135.46	96.23
D	89.03	9.85
F	174.23	311.86
Total	540.96	486.18

Figure 8 and Figure 9 present a visual representation of the volume by species in both Salten Langsø and Stenholtvang.

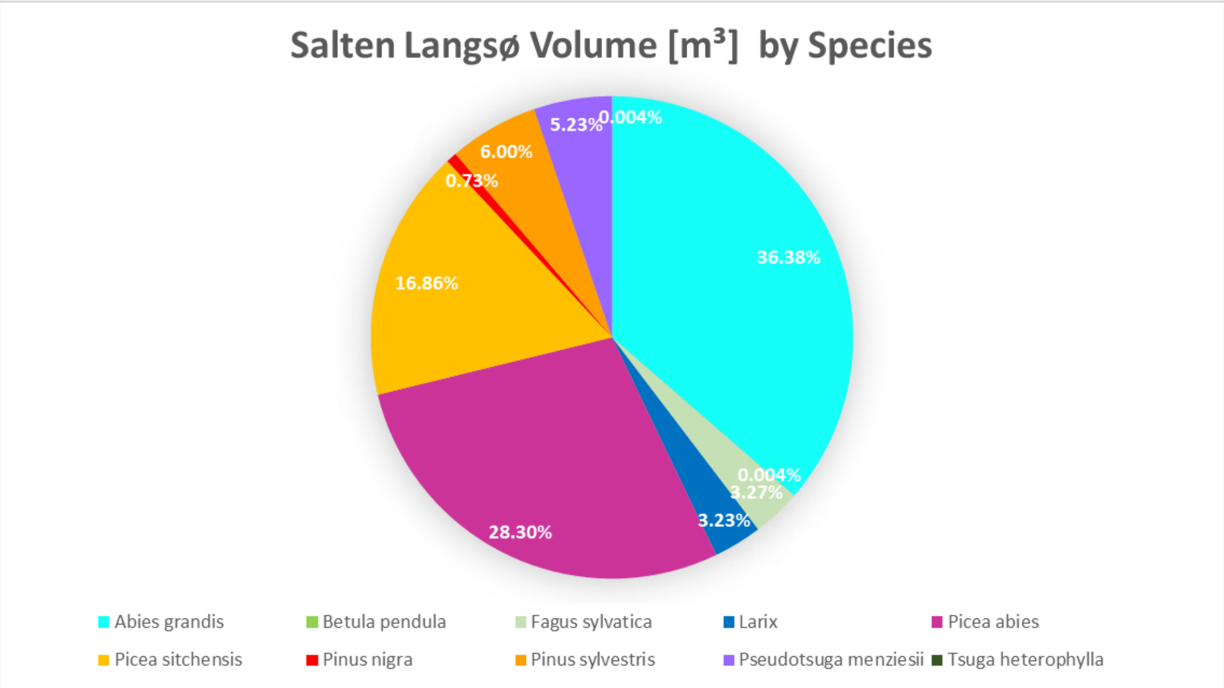

Figure 8: Volume distribution by species in Salten Langsø

As seen in Figure 8, in Salten Langsø grand fir represents more than a third of stand volume followed closely by Norway and Sitka spruce. The rest of the volume is distributed in small amounts across several other species.

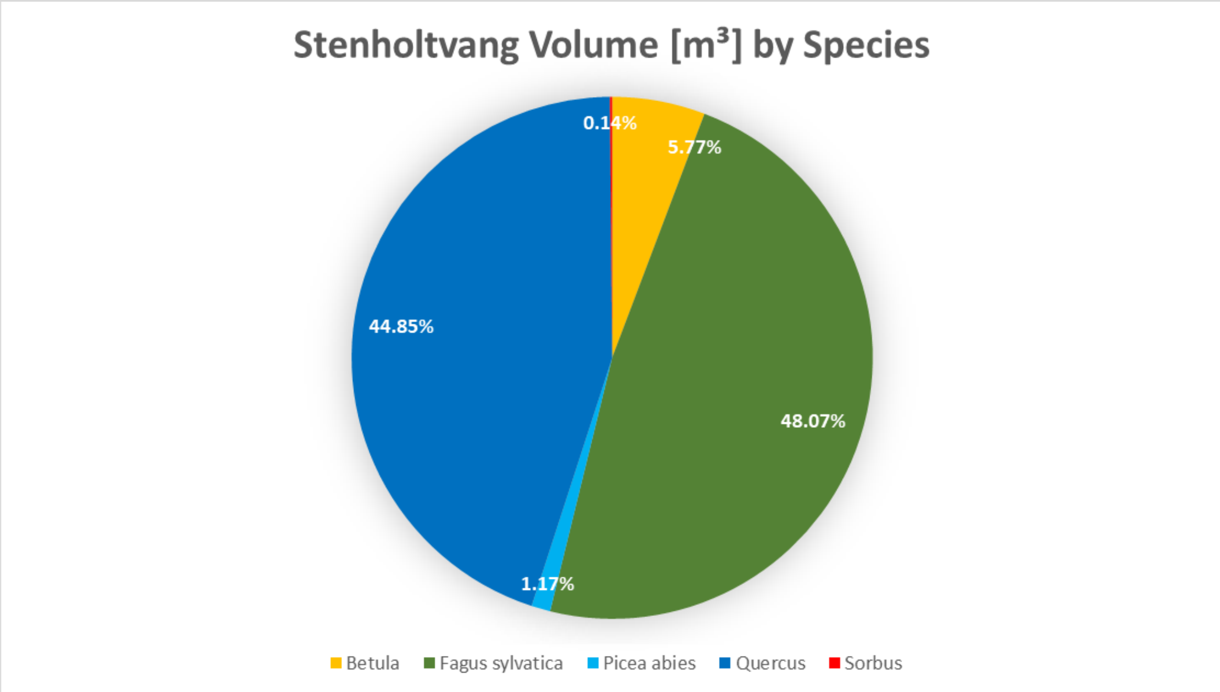

Figure 9: Volume distribution by species in Stenholtvang.

Figure 9 shows that volume in Stenholtvang is split nearly evenly between oak and beech. A small number of birch contributes to the remaining volume with negligible amounts of Norway spruce and rowan.

Table 9: Economic value, habitat value, and carbon content by species in Salten Langsø.

Salten Langsø			
Species	Economic Value [DKK]	Habitat Value [points]	Carbon Content [Mg C]
Abies grandis	53,122	128	42.40
Betula pendula	6	0	0.005
Fagus sylvatica	5,918	411	5.36
Larix sp.	5,971	92	4.17
Picea abies	51,711	321	34.67
Picea sitchensis	29,929	288	18.37
Pinus nigra	1,035	0	0.88
Pinus sylvestris	8,338	108	6.95
P. menziesii	18,398	15	7.27
T. heterophylla	5	0	0.007
Total	174,437	1,363	120.10

Table 10: Economic value, habitat value, and carbon content by species in Stenholtvang.

Stenholtvang			
Species	Economic Value [DKK]	Habitat Value [points]	Carbon Content [Mg C]
Betula sp.	9,392	176	5.26
Fagus sylvatica	91,293	255	67.81
Picea abies	1,728	4	1.10
Quercus sp.	256,611	1,355	60.79
Sorbus sp.	226	39	0.19
Total	359,253	1,829	135.15

By comparing the economic values for both stands in Table 9 and Table 10, we see that Stenholtvang holds twice the economic value of Salten Langsø. Table 10 also shows that this value stands primarily in the oak which holds 71.4% of the total value in Stenholtvang.

These two tables also indicate that Stenholtvang has 34.2% more habitat value points than Salten Langsø. Additionally, by looking at both Figure 8 and Table 10, it can be seen that 30.15% of the habitat value in Salten Langsø is coming from only 3.27% of the total volume of the stand (five beech trees) whereas in Stenholtvang, 74.08% of the total habitat value in the stand is derived from the oak and 13.94% from the beech.

In terms of carbon content in Salten Langsø, Table 9 shows the bulk of it resides in the grand fir, followed by Norway spruce, and Sitka spruce. The rest of the carbon content is distributed in small amounts in various species. Table 10 shows about half the total carbon content in Stenholtvang resides in beech with about 45% in oak.

5.2 Spatial distribution of trees, habitats, and carbon

The maps below, generated with the I+ trainer marteloscope exercise software, present an initial stand picture of both stands.

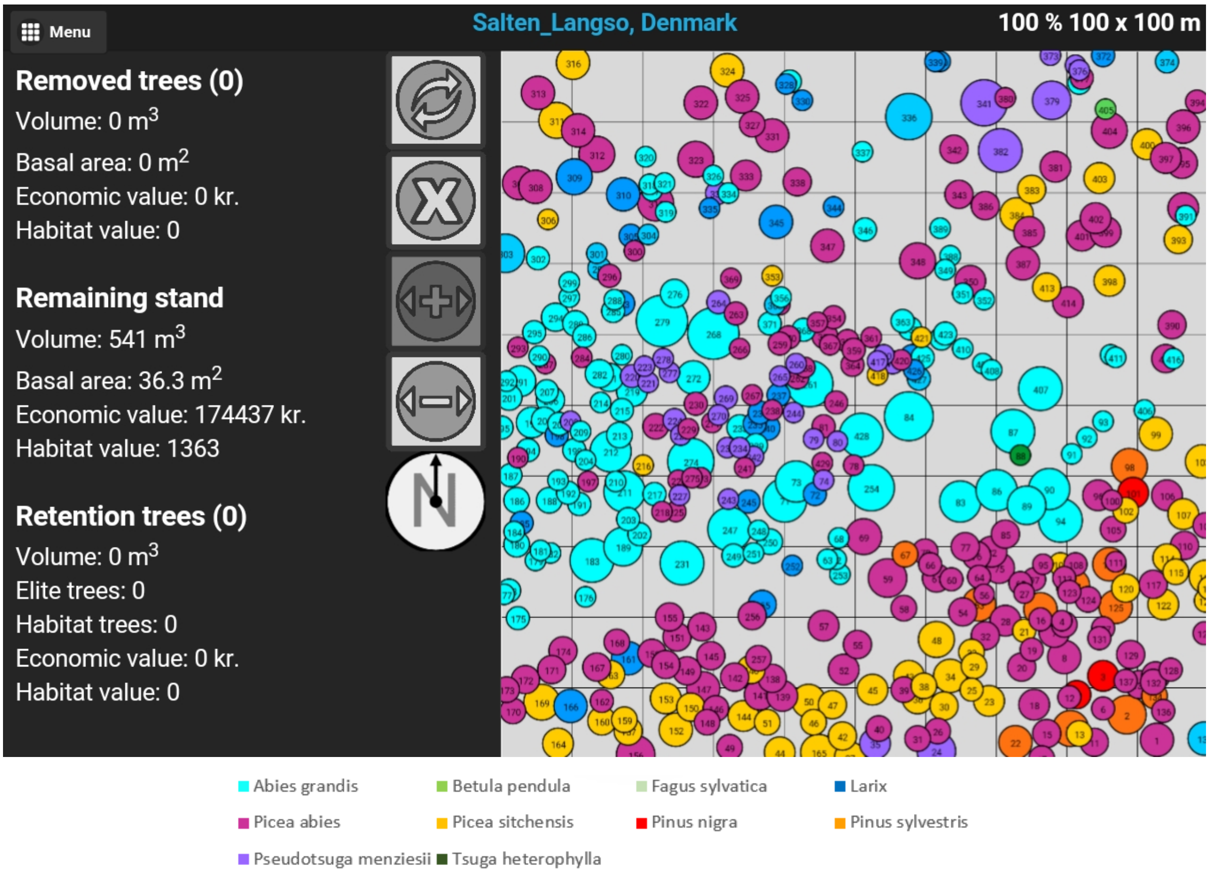

Figure 10: Screenshot from I+ marteloscope software depicting the Salten Langsø marteloscope.

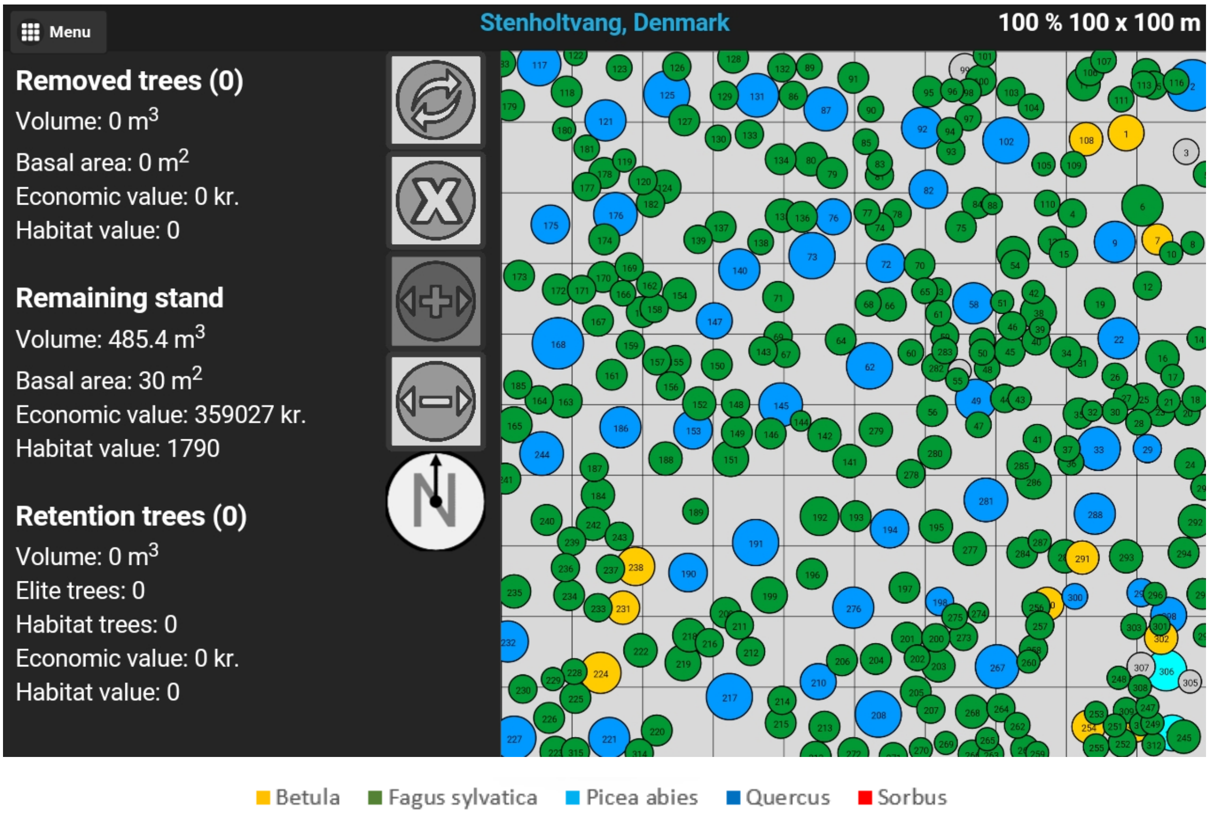

Figure 11: Screenshot from I+ marteloscope software depicting the Stenholtvang marteloscope.

As the size of the circles are reflective of volume, the stand maps in Figure 10 and Figure 11 can be used to infer approximate spatial distribution of carbon within the stand while acknowledging that different trees have different densities. Many of the veteran trees hold much of the carbon content in Salten Langsø and it is distributed fairly evenly between many different species. In Stenholtvang, the oaks are larger overall than the beech, thus having more carbon content per tree. There are more beech trees in the stand but they have less carbon content per tree.

Conflict maps can be produced with the I+ trainer software and illustrate which individual trees have both a high economic value and a high biodiversity score. Maps for each stand are displayed in Figure 12 and Figure 13. As described in the marteloscope software, these maps depict an overlay of economic and habitat value where red circles signify economic value and green circles indicate habitat value. The size of the circle is directly related to the particular value a tree holds. High values have large circles and very low values are invisible; trees that overlap are considered conflict trees.

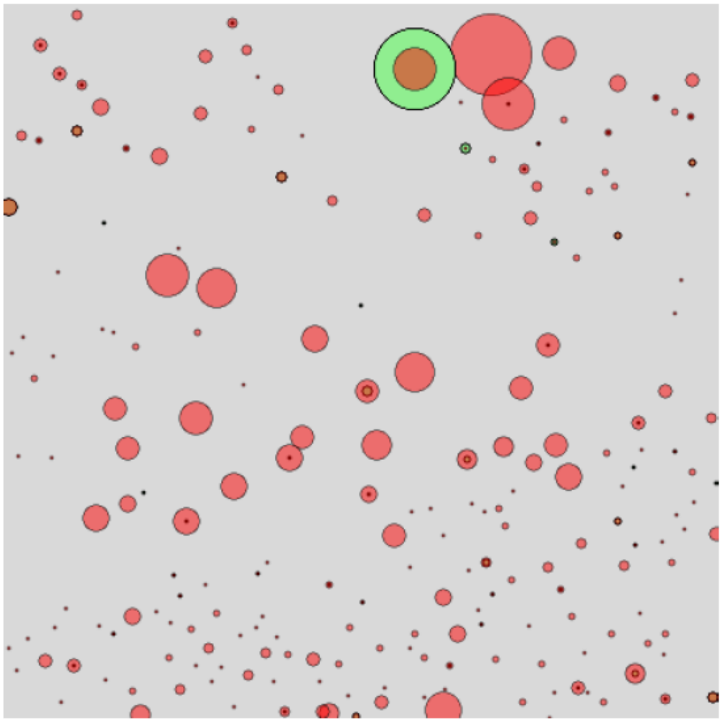

Figure 12: Salten Langsø conflict trees showing overlay of economic (red) and habitat value (green). Map produced from Marteloscope I+ software and shows 100m x 100m area of marteloscope.

As Figure 12 demonstrates, there are few major conflict trees within Salten Langsø. The largest habitat value within the stand is found in a single large, old beech which presents an economic conflict purely from the sheer volume of fuelwood it contains. For most of the trees within the stand, the economic value outweighs that of the habitat value.

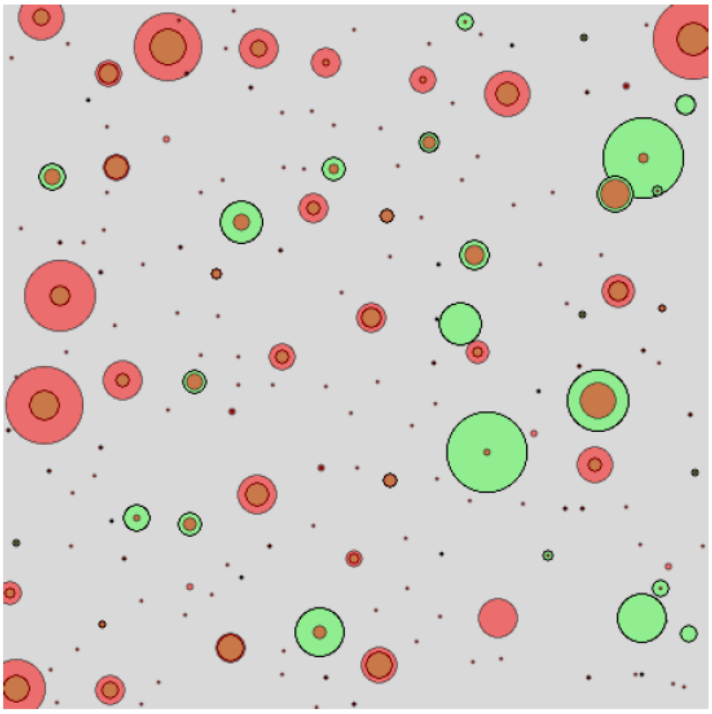

Figure 13: Stenholtvang conflict trees showing overlay of economic (red) and habitat values (green). Map produced from Marteloscope I+ software and shows 100m x 100m area of marteloscope.

Without counting the values that are very low, the depiction of Stenholtvang in Figure 13 illustrates about 16 trees where the habitat value is clearly greater than that of the economic value. In contrast, there are about 27 trees where the economic value outweighs that of the habitat value.

5.3 Model diagram

While developing the model was a process described in the methods, the model also represents a key result. It was therefore decided to represent this finished product in a graphical way. The process diagram that follows illustrates the general flow of data through the model framework, from individual tree data to stand carbon balance.

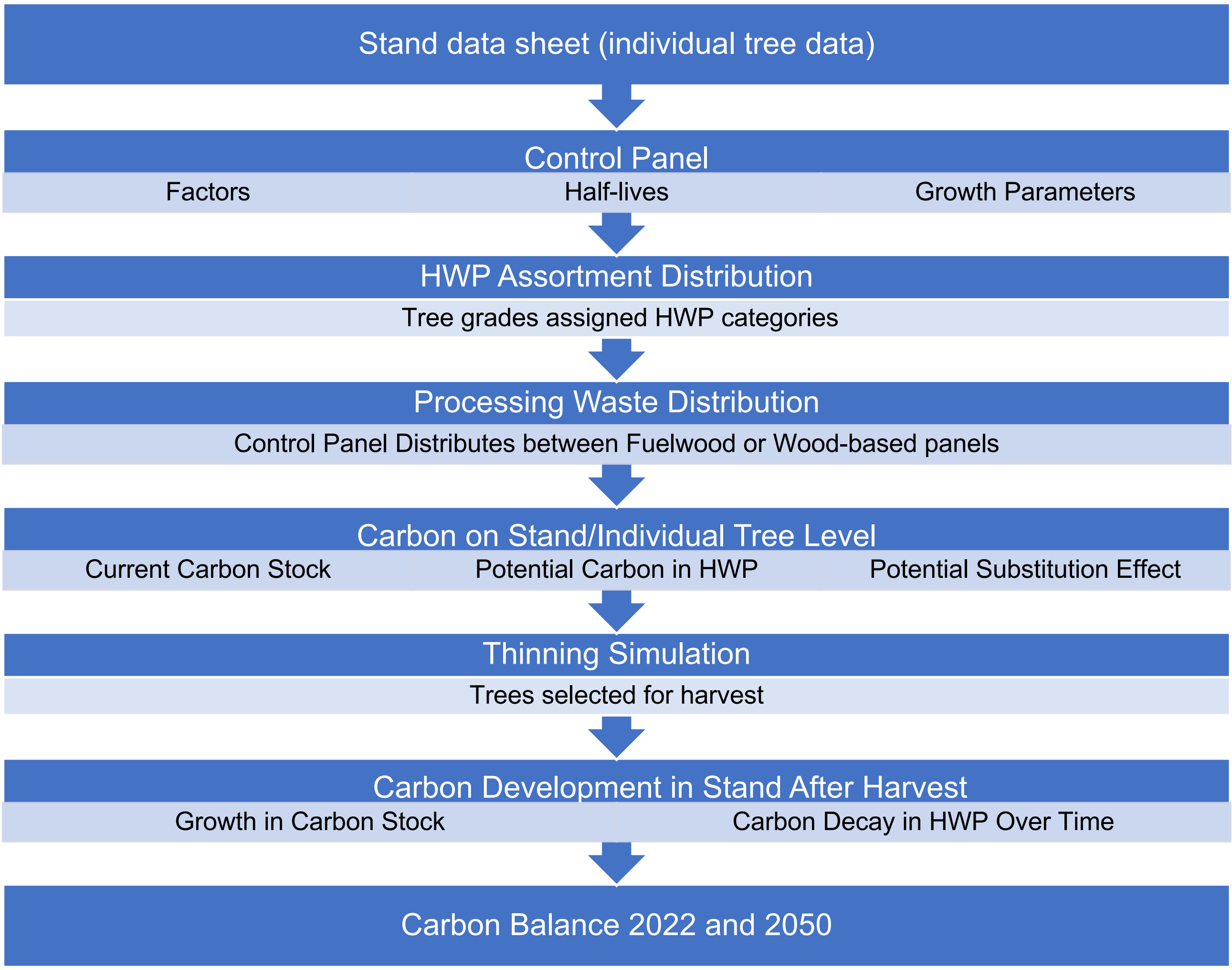

Figure 14: Model process diagram.

After stand data sheets containing individual tree data are loaded into the model, desired settings are programmed into a control panel. Here the user can set various factors, from wood carbon content to HWP half-lives, sawmill efficiency, and desired growth parameters. It must also be decided where harvested wood volume will go; each species and quality grade may be distributed among the default HWP categories or custom categories. During processing into the semi-finished HWP categories, a percentage of the volume becomes waste, which is then distributed back into the HWP categories according to the control panel settings.

Using the prescribed settings, the model calculates current carbon stored in the above-ground biomass for each tree, and the CO_2 equivalent of that carbon. It then models the decay over time of that carbon, were the tree to be harvested and turned into wood products. The potential substitution effect of each tree is also estimated.

At this point, stand level totals are provided for carbon stored, HWP carbon storage potential at a given point in the future, and substitution potential. Trees can then be selected for removal which enables the user to see the effects of a single thinning in relation to carbon balance, economic value, and biodiversity score.

Regrowth of the stand after harvesting is then estimated alongside a baseline scenario of growth if no harvesting had been done, to determine carbon accumulation in future years. These results are presented visually and also include the substitution effect of the harvest and the HWP wood product pool decay over time.

5.4 Model simulation results

5.4.1 Stand characteristics after thinning

The effect of the simulated thinnings on stand characteristics at the two sites can be seen in Table 11 and Table 12.

Table 11: Salten Langsø initial stand attributes, attributes removed during the thinnings, and attributes left after the thinning.

Salten Langsø		Thinning 1		Thinning 2	
Attributes	Initial	Removed	After	Removed	After
Stem number [n]	429	60	369	76	353
Basal area [m²]	36.29	10.42	25.87	18.38	18
Volume [m³]	540.96	164.09	376.87	295.25	246
Economic Value [DKK]	174,437	46,453	127,984	94,947	79,491
Habitat Value	1,363	116	1,247	308	1,055
Carbon [Mg]	120.10	35.32	84.78	54.25	65.84
CO_2-eq [Mg]	440.35	129.49	310.86	198.92	241.43
C Substitution Potential [Mg C]	132.22	40.02	92.20	72.88	59.35

For Salten Langsø, Table 11 illustrates that Thinning 1 harvests 26.63% of the total economic potential and 30.41% of the total substitution potential while removing 30.27% of the total volume, and 8.51% of the stand's habitat values. Thinning 2 harvests 54.43% of the total economic potential and 55.12% of the total substitution potential while removing 54.58% of the stand's total volume, and 22.59% of the total habitat values.

Table 12: Stenholtvang initial stand attributes, attributes removed during the thinnings, and attributes left after the thinning.

Stenholtvang		Thinning 1		Thinning 2	
Attributes	Initial	Removed	After	Removed	After
Stem number [n]	315	124	191	131	184
Basal area [m²]	30.06	9.07	20.99	13.66	16
Volume [m³]	486.18	140.79	345.40	228.63	258
Economic Value [DKK]	359,253	55,883	303,370	249,914	109,339
Habitat Value	1,829	96	1,733	933	896
Carbon [Mg]	135.40	15.82	119.58	64.31	71.09
CO_2-eq [Mg]	496.45	58.00	438.45	235.80	260.65
C Substitution Potential [Mg C]	128.33	36.88	91.45	63.55	64.78

In Table 12, Thinning 1 in Stenholtvang resulted in a harvest of 15.56% of the total economic potential and 28.75% of the substitution potential while removing 28.96% of the total volume and 5.25% of the total habitat values. Due to the economic value primarily residing in the oak, Thinning 2 resulted in a harvest of 69.56% of the total economic potential and 49.54% of the carbon substitution potential with a removal of 47.03% of the total volume, and 51.01% of the total habitat value in the stand.

5.4.2 Model simulation of stand carbon balance

The four graphs shown present the carbon balance for each simulated thinning in both stands. Each graph includes a baseline growth curve of carbon accumulation with no thinning conducted. The other curves illustrate carbon trends in stand regrowth after thinning, stand regrowth with HWP carbon from the thinning, and stand regrowth combined with HWP carbon and the substitution effect.

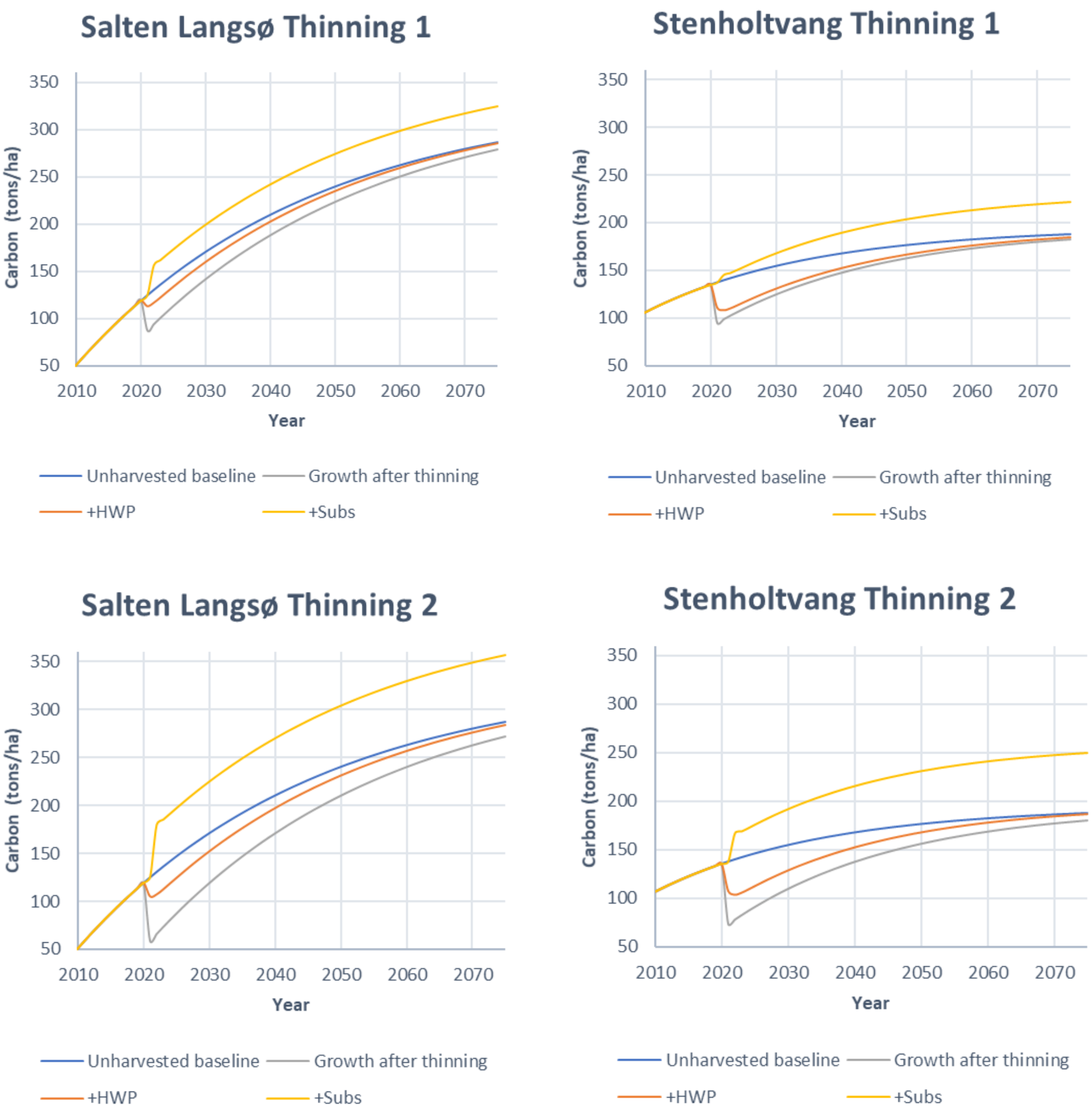

Figure 15: Carbon Balance in Salten Langsø and Stenholtvang for all 4 simulated thinnings.

In the upper left graph of Figure 15, it can be seen that the carbon benefit from this first simulated thinning at Salten Langsø in 2022 is at least 25 Mg C more than if the stand had been left to grow unharvested. With the added effect of the carbon accumulating in the re-growth, it jumps to around 35 Mg C in 2050. Similar trends are observed in bottom left graph showing the second thinning but are more pronounced than the first as more wood is being removed. This amplifies the substitution effect and creates a bigger HWP carbon pool. The carbon benefit is approximately 50 Mg C more than the unharvested stand in 2022 and 65 Mg C more in 2050.

In the upper right graph in Figure 15, the carbon benefit of the first thinning in Stenholtvang is around 5 Mg C higher than the unharvested stand; the difference grows to more than 25 Mg C in 2050. In the bottom right graph, the second thinning has a higher carbon benefit than the first with at least 25 Mg C more than the reference unharvested stand; the difference between the two increases to around 55 Mg C by 2050.

While these graphs illustrate overall trends, it is useful to take a closer look at carbon balances at specific points in time, especially when adjusting assumptions in model parameters. The charts below contrast carbon balances in 2022 and in 2050 at Salten Langsø and in Stenholtvang under the two modeling scenarios.

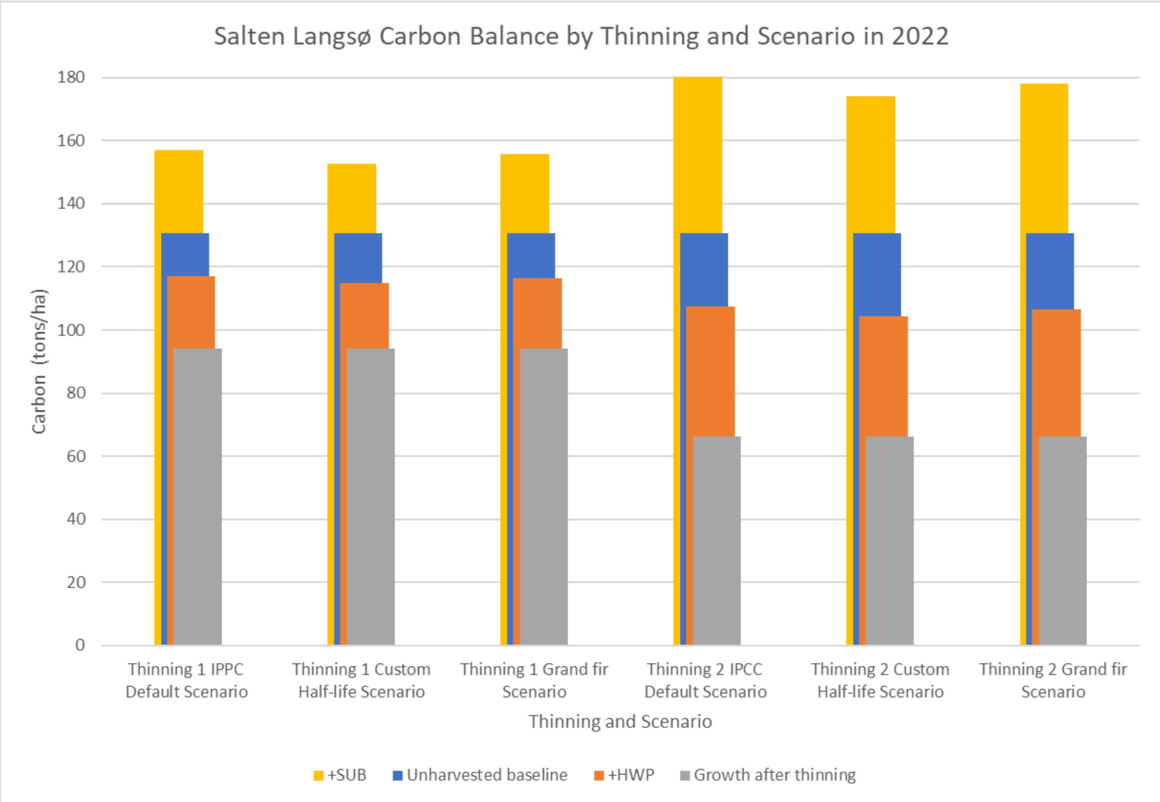

Figure 16: Salten Langsø carbon balance showing the amount of carbon in the growth after thinning, growth in unharvested baseline, the +HWP pool (re-growth and HWP pool together) and +SUB pool (re-growth, HWP pool, and substitution effect together) in the default scenario, custom half-life scenario, and grand fir scenario in 2022.

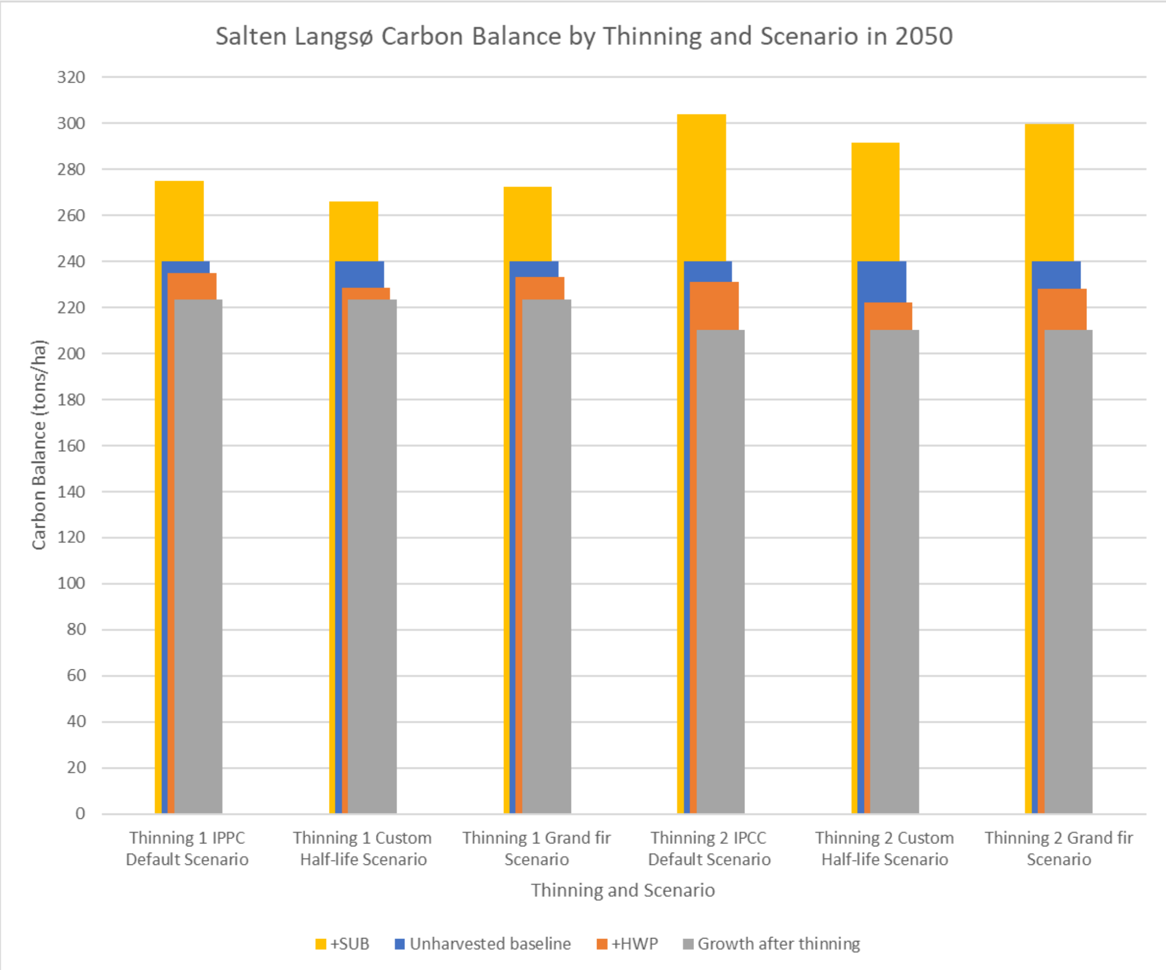

Figure 17: Salten Langsø carbon balance showing the amount of carbon in the growth after thinning, growth in unharvested baseline, the +HWP pool (re-growth and HWP pool together) and +SUB pool (re-growth, HWP pool, and substitution effect together) in the default scenario, custom half-life scenario, and grand fir scenario in 2050.

When comparing the default scenario Thinning 1 and custom half-life scenario +SUB balance in Figure 16, treating emballage with a half-life of three years results in an overestimation of the carbon benefit of more than 4 Mg C in 2022. In Figure 17, when comparing the two scenarios the overestimation in 2050 is shown to be at least 8 Mg C. This is due to first-order decay depreciating the HWP pool more rapidly with the shorter half-life of three years. A similar result is seen in Thinning 2 between the default and custom half-life scenario in Figure 16 and Figure 17; the effect of the heavier thinning causes a greater difference with around 6 Mg C and 12 Mg C overestimation in carbon benefit in 2022 and 2050, respectively.

When comparing the +SUB balance in the custom half-life scenario and grand fir scenario for Salten Langsø Thinning 1 in Figure 16, a gain in carbon benefit of 3 Mg C is realized in 2022. This is from shifting grand fir B and C assortments to the sawnwood pool. A gain of about 6 Mg

C can be seen in 2050 when looking at Figure 17. In Thinning 2, this gain increases to 4 Mg C and 8 Mg C in 2022 and 2050, respectively. Two effects are at play here: the slower rate of decay from the higher half-life in the sawnwood pool as well as the higher substitution factor for sawnwood.

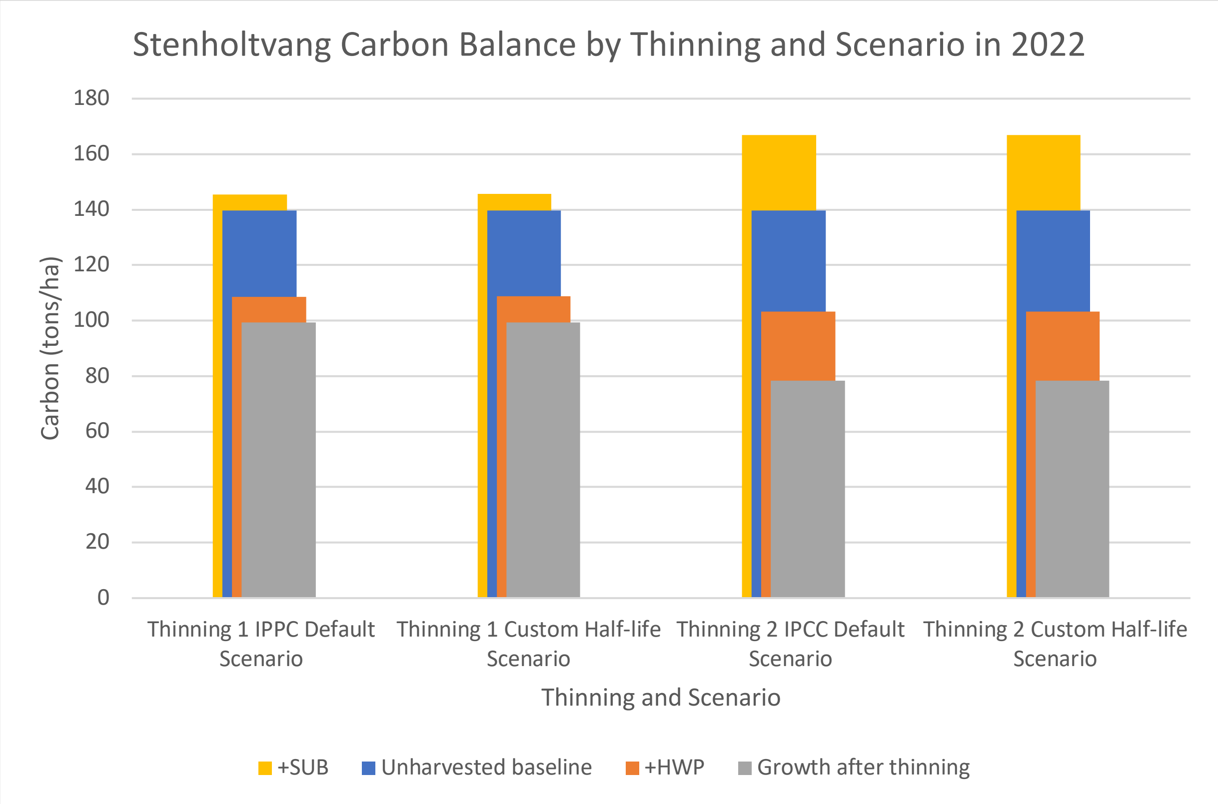

Figure 18: Stenholtvang carbon balance showing the amount of carbon in the growth after thinning, unharvested baseline, the +HWP pool (re-growth and HWP pool together) and +SUB pool (re-growth, HWP pool, and substitution effect together) in the default scenario and custom half-life scenario in 2022.

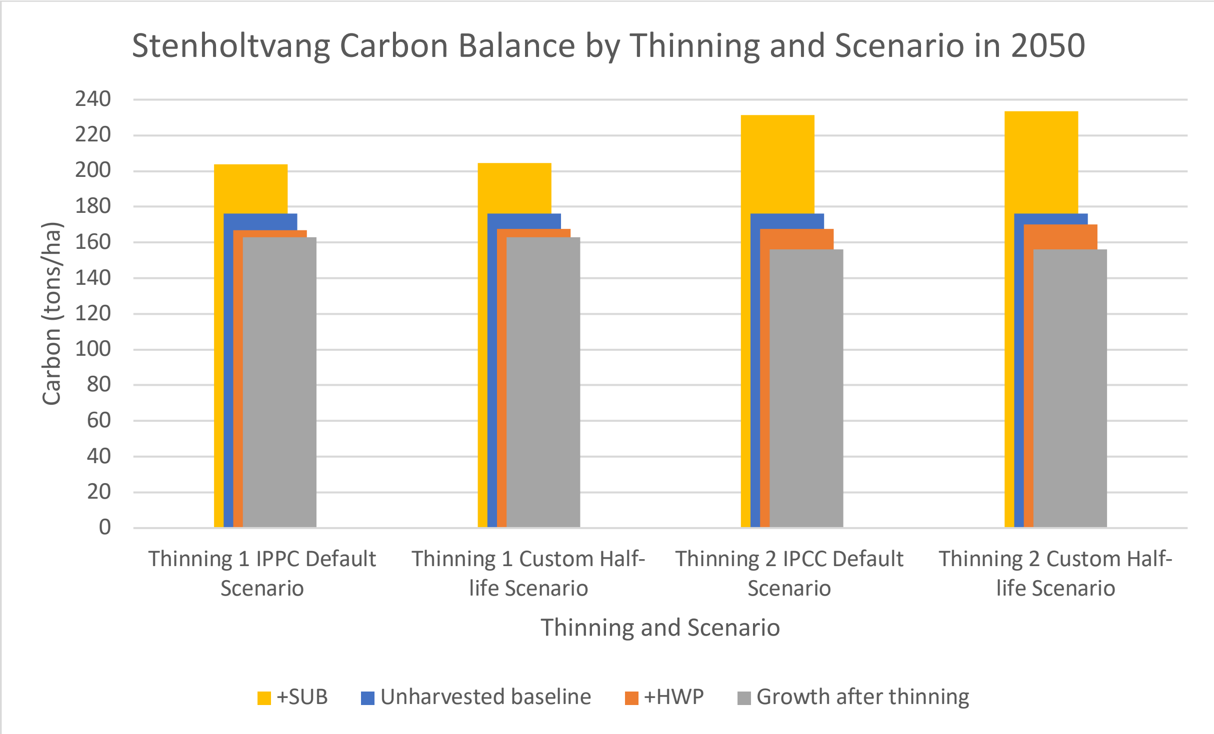

Figure 19: Stenholtvang carbon balance showing the amount of carbon in the growth after thinning, unharvested baseline, the +HWP pool (re-growth and HWP pool together) and +SUB pool (re-growth, HWP pool, and substitution effect together) in the default scenario and custom half-life scenario in 2050.

In Stenholtvang, the difference between the +SUB balance in the default and custom half-life scenarios in Figure 18 (after switching the half-life of sawnwood to 67 years) results in a minimal difference in 2022; the carbon benefit is hardly visible on the chart and according to the data is only 0.04 Mg C and 0.12 Mg C for Thinning 1 and 2 respectively. The change is minor since such a half-life increase makes little impact on early first order decay. It can be seen in Figure 19 that by 2050, the advantage of longer half-lives in Thinning 1 and Thinning 2 is 0.83 Mg C and 2.29 Mg C, respectively. The gain seen in Thinning 2 with the removal of the oaks is more substantial since the increased half-life is also acting on a larger pool of sawnwood.

6 Discussion

6.1 Overview of stand characteristics

While the varying site characteristics, ages, and species composition of the two stands do not necessarily allow for direct comparison of stand attributes between each other, the corresponding species differences affect stand attributes and offer salient insights for forest and nature management. Economic value in Stenholtvang is presently concentrated in a single species –

oak. However, the species mixture in Stenholtvang (and consequently other stand attributes) is likely to change without specific management for the oak as the beech have begun to outcompete them while preventing their regeneration. In contrast, the economic value is distributed more evenly between several species in Salten Langsø with many species naturally regenerating in the understory. This diverse species mixture might enable a wider range of future management options and therefore a potentially more resilient future.

When considering habitat values, Salten Langsø scores only 25% lower than Stenholtvang. This may be surprising given the prevailing notion that non-native conifer stands support less biodiversity than stands of native tree species. However, Salten Langsø is a near-naturally managed stand with a wide mix of species and age classes offering more variations in structure than monoculture conifer stands. Further examination of the scores reveals a significant portion of the habitat score is actually coming from a few inmixed beech; this underlines how just a few trees may contribute to a large proportion of the total stand's capacity to support biodiversity. It is perhaps less surprising that in Stenholtvang, most of the total habitat value in the stand is derived from oak while a relatively small portion is from beech; this may be due to the fact that the oak is older and has had more time to develop microhabitats. It should be noted that the birch in Stenholtvang represent a more significant contribution to the overall score by volume than do the beech, providing 10% of the habitat score while representing only 5.7% of the volume. Beech on the other hand represents 48% of the volume but only 13.4% of the habitat score. Similar to the benefit that the beech offer in Salten Langsø, the birch in Stenholtvang serve as valuable contributors to stand biodiversity, reinforcing the benefit of setting aside at least a few veteran trees without commercial value.

Salten Langsø has a higher basal area and volume than Stenholtvang, however this does not translate to more biomass. When species specific biomass is calculated, the importance of density becomes apparent; Stenholtvang evidently has more biomass and therefore more carbon. This is not necessarily surprising since Stenholtvang consists largely of denser broadleaf species while Salten Langsø is primarily composed of less dense conifer species. However, calculated basal area in both stands is not inclusive of regeneration as trees with a DBH under 7.5 cm were not measured. Salten Langsø has significant regeneration of various species that is not contributing to the final calculation whereas Stenholtvang has less regeneration, meaning that the basal area and volume as calculated here is closer to reality.

6.2 Stand carbon dynamics and thinning simulations

While the initial state of the two stands is a starting point for analysis, a more useful comparison necessitates considering stand dynamics, especially growth. By examining the graphs depicting carbon balances over time after thinnings, we gain further insight into the potential of each stand to remove carbon from the atmosphere and contribute to carbon storage and substitution outside of the forest.

Salten Langsø has both a faster potential growth rate and a higher eventual carrying capacity then Stenholtvang. This is primarily a function of species composition, with the presence in Salten Langsø of the fast-growing North American conifer species that produce large standing volumes. The oak and beech at Stenholtvang are on much richer soil – if the species mixture at Salten Langsø was growing at Stenholtvang, it would probably have even higher growth potential than Salten Langsø does today. Likewise, if the Stenholtvang species mixture was growing at Salten Langsø, it would likely result in poorer growth than Stenholtvang has today.

Perhaps the most striking result across all scenarios is the magnitude of importance of the substitution effect. In all cases, the carbon parity time is effectively zero when substitution is included. We believe this is accurate and reflects both society's current dependence on fossil fuels while suggesting the importance of using biomass to offset fossil fuel, particularly coal, which was assumed to be our substituted fossil fuel. Further, as biomass for energy has a lower substitution factor than the other HWP categories in our model, the use of wood for non-fuel products has an even greater substitution effect. This is particularly visible in the relative difference between the curves at Salten Langsø and Stenholtvang. Salten Langsø clearly has more harvested carbon retained in HWP relative to volume harvested, and correspondingly a higher substitution benefit. Stenholtvang has a lower relative percentage of HWP carbon retained and therefore a lower substitution effect. This reflects the greater relative allocation of wood to the fuelwood category at Stenholtvang – more of the wood is being burned and therefore has a lower substitution value (of 0.81) compared to the higher substitution values (1.4) credited to sawnwood at Salten Langsø.

The difference in species composition between the two thinnings at Stenholtvang is also hinted at in the graphs. This can be seen in the differences between the HWP pools after harvest – the second thinning has stored more carbon in HWP relative to the harvest than the first. The first thinning left the large oaks in place, removing mostly poor-quality beech destined for fuelwood. The second thinning simulated removal of the oaks which have large volumes of sawnwood, more carbon storage, and a higher substitution value.

Interestingly, this large standing substitution potential in the oak parallels large standing economic value. The same question can be asked about the ideal to time to harvest and realize these values: is it better to extract the value now, or is it still accumulating at a rate that would make current extraction illogical? This is a salient question if it is believed that substitution factors may decrease over time as fossil fuel energy is replaced with renewable energy. Similar to economic considerations in forestry where high interest rates tend to shorten rotation ages, a decreasing substitution factor over time may suggest that current action is most important – the wood should be harvested now while substitution factors are high, rather than later when it will be less able to substitute for fossil fuel and less valuable from a climate perspective.

Without including the substitution effect, none of the four graphs show the line representing the carbon in stand growth and HWP crossing the line representing carbon stored in the unharvested scenario in the time shown. The thinning scenarios all have higher growth rates immediately post-thinning than in the unharvested scenario, but this is not enough to compensate for the rapid oxidation of harvested carbon in fuelwood.

From the graphs it is apparent that Salten Langsø has more potential for climate impact than Stenholtvang. This is largely a result of the differences in growth potential with different species composition, and a higher theoretical carrying capacity. Over the long term this growth is especially important, though the climate crisis may demand more immediate action. Interestingly, in the shorter term, the net positive carbon benefit in both stands by 2050 is of similar magnitude, demonstrating that existing stands of very different forest types offer potential for climate benefit now.

6.3 Assumptions and Limitations

As with any model, assumptions are made that represent generalizations. When these assumptions take the form of easily changed factors or rates such as growth and decay, they can be changed to understand how they affect results. However, there are also less easily adjusted passive assumptions incorporated into the model that may affect the results, such as relying on derived formulae to estimate volume and biomass.

When estimating growth, it was assumed that future stand composition would remain the same, in terms of relative volumes of each species. It is more likely that there would be variation over time due to harvesting of individual trees and natural stochasticity. Climate change also increases uncertainty around future growth or even viability of particular species. Furthermore, the Danish common experiment focuses on the growth development of monoculture stands with regular thinnings; this does not necessarily reflect the dynamics, namely competition, in an uneven aged stand that grows unaffected by thinnings.

There are also assumptions inherent in using first-order decay functions or particular decay rates for HWP. While these are scientifically accepted methods and represent carbon accounting standards it is worth noting that as they are applied at the international level they represent more of a “one size fits all” approach. This is one reason we have established a custom HWP category in the model to allow for experimentation using more detailed real data or “what-ifs” to represent alternatives.

An important limitation when considering habitat values and biodiversity is that TrEMs are a proxy measure, relying on the assumption that the presence of certain structures supports the presence of certain species. The index was designed for ease of use to allow biodiversity indicators to be easily quantifiable and for comparisons to be made across sites. One tradeoff of using a structural proxy index is that it does not consider any differences in species specific relationships between trees and organisms. That is to say that a particular habitat on an exotic species may represent a different biological value than the same habitat on a native species.

6.3.1 Notes on single thinning model design

The model only considers one thinning, in order to allow the user to compare the consequences of different thinnings in the present time. This is a limitation by design - if multiple thinnings over time were modeled, the HWP carbon pool would accumulate differently and a more complete picture may emerge that would enable more broad comparisons of management regimes over time. However, modeling over time would introduce higher degrees of uncertainty as more assumptions would be needed, ranging from future stand growth and composition to future substitution factors and HWP uses.

6.4 Tradeoffs between biodiversity, economy, and carbon

As illustrated by the conflict maps, the spatial distribution of the habitat values and economic values presents a powerful picture in Stenholtvang. Simply put, Stenholtvang has a more homogenous distribution of conflict than Salten Langsø. Most of the economic value cannot be removed from the stand without also losing a considerable number of microhabitats. Equally compelling is the lack of conflict within Salten Langsø. The majority of the habitat score is concentrated in a few veteran trees, which can be preserved while other trees are harvested. This also suggests that in Salten Langsø there may also be less tension between achieving a climate benefit and preserving biodiversity, if harvesting wood achieves a bigger climate benefit. Since the oak in Stenholtvang has both the lion's share of habitat values and the highest climate impact potential, one has to manage for one or the other. If maximization of the carbon benefit was not the aim, habitat trees could be left to continue sequestering carbon—albeit with lower climate benefit than harvesting.

The relationship between carbon and economy is highly contingent on the quality of the wood which determines its end use, respective half-life, and price. It is evident that very poor-quality timber, (and therefore low-priced timber) has a minimal overall impact in the HWP pool since it becomes fuelwood and has a short half-life, yet it can still have significant climate benefit when the substitution effect is factored in. High quality wood may fetch higher prices on the market when sold as veneer (winding up in panels with a 25 year half-life) but may not mitigate the climate as well as lower priced 'B' and 'C' quality wood that tends to be sold as sawnwood (with a 35 year half-life). If climate mitigation impacts of wood products factored into a higher price for wood, this could alter how tradeoffs and synergies with economic value would play out.

6.5 Implications for HWP, future work, and final words

Our results suggest there are opportunities to enhance the climate benefit of already-existing forest resources. If half-lives of wood products can be increased, the size of the carbon pool outside of the forest will increase. It is possible that longer half-lives will also increase the substitution effect, if a product made from wood has a longer life than a fossil fuel derived one. This could be achieved with technological innovation or encouraged through policy change regarding the use of wood in construction, for example. Encouraging or requiring the recycling of carbon containing wood products could further increase the half-life of forest carbon.

We have also shown that more accurate local data on HWP and half-lives is important to develop accuracy in carbon accounting. The broad classifications of the IPCC Tier 2 categories may not reflect local realities and could lead to over- or under-estimating carbon stored in that pool. Using a custom category for emballage illustrates the difference could be significant.

Modeling carbon dynamics at the individual tree level within a stand has also revealed a detrimental climate effect when wood is underutilized. While the use of wood in any of our HWP categories has a positive substitution effect, the effect is greatest in the sawnwood category. As with the example of grand fir, using wood that has a greater substitution potential (as sawnwood) for a purpose that has less substitution potential (emballage) represents a missed opportunity to maximize climate impact. If a forest manager has the option to sell similar quality wood for packaging wood or as fuelwood at the same price, might they use this knowledge to sell it for packaging wood instead? At a national level, it may be wise to fund research into the bio-economy that could develop new uses for existing wood resources.

These are all issues that could be explored by marteloscope users with the added benefit of the carbon perspective. In addition to prompting discussions as above, users would be able to compare the effects of management action across the three dimensions of carbon, biodiversity, and economy, likely finding many examples of synergies and not a few examples of conflict. We therefore believe that the carbon model is a valuable addition to the marteloscope concept.

This project has established two marteloscopes and developed a model that can calculate climate impact of forest management actions using marteloscope data. To the best of our knowledge this has not been done before. With some adaptation, the model could use data from any marteloscope in Europe or worldwide. If these marteloscopes are representative of larger forest areas, results could be extrapolated to examine carbon balances after management on a far greater scale.

Acknowledgements

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References

Aleinikovas, M., et al. (2018). "Assessing the Effects of Accounting Methods for Carbon Storage in Harvested Wood Products on the National Carbon Budget of Lithuania." Forests **9**(12): 737.

Bastin, J.-F., et al. (2019). "The global tree restoration potential." Science **365**(6448): 76-79.

Bonan, G. B. (2008). "Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests." Science **320**(5882): 1444-1449.

climate-data.org. "Silkeborg climate summary." Retrieved 1 July 2020, 2020, from https://en.climate-data.org/europe/denmark/central-denmark-region/silkeborg-7501/.

Dansk Skovforening (2020). Årsstatisk for Danmark.

European Forest Institute (2020). "Marteloscopes and Data." Retrieved May 28 2020, from http://iplus.efi.int/marteloscopes-data.html.

Forsøgsvæsen, S. F., Ed. (1990). Skovbrugstabeller. Copenhagen, Denmark.

Handelsudvalg, D. S. (2008). "Råtræhæftet: Klassificering, opmåling, og afregningsprincipper i dansk skovbrug." **Version 1**.

Hansen, K. (2003). "Næringsstofkredsløb i skove - ionbalanceprojektet." Forest & landscape research.

IPCC (1997). Revised 1996 IPCC Guidelines for National Greenhouse Inventories. IPCC/OECD/IEA, Paris, France, Intergovernmental Panel on Climate Change.

IPCC (2006). (Chapter 12 HWP, Corr 2010) 2006 IPCC guidelines for national greenhouse gas inventories, Institute for Global Environmental Strategies Hayama, Japan. **5**.

IPCC (2014). 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol, Intergovernmental Panel on Climate Change.

Jasinevičius, G., et al. (2018). "Carbon Accounting in Harvested Wood Products: Assessment Using Material Flow Analysis Resulting in Larger Pools Compared to the IPCC Default Method." Journal of Industrial Ecology **22**(1): 121-131.

Johannsen, V. K., et al. (2019). "Danish National Forest Accounting Plan 2021-2030."

Keith, H., et al. (2009). "Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests." Proceedings of the National Academy of Sciences **106**(28): 11635-11640.

Kraus, D., et al. (2016). Catalogue of tree microhabitats – Reference field list.

Kraus, D., Krumm F., Ed. (2013). Integrative approaches as an opportunity for the conservation of forest biodiversity, European Forest Institute.

Kraus, D., et al. (2018). Seeing is building better understanding - the Integrate+ Marteloscopes.

Leskinen, P., et al. (2018). "Substitution effects of wood-based products in climate change mitigation." From Science to Policy **7**: 28.

Lindsey, R. (2020). "Climate Change: Atmospheric Carbon Dioxide | NOAA Climate.gov." Retrieved June 4, 2020, from https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide.

Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla,, et al. (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty., IPCC.

Mitchell, S. R., et al. (2012). "Carbon debt and carbon sequestration parity in forest bioenergy production." GCB Bioenergy **4**(6): 818-827.

Nielsen, A. T., et al. (2020). CHPs in Transition.

Nielsen, O.-K., et al. (2016). "Denmark's National Inventory Report 2015 and 2016: Emission Inventories 1990-2014-Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol."

Nord-Larsen, T. and V. K. Johannsen (2016). "Danish National Forest Inventory: Design and calculations."

Nord-Larsen, T., et al. (2017). "Simultaneous estimation of biomass models for 13 tree species: effects of compatible additivity requirements." Canadian Journal of Forest Research **47**(6): 765-776.

Nord-Larsen, T. and H. Pretzsch (2017). "Biomass production dynamics for common forest tree species in Denmark – Evaluation of a common garden experiment after 50yrs of measurements." Forest Ecology and Management **400**: 645-654.

Nord-Larsen, T., et al. (2019). "Ecosystem carbon stocks and their temporal resilience in a semi-natural beech-dominated forest." Forest Ecology and Management **447**: 67-76.

Pödör, Z., et al. (2014). Application of Sigmoid Models for Growth Investigations of Forest Trees. **282**.

Poeplau, C., et al. (2011). "Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach." Global Change Biology **17**(7): 2415-2427.

Pugh, T. A. M., et al. (2019). "Role of forest regrowth in global carbon sink dynamics." Proceedings of the National Academy of Sciences **116**(10): 4382-4387.

Röser, D., et al. (2008). Sustainable Use of Forest Biomass for Energy A Synthesis with Focus on the Baltic and Nordic Region. Dordrecht, Springer Netherlands.

Sabine, C. L. and e. al. (2004). The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World.

Schuck, A., et al. (2015). Integrate+ Marteloscopes - Calibrating silvicultural decision making.

Schuck, A., et al. (2015). "Integrate+ Marteloscopes: Description of parameters and assessment procedures." European Forest Institute. Integrate+ Technical Paper(18): 16.

Smith, P. (2005). "An overview of the permanence of soil organic carbon stocks: influence of direct human-induced, indirect and natural effects." European Journal of Soil Science **56**(5): 673-680.

Tærø, A., et al. (2017). "Do forests best mitigate CO2 emissions to the atmosphere by setting them aside for maximization of carbon storage or by management for fossil fuel substitution?" Journal of Environmental Management **197**: 117-129.

Ter-Mikaelian, M. T., et al. (2015). "Carbon debt repayment or carbon sequestration parity? Lessons from a forest bioenergy case study in Ontario, Canada." GCB Bioenergy **7**(4): 704-716.

Thomas, S. C. and A. R. Martin (2012). "Carbon content of tree tissues: a synthesis." Forests **3**(2): 332-352.

US Department of Commerce, N. G. M. L. (2020, 2020-05-05). "Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases." from https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html#global.

Waring, B., et al. (2020). "Forests and Decarbonization – Roles of Natural and Planted Forests." Frontiers in Forests and Global Change **3**(58).