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Forest Carbon Pool Projections 2024

Thomas Nord-Larsen, Prescott Huntley Brownell II, and Vivian Kvist Johannsen

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Authors
Thomas Nord-Larsen, Prescott Huntley Brownell II, and
Vivian Kvist Johannsen

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Vivian Kvist Johannsen

External/internal review
Professor Henrik Meilby, University of Copenhagen
Associate professor Niclas Scott Bentsen, University of Copenhagen

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Preface

The large carbon pools of the forests have a relatively significant importance for the Land Use, Land-Use Change, and Forestry (LULUCF) segment of the Danish emissions inventories and thereby the overall climate accounting. In order to navigate towards the objectives of the Danish climate goals, it is therefore necessary to know what emissions are expected from the forests. Department of Geoscience and Natural Resource Management at University of Copenhagen has previously made various projections of the forest carbon pools in different contexts and with different assumptions to provide estimates of forest greenhouse gas emissions.

As a result of the diversity in the data used and the underlying assumptions, the projections have led to different results. The models have moreover been aimed at a long-term projection but have had difficulties in the short term in describing the actual development. There is thus a need for a renewed projection, which shows the expected development in the carbon pools up to 2025 and 2030 and reflects the recent years' development. Consequently, this project was initiated on an assumption that a simplified projection of forest carbon pools focusing on 2025 and 2030 and linking to previous projections for the years up to 2040 would produce sufficiently accurate estimates. However, during the project it proved difficult to simplify calculations while still incorporating known changes in forest area, age and species distribution, and in forest management practices on areas set aside for biodiversity protection.

Because of issues arising from simplification of the projections it was decided to take on a, for Denmark, novel projection tool called *EFISCEN-space*. The EFISCEN (European Forest Information SCENario) model, specifically the EFISCEN-space variant, is a spatially explicit forest model developed to assess the future development of forests at regional to European scales. It simulates forest growth and dynamics based on inventory data and user-defined management rules, allowing for the analysis of different forest management and policy scenarios. The model accounts for various factors such as age class distribution, volume, increment, and forest management practices, making it a useful tool for predicting forest growth, timber production, and carbon sequestration under various scenarios. The "space" component in EFISCEN-Space enhances the model by incorporating spatially explicit information (i.e. plot locations), enabling more detailed analyses of spatial patterns and processes in forest ecosystems. The foundation for setting up the model was made on a study visit to Wageningen in November 2023.

Similarities and deviations from previous projections are described and justified in this report, and it is explained why the chosen projection method is expected to provide a more accurate projection towards and beyond 2030. The deliverable also includes a brief description of alternative projection models, based on preliminary work with a larger project about forecasts for the forests' contributions to climate and climate accounts.

The results of this study / project are partly based on the EFISCEN-Space model. We acknowledge the use of the EFISCEN-Space model as developed by Stichting Wageningen Research, Wageningen Environmental Research and Wageningen University, Department of Environmental Sciences since 2013.

Content

1 Introduction

Forests play a pivotal role in the global climate system, acting as significant carbon sinks that absorb and store carbon dioxide (CO_2) from the atmosphere, thus mitigating the impacts of climate change. The ability of forests to sequester carbon makes them invaluable in the fight against rising global temperatures and the associated adverse effects on ecosystems and human societies. However, this capacity is not static and it is influenced by a myriad of factors including forest management practices, land-use changes, and natural disturbances, all of which can transform forests from carbon sinks to sources of emissions.

In this context, projections of forest carbon stocks and emissions become crucial. They offer a window into the future, enabling us to anticipate how different scenarios – ranging from business-as-usual to wide spread management for nature conservation – might play out in terms of forest health, biomass, and carbon sequestration capabilities. Such foresight is invaluable for policymakers and environmental planners as it provides a scientifically grounded basis for formulating strategies and policies aimed at climate change mitigation.

By understanding potential future states of forest ecosystems, decision-makers can better design policies that not only protect these critical natural resources but also optimize their role in sequestering carbon. This is essential for meeting international climate targets, such as those set by the Paris Agreement, and for developing national strategies that align with sustainable development goals. Thus, forest carbon stock and emissions projections are not just academic exercises; they are essential tools for guiding global efforts towards a more sustainable and climate-resilient future.

This report presents a projection of forest carbon stocks and related emissions, offering insights into the dynamic interplay between forest ecosystems and atmospheric carbon levels. Our findings aim to inform policymakers, environmental scientists, and forest managers, providing a scientific basis for sustainable forest management practices and climate change mitigation strategies. Through comprehensive data analysis and modelling, this report underscores the role of forests in global carbon cycling and the importance of informed decision-making in preserving these natural resources for future generations.

1.1 Aim

The aim of this report is to make forest carbon projections to provide estimates of CO_2 emissions from Danish forests, including the five principal forest carbon pools as well as harvested wood products. The aim is further perform a first evaluation of model results in comparison to observed historical emissions.

2 Carbon pool projection

2.1 Previous projections of Danish forest resources and carbon pools

Previous projections of forest resources, carbon pools, and greenhouse gas (GHG) emissions were based on Markov chain models. Markov chain models are a type of stochastic model that can be used to project changes in the age class distribution over time. These models involve transition and conversion probabilities that describe the likelihood of the forest moving from one condition (e.g., age class or species composition) to another in a given time period. The probability that the forest area is transferred to the subsequent age class after a given period is termed the transition probability whereas the net flow to or from the species classes is termed the conversion probability.

Early projections [1-3] were based the observed species and age-class distribution from questionnaire surveys conducted by Statistics Denmark. In these studies, 10-year transition probabilities were derived from the changes in species and age-class distributions observed from consecutive surveys. For each species class, the aggregated probability that the forest area was harvested at any given point in time was modelled from the observed area transition and the area weighted site class in each county, using a logistic function. When applying the model, areas transferred to the subsequent age-class were estimated as the conditional probability of surviving into the next age-class (the transition probability) while areas transferred to the youngest age-class was estimated as one minus the transition probability. The conversion probability was assumed to be 0. Afforestation was assumed to always enter into the youngest age-class. The development of forest growing stocks and harvest volumes were modelled from a mathematical formulation of existing yield tables for the most common Danish forest tree species.

In later projection models, the transition probabilities were modelled from transfers between age-classes observed on the permanent plots of the Danish National Forest Inventory (DNFI) [4-7]. In the most recent projection of forest carbon emissions, the survival probability model was estimated from data collected between 2002-2020 [4], reflecting the management of Danish forest land during this period. The model used forest age, forest type (deciduous, coniferous, or Christmas trees/ornamental greenery), and region (Jutland or the Islands) to predict the likelihood of a forest area progressing to the subsequent age class. Here, growing stocks and harvested volumes were estimated from observed growing stocks of the sample plots, rather than being modelled from yield tables. The model furthermore included explicit modelling of afforestation and changes to forest management resulting from the setting aside areas for biodiversity protection.

The Danish Forest Inventory data pose some challenges to the modelling using Markov chain models as the data is much more detailed and comprehensive than the data from the earlier assessments, reflecting the actual state of the forest to a much larger degree. Consequently, albeit being used for more than three decades, modelling forest development from transition probabilities has some inbuilt shortcomings in relation to contemporary forest management practices:

1) According to the DNFI data, large part of the forest is being managed according to other principles than the clear-cutting system prescribed in the model, where harvested areas are always transferred to the first age-class. Although the model could principally be built to represent transfers to other age-classes, the complexity of the model increases dramatically.
2) To be operational, in the Markov-chain model each forest plot is represented by one dominant species with one stand age in the model. However, a large proportion of the forest area includes mixtures of tree species having different ages. Those forests are not represented particularly well by the species and age-class specific model.
3) The transition probabilities have traditionally been modelled using different forms of logistic models with a log-linear combination of parameters. Seemingly, the actual patterns deviate from the model with a shape that is difficult to reproduce. Moreover, transitions at stand level are rare occurrences and the data available is insufficient to capture the actual system behaviour.
4) Age used in the models to determine harvesting probability is not the principal harvesting criteria, which is rather being determined by tree size that is closer related to the resulting forest products.

To summarize, the previous approach to forest carbon projections has become increasingly inadequate owing to changes in contemporary forest management and forest structure. To alleviate the problems with the Markov chain models, a shift in modelling approach towards projections based on the growth and transition probabilities related to the individual tree, rather than the regional or national species and age class distribution, is required. When the original models were developed, this approach was not possible, as no model yet existed that could make such individual tree projections on a national scale, and long-term data of sufficient resolution was not available. However, the accumulation of Danish NFI data over two decades now represents a rich time series of data making it possible to estimate these individual tree probabilities, and continued advancements in computing power have enabled a new generation of models that is capable of handling such tasks. To select an appropriate model for these projections, a Europe-wide analysis was conducted with several criteria to identify an appropriate platform for the Danish forest carbon projections.

2.2 International projection models

Forest projection tools are essential for understanding the dynamics of forest ecosystems, predicting future changes, and aiding in sustainable forest management and policy making. Consequently, a wealth of mostly local or national forest projection models have been developed but they are rarely distributed outside their region of origin. However, a number of forest projection models have been designed for and used at larger scales and across different climatic and geographical regions. Three commonly used tools in this domain are EFISCEN, EFISCEN-space, EUREKA, and CBM. Each of these models has unique features and applications.

EFISCEN (European Forest Information SCENario model) and EFISCEN-space

EFISCEN [8, 9] is a large-scale forest model that projects forest development at regional to European scales based on national forest inventory data and scenarios of forest management. It focuses on the volume and biomass of forest stands, considering different tree species, age classes, and management regimes.

The first versions of the EFISCEN model [8] were built much like the earlier Danish projection models relying on Markov chains to model age-class distribution development. More recently, the modelling concept has been changed to rely on single tree observations in the novel EFISCEN-Space model [9]. This model relies on individual tree observations from forest inventory data typically from the sample plots of national forest inventories to project forest growth, thinning, and felling. By making changes to the individual tree harvesting probabilities or climate attributes, the model can analyse various scenarios related to forest management, climate change, and policy impacts. Such changes may be applied locally, allowing differentiated treatments according to local conditions. Outputs include timber volume, biomass, carbon storage, and potential wood supply.

EUREKA (European Forest Ecosystem Research Network)

EUREKA is not a single model but rather a network that facilitates the use and development of various forest models and tools across Europe. It aims to support research, policy-making, and sustainable forest management by providing a platform for sharing knowledge and methodologies. The collaborative platform integrates different forest modelling approaches and tools and supports a wide range of research themes from forest growth and yield to biodiversity and other ecosystem services. The emphasis on collaboration across different research spheres facilitates data exchange, methodological standardization, and the application of best practices in forest modelling.

EUREKA mainly supports research and academic studies on forest ecosystems and their management. The model network has however been used for policy support and decision-making through the integration of various modelling tools and approaches.

CBM (Carbon Budget Model of the Canadian Forest Sector)

The CBM is a forest carbon accounting model developed by the Canadian Forest Service. It is used to estimate carbon stocks and stock changes in forest biomass, dead organic matter, and soil carbon pools under different land-use scenarios and management practices.

The CBM offers detailed accounting of carbon fluxes in forest ecosystems, including emissions from disturbances like fires, harvesting, and natural disturbances. The model can be applied at various scales from stand-level to national inventories and supports scenario analysis for forest management, land-use change, and climate change impacts.

The CBM is tailored for national and sub-national greenhouse gas reporting and carbon accounting. Furthermore, the model offers potential for making research on forest carbon dynamics and the impact of management practices on carbon sequestration.

Each of the three tools presented above, offers detailed projections based on inventory data and contribute to a comprehensive understanding of forest carbon dynamics hereby enabling valid projections for forest carbon stocks and emissions. However, when selecting the most appropriate model, we set up a set of criteria including that the candidate model should:

1) have been successfully tested under European conditions and initialised using data from more than one country,
2) be freely available. This excluded proprietary models designed for country-specific circumstances or data sources as they would likely require further effort to implement,

3) be able to project forest development under different management scenarios, enabling the consideration of planned management changes in the state forests,
4) be capable of handling mixed stands and growth and development of unmanaged forests.
5) make use of the multi-decade dataset from the Danish NFI, and
6) enable the use of Danish-specific volume and biomass functions.

Based on these criteria and the time available for this study, we chose to use the EFISCEN-Space model.

2.3 EFISCEN-Space model

The EFISCEN-Space model [9] represents a state-of-the-art, spatially explicit model designed for comprehensive simulations of forest dynamics, management interventions, and policy scenarios. Developed collaboratively by European forestry research institutions, EFISCEN-Space integrates advanced ecological, economic, and social components to provide a nuanced understanding of the intricate interplay between forests and anthropogenic influences.

At its core, EFISCEN-Space utilizes a dynamic, individual-tree-based approach to simulate forest stand development over time from national forest inventory sample plots (Figure 2.1). The model captures the growth and mortality of individual trees, considering factors such as tree species, age, and environmental conditions. By employing a spatially explicit grid, EFISCEN-Space enables detailed assessments of forest dynamics at regional and national scales, allowing for a more accurate representation of diverse ecosystems.

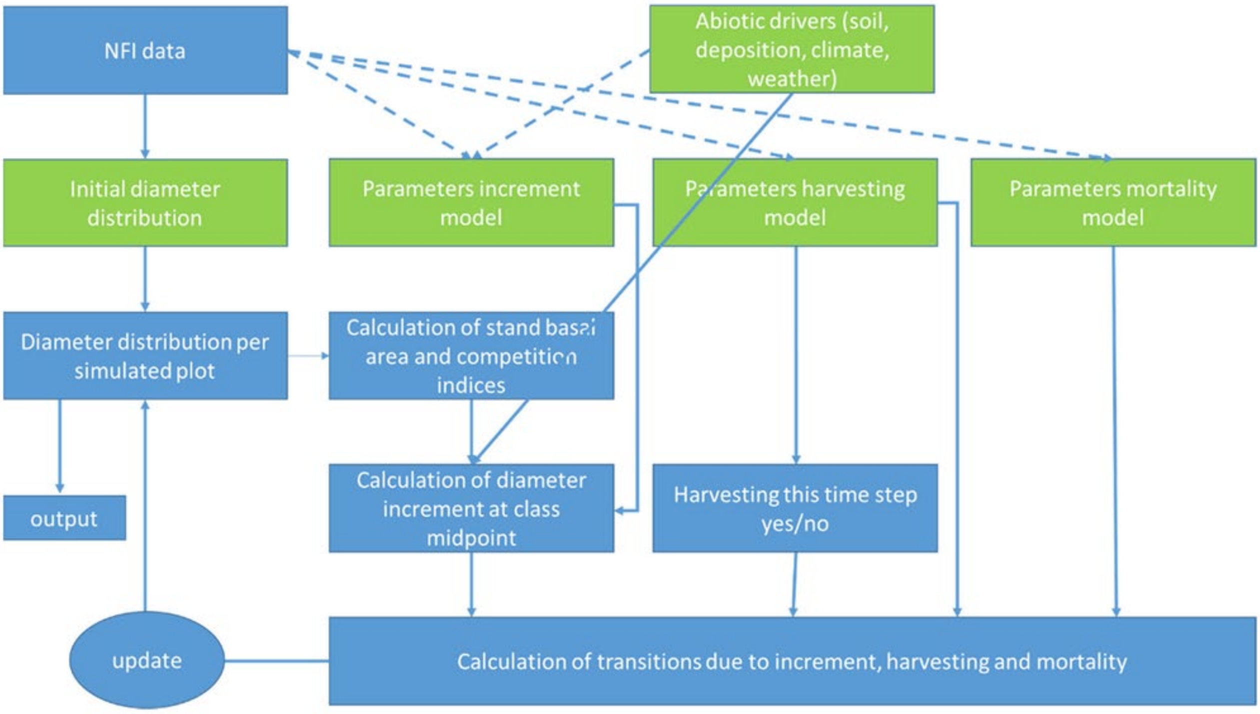

Figure 2.1. The EFISCEN-Space matrix model (from [10]). The modelling of tree increment includes a large set of geographically explicit factors such as climate and soil conditions that enables adaptation to local growing conditions.

EFISCEN-Space's temporal dynamics are driven by a combination of ecological processes, including natural disturbances such as wildfires, storms, and insect outbreaks. The model furthermore enables the integration of climate data to project the impact of future climate scenarios on forest growth and composition. Additionally, land-use changes, reflecting both societal and economic influences, are incorporated to assess the consequences of evolving human interventions on forest landscapes.

One of EFISCEN-space's notable features is its ability to simulate various forest management scenarios. The model incorporates parameters related to thinning, harvesting, and regeneration, allowing for the exploration of different management strategies and their implications on forest structure and composition. This functionality is crucial for evaluating trade-offs between competing objectives, such as maximizing timber yield while maintaining ecological integrity.

EFISCEN-Space's versatility extends to its capacity for simulating multiple ecosystem services. Beyond timber production, the model enables assessment of biodiversity, carbon sequestration, and water regulation, providing a comprehensive perspective on the multifaceted contributions of forests to society. This holistic approach facilitates the development of policies that prioritize sustainability and balance diverse societal needs.

In its inaugural years, EFISCEN-Space has demonstrated its utility in informing forest management practices and policy decisions. Ongoing technical refinements, calibration efforts, and validation exercises continue to enhance the model's accuracy and reliability. As EFISCEN-Space evolves, it stands as a powerful tool for addressing the complex challenges associated with sustainable forest management, contributing to the advancement of resilient and adaptive strategies for European forests in the face of changing environmental conditions.

3 Materials

3.1 The Danish National Forest Inventory

The EFISCEN-Space model at its core is developed and initiated from national forest inventory data. The Danish National Forest Inventory is based on a nationwide 2 x 2 km grid [11]. In each of the grid cells, a cluster consisting of four sample plots is placed in the corners of a 200 x 200-meter square. All clusters are measured over a five-year period, with one-fifth of the sample plots evenly distributed across the country being measured each year. One-third of the groups are permanent and are located in the southwest corner of the grid cells. These are re-measured for each five-year rotation of the forest statistics measurements. Two-thirds of the groups are temporary and are randomly moved within the respective 2 x 2 km cell in the grid for each repetition of the five-year rotation. With particular reference to the present study, the permanent plots may be used for assessing growth, probabilities of natural mortality and ingrowth, and management activities related to harvest of trees and planting of trees.

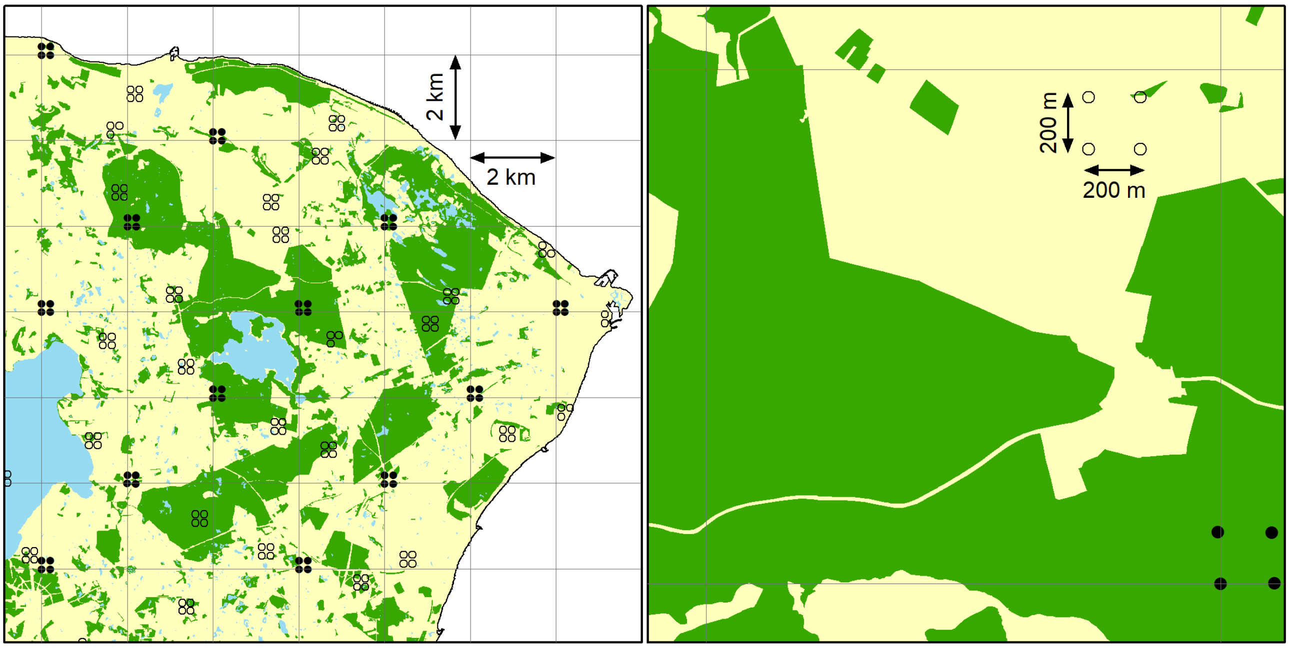

Figure 3.1. Design of the Danish NFI [11].

The sample plots in the forest statistics are circular and have a radius of 15 meters. In total, there are approximately 43,000 sample plots in the network, with only forest-covered sample plots being measured over a five-year period. The forest-covered sample plots are identified before each measurement season based on the latest aerial photos (typically less than one year old). In the forest, each individual sample plot is located with high geographical precision, allowing for accurate remeasurement of permanent sample plots as well as linkage with other geographical registry information. In each sample plot, measurements of many variables are taken, including measurements of tree size, age, and species, quantity of deadwood, and thickness of the litter layer (forest floor branches, leaves, etc.), which are among the key factors for estimating forest carbon pools.

3.2 National Inventory data 2018-2022

The National Forest Inventory data from the latest rotation of measurements is of particular importance to the carbon pool projections as it forms the baseline and starting point [12]. The measurements totalled 9.693 sample plots within clusters for which at least one of the sample plots had forest cover (Table 3.1). Of the total amount of sample plots, 33 % were within permanent clusters and in most cases remeasured from earlier rotations.

Table 3.1. Number of measured clusters and sample plots in the five-year rotation 2018-2022.

Year	Clusters		Plots	
	Total	Forest	Total	Forest
2018	2.191	903	8.586	2.018
2019	2.186	844	8.597	1.896
2020	2.190	887	8.569	1.886
2021	2.175	883	8.528	1.951
2022	2.207	879	8.643	1.942
Total	10.949	4.396	42.923	9.693

During the measurements in the 2018-2022 cycle, 114,426 trees were measured for diameter in the NFI. The diameter distributions for broadleaves follows a log-linear pattern in which there are many more small trees than large. This pattern is expected but to some extent influenced by the sample plot design, where larger trees have a higher probability of being measured.

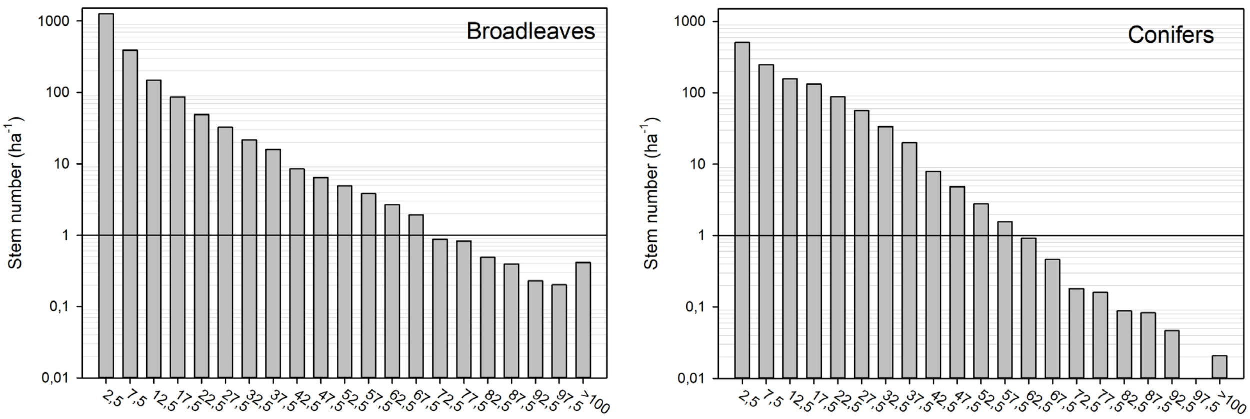

Figure 3.2. Diameter distribution for broadleaves and conifers based on the 2018-2022 rotation of measurements with the Dansh NFI. Note the log-scale on the y-axis.

3.3 Projections of Danish forest carbon pools and emissions with the EFISCEN-Space model system

In EFISCEN-space, the plot specific diameter measurements and species registrations are expanded to a per hectare diameter distribution used to initialize the projection. Owing to the design of the Danish National Forest Inventory, where trees with a diameter at breast height of less than 10 cm are only measured in the inner 3.5 m radius circle, including plots with only partial forest cover would result in diameter distributions lacking smaller trees. Therefore, we only included plots where the plot centre had forest cover in the simulations.

While the National Forest Inventory data was used for initializing the EFISCEN-Space model, it was also used for training the individual modelling components including harvest and natural mortality probability models.

Although we adopted the core EFISCEN-Space model unchanged, the model was executed through a SAS (Statistical Analysis Software) script that enabled the model to run repeatedly in 5-year cycles (Figure 3.3). This enabled us to add forest area to the model runs every 5 years to account for afforestation, as well as apply changing management scenarios over time as described for the state forest below. The SAS script further allows the application of Danish volume and biomass calculations to the raw output of plot development from the EFISCEN-Space model. A brief description of key model components and specific setup for the projections in this report follows.

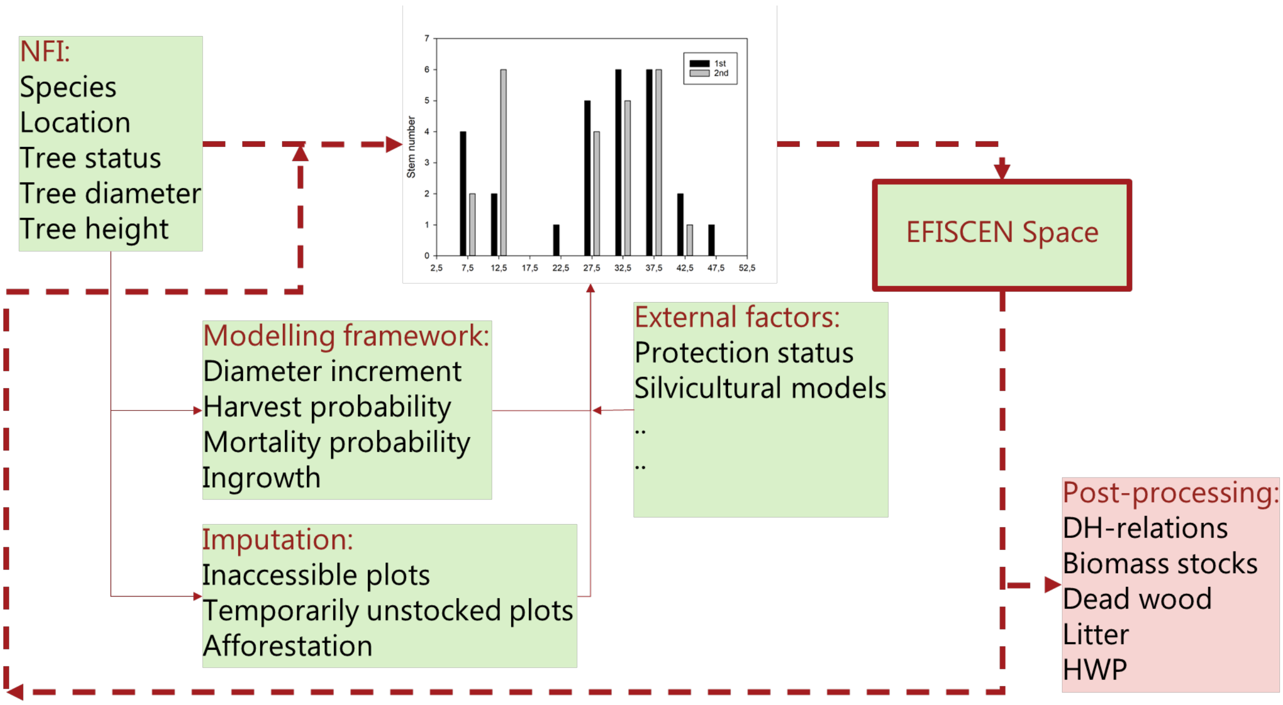

Figure 3.3. Brief description of the application of the EFISCEN-Space model for carbon pool projections in Denmark.

3.3.1 Growth model

EFISCEN-Space utilizes an individual-tree-based growth model to capture the dynamic development of forest stands over time. EFISCEN-Space uses a Gompertz model, describing a sigmoid growth pattern [13]. The Gompertz model is defined as:

$$D(t) = A \cdot e^{-b \cdot e^{-c \cdot t}}$$

Where D(t) represents the diameter of a tree at time t, A is the upper asymptote, which represents the maximum achievable diameter, b and c are parameters that influence the shape of the curve, and e is the base of the natural logarithm. The Gompertz model and its derivatives have been widely applied in forestry and ecology to understand and predict tree growth. The model is flexible and can be adjusted to fit different species and environmental conditions.

The derivative of the Gompertz model describes the rate of change in diameter (or diameter growth) at any given point in time. The model is estimated from repeated NFI tree measurements of 2.3 million trees across Europe and considers factors such as tree species, age, competition among trees, and local environmental conditions such as temperature and precipitation to simulate the annual tree diameter growth [13]. At the time of the present study, the growth model had not been fitted including Danish data and the simulations relied on the breadth of data collected across Europe.

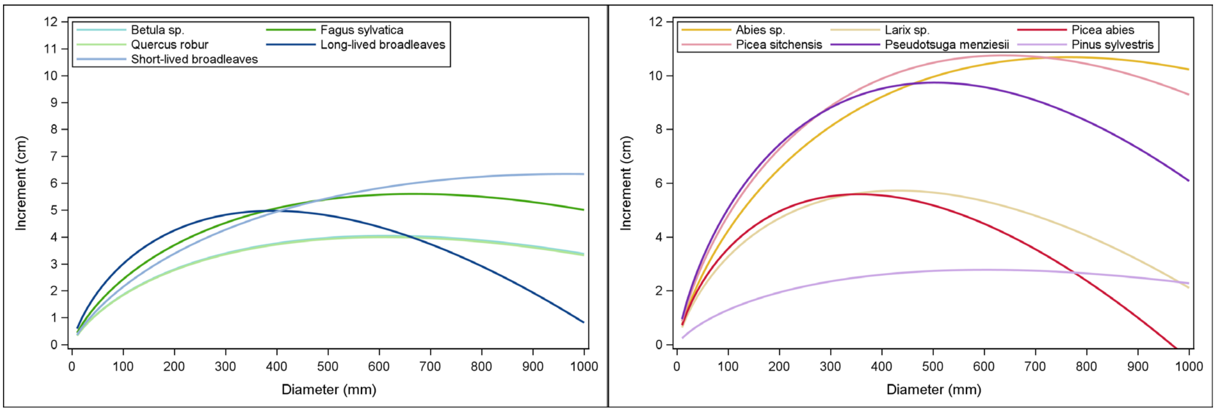

Figure 3.4. Examples of forest growth curves with the derivative of the Gompertz model. Note that the modelled growth is specific for each plot location, species, stand conditions, and diameter class. In this case, modelling is made for a stand basal area of 20 sq. m and for a tree that resembles the stand quadratic diameter tree. Also note that the growth pattern her for Betula sp. and Quercus robur are very similar and that the two growth curves cannot be distinguished in the graph.

3.3.2 Harvest probability

EFISCEN-Space integrates a detailed harvest probability model to simulate the impact of forest management interventions. To this end, a matrix specifies annual species and diameter class-specific harvest probabilities. These may be user specified, modelled, or simply extracted from repeated NFI measurements to reflect observed patterns (Figure 3.7). Harvest probabilities may be specified for individual plots reflecting e.g. geographical differences or may be generic across all parts of the country.

Harvest probability is commonly affected by tree species, size, and age as well as by overall management objectives and intensity. The harvest model incorporates the impact of these activities on individual trees, assessing their susceptibility to removal based on size, species, and management intensity. The harvest probabilities may be defined based on management rules, estimated based on statistical analysis or may simply be included as a species and size class specific harvest probability observed from repeated NFI measurements.

For this report, we extracted national harvesting probabilities from the repeated measurements in the Danish NFI (2002-2022) to represent the historical harvesting probabilities for each species (Figure 3.5). The harvesting probabilities show some erratic and much fluctuating patterns, reflecting the often-few observations especially in large diameter classes. In this study, we opted to use the observed probabilities directly when making the projections. This is something we could have modelled to produce smooth curves, but we opted to keep the projections as close to actual data as possible.

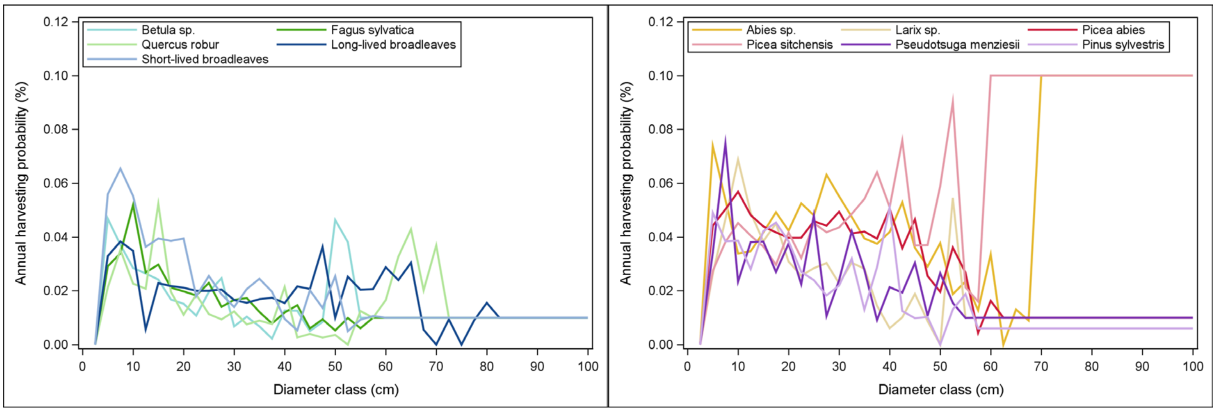

Figure 3.5. Observed annual harvest probability curves of the most common broadleaf and conifer species and species groups in the Danish forests. Harvest probabilities for large diameter classes, depending on species, are based on expert judgement owing to the lack of observations in the data.

3.3.3 Designation of areas for nature protection

Different probability matrices may be applied to individual plots to account for different management scenarios. In this way, the model may account for differences in ownership, regulatory constraints, and conservation objectives, which affect the likelihood of harvesting in specific areas.

For the relatively short period of the projections, the future harvest will largely be determined by the current forest structure and trees already present in the forest, and it is unlikely that overall management priorities will change in the private sector. When projecting future forest management, we therefore applied the assumption that management and hence harvesting probabilities in privately-owned forests will remain similar over the projection period.

However, the case is different for the state-owned forest, where under current policy there will be significant changes in the management of much of the forest area. The plans to designate large parts of the forest to be unmanaged (or managed without wood production) should be accounted for in the model, as the conversion of these areas will occur during the period of our projections. This includes areas planned to be set-aside as Unmanaged Forest (*Urørt skov*) as well as areas designated to be Nature National Parks (*Naturnationalparker*). After consultation with the Danish Nature Agency, a future management matrix was developed for the designated areas within the state forests. This enabled us to specify harvesting probabilities for designated areas for the next 25 years while accounting for the differing timelines for the transition of the designated areas between the western and eastern part of the country (Figure 3.6).

First, areas owned by the Nature Agency were identified on a map and each NFI plot part of the projection was assigned a category according to the specific designation. For this projection, we identified five different categories including 1) Managed forest (i.e. not designated for nature protection), 2) Nature National Park, east, 3) Nature National Park, west, 4) Unmanaged Forest, east, and 5) Unmanaged Forest, west. Differences in harvest probabilities between east and west Denmark are driven by different lengths of the transition period in the two parts of the country.

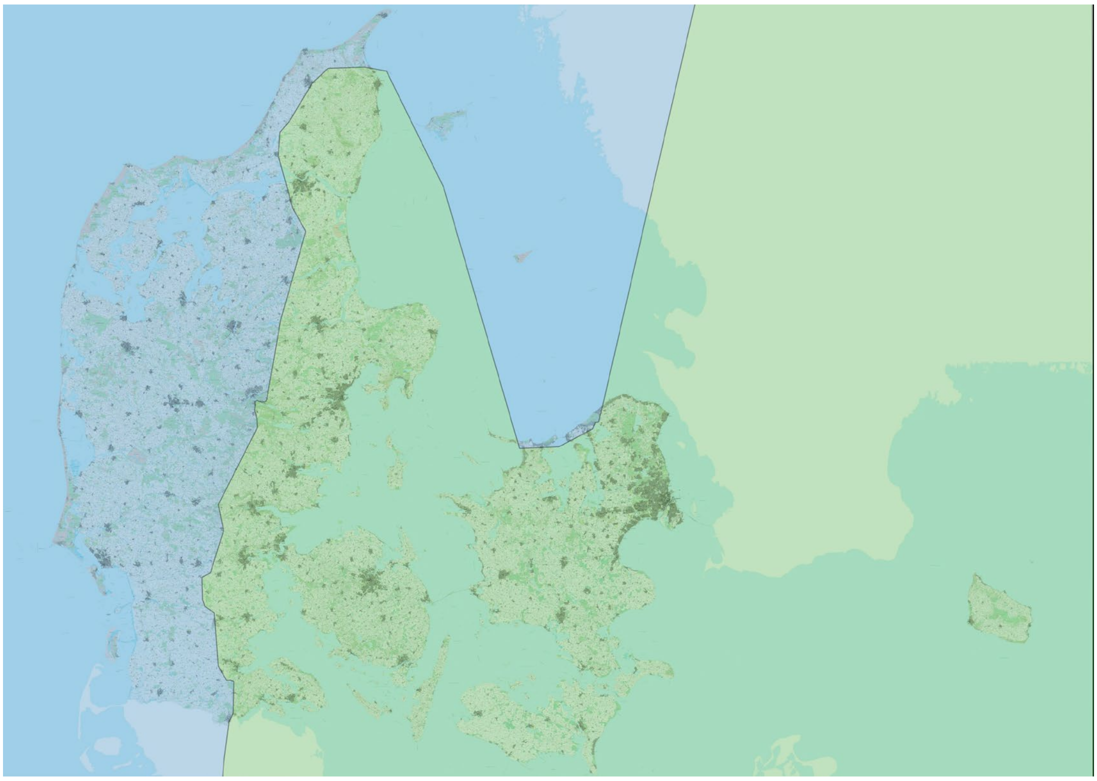

Figure 3.6. Regions identified by the Nature Agency to designate differing timelines for the transition of the state forests to Nature National Parks and Unmanaged Forest between the western (blue, typically 25 years transition) and eastern (green, typically 6 years transition).

For the entire projection period, we assumed that areas of the state forest that have not been designated for nature protection will continue with the national historical harvesting probabilities as earlier described. This differs from the projections made in relation to Climate projections 2023 [4] in which a 20 pct. decrease in harvesting levels in the state forests was assumed as part the frozen policy scenario. However, part if the effect of reduced harvesting in the state forests will be observable in the harvesting probabilities. For the designated areas, we have implemented a matrix as described below (Table 3.2).

In the first five-year period of the projection (from 2022 to 2027), we assumed that exotic species, largely understood as species exotic to Denmark and Northern Europe, of 40 cm or more in diameter at breast height (DBH) will be harvested in all set aside areas. Otherwise, we assumed harvesting according to the historical probabilities for both the exotic conifers and all other species, taking into account that some harvest will be made to create a desired forest structure prior to the setting aside (e.g. gap creation, removal of undesired species, or altering understorey light conditions).

In the eastern part of the country (Figure 3.6), we assume harvesting of all exotics irrespective of their diameter in the following five-year period (2028 to 2032) and onwards. In this region, we furthermore assume that all other harvesting ceases.

In the western part of the country, we assume a similar pattern, but the conversion period is 25 rather than 5 years. Hence, in the following five-year period (2028 to 2032) and onwards, we here maintain a 40 cm target diameter for the exotic species and otherwise assumes continued harvesting according to the historical probabilities. This regime continues until the final run beginning in 2043, when all non-native conifers of all diameters are also removed in the western part of the country.

Harvest of native tree species (including Norway spruce, larch, mountain pine, and silver fir native to northern Europe) is expected to gradually cease in the initiation phase. We therefore set the harvesting probabilities to one quarter of the probabilities observed in the normal harvesting regime. The harvesting ceases completely after the conversion is completed (after year 2026 in eastern Denmark and after year 2032 in western Denmark). We are aware that in some areas, actual harvest strategies may much different from the above described e.g. aiming at creating gaps in the forest canopy or removing undesired tree species in specific areas. However, such specific modelling was not possible within the current project although the EFISCEN-Space model would in principle allow for it.

Deforestation within areas designated for nature protection

Setting-aside forest for both Nature National Parks and Unmanaged Forest has modelling implications beyond merely the effect on harvesting probabilities described above. The management required to prepare forest areas to be set-aside for biodiversity protection can be extensive and commonly involves a variety of actions such as restoring natural hydrological conditions or historical landscapes, conducting harvests to create a favourable forest structure, veteranization of trees, and the introduction of grazing by larger animals such as cows and horses. These measures likely heavily impact the forest carbon pools but are equally difficult to describe in a modelling context. There is also a general lack of data regarding the potential future development of these forest types in Denmark.

In this case, we opted to simulate the loss of forest owing to restoration of hydrological conditions by converting 20 pct. of the Norway spruce dominated forest plots (in the state forest areas to be set-aside) to non-forest during the conversion period (i.e. 5 years in the eastern part of the country and 25 years in the western part of the country).

We furthermore assumed that 50 pct. of *Pinus mugo* and *Abies alba* dominated forest will be converted to Atlantic heathland as part of the conversion (Table 3.2).

In the simulation, plots corresponding to the 20 and 50 pct. of the forest area respectively were removed at random from the simulations and the trees on the plots were considered harvested, simulating that the area was clearcut prior to flooding or other restoration of the landscape.

Table 3.2. Modelling the transition of areas designated for biodiversity conservation as Nature National parks and Unmanaged Forests within areas owned by the Nature Agency. Areas not designated for nature conservation are assumed to be managed according to the observed harvesting probabilities in the NFI and similar to forest not owned by the Nature Agency. The table has been developed in close dialogue with the Danish Nature Agency. Grey shaded areas show species where harvesting probability is reduced to ¼ of normal harvest probabilities during the conversion period.

		Eastern Denmark*			Western Denmark*			Deforestation
		Conversion (years)	Harvesting probability after conversion (%)	Target diameter prior to conversion (cm)	Conversion (years)	Harvesting probability after conversion (%)	Target diameter prior to conversion (cm)	%
1	Abies. sp.	5	0	40	25	0	40	50
2	Larix sp.	5	0	-	25	0	-	20
3	Picea abies	5	0	-	25	0	-	20
4	Picea sitchensis	5	100	40	25	100	40	0
5	Pseudotsuga menziesii	5	100	40	25	100	40	0
6	Pinus sylvestris	5	0	-	5	0	-	0
7	Pinus nigra and mugo	5	0	-	5	0	-	50
8	Other Pinus	5	100	40	25	100	40	0
9	Other conifers	5	100	40	25	100	40	0
10	Betula sp.	5	0	-	5	0	-	0
11	Castanea sativa	5	100	40	25	100	40	0
13	Fagus sylvatica	5	0	-	5	0	-	0
14	Robinia pseudoacacia	5	100	40	25	100	40	0
16	Quercus robur and petraea	5	0	-	5	0	-	0
19	Long-lived broadleaves	5	0	-	5	0	-	0
20	Short-lived broadleaves	5	0	-	5	0	-	0

* According to the map in Figure 3.6.

3.3.4 Mortality

The mortality component of EFISCEN-Space accounts for natural causes of tree death. In a setup reflecting current management practices, a matrix specifies species and diameter class-specific mortality probabilities much in the same way as the harvest probabilities. These may be user specified, modelled, or simply extracted from repeated NFI measurements to reflect observed patterns (Figure 3.7). Mortality matrices may be specified for individual plots reflecting e.g. geographical differences or may be generic across all parts of the country.

To simulate the development of the Danish forests, natural mortalities were extracted from repeated measurements in the Danish NFI (2002-2022) and used to derive historical annual mortalities for each species (Figure 3.7). These mortalities reflect current forest practices and can be considered to reflect minor changes in abiotic factors likely occurring for a relatively short projection period. In initial runs of the model, we opted to use the observed mortalities from the Danish NFI as the basis for our projections. These were manually adjusted by expert opinion where there were a limited number of observations for mortalities of a given species and diameter.

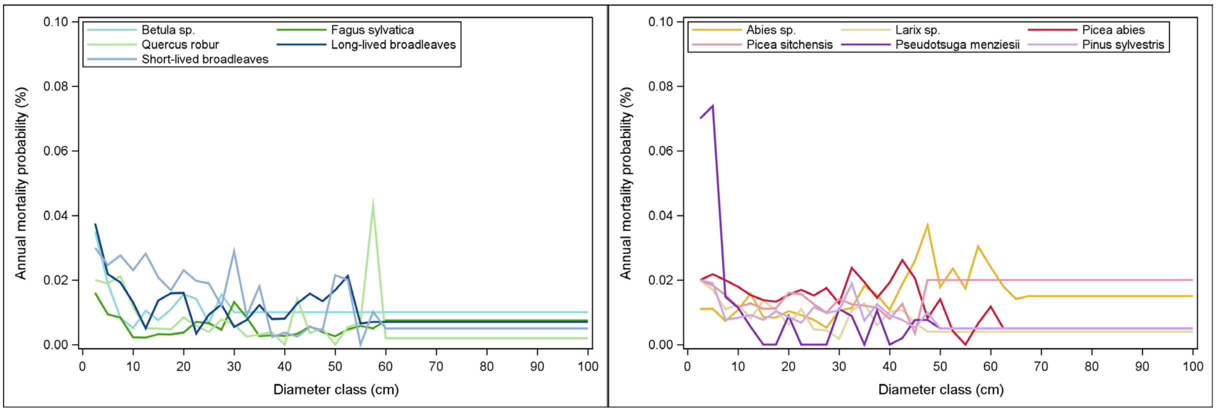

Figure 3.7. Observed mortality curves of the most common broadleaf and conifer species and species groups in the Danish forests. Mortalities for large diameter classes, depending on species, are based on expert judgement owing to the lack of observations in the data.

Later adjustments of the underlying assumptions of forest management on set aside areas for biodiversity protection in the areas owned by the Nature Agency is likely to alter the mortality owing to low or absent harvest affecting stocking severely within the projection period. To accommodate the likely increase in competition resulting from reduce harvesting, we opted to use the inbuild dynamic mortality functions in the EFISCEN-Space model [14] in the final simulations. These models include density parameters and the result of one-sided competition from trees larger than the subject trees and may therefore better accommodate simulations with altered basic conditions.

3.3.5 Afforestation

In the EFISCEN-Space model, afforestation can be simulated implicitly in the model, using the included ingrowth module to produce growth on empty plots. However, to accommodate a more realistic and data driven representation of afforestation, we simulated the afforestation through imputation of sample plots corresponding to the desired afforestation area at the end of every 5-year rotation of the model. Imputed plots were selected at random from a sample of 388 reference afforestation plots less than 10 years old identified from the NFI data.

The selection of imputation samples is conducted via unrestricted simple random sampling with replacement from the reference afforestation plots. The number of sampled plots correspond to the anticipated afforestation divided by the area represented by each NFI sample plot (~100 ha). The imputation involves allocating these selected plots onto non-forested NFI sample plots of the 2018-2022 rotation of measurements. Imputation was only allowed on plot locations where afforestation is desired according to municipality plans. The imputation process accounts for both spatial allocation and, if relevant, temporal dynamics, ensuring a robust representation of afforestation scenarios in the model.

Historical afforestation levels were determined as the sum of afforestation (both regular forest and Christmas trees) subtracted the annual deforestation reported in the national inventory report [15]. Historical afforestation from the national greenhouse gas inventory differs from then estimates obtained in the National Forest Inventory [12] owing to statistical uncertainty as well as due to a need in the inventory reporting to match the forest area with other land-use types. Hence, the national greenhouse gas inventory to a larger degree relies on cadastral records rather than actual observations leading to slightly different forest definitions in the two inventories. For simulations onwards, we used a frozen policy scenario for the afforestation supplied by the Environmental Protection Agency (Table 3.3).

Table 3.3. Historical and projected afforestation levels based on a frozen policy approach. For the historical afforestation, we collected all private and public afforestation in the column "Private/Total" as the figures are derived from the land-use matrix underlying the emissions reporting in which the ownership is unknown.

Year	Public	Private/Total	Climate forest fund	Year	Public	Private	Climate forest fund
			ha				
2002		4110		2025	270	2570	700
2003		4110		2026	270	2570	660
2004		4110		2027	270	2570	870
2005		3372		2028	210	2570	820
2006		3372		2029	210	2570	1000
2007		3372		2030	0	880	1200
2008		3372		2031	0	880	0
2009		3372		2032	0	880	0
2010		3372		2033	0	0	0
2011		3372		2034	0	0	0
2012		1537		2035	0	0	0
2013		4641		2036	0	0	0
2014		364		2037	0	0	0
2015		2115		2038	0	0	0
2016		678		2039	0	0	0
2017		1107		2040	0	0	0
2018		1130		2041	0	0	0
2019		1248		2042	0	0	0
2020		1800		2043	0	0	0
2021		4887		2044	0	0	0
2022		1485		2045	0	0	0
2023	280	2000	100	2046	0	0	0
2024	300	2000	480	2047	0	0	0

3.3.6 Ingrowth and reforestation

The data from the NFI includes areas that have been recently harvested and are temporarily unstocked which are likely to become re-stocked with trees. Furthermore, EFISCEN-Space produces empty plots when the simulation results in all trees on a plot becoming dead or harvested. As EFISCEN-Space utilizes an observed diameter distribution to produce the projection, plots with no trees cannot be projected into the future unless the plot is populated with new trees.

The problem is similar to introducing afforestation as afforested plots initially have no trees to be projected into the future. An option would be to use a similar approach as for afforestation, populating the plots using imputation from known reforested plots, or otherwise specifying the number of replanted trees of a certain species. As it is difficult to make realistic assumptions on future species composition reflecting local conditions, we opted for the default EFISCEN-Space process which regrows the species most recently present on the sample plot. In cases where there are no trees present on the plot at the initialization of the model, the model re-populates the plot with a “short-lived broadleaves” species group (such as rowan, birch, and aspen).

3.3.7 Dead wood

The EFISCEN-space model outputs species and diameter distributions of trees dying in the projection period. Although it would be possible to estimate the inflow of dead wood to the carbon pool, the outflow in terms of degrading wood is largely unknown. As the dead wood pool is relatively minor to the other forest biomass pools, we considered it outside the scope of this project to attempt advanced modelling of this aspect of forest carbon dynamics. We therefore assumed an unchanged level of dead wood, well aware that the activities in the set aside forests will likely increase the amount of dead wood locally, but also expecting that the overall effect on the forest carbon pool will be relatively minor.

3.3.8 Litter

The YASSO-model tailored for modelling soil carbon pool development may run within EFISCEN-space providing estimates of forest litter carbon pool development. However, we found that the time was too limited to test the results for Danish conditions. Instead, we opted to use a constant litter pool owing to the short projection horizon.

3.3.9 Harvested wood products (HWP)

The EFISCEN-space model outputs species and diameter distribution of harvested trees. In this projection, we estimated the biomass in harvested trees in the same way as estimating carbon stocks in live biomass using species specific d/h-functions and national biomass functions [16]. Recognizing that contemporary forest management often involves harvesting of the entire above ground biomass (including branches), we estimated biomass in harvested timber from the projected above ground biomass and the share of timber (46.8 pct. for conifers, 14.1 pct. for broadleaves) in the national harvest statistics reported by Statistics Denmark. The inflow of biomass in HWP was subsequently calculated from the cutting yield observed in Danish sawmills (42.3 pct. for conifers, 42.4 pct. for broadleaves). As for previous projections, we did not make assumptions on exported or imported quantities of round-wood, which are not reported in the sourcing country while the sawn volumes are part of the HWP pool. For the period 2020-2023, imported and exported amounts were reported at 224,000 and 137,000 tons, respectively. Given that these figures are reported in kg's by the importing party with an unknown moisture content, the uncertainty involved in making more detailed assumptions was evaluated to be prohibitively high.

Emissions from HWP were estimated using the methodology developed for the national greenhouse gas reporting using the inflow of biomass from the EFISCEN-space model and previously determined product half-lives to determine the outflow from this pool.

4 Results

The model predictions of forest carbon stocks in above-ground biomass, below-ground biomass, and total biomass showed a continuous uptake of CO_2 in the forests during the entire projection (Figure 4.1). Mortality started slightly higher than in the later parts of the projections but declined in the first simulation period to around 1.5 mi. tons CO_2-eqv.

Harvesting levels peaked at ~6 mi. tons CO_2-eqv. during the first five-year simulation cycle and hereafter declined to an ultimate low at ~4 mi. tons CO_2-eqv. During the remainder of the simulations, harvest levels are projected to increase, reaching a level similar to the levels observed in the first cycle of simulations. The harvest fluctuates across the years, likely owing to spikes in the harvest probabilities as well as in the diameter distribution. However, the projections show a cyclic pattern which is largely caused by the way the EFISCEN-Space is set up. As the model does not allow harvesting of the same plot twice in each 5-year run, a random parameter assigns a time for harvesting each plot. This time (from the beginning of each cycle) is repeated on each rotation of the model causing a cyclic pattern. This pattern is further exaggerated by the five-year rotation of the model, where afforestation is added to the forest area and deforestation is simulated by harvesting and removing plots at the beginning of each rotation.

The resulting projected emissions indicated a continuous uptake in the forest, that was relatively low in the first 5-year period owing to the larger harvests projected in this period. Later, emissions projections total an average CO_2-uptake ranging between 3 and 3.5 mi. CO_2-eqv. slightly increasing as a result of the increasing forest area.

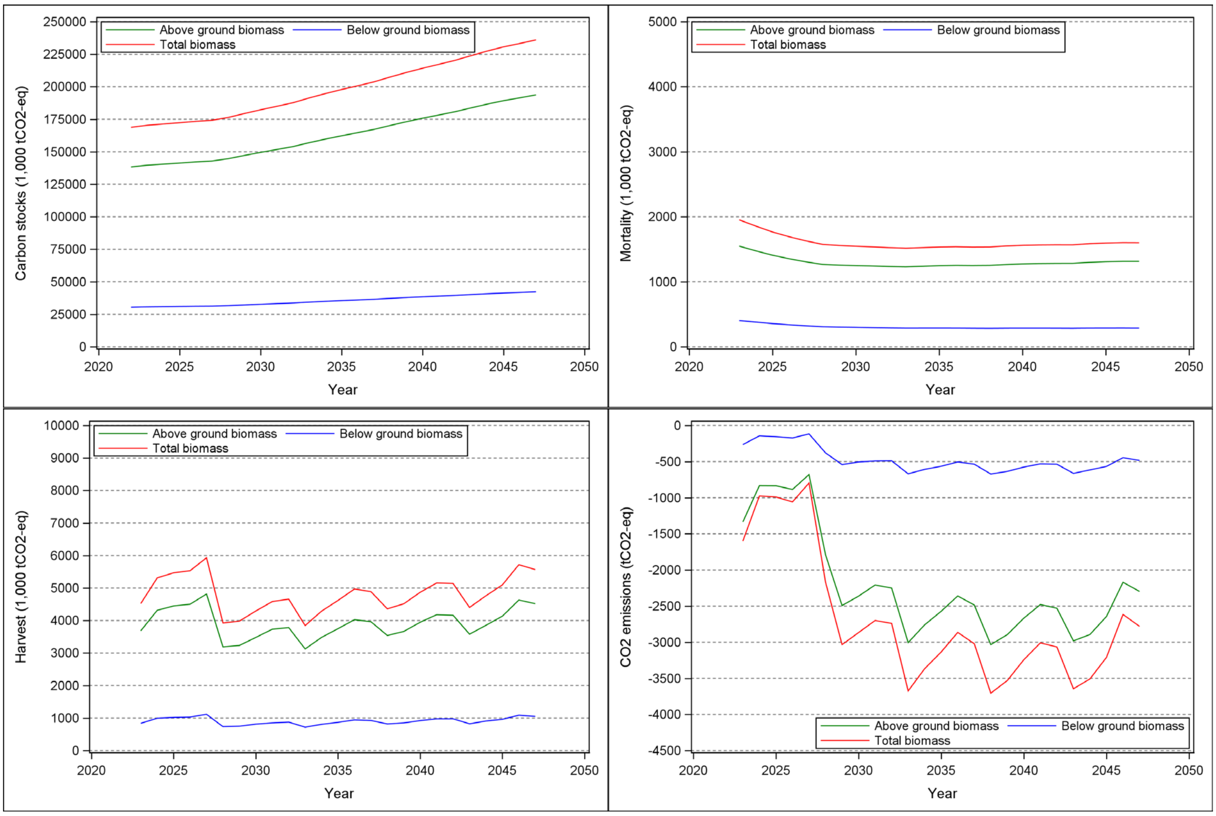

Figure 4.1. Carbon stocks, mortality, harvest, and emissions expressed in CO_2-eq. Projections are made from NFI data collected in 2018-2022 forming the 2022 base line.

In general, the broadleaves delivered a net-uptake resulting in negative emissions with the largest uptake in beech and long-lived broadleaves such as sycamore maple and cherry (Figure 4.2). Oppositely, many of the conifer species had near zero emissions and in some notable cases even substantial emissions for Sitka spruce and Norway spruce.

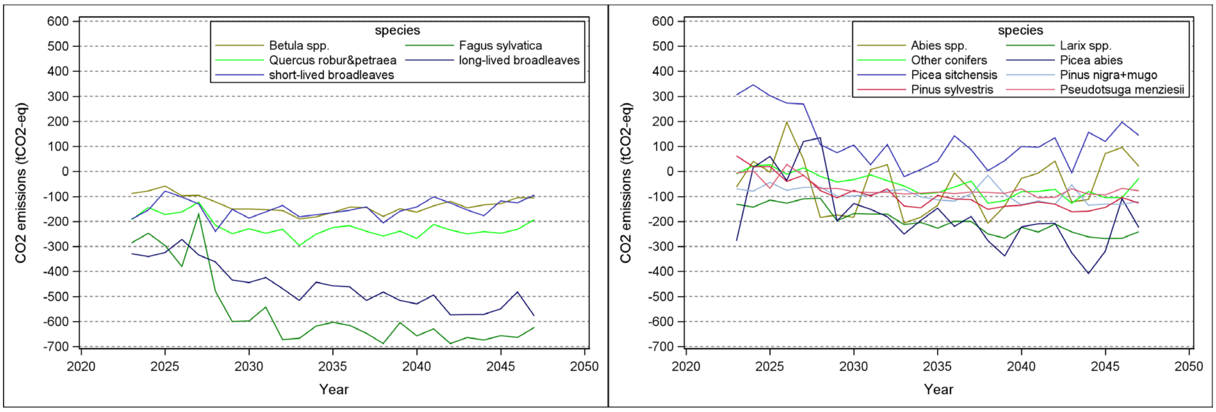

Figure 4.2. CO_2 emissions distributed to species and species groups Left: broadleaves, Right: conifers.

The levels and fluctuations of CO_2 emissions are comparable with historically reported emissions [15] replicating the current peak in emissions and subsequently declining to a credible net uptake of 1.5-3.0 mi. tons CO_2 in above and below ground biomass (Figure 4.3). The overall fluctuations are at a similar magnitude to what is observed in the reported figures, but the annual fluctuations seem somewhat more erratic owing to the previously described harvesting patterns in EFISCEN-space. However, it should be noted that in the emissions reporting, figures are smoothened as 5-year averages and reporting of individual years, such as in the projected numbers in (Figure 4.3) would be expected to show more variation.

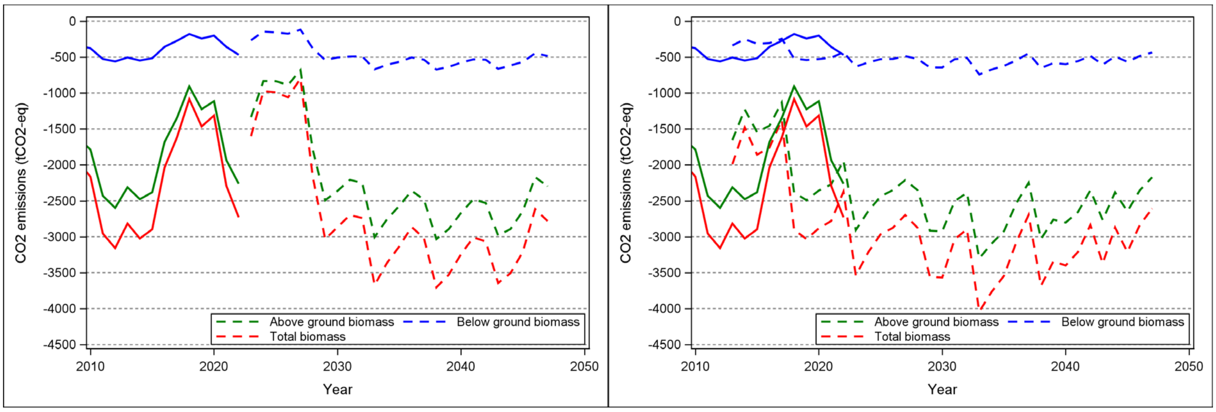

Figure 4.3. Reported ([15], full line) and projected (dashed line) emissions from above-ground (green), below-ground (blue), and total biomass (red). Left: Projection from a NFI 2022 baseline, Right: Projection from a NFI 2012 baseline.

4.1 Effects of forest management and programme settings

To illustrate the effect of changes to the model input, we changed a number of parameters in the model settings to illustrate 1) the choice of static vs. dynamic mortalities in the model, 2) the effect of setting aside forest for biodiversity protection, and 3) the effect of afforestation.

Static vs. dynamic mortalities

In the basic setting, mortalities were projected using the dynamic functions included in the EFISCEN-Space model and estimated on a pan-European dataset. Realizing that the underlying model was estimated absent of Danish data, we intended to analyse how this choice affected the results, by making the projections with a static mortality observed directly from Danish NFI data (Figure 3.7). Our analyses show that the static and dynamic mortalities produce quite different mortality levels (Figure 4.4) reflecting that the static model does not adjust to altered forest conditions e.g. when forest is designated for biodiversity conservation or standing stocks are altered owing to projected harvesting. However, differences in mortalities arising from the choice of model had little effect on overall emissions EFISCEN-Space (Figure 4.4), reflecting the relative minor importance of dead wood in the overall carbon budget.

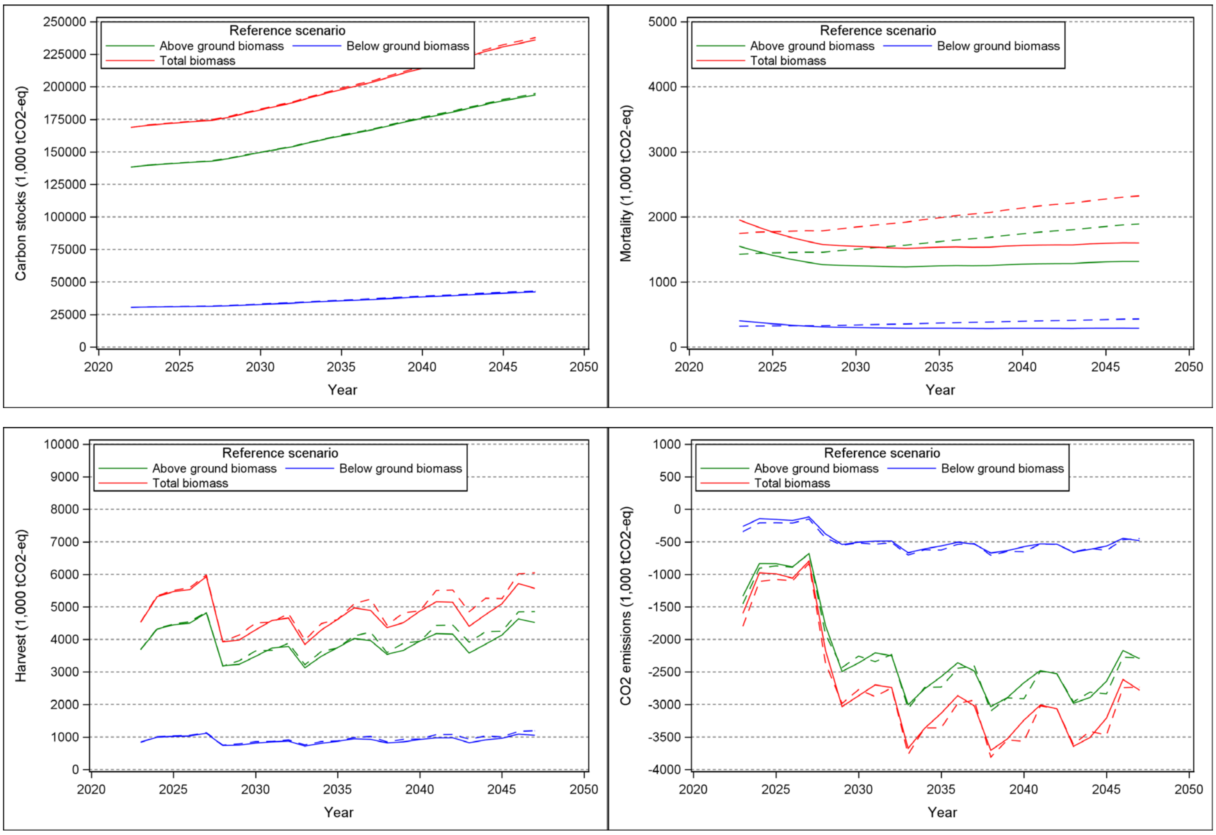

Figure 4.4. Carbon stocks, harvest, mortality, and associated emissions for a scenario using a static mortality function (dashed lines) with the reference scenario using the dynamic mortality function (solid lines) (Figure 4.1).

Setting aside forest for biodiversity protection

When simulating the effect of setting aside forest for biodiversity protection, we made a counterfactual setting of the model to harvest trees in accordance with the historical probabilities, although realizing that these observations to some extent includes ongoing conversion of set aside forests. The simulations indicate a very minor change in carbon pool development and associated emissions from biomass carbon pools compared to the basic settings (Figure 4.5, Table 4.1). In the first, 5-year period, harvesting levels were similar for the counterfactual and the reference scenario. This is likely the result of contrasting effects. On the one hand, reduced harvesting of particularly native broadleaves increased carbon pools on parts of the forest area, while deforestation and removal of exotic conifers as the result of nature restoration leads to reduction of carbon pools in other parts. The setting aside of forest for biodiversity, however, significantly altered the harvesting levels in later rotations of the simulations reflecting that no harvesting is conducted on the ~75.000 hectares set aside.

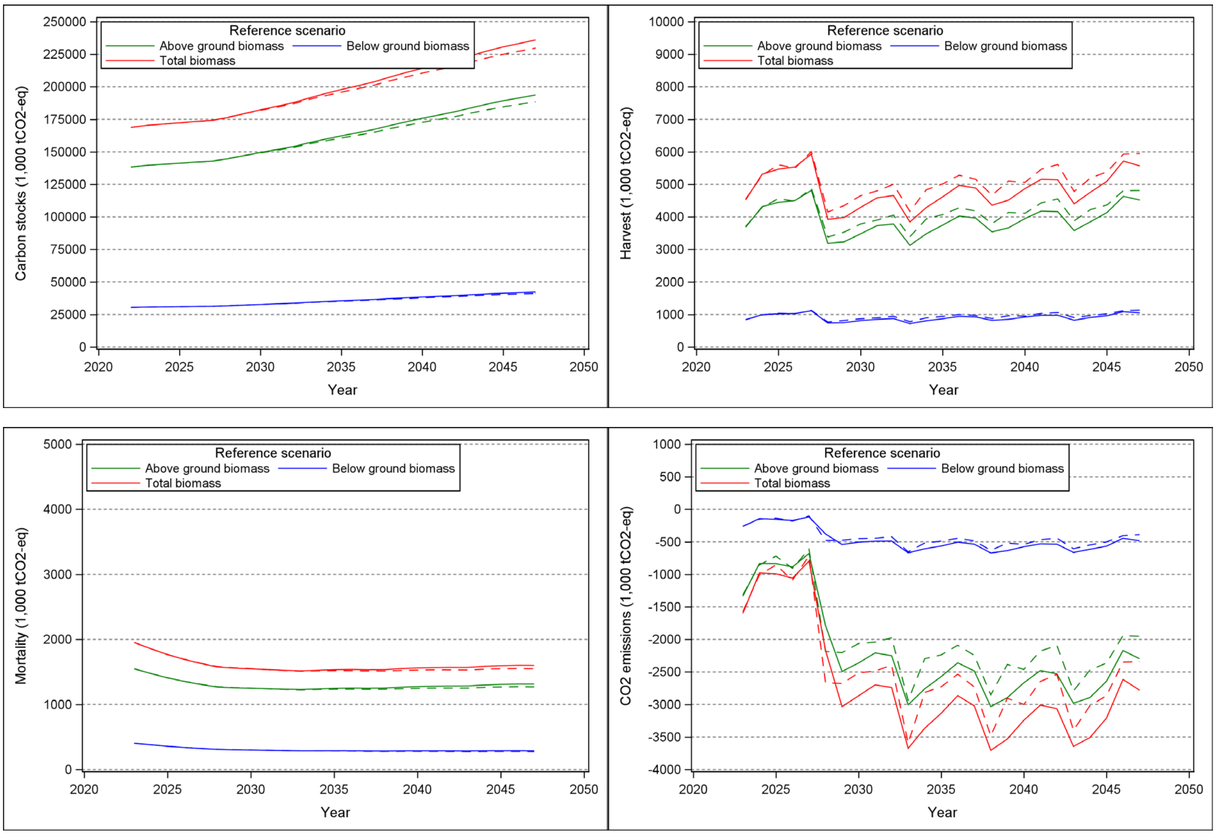

Figure 4.5. Projected forest carbon pools, harvesting, mortality, and associated emissions from a scenario assuming no designation of forest for biodiversity conservation (dashed lines) compared with the reference scenario (solid lines) (Figure 4.1).

Afforestation

To isolate the effect afforestation, we maintained all model settings to be similar to the basic setting (Figure 4.2) including the setting aside forest for biodiversity protection. The simulations resulted in a total forest loss of 4,566 ha during the simulations owing to the deforestation occurring on the set aside forest. Compared to the standard settings, the resulting forest area at the end of the simulations was 28,565 ha or 4.3 pct. lower. Considering that the afforestation will have comparably low biomass, it is no real surprise that the no afforestation scenario only had slightly lower carbon pools and hence also slightly higher emissions than the standard scenario (Figure 4.5, Table 4.1).

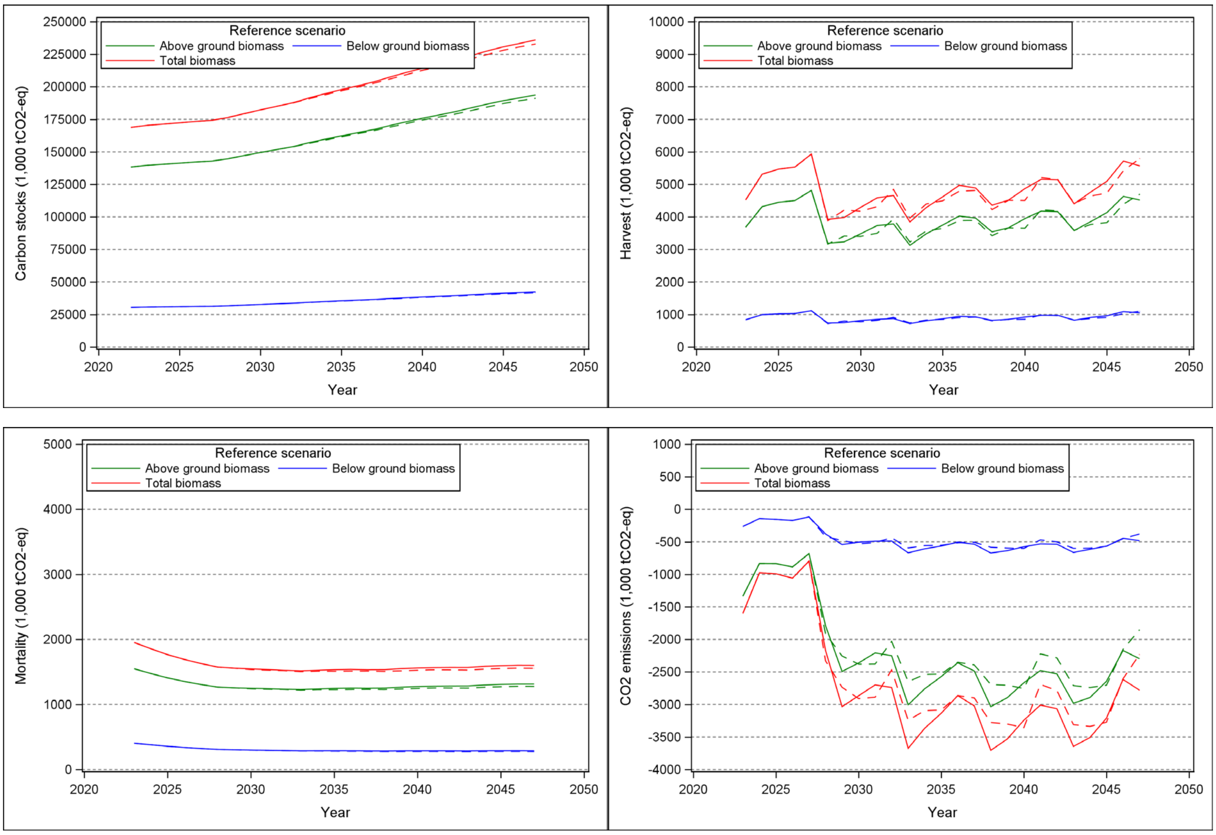

Figure 4.6. Carbon stocks, harvests, mortality, and associated emissions for a scenario with no afforestation (dashed lines) and a comparison with the reference scenario (solid lines) (Figure 4.1).

Table 4.1. Forest area, carbon stocks, and emissions for the reference scenario and for the two scenarios where no areas is set aside for biodiversity conservation and where no afforestation is carried out. Figures are provided for 5-year averages with the initial year (2022) as the overall reference.

		Forest area	Biomass carbon stocks		Carbon emissions		Harvest		Mortality	
Scenario	year		Above ground	Below ground	Above ground	Below ground	Above ground	Below ground	Above ground	Below ground
		ha	1,000 tCO_2-eq							
Reference	2022	642,976	138,339	30,441	-	-	-	-	-	-
	2023-2027	642,976	141,330	31,005	-913	-170	4,354	1,000	1,419	361
	2028-2032	656,222	149,438	32,703	-2,220	-481	3,484	805	1,250	299
	2033-2037	667,556	162,200	35,501	-2,636	-576	3,670	853	1,243	287
	2038-2042	667,825	175,630	38,425	-2,720	-590	3,899	909	1,271	286
	2043-2047	666,975	188,995	41,300	-2,597	-555	4,144	967	1,304	287
No setting aside for biodiversity	2022	642,976	138,339	30,441	-	-	-	-	-	-
	2023-2027	642,976	141,251	30,997	-881	-167	4,384	1,004	1,420	361
	2028-2032	658,876	149,139	32,667	-2,093	-455	3,732	860	1,251	300
	2033-2037	671,060	160,614	35,184	-2,361	-519	3,974	918	1,231	285
	2038-2042	671,754	172,544	37,785	-2,394	-520	4,206	977	1,245	281
	2043-2047	671,754	184,339	40,326	-2,304	-490	4,420	1,030	1,265	279
No afforestation	2022	642,976	138,339	30,441	-	-	-	-	-	-
	2023-2027	642,976	141,330	31,005	-913	-170	4,354	1,000	1,419	361
	2028-2032	640,640	149,404	32,706	-2,191	-476	3,482	805	1,245	298
	2033-2037	640,003	161,474	35,350	-2,492	-545	3,645	849	1,227	283
	2038-2042	639,153	174,173	38,106	-2,532	-551	3,829	893	1,244	279
	2043-2047	638,410	186,732	40,825	-2,432	-519	4,055	949	1,269	279

5 Discussion

5.1 Forest carbon projections

The projection indicated in increasing carbon pools corresponding to the levels observed in recent years [12, 17, 18]. The increase in forest carbon pools was less in the beginning of the projections, corresponding to an initial peak in emissions in the first five-year period, likely as a result of several different factors.

Firstly, as evidenced in national reporting on forest statistics [12, 17, 18], the age- and diameter distribution of trees in Danish forests is skewed (Figure 5.1) with large quantities of mature trees with a high probability of being harvested according to the historical harvesting probabilities used in the projection (3.3.2 Harvest probability). This is particularly pronounced for species such as beech, where prices have been low for several decades, resulting in a build-up of the volume of mature trees. Consequently, according to national forest statistics (recalculation of figures presented in [12]), more than 1/3 of the CO_2-eq in beech is found in trees with a diameter (measured at breast height) of more than 60 cm, which would generally be considered mature. Similarly, about 1/4 of the CO_2-eq in Sitka spruce is found in mature trees with a breast height diameter of more than 40 cm.

Recent increase in prices of both broadleaf and conifer timber as well as a favourable market for forest fuels have resulted in increased harvest levels reflected both in our projections and in the reported harvesting levels from Statistics Denmark [19]. Also, the conversion of areas set aside for biodiversity protection in the state forests, which involves clearing of exotic tree species as simulated in the projection, albeit to a minor degree affects overall harvesting levels and carbon pools (Figure 4.5).

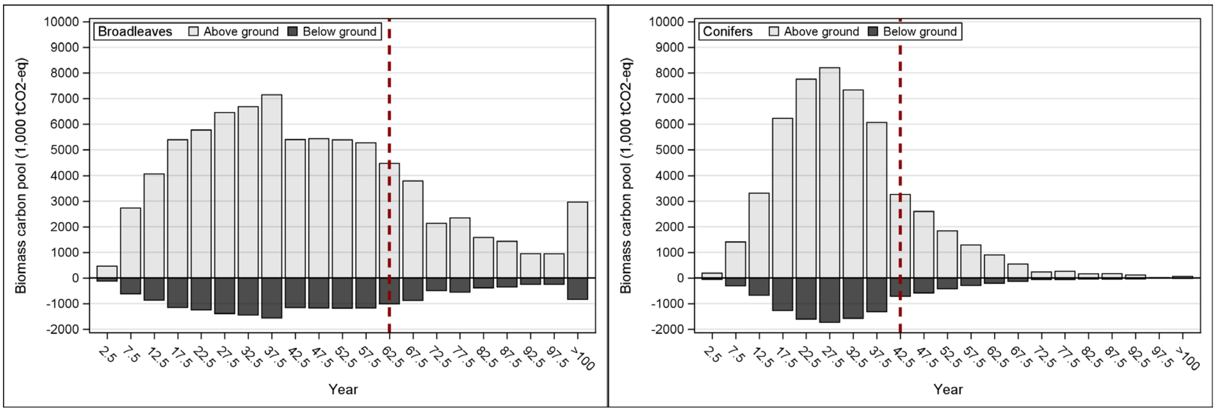

Figure 5.1. Carbon pools in above and below ground biomass for broadleaves and conifers. The red vertical line indicates approximate maturity for most species in the two categories.

In an attempt to compare the harvesting levels reported from Statistics Denmark [19] to our projected harvesting, we converted the volumes reported from Statistics Denmark to CO_2-equivalents, using a basic density of 0.55 ton biomass/m^3 for broadleaves and 0.38 ton biomass/m^3 or conifers, a carbon density of 0.47 gC/g, and a conversion from carbon to CO_2 of 44/12. Realizing that we have no knowledge on the extracted fraction of the total harvest reported to Statistics Denmark, we compared the reported harvesting expressed in CO_2-equivalents to our projected above-ground biomass. Our results indicated that the projected harvesting is similar to that reported by Statistics Denmark in recent years, indicating a similar trend (Figure 5.2) albeit a slightly higher peak in the harvests in the coming years. It should be noted that we expect the projected harvests to be systematically higher than the values reported by Statistics Danmark, since the projected values include all above ground parts of the tree, whereas only parts of these are expected to be extracted and reported to Statistics Denmark.

Whether the projected peak in harvest levels and therefore also in emissions will be observed in the coming years depends largely on the future price structure of wood products and bioenergy, which is not reflected in the model. A special challenge to this end is that the NFI data used as the baseline for the projections was collected during 2018-2022, meaning that some of the trees measured in 2018 and 2019 may have been harvested during the increased harvest in the last years of this period. Hence, some of the peak observed may in fact reflect harvesting that has already commenced. To what extent is not possible to say.

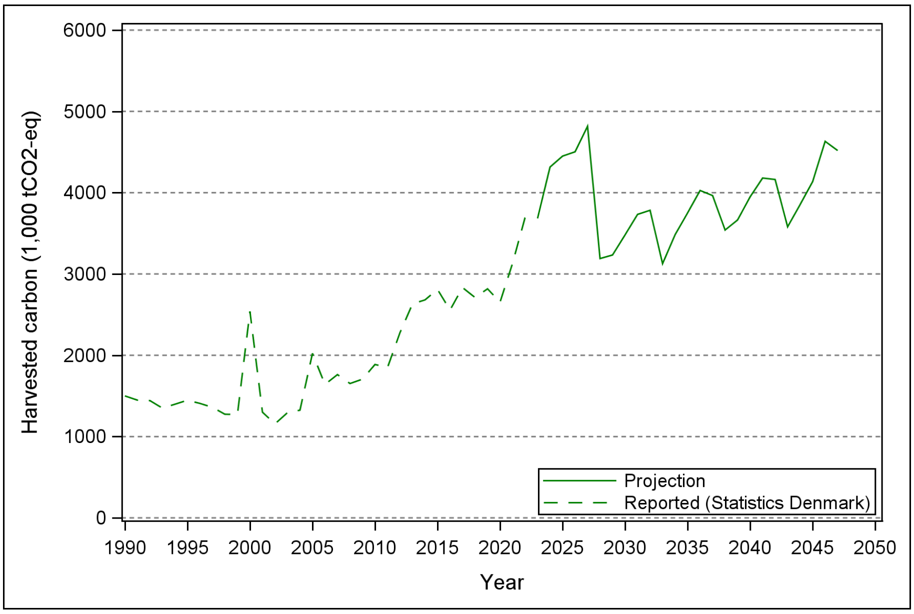

Figure 5.2. Comparison of projected and reported (Statistics Denmark) harvesting levels expressed in CO_2-equivalents. The recalculating of reported volumes to CO_2-equivalents is highly uncertain and the ratio of extracted (and sold) volumes to total harvest volumes is unknown. Therefore, the direct comparison on projected and reported volumes is uncertain.

Owing to the large amount of mature beech the model projects increased harvest levels in beech and hence less uptake of CO_2 in the coming years. Another important finding is that we project a significant net uptake of carbon in oak. This is presumably due to the extensive use of oak in afforestation projects in recent decades [12], ensuring a large net uptake in the young forests a long way from maturity and final felling.

Interestingly the model projects only limited net uptakes in conifers and even periodic emissions from Sitka spruce and Norway spruce, owing to annual harvests and mortality exceeding increment. This may have several reasons including good prices on softwood timber in recent years, increasing the harvest probabilities and therefore also the predicted harvest levels. However, increasing health problems for these two species in particular caused by extended periods of drought during the summer, pest such as bark beetles and aphids, and windthrow may also have impacted both the mortality of the species but also the forest owner's decision to harvest the two species earlier.

In general, the model provided credible projections of forest carbon pool development and associated emissions. In particular, the model projected similar patterns of emissions as have been observed from the national estimates based on forest inventory data.

5.1.1 Forest growth models

In the current project, the EFISCEN-space model was for the first time parameterized to Danish conditions, including the setting of harvest and mortality probabilities, and adjusting to local conditions such as expected afforestation and specific management of forest designated to protection of biodiversity. During the project, we further attempted to reparametrize the underlying growth model with observations of tree growth from the Danish National Forest Inventory. However, we found that despite of the rich data available (about 70,000 trees with repeated measurements were included), the modelling seemed less robust compared to the in-build growth model relying on 2.3 mi. trees with repeated measurements observed from a wide range of geographical conditions across Europe [13].

To enhance the accuracy of EFISCEN-Space model predictions for Danish forest biomass pools, reparametrizing the model with Danish data is essential. However, as a simple fitting of the models with Danish data proved insufficient, this entails a full recalibration of the growth models underlying EFISCEN-Space with the pan-European and Danish data. Such an effort includes also validation of the models using independent datasets and sensitivity analysis to ensure the reliability of the reparametrized model. Such an effort was not possible within the current project.

When reviewing the growth patterns simulated in the current version of the EFISCEN-Space model, we found that some of the models produces simulations inconsistent with current knowledge of tree growth, such as unlikely late peaking growth or even growth not peaking at all and excessive growth levels under low or high competition. A likely reason is that although the underlying data collected from National Forest Inventories across most of Europe has an impressive breadth and depth, the vast majority originates from forests managed according to some similar standards. This results in well behaved functional forms under standard conditions but less so when conditions deviate from the normal. We speculate that data from forest experiments, typically including deviating forest management and long time series could substantially improve the growth functions in EFISCEN-Space.

5.1.2 Uncertainties

The projection of forest carbon pools entails a wealth of uncertainties of which we may here only describe a few.

Input data

The input data is measured with a very low uncertainty but represents a sample of the Danish forest area. Earlier studies have demonstrated that the uncertainty of forest carbon pool estimates are small (0.9 pct.) but also demonstrated that even a proportionally small uncertainty may have a large effects when applied to large pools. With more than 160 mi. tons CO_2-eq stored in the biomass, the uncertainty expressed as the standard error is around 1.5 mi. tons CO_2-eq. As the uncertainty of projections presented here will always be larger than the direct estimates from actual measurements a numerically substantial uncertainty should be expected. In particular when considering that emissions are calculated as the difference between two subsequent and uncertain estimates of forest carbon pools.

Natural catastrophes

The model used in this study assumes harvesting probabilities and natural mortalities to follow some previously observed patterns. However, climate change is projected to result in warmer summers with more frequent droughts, winters with more precipitation and more frequent flooding, as well as more frequent and heavier storms. It is thus likely that mortality patterns will change during the projection period as it has been observed in southern and central Europe.

Specifically for Denmark and building on historical observations, it is far from unlikely that we will see catastrophic windthrow one or more times during the projection period. In the largest-ever windthrow observed in Denmark, 3.6 million cubic meters of wood were windthrown corresponding to a similar number expressed in ton CO_2-eq. Such a windthrow would significantly alter the reported emissions from the LULUCF-sector depending on assement method for reporting.

Changed growing conditions and climate change

As stated in the methods section, we opted to use the currently available growth models obtained from repeated measurements of trees on National Forest Inventory sample plots. However, climate change is currently altering the conditions for forest growth in Europe [20] and may impact also the growth of Danish forests. Effects of climate change are expected to be more elaborate in extreme latitudes and altitudes. Some tree species may increase vitality and growth at higher boreal latitudes or higher altitudes and the opposite at lower dry and warm locations [21, 22]. Regional growth trends are less clear in areas currently better suited for tree growth and recent studies report overall increasing growth trends for European trees [23] and forests [20]. However, despite this general pattern, severe drought events and generally changed precipitation patterns in some regions result in declining vitality and growth of some of the most abundant European forest tree species [24-27].

The cumulative effect of changed temperature and precipitation patterns in Denmark is unknown, but the EFISCEN-Space model holds the possibility to alter the underlying growth drivers by changing model factors to simulate growing conditions currently native to other parts of Europe. However, with the relatively short projection scope used in this study (25 years), we found that climate change and its effect on forest growth during this period would likely be moderate and opted to use current climate conditions in the model.

Human behaviour

In the projections, we have assumed that human behaviour related to harvesting of trees follows historical patterns. This is a far from likely assumption when realizing that societal changes may heavily affect the way we use the forests. As an example, a change in the Chinese market for beech wood in combination with heavy windthrow in central Europe caused an abrupt decline in demand and more than halved the price of beech wood around year 2000. The prices have so far not recovered entirely and the change in prices has for more than 20 years reduced the harvesting of beech substantially. As such the harvest is currently around half of what was reported to Statistics Denmark in 1990-1999 and only on third of the reported figures in 1960-1970. Oppositely, the breakout of the war in Ukraine in February 2022 caused a massive increase in energy prices causing an enormous demand for firewood. Although the price change was only temporal and therefore had limited impact, the harvesting of firewood went up in the forest likely having an impact on forest carbon pools.

The forests have many other functions aside from their climate change mitigation potential. Aside from the changes in price and market dynamics, their treatment may be affected by other desires regarding the services they provide. A notable example is the setting aside forest for biodiversity protection. As also reflected in this study, the Danish government in 2020 decided to set aside 75,000 ha of forest for conservation purposes. This drastically changed the forest management on more than 10 pct. of the forest area. Future political goals therefore have the potential to introduce even more drastic changes to future forest management and hence to the development of the forest carbon pools and their climate change mitigation potential.

Carbon pool development on set aside forest areas

Albeit we succeeded in differentiating management of the forest resource according to geographical data on set aside forest in eastern and western Denmark, very little knowledge is available on the actual implications of the management on forest carbon pools.

We assumed that a proportion of the area will be deforested but have no actual knowledge if the area is correct or whether the areas will grow into forest again. In particular, a portion of the set aside area will be rewetted and although we have assumed that this will not impact emissions of other green house gasses such as nitrous oxide and methane, we know that rewetting might affect the emissions of these very potent climate gasses.

We have assumed limited harvesting of the areas but have no knowledge on the possible reduction in forest biomass owing to the introduction of large grazers (horses and cattle) in particular in the nature national parks. It is likely that the animals will both damage trees and hence affect the present carbon pools while also hampering regeneration of the forest and in time cause substantial deforestation *in sensu* climate reporting.

5.2 Connection with greenhouse gas reporting

To enable comparison of reported and projected values possible, we entered the projection results into the reporting tool routinely used for making emissions estimates based on carbon pool estimates from the national forest inventory. The reporting tool calculates emissions as the average annual differences between 5-year moving averages of the forest carbon pool estimates to alleviate significant inter-annual fluctuations in emissions resulting from overlapping cycles of the national forest inventory [28]. Consequently, the reporting tool is well suited to flatten the cyclic emission pattern resulting from the EFISCEN-space model repetition of harvesting cycles, which is an artefact of the model setup rather than reflecting overall model trends.

When merging reported and projected emissions it should be noted that there are prominent methodological differences in the calculations of carbon pools between the reporting on one hand and the projection on the other. Firstly, the height of individual trees that is used in the tree biomass estimation is largely estimated from local diameter/height regression specific to the individual plots [11]. When making the calculations from the EFISCEN-Space output it is not possible to produce localised diameter/height regressions and we used a set of general, albeit species specific, equations estimated from the national forest inventory data. Secondly, to allow for the scaling also of small trees in plots covering more than one land use, we included only sample plots with the plot centre covered by forest in the projections. To accommodate for the difference in statistical design, we used a consistent estimator assuming full forest cover of included plots and zero cover for plots not included. However, although the estimator is consistent, one should not expect numerically identical results. For the initialization of the EFISCEN-space model, we estimated the above ground biomass carbon pool at 37,728.71 kt C whereas the estimate provided from the usual calculation used for the reporting estimated 36,206.40 kt C – a difference of 4 pct.

The difference between the most recent reported value of forest carbon stocks and the first year of the projection makes coupling of the reporting and projection difficult as the difference will result in technical emissions or uptake, not resulting from forest growth or management but from a basic difference in statistical design. We therefore made a technical correction to the reporting tool by subtracting the difference between observed and projected carbon pools in year 2022 that constitutes the last year in the reporting and first year of the projection (37,728.71 kt C - 36,206.40 kt C ~1,500 kt C for above ground biomass) respectively, hereby alleviating the effect of the difference in sampling scheme between the NFI data and the data used in the projections. This correction has no implications for the projected emissions except for the first year of the projections, where observed and projected carbon pools are linked. The observed pattern now shows fluctuations that are not different in magnitude from historical observations (Figure 5.3).

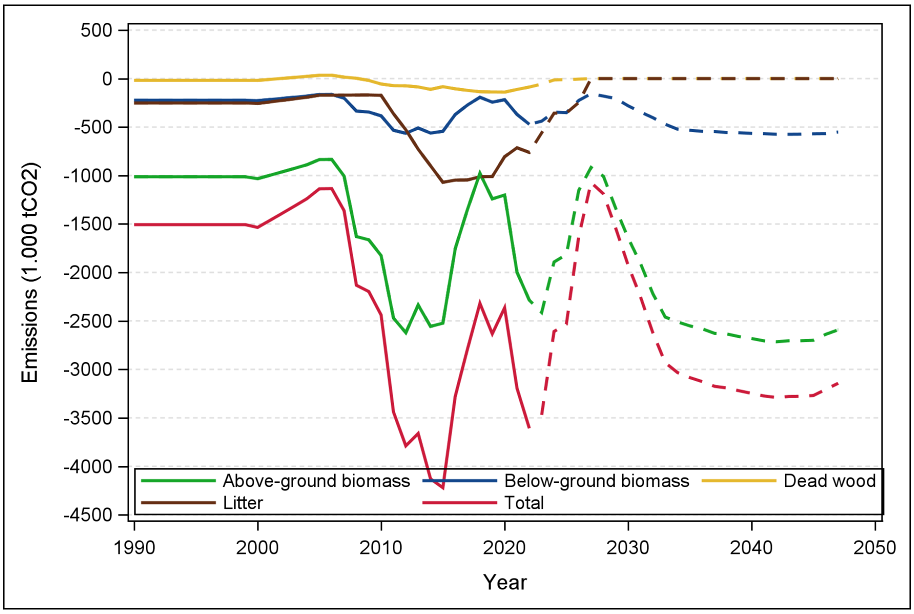

Figure 5.3. Observed (solid lines) and projected (dashed lines) emissions connected by the normal reporting tool.

5.2.1 Comparison to previous projections

The methods applied in this projection differ largely from previous projections in many aspects. Previous projections relied on an age-class based approach in which the underlying assumption in both model estimation and application was the harvesting of entire forest stands rather than individual trees. Oppositely, EFISCEN-Space relies on an individual tree-based approach, in which individual tree development is projected into the future. Here, the model estimation and application relied on individual tree observations on national forest inventory plots. Based on an analysis of the National Forest Inventory data, we found that the approach used in this study is much closer to the actual management of the Danish forests and also that the model makes a more direct use of the available data.

In this study, we compared the *Forest Carbon Pool Projections 2022* (KF22) with the current *Forest Carbon Pool Projections 2024* (KF24) (Figure 5.4). The differences between methods, and not least in the underlying models, are expected to result in differences between previous and present projections. However, there are also differences in the underlying frozen policy scenario, that should be observed when comparing the two projections. Such differences include differences in the size and composition of afforestation, the pace of implementation of set-aside forest for biodiversity protection, as well as the expected composition and growth of forest regeneration.

The KF22 projected a decline in forest stocks at the onset of the projections (dashed red line in Figure 5.4) owing to an initial increase in harvesting. This was presumably caused by a skewed age class distribution, in particular for beech where low prices for decades had resulted in a buildup of large resources of mature trees. Notably, the current projections (KF24) predict a similar initial increase in harvests similar to but not of the same magnitude as projected in KF22. Oppositely, the recovery of net carbon uptake is faster in the current projections, seemingly owing to the use of a tree-based approach rather than the previous approach assuming harvest of entire stands. The observed difference may likely be attributed to the modelling of individual trees, that allow for a gradual turnover of the stand as is normal practice in particular in beech in Denmark, but likely also in the stability of the underlying modelling framework. In previous modelling efforts, the Markov chain models were built upon statistical modelling of the chance of forest transition from one age-class to the next and the associated chance that the forest is converted to the youngest age-class (age 0). Owing to the scarce number of incidents where such conversion took place, and the common conversion of forest to entirely different age-classes made such modelling difficult and uncertain.

This in turn likely results in less certain projections of emissions from forests and is likely responsible for much of the difference observed between current and previous projections.

Collectively, when comparing the 5-year moving averages produced by the climate reporting tool this leads to differences in emissions projections from live biomass between KF22 and KF24 totalling 1.7 mi. tCO_2-eq/yr in 2030 and 3.1 mi. tCO_2-eq/yr in 2040 (Figure 5.4, Table 5.1 labelled "MA"). Since the moving averages in the climate reporting tool utilize data from two consecutive 5-year periods, the resulting emissions are affected by previous reported/projected emissions. If instead considering the periodic averages (i.e. average emissions of 2023-2027, 2028-2032, 2033-2037, 2038-2042, and 2043-2047) differences in emissions totalled 2.5 mi. tCO_2-eq/yr in 2030 and 3.2 mi. tCO_2-eq/yr in 2040 (Table 5.1 labelled "PA"). In particular the peak in emissions in the first 5-year period of the projection (2023-2027) affects the moving average the following years and hence the 2030 estimate. Subsequently, the stable level of emissions from 2028 and onwards leads to lesser differences between the moving and periodic averages.

As the project evolving around *Forest Carbon Pool Projections 2024* was at the initiation meant to entail only a simple projection, we opted to assume no change in the dead wood and litter layer carbon pools. This assumption was based on the relatively minor size of these two pools and their commonly slow change, collectively resulting in only minor contribution to the annual emissions. As a consequence of this assumption, it is not meaningful to compare emissions from dead wood and litter between the *Forest Carbon Pool Projections 2022* and *Forest Carbon Pool Projections 2024*.

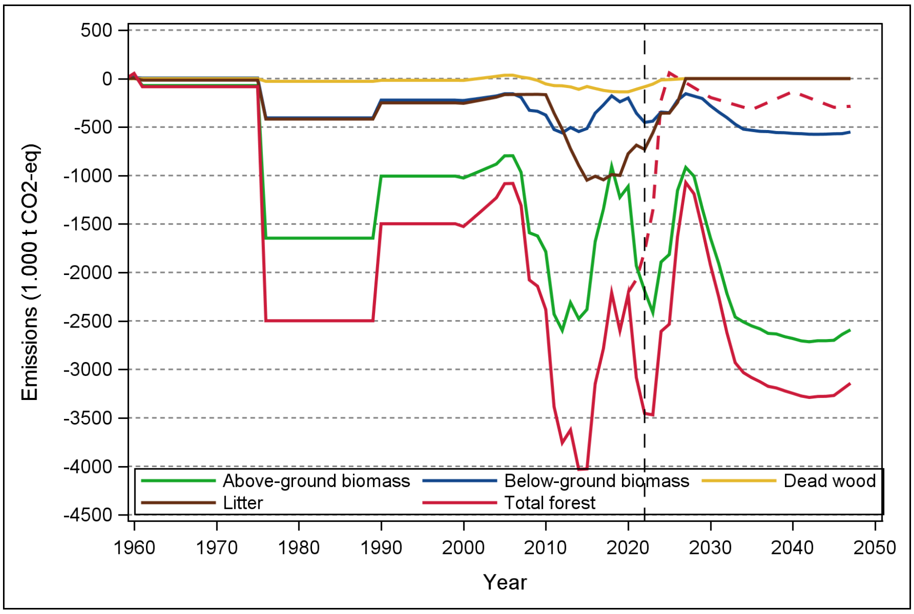

Figure 5.4. Comparison of projections of forest emissions. Here we compare the KF22 (total emissions, dashed red line) projection and the present KF24 projection (from 2022, solid red line). Prior to 2022 (marked with a vertical dashed line), lines show the reported emissions.

Table 5.1. Comparison of emissions from live biomass (above and below ground) for the forest carbon pool projections Klimafremskrivning 2022 and Klimafremskrivning 2024. Climate projections 2024 (MA) represents the moving averages depicted in Figure 5.4; Climate projections 2024 (PA) represents simple 5-year averages of the emissions depicted in Figure 4.1.

Year	Climate projections 2022			Climate projections 2024 (MA)			Climate projections 2024 (PA)		
	Above ground	Below ground	Total	Above ground	Below ground	Total	Above ground	Below ground	Total
	1,000 tCO_2-eq								
2025	119	88	207	-1,815	-352	-2,167	-913	-170	-1,084
2030	-181	-35	-216	-1,645	-281	-1,925	-2,220	-481	-2,701
2035	-305	-51	-357	-2,552	-533	-3,085	-2,636	-576	-3,212
2040	-124	-14	-138	-2,682	-566	-3,247	-2,720	-590	-3,310
2045	-247	-40	-287	-2,700	-570	-3,269	-2,597	-555	-3,152

Although not relying on species and age-class specific treatment of the forest but rather on individual tree projections from a mere scaling of observed diameter and species distributions observed on inventory plots, the data used in the previous *Forest carbon pool projection 2022* and the current *Forest carbon pool projection 2024* are the same: data from the national forest inventory. Nonetheless, the projections produced here differ largely from recent projections. Importantly, however, is that both methods entail uncertainties. As explained in section 5.1.2 on uncertainties, the uncertainty (standard error) of the biomass carbon pool estimate is around 0.9 %

of the total, resulting in an uncertainty of 1.5 mi. tCO_2 eq. As the emissions are calculated as differences between pools, the associated uncertainty may be estimated as the sum of the uncertainties of the two carbon pool estimates minus their covariance. Although we do not know the covariance, the uncertainty is likely to be even larger than the uncertainty related the estimate of carbon pools; i.e. larger than 1.5 mi. tCO_2 eq. Consequently, although the differences in carbon emission projections may seem large, they are likely not statistically different.

5.3 Forest carbon projection methods

5.3.1 Simple projections

Initially, the assignment for this task was to produce a simple projection of forest carbon pools and the associated emissions. It should be noted that even apparently simple projections require underlying assumptions, which must be valid in order to justify the projections. From the beginning of the project, it was appreciated that a simple method that captures the current diversity in forest structure and developments in forest management does not exist. Nonetheless, to demonstrate the possible application of a very simple projection method, we made an analysis of carbon pools and emissions from the mere reported values from the forest inventory and the emissions reporting for the UNFCCC. Furthermore, we intend to demonstrate that even a very simple method for projecting carbon emissions produce estimates with significant uncertainty and hence that results should be interpreted with care, when developing policies upon the estimates.

Projections were made using the Autoreg procedure in SAS with a 2nd order autocorrelation (AR(2)) model estimated through maximum likelihood. The model fits a linear regression model to the time series data, where each data point is predicted based on a linear combination of its two most recent past values. The coefficients of this linear combination are estimated using maximum likelihood, and the model is then used to forecast future values in the time series based on this learned pattern.

The forecasting of the carbon pools shows an increasing trend and a relatively narrow confidence interval (Figure 5.5). This is well in line with previous studies that the uncertainty of the live biomass estimates is around 0.9 pct. and hence a narrow confidence interval is expected. However, this estimate does not include uncertainties related to e.g. future afforestation, age distribution of the forest and resulting changes to the harvest levels, or uncertainties related to changes in forest management on set-aside areas.

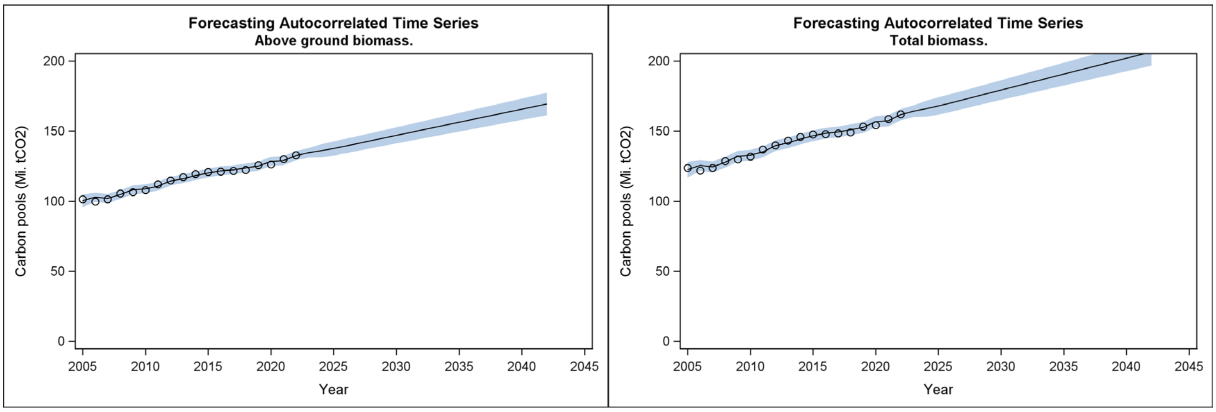

Figure 5.5. Examples of forecasting carbon pools in living biomass using an autoregressive model on reported carbon stocks from the Danish NFI.

When applying the autoregressive model to reported emissions, confidence intervals became very large (Figure 5.6), owing to the large variations resulting from estimating differences between large pools with a relatively small change (~1-2 pct.) even if the pools are estimated with a small standard error. The figures illustrate the effect of even small uncertainties in the carbon pool estimates when considering annual differences that make up the emissions estimates. This effect should also be kept in mind when evaluating the more complex projections made with the EFISCEN-Space model.

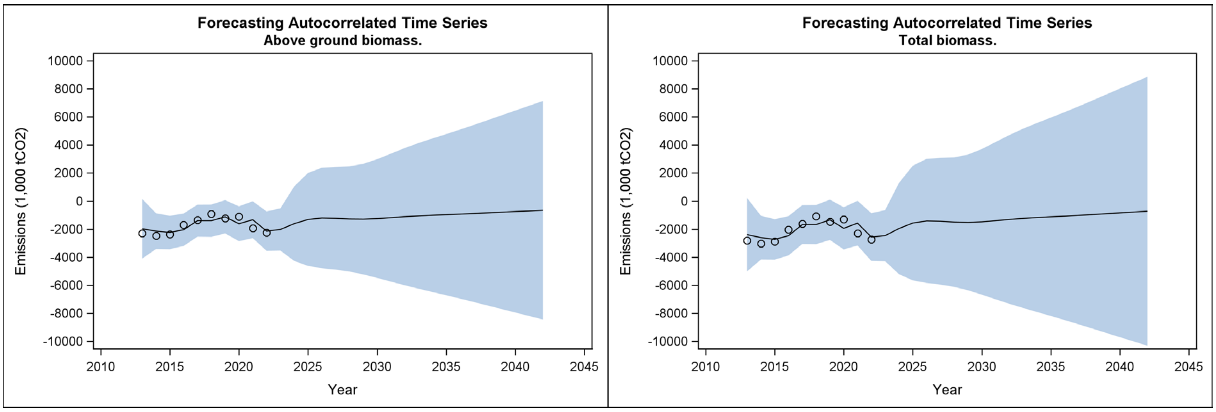

Figure 5.6. Examples of simple projections using an autoregressive model (lag=2) on reported emissions data from above-ground biomass and total biomass.

5.4 Future development

This project has made it possible to implement a new modelling framework that has the potential to continuously refine the projection of forest carbon and other resources in the Danish forests. However, the short timeframe of this project did not allow for implementation of all the capabilities of the EFISCEN-Space model.

A roadmap of future development and testing is envisioned, both to further take advantage of the capabilities of EFISCEN-Space and to complement the existing input data from the NFI with auxiliary data e.g. from long-term experiments and remote sensing. An example is to further develop new Danish growth increment functions based on data from the NFI that could be used within the EFISCEN-Space model. These were in fact developed during this project but have not been adequately tested to include in this report.

Some specific additions to the modelling framework should be considered in future editions. Firstly, our analyses do not take into account possible effects of changing forest management on dead wood carbon pools. Especially when analysing various scenarios of setting aside forest for biodiversity protection where increasing dead wood carbon pools is expected, the current projection system would fall short of the target. However, such an analysis would to some extent be possible, as the model provides projections on natural mortality and hence the contribution to dead wood pools. This would, however, require knowledge on the oxidation of the dead wood pool, commonly expressed in half-lives of the biomass [29, 30]. Albeit this could be an important extension of our analyses, we expect that the effect on overall carbon pools would be limited owing to the size of the dead wood relative to the live carbon pool and the 25-year time perspective in our analyses in which it is unlikely that any significant build-up of dead wood would occur.

In addition to the pool estimates, the current modelling framework does not take into account emissions of other greenhouse gasses such as methane or nitrous oxide from the soil. A prominent feature of current trends in closer-to-nature forest management and the setting aside forest land for biodiversity protection is the reversion to natural hydrological conditions by ceased maintenance and even destruction of ditches and drainage pipes. Inhibited soil drainage eventually leads to wetter conditions in forest soils and to the formation of intermediate or permanently wet soils that may affect emissions of CO_2, methane, and nitrous oxide. As the latter two greenhouse gasses have a high global warming potential, this may have significant impact on the climate effect of changed forest management practises, as even small proportions of wet soils contribute substantially to the emissions of methane and nitrous oxide [31].

As we have little knowledge on the actual rewetted area resulting from e.g. the setting aside of forest for biodiversity protection in our scenarios, we referred from analyses on the consequences on emissions of other climate gasses in our study. However, the EFISCEN-Space model has been coupled with the YASSO soil carbon model in a way that enables outputs and plot data from

EFISCEN-Space to serve as inputs to YASSO (i.e., biomass inputs from mortality, harvesting, and litterfall). Such development could enable soil carbon projection that reacts in a dynamic way to changes in modelling future climate scenarios or forest management.

The EFISCEN-Space model is itself under continuous testing and development with a dedicated team of software developers and forest scientists. It is planned to add functionality to e.g., explicitly simulate plot level development under future climate scenarios as well as to consider inputs to Harvested Wood Product (HWP) pool development from forest harvesting.

5.5 Assessing actual climate effects

In the context of assessing the climate impact of forestry activities, it is imperative to adopt a comprehensive approach that goes beyond merely accounting of direct emissions associated with changes in forest carbon pools as is the basis of this report. Traditional metrics including the climate reporting often focus on the immediate carbon fluxes resulting from forest management practices, such as carbon sequestration and emissions related to deforestation or afforestation. However, this narrow perspective overlooks the broader climate benefits derived from the utilization of forest products and the substitution of these products for more carbon-intensive materials and energy sources [29, 30].

Wood harvested from forests serves as a critical input for a variety of products and energy solutions that play a significant role in the transition towards a green economy. When wood products replace materials that are more carbon-intensive to produce, such as concrete, steel, or plastic, there is a net reduction in greenhouse gas emissions. This substitution effect extends to the energy sector, where biomass sourced from sustainably managed forests can displace fossil fuels, further contributing to the reduction of greenhouse gas emissions. The processing of wood into products and energy is generally less energy-intensive compared to the manufacturing processes for other materials. This results in lower emissions from the production phase, enhancing the overall climate benefit of using wood.

It's essential to recognize that the energy requirements and emissions associated with the processing of wood are significantly offset by the carbon storage in wood products and the substitution benefits. However, our analyses do not account for the possible effects of forest products in total societal emissions to a large degree occurring outside the forests. As an example, designating forest areas for nature protection obviously results in a decline in the wood production after the conversion and hence in time the inflow of wood to the HWP pool. This will result in increased net-emissions from the HWP pool, since only nationally produced wood is accounted for in the pool while part of the HWP pool is continuously being oxidized. This effect is included in our model, as HWP are being projected in the simulations.

While the direct emissions from changes in forest carbon pools provide valuable information on the immediate impacts of forest management, they fail to capture the full climate effect of forestry activities. The reduction in wood production resulting from designating forests to biodiversity protection further results in increased emissions from related sectors such as the energy (relying more on fossil resources rather than bioenergy), building (relying more on fossil-expensive materials such as concrete and steel), and transport (transporting wood from larger distances) sectors. These emissions are however not accounted for in the LULUCF sector and hence also not in our model. Ignoring the substitution effects of wood products and biomass energy overlooks a crucial component of the forest's role in climate mitigation. Furthermore, emerging practices such as Bioenergy with Carbon Capture and Storage (BECCS) present additional opportunities to enhance the climate benefits of using wood for energy by potentially reducing the carbon debt associated with biomass energy use.

The developments to the EFISCEN-Space model presented in this study, allows for expansion of the scope including scenario analyses, not only of direct emissions but including the entire systemic emissions related to changes in forest management, wood production, and the utilization of wood. This comprehensive perspective is essential for accurately assessing the potential contribution of forestry to climate change mitigation and for informing policies and practices that maximize the climate benefits of forest resources.

5.6 Concerns Related to the Discontinuation of the National Forest Inventory

The methodologies employed in this report are fundamentally dependent on the comprehensive data provided by the National Forest Inventory (NFI). The NFI has been instrumental in supplying the foundational data necessary for initiating our projections and crafting the underlying models that inform our analyses. Recently, the Environmental Protection Agency decided to discontinue the NFI in its current form. This decision poses profound challenges and raises significant concerns regarding our capacity to accurately monitor, report, and project the climate effects of the nation's forests within the Land Use, Land-Use Change, and Forestry (LULUCF) sector. This section delves into the critical implications of this discontinuation, focusing on its impact on climate reporting, the feasibility of forest climate effect projections, and the integrity of future projections due to the potential loss of continuous data series.

Impact on Climate Reporting for the LULUCF Sector

Adherence to the Intergovernmental Panel on Climate Change (IPCC) guidelines for greenhouse gas inventory reporting, especially emissions and removals in the LULUCF sector [32], has been underpinned by the accurate and comprehensive field measurements conducted by the NFI. The cessation of the NFI's operations in 2024 threatens Denmark's compliance with these international reporting standards, as remote sensing, in isolation, lacks the capability to capture the nuanced biophysical parameters essential for thorough LULUCF accounting. This transition jeopardizes the integrity of Denmark's climate commitments by potentially compromising the credibility of its reported data.

The potential impact of the decision to discontinue the NFI in its current form is particularly surprising given the role that forests play in Danish and EU strategies for climate change mitigation. The Danish government has decided to afforest 250,000 ha with the explicit aim to gain climate neutrality and in time even net negative emissions. Afforestation is furthermore a pivotal part of European Green Deal and the EU ambition to be the first climate-neutral continent. Given the apparent role of forests in climate change mitigation, it is remarkable that Denmark so chooses to discard of the only available tool for analysing the impact of political initiatives on forest carbon emissions.

Implications for Forest Climate Effect Projections

The ability to project the climate effects of forests is indispensable for informing climate policies and strategies at both national and international levels. Such projections are heavily reliant on robust historical and present-day data regarding forest composition, growth rates, and carbon sequestration capacities. The continuity of data series provided by the NFI has been invaluable for understanding the dynamics of forest ecosystems, particularly in the context of changing management and evolving climate conditions. This longitudinal data has enabled a nuanced understanding of trends, the assessment of forest management practices, and the formulation of informed policy decisions. With the termination of the NFI, this continuity is at risk, creating a significant knowledge gap in our understanding of how forest ecosystems respond to environmental changes. The resultant data discontinuity will severely hamper future ecological and climate projections, detracting from the effectiveness of research initiatives and policy formulations. Specifically, the discontinuation of the NFI disrupts the flow of this critical data, thereby impeding the generation of reliable and accurate forest climate effect projections. This impediment significantly undermines Denmark's strategic planning for climate change mitigation and adaptation, diminishing the nation's contribution to global climate objectives.

The discontinuation of the National Forest Inventory presents significant obstacles to Denmark's climate reporting capabilities, forest management strategies, and scientific research endeavours. It undermines the nation's ability to fulfil its international reporting obligations, generate precise forest climate effect projections, and maintain vital long-term ecological data series. In light of these challenges, it is critical to reassess the decision to discontinue the NFI or to develop an alternative solution that ensures the continuation of comprehensive, field-based forest monitoring practices in line with IPCC guidelines.

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6 Appendix

Table 6.1. Projected carbon pools in above and below ground biomass distributed to total pools and pools in the afforestation made during the simulations (i.e. not including afforestation prior to the initiation of simulations in 2022).

Year	Forest Area	Total		Forest less than 30 year	
		Above ground biomass	Below ground biomass	Above ground biomass	Below ground biomass
	ha	1,000 t CO_2-eq			
2022	642.976	138.339	30.441		
2023	642.976	139.673	30.705		
2024	642.976	140.505	30.848		
2025	642.976	141.339	31.004		
2026	642.976	142.225	31.176		
2027	642.976	142.905	31.293		
2028	656.222	144.694	31.672	230	13
2029	656.222	147.186	32.214	286	17
2030	656.222	149.548	32.718	339	20
2031	656.222	151.755	33.210	402	23
2032	656.222	154.005	33.699	466	27
2033	667.556	157.011	34.368	686	40
2034	667.556	159.769	34.975	799	46
2035	667.556	162.340	35.540	912	53
2036	667.556	164.699	36.044	1.034	59
2037	667.556	167.184	36.580	1.169	67
2038	667.825	170.217	37.252	1.311	75
2039	667.825	173.112	37.888	1.443	83
2040	667.825	175.779	38.463	1.592	91
2041	667.825	178.256	38.994	1.753	100
2042	667.825	180.786	39.530	1.884	108
2043	666.975	183.767	40.193	2.036	117
2044	666.975	186.660	40.808	2.204	126
2045	666.975	189.303	41.375	2.335	133
2046	666.975	191.473	41.820	2.504	143
2047	666.975	193.770	42.304	2.676	153

Table 6.2. Projected carbon pool contribution to harvested wood products.

Year	Total	Sawn timber	Panels	Paper
	1,000 t CO_2-eq			
2022	-	-	-	-
2023	515	386	129	-
2024	619	464	155	-
2025	636	477	159	-
2026	654	491	164	-
2027	689	517	172	-
2028	454	340	113	-
2029	466	349	116	-
2030	512	384	128	-
2031	545	409	136	-
2032	569	427	142	-
2033	444	333	111	-
2034	498	373	124	-
2035	539	404	135	-
2036	587	441	147	-
2037	584	438	146	-
2038	499	375	125	-
2039	515	386	129	-
2040	581	435	145	-
2041	598	448	149	-
2042	615	461	154	-
2043	503	377	126	-
2044	556	417	139	-
2045	596	447	149	-
2046	679	509	170	-
2047	652	489	163	-

Table 6.3. Emissions reported from previous inventories and in the previous (KF22) and present (KF24) projection based on the 5-year moving averages of forest carbon pools used in the reporting tool applied for annual reporting to the UNFCCC. The year 2022 separates reported and projected values from KF24.

Year	Climate projection 2022					Reorted values/Climate projection 2024				
	Above ground biomass	Below ground biomass	Dead wood	Soil	Total	Above ground biomass	Below ground biomass	Dead wood	Soil	Total
	1,000 t CO_2-eq									
1959						-	-	-	-	-
1960						41	11	-1	3	54
1961						-72	5	-1	-16	-84
1962						-72	5	-1	-16	-84
1963						-72	5	-1	-16	-84
1964						-72	5	-1	-16	-84
1965						-72	5	-1	-16	-84
1966						-72	5	-1	-16	-84
1967						-72	5	-1	-16	-84
1968						-72	5	-1	-16	-84
1969						-72	5	-1	-16	-84
1970						-72	5	-1	-16	-84
1971						-72	5	-1	-16	-84
1972						-72	5	-1	-16	-84
1973						-72	5	-1	-16	-84
1974						-72	5	-1	-16	-84
1975						-72	5	-1	-16	-84
1976						-1.646	-406	-29	-418	-2.498
1977						-1.646	-406	-29	-418	-2.498
1978						-1.646	-406	-29	-418	-2.498
1979						-1.646	-406	-29	-418	-2.498
1980						-1.646	-406	-29	-418	-2.498
1981						-1.646	-406	-29	-418	-2.498
1982						-1.646	-406	-29	-418	-2.498
1983						-1.646	-406	-29	-418	-2.498
1984						-1.646	-406	-29	-418	-2.498
1985						-1.646	-406	-29	-418	-2.498
1986						-1.646	-406	-29	-418	-2.498
1987						-1.646	-406	-29	-418	-2.498
1988						-1.646	-406	-29	-418	-2.498
1989						-1.646	-406	-29	-418	-2.498
1990						-1.006	-222	-18	-251	-1.498
1991						-1.006	-222	-18	-251	-1.498
1992						-1.006	-222	-18	-251	-1.498
1993						-1.006	-222	-18	-251	-1.498
1994						-1.006	-222	-18	-251	-1.498
1995						-1.006	-222	-18	-251	-1.498

Year	Climate projection 2022					Reorted values/Climate projection 2024				
	Above ground biomass	Below ground biomass	Dead wood	Soil	Total	Above ground biomass	Below ground biomass	Dead wood	Soil	Total
	1,000 t CO_2-eq									
1996						-1.006	-222	-18	-251	-1.498
1997						-1.006	-222	-18	-251	-1.498
1998						-1.006	-222	-18	-251	-1.498
1999						-1.006	-222	-18	-251	-1.498
2000						-1.026	-227	-19	-255	-1.526
2001						-991	-215	-8	-240	-1.454
2002						-955	-203	2	-224	-1.380
2003						-919	-191	12	-208	-1.305
2004						-882	-179	23	-191	-1.229
2005						-797	-157	34	-165	-1.084
2006						-796	-156	35	-164	-1.082
2007						-967	-194	16	-164	-1.309
2008						-1.590	-328	3	-163	-2.078
2009						-1.624	-337	-19	-163	-2.142
2010						-1.786	-377	-56	-166	-2.384
2011						-2.430	-525	-73	-356	-3.383
2012						-2.598	-560	-74	-524	-3.757
2013						-2.311	-505	-86	-723	-3.625
2014						-2.478	-547	-111	-896	-4.031
2015						-2.381	-515	-82	-1.048	-4.027
2016						-1.680	-356	-102	-1.007	-3.146
2017						-1.347	-272	-122	-1.044	-2.785
2018						-907	-178	-134	-990	-2.209
2019						-1.225	-240	-137	-999	-2.601
2020	-1.114	-203	-133	-756	-2.206	-1.113	-200	-137	-775	-2.224
2021	-1.135	-192	-166	-580	-2.072	-1.933	-357	-110	-687	-3.087
2022	-1.027	-171	-195	-392	-1.784	-2.188	-452	-84	-730	-3.454
2023	-862	-120	-225	-152	-1.359	-2.413	-439	-57	-560	-3.469
2024	-151	45	-241	122	-226	-1.892	-346	-14	-357	-2.608
2025	119	88	-298	150	59	-1.815	-352	-11	-356	-2.534
2026	59	63	-252	138	8	-1.153	-225	-6	-246	-1.630
2027	-1	39	-206	126	-43	-917	-156	-	-	-1.073
2028	-61	14	-160	113	-94	-1.008	-181	-	-	-1.189
2029	-121	-10	-114	101	-144	-1.340	-205	-	-	-1.546
2030	-181	-35	-68	89	-195	-1.645	-281	-	-	-1.925
2031	-206	-38	-65	89	-220	-1.907	-345	-	-	-2.252
2032	-231	-42	-63	90	-245	-2.219	-403	-	-	-2.622
2033	-256	-45	-60	90	-270	-2.460	-471	-	-	-2.931
2034	-281	-48	-58	91	-295	-2.511	-522	-	-	-3.033
2035	-305	-51	-55	92	-320	-2.552	-533	-	-	-3.085
2036	-269	-44	-56	85	-283	-2.582	-545	-	-	-3.126

Year	Climate projection 2022					Reorted values/Climate projection 2024				
	Above ground biomass	Below ground biomass	Dead wood	Soil	Total	Above ground biomass	Below ground biomass	Dead wood	Soil	Total
	1,000 t CO_2-eq									
2037	-233	-37	-56	79	-246	-2.628	-546	-	-	-3.175
2038	-197	-29	-56	73	-209	-2.635	-557	-	-	-3.192
2039	-160	-22	-56	67	-172	-2.662	-559	-	-	-3.221
2040	-124	-14	-57	61	-134	-2.682	-566	-	-	-3.247
2041	-149	-19	-55	56	-167	-2.706	-568	-	-	-3.274
2042	-173	-24	-53	51	-199	-2.715	-574	-	-	-3.289
2043	-198	-30	-51	47	-232	-2.705	-575	-	-	-3.279
2044	-223	-35	-49	42	-264	-2.704	-573	-	-	-3.278
2045	-247	-40	-47	37	-297	-2.700	-570	-	-	-3.269
2046	-246	-39	-45	39	-291	-2.638	-568	-	-	-3.206
2047	-244	-38	-44	41	-286	-2.592	-551	-	-	-3.143

UNIVERSITY OF COPENHAGEN

DEPARTMENT OF GEOSCIENCES AND
NATURAL RESOURCE MANAGEMENT

ROLIGHEDSVEJ 23
DK - 1958 FREDERIKSBERG

TEL. +45 35 33 15 00
IGN@IGN.KU.DK
WWW.IGN.KU.DK