Veteranisation and ring barking in beech forest restoration

A long-term analysis of mortality, dead wood availability, and structural diversity

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Veteranisering och ringbarkning som metoder för att restaurera bokskog

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Abstract

European beech (*Fagus sylvatica*) forests have been heavily altered through centuries of forest management resulting in homogenous stand structures, reduced dead wood availability and a lack of important habitat structures associated with old-growth forests. As the European Union's Nature Restoration Regulation (NRR) is enacted there is an increasing need to evaluate restoration methods capable of accelerating the development of ecologically valuable forest.

This thesis analyses whether veteranisation and mortality inducing treatments can accelerate structural restoration in previously managed beech forest stands. The study was conducted in the nature reserve "Osbecks boksskogar" in southern Sweden where restorative treatments have been applied since 2008. A chronosequense of 39 plots created between 2008 and 2023 were inventoried and analysed together with recently established control plots. The treatments included ring barking, partial ring barking, high stump creation, creation of living high stumps, basal bark damage and artificial cavity creation. Variables related to mortality, vitality, dead wood occurrence, and decay stage were inventoried and statistically analysed.

The results show that veteranisation and ring barking increased structural heterogeneity significantly compared to untreated control plots. Mortality inducing treatments such as ring barking and high stump creation generated substantial amounts of standing and lying dead wood across multiple decay classes. Lower intensity treatments created long-lasting tree related microhabitats and generally generated low mortality in treated trees. Dead wood volume and decay variability increased with time since treatment and treated plots showed greater variation and volume of dead wood than control plots.

The study suggests that veteranisation and mortality inducing treatments can accelerate the development of structural characteristics otherwise associated with natural beech forests and sustain these characteristics over time. They may therefor function as effective restoration techniques for increasing the availability of niche habitat and key dead wood structures in stands previously managed for wood production.

Keywords: Veteranisation, active restoration, beech forest restoration, dead wood availability, dead wood volume, decay stage. Tree related micro habitats.

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Abbreviations

Abbreviation	**Description**
TreMs	Tree related microhabitat
RB	Ring barking
HST	High stump
LHST	Living high stump
PRB	Partial ring barking
BD	Basal damage
NRR	Nature restoration regulation
CF	Continued function

1. Introduction

1.1 Background

1.1.1 EU regulations and forest restoration

As of 2024 the countries within the European Union have voted to accept the proposed Nature Restoration Regulation (NRR), the first continent encompassing EU law of its kind (European Union, 2024). The NRR aims to ensure the long-term recovery of European biodiversity and resilient ecosystems through the restoration of degraded ecosystems, while also contributing to the EU's climate change mitigation and adaptation objectives (European Union, 2024). The NRR stems from several reports which have concluded that 80% of European ecosystems are in decline and vital ecosystem services are under threat (EEA, 2020). Through this regulation the EU strives to ensure the longevity of restoration efforts and compliance with the EU habitat directive (EEA, 2020). To achieve this, member countries are obligated to restore 20% of all terrestrial and marine ecosystems which are under threat of degradation by 2030 and all ecosystems in need of restoration by 2050 (European Union, 2024). For forest ecosystems specifically the trends of decreasing dead wood amounts should be addressed, structural heterogeneity increased and abundance of forest dwelling bird species ensured (European Union, 2024). National restoration plans are to be submitted by September 2026, and progress monitored and recorded (European Union, 2024). Member countries must ensure that the identified habitats and species which need restoration (according to the 1992 species and habitat directive) are addressed within the time frames set by the NRR. In this way the regulations operationalize the species and habitat directive, ensuring that member states actively work with and secure the goals of the directive (European Union, 2024).

Sweden, as other member states, is legally bound to ensure the application of the NRR into national targets for biodiversity and habitat conservation (European Environment Agency, 2020). Given the urgent policy demand for forest restoration under the NRR there is a need to evaluate whether active interventions can accelerate the development of ecologically significant forest structures.

1.1.2 Beech forests: Current state in Europe and Sweden

Beech (*Fagus sylvatica*) is an autochthonous species to the European continent and serves as an important host for many endemic species, about 14-15 Mha of beech forest exists in Europe today (Brunet, Fritz and Richnau, 2010). Beech forests have for extended periods of time been subject to human interference, largely due to many major developing civilizations historically emerging in the European continent (Kirby and Watkins, 2015). This has altered the state of these forests to such an extent that "natural" or old growth beech forest are rarely found in the landscape today (Hahn and Fanta, 2001). Heterogenous uneven aged stands have turned homogenous through centuries of logging and wood commodity production. Today, European beech forests are among the most altered forest ecosystems in the world (Hannah, Carr and Lankerani, 1995). Because of conventional forest management aimed towards wood production, many natural beech-forest have been converted to even aged stands suffering from light deficiency and an absence of dead wood (Hannah, Carr and Lankerani, 1995). These stands lack structural variability and many of the components found in older beech forests, due to this, they are less biologically diverse. Consequently, what little intact relic old growth beech forest serves as important benchmarks for naturalness (Rugani, Diaci and Hladnik, 2013).

In Sweden beech forests are at their climactic edge and their northern distribution is limited by occurrence of spring frosts (Bolte, Czajkowski and Kompa, 2007). This confines beech to the southern parts of the country where it alongside the English oak (*Quercus robur*) is host for the highest species abundance attributed to any tree species in the Swedish nemoral zone (Jonsell, 1998). The remaining natural beech forest fragments are however few and sparingly situated in the southern Swedish landscape (Brunet, Fritz and Richnau, 2010). To reprimand the lack of beech forests available with high conservation values there has been an increase in the conservation of younger forest previously managed with contemporary beech forest management (Niklasson, 2017). By examining the dynamics of natural beech forest, we can better estimate the desired goals for restoration.

1.1.3 Beech ecology: Succession and disturbance dynamics

European beech occurs on a wide range of soil types, including base-rich calcareous rendzic leptosols and acidic podzols, as well as cambisols and fertile luvisols (Peters, 1997). They reach heights of up to 40 meters in favourable environments and can in closed canopy conditions become 100-150 cm at breast height (DBH) regularly reaching ages of 200-300 years (Peters, 1997). Beech is shade tolerant, often becomes the dominant species in monocultural stands. Their dense canopies inhibit the regeneration of other species causing a self-reinforcing cycle of regeneration (Brunet, Fritz and Richnau, 2010). Beech seedlings can survive suppression well and re-establish their growth once sufficient light is available (Peters, 1997).

As previously established beech forest have been altered heavily throughout history, mainly by wood commodity production and rational forest management (Brunet, Fritz and Richnau, 2010). Studies conducted in the relic fragments of natural beech forest have however increased our understanding of disturbance regimes and successional patterns. Beech forests rely on small-scale, low severity gap dynamics for regeneration, older trees break or die creating canopy gaps where young seedlings can establish (Trotsiuk, Hobi and Commarmot, 2012; Hobi et al., 2015; Rugani et al., 2013). Background mortality rates among trees in natural beech forest have been observed as 0.25% - 1% yearly (Hobi et al., 2015; Ruhoni et al., 2013). Stem density in natural European beech forests typically ranges from approximately 100 to 400 trees per hectare in mature stands, with lower densities in old-growth phases due to self-thinning and disturbance processes (Standovár and Kenderes, 2003; Hobi et al., 2015). The predominant disturbance is attributed to wind, where old trees tend to have stem rot which increases the chances of stem breakage and the creation small single tree gaps (Trotsiuk, Hobi, and Commarmot, 2012). Snow can also create similar stem breakages but is less common (von Oheimb et al., 2005). These processes create spatially heterogenous mortality processes where the accumulation of dead wood and recruitment of new seedlings occurs unevenly across the forest. Similar patterns have been seen in Sweden at the natural reserve “Biskopstorp” where beech trees of advanced ages have begun to fall apart due to rot (Fuentes et al., 2010).

In contrast to the small-scale gap dynamics characteristic of natural beech forests, managed beech stands are typically shaped by even aged silvicultural systems based on cohort harvesting with shelterwoods driving natural regeneration (Hahn and Fanta, 2001). Such practices replace gradual, small-scale gap dynamics with large-scale cohort harvesting. Consequently, managed stands often lack canopy gaps, structural heterogeneity, and the dead wood that defines natural beech forest dynamics. The continuity of small canopy gaps is interrupted, and the development of tree-related microhabitats associated with ageing and decay is substantially reduced. Understanding these processes is essential when evaluating restoration strategies aimed at reintroducing structural variability.

1.1.4 Dead wood in temperate beech forests

Dead wood serves many important ecological functions in temperate European beech forest. Substantial dead wood logs act as storage for nutrients and water while also binding large amounts of carbon (Zumr et al., 2023; Martin et al., 2021). They provide habitat for many taxonomic groups; vascular plats, bryophytes, lichens and saproxylic beetles, among others (Christensen et al., 2005; Gao et al., 2015). The structure of the dead wood is of particular importance as different species rely on different stages of decay, and dead wood structure for habitat (von Oheimb et al., 2007). Saproxylic beetles for example show a larger diversity in standing dead wood snags compared to laying logs (Zumr et al., 2023). Consequently, the variety and availability of dead wood is important for the biodiversity in beech forests. Managed stand often lacks dead wood across all stages and sizes but particularly larges logs as these often are removed at harvesting (Christensen et al., 2005). Von Oheimb et al (2007) suggests that dead wood in natural beech forests occur in large quantities and across many stages of decay and that the structural complexity in managed beech stands is limited in comparison. Therefore, analysing the outcomes of restorative action on dead wood variability and amount is of particular importance. Examples of restoration outcomes on deadwood can be seen in figure 1.

Figure 1: Standing and lying dead wood created by restoration treatments at the study site. Tree pictured on the right was treated in 2008 and on the left in 2013.

1.1.5 Conservation through active or passive restoration

Traditionally ecologists have conserved valuable ecosystems by setting them aside, passively letting them recover or sustain their ecological function, for example in nature reserves or national parks. This could either be considered conservation or passive restoration given the goal of the application. Either letting an ecosystem recover its function and return from degradation over time (passive restoration by removing human interference) or preserves an ecosystem in a given state of natural processes (conservation) (Holl and Aide, 2011; Hunter et al., 2021). These approaches are the most suitable for ecosystems that are not severely degraded and have retained intact disturbance regimes, they are most commonly applied in areas that already possess high ecological values (Hunter et al., 2021). While a passive approach may, over time, produce satisfactory results and sustain biodiversity, the uncertainties associated with anthropogenic climate change and accelerating biodiversity loss introduce significant complexities. Will the current state of a preserved ecosystem be able to adapt to new climatic conditions?

Active restoration measures, conversely, aim to restore or rehabilitate ecosystems through direct intervention (Holl and Aide, 2011). An ecosystem that has undergone degradation, such as land-use change, intensive forestry, or habitat fragmentation, may lack the structural complexity and regenerative capacity required for natural recovery. By implementing an active approach to restoration, conservationists can restore the key ecosystem functions required for the re-establishment of ecological processes (Holl and Aide, 2011).

Previously managed single-story beech forests would, given enough time, likely recover aspects of their small-scale gap dynamics and structural heterogeneity. Natural mortality, windthrow, and other small-scale disturbances would gradually reintroduce structural complexity. However, from a human-centered perspective, this process may unfold over many decades or centuries (von Oheimb et al., 2005). During this time, the forest may remain characterized by even-aged structure, limited dead wood availability, and reduced habitat diversity. If conservation goals prioritize the recovery of biodiversity within shorter timeframes, active interventions may accelerate the development of late-successional structures (Holl and Aide, 2011).

1.1.6 Veteranisation: Techniques and intended outcomes.

Ancient trees fulfil many important functions in forest ecosystems and are often described as habitat trees, as they provide specialised and often rare habitat (Bütler et al., 2013). Over time, trees are subject to disturbances that can cause stem and branch damage, leading to the formation of features such as cavities, cracks, broken branches, hollows, and stem rot (Lindenmayer, 2017). These structural components are referred to as tree related microhabitats (TreMs) and serve as important habitat for many taxonomic groups (Bütler et al., 2013). Trees with these features have a disproportionately large impact on the biodiversity of a forest (Lindenmayer, 2017). They are, however, rare in the landscape, resulting in a lack of available habitat (Lindenmayer, 2017).

As an active restoration approach, veteranisation has emerged as an experimental management option striving to artificially mimic the natural processes which generate TreMs and reduce the delivery time of important habitat trees (Bengtsson et al., 2012). By mimicking damaging agents' managers can through veteranisation artificially create habitat in young trees usually reserved for their older counterparts. This also aims to expedite the process of degeneration, influx of dead wood and creation of TreMs. Several studies have been conducted to establish a connection between veteranisation and increased biological diversity and natural structural characteristics. Results from oak veteranisation experiments demonstrate that freshly veteranized trees can rapidly attract diverse and abundant communities of saproxylic beetles, including threatened species, already within the first year following treatment (Čížek et al., 2024). There is however a lack of research regarding the effects of veteranisation on different taxonomic groups in beech forests. A 2014 report by Lindström (2014) did, however conclude the feasibility of artificial cavities as habitat for saproxylic beetles in beech, as he found a higher abundance of species in artificial cavities compared to natural ones.

1.2 Problem description

The restoration of valuable and degraded ecosystems is increasingly recognised as a global priority, the practices used to achieve these goals must be evaluated and improved. As the new nature restoration regulation is enacted, Sweden, along with other EU Member States, is obligated to ensure that national restoration efforts comply and are effectively executed.

As natural and old beech forests are rare the species which depend on those conditions are threatened by the lack of available habitat (von Oheimb et al., 2007). Consequently, as a mean to ensure the existence of the forest type in the future, many previously managed beech forests have been increasingly protected through formal protection (Niklasson, 2017). Unfortunately, these stands exhibit little of the complex habitat structures needed to ensure the continuation of associated species (Hannah, Carr and Lankerani, 1995). If we believe the need for available habitat is urgent then active restoration measures are needed to expedite this process.

The study site for this thesis, Osbecks boksskogar has been subject to restoration over a 17-year period where veteranisation and mortality inducing techniques have been applied in even aged stands. This thesis analyses a chronosequense of established plots (2008, 2013, 2018, 2023) to determine the effectiveness of restoration at delivering key habitat structures. To achieve this, single tree variables such as mortality, vitality, decay stage and the continued function of trees within the stand (standing or lying), were inventoried and analysed. A visual example of a treated plot can be seen in figure 2.

Figure 2: Plot from the study site in which veteranisation and ring barking was used as a tool for restoration in 2013.

Hypothesis:
Active restoration through veteranisation and mortality inducing treatments lead to structural changes which have increased habitat heterogeneity in Osbecks bokskogar nature reserve faster than would have occurred in unmanaged even-aged stands. This has shifted stand conditions closer toward those found in naturally disturbed beech forests.

1.3 Purpose and scientific questions

The aim of this thesis is to better understand whether veteranisation can accelerate structural restoration in previously managed beech stands by comparing treated plots with untreated control plots and by relating observed stand characteristics to published benchmarks from naturally disturbed beech forests.

1. Have mortality-inducing treatments and veteranisation increased dead wood volume and the variety of decay stages in treated plots?

2. How has mortality inducing treatments and veteranisation altered dead wood structure (standing/lying) over time following the treatments?

3. How has the vitality and mortality of veteranized trees developed over time following the treatments?

1.4 Delimitations

This thesis evaluates the effectiveness of the restoration measures implemented in Osbecks boksskogar by examining resulting structural characteristics. The study focuses exclusively on structural indicators and does not include inventories of taxonomic groups.

Furthermore, the study is spatially limited to the study area within Osbecks boksskogar. While the findings may provide insights relevant to restoration practices in other beech forest stands, broader generalisations should be made with caution.

2. Methods

2.1 Site description and restoration model

The study site is part of a larger nature reserve in southern Sweden called Osbecks boksskogar situated in Halland county. The reserve was established in 2008 with the intention to protect a series of woodland key habitats and important natura 2000 habitat types as a single large piece of protected land (Länsstyrelsen Hallands län, 2008). The northern slope of the ridge Hallandsåsen on which Osbecks boksskogar is located has been recognized as one of the most important areas in the county regarding the protection of rare species and unique habitat (Länsstyrelsen Hallands län, 2008).

The study site consists of several even-aged stands located within a 24-ha subsection of the reserve. These were previously managed through conventional forestry means and regenerated through natural regeneration. Consequently, they exhibit structural attributes typical of industrially managed beech forests, including limited light availability, lacking tree related horizontal/vertical structures and minimal recruitment of new seedlings. A previous tree age inventory of Halland county's beech forests completed in 2003 determined that the time of establishment for Osbecks boksskogar ranged from the beginning of the 1800s to the 1920s (Niklasson, 2003). The studied stands are in the younger section of the forest, making the dominant trees approximately 100-120 years old (Fig 3).

Figure 3: Veteranized plot from 2023 representing current stand conditions of the study site.

By restoring the even aged stands the managers strive to increase the amount of habitat available for rare beech forest related species found in the nearby woodland key habitats. The goal is to simulate disturbance similar to the natural small scale disturbance dynamics found in natural beech forests. This process strives to increase the availability of light, dead wood and occurrence of rare tree related microhabitats. The model was first implemented in 2008 the same year as the reserve was established and has since then resulted in four management interventions conducted at approximately five-year intervals. During each intervention, ten sites of varying size and irregular spatial distribution were subjected to veteranisation and ring barking using different treatment methods. The plot distribution and sizes within the study site can be seen in Figure 4.

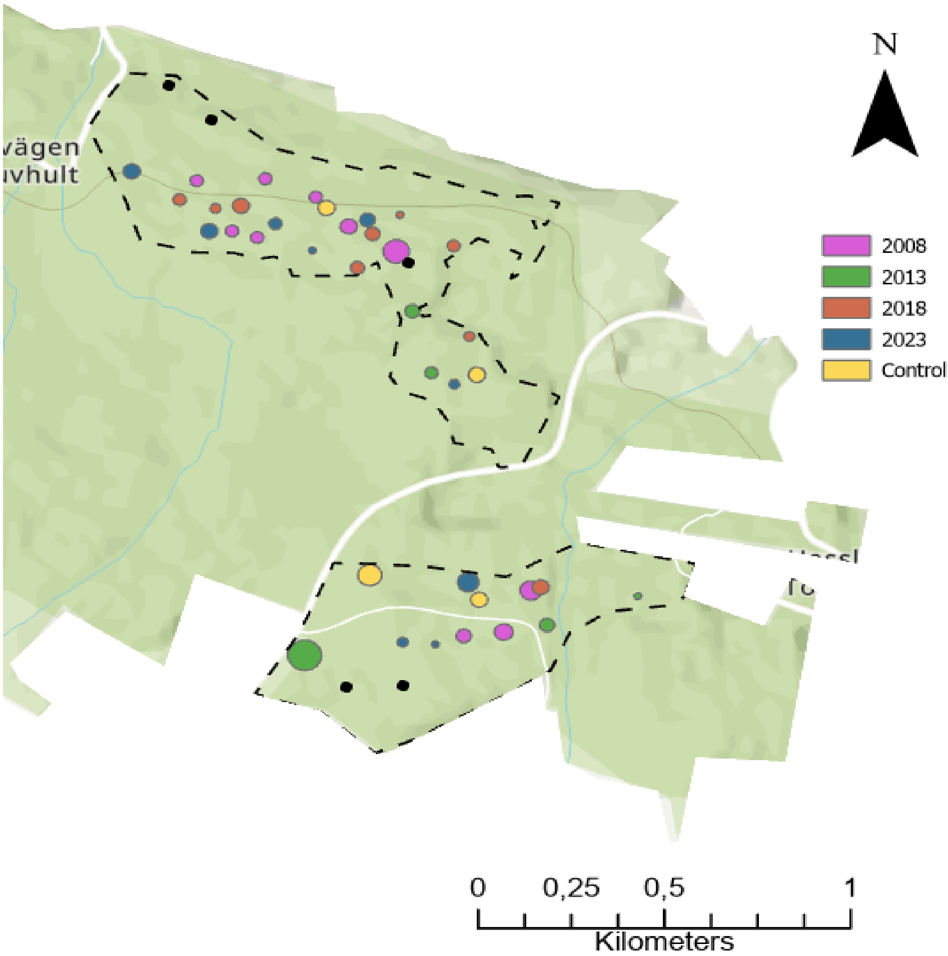

Figure 4: Plot distribution across treatment years with proportionally accurate sizes in m^2. Black dots are the location of the five plots from 2013 that do not have accurate size estimations. Dotted boarder outlines the treated compartment within the reserve.

2.2 Ring barking and veteranisation

In each plot both ring barking and veteranisation techniques have been used. Ring barking has the intent to kill the tree quickly resulting in a rapid increase of dead wood and light, while veteranisation techniques are used to create rare tree related microhabitats which remain in the stand for long periods of time (Table 1). Pictures of all treatments and their development can be seen in Appendix 1.

Table 1: Description of mortality inducing and veteranisation techniques used in Osbecks boksskogar and their intended outcomes.

Technique	Description	Intended Ecological Function
Complete ring barking (RB)	Removal of bark around the entire circumference of the stem.	Creates standing dead wood that may later fall and contribute to lying dead wood.
Creation of high stump (HST)	Trunk cut at several meters above ground level with no branches below the damage.	Instantaneously creates standing dead wood high stumps and logs which fulfils many ecosystems functions.
Partial ring barking (PRB)	Removal of bark from part of the stem circumference	Induces gradual decline in vitality making the tree more susceptible to biotic damaging agents which eventually can kill the tree.
Creation of living high stumps (LHST) .	Trunk cut at several meters above ground level with one or several live branches below the cut.	Provides habitat for saproxylic organisms, cavity-forming species and lowers the canopy, creating a multi layered forests structure.
Basal bark damage (BD)	Mechanical damage applied low on the stem to simulate herbivory or physical damage	Initiates decay processes and promote microhabitat formation reducing vitality.
Artificial hollow creation (Cavity)	Deliberate carving of cavities in the trunk	Accelerates the development of the rare tree-related microhabitats stem cavities and introduces rot into the tree thereby influencing vitality.

2.3 Study design

The thesis is a quantitatively based on data collected from the veteranized plots within the study site, the collected data was later analysed with the intended purpose of answering the scientific questions. The data was further compiled into excel files which were structured for use in R-code. The inventory took place over a 2-week period during the summer of 2025 and the compilation and analysis during the spring of 2026.

Between 2008 and 2023 40 plots were treated according to established management plans. As the plots were restored at approximately 5-year intervals the results will be treated as a chronosequense. Out of 40 plots, 39 plots could be re-located during the inventory, and 4 new control plots were established. Each treated tree within each plot was examined according to an inventory protocol. Variables include vitality, decay class, and the continued function of the tree within the stand.

Originally, at the time of plot establishment, each plot was measured using a central reference point, from which trees were located and identified based on their compass bearing and distance from the centre. Tree selection began at 0° (north) and proceeded sequentially in a circular pattern around the plot (Fig 5). For the current inventory this data could be used to locate the position of veteranized trees using compass bearing.

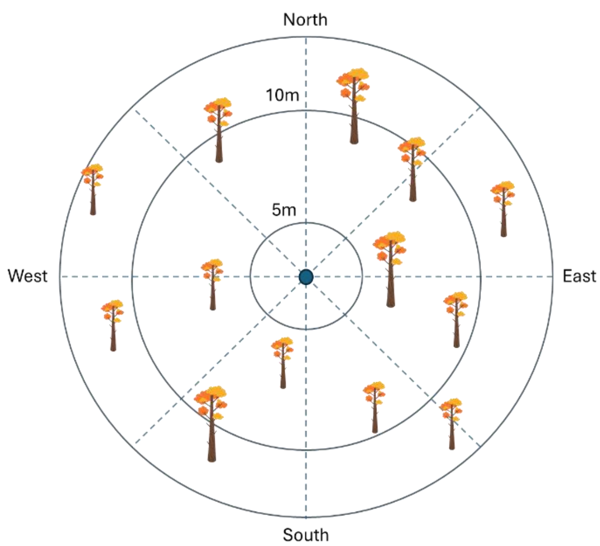

Figure 5: Original plot inventory procedure used at the time of establishment.

2.4 Control plot establishment

To ensure comparability to existing natural dynamics 4 control plots were established in 2026. These were inventoried following the same procedure as the veteranized plots. Control plots were semi-randomly placed within untreated sections of the stand while considering the proximity to other treated plots. Three plots were established with a 500 m^2 size and one as 1000 m^2 to account for larger outliers found in already established plots. In the control plots, all dead trees were noted and their time of death estimated based on the stage of decomposition, a subjective method but based on the observers experience with inventorying decaying trees in the treated plots with known treatments years. Height and circumference of each tree in each control plot was measured, to then be able to estimate the volume of dead wood and living trees. Control plots were established after the initiation of the veteranisation treatments due to the fact that the plots were originally not intended to be used in a scientific study.

When comparing across years the newly established control plot was assigned to a specific treatment year to better understand the effect and increase comparability. For example, control plot 4 was assigned to the treatment year 2023 and thus the almost fully decomposed tree found in control plot 4 was removed from the result because its death could not have been a product of the treatment started in 2023. In total 4 trees were omitted from the data based on their decay stage.

2.5 Data collection of single tree variables

2.5.1 Decay class

To get a better understanding of the introduced process of decay following veteranisation treatments each tree was subject to a knife test where the tip of a blade was inserted into the stem of the tree with an even force. The depth of which the blade could penetrate determined the decay class the tree was recorded in. This approach, while being semi-subjective is regularly utilized in large scale forest structure inventories such as national inventories in both Norway and Finland (Liepiņš et al., 2023). It has also been used in several published works regarding dead wood distribution patterns (Hottola and Siitonen, 2008; Ekblad, 2015). While it will not reach the precision of measuring density in a lab or using tools such as a penetrometer, it can be exact enough to showcase the variable structure of dead wood present in the studied forests (Larjavaara and Muller-Landau, 2010). The national inventories in Finland use a 5-class system but as many stems fell outside the scope of these categories a sixth was used, as was similarly done by the authors Jenni Hottola and Juha Siitonen (2008). While it should be noted that similar methods have largely been used in boreal ecosystems it has also been used as an indicator of tree degradation through decay in temperate broadleaved forests (Dhiedt et al., 2019; Lombardi et al., 2008). The decay classes are defined as the following (Table 2):

Table 2: Description of decay classification.

Scale	Definition
1	Hard, blade enter only a few mm
2	Relatively hard (1-2 cm)
3	Relatively soft (3-5 cm)
4	Soft throughout (uniformly soft)
5	Very soft (mouldable)
6	Nearly fully decayed, partially buried

On a standing dead tree, the test was performed on three points around the stem whereas on lying dead wood the test was performed three times along the stem. For the cavity treatment the test was used to assess the rot within the cavity itself. For trees which both had standing dead wood and laying dead wood an assessment was done for both parts of the tree. A representation of all decay classes can be seen in appendix 2.

2.5.2 Vitality class

Vitality was determined using an ocular inspection of the crown leaf area intactness, the more defoliated a tree was the higher the vitality score. Defoliation has been recognized as a good indicator for single tree vitality (De Vries, Klap and Erisman, 2000). Using defoliation as a proxy for vitality has been adopted by the EUs ICP protocol for European forest health (ICP Forests, 2023). Several published works have utilized the same set of parameters for assessing vitality conditions (Dobrowolska et al., 2017; Ognjenović et al., 2022). The original method determines vitality uses 5% increments of defoliation in the crown, in this case we have grouped the 5% increment scores into 5 classes for ease of estimation and precision in the field inventory as previously done by Dobrowolska et al., 2017 (Table 3).

Table 3: Description of vitality classification

Scale	Definition
1	Excellent (0-10%)
2	Good (15-25%)
3	Fair (25-60%)
4	Poor (60-95%)
5	Dead or Nearly Dead (96 -100%)

2.5.3 Continued function

Each inventoried tree was catalogued according to its continued function (CF) in one of four categories. This includes standing trees which are alive (1), standing trees which are dead (2), lying dead wood (3) and trees which have broken in the middle and exhibits a standing/laying structure (4). Trees that are in category 4 had a minimum standing dead wood section of 3 m.

2.6 Plot size estimation

As plot sizes were unavailable due to the irregular spacing of veteranized trees among living trees, the area of each veteranized plot was estimated based on the spatial distribution of treated trees. The distance and angle of each treated tree (ring barked or veteranized) from a central reference point were recorded during plot establishment (Fig 4.). These measurements were converted to x and y positions using sine and cosine functions. In R (Version 4.6.0; R Core Team, 2026) a convex hull function from the package *sf* was used to delineate the minimum convex polygon enclosing the outermost treated trees (Pebesma, 2018). Convex hull algorithms are often used in ecological studies to estimate the spatial extent of habitat ranges, for example Zhang, Liu and Di Marco (2026). The *st_convex_hull* function calculates the most effective spatial size of each plot and the square meter (m^2) size of this polygon. This is referred to as the plot size and is used to estimate hectare values for the collected variables.

As the convex hull function uses the most effective size of the spatial area which contains all trees it later overestimates the volume of dead wood when these are scaled to hectares. As such a 1 m buffer was applied to the estimated hull area to reduce this effect on hectare value conversions. The result is presented with variance which describes the volume with a 2 m buffer and compared to the volume with no buffer (Fig 6.).

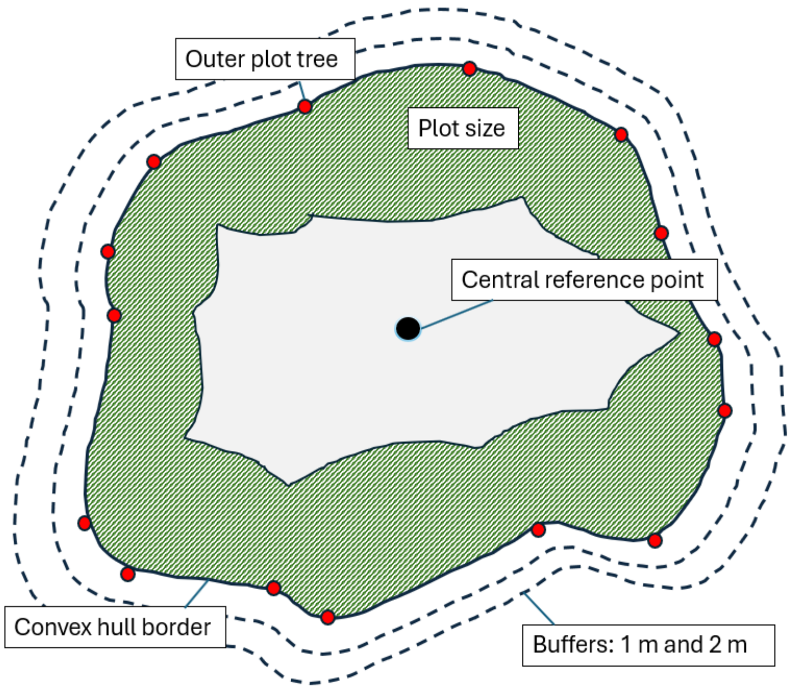

Figure 6: Visualisation of plot size estimation and included buffers for the convex_hull function.

2.7 Materials

The inventory needed basic tools to determine the state of the veteranized trees according to the above introduced inventory variables.

The knife test was performed using a 10 cm long and 2 mm thick blade. The same knife was used for each tree and an even pressure applied.

The height of each tree within the control plots were measured using a Vertex model 3. This tool has been recognized as both easy to use and quick (Božić et al., 2005). For smaller diameter trees a 4 m stick was used with marked 1 m increments to estimate the height, a method similar to telescopic measuring poles used in forest inventories.

2.8 Data analysis

2.8.1 Tree variable proportion

Proportion of trees within different decay classes, vitality classes and function is displayed as a percentage of available trees within each class. The percentage was calculated by counting the number of stems for each variable and dividing it by the total number of stems in that year.

$$Proportion_{\{class\}} = \{Number\ of\ stems\ in\ class\}/\{Total\ stems\ in\ treatment - year\}$$

The resulting figures was created using the function ggplot2 (Wickham, 2016)

2.8.2 Height function

In each plot the circumference of the stem was measured at breast height at the time of treatment with the exception of 5 plots from 2013 where circumference measurements are missing along with 1 plot from 2018 which could not be located in 2025. In the control plots the circumference was measured at the time of establishment (2026) and height was calculated for each tree in the plot using a Vertex III. The vertex was used with a 20 m distance from the base of the stem and ultrasonic transmitting to calculate the height. Smaller stems (10-15 m in height) were estimated using a measured 4 m stick with 1m intervals market, a rudimentary version of telescopic pole often used in forest inventories. This stick was placed at the bottom of the stem and the measurer backed up and visually estimated the height based on stick length. Circumference was later re calculated to diameter at breast height (DBH).

A logarithmic regression was applied in excel to model the relationship between DBH and heights in the measured control plots. The relationship between height and diameter in control plots fit better in logarithmic trend lines (r2 = 0.76) than in linear (r2 = 0.61). The function predicted heights in unmeasured trees based on the available model relationship in the control plots.

2.8.3 Dead wood volume estimations

Individual tree stem volume was estimated using the beech volume equation presented by Hagberg and Matérn (1975) as was previously done by the authors Nordén et al (2004) to estimate dead wood volumes of beech.

$$\mathrm{VS} = 0.01275\mathrm{D}^2\mathrm{H} + 0.12368\mathrm{D}^2 + 0.0004701\mathrm{D}^2\mathrm{H}^2 + 0.00622\mathrm{DH}^2$$

where *VS* is stem volume (dm^3), *D* is diameter at breast height (cm), and *H* is tree height (m). Diameter was measured in the field, while tree height was measured for the control plots and heights assigned to unmeasured trees using a logarithmic regression function.

Only trees recorded as dead were included in the dead wood analysis. Each dead tree was assigned to a rot class based on field assessments, and the estimated stem volume was allocated to its corresponding decay class. For each plot, dead wood volume was summed within each rot class. It should be noted that because 5 plots from 2013 are missing circumference measurements they are not included in volume summarised as the logarithmic relationship between height and diameter could not be used on this occasion.

Because plot sizes differed among years, plot-level volumes were standardized to a per-hectare basis. Dead wood volume per hectare (m^3/ha) was calculated as:

$$V_{ha} = \frac{V_{plot}}{A_{plot}}$$

where *Vha* is dead wood volume per hectare, *Vplot* is the summed dead wood volume within a plot, and *Aplot* is plot area (ha).

The values were summarized by treatment, inventory year, and rot class. All volumes and rot classes are presented as either standing or lying dead wood indicating the current amounts of the two structures. Finally trees which were recorded as category 4 (standing/lying) in the continued function categories were when presented as volumes divided evenly across the categories standing and lying. The resulting figure was created using the function ggplot2 (Wickham, 2016).

2.8.4 Mortality per treatment

The total mortality (TM) for a given treatment was calculated as the number of trees alive at the start of the period (Ntotal) divided by the number of dead trees at the latest inventory (Ndead) using:

$$TM = \frac{N_{dead}}{N_{total}}$$

This was done for each treatment in each year from which an annual mortality was produced by dividing that year's total mortality with the number of years since treatment was applied.

2.9 Statistical analysis

The data is structured as a chronosequence and not a true time series. To better understand the effects of treatments across years, several statistical tests were run in the program R (Version 4.6.0; R Core Team, 2026). The study considers several response variables within different categories all listed below. Table 4 provides an overview of the statistical models run and their model variables.

Table 4: Summary of statistical models and their attributes.

Response variable	Variable & level	Independent variable	Random effect	Model / test	Research question
Decay stage (standing dead wood)	Ordinal (1-6) Tree-level, nested in plots	Time since treatment (years)	Plot ID	Cumulative link mixed model (CLMM)	1
Decay stage (lying dead wood)	Ordinal (1-6) Tree-level, nested in plots	Time since treatment (years)	Plot ID	Cumulative link mixed model (CLMM)	1
Mortality	Binary (1/2) Tree-level, nested in plots	Treatment type	Plot ID	Generalized linear mixed model (GLMM)	3
Vitality	Ordinal, aggregated to plot-level mean	Time since treatment (years)	-	Spearman's rank correlation	3
Continued function	Proportion per plot	Time since treatment (years)	-	Spearman's rank correlation	2
Dead wood volume	Continuous (m^3/ha), summed per plot	Time since treatment (years)	-	Spearman's rank correlation	1

Decay stage

Decay stage is analysed on a tree level and is therefore nested within plots. The aim of the analysis was to see if there was a general increase or decrease along the chronosequense. Because of decay stage's ordinal nature (1-6), it was tested using a cumulative link mixed model (CLMM) with a logit link function from the package "ordinal" which can account for non-independence among trees using random effects (Christensen, 2024). It was also divided into standing and lying dead wood before analysis and consequently two CLMM models were fitted.

Decay stage utilized the "time since treatment" as a fixed effect and plot ID as a random effect. Time since treatment is defined as the number of years since the treatment was applied using the time of the inventory (2025) as a baseline. The rational for time since treatment as a fixed effect was tested with a comparison to a null model using a likelihood ratio test (LRT), this concluded that time since treatment improved fit. Random effect necessity was also determined by an LRT test against a non-mixed model (CLM vs CLMM). The random effect LRT confirmed that for standing deadwood including random effect improved model fit but for lying deadwood the same relationship was non-significant. The structure of the CLMM was however kept for both variables to remain consistent throughout the analysis.

After fitting the models, tests were run to assess whether decay stage passed or failed the proportional odds assumption (POA). Decay stage for both standing and lying dead wood pass the assumption. This means that for decay stage, the effect of time since treatment on the probability of being in a higher category is consistent across all thresholds. To control for family wise error inflation the p-values were adjusted using Holm-Bonferroni method (Holm, 1979). The CLMM model answers if the probability of moving into a higher decay stage category increases with time since treatment while accounting for non-independence for trees within plots. Full statistical output can be found in Appendix 3.

Mortality

Mortality was also analysed on a tree level using a generalized linear mixed model (GLMM) with a logit link function. The GLMM was considered appropriate because the mortality variable is binary (Living/Dead) and trees are nested within plots. Therefor a mixed model was used as it can account for non-independence among sampled trees. The model was fit using the package "lme4" (Bates et al,. 2015). Treatment type was used as a fixed effect with the control treatment mortality as a reference category and plot ID as a random effect. This structure was tested using an LRT against a null model which confirmed that treatment as a fixed effect improved model fit. Similarly random effects necessity was verified by an LRT against a non-mixed model fit to the same dataset (GLM vs GLMM). Furthermore, the package "DHARMa" was used to evaluate model fit testing uniformity, dispersion, and outliers all of which were non-significant (Hartig 2026). The model answers which treatments differed significantly in mortality compared to control. To address family wise error inflation a post-hoc Dunnett's adjustment was applied (Dunnett, 1955). Full statistical output can be found in Appendix 4.

Vitality, continued function, and dead wood volume

The response variables vitality, continued function (CF) and dead wood volume were all analysed using a non-parametric spearman's rank correlation found in the core stats package in R (Version 4.6.0; R Core Team, 2026). To standardize the analysis, each response variable was summed to plot level values and evaluated against time since treatment (years) as the independent predictor variable. Time since treatment gave us four distinct timestamps cohorts across the 17-year period.

1. *Vitality:* Ordinal vitality scores were aggregated to plot level means for each individual plot.
2. *Continued function:* Each category was standardized as a proportion within each plot.
3. *Dead wood volume:* Total dead wood volume was converted to m^3/ha to account for plot size variation and summed per plot to calculate the aggregate dead wood volume.

Vitality and dead wood volume display monotonic trends after visual assessment meaning they are suitable for the analysis using Spearman's rank correlation. CF however had some caveats. CF category 1, 3 and 4 were monotonic meaning they can be assessed with a spearman's rank correlation. However, standing dead trees (category 2) showed a non-monotone relationship with time since treatment and was therefore excluded from Spearman's rank correlation analysis. The pattern is instead described visually in Figure 8. Family wise error between response variables was controlled using Holm-Bonferroni method for CF categories (Holm, 1979). Plot vitality and total dead wood volume, however, remained unadjusted as they address separate research questions and were single tests. Full statistical output can be found in Appendix 5.

A significance level of $\alpha = 0.05$ was used for all tests.

3. Results

3.1 Treatment effects on vitality

A spearman's rank correlation revealed a significant increase of higher mean vitality classes in each plot given time since treatment ($\rho = 0.64$, $p < 0.001$), indicating a decreasing vitality trend along the chronosequence. Figure 7 suggests that the proportion of trees within different vitality classes changed over treatments and years. Based on a visual assessment of the figure, some treatments seem to have generated a large impact on vitality whereas some had little effect.

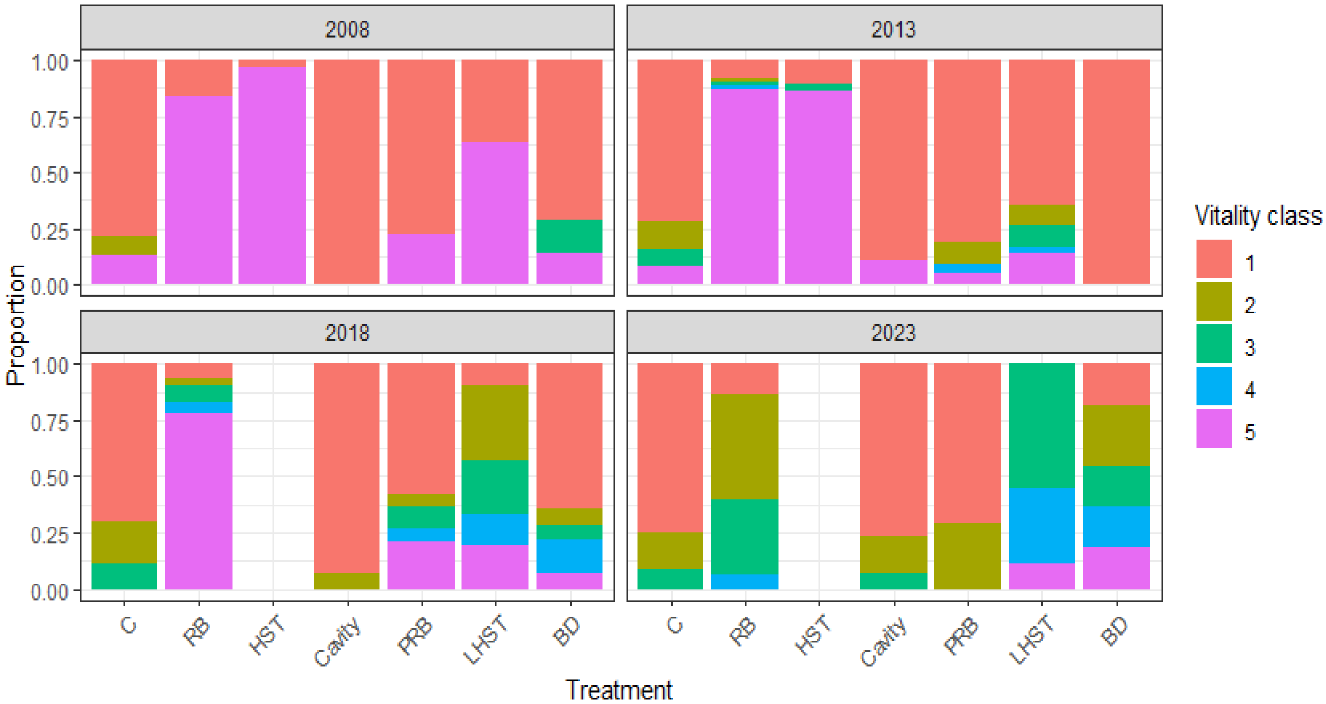

Figure 7: Proportion of vitality classes in treatments across years. On the x axis treatments are displayed as abbreviations; C = Control, RB = Ring barking, HST = Hight stump, PRB = Partial ring barking, LHST = Living hight stump, and BD = Basal damage.

3.2 Treatment effects on mortality

The result from the GLMM model indicate that tree mortality differed significantly among veteranisation treatments. Both mortality inducing treatments (HST and RB) had a significant impact on mortality relative to control (HST;OR = 194.74, $p_{adj} < 0.0026$, RB; OR = 59.79, $p_{adj} = 0.0024$). Veteranisation treatments such as artificial cavities, basal damage, partial ring barking and living high stumps did not have a significant impact on mortality compared to control (Appendix 4)

Ring Barking (RB)
The ring barking treatment (RB) had a total mortality percentage in the years 2008-2018, ranging between 78.6% and 86.7% (Table 5). The year 2023 in the same treatment had a 0% mortality rate. The annual mortality rate ranged between 6.7% and 9.8% per year during 2008-2018.

Hight stump (HST)
The high stump (HST) treatment had an induced mortality rate of 97% from the treatments conducted in 2008 and 86.5% for the 2013 treatment year (Table 5). The treatment was only performed during these two years.

Partial ring barking (PRB)
The partial ring barking treatment had a lower mortality than both the RB and the HST treatment ranging between 5% and 22% total mortality for 2008-2018. The year 2023 had 0% mortality of partially ring barked trees (Table 5). The annual mortality of partially ring barked trees ranged from 0.4% to 2.1%.

Living high stumps (LHST)
The living high stump treatment had a wide variation in total mortality (TM) across treatment years, ranging from 10%-63.2% between 2008 and 2023. The range is high when compared to the partial ring barking treatment. Although 2008 has a higher mortality than the other years in the treatment (Table 5).

Artificial cavity
The artificial cavity treatment was the treatment with the lowest mortality across treatment years. In total 3 out of 86 trees died in the cavity treatment (Table 5).

Basal trunk damage (BD)
The basal trunk damage treatment ranged from 0%-18.2% mortality. The year 2023 had the highest mortality and 2018 the second highest (14.3%) (Table 5). Annual mortality ranged from 0.8% to 6% (Table 5). It should be noted that the BD treatment had very few trees in the treatment group.

Control
The control plots exhibited a low mortality across all plots, Plot 1 (C1) which is attributed to the year 2008 had a total mortality of 13% which corresponds to 3 out of 23 inventoried stems. Plot 2 (C2) which corresponds to 2013 had a TM of 4% which is 1 out of 25 stems (Table 5). The other two plots showed no signs of dead trees.

Table 5: Description of mortality across treatments and cohort years. ; C = Control, RB = Ring barking, HST = Hight stump, PRB = Partial ring barking, LHST = Living hight stump, and BD = Basal damage. TM = Total mortality

Date	Treatment	Ndead_trees	N_trees	Annual_mortality	TM
2008	HST	33	34	5.4%	97.1%
2013	HST	32	37	6.7%	86.5%
2008	Cavity	0	20	0.0%	0.0%
2013	Cavity	3	20	1.2%	15.0%
2018	Cavity	0	15	0.0%	0.0%
2023	Cavity	0	31	0.0%	0.0%
2008	LHST	12	19	3.5%	63.2%
2013	LHST	6	42	1.1%	14.3%
2018	LHST	4	21	2.4%	19.0%
2023	LHST	1	10	3.3%	10.0%
2008	PRB	8	36	1.2%	22.2%
2013	PRB	1	21	0.4%	4.8%
2018	PRB	3	19	2.0%	15.8%
2023	PRB	0	17	0.0%	0.0%
2008	RB	47	56	4.7%	83.9%
2013	RB	52	60	6.7%	86.7%
2018	RB	66	84	9.8%	78.6%
2023	RB	0	144	0.0%	0.0%
2008	BD	1	7	0.8%	14.3%
2013	BD	0	8	0.0%	0.0%
2018	BD	1	15	0.8%	6.7%
2023	BD	2	11	6.1%	18.2%
C1	Control	3	23	0.7%	13.0%
C2	Control	1	25	0.3%	4.0%
C3	Control	0	28	0.0%	0.0%
C4	Control	0	15	0.0%	0.0%

3.3 Continued function of treated trees

The proportion of living trees within treated plots decreased significantly with time since treatment ($\rho = -0.804$, $p_{adj} < 0.001$). Conversely, the proportion of lying dead wood and broken snags/logs structures increased strongly over time ($\rho = 0.839$, $p_{adj} < 0.001$; $\rho = 0.776$, $p_{adj} < 0.001$). Based on figure 8 we can see an increase of standing dead wood during 2018 and 2013. This trend reverses in 2008 and standing dead wood is almost entirely absent. RB and HST visually produced the greatest structural variety across the CF categories, whereas lower-intensity treatments (Cavity, BD, PRB and LHST) generally remained standing alive.

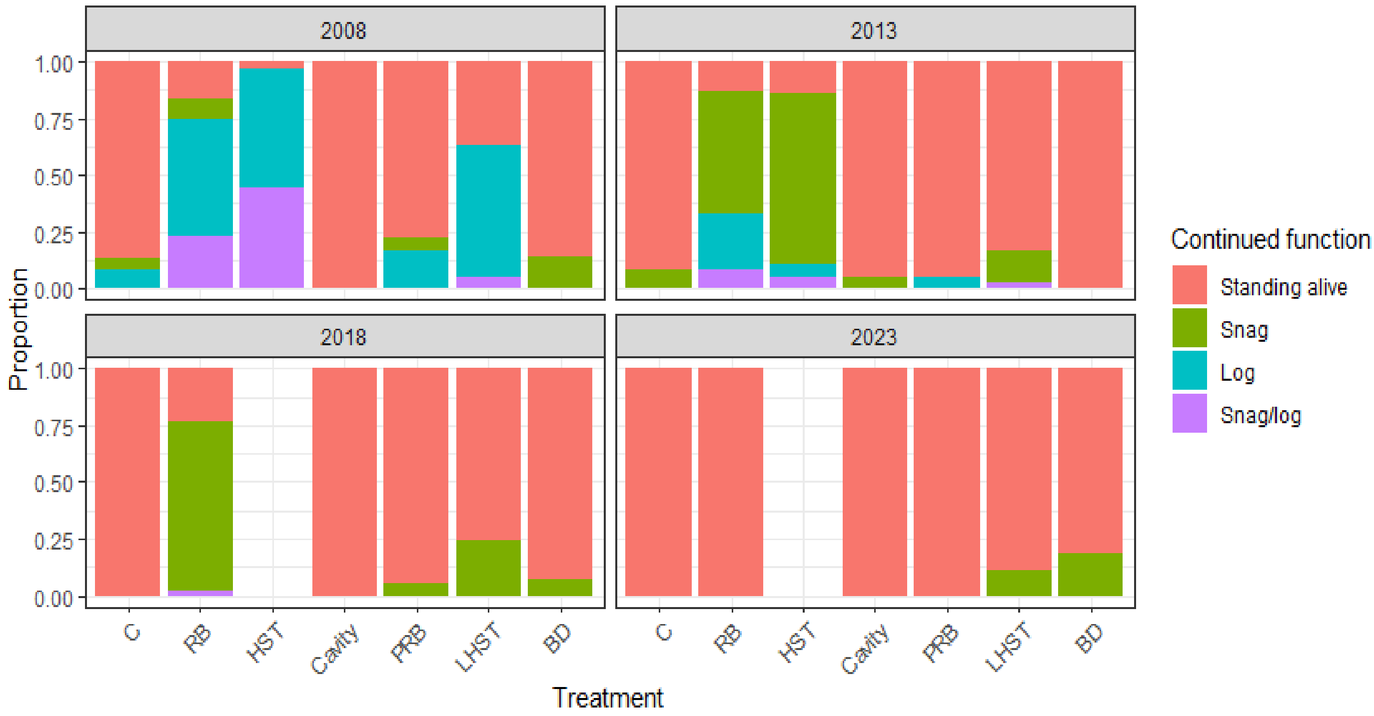

Figure 8: Proportion of CF classes across treatments and years. On the x axis treatments are displayed as abbreviations; C = Control, RB = Ring barking, HST = Hight stump, PRB = Partial ring barking, LHST = Living hight stump, and BD = Basal damage.

3.4 Dead wood volume and decay class distribution.

Figure 9 shows the differences in decay class development and dead wood volume across treatments and years for both standing and lying dead wood. The CLMM model revealed that the chance of belonging to a higher vitality class increased significantly with increasing time since treatment for standing dead wood (OR = 1.68, $p_{adj} < 0.001$). A similar but weaker trend was observed for lying dead wood (OR = 1.28, $p_{adj} = 0.001$). Overall, based on the visual interpretation of figure 9, RB and HST produced the greatest variety of decay stages for both standing and lying dead wood, whereas lower-intensity veteranisation treatments had a lower impact (Cavity, BD, LHST, PRB) (Fig 9.). Standing dead wood generally had lower decay classifications, while lying dead wood had higher decay classifications. The control treatment (C) had low amounts of dead wood across all years, treatments, and structures.

Furthermore, total dead wood volume showed a positive correlation with time since treatment ($\rho = 0.847$, $p < 0.001$). Across years, several treatments increased their contribution to dead wood, suggesting that some treatments had a latent effect on the trees and did not cause mortality instantaneously. This could indicate an ongoing trend of development for older dead wood structures. In year 2013 only 5 out of 10 plots is represented as described in the methods.

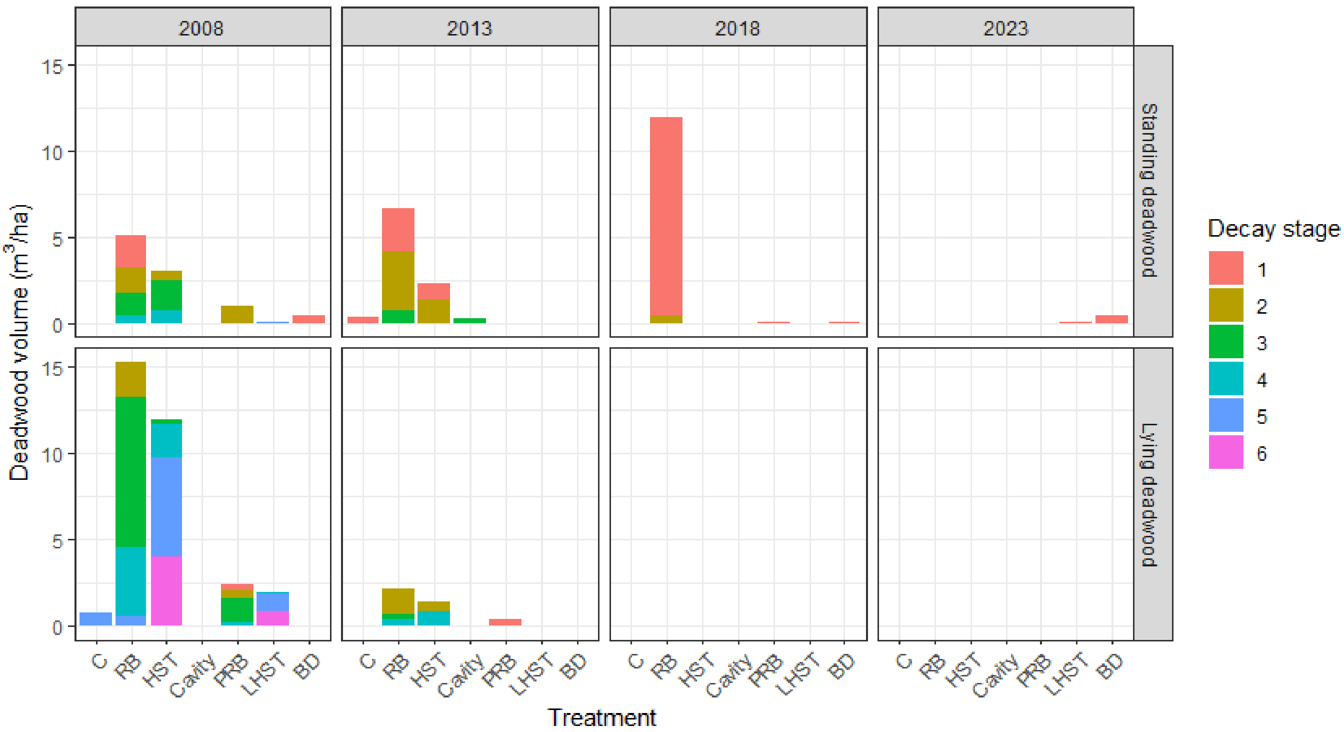

Figure 9: Total dead wood amounts (m^3/ha) divided across decay classes in each treatment and across cohort years. Standing and lying dead wood is displayed separately. On the x axis treatments are displayed as abbreviations; C = Control, RB = Ring barking, HST = Hight stump, PRB = Partial ring barking, LHST = Living hight stump, and BD = Basal damage.

3.5 Comparative benchmarks for dead wood volume

Mean dead wood density in treated plots was 67.5 m^3/ha, substantially higher than control plots (9.34 m^3/ha). Treated plot values exceeded control conditions and are higher than several published managed forest references, while remaining below mean values reported for unmanaged beech reserves in Sweden and Europe. The total volume in treated plots is presented with a 1m buffer to the convex hull plot size estimates; variance is displayed as a 2 m buffer and no buffer.

Table 6: Compilation of dead wood reference values and summarized dead wood volumes from treated and control plots. Presented as unmanaged, managed and swedish benchmarks.

	Lying dead wood m^3/ha	**Standing dead wood m^3/ha**	**Total dead wood m^3/ha**
Treated plots	35.7+/- 10.0	31.8 +/-10.0	67.5 +/- 10.0
Control plots	6.14	3.2	9.34
Unmanaged stands			
Christensen et al. 2005 mean	94.0	39.0	133.0
Oder et al. 2021 unmanaged	84.6	29.8	114.5
Merce et al. 2025	51.84	36.09	87.93
Managed stands			
Christensen et al. 2005 mean	-	-	10.0
Vandekerkhove et al. 2009 mean	-	-	1-3.0
Erdmann and Wilke, 1997	-	-	1-10.0
Sweden			
Fuentes et al. 2010 semi-natural beech, Biskopstorp	21.2	32.6	53.8
Jönsson and Jonsson, 2007, woodland key habitats	11.7	9.9	21.6
Brunet, 2008, Söderåsen	13.0	2.2	15.2

4. Discussion

4.1 Treatment effects on restored plots

Ring barking

The ring barking (RB) treatment had a significant impact on both survival and vitality of treated trees, which was part of the intended goal for the treatment. Over time the vitality of RB trees has homogenised and stabilized resulting in older trees either having died or were fully healthy (Fig 7.). The surviving trees did so by growing over the RB treatment (observation from inventory) a process which could have been prevented if larger diameter and deeper cuts had been used for larger trees. Average yearly mortality rates for RB trees were 5.3%, far above the background mortality rates of 0.25-1% found in natural beech forests or in the control plots (Hobi et al., 2015; Ruhoni et al., 2013). The RB treated trees from 2023 had not yet fully died but exhibited low vitality while the RB trees from 2018 had fully died (Fig 7.), indicating that the observations by Niklasson (2017) are accurate, the effects of the RB treatment have an approximate 4-6 year delay until death occurs.

Furthermore, the RB treatment had other effects such as effectively introducing structural variability and dead wood by producing snags, logs and broken stems (Fig 8.). The proportional variety of structures increased over time but shifted towards more logs than snags when comparing the 2013 and 2008 treatments years (Fig 8.). Consequently, the introduction of decay from the treatment showed a similar pattern of increased variability over time, older treatment years had a more variable decay structure compared to more recent years (Fig 9.). The RB treatment has thereby succeeded in generating structural variability quickly and introduced dead wood in different decay stages.

High stumps

Similarly to the RB treatment the high stump (HST) had as expected high mortality rates and did therefore introduce dead wood quickly, even more so than RB because of the mentioned delay effect. By creating HST it is possible to purposefully ensure the influx of standing dead wood, which is known to be an important feature of beech forests dead wood ecology (Zumr et al., 2023). The treatment was even more variable in its decay stages than RB, especially in lying dead wood suggesting that the stems have been on the forest floor for longer. In figure 8 we can see the process of snags breaking over time when comparing the occurrence of log/snag structure between the years. The treatment was replicated for two years (2008 and 2013) so the result we are seeing is the later developments of the treated trees. Therefore, it is hard to draw any conclusions about the speed at which decay is introduced.

Nevertheless, if a tree is cut at a given height without living branches underneath the cut, it is likely to die directly, so hypothetically if the HST treatment was replicated in 2023 we would probably already see an introduction of dead wood. If the HST and RB treatments then are used in combination with each other they could potentially produce two cohorts of fresh dead wood, one which is produced instantaneously and one which arrives 6 years after treatments. This would at least in a short time frame continuously accumulate fresh dead wood substrates available for saproxylic species.

Cavity

Tree cavities are among the most important tree-related microhabitats in temperate forests and are strongly associated with old veteran trees and high biodiversity value (Larrieu et al., 2018). The treatment aimed to artificially generate cavities and introduce decay into living trees. Almost all cavity-treated trees survived the veteranisation and only 3 out of 68 cavities had been overgrown at the time of inventory, based on field observations. Signs of rot development within the cavities can also be observed (Fig 9.), although this appeared to be a relatively slow process compared to the more invasive mortality treatments. This could perhaps be explained by the good health of the treated trees at the time of treatment, allowing them to effectively compartmentalize the artificial wounds. This does not, however, indicate that the treatment was unsuccessful. On the contrary, by creating stable dead wood cavities, the treated trees will, similarly to the other veteranisation treatments, continuously provide important tree-related microhabitats.

Observations of red-listed and other rare saproxylic species have previously been recorded in artificial cavities (Lindström, 2014; Brunet & Isacsson, 2009). The cavity-treated trees also displayed low vitality scores, indicating that most trees remained in relatively good condition at the time of inventory (Fig 7.). The cavity treatment therefore appears to have successfully reintroduced a rare TreM typically associated with older and more structurally diverse forests while retaining the structure over time. It may therefore contribute to restoring structural features characteristic of old-growth beech forests, where veteran trees and tree microhabitats occur more frequently (Brunet et al., 2010).

Living high stumps

As the name suggests the purpose of the living high stump treatment (LHST) was not to instantaneously kill the tree but to artificially create habitat trees with low crowns. To this end the treatment was successful as many LHST treated trees survived the process although the mortality was still higher than control (Table 5). As most surviving LHST trees are of good vitality (Fig 4.) they will remain in the stand for longer periods of time, thus providing a stable microclimate for dead wood dwelling species. The LHST treatment has also lowered the canopy of treated trees creating, in some plots, a second canopy and in others single low growing trees with wide crowns. Forests which are vertically stratified have been shown to be good habitat for birds because low canopy layers create ecological niches to forage, and breed (Kati et al., 2009)

Basal damage

Similarly to the cavity treatment, basal trunk damage (BD) aimed to deliberately expose xylem creating pockets of dead wood in healthy trees and introducing decay, creating long lasting habitat for saproxylic species. Many BD treated trees survived and are as a result still fulfilling their function in the stand (Table 5). As the basal damage was mechanically done along the vertical length of the stem it could potentially represent a dryer form of stable dead wood as water would run along its length and does not become stagnant. In cavities on the other hand the environment would have more moisture as water gets trapped. Both treatments therefore contribute to two different types of stable microclimate conditions.

Partial ring barking

The expected outcome of the partial ring barking (PRB) treatment was a reduced vitality and a slow process of mortality, introducing dead wood stems over time and not in cohorts as the RB treatment does. To this end the treatment was largely unsuccessful, PRB treated trees show no slow process of mortality, most treated trees have survived each year except in 2008 where 22% of treated trees have died (Table 5). Given the vitality of PRB treated trees in 2013 it is unlikely that these trees will in the coming years show a similar mortality pattern as the 2008 cohort. PRB trees showed little introduction of dead wood and variability in structures (standing/lying). In 2013 the dead PRB trees are in decay class 1 meaning that they probably fell quite recently to the time of inventory (Fig 9.).

However, when considering the mortality effects across years the PRB treatment had almost a 0.7% mortality over the whole time series which is at the higher end of observed background mortality rates of natural beech forests (Hobi et al., 2015). Considering that in each treatment years some PRB trees have died it will be interesting to see how the PRB treated trees from 2023 develop and if it can sustain this trend over time.

4.2 Dead wood volume

Dead wood quantity is an important indicator of habitat quality in temperate forest ecosystems, particularly in beech forests where many saproxylic organisms depend on decaying wood (Brunet, Fritz and Richnau, 2010). Comparing dead wood volumes between restored and unrestored stands can therefore help to interpret the ecological effects of veteranisation and ring barking treatments. To better understand whether the treated stands resemble more natural forest conditions, the observed dead wood volumes are compared with published reference values from managed, semi-natural, and relic European beech forests.

Christensen et al (2005) published a literature review comparing the reported availability of dead wood in 86 different beech forest reserves across Europe. The average total amount of dead wood found was very variable and ranged between 0 and 550 m^3/ha with a mean total of 130 m^3/ha. In a closer regional context, Fuentes et al (2010) found total dead wood volumes in semi-natural beech forests in southern Sweden to be 56 m^3/ha while Söderåsen national park and beech dominated woodland key habitats had 15.2 m^3/ha and 21.6 m^3/ha respectively (Table 6). The treated plots had an average of 67.5 m^3/ha of total dead wood (Table 6) placing them withing the range reported in protected beech forests across Europe and Sweden. The control plots did however have 9.2 m^3/ha meaning they are close to the upper limits of dead wood volume found in managed beech (Table 6).

When looking at targets for restoration, threshold values are often used as baselines. For recommended amounts of dead wood in European beech forests the treated plots fall within the recommended range of 20-70 m^3/ha (Müller & Butler, 2010). These thresholds vary depending on the specific restoration objectives and on target species groups. Birds dependant on dead wood generally requires 5-10 m^3/ha whereas saproxylic beetles require 38-58 m^3/ha for sustained populations (Müller-Using and Bartsch, 2009).

The volumes recorded within the treated plots are comparable or exceed those found in semi natural beech, national parks, woodland key habitats and reference values (Table 6; Müller-Using and Bartsch, 2009). The treated plots may therefore act as local habitat hotspots for dead wood dependant species. Relative to the control conditions treated plots showed greater dead wood accumulation, indicating improved habitat conditions for dead wood dependent species and a shift towards more natural conditions.

4.3 Dead wood structure and decay stage

Dead wood is important not only in large quantities, but also in terms of structural diversity and across different decay stages, particularly the occurrence of standing and lying dead wood (Gao et al., 2015). The study confirms that the restoration treatments have increased the occurrence and variability of these important habitat structures relative to the control plots (Fig 8.). Treated plots exhibited greater variation in structures, and decay stage, whereas the control plots contained comparatively little structural diversity. Older treated plots contain more lying dead wood structures and a greater diversity of decay classes (Fig 9.). This result confirms an ongoing process in which standing dead wood gradually falls and transitions into more decomposed lying dead wood. In the present study, standing dead wood was generally concentrated in earlier decay stages, while lying logs were more decomposed, likely because of the higher moisture conditions and increased presence of decomposer organisms and saproxylic species on the forest floor. A similar distribution pattern was observed by Merce et al. (2025) in natural beech forests, where lying dead wood supported a broader range of decay stages than standing dead wood. Thurell (2024) observed the same pattern in Söderåsen national park where lying logs were more decayed than standing dead wood.

The occurrence and stage of decay of these structures are linked to the biodiversity of saproxylic beetles in beech forests. Brunet & Isacsson (2009) demonstrate that beetle communities are strongly influenced not only by the amount of dead wood in the forest, but also by its decay stage and structure. Fungal community diversity has also been shown to increase with decay stage and structural variability (Mamadashvili et al., 2024). As the restoration has increased the presence of these structures, the prerequisites for biodiversity may also have been improved.

Furthermore, the highest levels of saproxylic species diversity in beech snags was found in intermediate decay stages, of which the restoration at Osbeck has generated significant amounts (Fig 10; Brunet & Isacsson, 2009). Notably, the snags associated with the highest biodiversity in Brunet & Isacsson (2009) were artificially created. The ecological value of artificially created structures has also been demonstrated previously at the study site. A 2014 study by Lindström, (also conducted in Osbecks boksskogar) analysed the occurrence of Diptera (flies) and Coleoptera (beetles) species within the artificially created cavities available at the time with naturally occurring cavities at Biskopstorp. The results showed that the artificial cavities supported slightly higher diversity of Coleoptera species than the natural cavities while also having roughly the same total species richness.

The accumulation of snags, lying dead wood logs, and their decay stage suggest that the stand now demonstrates characteristics important for saproxylic species diversity. When compared to the control plots, there is a clear difference in these characteristics between the two. This strongly suggests that treated plots have more rapidly developed important habitat features compared to non-treated plots, demonstrating that management has accelerated the development of structural variability. Future species inventories could establish if this is the case.

4.4 Implications for restoration work in beech forests

The effects of the treatments are evident and is often in line with findings from natural beech forests across Europe suggesting that the restoration work has moved the stand towards more natural characteristics and increased habitat quality. The treatments influenced the measured variables at different rates; some causes an instant increase of dead wood whereas some develop habitat slowly. To accumulate dead wood in different decay stages and increase volumes quickly a manager could opt for using only ring barking and high stump treatments, but to build habitat that lasts across time the other veteranisation techniques are useful. Cavity treatments, basal trunk damage, living high stump treatments all contribute to variability by introducing important tree-related microhabitats (TreMs) which maintain in living habitat trees. The partial ring barking treatment was less successful in achieving its intended outcome as most trees have survived the process in the older cohorts. However, in each cohort except 2023 one or more PRB treated tree died, if the technique is used more across the stand it could contribute to increasing background mortality rates at a stand-level.

Furthermore, because of the applied treatments, the speed at which habitat has formed is quicker than would otherwise have occurred. This is evident when comparing treated plots to control plots, as well as when considering stand-level dead wood values in managed beech forests (Table 6). Vandekerkhove et al. (2009) found that dead wood accumulation in previously managed beech forests is a slow process which changes because of stand age. Their study showed that dead wood accumulates at a median rate of 1.9 m^3/ha/year while also indicating that accumulation is slowest in stands aged 100-150 years, which corresponds to the current age of the study site which is 100-120 years old. Given the average amount of dead wood found in the control plots at Osbeck (9.2 m^3/ha) and the time since the last forestry related management intervention (prior to 2008 when the reserve was established), accumulation remains very slow. Without restoration intervention, reaching the natural levels reported by Christensen et al. (2005) (130 m^3/ha) or the amounts found in swedish semi-natural reserves (54 m^3/ha) could take another century or more, assuming no stochastic disturbance events (von Oheimb et al., 2005).

4.5 Future research

This thesis presents a snapshot in time of the current characteristics and development of the treated plots and compare these values to benchmarks found in the literature to understand the effects on key structural variables. However, it does not aim to assess biodiversity directly, nor the effects of the treatments on species composition or ecological functioning.

Future research should therefore focus on linking the observed structural variables to biological diversity, such as the potential migration of the red listed species found in the nearby woodland key habitats into the restored compartments. This work has been started by Lindström (2014) but the study site provides further valuable opportunities to investigate the relationship between artificially created dead wood and saproxylic species. Understanding how different restoration treatments influence species richness, community composition, and habitat use would provide important insights into effectiveness of these treatments.

Long term monitoring would also be beneficial, as many of the processes observed, such as decay progression and habitat development, occur over extended timeframes. Repeated inventories could help determine whether the structural changes identified in this study translate into sustained increases in habitat quality and biodiversity over time.

4.6 Methodological restrictions

The study was not without limitations, and the results should therefore be interpreted with some caution. Most notably, the number of control plots was limited, which may not fully capture the structural characteristics of the stand. However, the plots were sufficient to indicate general stand conditions and trends.

Furthermore, the study likely suffers from an underestimation of available dead wood as only coarse dead wood stems were included in the analysis, an issue shared with many previous dead wood inventories (Stillhard et al., 2022).

5. Conclusion

Ecosystem restoration has gained increased attention in recent years due to its importance for maintaining ecosystem services. This is reflected in new policies such as the EU's Nature Restoration Regulation (NRR), which outlines targets for restoration (European Union, 2024). The findings from this study contribute to these objectives by demonstrating how restoration can influence dead wood structure and habitat quality in beech forest systems.

The result confirms that veteranisation and mortality inducing treatments can reintroduce dead wood in a wide range of decay stages (Fig 9.), increase structural diversity among dead / living steams (Fig 8.) and created a variety of rare habitat trees which sustain over time. Through active restoration the treatments produced variability among ecosystem functions quicker than would have occurred naturally and have therefore ensured a shorter delivery time of important habitat features. We can now also surmise the consequences of different treatments on beech tree health and mortality (Table 5; Fig 7.). Based on the result we can therefore assume that the proposed hypothesis does indeed correspond well with studied conditions. We can by analysing the results observe differences in outcomes between treatments and can based on this understand their practical implications for future restoration projects in beech forests.

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7. Popular science summary

As ecosystem restoration is becoming increasingly prevalent, the treatments used need to be evaluated to understand their effects. This requires long-term monitoring and assessment of restoration outcomes. In the EU, this is exemplified by the enactment of the Nature Restoration Regulation (NRR) which emphasises the importance of restorative ecosystem management.

Conventional forestry management has led to the loss of many natural features in previously managed beech forests. These forests are usually young, light deficient, and lack features commonly attributed to older forests. To restore these forests back to natural conditions we can use different restoration techniques. This study investigates the outcome of veteranisation and mortality inducing treatments which aim to re-introduce natural features to previously managed beech forests.

Veteranisation is a forest management technique where living trees are artificially aged to create the features normally found in natural forests or in old trees. This is done by deliberately injuring or stressing the trees in various ways, for example by drilling holes to create cavities, damaging bark at the bottom of the trunk, topping trees or partially ring-barking trees.

The studied site is in southern Sweden where veteranisation and mortality inducing treatments have been applied in a previously managed beech forests over a 20-year period. This has created an opportunity to track the effects of time on treated trees.

The results suggest that mortality inducing treatments create dead wood habitat rapidly, while veteranisation more slowly develops features associated with old-growth trees. This has implications for future restoration work as it suggests the speed at which habitat is formed using different techniques.

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This thesis would not have been possible without my supervisor, Mats Niklasson. He not only supported me throughout the thesis work and writing process but also assisted with the field inventories. His involvement in veteranisation as a method for beech forest restoration made the chronosequense studied in this thesis possible and, consequently, gave me the opportunity to carry out this work.

I would also like to thank my friends and family who read and commented on my work during the thesis process. Because of their support and feedback, this thesis improved significantly.

Appendix 1: Treatments

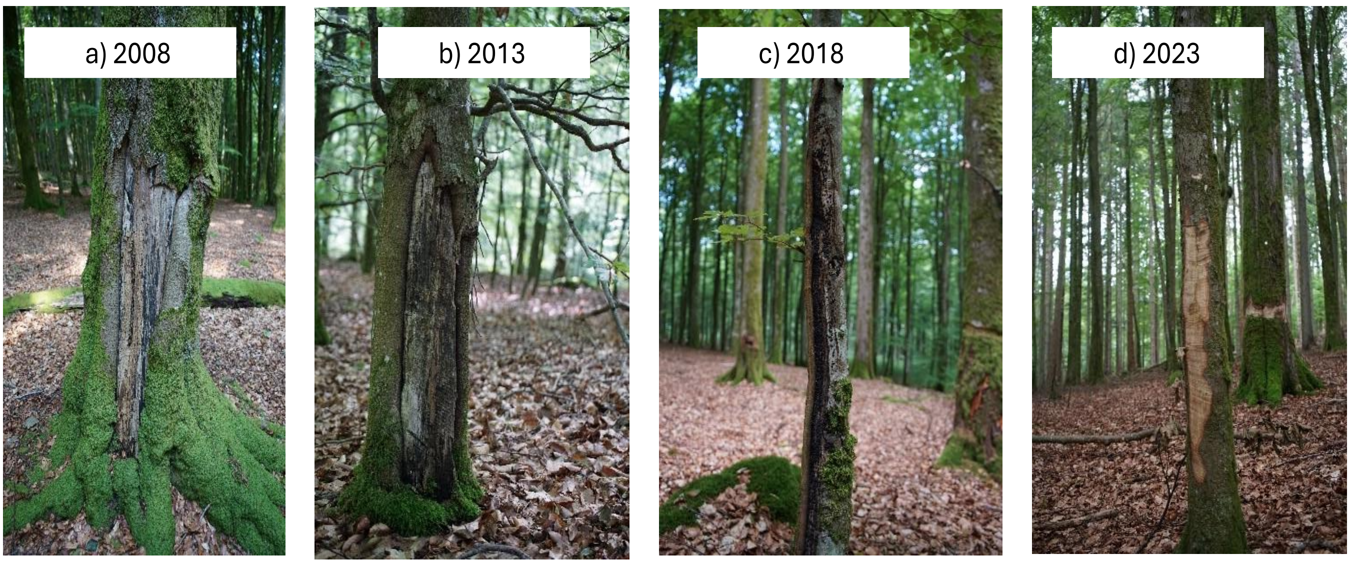
Note that these are not pictures of the same tree over time but a select tree from each treatment year.

A)

Cavity treatments

B)

Basal damage treatments



C)

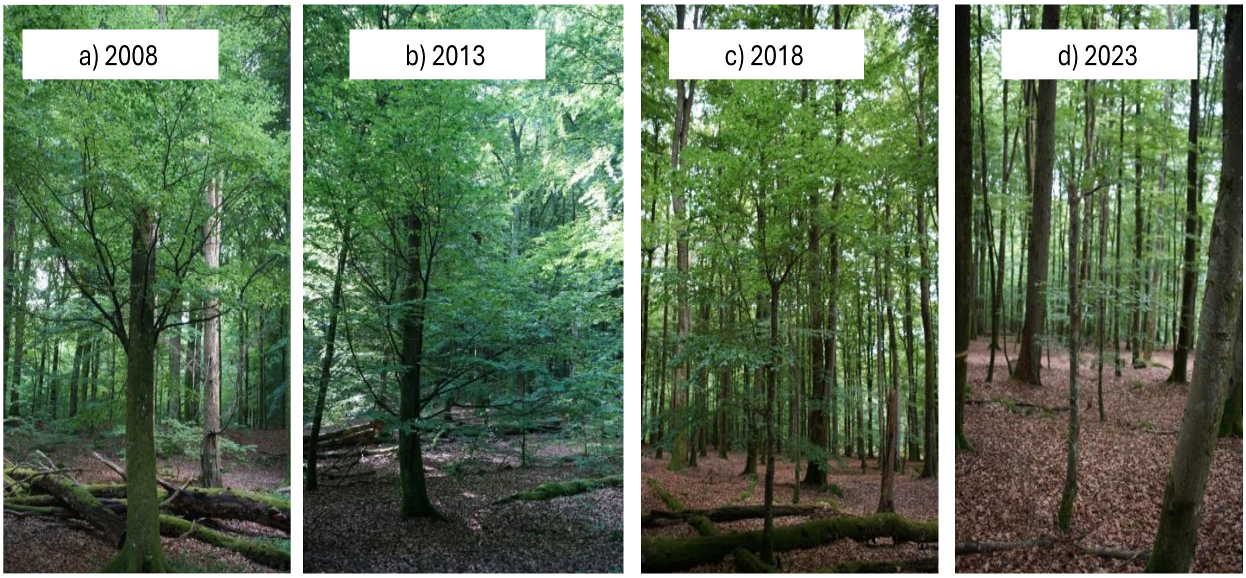
Partial ring barking treatments

D)

Ring barking treatments

E)

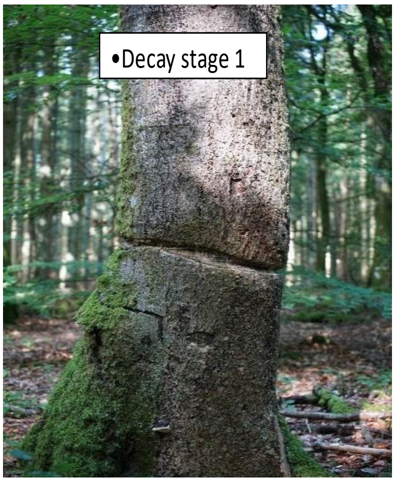
Living high stump treatments



F)

High stump treatments

Appendix 2: Decay stage visualisation



1 = Hard, blade enter only a few mm
2 = Relatively hard (1 - 2 cm)
3 = Relatively soft (3 - 5 cm)
4 = Soft throughout (uniformly soft)
5 = Very soft (mouldable)
6 = Nearly fully decayed, partially buried

Appendix 3: GLMM Mortality analysis

Model: mortality ~ treatment + (1 | plot_unique)

Fixed Effects	Estimate	SE	z	p-value	Dunnett adjusted p-value	Odds ratio
Intercept (Control)	-3.7514	1.3837	-2.711	0.0067	-	-
BD	0.5203	1.5397	0.338	0.7354	0.9889	1.683
Cavity	-0.2056	1.6148	-0.127	0.8987	0.9994	0.814
HST	5.2717	1.5043	3.504	<0.001	0.0026	194.738
LHST	1.2309	1.4572	0.845	0.3983	0.853	3.424
PRB	0.1874	1.4757	0.127	0.8989	0.9994	1.206
RB	4.0909	1.4421	2.837	0.0046	0.0242	59.795

Model Statistics	Value
Observations	794
Plots	43
Log-likelihood	-287.45
AIC	590.89
BIC	628.31
Random intercept variance	5.242
Random intercept SD	2.29

Model Comparison - Fixed Effect

Comparison	χ^2	df	p-value
Null model vs. Treatment model	251.46	6	<0.0001

Model Comparison - Random Effect

Comparison	χ^2	df	p-value
Fixed-only model vs. Mixed model	196.88	1	<0.0001

DHARMa Model Diagnostics

Test	Statistic	p-value
Uniformity (KS test)	0.0203	0.9
Dispersion	1.0296	0.434
Outliers	0	0.417

Appendix 4: CLMM Decay stage analysis

A)

Model specification: Lying dead wood decay stage ~ Time since treatment + (1 | Plot)

Fixed Effects	Estimate	SE	z	p-value	Holm adjusted p-value	Odds ratio
Time since treatment	0.246	0.075	3.28	0.001	0.001	1.278

Model Statistics	Value
Observations	139
Plots	20
Log-likelihood	-221.45
AIC	456.9
Random intercept variance	0.304
Random intercept SD	0.551

Model Comparison - Fixed Effect (LRT)

Comparison	χ^2	df	p-value
Null model vs. Time model	9.2594	1	0.0023

Model Comparison - Random Effect (LRT)

Comparison	χ^2	df	p-value
Fixed-only model vs. Mixed model	2.607	1	0.106

Partial Proportional Odds

Comparison	χ^2	df	p-value
Partial proportional odds vs. proportional odds model	5.4385	4	0.2452

B)

Model specification: Standing dead wood decay stage ~ Time since treatment + (1 | Plot)

Fixed Effects	Estimate	SE	z	p-value	Holm adjusted p-value	Odds ratio
Time since treatment	0.521	0.086	6.084	<0.001	<0.001	1.684

Model Statistics	Value
Observations	200
Plots	32
Log-likelihood	-165.13
AIC	342.26
Random intercept variance	1.065
Random intercept SD	1.032

Model Comparison - Fixed Effect			
Comparison	**χ^2**	**df**	**p-value**
Null model vs. Time model	40.62	1	<0.0001

Model Comparison - Random Effect			
Comparison	**χ^2**	**df**	**p-value**
Fixed-only model vs. Mixed model (GLM vs GLMM)	12.557	1	<0.001

Partial Proportional Odds			
Comparison	**χ^2**	**df**	**p-value**
Partial proportional odds vs. proportional odds model	4.4476	3	0.245

Appendix 5: Spearman's Rank correlation

A)

Relationship between mean plot-level vitality score and time since treatment.

Group	Mean plot vitality
2008	3.65
2013	3.14
2018	3.46
2023	2.17
Statistic	**Value**
Spearman's rho	0.643
S statistic	3529.2
p-value	< 0.001

B)

Relationships between time since treatment and plot-level proportions of CF categories

Variable	Spearman's ρ	p-value	Holm's adjusted p values
Proportion alive	-0.804	<0.001	<0.001
Proportion lying	0.839	<0.001	<0.001
Proportion broken	0.776	<0.001	<0.001

C)

Relationship between time since treatment and total dead wood volume per hectare.

Statistic	Value
Spearman's rho	0.847
S statistic	916.5
p-value	< 0.001

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