# Effects of helicopter topping on tree growth and stem interior

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# Effects of helicopter topping on tree growth and stem interior

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# Abstract

Managing tree heights near powerlines via helicopter topping has been a new subject of interests to forest owners and the energy sector. However, tree topping may have consequences on tree growth and tree health, as well as economic ramifications. This thesis aimed to evaluate the effects of helicopter topping on tree growth and the possible occurring economic losses.

On four locations topped and not-topped trees were selected and felled. Stem samples in form of discs were taken at specific heights, polished and used to measure tree rings. The tree-ring data was then analysed in R. Other stem samples were used to check for occurrence of pathogenic fungi.

The results showed that spruce trees are affected by topping, while pine trees are not. An analysis regarding the influence of pathogenic fungi showed occurrence of infection, but no influence on volume growth. Economic losses could be calculated for both species. Monitoring of topped trees for a longer time after topping and a larger sample size is recommended for better understanding of growth- recovery, influence of fungi infections and the effects of climatic factors like increased temperature and water stress on tree performance.

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# Abbreviations

| | |
|---|---|
| $\Delta Div$ | deltaDiv, volume increment growth loss (difference between projected and observed growth, divided by the observed growth) |
| ANOVA | Analysis of Variances |
| T | Topped |
| C | Control (not topped) |

# 1. Introduction

In Sweden, the practice of tree topping via helicopter has been a subject of interest within the forestry and energy sectors, since according to EIFS (Energimarknadsinspektionens föreskrifter) 2013:1 “transmission line corridors above 25kV must be tree-safe in order to prevent falling trees and branches from causing power outages” (*EIFS-2013-1-om-krav-som-ska-vara-uppfyllda-för-att-överföringen-av-el-ska-vara-av-god -kvalitet.pdf* n.d.), (*National risk-preparedness plan for Sweden´s electricity supply* 2021).

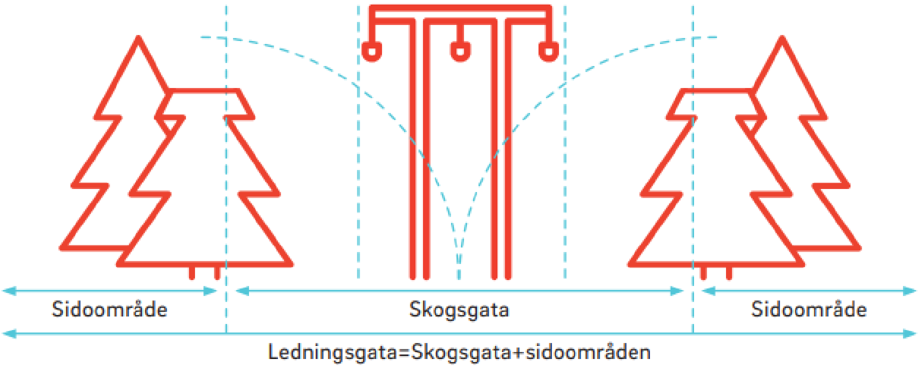

*Figure 1 Corridor with power line and adjacent trees, two trees with removed top (Energidistribution n.d.)*

This method, employed to prevent trees from interfering with power lines, involves the removal of the top part of trees (around 2-2.5 m), leaving them at a maximum height of 20 meters (Figure 1 and Figure 2). The cutting is done by helicopter-mounted saws. While this practice is efficient and cost-effective, it also raises concerns about the potential impact on the trees and the surrounding forest ecosystem.

*Figure 2 Helicopter- topped trees investigated during the study © D. Sadiković*

Tree topping involves removing the upper stem and crown portion of a tree. This can reduce the photosynthetic capacity of the tree and, depending on the severity of the cut, may lead to reduced growth rates earlier than in undamaged trees (Jones et al. 2019). It can also lead to a higher growth of the lateral branches right beneath the cut, to compensate for the lack of the tip (Långström & Hellqvist 1992).

In 2008, a master thesis assessed the impact of helicopter topping on decay in trees adjacent to power lines (Björnehall 2008). The study found that 75.7% of the topped spruce trees along power line corridors in southern Sweden showed signs of discoloration, 10.3% of those trees were also infected with root rot and a growth reduction (decrease of the average concluded that the risks of decay and helicopter topping are relatively small, especially if the topped trees are harvested within a reasonable short time after the intervention.

That thesis did not consider the topping effects on pine trees, economic consequences and differences in volume growth. Therefore, a more extensive follow-up study to research further consequences of tree topping was started in autumn 2023 and is still ongoing. The aim of that study is to assess the costs of topping with consideration of the individual reactions of different tree species, seasonal significance, how time after topping affects the growth and discoloration and how pathogenic fungi affect topped trees regarding volume growth and timber value reduction. Based on already collected data from that study, this thesis' objective is to answer the following questions:

1) does helicopter topping affect the volume growth of trees, and
2) are there any potential economic losses due to the topping.

Since the possible effects of  pathogenic fungi on topped trees are relevant, general information about rot fungi as well as some of the most common fungi /fungal diseases will be explained in the following sections.

## 1.1 Pathogens and tree growth

Tree pathogens can interfere with tree growth through natural disrupting physiological processes, changing recourse transportation and engaging with host defensive mechanism, therefore influencing overall natural growth performance. Pathogen infections also can have combine effect with environmental stress and furthermore leave the hosts vulnerable to secondary infections. Pathogenic fungi invade and damage host´s the cambium, xylem, and phloem resulting in stunned growth and reduced photosynthetic surface, thereby reducing photosynthetic potential of the host tree (Cherubini et al. 2002; Desprez-Loustau et al. 2006; Oliva et al. 2014).

## 1.2 Conifer hosts and rot pathogens in Sweden

In Sweden, about 68% of the land area is forest. Most of it is boreal forest, consisting mainly of *Picea abies* and *Pinus sylvestris.* The south has a small area with mostly deciduous forest. The species with the highest importance for Swedish forestry industry are *P. abies* and *P. sylvestris* (Black-Samuelsson et al. 2020), as well as *Betula pubescens* and *B. pendula* (Dahlgren Lidman 2022).

The main threats against the production forestry are game damage (mostly moose grazing), outbreaks of pests (mainly spruce bark beetle and pine weevil), diseases and severe weather events. The most serious fungus damage is root rot (Carlén et al. 2023). The following sections list the most common damages associated with fungi, which occur in managed conifer forests of Sweden.

## 1.3 Rot Fungi

Rot fungi or wood decay fungi is a common term for fungal species that digest various forms of wood (living, decaying and/or dead wood), thereby causing it to rot/decay. Depending on which type of decay they cause, rot fungi are classified into soft-rot fungi, brown-rot fungi and white-rot fungi (Fukasawa 2021; Li et al. 2022).

Soft-rot fungi are Ascomycota fungi that can grow on wood under adverse environmental conditions that inhibit colonization by other rot fungi (Hamed 2013; Langer et al. 2021), but typically colonize wood in wet environments (Goodell &

Jellison 2008; Hildén & Mäkelä 2018). They digest holocellulose, which is the polysaccharide content of wood, comprised of both cellulose and hemicellulose (Rowell 1984). The digestion of a wood portion then results in lignin-accumulation (see Figure 3c) (Fukasawa 2021). The appearance of affected wood is described as "greyish, soft and sponge-like" (Hildén & Mäkelä 2018) or, if the wood is drying, similar to brown rot, but finer in texture (Goodell & Jellison 2008). Cavities within cell walls are sometimes visible under microscopic view (Lee 2000; Goodell & Jellison 2008).

Brown-rot is caused by several groups of Basidiomycota. They cause a decay of cellulose and hemicellulose. The accumulation of lignin causes the affected wood to look brown with a cubical and brittle texture (see Figure 3b) (Fukasawa 2021).

White-rot is caused by several species of Basidiomycota and some Ascomycota, which are capable of decaying lignin, sometimes simultaneously with cellulose and hemicellulose. The wood looks whiteish and fibrous, the texture is soft and spongy (see Figure 3a) (Fukasawa 2021). Of all wood-rooting basidiomycetes, over 90 % cause white-rot (Tuomela & Hatakka 2019).

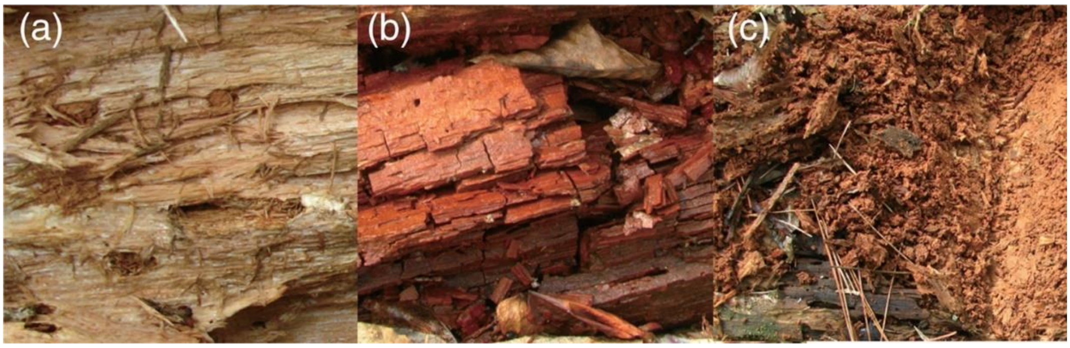

*Figure 3 White-rot (a), brown-rot (b), soft-rot (c) (Fukasawa 2021)*

### 1.3.1 *Heterobasidion* root rot

In the conifer forests of the northern hemisphere the economically most important pathogen is the *Heterobasidion annosum (s.l.)* species complex. This complex consists of a group of white-rot fungi causing root and stem rot and often tree death. *H. annosum (s.l.)* can operate both as saprotroph and necrotrophy. The ability to infect fresh stumps and its neighbouring trees through root contact (Garbelotto & Gonthier 2013) is causing economic losses that range between more than 790 million euros and 1 billion euros annually in European forests (Lind et al. 2014; Kovalchuk et al. 2022). Included are only losses due to the direct influence of *H. annosum (s.l.),* like decay and reduced diameter growth. Losses that occur due to the indirect influence of H. annosum (s.l.), like wind throw of weakened, infected trees are excluded (Garbelotto & Gonthier 2013). In Sweden around 15 % of the spruce trees are infected with *H. annosum (s.l.)* (*Biological control of root rot* 2024). Calculations showed that the overall damages caused by the root rot fungus *Heterobasidion annosum (s.l.)* are costing the Swedish forestry around 1 billion Swedish crowns per year (*Understanding and preventing root rot of conifers* 2024).

Within this species complex exist five intersterile groups (groups incapable of genetic exchange due to a reproductive barrier (Harrington & Rizzo 1999), three in Eurasia and two in North America. All five groups show a high host preference. Except for the northernmost regions, the eurasian species exist in all of Europe and have also spread to the Altai region in southern Siberia, which reflects the range of their host species (Garbelotto & Gonthier 2013). *H. annosum* sensu stricto *(s.s.)* has a preference for *Pinus* spp., *H. abietinum* is mostly associated with silver fir, but also other *Abies* species and *H. parviporum* has a strict preference for Norway Spruce (Garbelotto & Gonthier 2013). *H. annosum* (s.s.) is also able to infect other conifers (Norway Spruce, larch or common juniper) and broad-leaved trees (e.g. *Fagus sylvatica*, *Betula pendula* and *Carpinus betulus*) (Kovalchuk et al. 2022). According to Wang et al. (2014), in Sweden the groups *H. annosum (s.s.)* and *H. parviporum* occur.

Primary infection of *H. annosum (s.l.)* occurs through the surface of freshly cut stumps or wounds via basidiospores, where they germinate, develop infection hyphae, penetrate and invade the stumps and then spread into neighbouring healthy trees via root-to-root contact (see Figure 4 below).

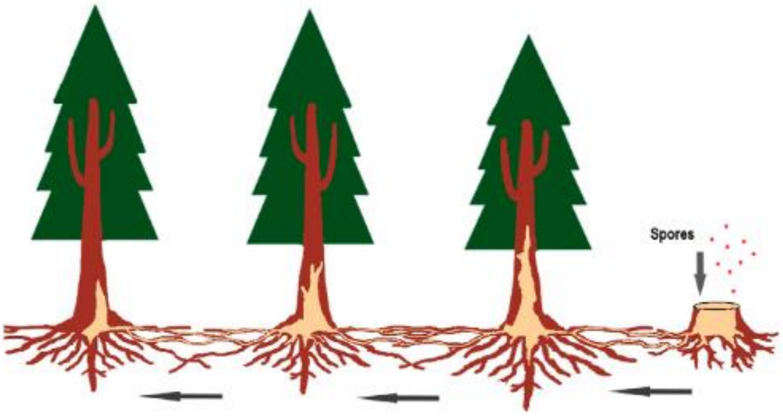

*Figure 4 Infection pathway of Heterobasidion annosum (Kovalchuk et al. 2022)*

Once inside the tree, the fungus feeds on cellulose, hemicellulose and lignin, causing degradation and loss of vigour (Kovalchuk et al. 2022). Depending on host species and climate, the colonization speed of the root system is approximately 20 cm per month. Stumps older than one month and stumps with a small diameter (e.g. after pre-commercial thinnings) are rarely colonized.

The severity of wounds and the host species play a role for successful infection. Other important factors are stand age and soil type (Garbelotto & Gonthier 2013). If a stand reaches a thinning age and later harvesting age, the infection risk rises due to the increasing number of fresh stumps. The fungus also has time to spread from these stumps to the remaining trees (Redfern et al. 2010). A higher diameter is also important, since larger trees often have a larger root system and therefore a higher probability to contact infected roots (Thor et al. 2005). J. Rishbeth (1951) discovered that infections of living roots in alkaline soils was higher than in acidic soil, however experiments done by Redfern et al. (2010) showed that serious infections can also develop on soils with lower pH. A reason for the higher occurrence of H. annosum (s.l.) in alkaline soils might be the lack of antagonistic fungi and microorganisms (Brūna et al. 2019). Trees on sandy soil also often experience more water stress, which leads to a higher susceptibility to become infected (Alexander 1975). Since the pathogen is incapable of surviving freely in the soil, direct root contact between trees and/or stumps is necessary (Kovalchuk et al. 2022).

Of all the Heterobasidion species in Europe, in general *H. annosum (s.s.)* is the most effective one regarding colonization of cambium and sapwood of its host, and therefore causes a higher mortality rate (Garbelotto & Gonthier 2013). Pine trees are mostly affected by *H. annosum (s.s.),* here the infection occurs mostly in the cambium. In Norway spruce *H. annosum (s.s.)* tends to colonize mainly the heartwood. *H. parviporum* also infects the heartwood in Norway spruce but does not damage Pine. The reason for the difference in tissue colonization is that the heartwood in pine presents a major barrier due to properties that inhibit the growth of fungi (Garbelotto & Gonthier 2013; Oliva et al. 2013).

Infected trees tend to die in clusters, spreading outwards in circles originating from the original infection site (Garbelotto & Gonthier 2013). Infection of the heartwood shows no outwards symptoms and is only detected during the harvest or with wind-throw, while sapwood infection causes reduced growth and chlorosis, often followed by crown-death (Bert et al. 2024). The decay occurs in the primary roots, root crown and stem, in freshly logged trees decay pockets are commonly visible. Within stumps and root-systems the pathogen is capable of surviving several decades (Garbelotto & Gonthier 2013).

To successfully prevent further infection on a strongly infected site it is necessary to completely remove the stumps and roots of, which is not only time- consuming and expensive, but also has a negative environmental impact and therefore seldom used in forestry. Therefore, the focus is on limiting the airborne infections. Since injuries and stumps are often created during thinning and logging, risk of infections can be lowered by choosing a time when spores are not active, e.g. during winter in northern Europe.

Another preventive measure against infection is to treat the stumps with chemical methods like urea or borax or using a biological control method like the saprophytic fungus *Plebiopsis gigante*a (Garbelotto & Gonthier 2013). In Sweden the main agent used for stump treatment against *Heterobasidion* spp. is RotStop S Gel, which contains living spores of P. gigantea. It is distributed either via a pump system for harvesters or by drilling holes in the sword of a chainsaw, through which the solution is sprayed (Inter Agro Skog AB 2024). Long-term methods of reducing or preventing the risk of infection are higher planting space, late thinnings, lower rotation length and mixture of tree species that might be in lesser risk of infection (Garbelotto & Gonthier 2013).

### 1.3.2 *Armillaria* rot

Another genus is *Armillaria (s.l.),* which is extensive in Europe and occurs in most places with woody vegetation (Kim et al. 2022). Currently, more than 40 different species are officially described worldwide (Heinzelmann et al. 2019). Species of this genus target many different tree species and wood shrubs in tropical, boreal and temperate regions. Infections result in white rot of roots and root collar, and may lead to crown dieback, root lesions and growth reductions, later death. It is also capable of infecting the heart wood of lateral roots and/or basal stem, compromising the structural integrity (Kim et al. 2022).

*Armillaria* has a wide distribution in Europe. *A. ostoyae* and *A. mellea* are considered aggressive primary pathogens, the other occurring European species act mostly as opportunistic pathogens and saprotrophs. *A. mellea* is the main cause of Armillaria root disease in southern Europe, in the rest of Europe *A. ostoyae* is the primary cause (Kim et al. 2022).

Infection of trees mainly happens via direct contact of colonized roots or rhizomorph growth, however it can also happen due to release of basidiospores that settle on freshly cut wood (Travadon et al. 2012) (see Figure 5 Life cycle of Armillaria species). The role of basidiospores within the life cycle and dispersal distance is still unclear, as is germination success. The development of rhizomorphs enables Armillaria species to survive in harsh environments (Heinzelmann et al. 2019), because increase the water and nutrient transport. The rhizomorphs have a melanized layer which provides protection against mechanical damage and heavy metals, while the presence of calcium in the outer layer provides a first defence against chemical attacks (Porter et al. 2022)

Even if infected trees are removed, the remaining mycelium on roots as well as the rhizomorphs in the soil can cause new infections (Baumgartner et al. 2011), (Yafetto 2018). Most species are capable of surviving decades in infected stumps and root systems, which can cause severe damages tree plantations or orchards (Kedves et al. 2021). The wide spectrum of possible hosts and the capability to not only colonize deadwood, but also to infect and possibly kill the host makes a successful management of infected sites problematic. The use of other fungi or bacteria as biocontrol has so far been difficult to apply and/or ineffective. Measures to prevent infection have mainly been focused on the reduction of inoculum in the soil. A recommended method for this is the mechanical removal of stumps and root system as soon as possible after logging. However, due to the negative environmental impact and the amount of time and costs that occur, it should only be done in areas with high mortality (Heinzelmann et al. 2019).

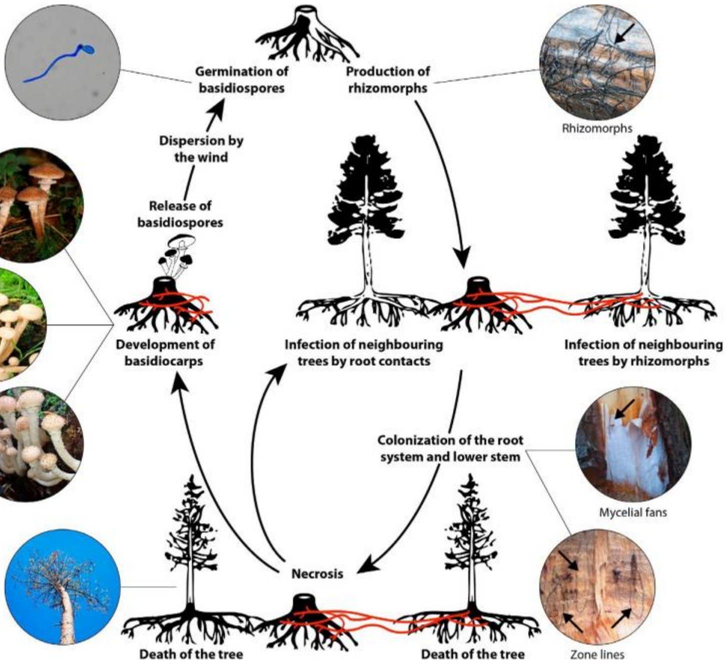

*Figure 5 Life cycle of Armillaria species. Photo credits: Renate Heinzelmann, Rubén Damián Elías-Román, Frédéric Labbé, and Tyson Ehlers (Kim et al. 2022)*

### 1.3.3 *Onnia* spp.

Specimens of *Onnia* include polypores with annual basidiocarps that cause white root rot. Most O*nnia* species grow on gymnosperms, and the most important pathogenic species can be found on *Pinaceae*. *Onnia tomentosa* and *O. leporina* have a circumboreal distribution and can mostly be found on *Picea*, while *O. triquetra* has an European distribution and is found mostly on *Pinus* (Ji et al. 2017; Palla et al. 2019). However, Germain et al. (2009) mentioned that *O. tomentosa* is the main root rot pathogen on both spruce and pine in the (sub)-boreal forests in North America. The pathogen mainly enters through the roots and causes breaking down of the wood structure with subsequent damage and devaluation of trees. Distribution of *Onnia* occurs via basidiospores and vegetative growth.

*Onnia tomentosa* causes the Tomentosus root rot disease, which spreads mainly via root-to-root contact, however infection by basidiospores on wounded roots may also occur. The death of an infected tree occurs after 15 to 20 years, often occurs earlier due to windthrow or infestation with bark-beetles. The fungus can survive in stumps and larger roots for some decades (Goheen & Willhite 2006; *Tomentosus Root Rot* n.d.).

### 1.3.4 *Stereum sanguinolentum*

*Stereum sanguinolentum* is a frequent basidiomycete in temporal and boreal forests, causing white-rot in recently felled conifer logs and stumps of conifers. It is also capable of infecting trees through open wounds, causing decay. In Sweden it is one of the most common fungi infecting wounds of *Picea abies* (Vasiliauskas 1998). The decay is usually in the main and top parts of the stem, often in the heartwood (*Wound Decays by Stereum Species* n.d.). The rot extension is fast, about 20 cm/year during the first years of infection. It spreads faster, if injuries are located at the root collar than on stem or smaller roots. On felled logs *S. sanguinolentum* causes a red-streaking discoloration (Schmidt 2006). Spreading occurs only via basidiospores, which land on open wounds and germinate (Calderoni et al. 2003).

### 1.3.5 *Ophiostoma* spp.

Fungi of the genus *Ophiostoma* belong to the Ascomycota with a broad global distribution (Roets et al. 2006). Several species are important tree pathogens like *Ophiostoma ulmi* and *O. novo-ulmi*, which cause the Dutch elm disease (Wingfield et al. 2017), while other species cause blue-stain in sapwood, f. ex. four species of the *O. piceae* complex (*O. piceae, O. canum, O. floccosum* and *O. setosum*), that mainly cause blue-stain in the timber of conifers (De Beer et al. 2003). They are adapted to insect transmission, with bark beetles being the most common vector (Solheim & Hietala 2015) and are currently regarded as the economically most significant fungi associated with bark beetles (Linnakoski et al. 2012). Since these fungi are unable to penetrate the bark, they rely on wounds created by insects, animals, wind damage or human activity (Solheim & Hietala 2015).

Regarding the species causing blue-stain, the main symptom of infected trees is the development of melanins on the cell walls of the invading hyphae for protection against drought, light and host tree defences in form of dark blueish or greyish colour (Lundell et al. 2014). The discoloration reduces the commercial value of the timber, but it does not significantly affect the mechanical properties of the affected wood (Szewczyk et al. 2020). However, several other species of *Ophiostoma* are capable of causing growth reduction, chlorosis, crown thinning or death of infected trees (Davydenko et al. 2017). Nevertheless, information regarding the capability to cause disease of ophiostomatoid fungi to host trees is still sparse in many instances (Linnakoski et al. 2012).

## 1.4 Objective

The objective of this thesis is to figure out, if topping affects the volume growth of trees, how pathogenic fungi are involved and if there are economic consequences due to topping.

# 2. Material and Methods

## 2.1 Effects on tree growth

### 2.1.1 Sampling

Tree sampling occurred 2023 in the following locations: Värnamo- Knäred, Hultsfred- Vimmerby, Sundsvall- Harmånger and Filipstad, along respective powerlines. The topping in Värnamo- Knäred and Sundsvall- Harmånga transpired in 2017, in Hultsfred- Vimmerby in 2019 and in Filipstad in 2021. Trees were selected using binoculars to look for visual signs like a missing tip, discoloration, and crown transparency. The selection of the trees was limited by the plots chosen by the topping company (see Figure 6).

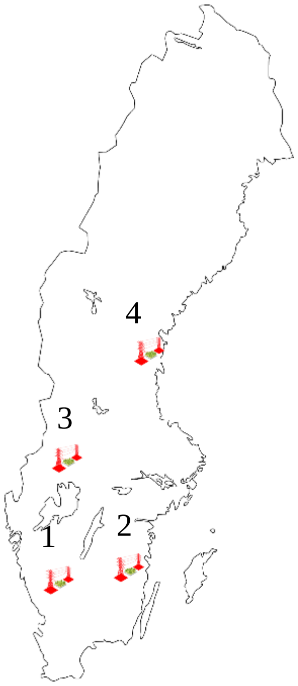

*Figure 6 Map of Sweden with sampling locations: 1=Värnamo- Knäred, 2=Hultsfred- Vimmerby, 3=Sundsvall- Harmånger, 4=Filipstad*
*© D. Sadiković, modified by J. Müntinga*

For this thesis, five trees per species (40 trees in total) were randomly chosen for analysis, three with topped crowns and two for control.

The height of each sampled tree was measured after felling. The tree was divided into approx. 10 sections.  To get the tree discs for tree-ring analysis, the first cross-section was taken at the tree base, at the lower part of section one. The positions of the remaining cross- sections were determined by taking them from the lower end of each following section, the last cross-section was taken at the top of the tree (see Figure 7). The total number of cross-sections (discs) per tree varied between 9 and 13 due to measurements being done in field conditions.

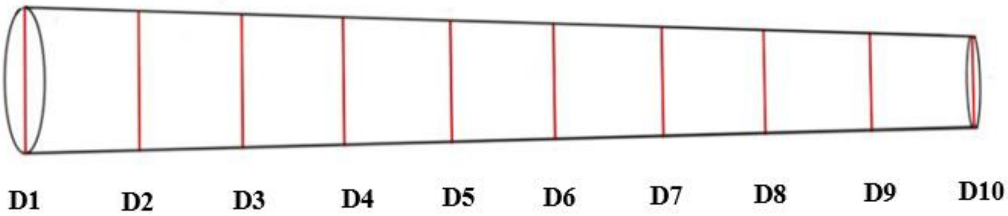

*Figure 7 Schematic drawing of a felled tree. The red lines indicate, where the cross-sections (discs) were taken*

Presence of rot infections in the base (Figure 8) and on the top was recorded. To identify the causal agent of recorded rot, discs containing rot symptom discolorations were harvested, incubated for up to two weeks and examined under the microscope.

*Figure 8 Heterobasidion sp. root infections recorded during the study © D. Sadiković*

### 2.1.2 Processing of samples

For this paper 40 trees in total were analysed. For each of the four locations five spruce trees and five pine trees were measured and a total of 480 discs were scanned and measured.

The discs were first cut on two opposite sides of the pith to obtain a rectangular shape (if size permitted it), then polished on one side to acquire a smooth surface with clearly visible tree rings (sanding grades were 40, 120, 240, 320 and 400). After sanding the discs were scanned with 2400 dpi resolution and converted into image files for measurement, using the scanner Epson Perfection V600 Photo and the software Epson Scan 2. For each disc two radii were taken.

For the analysis the software-package CDendro and CooRecorder (Cybis Elektronik & Data AB; (Larsson & Ossowski Larsson n.d.)) was used. CooRecorder 9.4 is used for measuring and cross dating the tree-ring samples, CDendro 9.4 is for organizing collections, metadata and also for cross dating (Maxwell & Larsson 2021). After measuring, the tree ring data was used in CDendro to verify the cross-dating, to organize the trees into collection and to see, if the rings were dated correctly.  The produced files were then, together with an excel file containing the meta data, loaded into R for further analysis.

### 2.1.3 Estimation of tree disc height

To obtain the different heights of the tree discs, an excel file with tree ID, tree height, condition (topped or control) and number of discs was developed. Using the total height of each tree and the total number of discs for the corresponding tree, the height of each disc could be calculated with the following formular: $H_{Disk} = \frac{H_{Tree}}{(N_{Disk}-1)}$ , where $H_{Tree}$ = height of one tree and $N_{Disk}$ = total number of discs for the corresponding tree. Subtraction by 1 is necessary to get the number of sections, since always one more cross-section than tree- sections exists (see Figure 7).

Starting with disc height 0 for the first disc, the height for the second disc was calculated. For the following discs the height of the second disc was always added to the height of the preceding disc, until the last disc. To get the tree ID, height and condition an already existing excel file with various tree data from the main study was used.

### 2.1.4 Tree ring analysis in R

For the analysis, the tree ring data in form of .rwl files along with the meta data was loaded in R, where it was used to produce and show the observed and predicted growth of the trees. Furthermore, it indicates if there were significant changes in growth after the topping and between the topped and control trees.

In R several packages were used for the analysis. The most important ones were *tReeglia* (Bascietto 2007), which is a collection of functions used for stem-analysis on tree cross-sections. The next package is *dplR* (Dendrochronology Program Library in R), a package for tree-ring analysis (e.g. cross-dating, detrending, chronology building, reading of .rwl files) (Bunn 2024). *nlme* helps to build linear and non-linear mixed-effect models and allows nested random effects (Pinheiro et al. 2023), while *lme4* gives linear mixed-effect models using "Eigen" and S4 and provides functions for fitting and analysing mixed models (Bates et al. 2024).

*LmerTest* was used to provide p-values for ANOVA and summary tables for *lmer* model fits (Kuznetsova et al. 2020). *Dplyr* (A Grammar of Data manipulation) helps to work with data frames (Wickham et al. 2023a), while *stringr* gives "simple, consistent wrappers for common string operations" (Wickham et al. 2023b)

The function *StemAnalysis* was used to provide the annual volume increment for each tree (Hoffmann et al. 2018; Wu et al. 2023). Then a chronology for basal area increment was built from the existing tree-ring-width series.

In the regression analysis first a data frame was created to show the cumulative observed and projected volume growth per tree. It furthers shows the loss of volume increment called $\Delta Div$ (deltaDiv, shows the increment loss for the time- period "topping till felling (2023) " by taking the difference of the projected and observed growth and dividing it by the observed growth

($\Delta Div = \frac{projected\ growth - observedgrowth}{observed\ growth}$)). The mean values of cumulative volume increment were also calculated.

The time period for all the calculations regarding effects of topping and fungal influence is the year the topping occurred until the felling (2023). Using a condensed version of this data frame, two boxplots were created to give a better overview of the data.

### 2.1.5 Mixed effects models

Mixed effects models allow to examine the variable of interest using both random and fixed effects. To figure out the influences of topping and potential infections with pathogenic fungi on tree volume growth, as well as possible differences in growth behaviour prior to the topping, linear mixed effects models were used in R, with the values for the observed and projected volume growth as fixed effects and the location as a random effect. Regarding replicates, per location 3 biological replicates for topped and 2 biological replicates for control trees exist for each species. Since topping and control was only done one time per sample- tree, no technical replicates exist.

*Volume growth prior to topping*

A mixed effect model was used to show, how the cumulative volume growth of Spruce and Pine prior to the topping looked like. For this, data frames showing the yearly volume increment and the cumulative volume increment per species were developed, with volume growth data only up to the year before the respective toppings. This will display, if topped and control trees are comparable (no differences in volume growth prior to topping) or not ( differences in volume prior to topping). The cumulative volume increment is the dependent variable, the condition (either topped or control) is used as fixed effect and the variable "short_treeID" was used as random effect, to account for the variability between different locations. ANOVA showed how significant the results were at significance level $\alpha = 0.05$. The calculated mean values were used to interpret the results.

*Effects of topping on volume growth*

To see, if topping has an impact on the tree volume growth, the table with observed and projected volume growth was modified to show only topped trees and was converted from wide table format to long table format for easier analysis. Then a second mixed model and subsequent ANOVA ($\alpha = 0.05$) was used on this data frame, with the values of the observed and projected volume growth ("Value") as dependent variable, the value type (observed or projected) as fixed effect and the location (called "short_treeID") as random effect. The time frame of this volume growth data is from the year of topping until the felling of the trees. The number of replicates is four.

*Effects of pathogenic fungi on volume growth*

For the impact of pathogenic fungi the tables with the observed and projected growth of topped trees were modified and used to show to top and base infections. For a better overview of the frequency of infected trees a bar chart was developed per species. A mixed effect model (dependent variable: "Value", fixed effects: top infection and base infection (and combination of top and base infection for spruce trees, for pine it was redundant), random effect: location) and subsequent ANOVA ($\alpha = 0.05$) was used to see, if an infection (top infections, base infections or both) had a significant effect on the volume growth of topped trees. Again the time frame of the volume growth is from the year of topping until the felling of the trees.

## 2.2 Potential economic losses

The potential economic losses were calculated by using $\Delta Div$, which shows the total increment loss from the time of the topping till felling and dividing it by the number of years from the topping till felling. This shows the loss of growth increment per year. Since we are interested in the economic gain or loss from topping, only topped trees were used for this calculation. In the next step the loss of growth increment per year was averaged per species and location and then multiplied with the corresponding SEK/m³-value to get the average economic loss in SEK per tree for each species and location.

Table 1 shows the average prices per m³ for sawlogs of Scots pine and Norway spruce. The prices are separated according to year and region. For this thesis the prices of 2023 were taken.

*Table 1 Annual average prices on delivery sawlogs (SEK/m³ ub) by Region, Assortment and Year (*1. Annual average prices on delivery logs, SEK per cubic meter solid volume excl. bark by Region, Assortment and Year. PxWeb *n.d.)*

| **Region** | **Species** | **2021** | **2022** | **2023** |
|---|---|---|---|---|
| Southern Norrland | *Pinus sylvestris* | 460 | 512 | 550 |
| | *Picea abies* | 443 | 493 | 549 |
| Svealand | *Pinus sylvestris* | 465 | 516 | 572 |
| | *Picea abies* | 434 | 482 | 560 |
| Götaland | *Pinus sylvestris* | 577 | 654 | 713 |
| | *Picea abies* | 631 | 713 | 799 |

Numbers of trees per hectare and stand density could not be obtained, therefore only a mean value per species and location was calculated.

# 3. Results

## 3.1 Effects on tree growth

The following boxplots give an overview of the observed and projected volume growth (Figure 9) and the volume growth increment loss (deltaDiv, Figure 10) for both conditions.

The boxplot of Figure 9 displays the observed (in red) and projected (in grey) growth in m³ of spruce and pine for both conditions for the time "year of topping till felling". The x-axis shows the two species, while the y-axis shows the growth in m³. It indicates that pine has a higher growth (observed and projected) than spruce and that for both species the projected growth is higher than the observed growth.

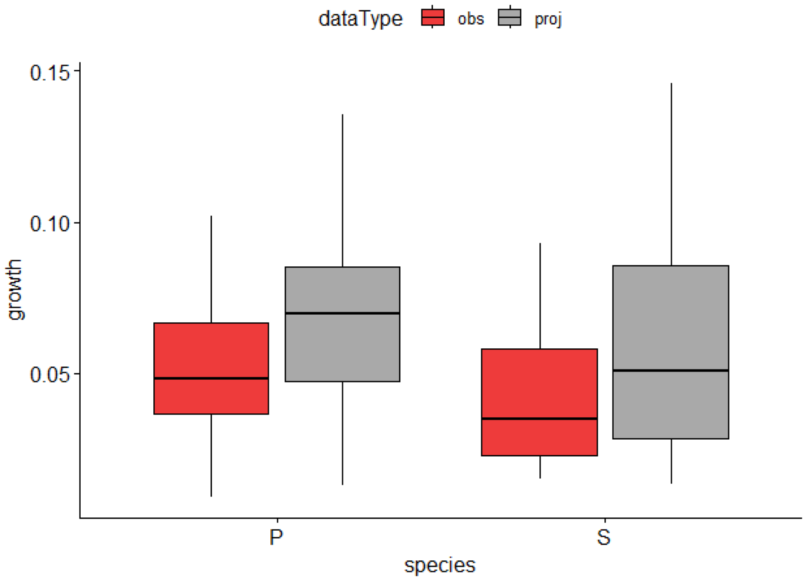

*Figure 9 Boxplot of observed (obs) and projected (proj) growth in m³ for pine (P, $n_{Pine}$=20) and spruce (S, $n_{Spruce}$=20)*

The table below (Table 2) displays the mean, standard deviation, standard error and variance for both species for observed and projected growth.

*Table 2 Mean, standard deviation, standard error and variance for spruce (n=20) and pine (n=20) on observed (obs) and projected (proj) growth*

| **Species** | **Data type** | **mean** | **SD** | **SE** | **variance** |
|---|---|---|---|---|---|
| Spruce | obs | 0.04 | 0.02 | 0.005 | 0.0005 |
| | proj | 0.06 | 0.04 | 0.008 | 0.001 |
| Pine | obs | 0.05 | 0.02 | 0.005 | 0.0005 |
| | proj | 0.07 | 0.03 | 0.007 | 0.0009 |

The boxplot of Figure 10 displays the volume growth increment loss (deltaDiv) for pine and spruce under two different conditions, control (not topped) and topped. The x-axis represents the species pine and spruce, the y-axis the loss of volume increment. The higher the $\Delta Div$-value, the higher the volume increment loss. The condition C (control) is represented by the beige-colored box, the condition T (topped) by the orange-colored box. For both species, the median of $\Delta Div$ for condition T is higher than for condition C. Pine shows a higher variability of $\Delta Div$ for topped trees than for control trees.

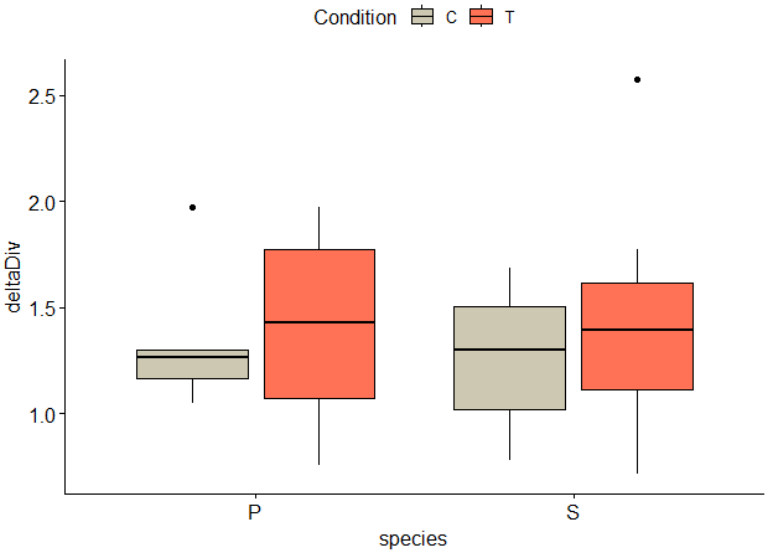

*Figure 10 Boxplot of the volume growth increment loss (deltaDiv) of Spruce (S) and Pine (P) under Conditions T (topped) and C (control)($n_{topped}$=12 per species, $n_{control}$=8 per species)*

The table below (Table 3) displays the mean, standard deviation, standard error and variance of deltaDiv for both species for topped and control trees.

*Table 3 Mean, standard deviation, standard error and variance of deltaDiv for topped (T, n=12) and control (C, n=8) trees for spruce and pine*

| Species | Condition | mean | SD | SE | variance |
|---|---|---|---|---|---|
| Spruce | T | 1.41 | 0.506 | 0.146 | 0.256 |
| | C | 1.26 | 0.337 | 0.119 | 0.114 |
| Pine | T | 1.39 | 0.431 | 0.125 | 0.186 |
| | C | 1.30 | 0.291 | 0.103 | 0.085 |

### 3.1.1 Volume growth prior to topping

Table 4 display the results of type III ANOVA, that was performed on the mixed effects model to show the significance of the treatment on volume growth of spruce and pine.

*Table 4 Type III ANOVA of fixed effect (Treatment) on volume growth of spruce (n=20) and pine (n=20) prior to topping*

| Species | Effect | SS | MS | Num. DF | Den. DF | F | *p* |
|---|---|---|---|---|---|---|---|
| Spruce | Treatment | 1.06 | 1.06 | 1 | 1322.6 | 26.7 | **2.741e-07** |
| Pine | Treatment | 0.026 | 0.026 | 1 | 1325.3 | 0.676 | 0.411 |

The mean cumulative volume increments for spruce are 0.531 m³ for topped trees and 0.336 m³ for control trees. The significant p-value (2.741e-07) suggests that the treatment has a significant effect on the volume growth of spruce. In this case it indicates that the group of spruce, that were topped, displayed a higher volume growth prior to topping than the group, that was used as control trees.

For pine the mean cumulative volume increments are 0.525 m³ for topped trees and 0.553 m³ for control trees. The non-significant p-value (0.411) suggests that the treatment has no significant effect on the volume growth of pine. In this case it indicates that the group of pine, that were topped, displayed a similar volume growth prior to topping as the control trees.

### 3.1.2 Effects of topping on volume growth

Table 5 displays the results of type III ANOVA, that was performed on the mixed effects models to show the significance of topping on volume growth of spruce and pine.

*Table 5 Type III ANOVA of fixed effect (ValueType) on volume growth of topped spruce (n=12) and pine (n=12)*

| **Species** | **Effect** | **SS** | **MS** | **Num. DF** | **Den. DF** | **F** | ***p*** |
|---|---|---|---|---|---|---|---|
| Spruce | ValueType | 0.003 | 0.003 | 1 | 19 | 4.469 | **0.048** |
| Pine | ValueType | 0.002 | 0.002 | 1 | 19 | 2.3 | 0.146 |

The results of table 5 suggest that for Spruce there seems to be a significant difference between the observed and projected growth (p=0.048). This would indicate that topping does have a significant effect on the volume growth of Spruce. For pine the results suggest that there is no significant difference between the observed and projected growth (p=0.146). This indicates, that topping seems to have no significant effect on the volume growth of pine.

### 3.1.3 Influence of pathogenic fungi on growth of topped trees

Incubation and microscope analysis determined that all recorded infections were caused by *Heterobasidion spp.* (Figure 11).

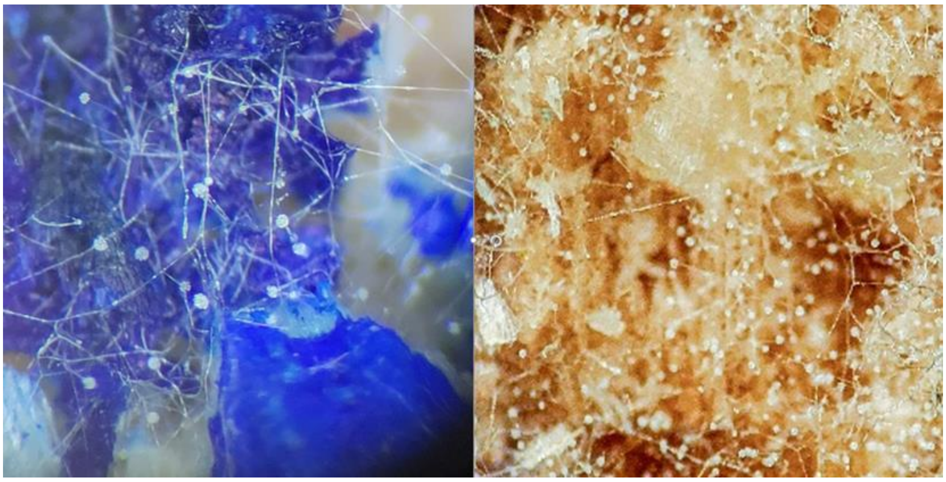

*Figure 11 Heterobasidion spp. conidiophores recorded during the study © D. Sadiković*

The bar charts below (Figure 12) show the frequency of top infections, base infections and both of topped spruces and pines. The total number of sampled topped trees is 12 per species. It shows that nearly all topped spruces showed signs of top infections, four of them had additional infections at the base. For pine, only three topped trees showed signs of top infections, another one had infection at its base. Of the control trees, no tree showed top infections (no data displayed).

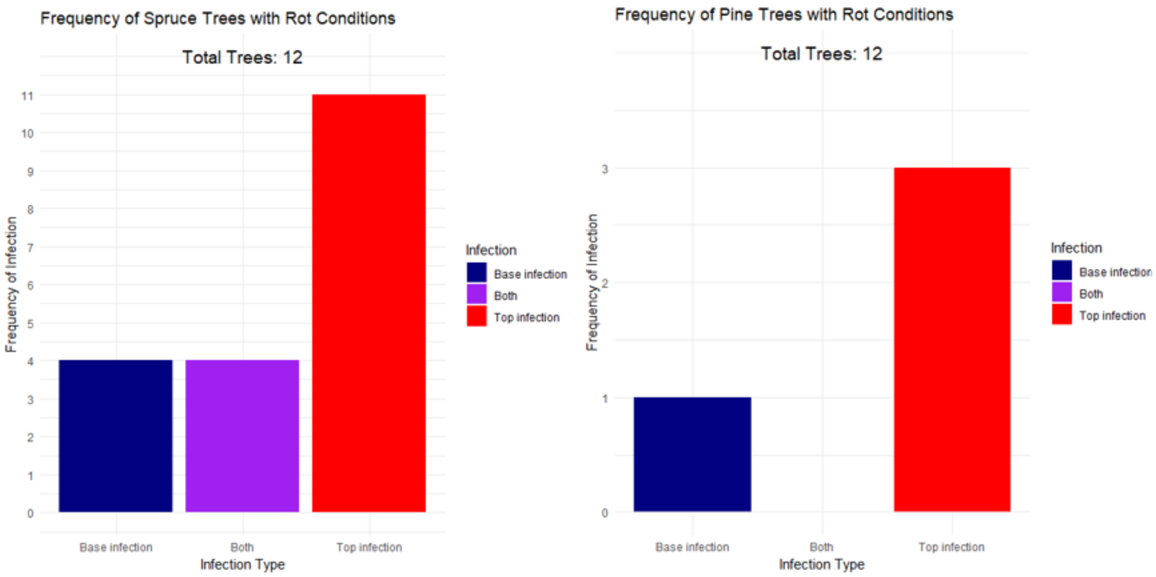

*Figure 12 Frequency and Type of Infection for topped spruce ($n_{Spruce}$=12) and topped pine ($n_{Pine}$=12)*

Table 6 displays the results of type III ANOVA, that was performed on the mixed effects models to show the significance of infection with pathogenic fungi on the volume growth of spruce and pine.

*Table 6 Type III ANOVA of fixed effects (Value type, top infection, base infection) on volume growth of topped spruce (n=12) and pine (n=12)*

| Species | Effect | SS | MS | Num.DF | Den.DF | F | *p* |
|---|---|---|---|---|---|---|---|
| Spruce | ValueType | 0.003 | 0.003 | 1 | 17.38 | 4.215 | **0.055** |
| | Top infection | 0.0002 | 0.0002 | 1 | 18.64 | 0.343 | 0.565 |
| | Base infection | 0.0004 | 0.0004 | 1 | 17.28 | 0.63 | 0.438 |
| Pine | ValueType | 0.002 | 0.002 | 1 | 17.9 | 2.461 | 0.134 |
| | Top infection | 0.001 | 0.001 | 1 | 1.55 | 0.999 | 0.447 |
| | Base infection | 0.004 | 0.004 | 1 | 15.46 | 5.743 | **0.03** |

According to table 6, both top infections and base infections show no significant influence on the volume growth of spruce (p-values 0.565 and 0.438, respectively). The difference between observed and projected growth is only marginal (p-value 0.05545), which would show that topping has a marginal effect.

For pine, base infections seem to have a significant effect on volume growth (p-value 0.03), but top infections do not (p-value 0.447). There is no significant difference between observed and projected growth (p-value 0.134).

### 3.1.4 Potential Economic Losses

Table 7 shows the calculated mean loss of growth increment per species and location as well as the mean value loss in Swedish crowns per topped tree.

*Table 7 Loss of Increment and Money per topped tree. Sites 1 and 2 correspond to Götaland, site 3 to Norrland and site 4 to Svealand. P=pine, S=spruce*

| **Species/Site** | **Mean yearly increment loss** | **mean value loss (SEK)/tree** |
|---|---|---|
| P1 | 0.090036793 | 64.2 |
| P2 | 0.219741158 | 156.7 |
| P3 | 0.112251417 | 61.7 |
| P4 | 0.226297416 | 129.4 |
| | | |
| S1 | 0.098185652 | 78.5 |
| S2 | 0.197274784 | 157.6 |
| S3 | 0.079345927 | 43.6 |
| S4 | 0.325525142 | 182.3 |

# 4. Discussion

The results indicate that the helicopter topping had some effect on the volume growth of spruce trees, but not on the volume growth of pine trees. The fungal infections developing in the tops because of open wounds created by topping did not have negative effects on volume increment of wood for both species. Infection at the base showed an effect on the volume increment of pine trees. But, since only a single pine tree was observed with base infection (see Figure 12), it is likely the result of a false positive analysis caused by small sample size (a single isolate with base infection). The economical calculations showed, that for both species losses could be calculated.

The boxplot in Figure 9 indicates a higher volume growth for the growth projections of spruce and pine. This can be explained by the fact, that the projected growth is based on the growth prior to the topping, therefore excluding the effects of topping and possible environmental stressors, that affected the trees after the topping.

The boxplot in Figure 10 indicates a lower median volume increment loss for control trees in both species. Here $\Delta Div$ is used, which displays the relative loss of volume increment (how much volume increment is lost relative to the observed growth), while the mixed effects model compares the absolute growth values (observed growth and projected growth). The relative value is helpful for comparing trees regardless of their absolute growth, because it shows the proportional impact of topping. In this case it indicates, that while pine trees do experience some volume increment growth loss, in regards to topping this loss is statistically not significant when the absolute loss is considered.

Regarding possible environmental stressors, the first topping started in 2017 on two locations (1 and 3), then in 2019 on location 2 and 2021 on location 4. One explanation for the reduced volume increment could be the heat wave and drought of 2018 and accumulated temperature anomalies of 2019 and 2021 (Lhotka & Kyselý 2022). Spruce is less equipped to deal with heat stress, while pine is thought to suffer more from water stress (Kunert 2020). If trees are topped, the sudden injury and loss of photosynthetic material may further increase the stress (Jones et al. 2019) and the tree may shift resources away from diameter growth towards growth of lateral branches below the cut, resulting in reduced volume growth during that time.

For several trees the observed growth was higher than the projected growth, which in that case would show increment gain instead of increment loss. An explanation for the higher observed growth could be, that prior to the event these trees experienced some negative impact. This would then show in the projected growth, since it is based on the observed growth prior to the event. But if that tree has a good recovery from the negative impacts, the actual growth post event would be higher. Another explanation is, that an error during tree-ring measurement of the rings past the event occurred, which would depict the growth higher than it actually is. Since topping seems to have no negative effect on the volume growth of pine, the calculated losses that occur for topped pine trees might be the result of other factors not included in this study, e.g. reduced increment growth due to temperature and water stress.

The effect of different locations is considered to be minimal for both species, therefore for spruce either the topping itself or other factors such as environmental stressors (or a combination of both) could be an explanation for the reduced volume growth. However, to show, if there are any significant long-term effects regarding fungi infections it would be good to measure topped trees a longer time-period after the topping, especially in younger stands.

An interesting observation was that the trees sampled in the first and third locations, which were topped in 2017, showed a lower mean loss of volume increment than the trees in locations topped in 2019 and 2021. An explanation for this could be, that the trees had more time to at least partially recover from topping by reclaiming photosynthetic capacity via growth of lateral branches (Långström & Hellqvist 1992).

It is assumed, that the better growth of topped spruce trees before the event is due to naturally better growth, which caused those trees to be selected for topping in the first place. This could likely be the effects of better site conditions or genetics. This also means, that for spruce the growth of control trees cannot be compared with the growth of topped trees, since they display different growth behaviours. For pine the comparison of topped and control trees is possible, since no significant different in the volume growth behaviour prior to topping could be detected.

Since so far no values exists for stand sizes, stand density or per ha values, it is difficult to make an estimation regarding economic losses for the forest owner. It was possible to show the mean increment loss as well as a mean loss in monetary values per topped tree on each site, based on the average of the trees per location. However, topped trees presumably form only a small part of a forest stand, so the real economic impact cannot be assessed in this paper due to lack of stand and hectare values. Also the calculation is operating under the assumption, that the growth behaviour of the trees will not change from its behaviour of the calculation period (year of topping till felling). Especially for economic calculations regarding the value of topped trees several years into the future, it would be good to measure tree growth of topped trees again after a certain period, e.g. 10 years or more. This could give an answer to how much the topping itself and possible infections with pathogenic fungi after the topping influence future tree growth.

The results of this study should not be used to make estimations about volume growth on stand level, due to edge effects. Since this thesis studied only trees close to the power line corridor, which is an open area (see Figure 1), edge effects like more light availability, higher air and soil temperature, higher wind speeds, less soil moisture and lower humidity (Gehlhausen et al. 2000) can influence the tree growth behaviour (Pöpperl & Seidl 2021) and make those trees incomparable with trees that are not influenced by edge effects.

The sample size for this study (N=40) was considered adequate since earlier publications (Wang et al. 2014; Drobyshev et al. 2019) have shown that a similar sample size is sufficient enough for the analysis.

Helicopter topping practise did not predominantly affect tree growth. More precisely, the fungal infections forming in the tops as a result of open wounds did not have negative effects on the volume increment of the trees. Since the surrounding trees are also less likely to be damaged, if they are topped by helicopters and not removed using conventional methods (chainsaw, harvester), helicopter topping can be recommended as a viable method to secure powerlines.

# 5. Conclusion

Based on the current study, helicopter topping might be having a negative impact on the volume growth of spruce trees, but not on pine trees. Infections of the topping injury with pathogenic fungi had no detrimental effect on the volume growth of spruce and pine trees. Base infections also had no influence on spruce tree

Mean loss of volume increment growth and corresponding monetary loss per species and location occurred for both species. Since the growth of pine trees was not affected by the topping, the most likely causes for the loss are environmental factors like temperature and water stress, that caused a growth decline.

An increased sample size and measurements of topped trees least a decade after topping or longer could help to determine, how much exactly the trees can recover from topping and how much external factors (drought, heat waves) play a role in volume growth reduction. This would also be helpful with calculations regarding the future value loss of topped trees.

Since helicopter topping also causes less damages to the surrounding trees than other methods, it can be recommended as an alternative to completely removing trees that might threaten the powerlines.

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# Popular science summary

## Tree topping via helicopter – what are the risks?

To prevent power outages, especially in areas where power lines run through forests, a method called helicopter topping is often used. In this process, helicopters equipped with saws trim off the tops of trees that are close to power lines, usually cutting off about 2 to 2.5 meters. This way, if a storm causes a tree to fall, it will not hit the power lines.

While this method is fast and cost-effective, it raises some concerns about the health of the trees and the financial impact on forest owners. When the top of a tree is removed, it can reduce the tree's ability to do photosynthesis and slowing its growth. The cut can also leave the tree vulnerable to infections from fungi.

Therefore this article explores the effect of topping on tree growth and possible negative economic effects. The results suggest that topping does reduce the growth of spruce trees, but pine trees do not seem to be negatively affected by topping. And while several topped trees had infections with fungi from their topping wounds, those did not seem to affect the growth of pine and spruce trees negatively.

Even though pine trees were not visibly affected, for both tree species economic losses could still be calculated. This could be due to other environmental stressors, like drought and high temperatures, which occurred around the same time as the topping.

Due to the short observation period and lack of forest stand data, it is difficult to draw conclusions about the long-term effects of topping, infections and calculating applicable results regarding economic consequences.

However, the results suggest that helicopter topping can be recommended as a practical method to keep powerlines secure.

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