Tree ring and dendrometer BAI relationships along different stem heights in Norway spruce

Deli Lei

Degree project/Independent project • 30 credits
Swedish University of Agricultural Sciences, SLU
Faculty of Forest Sciences
SUFONAMA
Alnarp, Sweden 2026

Tree ring and dendrometer BAI relationships along different stem heights in Norway spruce

Deli Lei

Supervisor:	Amanda de Castro Segtowich, SLU, Southern Swedish Forest Research Centre
Assistant supervisor:	Emma Holmström, SLU, Southern Swedish Forest Research Centre
Assistant supervisor:	Emily Viola Delin, SLU, Southern Swedish Forest Research Centre
Examiner:	Leonie Schönbeck, SLU, Southern Swedish Forest Research Centre

Credits:	30 credits
Level:	A2E
Course title:	Master's thesis in Forestry Science
Course code:	EX1034
Programme/education:	SUFONAMA
Course coordinating dept:	Department of Southern Swedish Forest Research Centre
Place of publication:	Alnarp, Sweden
Year of publication:	2026
Copyright:	All featured images are used with permission from the copyright owner.
Keywords:	Picea abies, dendrochronology, dendrometers, basal area increment, mixed-effects models

Swedish University of Agricultural Sciences
Faculty of Forest Sciences
Department of Southern Swedish Forest Research Centre

Abstract

Dendrometer measurements provide a non-destructive method for monitoring stem growth, whereas tree-ring analysis represents a traditional but destructive approach commonly used in dendrochronology. This study assessed the relationship between dendrometer-derived basal area increment (BAI_D) and tree-ring-derived basal area increment (BAI_{TR}) along the trunk of Norway spruce (*Picea abies*) and investigated whether root rot affects this relationship. The study was conducted at the Asa Research Station in southern Sweden, where 10 Norway spruce trees were selected from two plots, one of which was affected by root rot. Stem diameter measurements taken at breast height (1.3 m) using dendrometers to determine annual basal area increment (BAI_D) and compared with tree-ring-derived basal area increment (BAI_{TR}) at various heights along the stem (Base, 1.3 m, 4 m, 8 m, 12 m, 16 m, 20 m and 24 m). The results showed positive correlations between BAI_D and BAI_{TR}, with the strongest correlation observed at breast height (Pearson's r = 0.891). Model performance generally declined with increasing tree height, with the weakest correlations observed at 24 m. Including root rot as a factor slightly improved model fit, although this effect was not statistically significant. The results indicate that dendrometer measurements taken at breast height provide reliable estimates of overall annual stem growth in Norway spruce, particularly at lower stem positions. However, growth patterns become increasingly variable with increasing height. This study demonstrates the potential of the dendrometer as a non-destructive tool for long-term forest growth monitoring, whilst also highlighting the importance of accounting for vertical variation within the stem and root rot.

Keywords: Picea abies, dendrochronology, dendrometers, basal area increment, mixed-effects models

Table of contents

List of tables 5

List of figures 6

Abbreviations 7

1. Introduction 8
1.1 Norway Spruce in Swedish forestry 8
1.2 Climate change effect 9
1.3 Dendrochronology 9
1.4 Dendrometers 10
1.5 Hypotheses 11
1.6 Aim 11

2. Materials and Methods 12
2.1 Research area 12
2.2 Sampling Design 13
2.3 Dendrochronological analysis 13
2.4 Calculation of BAI 14
2.5 Statistical analysis 14
    2.5.1 Pearson correlation analysis 14
    2.5.2 Mixed-effects model 15
2.6 Model performance 15
    2.6.1 Residual diagnostics 15
    2.6.2 Random effects 15
    2.6.3 Statistical modeling 16

3. Result 17
3.1 Temporal variation in BAI across stem heights 17
3.2 Effect of root rot on model performance 17
3.3 Effect of height on model performance 18

4. Discussion 23
4.1 Relationship between BAI_D and BAI_{TR} 23
4.2 Vertical variation in growth relationships 23
4.3 Influence of root rot on growth relationships 24
4.4 Potential of non-destructive growth estimation 24
4.5 Limitations and future perspectives 24

References 26

Popular science summary 29

Appendix. Photographs from field sampling and stem disc collection 30

List of tables

Table 1. The tree characteristics used in this study include plot, tree ID, diameter at breast height. 13

Table 2. Pearson correlation between BAID and BAITR at different stem heights. 18

Table 3. Fixed-effect estimates from the mixed-effects model (1.3m as reference height). 20

List of figures

Figure 1. Location of the Asa research station and the experimental plots used in this study. 12

Figure 2. Tree-ring width measurement using CooRecorder software. 14

Figure 3. Mean annual basal area increment (BAI) derived from tree rings (BAI_{TR}) at different stem heights in Plot 3(A) and Plot 4(B) from 1993 to 2023 (n=5 trees per plot). 17

Figure 4. Comparison between dendrometer-derived annual BAI (BAI_D) and tree-ring-derived BAI (BAI_{TR}) at breast height. Error bars represent ±1 standard error (SE) of the mean (n = 10 trees). 19

Figure 5. Variation in the relationship between BAI_D and BAI_{TR} along the stem predicted by the mixed-effects model. 20

Figure 6. Fixed-effect slopes of general mixed-effects (without root rot) models across stem positions. 21

Figure A 1. Field sampling procedure. Trees were felled in the field (left), and predefined stem heights were measured and marked before stem disc sampling (right). . 30

Figure A 2. Examples of root rot observed in sampled Norway spruce trees in the study plots 3. 30

Abbreviations

Abbreviation	Description
BAI	Basal area increment
BAI_D	Annual basal area increment derived from dendrometers
BAI_{TR}	Annual basal area increment derived from tree rings

1. Introduction

1.1 Norway Spruce in Swedish forestry

Norway spruce (*Picea abies*) is one of the most significant and economically valuable tree species in Swedish forestry, occupying a central position in terms of forest area, timber production, and forest management systems (Hannrup et al. 2004). Among Sweden's approximately 30 native tree species, Norway spruce and Scots pine (*Pinus sylvestris*) are the two dominant species, accounting for 41% and 40% of Sweden's standing forest volume (SLU 2018). Norway spruce is widely distributed across most forested areas in southern, central, and northern Sweden, exhibiting particularly high growth potential in sites of medium to high productivity (FAO 2025).

The most common forestry practice in Sweden is the rotation felling of even-aged monoculture stands of Norway spruce or Scots pine (SLU 2018). As Norway spruce is recommended for moderately to fertile moist sites, most Norway spruce stands are concentrated in southern Sweden, rather than in the poorer soils of the north (Nilsson et al. 2019). The root system is generally shallow, with numerous lateral roots and no taproot. In rocky areas, the roots spread out widely and cling to the rocks. In peat soils, Norway spruce tends to form a mat-like root system (Sullivan 1994). The growth of Norway spruce is sensitive to climate, with drought being one of the key climatic factors affecting its growth -- precipitation has a greater impact on Norway spruce than temperature (Rybníček et al. 2010). Norway spruce is sensitive to early summer precipitation, and radial growth responds positively to spring temperatures, particularly in low-latitude regions (Ogana et al. 2024). In addition, drought tolerance increases linearly with latitude.

In addition to drought sensitivity, the main threats facing Norway spruce in Nordic countries are root rot caused by *Heterobasidion annosum s.l.* and the European spruce bark beetle (*Ips typographus*) (Piri & Vainio 2024; Wahlman 2024). As the climate warms, root rot is expected to have an increasingly severe impact on spruce-dominated forests (Wahlman et al. 2025). It enters Norway spruce via fresh wounds or stumps, spreads vertically within the heartwood, and is transmitted between trees through root contact. It causes decay in the heartwood and root system, reducing the quality of the timber whilst increasing the risk of the trees breaking during storms (Rommel 2012). Bark beetle penetrates the bark via pioneer individuals, which release pheromones to trigger a mass attack, thereby breaching the tree's defences; it then reproduces within the phloem and, with the aid of symbiotic fungi, further weakens the tree, ultimately causing its death (Toffin et al. 2018).

1.2 Climate change effect

The IPCC's Sixth Assessment Report (AR6) reveals that global temperatures have risen by 1.1°C, with all regions of the world facing unprecedented changes to the climate system, ranging from rising sea levels and frequent extreme weather events to the rapid melting of sea ice (IPCC 2023). Further rises in temperature will only exacerbate these changes.

Data from the European Drought Observatory (EDO) shows that droughts in Sweden have become increasingly frequent since 2001. Furthermore, the latest figures indicate that 47% of the EU is under a drought 'early warning', whilst 17% is under a drought 'alert'. The World Meteorological Oganization's (WMO's) 2025 State of the Global Climate Report confirms that the period from 2015 to 2025 was the hottest 11-year span on record, with 2025 ranking among the three hottest years on record, with temperatures approximately 1.43°C above the 1850–1900 average.

In the Nordic countries, rising temperatures are expected to alter the growth conditions of Norway spruce and Scots pine. Warmer conditions may promote earlier and more rapid photosynthesis in spring and prolong photosynthetic activity in autumn, thereby extending the growing season (Bergh et al. 2003). However, higher temperatures also increase evapotranspiration and water demand, which can intensify drought stress. As soil moisture declines below critical thresholds, water availability becomes limited, reducing tree growth and transpiration. Consequently, drought has become an increasingly important factor affecting the growth and survival of Norway spruce in recent decades. Severe and recurrent drought events have been identified as major causes of tree decline and mortality across Europe (Bréda et al. 2006). Temperate forests are particularly vulnerable to both short-term extreme drought events and long-term trends toward drier climatic conditions (Bréda et al. 2006). For example, the extreme heat and drought during the summer of 2018 had substantial drought impacts on Scandinavian forests. Climate projections further suggest that such extreme events may occur more frequently in the future, potentially increasing the ecological vulnerability of Nordic forest ecosystems (Rousi et al. 2023).

1.3 Dendrochronology

Dendrochronology is a scientific discipline that studies the formation and variation of tree rings to obtain information about time and the environment. By analysing the width, density and structural characteristics of tree rings, it can not only accurately determine the age of a tree, but also reconstruct past climate changes, environmental conditions and tree growth patterns (Fritts 1976; Speer 2010). Tree ring analysers are widely used to monitor changes in stem diameter and the annual growth patterns of trees.

Tree rings are a form of ecological memory, representing radial growth patterns recorded over time. Due to their clear structure, high temporal resolution and widespread distribution, tree rings are widely used as a tool for assessing the response of forest ecosystems to environmental changes, particularly in long-term time series (Zhou et al. 2020). Generally speaking, conifers in arid or cold regions form distinct annual growth rings, the width of which correlates with climatic conditions in the corresponding year and the preceding year (Fritts 1976).

In most cases, tree-ring width reflects environmental conditions. Factors such as frost or summer drought may have an immediate effect on tree-ring width, whereas factors such as winter drought may have a delayed effect, as the growing tissue is dormant (Koprowski & Zielski 2006). Tree growth is typically quantified by ring width, but ring width does not directly reflect biomass production. Consequently, basal area increment (BAI) is widely used in dendrochronological research as a more biologically meaningful indicator of tree growth (Biondi & Qeadan 2008).

1.4 Dendrometers

A dendrometer is an instrument used to measure the diameter of a tree trunk. Unlike tree-ring analysis, which requires destructive sampling, dendrometers can be installed on living trees and measured repeatedly over long periods of time (Clark et al. 2000). This makes them particularly useful in long-term forest experiments, where the same trees are monitored over many years.

Changes in stem diameter recorded by dendrometers are closely related to tree growth and environmental conditions. Previous studies have shown that stem radius variations are sensitive to climatic factors such as temperature and precipitation (King et al. 2013), and that dendrometer measurements can be used to track seasonal and interannual growth patterns in conifer species, including Norway spruce (Deslauriers et al. 2007).

Many long-term forest experiments in Sweden include dendrometer measurements at different time intervals throughout the growing season e.g. biweekly or monthly. Therefore, a better understanding of the correlation between dendrometer-derived and tree-ring-derived growth measurements would increase the value of existing dendrometer datasets. In particular, evaluating how the relationship between BAI_D measured at breast height and BAI_{TR} varies along the stem may improve our understanding of the extent to which dendrometer measurements reflect growth at different stem positions. The dendrometers used in this study were manual band dendrometers installed at breast height.

Within this context, the following research questions were raised: (i) Does root rot influence the relationship between BAI_D and BAI_{TR}? (ii) Does the relationship between basal area increment (BAI) at 1.3 m derived from dendrometers (BAI_D) and tree ring BAI (BAI_{TR}) vary with stem height? (iii) How well does BAI_D explain BAI_{TR} at different stem heights?

1.5 Hypotheses

H1

BAI_D measured at breast height (1.3 m) is positively correlated with BAI_{TR} throughout the stem, with the strongest correlation expected at 1.3m and progressively weaker relationships at increasing stem heights.

H2

The slope of the relationship between BAI_D and BAI_{TR} is expected to decrease with increasing stemn height since 1.3m.

H3

Root rot is not expected to affect the correlation between BAI_D and BAI_{TR}.

1.6 Aim

This study aims to evaluate whether basal area increment obtained from dendrometer measurements (BAI_D) correlates with BAI_{TR} derived from tree-ring analysis at different heights along the stem. The study also examines if this relationship changes in different stem heights and whether root rot has a significant effect on growth patterns.

2. Materials and Methods

2.1 Research area

The study was conducted at the Asa Research Station, located north of Växjö in southern Sweden (Figure 1). The study area lies within a semi-northern climate zone, with an average annual temperature of approximately 5.6°C. The station's geographical coordinates are approximately 57.16°N, 14.78°E, and it lies at an altitude of approximately 182 metres.

The station comprises three main research areas: the Asa Experimental Forest, the Asa High-Yield Experimental Forest and the Anneboeda Research Area. Established in 1988, the station covers an area of approximately 1,010 hectares, of which around 900 hectares are productive forest land.

The forest vegetation is dominated by coniferous species, with approximately half the area comprising Norway spruce (*Picea abies*), whilst the remaining areas consist of mixed coniferous and pine forests interspersed with deciduous species. The Asa Experimental Forest is managed using traditional methods and is primarily used for research into forest production and management.

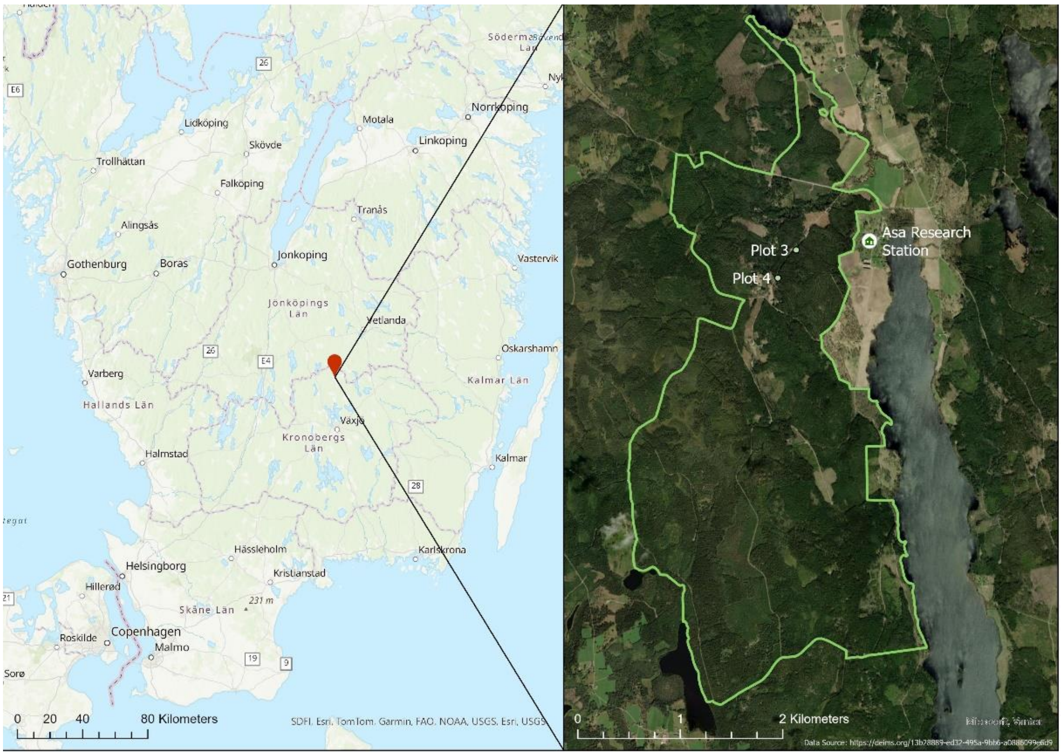

Figure 1. Location of the Asa research station and the experimental plots used in this study.

2.2 Sampling Design

The study area consists of ten circular plots distributed across different locations within the Asa Experimental Station. Each plot has a radius of 10 metres. For this study, two of these ten plots were selected (Plot 3 and Plot 4) (Figure 1). All sampled trees in plot 3 were affected by root rot.

Within each selected plot, five Norway spruce trees were chosen as sample trees, making a total of ten trees (Table 1). Dendrometer bands were installed at breast height (1.3 m) on all sample trees to monitor stem radial growth. Measurements were conducted repeatedly throughout the growing season, approximately every two weeks. For this study, I used only the first and last dendrometer measurements of the year to be able to capture the annual BAI of the individual trees. For dendrochronological analysis, stem discs were collected from the trunks of each sample tree at various heights. Sampling points included the base of the trunk and at breast height (1.3 m), followed by further sampling at 4-metre intervals (4 m, 8 m, 12 m, 16 m, 20 m and 24 m).

Table 1. The tree characteristics used in this study include plot, tree ID, diameter at breast height.

Plot	Tree ID	Diameter (cm)
3	1	17.19
3	7	25.97
3	21	29.70
3	30	18.91
3	37	18.69
4	8	23.71
4	14	23.63
4	27	24.22
4	38	22.00
4	47	20.32

2.3 Dendrochronological analysis

The stem discs collected from each tree were processed in accordance with standard dendrochronological procedures (Speer 2010). First, the discs were cut into blocks using an electric saw to facilitate handling and scanning. The samples were then sanded and polished using sandpaper of progressively finer grit to achieve a smooth surface, making the growth rings clearly visible.

Tree ring widths were measured using CooRecorder and CDendro software. The boundaries of the tree rings were marked by visual inspection using CooRecorder, and measurements were taken in the two direction. The data processed by CooRecorder was then imported into CDendro to extract the digitised ring width data. The resulting tree-ring width was used for further analysis, including the calculation of basal area increment from tree ring data ($\mathrm{BAI_{TR}}$).

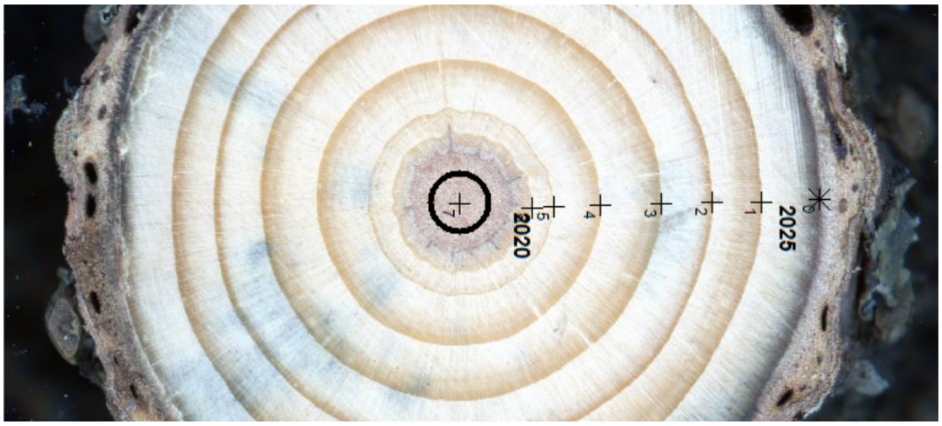

Figure 2. Tree-ring width measurement using CooRecorder software.

2.4 Calculation of BAI

Basal area increment ($\mathrm{BAI_D}$) derived from dendrometer measurements was calculated based on annual stem circumference measurements, considering the first and last radial measurements taken in the beginning of the growing season and at the end of the growing season. Circumference measurements were converted to stem diameter assuming a circular stem cross-section. Basal area was then calculated as:

$$BA_t = \pi \left(\frac{D_t}{2}\right)^2$$

where D_t is the stem diameter at year t. Annual BAI was then calculated as the difference between consecutive years:

$$BAI_t = BA_t - BA_{t-1}$$

2.5 Statistical analysis

2.5.1 Pearson correlation analysis

Pearson correlation analysis was used to quantify the strength of the linear relationship between dendrometer-derived annual basal area increment (BAID) measured at breast height (1.3 m) and tree-ring-derived annual basal area increment (BAITR) at each sampling height along the stem. Correlation coefficients (r) and associated p-values were calculated separately for each height. Correlation coefficients range from −1 to 1, where values closer to 1 indicate a stronger positive relationship, values closer to −1 indicate a stronger negative relationship, and values near 0 indicate little or no linear relationship (Zar 2010). All analyses were conducted in R version 4.5.0.

2.5.2 Mixed-effects model

Linear mixed-effects model was used to analyse the relationship between annual basal area increment at breast height (BAI_D) and basal area increment measured from tree-ring analysis at different stem heights (BAI_{TR}). The model was fitted using the lme() function from the nlme package in R (Pinheiro et al. 1999). BAI_{TR} was used as the response variable. Sampling height, BAI_D, their interaction, and the presence or absence of root rot were included as fixed effects, while tree identity was treated as a random effect.

Before analysis, the data was transformed using the square root transformation (sqrt) to linearize the data and to achieve normality of the residuals.

$$\sqrt{BAI_{TR,ij}} = \beta_0 + \beta_1\sqrt{BAI_{D,ij}} + \beta_2 H_{ij} + \beta_3(\sqrt{BAI_{D,ij}} * H_{ij}) + \beta_4 R_{ij} + u_i + v_j + \varepsilon_{ij}$$

Where $\sqrt{BAI_{TR,ij}}$ is the square-root transformed tree-ring-derived basal area increment for tree i, and year j. $\sqrt{BAI_{D,ij}}$ is the square-root transformed dendrometer-derived basal area increment, H_{ij} is stem height, and R_{ij} is root rot status. The terms u_i and v_j represent the random effects of tree identity and year. AIC comparison and ANOVA tests were performed on the models assessing the impact of root rot and the interaction between BAI_D and height on the stem.

2.6 Model performance

2.6.1 Residual diagnostics

Residual diagnostics were performed to assess the model assumptions. Homoscedasticity and model fit were evaluated by examining plots of residuals against fitted values. This method is capable of detecting systematic patterns or heteroscedasticity in the residuals.

2.6.2 Random effects

The contribution of random effects is assessed by examining the variance components associated with each random factor. In this study, I treat tree ID and year as random variables. The variance based on tree ID is used to assess inter-individual variation, whilst the variance attributable to year is used to capture interannual variation in growth. To measure the impact of root rot, the term ‘plot’ was included in the model fitting when root rot is present in one plot but absent in another.

2.6.3 Statistical modeling

All statistical analyses were conducted using R (version 4.5.0; R Core Team, Vienna, Austria) in RStudio (version 2024.12.1; Posit Software, PBC). Data processing, visualization, and modeling were performed using relevant R packages.

3. Result

3.1 Temporal variation in BAI across stem heights

Figure 3 shows the interannual variations in the average BAI at different stem heights for Plot 3 (A) and Plot 4 (B). It can be seen that the BAI is highest at the base for both plots; the higher the measurement, the smaller in BAI, and a peak occurred between 2008 and 2010. Fluctuation decreases with increasing height, and the curve at 24 m flattens noticeably compared to the Base level. Overall, the BAI is also lower in Plot 3 than in Plot 4.

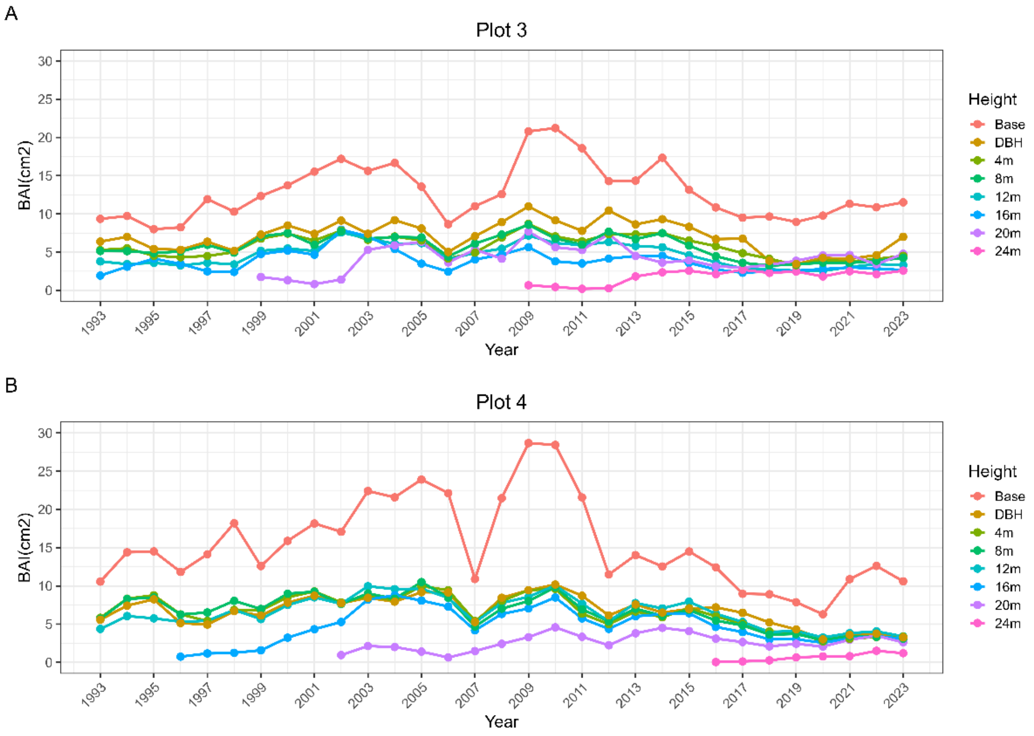

Figure 3. Mean annual basal area increment (BAI) derived from tree rings (BAI_{TR}) at different stem heights in Plot 3(A) and Plot 4(B) from 1993 to 2023 (n=5 trees per plot).

3.2 Effect of root rot on model performance

The AIC of the model including root rot was slightly lower (1824.95) than that of the model without root rot (1826.78), indicating a small improvement in model fit when root rot was included. However, the root rot term was not significant in the general model ($p = 0.0505$). The fact that $\Delta AIC < 2$ further indicates that this improvement is not significant, meaning that root rot does not have a strong overall impact on the model.

The BAI is also lower in Plot 3 than in Plot 4 (Figure 3). This may be due to the influence of root rot in Plot 3. However, as the formula was established by modelling the BAI_D and BAI_{TR} of the same tree, the differences between plots have a relatively minor impact.

3.3 Effect of height on model performance

Pearson correlation analysis indicated a significant positive relationship between BAI_D and BAI_{TR} across most stem heights (Table 2). The strongest correlation was observed at breast height (1.3 m). Correlation strength generally decreased with increasing stem height, although strong relationships were still observed from the stem base up to 16 m. The relationship became notably weaker at 20 m and was no longer significant at 24 m. The result at 24 m should be interpreted with caution because of the substantially smaller sample size available at this height.

Table 2. Pearson correlation between BAID and BAITR at different stem heights.

Height	n	Pearson's r	p-value
Base	310	0.728	<0.001
1.3 m	310	0.891	<0.001
4 m	310	0.855	<0.001
8 m	310	0.815	<0.001
12 m	310	0.743	<0.001
16 m	254	0.717	<0.001
20 m	130	0.381	<0.001
24 m	29	-0.024	0.903

Figure 4 shows that between 1993 and 2009, although there were some fluctuations, the overall trend was one of steady increase, peaking between 2008 and 2010. The trend declined steadily after 2012, before recovering slightly after 2021. This figure shows that the data derived from dendrometers (BAI_D) was able to capture the overall trend of BAI_{TR} at 1.3 m over the years.

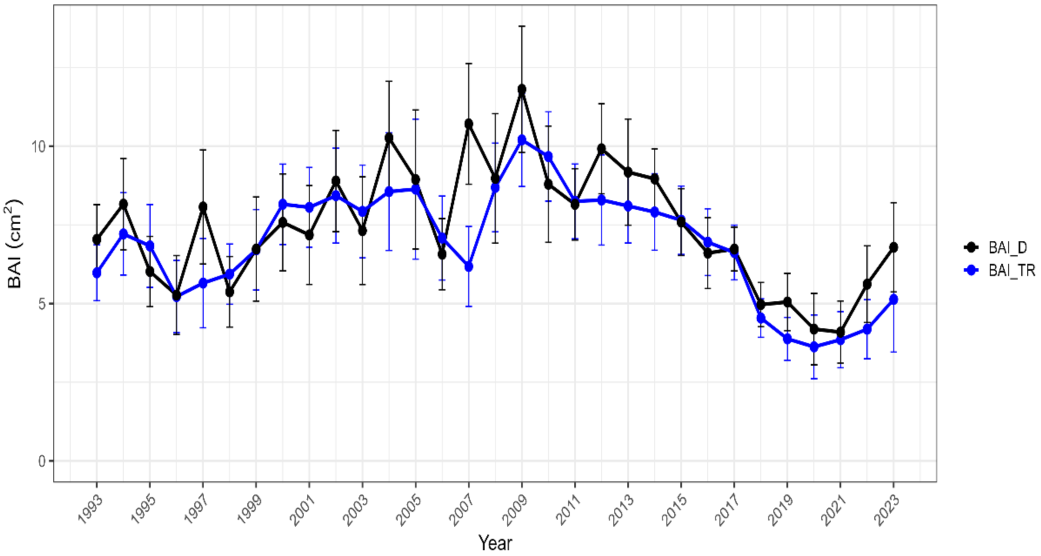

Figure 4. Comparison between dendrometer-derived annual BAI (BAI_D) and tree-ring-derived BAI (BAI_{TR}) at breast height. Error bars represent ±1 standard error (SE) of the mean (n = 10 trees).

Figure 5 shows that the slope is positive from the Base to 20 m, indicating that as annual BAI_D increases, the model-predicted BAI_{TR} also increases. This trend is evident across height classes: Base, 1.3m, 4 m, 8 m, 12 m, 16 m and 20m. Among these, the positive relationship is most evident for 1.3m and 4m, with the data points distributed more concentratedly compared to the other categories. This is consistent with the higher Pearson's r for 1.3m and 4m height shown in Table 2, further demonstrating that the model exhibits greater explanatory power at the 1.3m height. Although 8m and 12m still show a positive correlation, the scatter of data points is more dispersed than for 1.3m and 4m, indicating that the model's explanatory power begins to diminish.

The 24 m model is the most unusual. Its blue fitted line shows a downward trend, indicating that, at this height, as the annual BAI increases, the predicted BAI for this height actually decreases.

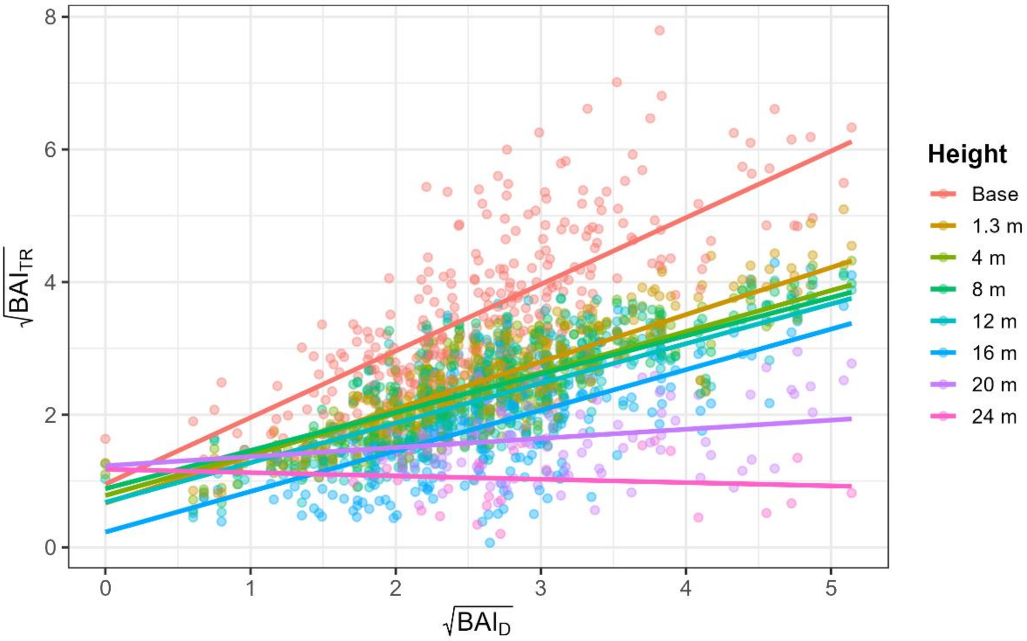

Figure 5. Variation in the relationship between BAI_D and BAI_{TR} along the stem predicted by the mixed-effects model.

The fixed-effect estimates of the mixed-effects model are presented in Table 3. Significant effects were detected for $\sqrt{BAI_D}$ and several height classes. BAI_D showed a significant positive effect on BAI_{TR}. Several stem heights differed significantly from the reference height (1.3 m), although the significance of the height effect varied among stem positions. Significant interaction terms were observed between annual BAI_D and all stem heights. The interaction coefficient was positive at the Base and progressively more negative towards the upper stem positions, with the strongest negative interaction estimates occurring at 20 m and 24 m.

Table 3. Fixed-effect estimates from the mixed-effects model (1.3m as reference height).

Fixed effect	Estimate	SE	p-value
Intercept	0.666	0.113	<0.001
$\sqrt{BAI_D}$	0.711	0.036	<0.001
Height.Base	0.286	0.123	0.020
Height.4m	0.116	0.059	0.050
Height.8m	0.218	0.058	<0.001
Height.12m	0.013	0.079	0.868
Height.16m	-0.436	0.133	0.001
Height.20m	0.564	0.198	0.004
Height.24m	0.511	0.333	0.125

Fixed effect	Estimate	SE	p-value
$\sqrt{BAI_D}$ × Height.Base	0.294	0.045	<0.001
$\sqrt{BAI_D}$ × Height.4m	-0.092	0.022	<0.001
$\sqrt{BAI_D}$ × Height.8m	-0.134	0.021	<0.001
$\sqrt{BAI_D}$ × Height.12m	-0.113	0.029	<0.001
$\sqrt{BAI_D}$ × Height.16m	-0.099	0.047	0.036
$\sqrt{BAI_D}$ × Height.20m	-0.573	0.065	<0.001
$\sqrt{BAI_D}$ × Height.24m	-0.760	0.106	<0.001

Figure 6 shows the slopes of the model without the influence of root rot at different heights. It can be seen that the slope at Base exhibits a maximum value of 1.00 here, whilst the 24 m model has a minimum value of −0.05. As the height increases from Base to 8 m, the slope gradually decreases; it rises slightly at 12 m but drops sharply at 20 m, showing a trend similar to that of the mixed models at different heights.

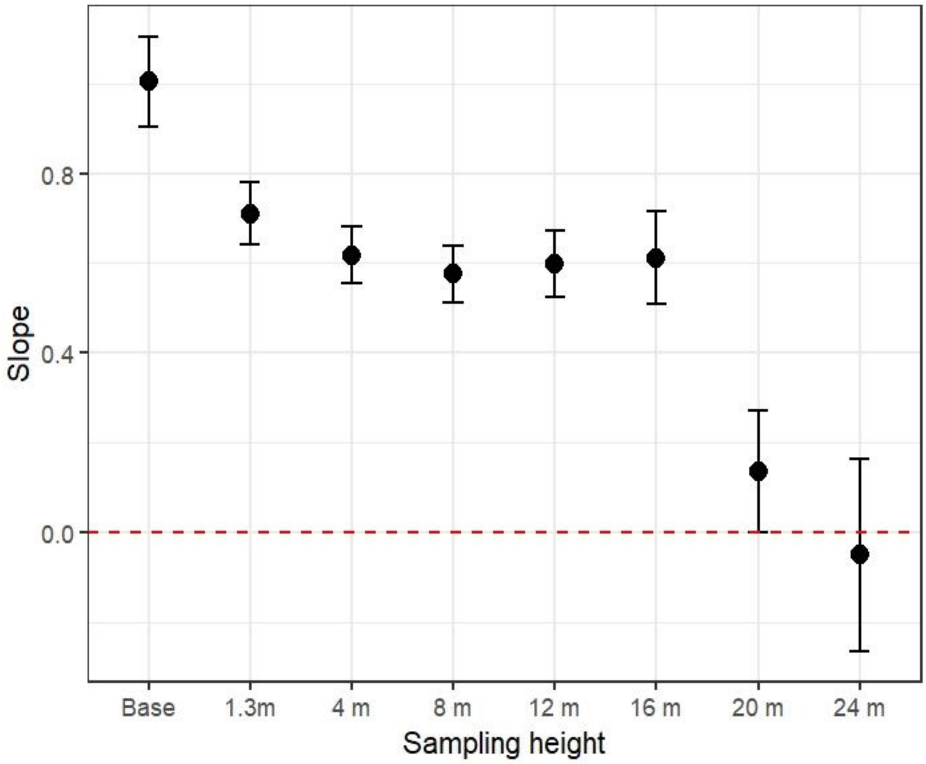

Figure 6. Fixed-effect slopes of general mixed-effects (without root rot) models across stem positions.

The slope is steepest at the Base and gradually flattens with increasing height, indicating that the relationship between BAI$_{D}$ and BAI$_{TR}$ weakens progressively higher up the stem. A positive correlation persists at 4 m, 8 m,12 m and 16 m, although the rate of radial growth decreases with height. At 20 m, and particularly at 24 m, this relationship is weaker, suggesting greater variability or reduced performance in the upper part of the stem.

4. Discussion

4.1 Relationship between BAI_D and BAI_{TR}

The results indicate that there is a positive correlation between BAI_D and BAI_{TR} for Norway spruce, with the correlation being the strongest at the same height as BAI_D (1.3 m), where the Pearson's r is highest. The results indicate that BAI_D reflects the growth status of the whole stem to a certain extent.

It is to be expected that the strongest correlation is observed at 1.3 m, as the BAI_D and BAI_{TR} samples modelled at this height are both taken from the same position on the trees. DBH measurements are widely used in forest ecology and forest inventories, as an increase in diameter at breast height serves as a practical and reliable indicator of tree growth and biomass accumulation (Pretzsch 2009). As the most common location for forest surveys, DBH and its variants, such as the quadratic mean DBH, basal area per hectare, and basal area of larger trees, are widely used in production activities (Ciceu et al. 2022). This result supports the use of dendrometer measurements as a non-destructive method for estimating annual stem growth.

BAI_D showed temporal patterns broadly similar to those observed for BAI_{TR} throughout the study period. This indicates that both methods captured comparable long-term growth trends, despite differences in measurement approach.

4.2 Vertical variation in growth relationships

The relationship between BAI_{TR} and BAI_D decreases with increasing height; a possible reason for this is uneven growth resulting from carbon allocation (Lacointe 1998). Most of the nutrients required for tree growth are absorbed by the roots and transported to the upper parts of the tree via transpiration (Oberhuber et al. 2017). At the same time, the lower stem serves a mechanical support function and therefore requires a more robust structure (Lehtonen et al. 2025). The upper parts are also subject to factors such as water limitation and are more significantly influenced by climatic conditions than the lower parts (Zweifel et al. 2005).

The negative correlation observed at 24 m may indicate a weakening of the coupling between breast-height growth and radial growth near the crown. This may suggest that the relationship between BAI_D and BAI_{TR} at the 24 m height is unstable, or it may be influenced by insufficient sample size or noise in the upper canopy structure.

4.3 Influence of root rot on growth relationships

A comparison of the root rot models reveals that the AIC of the model including root rot is slightly lower, indicating a slight improvement in the model. However, as this difference is not statistically significant, it suggests that root rot has little effect on the relationship between BAI_D and BAI_{TR} in this study.

There is a limitation that root rot status was confounded with plot identity. All trees affected by root rot were located in Plot 3, whereas all non-infected trees were located in Plot 4. As a result, the effects of root rot could not be fully separated from plot influences, such as differences in site conditions, stand structure, or microclimate. Therefore, the observed differences between infected and non-infected trees should be interpreted with caution.

The size of the trees, altitude and the proportion of forest cover may all influence the incidence of root rot (Suvanto et al. 2026). Root rot infection is also associated with reduced diameter growth and increased physiological stress in Norwegian spruce stands (Wahlman 2024). The absence of a strong root rot effect may be related to the limited sample size in this study. Furthermore, as the years in which the trees were affected by root rot are unknown, it is possible that the trees were infected close to the time of harvest, thereby minimising the impact.

4.4 Potential of non-destructive growth estimation

The results of this study demonstrate the potential of dendrometer measurement as a non-destructive tool for monitoring annual tree growth. Compared with traditional tree ring analysis, dendrometer measurements do not require destructive sampling and can be collected repeatedly over extended periods. This makes dendrometers particularly useful in long-term forest monitoring programmes and climate growth studies.

The strong correlation between BAID and BAITR at lower stem heights indicates that manual dendrometers can reliably estimate annual stem growth in Norway spruce. However, the weaker relationship observed in the upper stem suggests that caution should be exercised when extrapolating measurements of growth at breast height to the entire stem profile.

4.5 Limitations and future perspectives

This study has several limitations. The sample size was relatively small, comprising only ten trees distributed across two plots. The limited number of samples taken from the upper stem height may have increased the uncertainty of model.

Future research should encompass a greater number of plots and trees across different site conditions and levels of root rot infection. A longer monitoring period would also aid in better understanding interannual growth variability. Furthermore, incorporating climatic variables such as temperature, precipitation and soil moisture would help explain the environmental drivers underlying the observed growth patterns. The use of high-resolution dendrometers with higher temporal resolution may also improve the accuracy of non-destructive growth monitoring.

Future studies could also evaluate the predictive capacity of the mixed-effects model by testing whether dendrometer-derived growth measurements at breast height can accurately predict radial growth along the entire stem. Such an approach would help determine the potential of dendrometers as a non-destructive tool for estimating whole-tree growth.

References

Bergh, J., Freeman, M., Sigurdsson, B., Kellomäki, S., Laitinen, K., Niinistö, S., Peltola, H. & Linder, S. (2003). Modelling the short-term effects of climate change on the productivity of selected tree species in Nordic countries. *Forest Ecology and Management*, 183 (1), 327–340. https://doi.org/10.1016/S0378-1127(03)00117-8

Biondi, F., & Qeadan, F. (2008). A theory-driven approach to tree-ring standardization: Defining the biological trend from expected basal area increment. Tree-Ring Research, 64(2), 81–96. https://www.researchgate.net/publication/228401214_A_Theory-Driven_Approach_to_Tree-Ring_Standardization_Defining_the_Biological_Trend_from_Expected_Basal_Area_Increment

Bréda, N., Huc, R., Granier, A. & Dreyer, E. (2006). Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. *Annals of Forest Science*, 63 (6), 625–644. https://doi.org/10.1051/forest:2006042

Ciceu, A., Bronisz, K., Garcia-Duro, J. & Badea, O. (2022). Age-independent diameter increment models for mixed mountain forests. *European Journal of Forest Research*,. https://link.springer.com/article/10.1007/s10342-022-01473-5

Clark, N., Wynne, R.H. & Schmoldt, D.L. (2000). A review of past research on dendrometers. *Forest Science. 46(4): 570-576*,. https://research.fs.usda.gov/treesearch/2112 [2026-05-14]

Deslauriers, A., Rossi, S. & Anfodillo, T. (2007). Dendrometer and intra-annual tree growth: What kind of information can be inferred? *Dendrochronologia*, 25 (2), 113–124. https://doi.org/10.1016/j.dendro.2007.05.003

FAO. (2025). The Second Report on the State of the World’s Forest Genetic Resources. Food and Agriculture Organization of the United Nations, Rome. https://doi.org/10.4060/cd4838en

Fritts, H.C. (1976). Tree Rings and Climate. Academic Press, New York. https://www.sciencedirect.com/book/monograph/9780122684500/tree-rings-and-climate

Hannrup, B., Cahalan, C., Chantre, G., Grabner, M., Karlsson, B., Bayon, I.L., Jones, G.L., Müller, U., Pereira, H., Rodrigues, J.C., Rosner, S., Rozenberg, P., Wilhelmsson, L. & Wimmer, R. (2004). Genetic parameters of growth and wood quality traits in Picea abies. Scandinavian Journal of Forest Research, 19 (1), 14–29. https://doi.org/10.1080/02827580310019536

Harrison, X.A., Donaldson, L., Correa-Cano, M.E., Evans, J., Fisher, D.N., Goodwin, C.E.D., Robinson, B.S., Hodgson, D.J. & Inger, R. (2018). A brief introduction to mixed effects modelling and multi-model inference in ecology. PeerJ, 6, e4794. https://doi.org/10.7717/peerj.479

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: Intergovernmental Panel on Climate Change. https://doi.org/10.59327/IPCC/AR6-9789291691647

King, G., Fonti, P., Nievergelt, D., Büntgen, U. & Frank, D. (2013). Climatic drivers of hourly to yearly tree radius variations along a 6 °C natural warming gradient. Agricultural and Forest Meteorology, 168, 36–46. https://doi.org/10.1016/j.agrformet.2012.08.002

Koprowski, M. & Zielski, A. (2006). Dendrochronology of Norway spruce (Picea abies (L.) Karst.) from two range centres in lowland Poland. Trees, 20 (4), 383–390. https://doi.org/10.1007/s00468-006-0051-9

Lacointe, A. (1998). Carbon allocation among tree organs: a review of basic processes and representation in functional–structural tree models. https://hal.science/hal-01191058v1

Lehtonen, A., Heikkinen, J., Boroski, C.A., Tikkasalo, O.-P., Rinne-Garmston, K.T., Sahlstedt, E., Korkiakoski, M., Kärkönen, A., Lintunen, A., Mäkinen, H., Peltoniemi, M., de Quesada, G., Salmon, Y., Young, G., Mäkipää, R. & Oren, R. (2025). Carbon allocation to roots of suppressed Norway spruce increases immediately after selection harvest. Forest Ecology and Management, 585, 122645. https://doi.org/10.1016/j.foreco.2025.122645

Nakagawa, S. & Schielzeth, H. (2013a). A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods in Ecology and Evolution, 4 (2), 133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x

Nakagawa, S. & Schielzeth, H. (2013b). A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods in Ecology and Evolution, 4 (2), 133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x

Nilsson, O., Hjelm, K. & Nilsson, U. (2019). Early growth of planted Norway spruce and Scots pine after site preparation in Sweden. Scandinavian Journal of Forest Research, 34 (8), 678–688. https://doi.org/10.1080/02827581.2019.1659398

Oberhuber, W., Gruber, A., Lethaus, G., Winkler, A. & Wieser, G. (2017). Stem girdling indicates prioritized carbon allocation to the root system at the expense of radial stem growth in Norway spruce under drought conditions. Environmental and Experimental Botany, 138, 109–118. https://doi.org/10.1016/j.envexpbot.2017.03.004

Ogana, F.N., Mensah, S., Karlsson, B., Löf, M., Felton, A. & Petersson, L.K. (2024). Growth response of Pinus sylvestris L. and Picea abies (L.) H. Karst. to climate conditions across a latitudinal gradient in Sweden. Agricultural and Forest Meteorology, 353, 110062. https://doi.org/10.1016/j.agrformet.2024.110062

Pinheiro, J., Bates, D., & R Core Team (1999). nlme: Linear and Nonlinear Mixed Effects Models. https://doi.org/10.32614/CRAN.package.nlme

Piri, T. & Vainio, E.J. (2024). Significance of Heterobasidion species among wood decay fungi in northern peatland forests. Forest Ecology and Management, 568, 122148. https://doi.org/10.1016/j.foreco.2024.122148

Pretzsch, H. (2009). Forest Dynamics, Growth and Yield: From Measurement to Model. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-88307-4

Rommel, S. (2012). Comparative analyses of Defense gene expression in Norway spruce sapwood. [Second cycle, A2E]. https://stud.epsilon.slu.se/4953/ [2026-04-07]

Rousi, E., Fink, A.H., Andersen, L.S., Becker, F.N., Beobide-Arsuaga, G., Breil, M., Cozzi, G., Heinke, J., Jach, L., Niermann, D., Petrovic, D., Richling, A., Riebold, J., Steidl, S., Suarez-Gutierrez, L., Tradowsky, J.S., Coumou, D., Düsterhus, A., Ellsäßer, F., Fragkoulidis, G., Gliksman, D., Handorf, D., Haustein, K., Kornhuber, K., Kunstmann, H., Pinto, J.G., Warrach-Sagi, K. & Xoplaki, E. (2023). The extremely hot and dry 2018 summer in central and northern Europe from a multi-faceted weather and climate perspective. Natural Hazards and Earth System Sciences, 23 (5), 1699–1718. https://doi.org/10.5194/nhess-23-1699-2023

Rubio-Cuadrado, Á., Camarero, J.J. & Bosela, M. (2022). Applying climwin to dendrochronology: A breakthrough in the analyses of tree responses to environmental variability. Dendrochronologia, 71, 125916. https://doi.org/10.1016/j.dendro.2021.125916

Rybníček, M., Čermák, P., Žid, T. & Kolář, T. (2010). Radial Growth and Health Condition of Norway Spruce (Picea Abies (L.) Karst.) Stands in Relation to Climate (Silesian Beskids, Czech Republic). Geochronometria, 36, 9–16. https://doi.org/10.2478/v10003-010-0017-1

SLU (2018). Skogsdata 2018: Aktuella uppgifter om de svenska skogarna från Riksskogstaxeringen. Institutionen för skoglig resurshushållning, Sveriges lantbruksuniversitet, Umeå. ISSN 0280-0543. https://www.slu.se/globalassets/slu.se/om-slu/organisation/institutioner/skoglig-resurshushallning/riksskogstaxeringen/dokument/skogsdata/skogsdata_2018_webb.pdf

Speer, J.H. (2010). Fundamentals of Tree Ring Research. ResearchGate,. https://www.researchgate.net/publication/259466472_Fundamentals_of_Tree_Ring_Research [2026-05-15]

Sullivan, J. (1994). Picea abies. In: Fire Effects Information System (FEIS), U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. https://www.fs.usda.gov/database/feis/plants/tree/picabi/all.html

Suvanto, S., Heikkinen, J., Holmström, E., Honkaniemi, J., Piri, T., Hantula, J., Räsänen, T., Riekki, K., Sorsa, J.-A., Hytönen, H., Höglund, H., Rajala, T., Lehtonen, A. & Peltoniemi, M. (2026). Rot or not? Uncovering the spatial patterns and drivers of Norway spruce root rot with harvester data. Forestry: An International Journal of Forest Research, 99 (2), cpaf061. https://doi.org/10.1093/forestry/cpaf061

Toffin, E., Gabriel, E., Louis, M., Deneubourg, J.-L. & Grégoire, J.-C. (2018). Colonization of weakened trees by mass-attacking bark beetles: no penalty for pioneers, scattered initial distributions and final regular patterns. Royal Society Open Science, 5 (1), 170454. https://doi.org/10.1098/rsos.170454

Vonesh, E.F., Chinchilli, V.M. & Pu, K. (1996). Goodness-of-fit in generalized nonlinear mixed-effects models. Biometrics, 52 (2), 572–587

Wahlman, W., Kasanen, R., Lappalainen, L. & Honkaniemi, J. (2025). Root rot increases the vulnerability of Norway spruce trees to Ips typographus infestation. Forest Ecology and Management, 577, 122409. https://doi.org/10.1016/j.foreco.2024.122409

Wahlman, W. (2024). The effect of Heterobasidion root rot on Ips typographus infestation risk on Norway spruce. Master thesis in University of Helsinki. https://helda.helsinki.fi/server/api/core/bitstreams/3fb8baff-1edb-41c2-b842-97cc4624f4a4/content

Zar, J. H. (2010). Biostatistical Analysis (5th ed.). Upper Saddle River, NJ: Pearson Prentice Hall. https://www.pearson.com/en-us/subject-catalog/p/biostatistical-analysis/P200000003409

Zhou, Y., Yi, Y., Jia, W., Cai, Y., Yang, W. & Li, Z. (2020). Applying dendrochronology and remote sensing to explore climate-drive in montane forests over space and time. Quaternary Science Reviews, 237, 106292. https://doi.org/10.1016/j.quascirev.2020.106292

Zweifel, R., Zimmermann, L. & Newbery, D.M. (2005). Modeling tree water deficit from microclimate: an approach to quantifying drought stress. Tree Physiology, 25 (2), 147–156. https://doi.org/10.1093/treephys/25.2.147

Popular science summary

Norway spruce (*Picea abies*) is one of the most important tree species in Swedish forestry and is widely used for timber production across the country. However, forests are increasingly affected by climate change, drought, storms, bark beetles and diseases such as root rot. These environmental changes make it more important than ever to understand how trees grow and how forest health can be monitored over time.

Tree growth is typically studied using tree rings. By analysing the annual rings within the trunk, researchers can estimate how much a tree has grown each year and how its growth is influenced by environmental conditions. Although this method provides highly accurate information, it usually requires destructive sampling, as a section of the trunk must be removed and processed.

Trunk growth monitors offer an alternative method. These instruments can continuously monitor subtle changes in trunk diameter throughout the growing season without causing any harm to the trees. They are currently widely used in long-term forest experiments in Sweden, but it is not known to what extent these measurements accurately reflect the actual annual growth along the trunk axis.

The aim of this study was to compare growth measurements in Norway spruce obtained using a stem growth meter with those obtained from tree-ring analysis. The study also investigated whether the correlation between the two methods varies with different heights along the stem, and whether root rot affects the growth patterns of the trees.

The results indicate that, in the lower part of the trunk (particularly at breast height), the readings from the trunk meter corresponded well with the tree-ring data. This suggests that the trunk meter can provide reliable estimates of annual stem growth without causing damage to the trees. However, as the height of the trunk increases, the correlation between the two methods gradually weakens. The study also found that root rot had a limited impact on the correlation between the two methods, although this may be partly attributable to the small sample size.

Overall, the results suggest that the stem meter is a promising tool for long-term forest monitoring and climate-related growth studies in Norwegian spruce forests. As the stem meter allows for repeated measurements over multiple years without the need for destructive sampling, it may play an increasingly important role in monitoring forest growth and health under changing environmental conditions.

Appendix. Photographs from field sampling and stem disc collection

This appendix contains photographs documenting the field sampling procedure and stem disc collection. The images are included to provide visual reference for the sampling design and field conditions during data collection.

Figure A 1. Field sampling procedure. Trees were felled in the field (left), and predefined stem heights were measured and marked before stem disc sampling (right).

Figure A 2. Examples of root rot observed in sampled Norway spruce trees in the study plots 3.

Publishing and archiving

Approved students' theses at SLU can be published online. As a student you own the copyright to your work and in such cases, you need to approve the publication. In connection with your approval of publication, SLU will process your personal data (name) to make the work searchable on the internet. You can revoke your consent at any time by contacting the library.

Even if you choose not to publish the work or if you revoke your approval, the thesis will be archived digitally according to archive legislation.

You will find links to SLU's publication agreement and SLU's processing of personal data and your rights on this page:

- https://libanswers.slu.se/en/faq/228318

☒ YES, I, Deli Lei, have read and agree to the agreement for publication and the personal data processing that takes place in connection with this

☐ NO, I/we do not give my/our permission to publish the full text of this work. However, the work will be uploaded for archiving and the metadata and summary will be visible and searchable.