University of Tartu
Faculty of Science and Technology
Tartu Observatory
Department of Remote Sensing

Bachelor's thesis in environmental technology (12 ECT)

Exploring the geographic variation in needle shoot architecture with 3D photogrammetry

Karl Käis

Supervisors:
PhD Jan Pisek
PhD Oleksandr Borysenko

Tartu 2025

Exploring the geographic variation in needle shoot architecture with 3D photogrammetry

The study examined Norway spruce (*Picea abies* (L.) H.Karst.) shoot architecture from three northern European sites using high-precision blue light 3D photogrammetry. The main parameters analysed were the silhouette to total shoot area ratio ($STAR_{shoot}$), Silhouette to total needle area ratio ($STAR_{needle}$), and silhouette contour length. The objectives were: creating accurate 3D models, calculating and comparing these parameters across a latitudinal gradient, and assessing the impact of different STAR definitions. The analysis revealed an average 11.8% difference between $STAR_{shoot}$ and $STAR_{needle}$, indicating the need for consistent definitions. No statistically significant geographic variation in shoot structure was found, suggesting potential architectural consistency across the study sites.

Keywords: 3D photogrammetry, STAR, *Picea abies*, shoot structure, forest canopy

CERCS code: T181 Remote sensing; B270 Plant ecology; B430 Sylviculture, forestry, forestry technology

Okaste ja võrsete arhitektuuri geograafilise varieeruvuse uurimine 3D fotogramm-meetria abil

Uuringus analüüsiti kolmest Põhja-Euroopa piirkonnast võetud hariliku kuuse (*Picea abies* (L.) H.Karst.) võrsete arhitektuuri, kasutades kõrgtäpset sinise valguse 3D fotogramm-meetriat. Peamisteks uuritud parameetriteks olid võrse silueti ja kogu võrsepinna suhe ($STAR_{shoot}$), silueti ja kogu okkapinna suhe ($STAR_{needle}$) ning silueti kontuuri pikkus. Eesmärkideks olid: täpsete 3D-mudelite loomine, nende parameetrite arvutamine ja võrdlemine laiuskraadide lõikes ning erinevate STARi definitsioonide mõju hindamine. Analüüs näitas, et $STAR_{shoot}$ ja $STAR_{needle}$ väärtuste vahel oli keskmiselt 11,8% erinevus, mis viitab vajadusele ühtlustatud definitsioonide järele. Võrsete struktuuris ei tuvastatud statistiliselt olulist geograafilist varieeruvust, mis võib viidata arhitektuurilisele sarnasusele uuritud paikades.

Märksõnad: 3D fotogramm-meetria, STAR, *Picea abies*, võrsete struktuur, metsavõra

CERCS kood: T181 Kaugseire; B270 Taimeökoloogia; B430 Metsakasvatus, metsandus, metsandustehnoloogia

Table of Contents

List of acronyms

A_n	Total needle area of a shoot
A_s	Total area of a shoot
A_t	Total twig area of a shoot
ANOVA	Analysis of Variance
CI	Clumping Index
eLTER	Integrated European Long-Term Ecosystem, critical zone, and socio-ecological Research
ICOS	Integrated Carbon Observation System
l_c	Silhouette contour length of a shoot
$MAPE_{sym}$	Symmetric Mean Absolute Percentage Error
RAMI	Radiation transfer Model Intercomparison
$\overline{SA}_s$	Average silhouette area of a shoot taken over all directions in space
$STAR_{needle}$	Silhouette to Total needle Area Ratio
$STAR_{shoot}$	Silhouette to Total shoot Area Ratio

1. Introduction

STAR has been originally defined as the shoot silhouette area to the total needle area ratio (Oker-Blom and Smolander 1988; Stenberg *et al.* 1995) and is fundamental for characterising radiation regimes in coniferous canopies (Therezien *et al.* 2007). It expresses the foliage clumping (clustered arrangement of leaves or needles within a plant canopy) at the shoot level (Fang 2021). It is also a valuable concept for light interception modelling because it quantifies the reduction in "effective" leaf area caused by the clumping of needles into shoots (Stenberg *et al.* 1995). A smaller STAR value indicates a more clumped shoot (Fang 2021). For instance, shaded shoots often become flatter with needles spread laterally, leading to an increase in their STAR compared to sunlit shoots. This higher STAR in shaded shoots implies an enhanced efficiency of light capture in low light conditions (Stenberg *et al.* 1999).

Pisek *et al.* (2023) state that measuring the needle-to-shoot area ratio can be challenging because optical instruments have generally been incapable of measuring gaps between needles within a shoot. Traditional methods for estimating the needle-to-shoot-area ratio also have destructive and/or highly labour-intensive aspects (Chen *et al.* 1997). The enhanced knowledge of needle shoot architecture will contribute to more realistic 3D forest representations and more accurate estimates of related parameters and processes by radiative transfer models (Pisek *et al.* 2023).

STAR provides a measure of the average light interception per unit of needle area and is influenced by the spatial arrangement of needles within a shoot (Stenberg *et al.* 1995). The exact definitions and subsequent calculation of STAR have exhibited variations across the literature, potentially leading to inconsistencies in reported values and their interpretation. One of the primary ambiguities lies in the denominator of the mean silhouette to total area ($\overline{STAR}$) ratio in equation (1) by Oker-Blom and Smolander (1988):

$$\overline{STAR} = \frac{\overline{SA_s}}{A_n}, \tag{1}$$

where $\overline{SA_s}$ is the average silhouette area of a shoot taken over all directions in space, and A_n is defined as the total surface area of the needles on the shoot.

Already Oker-Blom and Smolander (1988) pointed out that comparisons among studies were difficult because of the different definitions of total needle area. Smolander *et al.* (1994) found that including the twig area in the denominator changed the STAR value by only 2.4% in Scots pine. The effect was notably larger in a study by Stenberg *et al.* (1995) focusing on

Norway spruce, with differences of about 10%. This shows the importance of clearly defining and consistently applying the STAR denominator. As pointed out by Stenberg *et al.* (1995), their definition of STAR includes the silhouette area of both the needles and the shoot axis (twig) in the numerator, while only the needle area is included in the denominator. This leads to a potential overestimation of light interception efficiency and underestimation of within-shoot shading. They note that "ideally, the shoot silhouette area should represent the shadow area of needles only, but this would require a more advanced measuring technique. Another way of correcting the "error" would be to include the twig in the denominator of STAR" (Stenberg *et al.* 1995). Therezien *et al.* (2007) state how they adapted the definition of STAR from Stenberg *et al.* (1999), who calculated STAR using the total needle area plus the total twig area as denominator. Therezien *et al.* (2007) also mention that earlier introductions of STAR did not correct for the twig's contribution to the silhouette area. Some of the latest studies, for example by Kuusk *et al.* (2023) and Pisek *et al.* (2025), also use total shoot area as a denominator.

The high-precision blue light 3D photogrammetry allows for detailed reconstruction of shoot geometry and enables accurate measurement of both total needle area and total shoot area. This opens the possibility to systematically quantify how much the choice of denominator (needle area vs. shoot area) affects STAR, and to estimate the uncertainty introduced by different understandings and uses of the STAR definition among researchers.

In addition to STAR, the silhouette contour length has been highlighted as an important parameter in recent studies. It directly influences the forward scattering of light by conifer shoots (Kuusk *et al.* 2023) and serves as a measurable feature for characterising shoot structure (Pisek *et al.* 2025). This makes the silhouette contour length relevant for understanding radiation transfer within coniferous canopies and for developing accurate radiative transfer models.

The study focuses on one of the dominant boreal conifer tree species in Europe present at each of the studied sites – Norway spruce (*Picea abies* (L.) H.Karst.). This species was identified as the most important conifer tree species in Europe according to the spatially representative Level II monitoring network of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests, www.icp-forests.net) with 16 km grid size (Fleck *et al.* 2016). By using high-precision blue light 3D photogrammetry, this research seeks to improve the understanding of shoot-level clumping and its possible variability between different geographical locations.

1.1 Objectives

The primary objectives of this study are:

1. To obtain 3D models of Norway spruce shoots using high-precision blue light 3D photogrammetry scanning.
2. To calculate and compare STAR and silhouette contour length values for shoots collected from different geographic locations along a latitudinal gradient.
3. To analyse uncertainties arising from different understandings and uses of the STAR definition among researchers.

2. Materials and methods

2.1 Site Description

Samples were collected from two locations in Finland and one location in Estonia, forming a 10-degree latitudinal gradient with different climatic conditions. Starting from north, Värriö (67° 45' 17.64" N, 29° 36' 36" E) is in northern Finland, Hyytiälä (61° 50' 50.676" N, 24° 17' 41.172" E) is in southern Finland, and Järvselja RAMI pine stand (58° 18′ 47.13″ N, 27° 17′ 48.23″ E) is in southern Estonia.

2.1.1 Värriö research site

As stated by Ezhova *et al.* (2023), the Värriö research site is situated at 180 meters above sea level in the boreal forest zone of Finland. The site experiences a mean annual temperature of -0.5°C and receives 601 mm of mean annual precipitation. The forest stand is dominated by Scots pines. The trees reach approximately 19.9 meters in height (measured in 2023), forming an open canopy structure. The site is integrated into the Integrated Carbon Observation System (ICOS) and Integrated European Long-Term Ecosystem, critical zone, and socio-ecological Research (eLTER) networks (Ezhova *et al.* 2023).

2.1.2 Hyytiälä research site

Located at an elevation of 80 meters in southern Finland’s boreal forest zone, the Hyytiälä research site features a milder climate than Värriö, with a mean annual temperature of 3.5°C and an average annual precipitation of 710 mm (Ezhova *et al.* 2023). The forest is composed predominantly of Scots pine trees aged between 60 and 65 years, and Norway spruce. In 2023, the average tree height was recorded at approximately 10 meters, and the canopy is characterized as closed. Hyytiälä is also a part of the Integrated Carbon Observation System

(ICOS) and the Integrated European Long-Term Ecosystem, critical zone, and socio-ecological Research (eLTER) networks (Ezhova *et al.* 2023).

2.1.3 Järvselja research site

The Järvselja RAMI pine stand consists almost entirely of Scots pine trees in the overstory, and isolated Norway spruce trees in the understory, growing on a transitional bog. The average tree height was 17.4 m with the age of 139 years in 2022 (Lang *et al.* 2021). Excess water and poor nutrient availability are strong growth-limiting factors. The forest understory consists of various Sphagnum moss species, marsh tea (*Ledum palustre* L.), and small ($H < 2$ m) isolated Norway spruce trees. There has not been any management in the stand (Pisek *et al.* 2023). At Rõka, the Järvselja Training and Experimental Forest Centre (altitude 40–48 m), the long term average annual precipitation of the region is 650 mm, and the average temperature is 17.0 °C in July and -6.7 °C in January (Krasnova *et al.* 2019).

2.2 Field sampling

The field sampling methodology followed the approach outlined in Pisek *et al.* (2023). At each site, branches bearing current‑year shoots were collected from different heights using a telescopic tree pruner. Special care was taken to select branches from varied canopy positions (including differing heights and orientations) to ensure that the natural variability in light exposure and shoot development was captured. Immediately after collection, all samples were placed in a cooling box to preserve the structural integrity of the needle shoots (Pisek *et al.* 2023).

Samples from Värriö and Hyytiälä were originally collected by J. Pisek, and from Järvselja by J. Pisek and O. Borysenko (Pisek and Borysenko 2023).

2.3 3D scanning procedure

Shoot samples were scanned using a structured-light 3D photogrammetry system – GOM Scan 1 (Carl Zeiss GOM Metrology GmbH, Germany). The scanning methodology followed the approach outlined in Pisek *et al.* (2023). Needle shoots were attached to a rotating table GOM ROT 350 (Carl Zeiss GOM Metrology GmbH, Germany) using plasticine clay to keep them upright. The GOM Scan 1 (MV 200 version) industrial non-contact 3D scanner was used, which uses structured, narrow-band blue light and two cameras based on the stereo camera principle to deliver precise, high-resolution scans at high speed. Up to 60 scans, covering the full 360° view of the needle shoot, were acquired for one scanner position within 5 minutes. The number of scans varies depending on the complexity of the shoot. A custom frame with reference point stickers was used to facilitate scanning accuracy and co-registration. Different exposure times (16.81 ms and 27.67 ms) were set in the GOM Inspect software (GOM Inspect v2.0.1) to capture the appropriate amount of reflected light from light and dark surfaces. The reference points exposure time was 8.40 ms (Pisek *et al.* 2023).

The original scanning of the shoot samples from Värriö and Hyytiälä was conducted by J. Pisek, while the scans from Järvselja were performed by and originally published in Pisek and Borysenko (2023).

2.4 Post-processing

The post-processing methodology also follows the approach outlined in Pisek *et al.* (2023). The Järvselja shoot scans were post-processed by Pisek and Borysenko (2023), following the same methodology. The author post-processed the Värriö and Hyytiälä 3D models. In the acquired models (Figure 1), all structures had to be carefully checked and manually corrected using interactive tools in the GOM Inspect software. Due to the varied angles of needles and complex shoot structure, the scanner could not always create complete models. This resulted in many unfilled gaps or in some cases, the scanner captured needles as separate objects, lacking a connection between the needle and the twig.

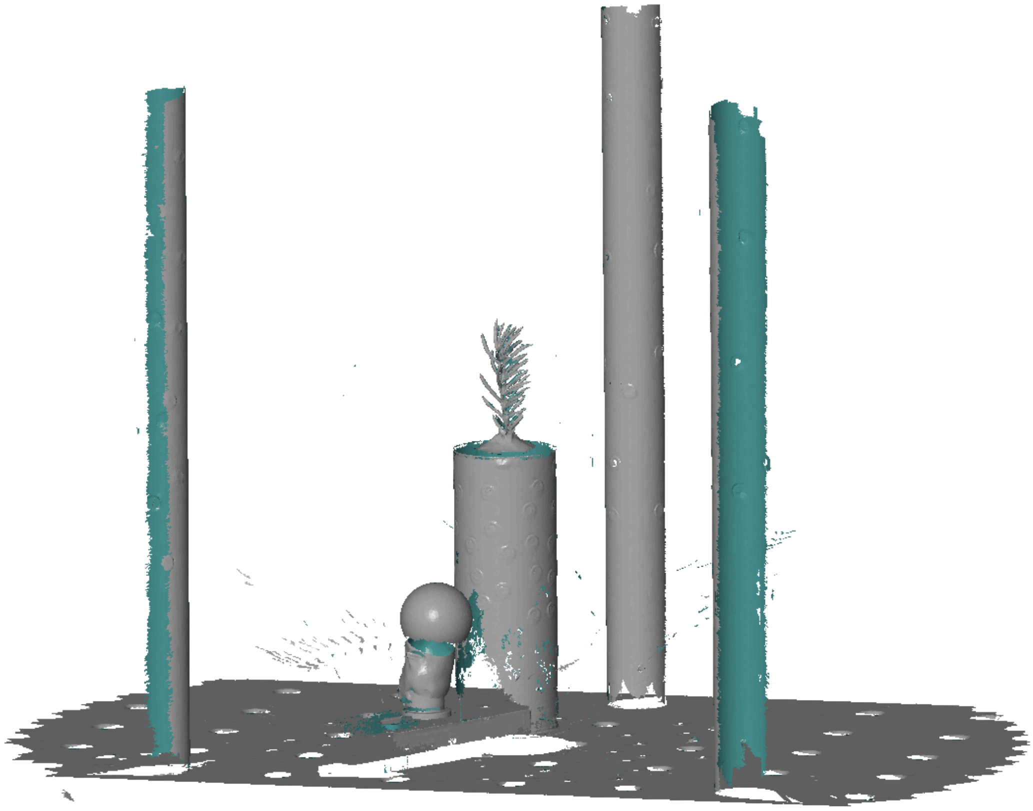

Figure 1. Unprocessed 3D scan of a Norway spruce shoot (NS3) from Värriö. This shoot corresponds to the sample labeled NS3 in Table 1 and exhibit (c) in Figure 6.

In some scans, the initial model had too large gaps or was too defective, which resulted in the whole shoot (Figure 2) being not reconstructable. Thesis author assessed such scans as unprocessable and the models' data was not used for the thesis. The scans that had part of it (e.g. one needle) not reconstructable (Figure 3) were still used in this thesis.

a) b)

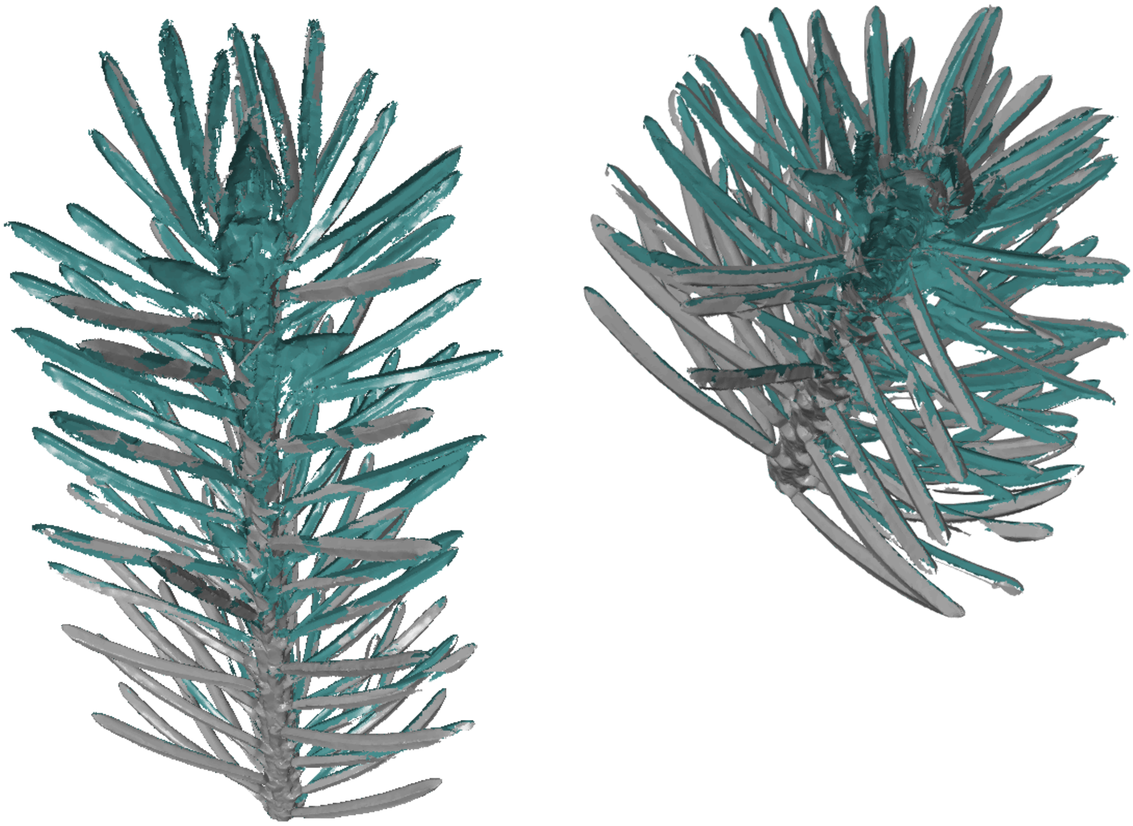

Figure 2. Example of a Norway spruce shoot in different angles (a and b) from Hyytiälä site, evaluated as unprocessable shoot scan by the author. A significant portion of the shoot's exterior front surface was not captured from this angle, making it impossible to guess the original shape and could not be post-processed into a closed 3D object. Green indicates the internal side of the object's surface, which would normally be occluded in a complete 3D model. This issue may have been caused due to occlusion, insufficient angles, or surface reflectivity issues.

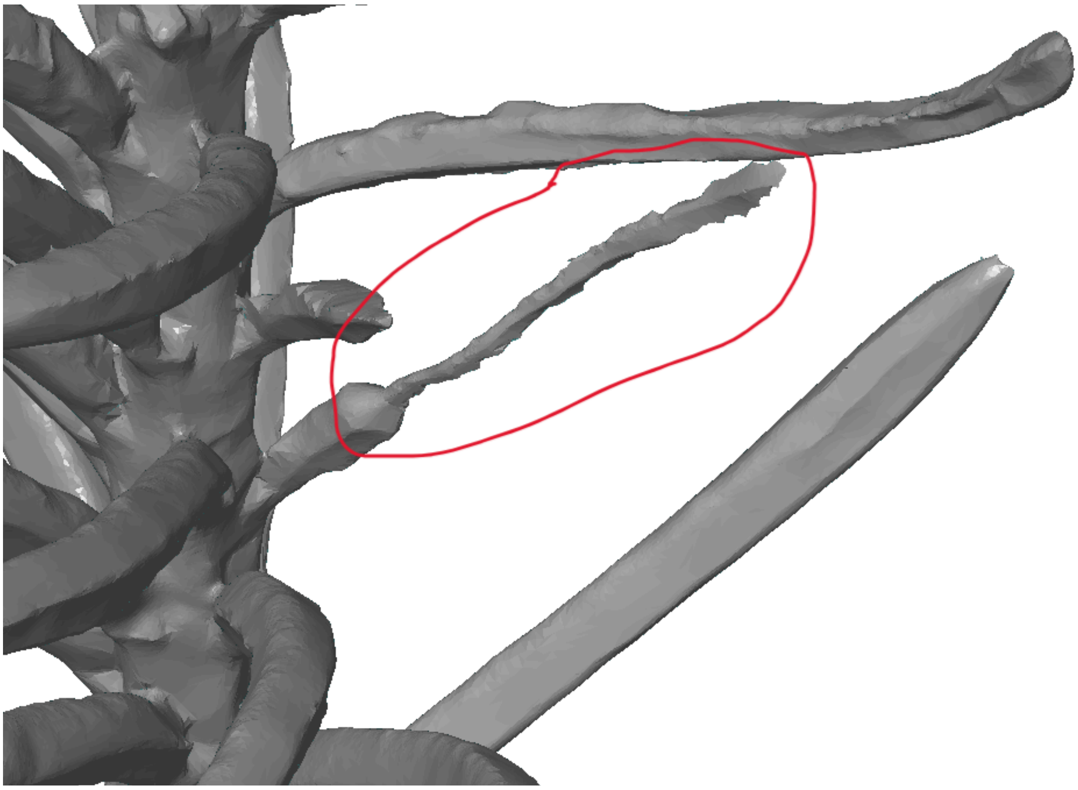

Figure 3. Example of a Norway spruce shoot (NS4) from Värriö – it is not possible to reconstruct the shape of the needle because during the scanning process, GOM Scan 1 was unable to collect a point cloud with sufficient coverage over the whole shape of the highlighted needle. This shoot corresponds to the sample labeled NS4 in Table 1 and exhibit (d) in Figure 6.

Post-processing of initial models took an estimated 1–8 hours, depending on the size of the gaps in the model and the difficulty of the reconstruction. Finished models (Figure 4b) of individual shoots contained between 0.15–1.2 million points. Meshes of the scanned shoots were exported into .stl format for further processing in an open-source mesh processing tool MeshLab (Cignoni *et al.* 2008).

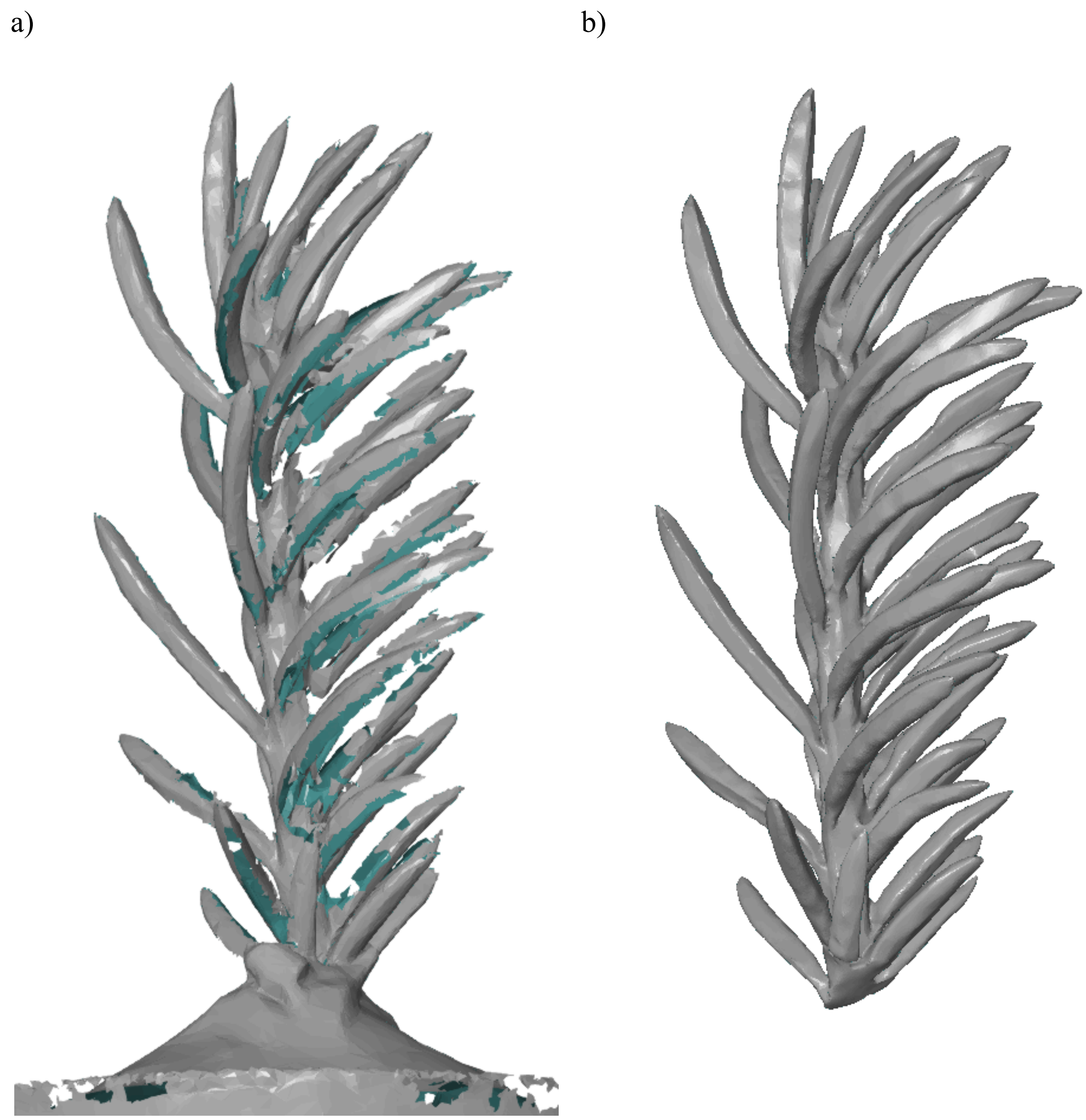

Figure 4. Example of a) before and b) after post-processing 3D model of a Norway spruce shoot from Värriö. This shoot corresponds to the sample labeled NS3 in Table 1 and exhibit (c) in Figure 6.

2.4 $STAR_{shoot}$, $STAR_{needle}$ and contour length calculation

2.4.1 $STAR_{shoot}$ and silhouette contour length

$STAR_{shoot}$ and silhouette contour length values were calculated following the method developed by Kuusk *et al.* (2023) as summarised below. First, the total shoot area (A_s) was determined. The total surface area of the shoot was obtained by exporting the point cloud to a 3D mesh processing software MeshLab, and its tools were used to calculate the total surface area. For calculating silhouette area and silhouette contour length (l_c), the 3D point cloud of the shoot was projected onto a 2D plane (x-y plane). This plane was discretised into small pixels (0.1 mm squares). The pixels that contained at least one projected hit from the point cloud were identified. The total number of these non-zero pixels represented the silhouette area of the shoot for that particular orientation. This black-and-white raster image of the silhouette was then analysed with the software package ImageMagick (ImageMagick Studio LLC 2021). The silhouette contour length was determined using the *Edge detect* and *Identify* procedures within ImageMagick, which calculated the number of border pixels of the silhouette. To account for the fact that a shoot can have many different orientations relative to incident light, the point cloud of the shoot was randomly rotated 10,000 times along its principal axes. For each of these rotations, both the silhouette area and silhouette contour length were calculated, leading to a distribution of these values for the shoot. Finally, the mean $STAR_{shoot}$ value for the shoot was determined by averaging the STAR values obtained from all the random rotations (Kuusk *et al.* 2023).

2.4.2 Derivation of $STAR_{needle}$

To find the $STAR_{needle}$, the surface area of the shoot twig was required. For isolating the surface area of the twig (A_t), the needles were manually removed from the 3D model utilizing GOM Inspect software, preserving the integrity of the twig's geometry (Figure 5). Any gaps or voids created by the removal of the needles were closed using interactive tools in the GOM Inspect software. The surface area of the isolated twig was calculated in MeshLab, in the same way as previously done with the total surface area of the shoot (section 2.4.1). To derive the $STAR_{needle}$ value without the need to re-run each 3D model calculations with 10,000 random rotations with the total needle area (A_n) as denominator, the following equation (2) was used:

$$\overline{STAR}_{needle} = \frac{A_s \times \overline{STAR_{shoot}}}{\left(A_s - A_t\right)}, \qquad (2)$$

which result is the same as $\overline{STAR}$ in equation (1).

Figure 5. Example of a) before and b) after removing the needles from 3D model of a Norway spruce shoot (NS10) from Hyytiälä. This shoot corresponds to the sample NS10 in Table 1 and exhibit (j) in Figure 6.

2.5 Data analysis

2.5.1 Symmetric percentage difference analysis between $STAR_{shoot}$ and $STAR_{needle}$

The symmetric percentage difference, also known as $MAPE_{sym}$ in forecasting literature, is a statistical method for quantifying relative differences between two measurements without designating a reference value (Makridakis and Hibon 1995).

For estimating how much STAR values, calculated by two definitions commonly found in literature ($STAR_{shoot}$, $STAR_{needle}$), might differ, the symmetric percentage difference ($MAPE_{sym}$) was calculated for each shoot. The potential discrepancy between $STAR_{shoot}$ and $STAR_{needle}$ was calculated with the following equation (3):

$$MAPE_{sym} = \frac{2 \times \left| STAR_{shoot} - STAR_{needle} \right|}{STAR_{shoot} + STAR_{needle}} \times 100 \quad (3)$$

2.5.2 Statistical analysis of geographic variation

To analyze the geographic variation in needle shoot architecture across the three study sites (Värriö, Hyytiälä, and Järvselja), one-way Analysis of Variance (ANOVA) was performed to test for significant differences ($p < 0.05$) in both shoot silhouette to total shoot area ratio ($STAR_{shoot}$ mean), shoot silhouette to total needle area ratio ($STAR_{needle}$ mean) and silhouette contour length (l_c mean).

3. Results

All 3D models sampled in this study are shown in Figure 6.

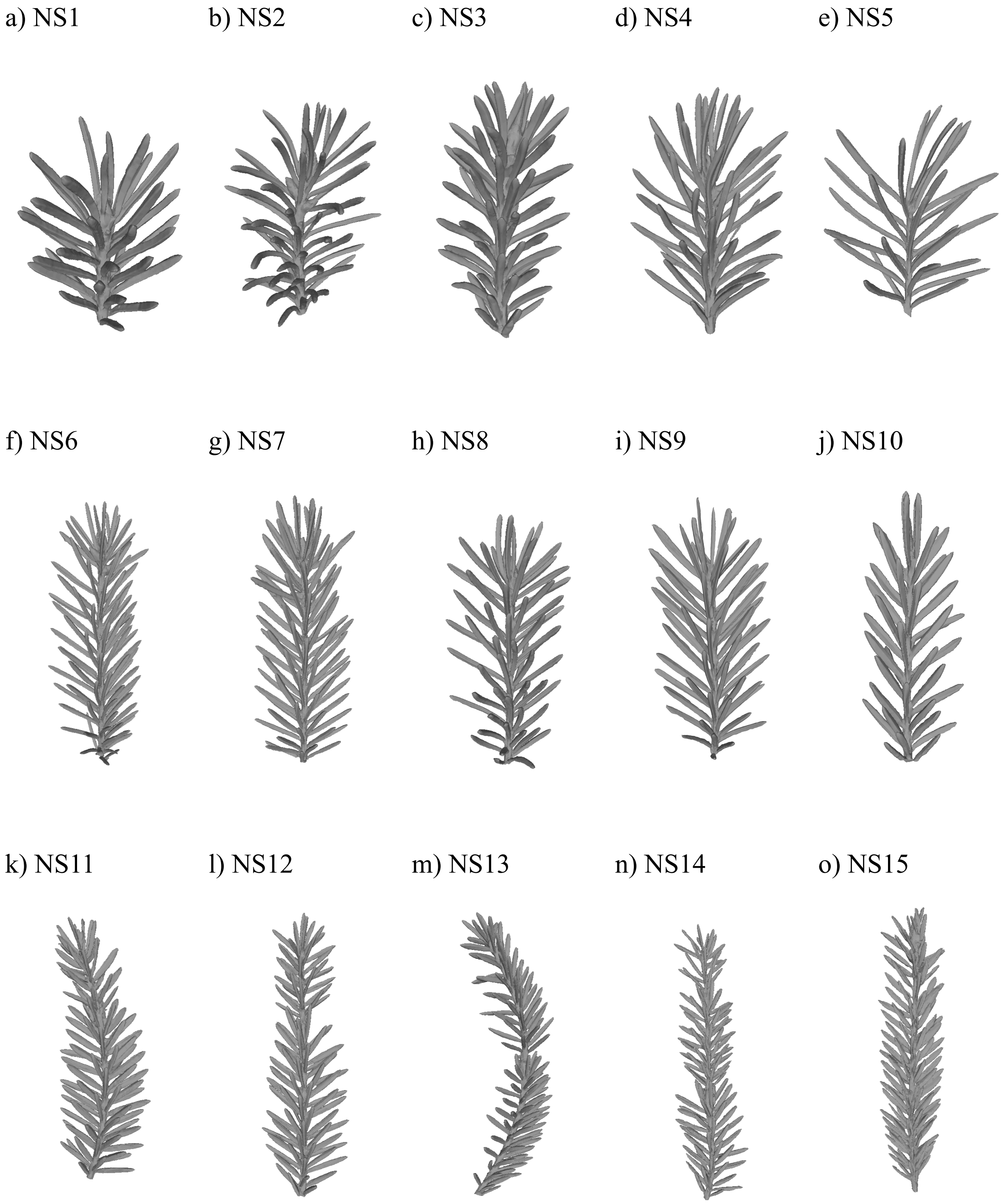

Figure 6. Overview of all Norway spruce 3D models used in this study. Models from Värriö (a-e), Hyytiälä (f-j) are produced in this study and models from Järvselja (k-o) were produced by Pisek and Borysenko (2023).

3.1 Symmetric percentage difference

Based on the definitions, the symmetric percentage difference between $STAR_{shoot}$ and $STAR_{needle}$ values for Norway spruce (Table 1) was, on average, 11.8%. Meanwhile, the average difference by location was 11.6% for Värriö, 11.4% for Hyytiälä, and 12.5% for Järvselja.

Table 1. Values of all shoot samples along latitudinal gradient – total shoot area (A_s), shoot twig area (A_t), silhouette contour length (l_c), mean $STAR_{shoot}$ and $STAR_{needle}$ values and symmetric percentage difference of STAR values of different definition.

Shoot	Location	A_s (mm^2)	A_t (mm^2)	l_c mean (mm)	$STAR_{shoot}$ mean	$STAR_{needle}$ mean	Symmetric difference (%)
NS1	Värriö	1311.54	131.36	298.8	0.1793	0.1993	10.5
NS2	Värriö	1788.44	211.10	413.3	0.1774	0.2011	12.5
NS3	Värriö	1110.9	151.02	230.2	0.1627	0.1883	14.6
NS4	Värriö	1412.88	163.68	365.8	0.1795	0.2030	12.3
NS5	Värriö	897.56	68.59	391.2	0.2235	0.2420	7.9
NS6	Hyytiälä	2626.75	319.35	636.2	0.1793	0.2041	12.9
NS7	Hyytiälä	2257.36	231.90	560.1	0.1852	0.2064	10.8
NS8	Hyytiälä	2273.08	226.64	505.5	0.1769	0.1965	10.5
NS9	Hyytiälä	1354.2	134.08	402.9	0.1952	0.2166	10.4
NS10	Hyytiälä	536.55	62.39	202.6	0.2096	0.2372	12.3
NS11	Järvselja	1731.27	184.50	378.7	0.1743	0.1951	11.3
NS12	Järvselja	1941.08	220.90	434.4	0.1716	0.1936	12.1
NS13	Järvselja	2964	379.20	566.8	0.1638	0.1878	13.7
NS14	Järvselja	1996.48	265.40	423.9	0.1658	0.1912	14.2
NS15	Järvselja	2002.68	215.40	364.3	0.1591	0.1783	11.4
Average:							11.8

3.2 Geographic variation

One-way Analysis of Variance (ANOVA) was performed to examine geographic variation in needle shoot architecture across three study sites (Värriö, Hyytiälä, and Järvselja). The analysis focused on three key parameters: shoot silhouette to total shoot area ratio ($STAR_{shoot}$), shoot silhouette to total needle area ratio ($STAR_{needle}$), and silhouette contour length (l_c).

3.2.1 Silhouette to total shoot area ratio

The distribution of mean $STAR_{shoot}$ values across sites is shown in Table 2.

Table 2. Mean values of $STAR_{shoot}$ of all three locations along latitudinal gradient.

Location	$STAR_{shoot}$ mean	Standard deviation
Värriö	0.1845	0.0223
Hyytiälä	0.1892	0.0139
Järvselja	0.1669	0.0059

One-way ANOVA calculated over the values in Table 1 revealed no statistically significant differences ($p > 0.05$) in $STAR_{shoot}$ values between sites ($F(2,12) = 2.797$, $p = 0.101$).

3.2.2 Silhouette to total needle area ratio

The mean $STAR_{needle}$ distribution across sites is shown in Table 3.

Table 3. Mean values of $STAR_{needle}$ of all three locations along latitudinal gradient.

Location	$STAR_{needle}$ mean	Standard deviation
Värriö	0.2067	0.0224
Hyytiälä	0.2122	0.0139
Järvselja	0.1892	0.0059

The ANOVA analysis performed over the values in Table 1 indicated no statistically significant differences ($p > 0.05$) in $STAR_{needle}$ values between sites ($F(2,12) = 3.028$, $p = 0.086$).

3.2.3 Silhouette contour length

Table 4. Mean values of shoot silhouette contour length of all three locations along latitudinal gradient.

Location	l_c mean (mm)	Standard deviation
Värriö	339.86	74.86
Hyytiälä	461.46	167.81
Järvselja	433.62	80.08

The ANOVA analysis performed over the values in Table 1 revealed no statistically significant differences ($p > 0.05$) in silhouette contour length between sites ($F(2,12) = 1.515$, $p = 0.259$).

4. Discussion

Achieving consistent and complete scans remains challenging due to the complex needle structure and occlusion effects. Additionally, vibrations generated by the rotating table during scanning may cause subtle movements in the shoot, which can contribute to incomplete point clouds or distortions, further increasing the need for manual correction. While high-precision blue light photogrammetry enabled unrivalled, state-of-the-art detailed 3D reconstruction of shoot geometry, several practical limitations remain. The scanning process is relatively slow, requiring up to 8 hours of manual post-processing per shoot, and often involves subjective decisions, when closing gaps or reconstructing missing geometry. These steps introduce a degree of "artistic" interpretation that may reduce reproducibility and limit scalability. For this method to become widely usable in larger ecological or forestry studies, automated processing, scan completeness, and acquisition speed should be improved.

The primary objectives of the study were: (1) to obtain accurate 3D models of Norway spruce shoots, (2) to calculate STAR and silhouette contour length metrics across multiple sites, and (3) to assess the uncertainty introduced by different STAR definitions. These objectives were achieved. High-quality 3D models were generated, $STAR_{shoot}$ and $STAR_{needle}$ were calculated, and discrepancy between the two definitions was quantified.

The results suggest that while there are observable differences in needle shoot architecture across the three sites, these differences are not statistically significant ($p > 0.05$) when accounting for variation along latitudinal gradient. This indicates that for Norway spruce, needle shoot architectural characteristics (silhouette contour length and STAR) may be relatively consistent across the studied geographic gradient.

Although this study focused exclusively on Norway spruce, all research sites (Värriö, Hyytiälä, Järvselja) are predominantly Scots pine stands. At the Järvselja transitional bog site, Norway spruce occurs only sporadically in the understory and is not a dominant canopy species. Consequently, the sampled individuals may not fully represent typical Norway spruce growing conditions, especially in mature spruce-dominated stands. This introduces a potential sampling bias, as shoot architecture could be influenced by local environmental constraints such as reduced light, excess water, or competition with pine. However, as being one of the most widespread and ecologically important conifers in Europe, the observed consistency in STAR and silhouette contour length values across all sites may also suggest a degree of structural resilience or plasticity in Norway spruce shoot morphology, potentially contributing to its success across a wide geographic range.

It is important to note that the definition of STAR has evolved over time and with a posed research objective, with variations in whether the denominator includes only needle area or the total shoot area (including twig), and in the methods used for calculation due to advancements in measurement techniques. Both Kuusk *et al.* (2023) and Pisek *et al.* (2025) reference their STAR calculation method on the definition by Oker-Blom and Smolander (1988), where STAR was originally defined as the Silhouette to Total needle Area Ratio, with total needle area as the denominator. However, in practice, all of these studies used total shoot area as the denominator in their calculations. Using total needle area or total shoot surface area as the denominator is not inherently incorrect. The choice depends on the specific physiological or radiative process being studied. For example, when focusing on the clumping effect of the photosynthetically active elements, total needle area may be better as a denominator. For modeling light transmission, interception, or reflection in radiative transfer models, it may be more meaningful to include the entire shoot surface area, including twigs, since twigs also contribute to scattering and shading within canopies, as Stenberg *et al.* (1995) already recommended.

With 3D models, it is technically straightforward to process and analyze shoot geometry according to different needs. The silhouette area can be computed either including or excluding the twig, depending on how the model is prepared. For instance, in GOM Inspect, needle points can be removed to isolate the twig and calculate its area in MeshLab. However, this manual modification introduces additional uncertainty, as removing the needles creates voids in the 3D mesh that must be artificially closed. The gap-filling process reconstructs surfaces that were not captured by the scanner, potentially leading to over- or underestimation of the twig surface area compared to its natural geometry. As a result, the derived twig area may not accurately reflect the actual geometry of the shoot in its natural state.
In the case of Norway spruce, this thesis showed that the 11.8% difference between STAR values calculated using total needle area (larger STAR) versus total shoot area (smaller STAR) as the denominator is similar to the 10% reported by Stenberg *et al.* (1995) and 13% calculated by the author, using Palmroth *et al.* (2002) results listed in Therezien *et al.* (2007). This discrepancy should not be overlooked, as it can significantly affect the interpretation and comparability of results.

Possible impacts if denominator differences are ignored are as follows:

- Comparing values calculated with different denominators (total needle area versus total shoot area) is misleading. A smaller STAR value could be due to a larger denominator, not actual structural differences.
- Radiative transfer models are sensitive to STAR. Using inconsistent STAR values can affect canopy transmittance estimates.
- If studies cite the same STAR definition but use different methods (using total needle area or total shoot area as denominator), meta-analyses or synthesis studies may be flawed.
- Species with thicker or more complex twigs (e.g., Scots pine) may have disproportionately lower STAR values than species with slender twigs (e.g., Norway spruce) if the twig is included in the denominator.

To help address these issues and ensure comparability between studies, future studies in forest canopy modelling and radiative transfer should account for the variability introduced by different uses of STAR definition among researchers. We recommend standardising STAR definition in the literature or, where alternatives are used, clearly stating and justifying the chosen method.

5. Conclusion

This study set out to investigate the shoot architecture of Norway spruce across different geographic locations using high-precision blue light 3D photogrammetry. The research successfully achieved its three main objectives: (1) obtaining accurate 3D models of Norway spruce shoots, (2) calculating and comparing STAR and silhouette contour length values from three different geographic locations, and (3) analyzing uncertainties in different STAR definitions.

The research revealed two aspects of Norway spruce shoot architecture:

1. There seems to be consistency in shoot architecture across the latitudinal gradient, with no statistically significant differences ($p < 0.05$) in STAR and silhouette contour length values. This finding suggests that Norway spruce maintains similar structural characteristics despite geographic variation, which may reflect the adaptability or structural plasticity of Norway spruce across diverse conditions, though this finding should be interpreted with caution given sampling limitations, that Norway spruce was ecologically rather marginal at the studied sites.
2. An average 11.8% difference between STAR values was identified when calculated using different denominators (total needle area versus total shoot area). This finding aligns with previous work by Stenberg *et al.* (1995) and Palmroth *et al.* (2002). The identified discrepancy underscores the need for standardization in research methodologies to ensure comparable results across different studies.

The study showed the technical and methodological potential, but also current limitations of using 3D blue light photogrammetry for exploring shoot architecture. Improving scan completeness, automating post-processing, and minimizing manual intervention would increase reproducibility and scalability. The need for standardization in STAR calculations was demonstrated, while also providing insights into the consistency of Norway spruce shoot architecture across northern Europe. Future studies should focus on expanding these findings to other conifer species and different climatic regions to develop a more comprehensive understanding of global patterns in conifer shoot architecture. Such knowledge will be invaluable for forest management and conservation efforts, particularly in the context of climate change and its impact on forest ecosystems.

Okaste ja võrsete arhitektuuri geograafilise varieeruvuse uurimine 3D fotogramm-meetria abil

Karl Käis

Kokkuvõte

Käesolevas uuringus kasutati sinise valguse 3D fotogramm-meetriat, et uurida hariliku kuuse (*Picea abies* (L.) H.Karst.) võrsete olulisi arhitektuurilisi parameetreid – silueti ja kogu võrsepinna suhet ($STAR_{shoot}$), silueti ja kogu okkapinna suhet ($STAR_{needle}$) ning silueti kontuurjoone pikkust. Uuringu põhieesmärgid olid võrsetest detailsete 3D-mudelite loomine, STAR väärtuste ja silueti kontuurjoone pikkuse arvutamine ning erinevate STAR definitsioonide kasutamisest tulenevate määramatuste analüüsimine, samuti võimaliku geograafilise varieeruvuse uurimine sarnasel laiuskraadil. Töö käigus täideti kõik püstitatud eesmärgid.

Proovid koguti kolmest paigast: Värriö ja Hyytiälä Soomes ning Järvselja Eestis, hõlmates ligikaudu 10 laiuskraadi. 3D skaneerimine ja sellele järgnev töötlus toimusid meetodi alusel, mille töötasid välja Pisek *et al.* (2023). Tulemusena loodi 3D-mudelid, mis mõningatel juhtudel vajasid mahukat käsitsi järeltöötlust – võrsete keeruka struktuuri tõttu. $STAR_{shoot}$ ja silueti kontuurjoone pikkuste arvutamiseks kasutati Kuusk *et al.* (2023) välja töötatud meetodit, mis hõlmas 3D-mudelite projitseerimist 2D-tasapinnale ning analüüsi tarkvaradega *MeshLab* ja *ImageMagick*. $STAR_{needle}$ tuletati olemasolevatest andmetest. Okaste kogupindala määramiseks eemaldati mudelitel, kasutades *GOM Inspect* tarkvara, okkad, säilitades võrse rootsu geomeetria, mille pindala sai lahutada võrse kogupindalast. Selline lähenemine võimaldas vältida dubleerivaid arvutusi ja tagas väärtuste võrreldavuse.

Analüüsist ilmnesid kaks peamist tulemust hariliku kuuse kohta:

1. STAR väärtuste vahel on märkimisväärne erinevus sõltuvalt sellest, kas nimetajaks kasutatakse kogu võrse pindala (STAR väärtus on väiksem) või kogu okaste pindala (STAR väärtus on suurem). Sümmeetriline protsentuaalne erinevus $STAR_{shoot}$ ja $STAR_{needle}$ väärtuste vahel oli keskmiselt 11,8%. Selline erinevus on oluline ja vastab varasematele leidudele, mis näitab, et kasutatav definitsioon mõjutab tugevalt STAR väärtuse suurust. Definitsioonilistest erinevustest tulenevate STAR väärtuste erinevuse eiramine võib põhjustada eksitavaid võrdlusi, mõjutada valguslevi mudelite täpsust, mis on tundlikud STAR väärtuse suhtes, ning moonutada meta-analüüse juhul, kui erinevad uuringud kasutavad eri meetodeid, kuid viitavad samale

definitsioonile. Saadud tulemused näitavad vajadust STAR definitsiooni standardiseerimisele teadustöödes.

2. Ühesuunaline dispersioonanalüüs (ANOVA) ei näidanud statistiliselt olulisi erinevusi (kõik *p*-väärtused > 0,05) hariliku kuuse võrsete keskmistes $STAR_{shoot}$, $STAR_{needle}$ või silueti kontuurjoone pikkuste väärtustes kolmes uurimiskohas (Värriö, Hyytiälä, Järvselja) mööda uuritud laiuskraadi vahemikku. See viitab, et harilikul kuusel võivad need konkreetsed arhitektuursed omadused (STAR ja silueti kontuurjoone pikkus) olla uuritud geograafilises ulatuses suhteliselt stabiilsed. Samas tuleb arvestada proovide kogumise piirangutega kõigis uuringualades – harilik kuusk kasvas männikus allasurutud tingimustes.

Lisaks käsitleti töös sinise valguse fotogramm-meetria praktilisi piiranguid – pikk järeltöötlus, käsitsi sekkumine ja võimalikud vibratsioonist tingitud skaneerimisvead – mis vähendavad meetodi reprodutseeritavust ja ulatuslikku rakendatavust. Kuigi hariliku kuuse võrse arhitektuur, iseloomustatuna STAR väärtuse ja silueti kontuurjoone pikkusena, näib mööda uuritud laiuskraadi suhteliselt ühtlane, siis STAR väärtuse arvutusmeetodis valitud nimetaja (kogu võrse pindala vs. kogu okaste pindala), põhjustab olulist varieeruvust. Tulevastes STAR-i käsitlevates uuringutes tuleks selgelt välja tuua kasutatud definitsioon ja arvutusviis, et tagada tulemuste võrreldavus ja parandada metsastruktuuri kirjeldamise ning valguse neeldumise modelleerimise usaldusväärsust. Samuti peaksid tulevased uuringud keskenduma nende tulemuste laiendamisele teistele okaspuuliikidele ja erinevatele kliimavööditele, et kujundada põhjalikum arusaam okaspuude võrsearhitektuuri globaalsetest mustritest.

Acknowledgements

This work was supported by the Estonian Research Council grant PRG1405 (PI: Jan Pisek).

I would like to thank Andres Kuusk for his valuable help in calculating the STAR values and silhouette contour length, as well as for the insightful discussions regarding the choice of denominator in STAR estimation. I thank Oleksandr Borysenko for teaching me how to post-process the 3D models in particular. I would like to thank Mait Lang for his valuable suggestions and feedback on improving the structure and clarity of this thesis. Special thanks to Jan Pisek for always being available to help with ideation, editing, and refining the logical flow of the thesis.

Bibliography

Chen, J. M., Rich, P. M., Gower, S. T., Norman, J. M. and Plummer, S. 1997. Leaf area index of boreal forests: Theory, techniques, and measurements. *Journal of Geophysical Research: Atmospheres*, **102**(D24), 29429–29443. https://doi.org/10.1029/97JD01107

Cignoni, P., Callieri, M., Corsini, M., Dellepiane, M., Ganovelli, F. and Ranzuglia, G. 2008. MeshLab: an Open-Source Mesh Processing Tool. *Eurographics Italian Chapter Conference*, 8 pages. https://doi.org/10.2312/LOCALCHAPTEREVENTS/ITALCHAP/ITALIANCHAPCONF2008/129-136

Ezhova, E., Laanti, T., Lintunen, A., Kolari, P., Nieminen, T., Mammarella, I., *et al.* 2023. Explainable machine learning for modelling of net ecosystem exchange in boreal forest. https://doi.org/10.5194/egusphere-2023-2559

Fang, H. 2021. Canopy clumping index (CI): A review of methods, characteristics, and applications. *Agricultural and Forest Meteorology*, **303**, 108374. https://doi.org/10.1016/j.agrformet.2021.108374

Fleck, S., Cools, N., De Vos, B., Meesenburg, H. and Fischer, R. 2016. The Level II aggregated forest soil condition database links soil physicochemical and hydraulic properties with long-term observations of forest condition in Europe. *Annals of Forest Science*, **73**(4), 945–957. https://doi.org/10.1007/s13595-016-0571-4

ImageMagick Studio LLC. 2021. https://github.com/ImageMagick/ImageMagick (accessed 2025-04-24)

Krasnova, A., Kukumägi, M., Mander, Ü., Torga, R., Krasnov, D., Noe, S. M., *et al.* 2019. Carbon exchange in a hemiboreal mixed forest in relation to tree species composition. *Agricultural and Forest Meteorology*, **275**, 11–23. https://doi.org/10.1016/j.agrformet.2019.05.007

Kuusk, A., Borysenko, O. and Pisek, J. 2023. Optical model of a conifer shoot. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **310**, 108715. https://doi.org/10.1016/j.jqsrt.2023.108715

Lang, M., Kuusk, A., Kaha, M., Pisek, J., George, J.-P., Kiviste, A., *et al.* 2021. Changes during twelve years in three mature hemiboreal stands growing in a radiation model intercomparison test site, Järvselja, Estonia. *Forestry Studies*, **74**(1), 112–122. https://doi.org/10.2478/fsmu-2021-0007

Makridakis, S. G. and Hibon, M. 1995. Evaluating Accuracy (or Error) Measures in Forecasting. *International Journal of Forecasting*, **11**(3), 419–433.

Oker-Blom, P. and Smolander, H. 1988. The Ratio of Shoot Silhouette Area to Total Needle Area in Scots Pine. *Forest Science*, **34**(4), 894–906. https://doi.org/10.1093/forestscience/34.4.894

Palmroth, S., Stenberg, P., Smolander, S., Voipio, P. and Smolander, H. 2002. Fertilization has little effect on light-interception efficiency of Picea abies shoots. *Tree Physiology*, **22**(15–16), 1185–1192. https://doi.org/10.1093/treephys/22.15-16.1185

Pisek, J. and Borysenko, O. 2023. A dataset of detailed 3D representations of Scots pine, Norway spruce needle shoots from Järvselja RAdiation transfer Model Intercomparison (RAMI) pine stand in Estonia. https://doi.org/10.17632/RS3F6TRDVW.1

Pisek, J., Borysenko, O., Janoutová, R. and Homolová, L. 2023. Estimation of coniferous shoot structure by high precision blue light 3D photogrammetry scanning. *Remote Sensing of Environment*, **291**, 113568. https://doi.org/10.1016/j.rse.2023.113568

Pisek, J., Kuusk, A. and Borysenko, O. 2025. On the relationship between shoot Silhouette area to Total needle Area Ratio (STAR) and contour length. *Remote Sensing of Environment*, **317**, 114520. https://doi.org/10.1016/j.rse.2024.114520

Smolander, H., Stenberg, P. and Linder, S. 1994. Dependence of light interception efficiency of Scots pine shoots on structural parameters. *Tree Physiology*, **14**(7-8–9), 971–980. https://doi.org/10.1093/treephys/14.7-8-9.971

Stenberg, P., Kangas, T., Smolander, H. and Linder, S. 1999. Shoot structure, canopy openness, and light interception in Norway spruce. *Plant, Cell & Environment*, **22**(9), 1133–1142. https://doi.org/10.1046/j.1365-3040.1999.00484.x

Stenberg, P., Linder, S. and Smolander, H. 1995. Variation in the ratio of shoot silhouette area to needle area in fertilized and unfertilized Norway spruce trees. *Tree Physiology*, **15**(11), 705–712. https://doi.org/10.1093/treephys/15.11.705

Therezien, M., Palmroth, S., Brady, R. and Oren, R. 2007. Estimation of light interception properties of conifer shoots by an improved photographic method and a 3D model of shoot structure. *Tree Physiology*, **27**(10), 1375–1387. https://doi.org/10.1093/treephys/27.10.1375

Lihtlitsents lõputöö reprodutseerimiseks ja üldsusele kättesaadavaks tegemiseks

Mina, Karl Käis,

1. annan Tartu Ülikoolile tasuta loa (lihtlitsentsi) minu loodud teose "**Exploring the geographic variation in needle shoot architecture with 3D photogrammetry**", mille juhendajad on PhD Jan Pisek ja PhD Oleksandr Borysenko, reprodutseerimiseks eesmargiga seda säilitada, sealhulgas lisada digitaalarhiivi Dspace kuni autoriõiguse kehtivuse lõppemiseni.
2. Annan Tartu Ülikoolile loa teha punktis 1 nimetatud teos üldsusele kättesaadavaks Tartu Ülikooli veebikeskkonna, sealhulgas digitaalarhiivi DSpace kaudu Creative Commonsi litsentsiga CC BY NC ND 4.0, mis lubab autorile viidates teost reprodutseerida, levitada ja üldsusele suunata ning keelab luua tuletatud teost ja kasutada teost ärieesmärgil, kuni autoriõiguse kehtivuse lõppemiseni.
3. Olen teadlik, et punktides 1 ja 2 nimetatud õigused jäävad alles ka autorile.
4. Kinnitan, et lihtlitsentsi andmisega ei riku ma teiste isikute intellektuaalomandit ega isikuandmete kaitse õigusaktidest tulevaid õigusi.

Karl Käis

19.05.2025