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# Phenotypic relationships between non-destructive and volumetric methods of wood density estimation

Technical report from a study of Norway spruce, Scots pine, silver birch and hybrid aspen.

Mateusz Liziniewicz

Increment core sampling and non-destructive measurements by Hitman. Photo: G.Jones.

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# Förord

Veddensitet är den viktigaste egenskapen för träkvalitet och en viktig egenskap vid uppskattning av biomassa i skogens ekosystem. De detaljerade mätningarna av veddensitet kräver betydande resurser. Dessa detaljerade mätningar orsakar ofta en skada på trädet eftersom det mäts destruktivt. En kostnadseffektiv och effektiv metod för uppskattning av veddensitet är därför önskvärd.

I denna studie uppskattades vedtätheten hos gran, tall, vårtbjörk och hybridasp i olika bestånd i södra Sverige med olika icke-destruktiva metoder, allt från mycket enkel borrning med borr och inskjutning av pilodynnål till borrning med ett avancerat verktyg; resistograf.

Resultaten kan användas för ett urval av metod för uppskattning av den genomsnittliga veddensiteten på beståndsnivå som kan användas för framtida förvaltning och planering. Studien visade också ett behov av ytterligare studier som avses det mest avancerade verktyget.

Studien stöddes ekonomiskt av en Hildur och Sven Wingquist Stiftelse för Skogsvetenskaplig Forskning.

Svalöv, 2022-12-20, Mateusz Liziniewicz

# Foreword

Wood density is an important factor in wood quality, and is important for estimating biomass in forest ecosystems. Detailed measurements of wood density require substantial resources, and often cause damage to the tree because the measurement procedure is destructive. A cost efficient and effective method for estimating wood density is therefore needed.

In this study, wood density of Norway spruce, Scots pine, silver birch, and hybrid aspen in different stands in southern Sweden was estimated using four different non-destructive methods, from very simple drilling and injection of a Pilodyn needle to drilling with an advanced tool, a Resistograph.

The results could be used when selecting a method to estimate average wood density at stand level, which could benefit management and planning. The study also showed a need for more studies of the most advanced tool for wood density estimataion.

The study was supported financially by a Hildur and Sven Wingquist Foundation (Hildur och Sven Wingquist Stiftelse för Skogsvetenskaplig Forskning).

Svalöv, 2022-12-20, Mateusz Liziniewicz

# Summary

Cost effective and quick estimation of wood density is needed for various applications of this important wood property that is often considered affecting other wood traits. Information about wood density is also needed to calibrate biomass models used for carbon stock estimations. Such information might become a standard in the future when greater focus will be placed on biomass and fibre content than wood volume.

A range of methods can be used to estimate the wood density of individual trees, ranging from destructive measures of the whole tree or its parts, through semi-destructive measures of increment cores, to recently recommended non-destructive measures using various tools.

One objective of the study was to compare two semi-destructive methods of wood density estimation, the water displacement method and auger/drill method. Another was to examine the relationship between measured variables – wood density from the displacement method and diameter – and measurements derived from non-destructive methods involving the Pilodyn and the Resistograph. The primary focus was on correlation between wood density measurements derived from non-destructive measurements with those obtained from the displacement method.

Extraction of sawdust by drilling, from a cylindrical hole with a given volume, was generally accurate enough to estimate average wood density in stands of Norway spruce, Scots pine, birch, and hybrid aspen. The method was significantly less time consuming, but less accurate, than the water displacement method. Around 10 samples from each stand were needed to accurately estimate average wood density.

Correlation between non-destructive measurement with a Resistograph and wood density at individual tree level was poor. There was considerable variation in Resistograph measurements between species for aggregated data both within and between stands, regardless of the transformation method used for the Resistograph profile. There was no systematic result indicating which transformation method performed best, and the results were species dependent.

Phenotypic correlation between Pilodyn measurement and wood density was moderate for Scots pine and hybrid aspen but not for the other species.

In conclusion, the simple method of obtaining wood density using an auger might be used for a small number of measurements, although results are slightly poorer compared with the water displacement method. However, sawdust collection could be significantly improved, and differences might diminish. The method was less time consuming than the water displacement method, making it interesting for certain applications. The Resistograph should not be recommended for estimating wood density of individual trees. A more comprehensive study should be conducted on the Resistograph to ascertain its usefulness in assessments for the Swedish breeding programmes.

# Sammanfattning

Idag läggs störst fokus på virkesvolymer i hanteringar av och i affärer med skogliga råvaror. I framtiden spås att större fokus kommer läggas på biomassa och fiberinnehåll än vedvolymen, för att effektivisera utnyttjandet av råvaran: rätt råvara till rätt industri och slutprodukt. Då blir veddensitet en viktig egenskap att känna till. Redan idag används veddensitet för biomassaberäkningar, till exempel för beräkningar av kolflöden och kolförråd.

Detaljerade mätningarna av veddensitet kräver betydande resurser. En kostnadseffektiv och effektiv metod för uppskattning av veddensitet är därför önskvärd. Idag finns ett antal metoder för att mäta veddensiteten i enskilda träd, allt från metoder då trädet måste avverkas för att densiteten ska mätas (destruktiva metoder), via semi-destruktiva metoder då till exempel en borrkärna kan tas, till nyligen rekommenderade icke-destruktiva metoder då densiteten mäts med hjälp av olika digitala verktyg.

I denna studie har två semi-destruktiva metoder, vattenförträngnings- och skruv/borrmetoden, jämförts med två icke-destruktiva metoder, pilodynmätning och mätningar med resistograf. Korrelationen mellan icke-destruktiva mätmetoder och veddensitet var primärt fokus.

Uttagning av sågspån med vanlig borrning från en cylinder med en given volym, var i allmänhet tillräckligt noggrann för att uppskatta den genomsnittliga veddensiteten på beståndsnivå hos gran, tall, vårtbjörk och hybridasp. Metoden var betydligt mindre tidskrävande än den mycket exakta vattenförträngningsmetoden. Cirka 10 borrprover per bestånd behövdes för att uppskatta den genomsnittliga veddensiteten.

Icke-destruktiva mätningar med resistograf var ganska dåligt korrelerad med veddensitet hos enskilda träd. Det fanns också en stor variation mellan bestånden. Variation mellan trädslagen på beståndsnivå var stor. Det fanns inget systematiskt resultat som visade vilken transformationsmetod som fungerade bäst för resistografprofilen. Resultaten var trädslagsberoende.

Fenotypisk korrelation mellan pilodynmetoden och veddensitet var måttlig för tall och hybridasp men inte för de andra arterna.

Sammanfattningsvis kan den enkla borrmetoden användas för mätningar av begränsat material med antagandet om något sämre resultat än för vattenförträngningsmetoden. Borrmetoden var betydligt mindre tidskrävande än vattenförträngningsmetoden, vilket gör den intressant för nämnda applikationer. Varken resistograf- eller pilodynmetoden rekommenderas för uppskattning av densiteten hos enstaka träd. En mer omfattande studie om användning av resistograf bör genomföras för att utröna dess tillämplighet under svenska förhållanden.

# Introduction

Wood density is a ratio of the weight of oven-dry wood sample to its green volume. Density is a key property of raw wood, as it is strongly related to its other mechanical properties. The trait is a good predictor of overall wood quality for various end products. In recent years, the value of wood density in the forest industry has been increasing, as wood density is directly related to the quantity of wood fibres in wood volume, i.e., the biomass. Wood fibres have traditionally been used for production of a large range of commodities in the pulp and paper industry. Fibres are also used in the production of more sophisticated products, such as textiles. It is also likely that the range of commodities produced from wood fibres will gradually increase, as many ongoing development projects are examining the use of wood fibres.

In addition to the wood industry, knowledge about wood density is important for quantification of carbon stock and carbon sequestration in different forest ecosystems (Olale, et al. 2019). The biomass models have been developed using destructive measurements of trees (Repola 2008). Development of such models is laborious and requires substantial resources because of the need for destructive measurements to obtain information about volumes of different part of the trees and variations in wood volume. Biomass models are often developed on a small sample of trees, and are related to the woody biomass of trees with easily available biometrical measurements such as diameter and height. Such models are likely to be improved if more data is available, e.g., if wood density can be measured in a larger number of individual tree samples or from more trees per forest stand. Gathering more data would enable the inclusion of information from stands in different development phases, i.e., small trees and mature stands. The spatial variability of wood density over landscapes is also quite poorly recognised, and this could be improved with simpler methods of calculating wood density.

Although wood density is important for industry, it has not been considered in forest management and planning because of the expense of measurement. The most accurate assessment of wood density is delivered by a destructive analysis of a whole tree or its parts. Such measurements are rarely performed, as they are laborious, and are mostly restricted to data collection for a development of biomass functions (Claesson, et al. 2001, Marklund 1988, Petersson 1999, Petersson and Ståhl 2006, Repola 2008). Less extensive analysis of stem discs from one or several parts of the stem gives an accurate estimation of wood density, as it can be used for the whole circumference of the tree. However, both methods are destructive, and the measured tree is not available for production after measurement.

An alternative method for estimating wood density is a semi-destructive analysis of increment cores, at least in the parts of the tree that are accessible for measurement. Increment cores of different diameters are taken from the stem and subjected to measurement by the water displacement method or more sophisticated laboratory analysis using the Itrax X-ray microdensitometer (Cox Analytical Systems, Mölndal, Sweden) or Silviscan technology (Evans 1994, Evans 1999). In the water displacement method, fully saturated increment cores are used to estimate their volumes. The saturation of increment cores is species dependent, and it can take one to two days to fully submerge an increment core, and longer for some species. Moreover, extraction of an increment core could negatively affect the quality of the growing tree by increasing the risk of decay.

A similar method to increment cores is the auger method, which involves extraction of sawdust with an auger/drill from a hole in a tree where the hole has a known volume. The method has been recommended for wood density measurements of tropical timber, which is often very dense and from which it is hard to obtain increment cores (Krottenthaler, et al. 2015, Olale, et al. 2019)

For large-scale inventories of wood density, non-destructive tools (NDTs) have been tested and used. The most common tools are the Pilodyn (Pilodyn 6J Forest densitometer, PROCEQ, Zurich Switzerland) and the Resistograph ® (Rinntech, Germany), and these have been implemented in breeding programmes in several parts of the world (Fundova, et al. 2018, Isik and Li 2003, Lima, et al. 2007).

The Pilodyn method involves injecting a spring-loaded needle into the wood and reading the depth of penetration on a scale. The Pilodyn scale is not directly transformable to actual wood density and requires calibration with real density values. Pilodyn values have been used in breeding programmes to rank genotypes if wood density has been considered an objective breeding trait.

The Resistograph® is a device that measures resistance to drilling in the tree, recording trends caused by the increased friction when the drilling needle penetrates further into the wood. The method has been considered more accurate than Pilodyn, as it allows data to be collected from the whole-tree diameter. It takes longer to collect data with the Resistograph than the Pilodyn and, like the Pilodyn measurements, the collected data must be transformed to obtain a wood density.

Although an accurate estimation of woody biomass is important for quantifying local and global carbon stocks, data to calculate average density of stands is seldom collected, mainly because of limited resources and the long time needed to process increment cores to obtain wood density values. The transformation of NDTs data to real wood density values requires calibration of measurements with real wood density values obtained on the same site or from a specific area.

One objective of the study was to compare two semi-destructive methods of wood density estimation i.e., the water displacement method and the auger/drill method for Norway spruce, Scots pine, silver birch, and hybrid aspen. Another was to examine the relationship between measured variables – wood density from the displacement method and diameter – and non-destructive measurements of wood properties, i.e., Pilodyn and Resistograph. The main focus was on correlation of non-destructive measurements with wood density.

# Materials and Methods

## Location

Data for this study were collected around Ekebo in southern Sweden (55.9°N, 13.11°E), on the property belonging to the Forestry Research Institute of Sweden, Skogforsk.

## Stands

Three Norway spruce stands, three Scots pine stands, three silver birch stands, and one hybrid aspen stand were randomly selected from the stand register. The initial goal in the project was to collect data from 30 trees in each stand, distributed evenly between three diameter classes – 10-19,9 cm, 20-29,9 cm, and 30+ cm.

## Measurements and sample collection

In each stand, a sample of trees (N) was randomly selected and measured (Table 1).

For each selected tree, the following measurements were taken, and procedures carried out:

- Diameter of the stem, measured in two perpendicular directions
- Pilodyn measurement with the Pilodyn 6J Forest (PROCEQ, Zurich Switzerland)
- Resistograph measurement with R650-SC (Instrumenta Mechanic Labour, Germany)
- Collection of sawdust from a cylindrical hole in the tree with specific diameter and depth
- Collection of a 5-mm increment core

For all measurements the bark was first removed. A sample of sawdust was then taken, using a 10-mm drill with the depth limit set to 10 cm. An increment core sample was taken 3 mm above the first hole, and the Resistograph's sample a further 3 mm above. The Pilodyn measurement was taken close to the increment core hole. A total of 197 trees were fully sampled.

## Wood density analysis

### Auger method

The volume of a drilled hole in a tree was calculated using the hole's diameter and depth, and the average volume was approximately 7.85 $cm^3$. After the practical test, 10-mm cores were used for sampling, as this was the first drill diameter that proved suitable for extracting sawdust. Dry weight was obtained by drying the sample at 105°C until the decrease in moisture content was no greater than 0.001% per unit of time (1 second).

Density of the sample was calculated as the ratio between dry weight and volume, converted to kg $m^{-3}$.

## Increment cores

Increment cores were oven dried at 103°C ± 2°C for at least 48 hours. The section weights needed to be constant between two measurements, at least an hour apart, before the sections were considered dry. They were removed from the oven in sets of five and quickly measured to avoid them absorbing water from the air. For each individual section, oven dry weight was measured using digital scales and recorded in metric grams to three decimal places. Once weighed, sections were placed in a container of water and left to become fully saturated. Full saturation was the point at which the sections no longer floated and had settled on the bottom of the container. They were then left for another 24 hours to ensure they had absorbed the maximum amount of water possible and reach their maximum volume at full saturation.

The container of water was placed on the scale which was then set to zero, so that the weight of the container and the water in it was zero. Sections were removed from the water one at a time, and their surface water removed using blotting paper. The sections were rolled along until they did not leave any visible water on the paper, and then the flat faces were pressed against the paper. Each section was then weighed to obtain the fully saturated weight. If the scale did not show zero when the section was removed, the section was reweighed until repeated measurements were the same, zeroing the scale between each measurement.

The section was then inserted into the wire sample holder and submerged into the container of water. The weight of the water displaced by the submerged section was recorded. Separate submersions were made with just the wire sample holder, which had a displacement value of 0.004-0.012 g, depending on the configuration. The scale was zeroed and any water removed from the scale or sample holder between each measurement.

If there were any issues with either method, samples were replaced in the water for later remeasurement. Issues included samples falling out of the wire sample holder, rolling onto the bench, and being out of the water for more than 10 minutes. In each case, both wet weight and water displacement measurements were repeated.

If the increment core was longer than the length of the hole in a tree from which sawdust was taken, the core was shortened accordingly.

## Resistograph

The mean and median of each Resistograph profile was calculated according to four different methods:

1. Raw profiles delivered directly from the Resistograph (RES)
2. Trimmed profiles with the area representing bark removed (RES_DET)
3. Trimmed and detrended profiles with linear detrending (RES_LIN)
4. Trimmed and detrended profiles with GAM detrending (RES_GAM)

Trimming means that the bark and first ring of the profile were removed from calculations, while detrending means that the trend caused by the friction of the drilling needle was removed. The detrending was used to reduce measurement bias.

The *densitr* package (Krajnc 2022) in the R open-source software (R Core Team 2016) was used for the analysis. The profiles were automatically trimmed to remove bark from the profiles and detrended to remove the trend caused by drill friction as diameter increased. The graphical meaning of trimming and detrending is presented in Figure 1.

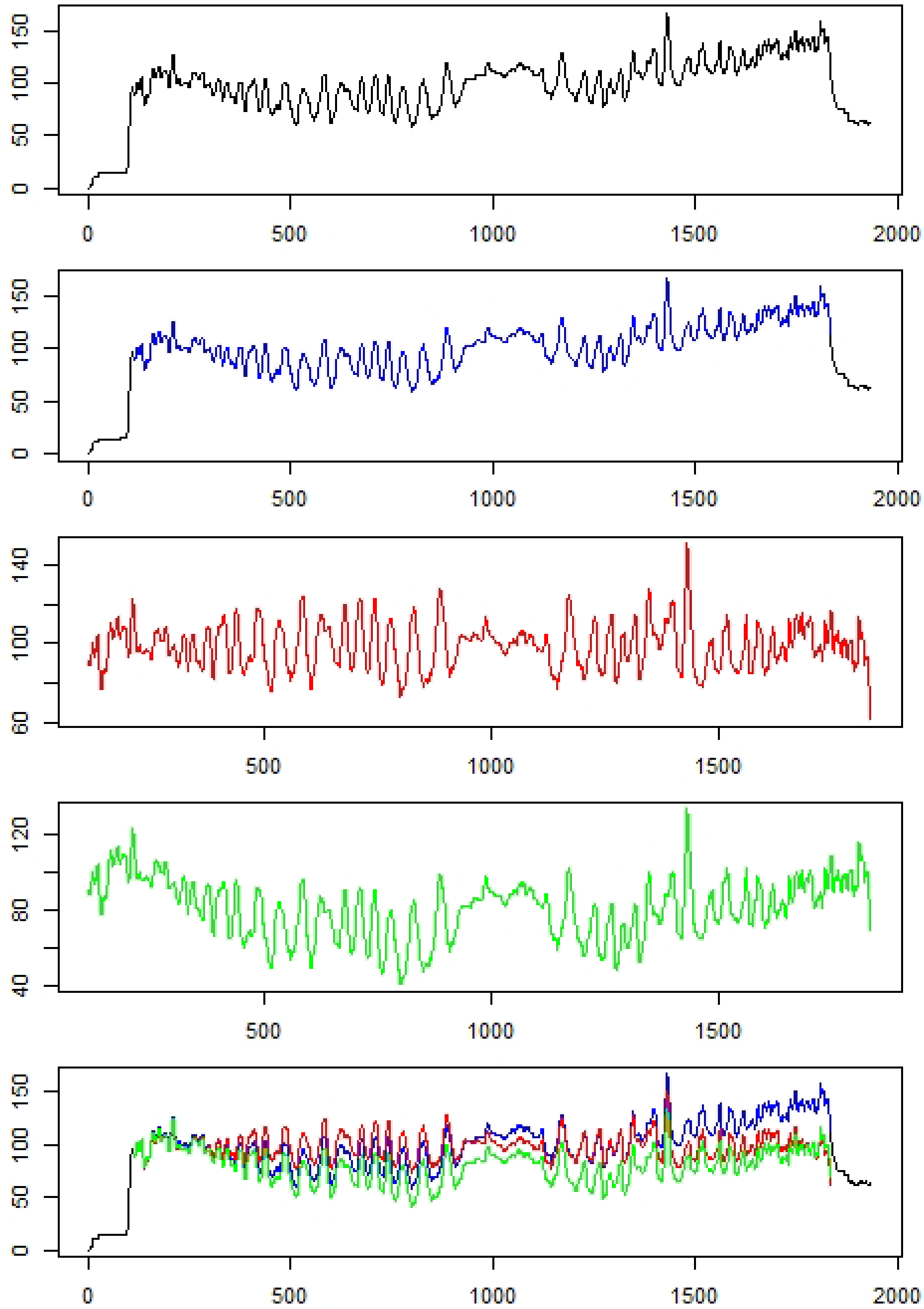

Figure 1. Graphical illustration of trimming and detrending of Resistograph values - original profile (black line), bark and first annual ring trimmed (blue line), linear detrending (red line), and GAM detrending (green line) of an individual Norway spruce tree.

## Data analysis

Data analysis was based on descriptive statistics and a visual assessment of correlations between measured traits. Pearson correlation was used on raw measurement values and Spearman correlation to calculate correlations between rankings of the trees within stands. The Spearman correlation was calculated to check the integrity of ranks based on different traits measured. The rankings of the trees within stands were based on measured values of the analysed traits.

The linear models for predicting wood density from the Resistograph's amplitude were developed separately for each species. Different values of Resistograph amplitude were tested, and the model with the highest value coefficient of determination (R2) was selected.

# Results

## Overall statistics

The relative differences in average stand wood density estimated from sawdust and increment cores did not exceed ±4% (Table 2). There was no systematic bias in estimations between methods and between species (Table 2).

The average wood density for Norway spruce was 308 kg $m^{-3}$ and was similar to hybrid aspen. The average for Scots pine was 368 kg $m^{-3}$ and for silver birch 399 kg $m^{-3}$.

The Pilodyn values were lowest, and various Resistograph values for silver birch were the highest.

Table 1. The averages of traits in the analysed stands. The phenotypic coefficient of variation (%) is given in brackets. The percentage in the "auger density" column shows a relative difference between the sawdust method and the increment core method.

| | STAND_ID | N | DIAMETER (mm) | AUGER DENSITY (Kg $M^{-3}$) | CORE DENSITY (Kg $M^{-3}$) | PILODYN (mm) | RESISTOGRAPH (RAW) | RESISTOGRAPH (TRIMMED) | RESISTOGRAPH (LINEAR) | RESISTOGRAPH (GAM) |
|---|---|---|---|---|---|---|---|---|---|---|
| Silver birch (B) | 2 | 29 | 194 (37) | 395 (11) 2% | 388 (7) | 17.6 (10) | 179 (21) | 191 (19) | 107 (11) | 130 (12) |
| | 3 | 19 | 146 (27) | 420 (8) 2% | 410 (6) | 16.9 (13) | 154 (12) | 169 (10) | 121 (9) | 123 (11) |
| Hybrid aspen (H) | 1 | 27 | 204 (45) | 308 (12) 0% | 308 (17) | 23.1 (13) | 99 (20) | 109 (19) | 93 (17) | 100 (16) |
| Scots pine (T) | 1 | 19 | 150 (23) | 349 (12) 4% | 337 (12) | 18.4 (14) | 99 (9) | 109 (10) | 86 (9) | 85 (9) |
| | 2 | 8 | 305 (10) | 384 (9) 2% | 391 (14) | 18.1 (10) | 106 (7) | 110 (5) | 88 (12.5) | 94 (4) |
| | 3 | 18 | 250 (21) | 364 (11) -3% | 376 (13) | 20.1 (12) | 111 (19) | 117 (17) | 85 (22) | 96 (11) |
| Norway spruce (G) | 1 | 21 | 167 (26) | 307 (7) -1% | 310 (5) | 18.8 (10) | 91 (10) | 98 (9) | 87 (7) | 101 (12) |
| | 2 | 28 | 205 (33) | 314 (15) -2% | 320 (12) | 19.9 (13) | 99 (12) | 108 (19) | 98 (30) | 109 (32) |
| | 3 | 28 | 208 (34) | 309 (13) 4% | 296 (7) | 19.8 (12) | 83 (12) | 89 (10) | 77 (11) | 99 (13) |

For clarification, wood density shown by increment cores will be used for further comparisons, as previous studies have shown that it measures accurately the actual wood density. The mean of Resistograph amplitude, trimmed and linearly detrended (LINEAR), will be used to represent Resistograph value.

## Increment core density vs auger density

Results for estimated wood density varied between two methods (Figure 2). The strength of the correlation varied between species (Figure 2) and between stands of the same species (Figure 3). The strongest correlation was for Scots pine (0.73) and hybrid aspen (0.6) (Figure 2). For Scots pine, the correlation coefficient varied between stands, ranging from 0.58 to 0.91. The correlations for silver birch and Norway spruce were approximately 0.3 (Figure 2).

There were two clear outliers in the silver birch data, where the density was shown to be lower than 300 kg $m^{-3}$. Removal of these increased the correlation coefficient to 0.51. There were outliers in Norway spruce, but they were more frequent and were not corrected to improve corelation coefficient.

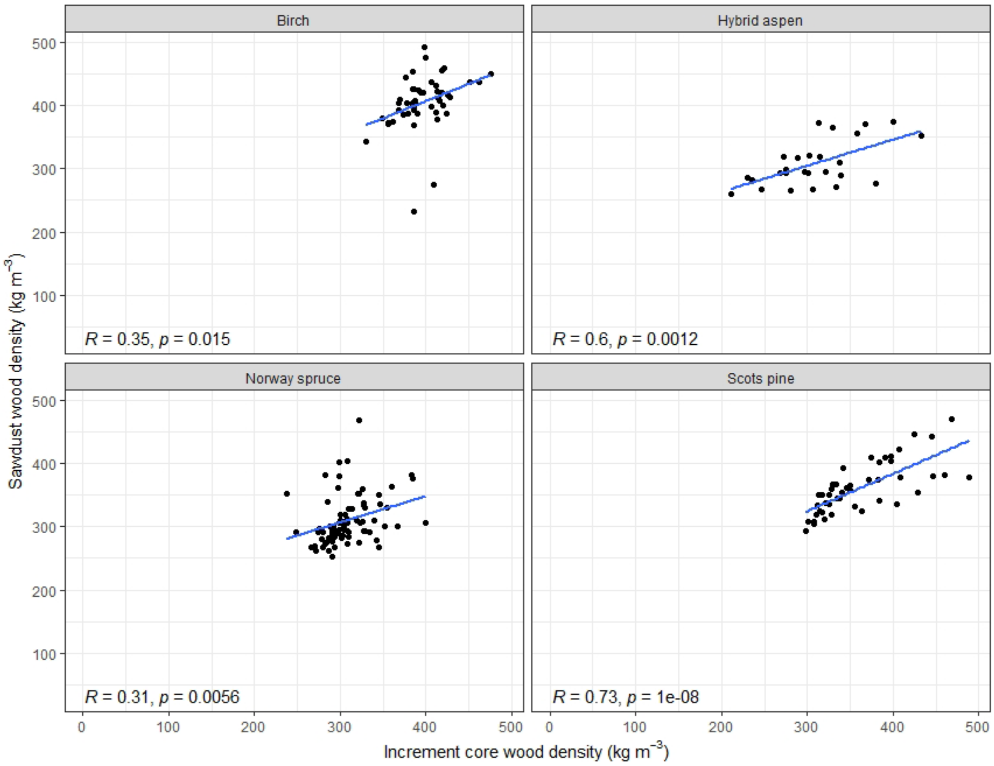


Figure 2. Relationship between increment core wood density (x-axis) and sawdust wood density (y-axis). Black dots represent wood density of individual trees. The blue line is a linear relationship between measurements.

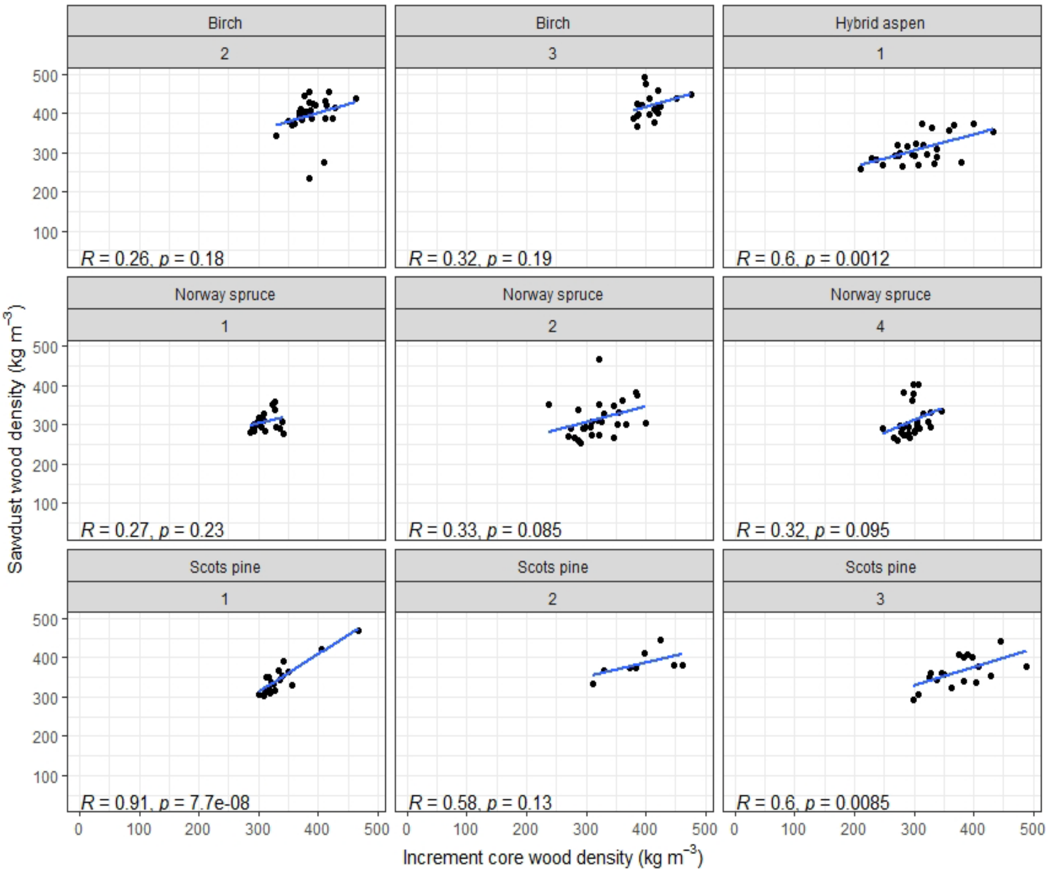


Figure 3. Relationship between increment core wood density (x-axis) and sawdust wood density (y-axis) in silver birch, hybrid aspen, Norway spruce, and Scots pine stands. Each dot is an individual tree measurement, and a blue line indicates a linear relationship between traits. The number under each species is the stand number, R is a correlation coefficient, and p is a significance value. A P-value less than 0.05 indicates significance at an alpha level of 0.05.

Calculated mean wood density for a single stand with a different number of observations (random order of samples) was more stable for increment cores than for sawdust (Figure 4). The sample size, between 5 and 10, was enough to obtain a stable value of average stand wood density for increment cores. A larger number of observations was needed to obtain a stable estimation of a stand mean, e.g., stand number two in Norway spruce (Figure 4, part a).

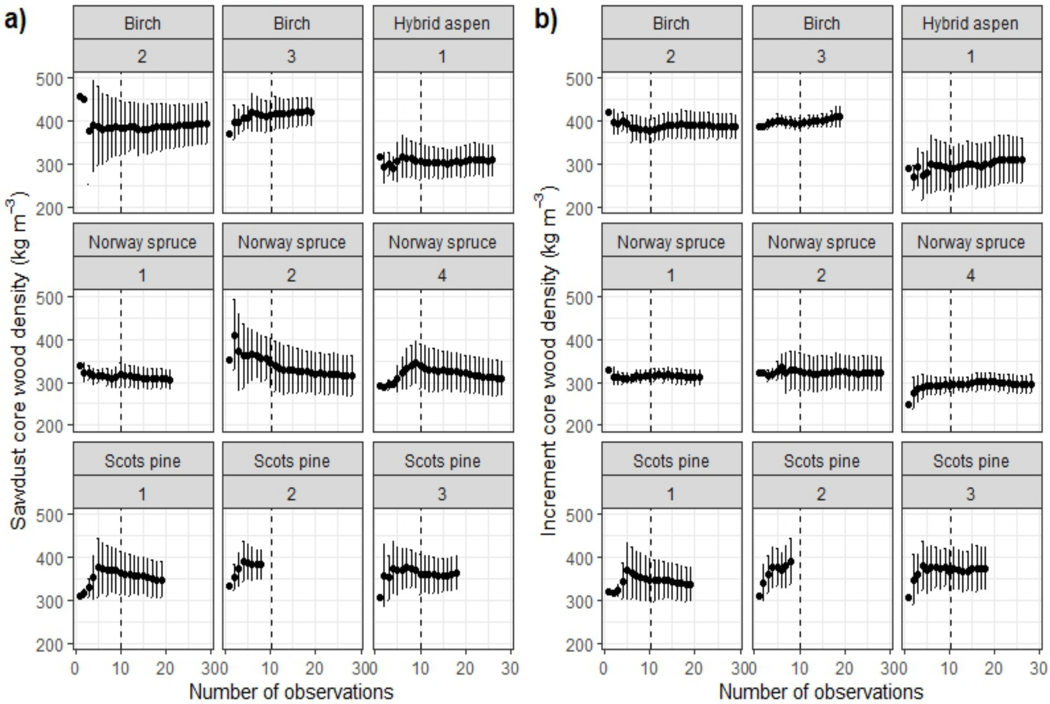


Figure 4. Relationship between number of observations (x-axis) and average wood density (y-axis) measured from a) sawdust and b) increment cores for analysed species and stands. The dots represent a moving average, the solid lines represent moving standard deviation. The dashed vertical line represents the number of observations equal to 10.

## Wood density and diameter

The relationship between breast height diameter and wood density was weak irrespective of species (Figure 5). The absolute value of correlation coefficient was lowest for silver birch (0.015). For other species the absolute value of correlation coefficient was around 0.2. For Norway spruce, a relationship was negative, while it was positive for hybrid aspen and Scots pine (Figure 5). For single stands there was a moderate correlation between variables for Scots pine, but not for other species (Figure 6)

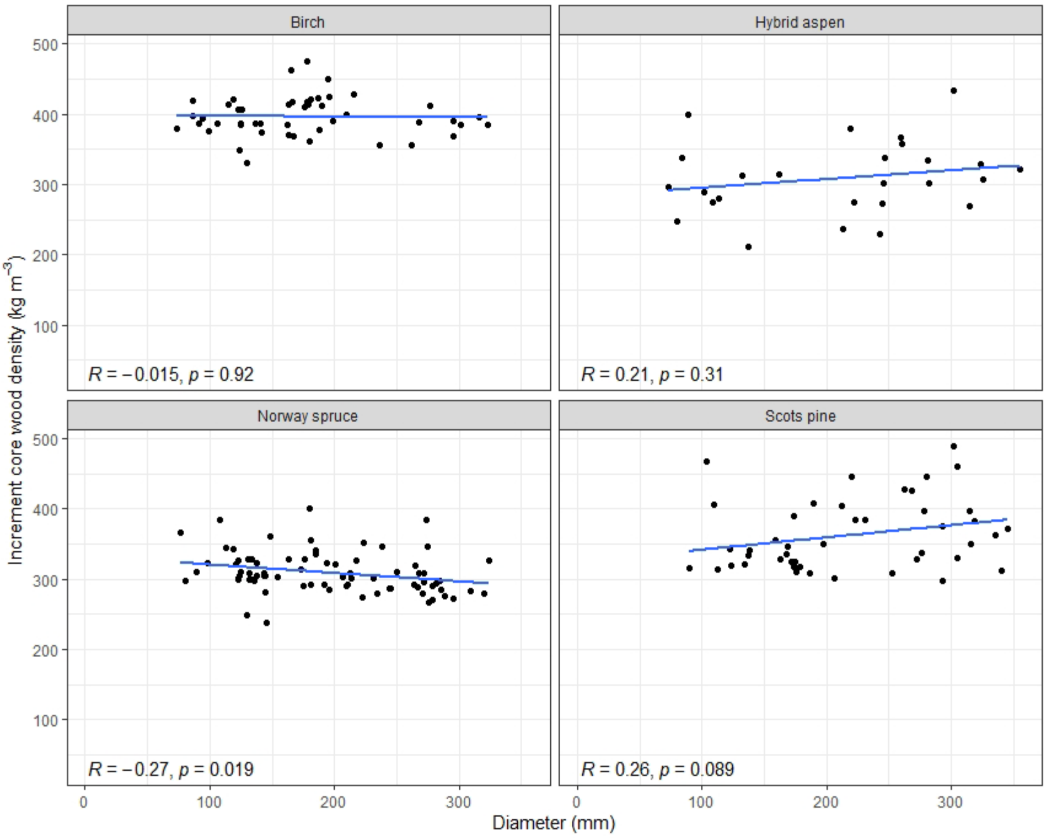


Figure 5. Relationship between breast height diameter (x-axis) and increment core wood density (y-axis) for silver birch, hybrid aspen, Norway spruce, and Scots pine. The blue line indicates a linear relationship between traits.

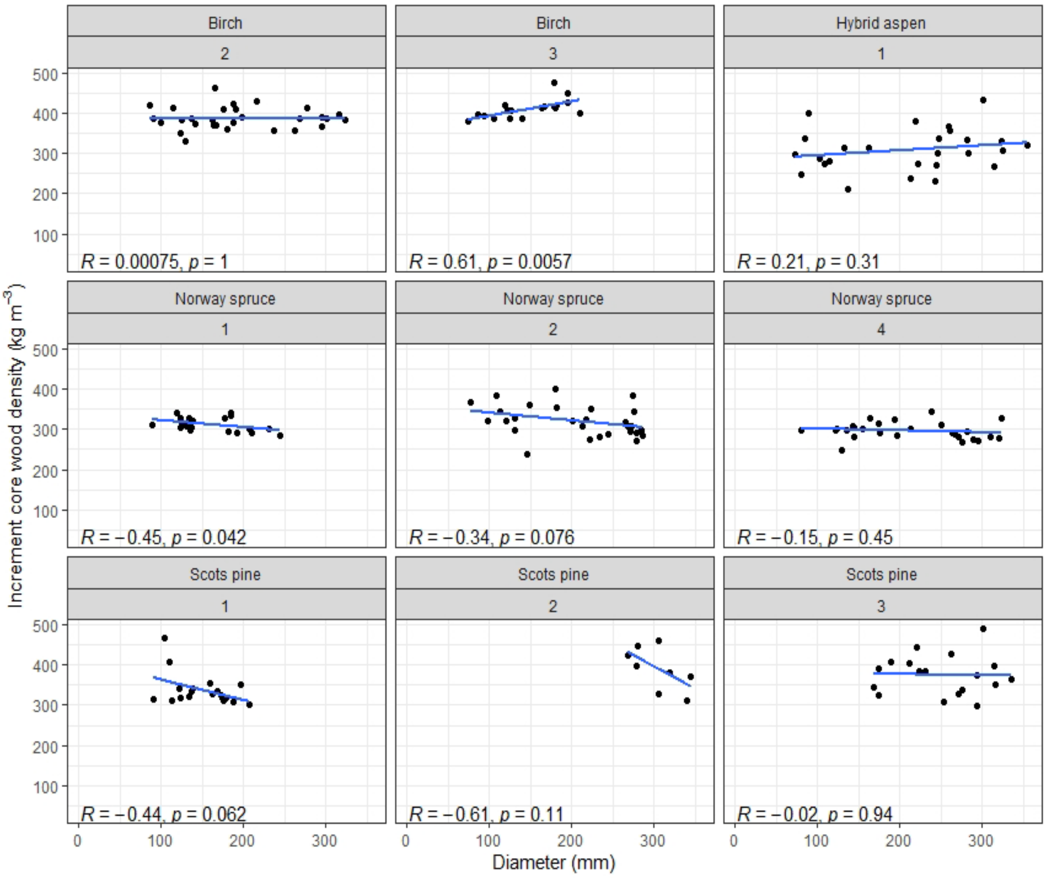


Figure 6. Relationship between tree diameter (x-axis) and increment core wood density (y-axis) in silver birch, hybrid aspen, Norway spruce, and Scots pine stands. Each dot is an individual tree measurement, and a blue line indicates a linear relationship between traits. The number under each species is the stand number, R is a correlation coefficient, and p is a significance value. A P-value less than 0.05 indicates significance at an alpha level of 0.05.

## Wood density and Pilodyn

The correlation between wood density calculated from increment cores and Pilodyn measurements was strong for hybrid aspen and Scots pine, but not for the two other species (Figure 7). For all species except birch, there was a positive correlation with inverse Pilodyn values.

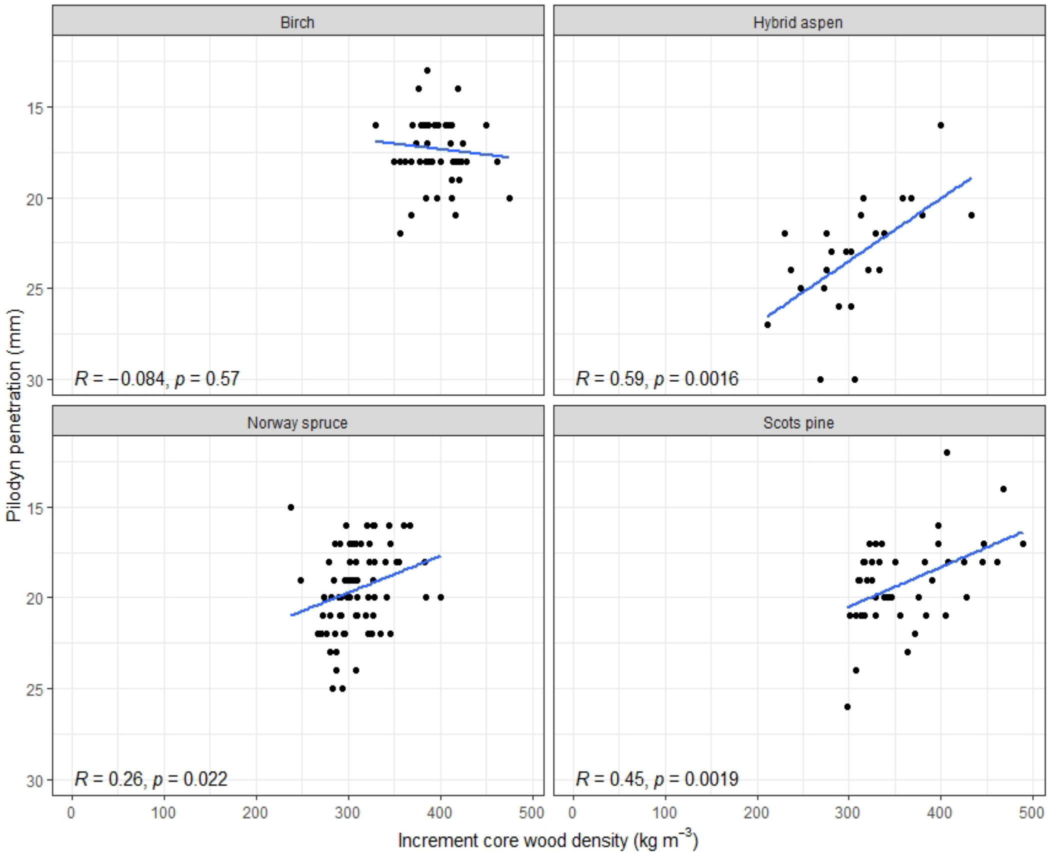


Figure 7. Relationship between increment core wood density (x-axis) and Pilodyn penetration (y-axis) for silver birch, hybrid aspen, Norway spruce, and Scots pine. The y-axis is inverted, as low Pilodyn values indicate high wood density.

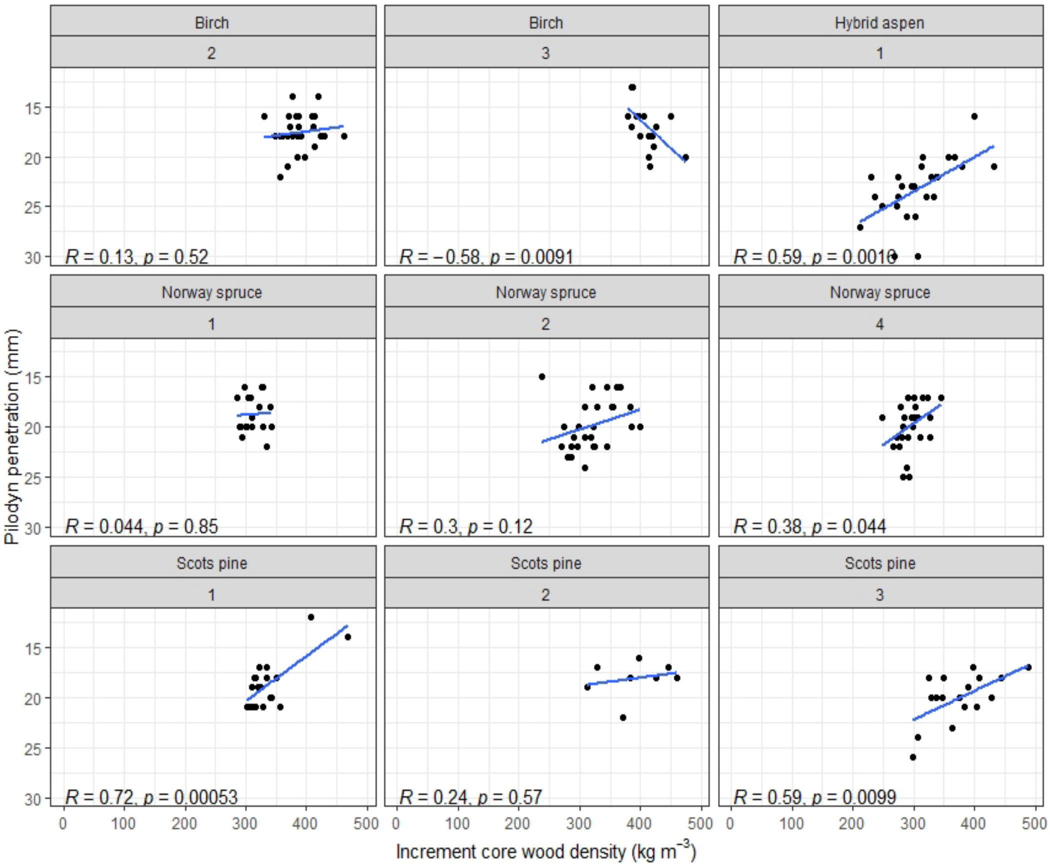


Figure 8. Relationship between tree wood density (x-axis) and Pilodyn penetration (y-axis) in silver birch, hybrid aspen, Norway spruce, and Scots pine stands. Each dot is an individual tree measurement, and a blue line indicates a linear relationship between traits. The number under each species is the stand number, R is a correlation coefficient, and p is a significance value. A p-value less than 0.05 indicates significance at an alpha level of 0.05.

## Wood density and Resistograph

Wood density and an amplitude from the Resistograph had a weak to moderate phenotypic correlation for all the analysed species. The magnitude of correlation coefficient was dependent on type of profile transformation and selected statistics, i.e., the mean or the median (Table 2). There was not a single transformation method that suited all species. In general, the higher correlations with wood density were obtained for a Resistograph value obtained as a median (Figure 9, Table 2), but not for Scots pine.

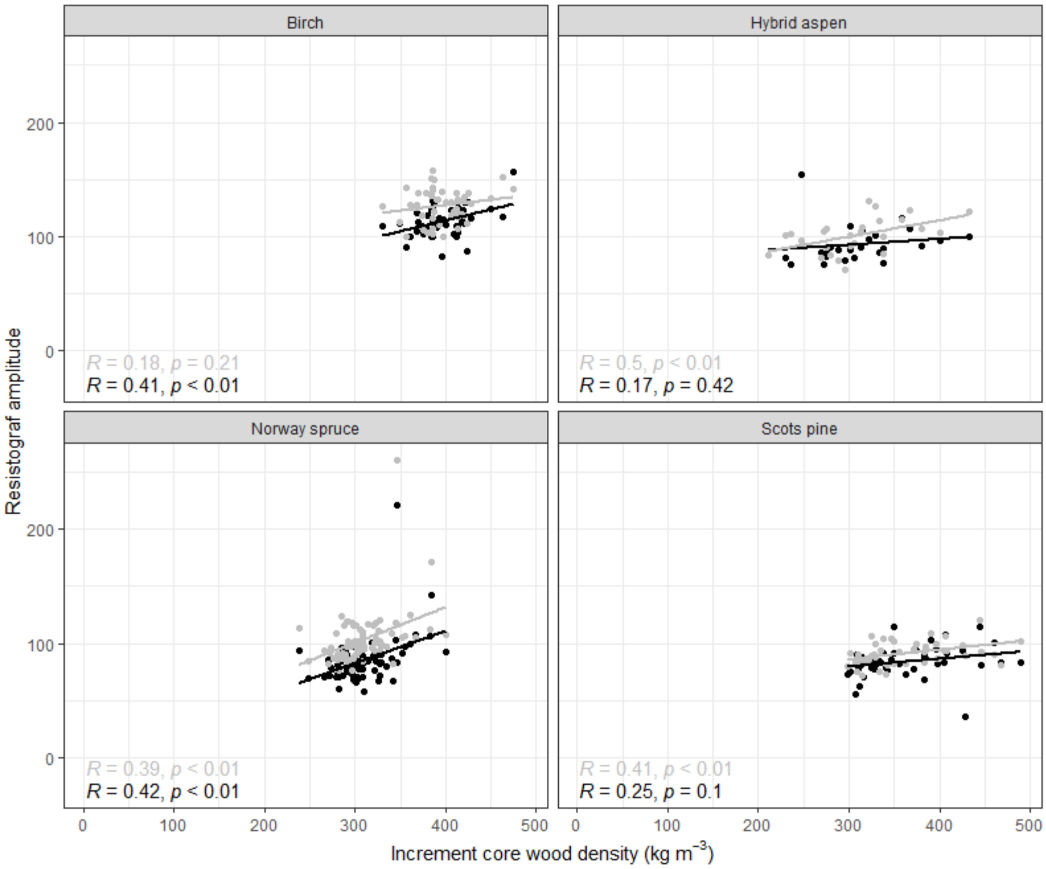


Figure 9. Relationship between wood density and Resistograph amplitude in silver birch, hybrid aspen, Norway spruce, and Scots pine. Black dots represent a median value of the Resistograph profile, trimmed and linearly detrended. Grey dots represent a mean value of a Resistograph profile, trimmed and GAM detrended. The solid lines are linear relationships between increment core wood density and Resistograph values. The number under the species is the stand number, R is a correlation coefficient, and p is a significance value. A p-value less than 0.05 indicates significance at an alpha level of 0.05.

In some cases, profile transformation and type of selected statistics (mean or median) had a great effect on the within-stand correlation. It was especially visible in the Scots pine stand 2, where correlations for a mean were weak, but strong for a median.

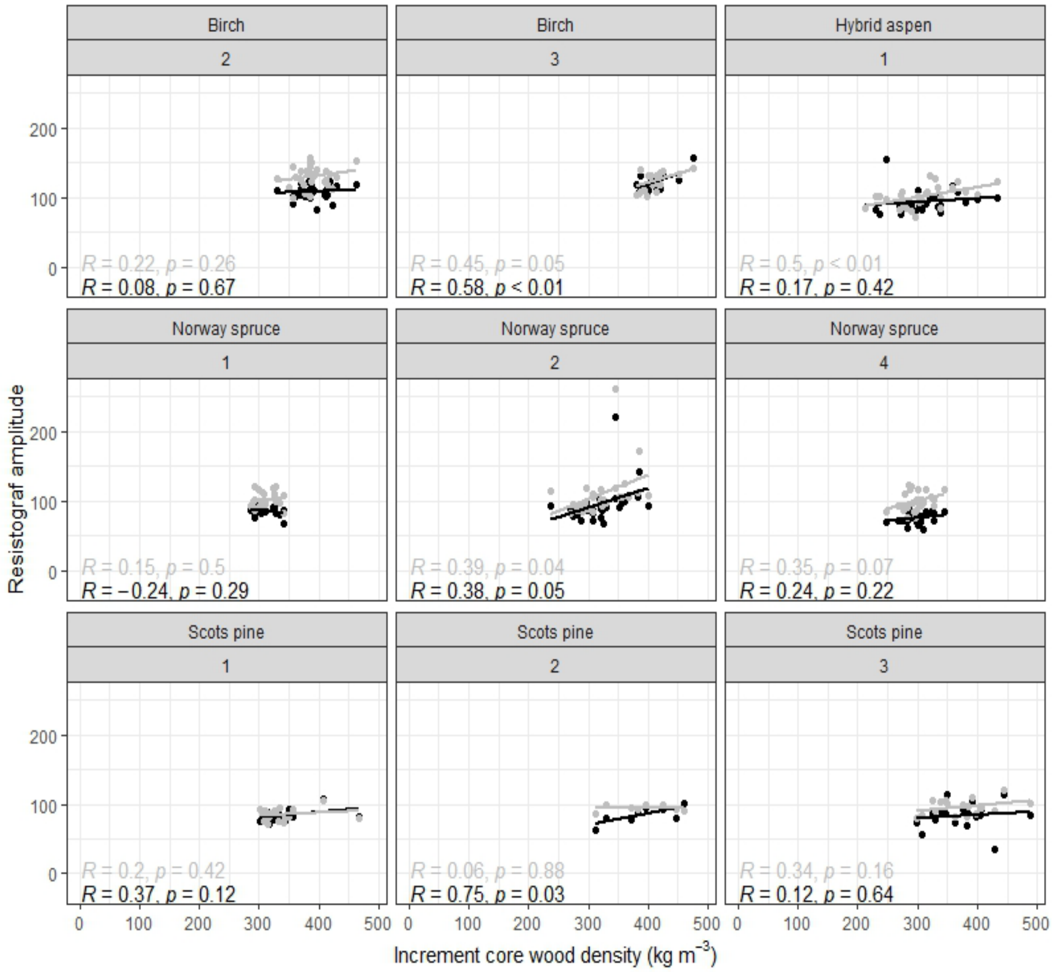


Figure 10. Relationship between tree wood density from increment cores (x-axis) and Resistograph amplitude (y-axis) in silver birch, hybrid aspen, Norway spruce, and Scots pine stands. Black dots represent a median value of the Resistograph profile, trimmed and linearly detrended. Grey dots represent a mean value of a Resistograph profile, trimmed and GAM detrended. The solid lines are linear relationships between increment core wood density and Resistograph values. The number under the species is the stand number, R is a correlation coefficient, and p is a significance value. A p-value less than 0.05 indicates significance at an alpha level of 0.05.

Table 2. Pearson correlations between wood density from increment cores and the Resistograph means and medians calculated for a raw profile, trimmed profile without bark, trimmed profile with linear detrending, and trimmed profile with GAM detrending.

| **SPECIES** | **RAW PROFILE** | | **TRIMMED** | | **LINEAR DETREND** | | **GAM DETREND** | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Mean | Median | Mean | Median | Mean | Median |
| Birch | -0.16 | -0.20 | -0.19 | -0.24 | 0.33 | **0.41** | 0.18 | 0.19 |
| Hybrid aspen | 0.51 | **0.57** | 0.46 | 0.49 | 0.18 | 0.17 | 0.50 | 0.51 |
| Norway spruce | 0.41 | **0.47** | 0.44 | 0.45 | 0.40 | 0.42 | 0.39 | 0.40 |
| Scots pine | **0.51** | 0.48 | **0.51** | 0.41 | 0.19 | 0.25 | 0.40 | 0.43 |

Simple linear regression models relating wood density to Resistograph amplitude were of poor quality (Table 3). The Resistograph value explained between 17% and 27% of the total variation in wood density.

Table 3. Individual tree linear regression models to predict wood density (WD) using a specific value of Resistograph amplitude (x) for four species.

| SPECIES | TYPE OF AMPLITUDE TRANSFORMATION (X) | MODEL R2 | REGRESSION EQUATION | N[1] | P[2] |
|---|---|---|---|---|---|
| Birch | Median Linear | 0.17 | 296 + 0.8845*x | 48 | <0.0001 |
| Hybrid aspen | Raw | 0.27 | 168.9 + 1.3873*x | 27 | <0.0001 |
| Norway Spruce | Median Trimmed | 0.21 | 224.8 + 0.8723*x | 77 | <0.0001 |
| Scots pine | Mean Trimmed | 0.26 | 165.5 + 1.75*x | 45 | <0.0001 |

N[1] – Number of observations
P[2] – Regression model probability

## Diameter and Pilodyn

The relationship between breast height (1.3 m) diameter and the Pilodyn penetration was strong for silver birch and Norway spruce, but not for the two other species (Figure 11).

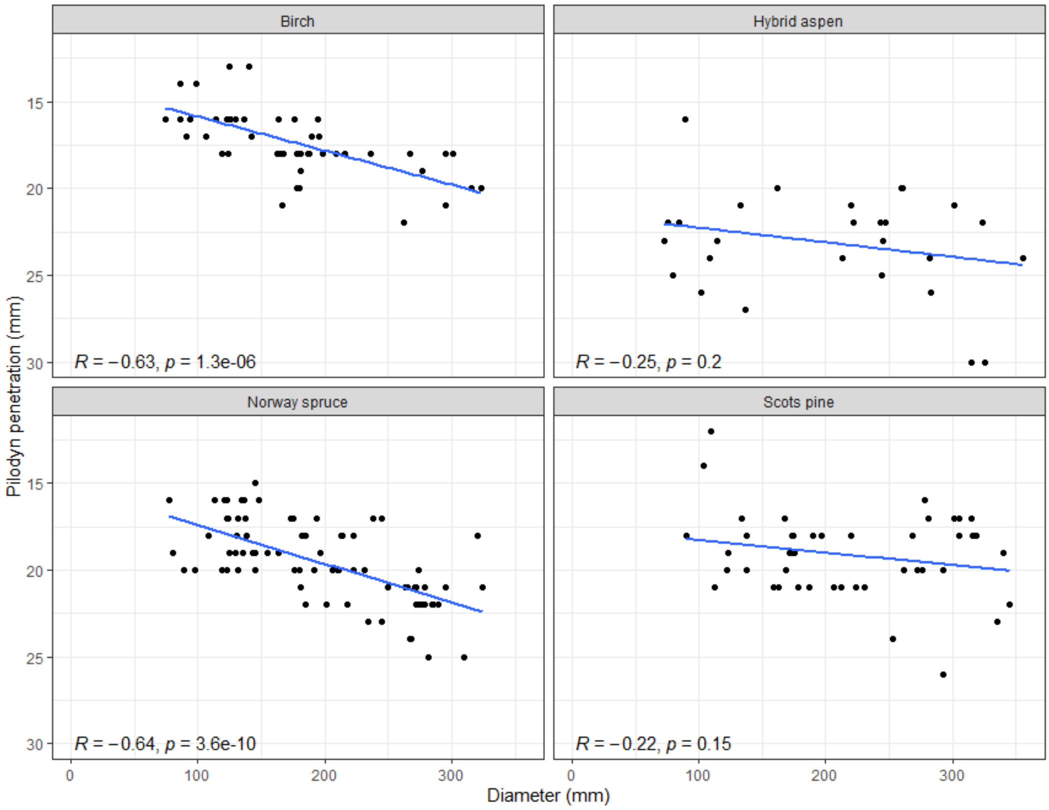


Figure 11. Relationship between diameter at breast height (x-axis) and Pilodyn penetration (y-axis) for silver birch, hybrid aspen, Norway spruce, and Scots pine over all analysed stands. Each dot is an individual tree measurement, and a blue line indicates a linear relationship between traits. The number under the species is the stand number, R is a correlation coefficient, and p is a significance value. A p-value less than 0.05 indicates significance at an alpha level of 0.05

Correlation between both traits varied substantially between stands (Figure 12). For each species except hybrid aspen, there was a stand with a strong correlation between measurements, e.g., birch stand 2 and Norway spruce stand 2. For these stands correlation exceeded 0.7.

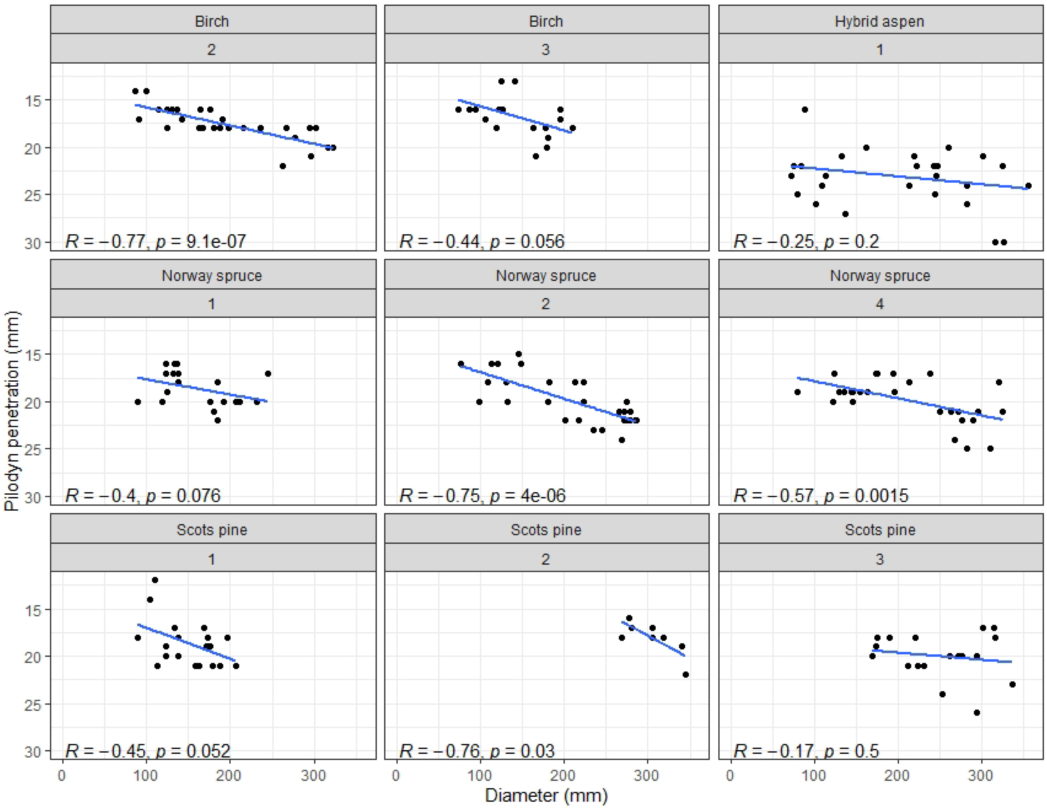


Figure 12. Relationship at stand level between tree diameter (x-axis) and Pilodyn penetration (y-axis) in silver birch, hybrid aspen, Norway spruce, and Scots pine stands. Each dot is an individual tree measurement, and a blue line indicates a linear relationship between traits. The number under the species is the stand number, R is a correlation coefficient, and p is a significance value. A p-value less than 0.05 indicates significance at an alpha level of 0.05.

## Diameter and Resistograph

No correlation was found between diameter and Resistograph for any of the analysed species (Figure 13).

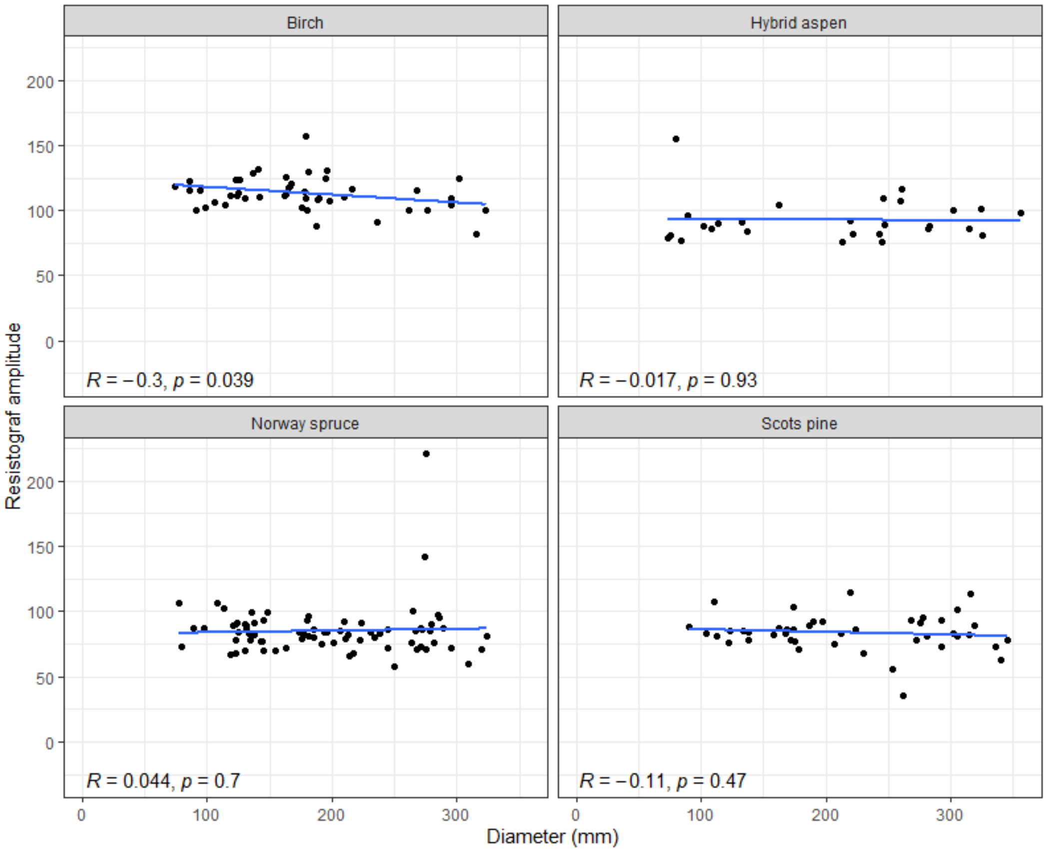


Figure 13. Relationship between diameter at breast height (x-axis) and amplitude of Resistograph, trimmed and detrended (y-axis) for silver birch, hybrid aspen, Norway spruce, and Scots pine for all analysed trees. Each dot is an individual tree measurement, and a blue line indicates a linear relationship between traits. The number under the species is the stand number, R is a correlation coefficient and p is a significance value. A p-value less than 0.05 indicates significance at an alpha level of 0.05

## Pilodyn and Resistograph

The relationship between the inverse Pilodyn penetration and the Resistograph was weakly positive, and only for Scots pine did it exceed 0.3 (Figure 14).

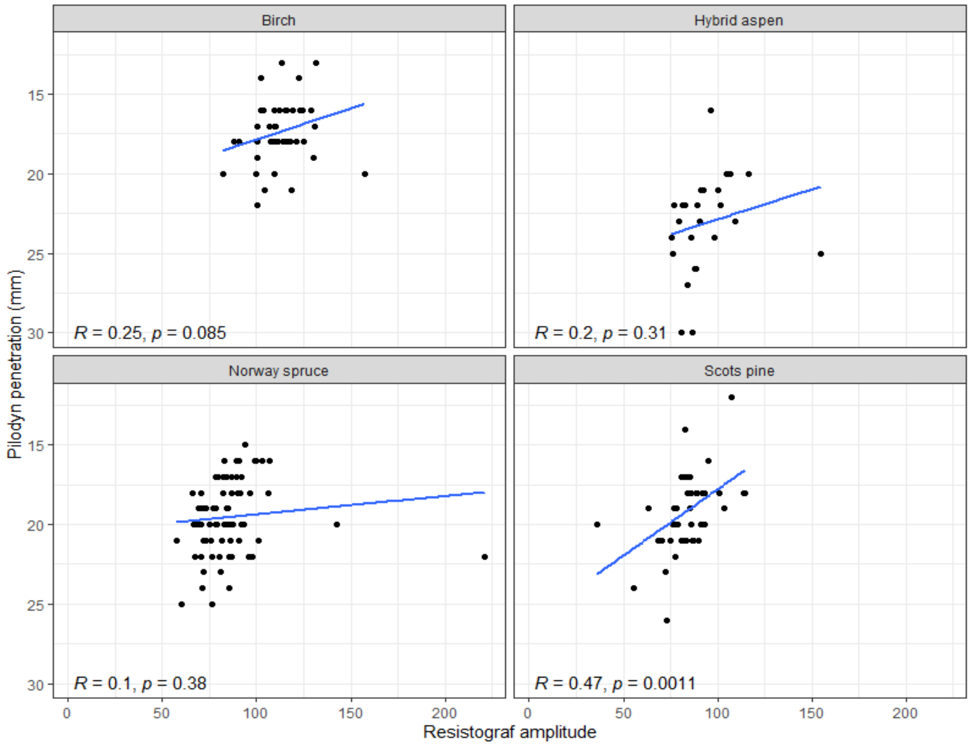


Figure 14. Relationship between mean amplitude of Resistograph, trimmed and detrended (x-axis), and inverse Pilodyn value (y-axis). Each dot is an individual tree measurement, and a blue line indicates a linear relationship between traits. The number under the species is the stand number, R is a correlation coefficient, and p is a significance value. A p-value less than 0.05 indicates significance at an alpha level of 0.05

Table 4. Phenotypic Pearson correlations between traits (upper) and rank Spearman correlations (lower) for birch, hybrid aspen, Norway spruce, and Scots pine.

| BIRCH | DIAMETER | WOOD DENSITY | PILODYN | RESISTOGRAPH | HYBRID ASPEN | DIAMETER | WOOD DENSITY | PILODYN | RESISTOGRAPH |
|---|---|---|---|---|---|---|---|---|---|
| Diameter | 1 | -0.15 | 0.63 | -0.30 | Diameter | 1 | 0.21 | 0.24 | -0.06 |
| Wood density | 0.05 | 1 | 0.08 | 0.41 | Wood density | 0.25 | 1 | -0.58 | 0.17 |
| Pilodyn | 0.67 | 0.08 | 1 | -0.25 | Pilodyn | -0.12 | -0.66 | 1 | -0.21 |
| Resistograph | -0.25 | 0.34 | -0.31 | 1 | Resistograph | 0.16 | 0.47 | -0.46 | 1 |
| **NORWAY SPRUCE** | **Diameter** | **Wood density** | **Pilodyn** | **Resistograph** | **SCOTS PINE** | **Diameter** | **Wood density** | **Pilodyn** | **Resistograph** |
| Diameter | | -0.26 | 0.64 | -0.11 | Diameter | 1 | 0.26 | 0.21 | -0.11 |
| Wood density | -0.37 | | 0.29 | 0.39 | Wood density | 0.23 | 1 | -0.45 | 0.25 |
| Pilodyn | 0.64 | -0.34 | | -0.10 | Pilodyn | 0.89 | -0.41 | 1 | -0.47 |
| Resistograph | -0.11 | 0.37 | -0.29 | | Resistograph | -0.09 | 0.38 | -0.47 | 1 |

# Discussion

## Relationship between the different volumetric methods of wood density measurement

Average wood density values in a single stand obtained using the auger and water displacement methods were similar. The relative differences between methods did not exceed ±4%. The magnitude of difference was neither dependent on species nor on the number of samples in a single stand. The number of samples per stand ranged from eight to 29 but only one stand had fewer samples than ten. A simple calculation of a mean to increase the number of observations showed that between five and ten observations are required to obtain a stable estimate of average stand wood density when increment cores are taken. A slightly higher number of samples is needed if mean wood density is calculated using collected sawdust.

On an individual tree level, the phenotypic correlations between methods were moderate for hybrid aspen (0.6) and Scots pine (0.71). The estimated correlations for Norway spruce and silver birch were low (< ~0.30). There were more outliers in the data for Norway spruce and birch that influence the results. Removal of outliers improved correlation between methods for birch. Norway spruce had a larger number of outliers (assessed subjectively from figures), and these outliers were not removed.

The collection of sawdust is likely to cause greater error in wood density estimation than estimation using increment cores. The main two error sources for wood density estimation from sawdust are imperfect measurement of the hole in a tree and a loss of sawdust during the extraction. Sawdust was extracted with a simple set up of electric drill with an auger with a restricted drilling depth. Martinez et al. (2020) found a correlation of 0.96 between the methods under laboratory conditions with a specially designed tool that allowed more accurate extraction of sawdust than in the present study. The field work for the present study was done directly in the forest, sometimes in poor weather conditions where low temperature and rain can cause inaccuracies in sawdust extraction.

The number of working hours needed to estimate wood density was significantly lower for auger samples. The volume of the cylinder containing the sample is known directly, and it takes from just five to 20 minutes to estimate the weight of a wood sample taken from a tree and to calculate wood density. In the case of increment cores, an estimation procedure takes at least two days and requires more intensive control. However, the variation in estimation of wood density from sawdust was higher than for increment cores. This indicated that the auger method might be more prone to sampling error due to imprecise estimation of cylinder volume and a greater likelihood of losing material when drilling into the tree.

## Resistograph

The Resistograph's amplitude had weak phenotypic corelation with wood density for all analysed species when the data were aggregated to species level. The magnitude of correlation did not exceed 0.4. Substantial differences were sometimes found within a stand for two estimation methods i.e., correlations calculated as a mean and as median. The nature of this variation was not studied and explained in the study, but needs to be investigated further.

For hybrid aspen, Norway spruce and Scots pine, the greatest value for correlation coefficient was obtained using raw values of the Resistograph's amplitude, and different detrending models did not improve the correlations with other variables. For hybrid aspen and Norway spruce, a median value calculated from the raw profile had the greatest correlation value, and the improvement was approximately 0.06. For Scots pine, a mean value of the profile was superior to a median. The use of median value was supposed to account better for not visible knots and other wood anomalies during drilling.

In the case of Scots pine, the results are contradictory to the findings shown by Fundova, et al. (2018) in a Scots pine genetic trial of similar age and average dimensions. Fundova et al. (2018) found the Resistograph value to be highly correlated with wood density of increment cores obtained from the SilviScan analysis. Resistograph measures correlated very well with wood density on a family level for maritime pine (*Pinus pinaster* Ait) in France (Bouffier, et al. 2008). In that study increment cores only 5-cm long were taken and related to Resistograph profiles of the same length. In our study we did not restrict a Resistograph profile to match exactly the length of the core taken from a tree, which can cause inaccuracies. If the core was slightly longer than half the diameter it may include a double quantity of juvenile wood, which is generally of lower wood density. On the other hand, phenotypic correlations for individual trees were similar to values found in our study. Similar results of high family correlations and moderate phenotypic correlation were found for loblolly pine (*Pinus taeda* L.) in four genetic trials (Isik and Li 2003). In that study correlation of wood density and Resistograph amplitude varied between 0.29 and 0.51.

In general, use of the Resistograph to quantify wood density was not successful in this study. This may be because there was no calibration for each tree species, as there is a knowledge development gap in that area. The Resistograph product description shows that a correlation with wood density of 96% can be reached after calibration for specific species. In this study, correlations between wood density and Resistograph values were low to moderate, and a simple linear regression model explained less than 30% of the wood density variation with the Resistograph as a linear predictor. The benefits of the Resistograph have been confirmed in a more comprehensive study, where potential confounding effects are considered, for example accounting for shaft friction as suggested by Sharapov, et al. (2017).

## Pilodyn

The Pilodyn is a very simple tool for obtaining data on wood density. It involves the injection of a needle into the tree circumference with a known force. The results are shown on a mm scale and indicate penetration depth. High Pilodyn values indicate a low wood density, and low values high density.

The Pilodyn and wood density were moderately correlated, with the results in line with other Swedish studies in Scots pine (Fundova, et al. 2018), birch (Jones 2022, Jones, et al. 2021), Norway spruce (Chen, et al. 2015, Liziniewicz, et al. 2020), and hybrid aspen (Liziniewicz, et al. 2023).

The correlation between diameter at breast height and inverse Pilodyn value was negative for all species, indicating that wood density decreases with increasing diameter. The correlation was greater for silver birch and Norway spruce than for the other two species. The results for birch are contradictory to the study by Jones, et al. (2021), involving two genetic trials where at the age of 19 years the correlation was lower, i.e., 0.08 and 0.18, than in this study, -0.63. The differences might be due to a different diameter of the measured trees. The mean diameter in this study was approximately 170 mm, but approximately 100 mm in the study by Jones et al (2021). In the current study, correlation value for hybrid aspen was much lower than that found in studies in young hybrid aspen in Sweden. In four six-year-old hybrid aspen stands, the correlation between the two variables was constantly around 0.4 (Liziniewicz 2022). In a study of three 11-year-old hybrid aspen stands, correlation between diameter and Pilodyn ranged between 0.21 and 0.53 (Liziniewicz, 2023).

**Conclusions**

The study provided new data on wood density for the most important tree species in Sweden and on the relationship between wood density with diameter and non-destructive measurements taken by Pilodyn and Resistograph.

Wood density might be easily obtainable using the auger method, which extracts sawdust from a cylinder of a known volume. The method is easier to perform than the water displacement method and would guarantee acceptable results. Results can be delivered in a couple of minutes while it takes minimum of two days for the water displacement method. A simple tool for taking samples would need to be developed to increase the precision of the method.

A more comprehensive study of the Resistograph use is recommended, with the aim of improving its calibration for different species.

At this stage the Pilodyn seems to be a good tool for obtaining an indication of wood density of individual trees for hybrid aspen, Norway spruce and Scots pine, but not for silver birch.

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