Deformations of boards from uneven-aged Norway spruce stands

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Abstract
This study focused on wood distortion of boards sawn from Norway spruce (Picea abies (L.) Karst.) trees grown in uneven-aged stands. The stands were multi-aged with tree ages up to 170 years. In total, 60 trees were harvested from six stands that had been managed by single-tree selection for decades. A butt log and a top log were sawn from each tree, both 2.5 m long. Wood deformations were measured from boards dried to an average moisture content of 7–10% from the 2.5 m long boards. A linear mixed model was constructed to describe the variation in twist deformations in the boards after drying. According to the model analysis, twist increased with greater grain angle, greater average annual ring width and relative ring width difference, greater knot size and count, and the interaction of grain angle with the vertical log position along the stem. Greater distance of the board from the pith was associated with lesser twist. Contrary to expectations, proportion of compression wood and tree position in the stand diameter distribution were not correlated with twist. Pin knots, although their occurrence and size was minimal, had a high degree of correlation with twist. The occurrence and severity of twist remained approximately at the same level as in even-aged Norway spruce as observed in other studies.

1 Introduction
Uneven-aged management is expected to gradually achieve a minor but established status in practical forestry in the Nordic countries. In Finland, the legal restrictions on its use were finally lifted in 2014 (Forest Act 2014). The management of even-aged stands has been the overwhelmingly predominant mode of silviculture in the area since 1950s, and the contemporary forests are characterized by uniform stands with the dominance of a single species with homogenous spacing, stem diameter, height, and canopy characteristics. They are mainly harvested with clearcutting at 50–100 years of age and artificially regenerated to initiate a new rotation. Selection silviculture is an alternative management system associated with a great degree of structural heterogeneity within and between stands. Stands are made up of trees of multiple ages and sizes mixed at small spatial scales, resulting in complex competitive interactions between the trees. Stands are managed with selection harvesting targeting mainly large tree individuals that are considered economically mature and are removed individually or in small groups or patches. Trees typically experience consecutive suppression and release phases, especially at early ages (Schütz 2001). The effects of the fluctuating growth patterns are generally poorly understood in wood science, although the influence of growth rate on wood properties is well studied.

Silvicultural practices can be utilized to control the environmental factors influencing wood formation and properties (Wimmer and Downes 2003), and wood properties can be expected to differ between even-aged and uneven-aged stands. Knowledge regarding wood properties and quality of sawn goods in uneven-aged stands is very scant in the Nordic area, and there is great demand for research results that will aid in the construction of practical guidelines and in the provision of extension and management services for uneven-aged methods.

Very few studies have directly focused on wood properties in selection stands (or any kind of uneven-aged stands) in the Nordic countries or more generally in the global literature. Piispanen et al. (2014) studied wood density in spruce stands, revealing a pattern specific to trees that had been subjected to prolonged growth suppression, as wood density closely reflects radial growth in spruce (Wilhelmsson et al. 2002; Jyske et al. 2008). Wood density was very high near the pith, followed by a decrease, an increase, and another decrease towards the bark, in that order (Piispanen et al. 2014). Nevertheless, studies conducted in stands at various
stages of transformation from even-aged to uneven-aged management are also relevant in this context (e.g., Seeling 2001, Macdonald et al. 2010, see review by Pretzsch and Rais 2016).

This study aims to examine how some of the underlying properties related to distortion and distortion itself vary in uneven-aged stands. The occurrence of the usual types of distortion in boards was assessed and focus was put on twist in a more elaborate analysis as the prime representative of distortions. Twist is regarded as the distortion with a closer relationship to wood properties (e.g., wood density, annual ring and knot properties) than warps, like bow, curved edge or cup (Forsberg 1999). Twist is also more consistently predictable in modeling than other distortions like bow or crook (Forsberg 1999). Boards are required to be distortion-free when they are used in many applications. Therefore, distortion is a quality trait. Distortion is a result of differential and anisotropic shrinkage that can be affected by other wood properties. Compression wood has higher longitudinal shrinkage than normal wood (Harris 1977) and in the study by Xu et al. (2009), severe compression wood showed the highest value of longitudinal shrinkage among annual rings that contained different types of compression wood. Wood density and its variation, and annual ring width and its orientation, are closely related to the proportion of juvenile wood in uneven-aged trees (Piispanen et al. 2014). Juvenility, its variation, ring curvature, knots, proportion of reaction wood and its distribution along the stem, and spiral grain angle are known to be correlated with the distortion of boards (Sandberg 2005; Bäckström and Johansson 2006; Gjerdrum and Bernabei 2009; Straže et al. 2011). Juvenile wood (Sandberg 2005), microfibril angle and large knots are common causes for higher longitudinal shrinkage (Perstorper et al. 2001), which together with growth ring curvature (Johansson et al. 2001; Straže et al. 2011) have been suggested as the main factors relating specifically to twist distortion. Grain pattern, although highly variable from the pith to bark, is closely related to deformations of boards, especially twist (Forsberg 1999; Gjerdrum and Bernabei 2009). Structural elements, like knots and undulating pith, are also related to irregularities in the grain pattern.

The effects of various factors on twist (and other deformations too) have often been researched individually, or in conjunction with a small number of other wood characteristics. Given their complexity and interrelated nature, it is critical to study these multiple factors simultaneously to parse out which are most important within this particular context. Therefore, the empirical approach was to analyze their combined effects within a model-based framework. Particular interest was on the features that would be associated with the consequences of structural and dynamic complexity of tree growth during the early development of trees in uneven-aged stands.

The present study aimed to (1) assess the degree and severity of distortions and wood characteristics behind distortions, especially twist, in boards from different classes of trees and positions within trees; (2) analyse the relationship between growth-related factors and twist; (3) consider how uneven-aged management relates to (1) and (2). The variables hypothesized to be correlated with the severity of twist were annual ring width, knot count, spiral grain angle, board position along the stem, proportion of compression wood, and tree canopy position.

2 Materials and methods

2.1 Sampling

Sample trees were harvested from permanent experimental plots belonging to a set of 20 experimental stands at three geographic locations (henceforth called sites) in southern Finland (60° 30′–62° 30′ N, 25°–27° E). Most stands in this study represented true selection stands, with some needing additional gradual adjustments in order to proceed from an irregular structure towards fully developed selection structures. The study stands had been systematically managed with single-tree selection for no longer than 25–30 years, but their prior development was also characterized by complex stand structures and partial harvests of variable intensity. The stands had emerged from natural regeneration with irregular initial development including suppression and release periods. In further development, structural complexity was characteristic for the stands throughout their development. However, intervals with development towards more uniform stand structures had occurred, especially when harvesting had been delayed and tree growth in the lower canopy layers decreased and mortality increased. Some low-intensity thinning from below had probably been carried out in some stands at some point with only low or modest impact on stand structures. Utilizing the existing structural complexity, single-tree selection was adopted and selection harvesting targeting on the maintenance or establishment of typical “Plenterwald” stand structures was adopted in the 1980s. A selection cutting was carried out in all of the stands in 1985–1988. After the establishment of the experiments in 1991–1996, the selection harvesting was repeated in 1996. All trees with defects or damage were removed first, and then healthy trees mainly from the larger diameter classes (> 25 cm), were removed until a target basal area was achieved. The stands were left alone until a new harvest in the winter of 2011–12, including the sampling for this study. All of the stands at that time can be characterized as truly multi-aged (with trees up to 170 years old) and full-storied (in the sense of Ahlström and Lundqvist 2015).
Six stands (two per site) were subjectively selected for this study (Table 1). The selection criteria were: (1) balanced coverage of geographic area and site conditions and (2) stand properties resembling those associated with single-tree selection (i.e. balanced spatial and size distribution of vigorous trees). The stands were located on mineral soil and classified as the submesic Myrtillus site type, except stand LAP01, which was on a mesic Oxalis-Myrtillus site type (Cajander 1949). Their altitude was 50–140 m and temperature sum 1150°–1360° days (Venäläinen et al. 2005) (annual sum of positive differences between diurnal mean temperature and 5 °C). The stands were about 1½–2 ha in area each. Each stand had one experimental plot of 0.16 ha (40 m × 40 m) in the central part of the stand and with good representation of site and structural variation within the stand.

Sample trees were selected in terms of a harvesting operation. Five trees from two size classes (20–29.99 cm and ≥ 30 cm stem diameter at breast height) were harvested per plot (Table 2). First candidates were selected within the 1600-m² sample plot among trees marked for removal in terms of a silviculturally optimized selection framework. If there were not enough trees available in a certain diameter class, they were selected from trees that had been designated to remain in the first phase. Furthermore, trees just outside the plot were selected next to fill possible remaining gaps in the sampling regime. In each experimental site, 20 trees were sampled, adding up to a total of 60.

### Table 1

| Plot | 1996 | 2012–2013 |
|------|------|-----------|
|      | N    | Dg        | G   | Hdom |
|      |      |           |     |      |
| LAP01| 4603 | 20.2      | 18.3| 18.0 |
| LAP13| 1606 | 19.7      | 15.3| 22.8 |
| VES01| 1738 | 20.6      | 19.1| 20.8 |
| VES02| 1967 | 18.4      | 16.2| 19.6 |
| SUO01| 1763 | 19.7      | 16.7| 20.0 |
| SUO06| 1325 | 20.1      | 17.9| 20.4 |

\(G\) basal area, \(m^{2}ha^{-1}\), \(N\) number of stems (\(d > 5\) cm), \(Dg\) quadratic mean diameter cm, \(H_{dom}\) average height of the 100 thickest trees \(ha^{-1}\), m

| Size class | \(t\) | \(d\) | \(d6\) | \(h\) | \(ch\) | \(cr\) | \(ca\) | \(cw\) |
|------------|------|------|-------|------|------|------|------|------|
| 20–29.99 cm | 81.1 ± 3.1 | 23.88 ± 2.53 | 20.65 ± 2.08 | 21.4 ± 1.9 | 6.8 ± 2.3 | 0.7 ± 0.1 | 15.0 ± 13.2 | 4.5 ± 0.8 |
| ≥ 30 cm | 98.5 ± 2.5 | 35.06 ± 3.77 | 30.39 ± 3.46 | 24.9 ± 2.1 | 5.7 ± 1.8 | 0.8 ± 0.1 | 12.8 ± 11.6 | 5.4 ± 0.8 |

Average value ± SD

\(t\) tree age at tree base, years, \(d\) stem diameter at 1.3 m height, cm, \(d6\) stem diameter at 6 m height, cm, \(h\) tree height, m, \(ch\) crown height, m, \(cr\) crown ratio, %, \(ca\) crown asymmetry, % (\(ca\) was visually estimated as the proportion of the missing part of crown volume), \(cw\) crown width, m

### Table 2

2.2 Timber processing

Two 2.5 m long logs were taken from each size class (20 to < 30 cm and ≥ 30 cm stem diameter at breast height) from each tree: the butt log at the base of the tree and the top log downwards from the point, where the decreasing stem diameter reached 18 cm (stands LAP01 and LAP13) and 20 cm (stands VES01, VES02, SUO01 and SUO06) (Fig. 1). Disks for annual ring width measurements were sawn at the height of 0 and 2.5 m, at both ends of the top log, and at the middle point between the logs. After cutting, the North direction was marked on the logs, they were covered with slash in order to prevent drying, and transported to a sawmill within a month. Decay, especially Heterobasidion root rot, was encountered in some cases, and trees with soft rot in secondary xylem were discarded and substituted with predesignated candidates. Trees with firm rot were accepted though.

Timber was debarked at sawmill with a Cambio Kockum 70–66 BA machine (UJ Trading Ab, Gusselby, Sweden) and sawn into boards with a circular saw Kara Master Y (Kallion Konepaja Oy, Raisio, Finland). A 100 mm cant was sawn through the log to North–South direction in each log (Fig. 1). A 50 mm thick board from both sides of the pith was sawn from the cant, and as many 22 mm boards as possible were sawn from the cant until cambium was reached. Size of the first boards was 2500 mm × 50 mm × 100 mm. In other boards, the size was 2500 mm × 22 mm × 100 mm. The boards were piled on stacks separated from each other by stickers (size 1000 mm × 25 mm × 25 mm). Each layer of
boards was lying on three stickers at 1 m intervals (Fig. 1). The working margin of the saw blade was 2.5 mm. The sawing pattern followed the Nordic rules (Nordic timber-grading rules 1994) (Fig. 1). The boards were dried in a condensation kiln dryer (Dryfinn 30) with a capacity of drying 10–20 m³ of wood per batch (Table 3). The total number of boards was 522. Board moisture content during the drying and storage processes was monitored with a Hydromette HT 85 T wood moisture measuring instrument (Gann Mess-u. Regeltechnik GmbH, Gerlingen, Germany). Boards were piled and partitioned with battens during the drying process. After drying, boards were stored 2–3 months indoors under controlled conditions (Table 3). They were piled and partitioned with stickers during storage (Fig. 1). The board storage layer was recorded; no relation between wood twist distortion and storage layer was found in data analyses. Air humidity and temperature of the indoor storehouse were monitored during storage (Table 3). The boards from the three sites were dried on separate batches with slightly different drying schedule and storage conditions, which resulted in slight variation in wood moisture content between the boards. As a control, the effect of wood moisture content on the amount of twist in boards was tested at the analysis stage as part of the twist model, but moisture content (measured immediately after the measurement of twist) was not correlated with twist. Drying differences could basically have emerged in the site effects in the twist model, but they were not significant.

### 2.3 Annual ring width measurements

Prior to ring width measurements, wood discs were stored at −20 °C and fine-sawn to allow adequate visualization. Annual ring width and latewood proportion were determined with a computer-aided system consisting of an Olympus stereo microscope connected to Heidenhain LS 303C transducer (Dr. Johannes Heidenhain GmbH, Traunreut, Germany). The annual ring width was determined with an accuracy of 1 µm, and data were captured in North–South

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**Table 3** Timber processing and storage conditions

| Site        | Felling time | Drying formula T, °C | Duration in days | Number of boards | Moisture content of boards, % | Storage of boards |
|-------------|--------------|-----------------------|------------------|------------------|-------------------------------|------------------|
|             |              |                       |                  |                  | Before drying                | Air humidity (%) |
|             |              |                       |                  |                  | After drying                 | Air temperature (°C) |
| Lapinjärvi  | May 2012     | 50                    | 5                | 174              | 25.2±7.0                     | 60–90            | 15–22            |
| Vesijako    | Oct. 2012    | 30                    | 9                | 181              | 27.2±3.3                     | 30–70            | 10–15            |
| Suonenjoki  | May 2013     | 39                    | 9                | 167              | 29.9±6.8                     | 50–75            | 15–25            |
The annual ring variables for individual boards were gained from the sawing and drying process rather than the wood, firm rot or blue stain. Mechanically torn or broken compression wood, and the existence of resin wood, wet-bark pockets, grain angle or distortion, proportion of cup, spring and twist), the number and size of pitch pockets and spiral grain angle were recorded and used in statistical analysis regardless of their direction.

Board distortions (twist, bow, curved edge and bottom) were measured. Twist and bow were measured as the maximum value for a 2-m span within a 2.5-m long board. The maximum distortion value was identified by moving the board along the surface of a 2-m long table. Spiral grain angle was measured on the outside face of the board by drawing a line along the tracheid direction from a knot-free area on the outer surface of each board. Spiral grain angle varies from left-handed (+) to right-handed (−) direction (Perstorper et al. 2001). Absolute values of twist distortion and spiral grain angle were recorded and used in statistical analysis regardless of their direction.

After measurements, boards were graded according to Nordic timber-grading rules (1994). As a default, the board was assigned to the best grade A1. All detected defects then lowered the class according to their seriousness from A1 down to A2–A4, B, C and D. The factors were the number, diameter and characteristics of knots, deformations (bow, cup, spring and twist), the number and size of pitch pockets and bark pockets, grain angle or distortion, proportion of compression wood, and the existence of resin wood, wet-wood, firm rot or blue stain. Mechanically torn or broken boards were excluded. Wanes and checks were recorded but not applied to grading because they were thought to originate from the sawing and drying process rather than the wood properties as such.

Time constraints prevented us from being able to measure the very narrow annual rings at the end of the boards in order to assign them to individual boards with sufficient precision. The annual ring variables for individual boards were gained from the disks sawn at the lower or upper end of the logs. The lower end was used for the top log. For the butt logs, it was not possible to reliably match the very narrow and irregular rings at the low end of the board. Consequently, the ring data at the top of the butt log at 2.5 m height was used for this purpose.

2.5 Data analysis

Empirical results on the quality traits and wood characteristics influencing them were calculated and presented as simple statistics (averages, standard deviations, correlation coefficients). A more elaborate analysis was conducted on twist as the prime representative of distortions using modeling as the analysis method. Modeling was applied as an analysis method to reveal the essential variables correlated with twist in the hierarchical and complex data. Linear mixed models with maximum likelihood estimation (ML) were applied with the MIXED procedure in the SPSS software. Fixed-variable coefficients had to be statistically significant at p < 0.05, but a variable with a lower significance could be exceptionally retained for a specific purpose. Individual quality parameters were also explored and described with average and deviation statistics.

Based on the results from the data exploration stage, the potential variables were selected for an initial model to constitute a starting point for the analysis, including spiral grain angle, annual ring width, knot properties, proportion of compression wood, board vertical position (log height along the stem) and horizontal position (board distance from the pith), moisture content and tree canopy position (\(d/D_{dom}\), stem diameter at breast height relative to the average diameter of the 100 thickest trees \(ha^{-1}\)). The individually measured knots were aggregated into compound variables describing their number and size in a board. For regular knots, the variable consisted of the maximum count of knots per meter on a board outer face, which was multiplied with the maximum knot diameter of the board; the value was first calculated separately for sound and dead knots and then added together. For pin knots, the variable was the maximum count of sound and dead pin knots per meter, first counted separately for sound and dead knots and then added together. Annual ring width was applied as the average annual ring width in a board. Relative annual ring width difference in a board was calculated by subtracting the minimum ring width in a board from its maximum ring width and dividing the difference by the average ring width.

The initial model contained all potential variables, interactions of log height and continuous factors, and a hierarchical two-level structure of nested variance components: plots and trees within plots. Site and plot-level random effects were not significant and not included in the final model. Stepwise variable selection was applied using backwards elimination starting from the initial model and dropping,
at each step, the least significant model term (interaction, main effect, variance component; in that order). Type III ANOVA was used for fixed effects and Wald test for random effects. The stepwise procedure was continued until all model terms were significant. Absolute and relative versions of continuous factors were compared using Akaike’s Information Criterion.

Transformations of the response variable twist were compared by visual assessment of normality and homogeneity of variance of the residuals from Q–Q-plots and scatterplots. Predictions from the selected log_{10}-transformed model were back-transformed after adding bias-correction equal to half of the sum of the variance estimates of the random components.

3 Results and discussion

3.1 Annual ring width

At stump height, annual increment (ring width) first increased from pith towards bark, reaching a local maximum around 35–55 years. There was a subsequent decrease towards the bark. In higher parts of the stem (height 2.5 m and 6 m), annual rings showed a constant decreasing trend from pith to bark (Fig. 2). Much of the variation in the wood properties that were detected are logically attributable to the typical growth pattern of trees in uneven-aged stands, involving a long period of slow growth as saplings and small trees in the lower canopy layers, recovery after gradual release in partial harvest, and a period of unconstrained growth as a dominant tree. (Schütz 2001, Piispanen et al. 2014). A slight, unstable increase was observed for the outermost rings at stump and at 2.5 m heights. Trees from both size classes (20 ≤ d < 30 cm and d ≥ 30 cm) had similar annual ring width profiles (Figs. 2, 3), but rings were generally narrower in smaller trees. The observed annual tree ring width patterns thus strongly supported the assumption that the study material represents typical tree development and properties in the most probable applications of selection management under such conditions. Wood properties in the butt logs exhibited the characteristics from all of these stages, while the upper stem parts had been formed during the latter phases only. Consequently, the upper logs tended to be more or less similar to those from even-aged stands and dissimilar to the butt logs in many respects.

3.2 Processing related defects in boards

Average board moisture content was 12.4% ± 1.5% (the quantity after ± is SD henceforth). Boards from stands LAP01 and LAP13 had slightly higher moisture contents and more surface checks than other stands, probably because the drying period was slightly shorter at a slightly higher temperature (Table 3). Based on the experience from LAP, the drying process was adjusted to be slightly slower for the rest of the stands (Table 3), and the amount of surface checks became smaller than in LAP. Altogether 23% of the boards had surface checks. Wood moisture content and the amount of checks were not correlated with twist.

26% of the boards contained wane in their radial surface. The average length of the rough-edged part was 46% ± 31%, 40% ± 34% and 38% ± 23% of board length, width and
3.3 Empirical results on wood properties

The frequencies of twist, bow, crook warp and cup were 99, 73, 80 and 19% of the boards, respectively. Twist was slightly greater in the first boards from pith than in boards closer to the bark, and differences between butt and top logs were generally small (Fig. 4). However, twist was somewhat greater in the first boards from pith in butt logs. The average twist was $3.0^\circ \pm 1.8^\circ$ in absolute value. Differences between plots were small (Fig. 5). In even-aged Norway spruce, average twist was $2.84^\circ \pm 2.58^\circ$ and $4.86^\circ \pm 4.57^\circ$ at 14.4% and 7.8% moisture content, respectively (Johansson et al. 2001). Other types of distortion, like bow, crook warp and cup, showed a decreasing trend from pith to bark. In the first boards of the butt logs, the average bow, curved edge and curved bottom were $2.7 \pm 2.7$ mm, $2.9 \pm 2.7$ mm per 2 m and $0.3 \pm 0.5$ mm in board width 100 mm per 2.5 m board length, respectively.

Twist was by far the most serious defect among deformations in the board grading procedure. Twist was the reason in 79.5% of cases for downgrading of a board due to a deformation. A large twist value commonly moved the board down several grade classes.

Traits that were measured and could be linked with distortions were firm rot, compression wood, spiral grain angle, and knots. Some 45% of the boards contained firm rot. The average proportion of the rot part was 35% of volume in the boards with rot. It was most pronounced in stands LAP01, VES01 and LAP13, which contained 45% firm rot on average. Soft rot was not present because such trees were rejected as sample trees already in the field because they were unsuitable for sawing. About 32% of boards contained more than 5% compression wood in volume. Compression wood was most frequent in stands with a high proportion of decayed wood.

Spiral grain angle deviated from zero in 76% of the boards. The average grain angle (as absolute value) in boards with a nonzero value was $2.1^\circ \pm 1.5^\circ$. The angle tended to increase slightly from pith to bark (Fig. 4). The vertical orientation of the pith was tortuous in 44% of first boards (= heart planks). Pith deviation was viewed at the cut end of the board, and a deviation of at least 5 mm from the inner face of the board was measured. According to this sawing pattern, the pith was sawn through and in case of no deviation both heart planks contained half of the pith. In first boards, 58% of the boards contained pith deviation in butt logs and 29% in top logs, respectively.

The average maximum diameter of sound and dead knots in the outside face of the board was $14.2 \text{ mm} \pm 12.2 \text{ mm}$ and $10.2 \text{ mm} \pm 4.8 \text{ mm}$, respectively. The amount and size of knots decreased from pith towards bark in butt logs, but their size increased in top logs (Fig. 6). In the butt log, the...
outermost boards (3rd to 5th) were almost free of sound knots and even the dead knot count per meter was very small (2.4 ± 1.6) there. The average maximum count of pin knots in butt logs was below 0.1 and 4.2 per meter for sound and dead pin knots, respectively. In top logs, the average maximum count of pin knots was 2.9 and 0.8 per meter for sound and dead pin knots, respectively. Pin knot count was highest in boards from near the pith and decreased towards the outermost boards.

3.4 Twist model

Modeling was applied as an analysis method to reveal the essential wood characteristics correlated with twist in the hierarchical and complex data. Twist was selected as the key object variable because it is the distortion type with the closest relationship to wood properties (Forsberg 1999), and because twist is often more consistently predictable than other deformations. The selection was further justified by its role as the most frequent and the most serious distortion in the data. The linear mixed model approach allowed us to take appropriately into account the effects of interactions between the factors and the hierarchical structure of the data on significance assessments. The resulting model applies to this data only, and is neither intended nor suitable for any kind of predictive purposes beyond this context.

The final model for twist, containing only significant effects, was according to Eq. (1):

\[
\log_{10}(t_{ijkl}) = \beta_0 + \beta_1 \cdot h_{ijk} + \beta_2 \cdot \text{dist}_{ijkl} + \beta_3 \cdot \text{kn}_{ijkl} \\
+ \beta_4 \cdot p_{ijkl} + \beta_5 \cdot \text{irr}_{ijkl} + \beta_6 \cdot \text{ir}_{ijkl} \\
+ \beta_7 \cdot \text{sga}_{ijkl} + \beta_8 \cdot h_{ijkl} \cdot \text{sga}_{ijkl} + \epsilon_{ij} + \epsilon_{ijkl}
\]  

(1)

See Table 4 for variable explanations.

Most of the variation in twist was explained by distance from pith, annual ring width, relative annual ring width variation, spiral grain angle, knot and pin knot effects and board height. The model accounted for most of the differences between the butt and top logs, and the fixed class variable \((h_{ijkl})\) indicating the remaining level of difference was only
almost significant (p = 0.098). It was retained in the model to explicitly focus on this feature. Twist showed a substantial decrease with greater distance from the pith in the top log and in the butt log (Fig. 7). An earlier study on even-aged Norway spruces showed a strong correlation (r = 0.51, p > 0.001) between annual ring width and twist (Johansson and Kliger 2002). Greater spiral grain angle ($sga_{ijkl}$) was associated with greater twist, and its predicted effect was greater in top logs than in butt log boards (Table 5). Higher variability of ring width (relative ring width difference $irrijkl$) was significantly correlated with greater twist, which is known to be a more frequent cause of distortion in complex versus homogenous stands according to Pretzsch and Rais (2016). The correlation between grain angle and twist was generally rather low in this data, which is in line with the results of Straže et al. (2011). In contrast, grain angle was in a rather close correlation (r = 0.77, p < 0.001) in the study by Johansson and Kliger (2002). The results of this study are difficult to compare with the studies by Johansson and Kliger (2002) and Straže et al. (2011) because of major methodological differences. The knot and pin knot terms, combining the size and number for knots, and the number for pin knots, had a strong correlation with twist. In even-aged Norway spruces, a moderate correlation has earlier been shown between knot area ratio and twist (Johansson and Kliger 2002). Variance between boards ($\sigma_{ijkl}^2$) was four times as large as variance between trees ($Tree, \sigma_n^2$) (Table 5). In a null model without fixed effects, the variance between boards (0.0455) was much greater than between trees (0.0060)

### Table 4 Variable explanations of the model for wood twist (Eq. 1)

| Variable abbreviation | Variable explanation |
|-----------------------|----------------------|
| Dependent variable, $tw_{ijkl}$ | Twist in the $l$th board of log $k$ from the $j$th tree in plot $i$ (mm (100 mm$^{-1}$) 2000 mm$^{-1}$) |
| Independent variables | |
| $h_{ijk}$ | Dummy variable for log height: butt log = 1 and top log = 0 |
| $dist_{ijkl}$ | Distance variable, which is the distance of board outer surface from pith (mm) |
| $kn_{ijkl}$ | Compound knot variable, where the maximum count of knots per meter on a board outer face is multiplied with the maximum knot diameter of the board; first counted separately for sound and dead knots and then added together |
| $pijkl$ | Pin knot variable, which is the maximum count of sound and dead pin knots per meter; first counted separately for sound and dead knots and then added together |
| $irrijkl$ | Relative annual ring width difference in a board, where minimum ring width is subtracted from maximum ring width, and the difference divided by average ring width |
| $ir_{ijkl}$ | Average annual ring width in a board (mm) |
| $sga_{ijkl}$ | Spiral grain angle (°) |
| $h_{ij} \cdot sga_{ijkl}$ | Interaction between log height and spiral grain angle |
| Variable coefficients | |
| $\beta_0$ | Overall mean |
| $\beta_1, \ldots, \beta_9$ | Coefficients for the fixed variables |
| Random parameters | |
| $\epsilon_{ij}$ | Random tree effect |
| $\epsilon_{ijkl}$ | Random residual |

![Fig. 7](image-url) Predicted twist by board outside distance from pith ($dist$) in top (a) and butt (b) log boards. The lines present predicted twist values, when the knot term was 5, 50, 100, 150, 200 and 250 and when the average annual ring width ($ir$) was 2.11 mm, the average annual ring width difference ($irr$) was 0.94, average pin knot term was 2.2 and average spiral grain angle was 1.1°.
### Table 5 Parameter estimates, their standard errors, degrees of freedom and p values for significant deviance from 0 of the model for wood twist (Eq. 1)

| Regression coefficients and variance components | Estimate | Std. error | df | p    |
|------------------------------------------------|----------|------------|----|------|

**Dependent variable:** \( \text{tw}_{ijkl} \)

**Fixed effects**
- \( \beta_0 \)
- \( h_{ijkl} \beta_1 \)
- \( \text{dist}_{ijkl} \beta_2 \)
- \( kn_{ijkl} \beta_3 \)
- \( p_{ijkl} \beta_4 \)
- \( irr_{ijkl} \beta_5 \)
- \( ir_{ijkl} \beta_6 \)
- \( sga_{ijkl} \beta_7 \)
- \( h_{ijkl} \times sga_{ijkl} \beta_8 \)

**Random effects**
- Residual, \( \sigma^2_{ijkl} \)
- Tree, \( \sigma^2_{ij} \)

Coefficient of determination \( R^2 \) (Xu 2003) = 0.553

\( \beta_0 \) is the overall mean (intercept), \( \beta_j \)…, \( \beta_8 \) are coefficients for the fixed variables, \( \text{tw}_{ijkl} \) is twist in the \( j \)th board of log \( k \) from the \( j \)th tree in plot \( i \) (mm \( 100 \text{ mm}^{-1} \) 2000 mm\(^{-1} \)), \( h_{ijkl} \) is a dummy variable for log height: butt log = 1 and top log = 0, \( \text{dist}_{ijkl} \) is distance variable, which is the distance of board outer surface from pith (mm), \( kn_{ijkl} \) is a compound knot variable, where the maximum count of knots per meter on a board outer face is multiplied with the maximum knot diameter of the board; first counted separately for sound and dead knots and then added together, \( p_{ijkl} \) is a pin knot variable, which is the maximum count of sound and dead pin knots per meter; first counted separately for sound and dead knots and then added together, \( irr_{ijkl} \) is relative annual ring width difference in a board, where minimum ring width is subtracted from maximum ring width, and the difference divided by average ring width, \( ir_{ijkl} \) is average annual ring width in a board (mm), \( sga_{ijkl} \) is spiral grain angle (°), \( \sigma^2_{ij} \) and \( \sigma^2_{ijkl} \) are variances between trees and boards.

Some of the knot parameters were also correlated with each other, but the correlation pattern was rather patchy (Table 6). Moisture content, reaction wood, and spiral grain angle (\( sga \)) were not closely correlated with any of the independent variables in the final model (Table 6). The variable tree canopy position \( (d/D_{dom}) \) was applied to indicate tree canopy position in terms of the complex stand structures as in Piispanen et al. (2014), but it was neither closely correlated with twist or other independent variables, nor significant in candidate models. However, the variation in canopy positions was perhaps too constrained to make it significant in this data. Reflecting current practices, the minimum top diameter of logs was set at 18–20 cm, which effectively removed the lower end of the canopy positions occurring in selection stands from the data. Somewhat unexpectedly, the proportion of compression wood in boards was not significant in this context. X-ray based measurements would be required to produce more accurate data on the amount of compression wood than the visual assessment on board surfaces that was applied in this study.

Twist was only slightly more pronounced in butt logs than in top logs. This was partly related to the data as such, as the annual ring variables were measured at the top of the butt log at 2.5 m height and not at its base (or stump height). Consequently, the extreme values and variations in the very lowest stem part were not involved in the analysis. Spiral grain angle showed less correlation with twist in butt logs than in top logs.

The results did not point to a major difference in twist and other deformations in boards between uneven-aged and even-aged management, but very few points of comparison were available anyway. The wood properties between the silvicultural systems may differ in many other ways than those focused in in this study. According to a review by Pretzsch and Rais (2016), there was a higher occurrence of crown eccentricity, stem bending, reaction wood, and variability in ring width in complex versus homogenous stands. Seeling (2001) found wider annual rings, a higher percentage of compression wood, higher taper, larger branches and higher values of twist in Norway spruce after a thinning promoting the conversion from even-aged to uneven-aged.

### 4 Conclusion

This study aimed to assess the degree and severity of distortions in boards from uneven-aged stands, especially focusing on twist as the most relevant representative of common distortion types. Wood characteristics linked with twist were described in a model framework, and the importance of individual variables was parsed out. They turned out to be: (I) board distance from stem pith, (II) tree diameter growth in terms of annual ring width and relative annual ring width compared to the full model. In addition to the variables in the final model, wood moisture content, compression wood and firm rot proportion and tree canopy position were applied as independent variables in candidate models, but they were not significant and were discarded in the process.

The effect of plank position in the sawing pattern and growth ring curvature and pattern have been identified as important causes of twist in Norway spruce boards (Straže et al. 2011). Studies conducted in even-aged stands generally indicate that twist tends to decrease from pith towards bark (Johansson et al. 2001; Sandberg 2005; Straže et al. 2011). This was the case in this study, too; twist was more pronounced in the first boards near the pith. Relative ring width difference (\( irr \)) and knot parameters (Table 6) were significant in the model but substantially correlated with \( ir \).
variation within a board, (III) knot and pin knot size and count, (IV) spiral grain angle and (V) height of the board origin along the stem. The uneven-aged stands yielded sawn goods with quality traits that are attributable to the complex stand structures and patterns of growth and wood formation in uneven-aged stands. Wood properties related to tree growth in uneven-aged stands were more pronounced at the base of the tree. The level of twist that was not explained by the model variables was not significantly different between butt and top logs. However, the average level of twist was not different from values observed in previous studies from Norway spruce even-aged stands.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest. There were no human participants or animals involved in this research. No external funding or support has been received for this study.
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