“Differences in stem form and bark anomalies of northern red oak trees in forest stands in Canada and Germany”

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1 Title Page

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Differences in stem form and bark anomalies of northern red oak trees in forest stands in Canada and Germany

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Abstract:

Northern red oak wood is valuable for a variety of applications not only in its natural distribution range in North America, but also in Europe. Timber quality and stem diameter largely determine timber prices and respective uses. Silvicultural management is key to influencing tree growth and stem quality. In Germany, crop tree thinning is currently the standard treatment, while in Canada the shelterwood system is common practice. The objective of this study was to compare stem characteristics related to stem quality of northern red oaks from Canada with those from Germany to determine effects of different silvicultural treatments on stem quality. We examined stem characteristics from a total of 150 dominant northern red oaks in Canadian and German forest stands using the terrestrial laser scanning approach. Northern red oak stems in Canada (shelterwood system) were significantly straighter, whereas German stems (crop tree thinning approach) were significantly smoother on the surface and rounder on the upper parts of the stems (height 4 – 8 m). The number of bark anomalies decreased with increasing tree competition, indicating that competition is the main driver influencing external stem form and the occurrence or persistence of bark anomalies.

Keywords: *Quercus rubra*, tree stem quality, competition index, silviculture, terrestrial laser scanning

1. Introduction

Northern red oak timber is valued for its variety of applications (Nicolescu et al. 2020) and can command high timber prices (Northeast Timber Exchange 2021). Northern red oak timber is considered valuable not only in its natural range (Dey et al. 2008), but also in Europe (Göhre and Wagenknecht 1955), although in Europe oak species from the white oak group (in Germany mainly pedunculate oak and sessile oak) are usually preferred due to more desirable wood properties (e.g., wood durability, suitability for outdoor applications). Yet northern red oak is able to compensate for its lower price on the timber market by higher volume output within a shorter rotation period (Seidel and Kenk 2003). Northern red oak timber quality itself can vary greatly, resulting in broad price variability (Marschall et al. 2014; Vansteenkiste et al. 2005).

Timber quality and stem diameter are the main criteria determining end use and thus price (Bosela et al. 2016). Factors influencing tree growth may also impact wood structure and thus timber quality (Zobel and Jett 1995). Hence, silvicultural treatment, genetics, or site conditions can modify stem quality (Macdonald 2002). Tree species selection and stand density control are important decision-making factors in silviculture (Schall and Ammer 2013). Stand density, and thus competition intensity between individual trees, is one of the most important factors affecting stem quality characteristics, such as branchiness or bending (Hein 2008). High competition intensity can lead to reductions in stem quality properties (Hein 2008; Kirk and Berrill 2016), but are usually associated with restricted radial tree growth (Mäkinen and Hein 2006; Oheimb et al. 2011), while low competition intensity can have the opposite effect (Sonderman and Rast 1988). Differences in site conditions can also modify growth processes (Bertness and Callaway 1994), with competition considered one of the main factors influencing stem quality characteristics in northern red oak (Burkardt et al. 2019). Therefore, scientific research attempts to regulate stand density and thus competition intensity using different silvicultural methods to improve tree growth and stem quality (Sonderman and Rast 1988).

The deciduous forests of central and eastern Canada and the United States, where oak species are ecologically and economically important (Johnson et al. 2002), form much of the native range of northern red oak (*Quercus rubra* L.), a common dominant in many of the forests there (Birchenko et

al. 2009). Northern red oak also grows outside its natural distribution range, in Ukraine (Lavnyy and Savchyn 2017), UK (Wilson et al. 2018), France (Timbal and Aussenac 1996), and Germany (Göhre and Wagenknecht 1955), where it was introduced from the late 17th to the 18th centuries, mostly as a park tree. Northern red oak accounts for 0.5% of the current forested area in Germany (Schmitz et al. 2014), making it the most common non-native broadleaved tree species in the country (Nagel 2015).

While several studies on silvicultural management of northern red oak have been conducted in its natural range (e.g.; Dey et al. 2008; Sonderman and Rast 1988), its silvicultural treatment has been less well studied in Europe (e.g.; Nicolescu et al. 2020; Rédei et al. 2010). To obtain high quality timber, crop tree thinning of northern red oak stands is the standard treatment applied in Germany (Nagel 2015; Nicolescu et al. 2020), while the shelterwood system is commonly used in North America (Groninger and Long 2008; Sonderman and Rast 1988; Ward 2002).

The effectiveness of a silvicultural procedure is usually determined after harvesting and during timber sorting (Bosela et al. 2016). In some cases it is necessary to assess timber quality on a standing tree, as in the case of selling timber "on the stump" (Bosela et al. 2016). Terrestrial laser scanning ("TLS") has been proven to be a suitable method to objectively (Liang et al. 2011) and non-destructively (i.e., Stängle et al. 2014) record tree morphology, including stem quality characteristics (Höwler et al. 2017; Juchheim et al. 2017). For example, methods have been developed to identify bark irregularities such as branch scars or bars (Kretschmer et al. 2013), as well as differences in stem form (Juchheim et al. 2017). Höwler et al. (2017) defined stem surface irregularities as bark anomalies and related them to competition intensity in beech stands.

The objective of our study was to investigate the influence of two different management regimes using terrestrial laser scanning data. We compare the North American shelterwood system with Central European crop tree thinning via their effects on timber quality of northern red oak.

We hypothesized that:

1. Stem form and the number of bark anomalies - both indicating stem quality of northern red oak trees - differ between Canadian and German stands due to different silvicultural practices.

2. Increasing tree competition is negatively related to external stem quality characteristics and this relationship is constant under both management systems (shelterwood system vs. crop tree thinning).

2. Material and Methods

2.1. Study sites and sample trees

We assessed the external stem characteristics of 150 study trees (10 trees each in 15 stands) in five northern red oak stands located in 5 stands in Canada (two stands each in Ontario and Nova Scotia, one stand in Prince Edward Island) and in 10 federal states within Germany (two stands each in Brandenburg, Thuringia, Lower Saxony, North Rhine-Westphalia and Baden-Württemberg; the same tree database in Germany as described in Burkardt et al. (2019)) (Table 1).

The study site selection was made according to the following criteria: (i) stands had to be middle-aged (mature but not yet ready to harvest), (ii) stands should be minimum one hectare in size, (iii) main tree species had to be northern red oak, and (iv) sites had to be considered representative of the natural distribution range (NRCS 2002); or, in Germany, recommended for future cultivation of northern red oak (i.a., NMELV 2004).

The geographically different study sites included dry sites such as Brandenburg (Germany) with mean annual precipitation of 560 mm and sites with high precipitation (e.g., more than 1300 mm in Nova Scotia, Canada). Annual average temperatures varied 4.3 °C and 11.1 °C; the length of vegetation period ranged between 154 days and 198 days (Table 1).

Please add Table 1 here

Silvicultural management of northern red oak stands differs in Canada and Germany. In Canada, northern red oak stands are usually thinned only once and finally harvested in a shelterwood system for natural regeneration (Loftis 1990). In contrast, frequent crop tree thinning to promote individual target trees and final harvest at target diameters of 65 cm+ are applied in Germany (Nagel 2015).

To analyse external quality-related stem characteristics, ten dominant target trees (tree classes 1 and 2 according to Kraft (1884)) were randomly selected within each of the 15 study sites. A competition index (Hegyi 1974) was calculated to determine the intensity of competition to which each target tree was exposed. For this, every neighbouring tree with a diameter at breast height (130 cm) ≥ 7 cm standing within a radius of 10 m around the target tree was included in the index calculation (Equation 1).

Equation 1 Hegyi-index = $\sum_{i=1}^n \frac{D_i}{D_j} \times \frac{1}{Dis_{ij}}$,

with subject tree j , competitor tree i , diameter at breast height (D in cm) and the distance between the target tree and the competitor tree (Dis in m).

2.2. Tree measurement and calculation of stem quality characteristics

Stems of the target trees were scanned with a terrestrial Faro Focus 3D 120 laser scanner (Faro Technologies Inc., Lake Mary, Florida, USA) to ensure a three-dimensional and objective assessment of target tree stems (Höwler et al. 2017). Four to six positions were recorded following the multiscan approach (van der Zande et al. 2008). For subsequent spatial co-registration of the scans with the software Faro Scene (Faro Technologies Inc, Lake Marry, USA), 15-25 targets were placed around each target tree as tie points. From each coregistered point cloud the target tree stems (from stem base to crown base height) were manually isolated using the CloudCompare software Cloud Compare 2.6, retrieved from (<http://www.cloudcompare.org/>) and saved as an .xyz-file (Cartesian coordinates). The accuracy of this method was demonstrated in previous studies focusing on beech (Höwler et al. 2017; Höwler et al. 2019).

Please add Figure 1 here

We used several stem quality criteria (e.g., straightness, roundness, bark anomalies) commonly used for such assessments (RVR 2015) and calculated a laser-based surrogate. First, the external stem characteristics *bending* and *sweep* as indices of the straightness of the lower stem parts as described in Höwler et al. (2017) were calculated. To do this, the stem point clouds were initially separated into

stem discs of 1.75 cm horizontal thickness. The distance between the lowermost fitted stem disc (stem base) and the uppermost fitted stem disc (crown base height) was defined as stem length (Fig. 1 a). *Lean* was calculated based on the horizontal difference between the midpoints of the lowermost and uppermost stem sections (computed for 0 m- 4 m and 4 m - 8 m) (Fig. 1 d). To obtain *lean per meter* for better comparison among stems of different lengths, the value was divided by the total length of the section to obtain a length-independent measure. The ratio between the shortest distance between the centers of the lowest and highest stem discs (Fig. 1 b) and the sum of the shortest distances between the centers of all consecutive stem discs (Fig. 1 c) along the vertical axis was defined as *sweep*. This measure was also converted to *sweep per meter* by dividing *sweep* by the length of the stem section (4 m each).

In addition, *stem non-circularity* and the *number of bark anomalies* as additional stem quality attributes introduced by Höwler et al. (2017) were calculated using Mathematica (Wolfram Research, Champaign, Illinois, USA). *Bark anomalies* were calculated to indicate irregularities such as bumps or scars on the stem surface, either of which indicates stem damage (Höwler et al. 2017; Richter 2010). The three-dimensional point clouds of the 150 stems were divided into sections of 4 m length to comply with the German sorting guidelines for log quality (general agreement for the German raw timber market (RVR 2015)), which defines tolerances for wood defects and quality categories. In addition, the 4 m divisions allowed a more accurate assessment of the quality of individual stem sections. To eliminate density fluctuations in the point cloud, the spatial resolution of the point clouds for each stem section was homogenized using a 1.75 cm point cloud grid (Höwler et al. 2017). For details on the calculation of stem characteristics see Höwler et al. (2017), Juchheim et al. (2017) and Burkardt et al. (2019).

2.3. Statistical analysis

All statistical analyses were conducted with the open access statistics software "R" (R Core Team 2018). The Shapiro-Wilk test was used to check for normal distribution and Levene's test to check for variance homogeneity. To confirm equality of variances between the two countries (Canada with the

shelterwood system and Germany with crop tree thinning), the F-test (to compare equality of variances between two samples in “R”) was utilized. Depending on the data distribution, the Mann-Whitney U-test or the T-test were applied to compare the means of the two groups. To obtain normally distributed residuals of stem non-circularity or sweep, we used sqrt or log-transformation. Competition intensity and local climatic effects, in this case mean annual precipitation and mean annual temperature, and country (Canada and Germany, as surrogates for the management approaches), were examined to capture unknown differences between the two countries (management approaches) as independent factors explaining the external stem features *stem-non-circularity*, *number of bark anomalies*, *sweep*, and *bending* as dependent variables in a multiple linear regression model. To avoid multicollinearity, the dependent variable *growing season* was excluded from the calculations, as it was highly correlated with *mean annual temperature*. Temperature and precipitation rates were available to cover the site conditions (local climatic effects). Detailed soil data were not available for every forest stand and therefore could not be included in our analyses. The significance level for all statistical analyses was $p < 0.05$.

3. Results

Competition intensity was significantly higher in Canadian northern red oak stands than in German stands ($p < 0.001$; Canada: 2.4 ± 1.1 ; Germany: 1.5 ± 0.7). A detailed overview of competition intensities on each study site is shown in Figure 2.

Please add Figure 2 here

In Canada, stem quality was negatively influenced by higher numbers of bark anomalies and higher stem non-circularity values compared to northern red oak trees in Germany (Table 2, Figure 3). These differences were only significant for upper stem sections (4 - 8 m). Conversely, stem quality in Germany was lower in terms of bending (0 – 4 m and 4 – 8 m) and sweep (0 – 4 m) (Table 2, Figure 3).

Please add Table 2 here

Please add Figure 3 here

The number of bark anomalies (in section 0-4 m) was significantly related to competition intensity, country as proxy for silvicultural approach, and mean annual temperature (Table 3). With increasing competition intensity, the number of bark anomalies decreased in both Canadian and German stands ($p < 0.001$). With decreasing temperatures, a higher number of bark anomalies was observed in Canada ($p < 0.001$), while in Germany the opposite was found ($p < 0.001$) (Table 3). In the case of section 4-8 m, a significant relationship between the number of bark anomalies, competition, country and mean annual precipitation was observed. We found significant negative correlations between competition intensity and number of bark anomalies ($p < 0.001$) as well as between precipitation and number of bark anomalies ($p = 0.01$) in both Canada and Germany (Table 3).

Please add Table 3 here

The number of bark anomalies is shown here to demonstrate the relationships among stem quality characteristics, different stem sections, the two countries, competition, and local climatic effects (i.e., differences between the two countries' mean annual temperatures and precipitation). Results on stem non-circularity, sweep, and bending of all sections can be found in the supplement (Table S1).

4. Discussion

Our results indicate that stem quality in the Canadian stands (shelterwood management) was negatively influenced by higher numbers of bark anomalies and higher stem non-circularity values compared to northern red oak trees in Germany managed with crop tree thinning. The number of bark anomalies includes all irregularities that could have resulted from former branches and old wounds (Richter 2010). Both theory and earlier studies suggest that increasing competition should result in a decreasing number of bark anomalies (Höwler et al. 2017). This relationship was confirmed within both management systems (CAN & GER). The higher number of bark anomalies and greater stem non-circularity with higher competition intensity in Canada may be due to shelterwood management. In Germany, the crop tree thinning method aims to promote individual valuable trees by careful but frequent removal of potential competitors. This involves a pre-selection of high-quality target trees at

226 younger ages; the dominant trees examined in this study may have had better initial stem quality as
227 compared to the non-treated northern red oaks in Canada (at the same levels of competition). In
228 addition, continuous reduction in stand density and thus in competition intensity aims at improving
229 tree growth. This could thus lead to faster branch occlusion processes, which would result in the
230 observed lower number of bark anomalies in Germany.

231 In contrast, the shelterwood system, as commonly applied in Canada, has the primary goal of
232 establishing natural regeneration. No interventions are performed over decades until a single thinning
233 is followed by a final harvest (Hannah 1988; Loftis 1990). High stand density and thus, high competition
234 intensity reduces radial tree growth (Mäkinen and Hein 2006). Consequently, trees that have been
235 grown densely over decades might require more time for branch occlusion (due to reduced secondary
236 growth) after natural self-pruning. This could explain the higher number of bark anomalies in Canadian
237 stands. However, high stand density in Canada may also have resulted in straighter stems; light
238 conditions in Canada change only gradually in the absence of frequent silvicultural interventions. In
239 contrast, with the regular thinning approach in Germany, an increased risk of northern red oak growing
240 into lateral light shafts could result in less straight stems.

241 It must be considered that pure northern red oak stands in Germany have higher intraspecific
242 competition when compared to the naturally regenerated northern red oak stands in Canada, where
243 there is an admixture of sugar maple and white pine. It is not clear, however, whether the Hegyi index,
244 which quantifies competition intensity, but which does not include tree species identity or tree height,
245 over- or underestimates the actual competition in Canadian stands. Overestimation would occur if the
246 competitive pressure by the admixed species was lower than that by conspecific neighbours;
247 underestimation would be expected if interspecific competition was stronger than intraspecific
248 interference.

249 In addition to the management effects addressed in our study, other factors can also affect quality-
250 related tree characteristics. Recent studies have shown that external stem quality characteristics

(Burkardt et al. 2019) or tree growth (Pederson et al. 2004; Rollinson et al. 2016; Tardif and Conciatori 2006) are influenced by more complex environmental processes than can be explained by competition alone. To inspect the relationship between external stem features, competition and local effects, further studies should also include nutrient availability in the soil, species identities of tree species mixtures, as well as climatic differences. The latter was also supported by our study, in which it was indicated that precipitation and temperature may have significant effects on timber quality attributes, even though our results were inconsistent (see supplement Table S 1). Furthermore, genetic differences may also impact tree growth, depending on seed origin and local climate in the respective stand. Further studies should therefore include results of provenance trials.

Conclusions

We investigated the influence of two different management regimes via terrestrial laser scanning (shelterwood system vs. crop tree thinning). We examined whether there are significant differences between quality-related stem characteristics of Canadian (shelterwood system) and German (crop tree thinning) northern red oak stands. We also tested how such characteristics change under conditions of individual tree competition and local climatic effects. We conclude that tree competition is the main driver influencing external stem characteristics and therefore enhanced stem quality in both Canadian and German stands. As recommended in previous studies (Burkardt et al. 2019), red oak should be kept rather dense in its early developmental stages to obtain desired branch free stem length. The results of our study suggest that stands should then be thinned in order to increase radial tree growth and thereby accelerate branch occlusion processes in order to eliminate irregularities in stem surfaces as rapidly as possible. According to the results of stem forms in the Canadian stands, these interventions could initially be conducted more cautiously than assumed previously to achieve straighter stem forms.

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References

- BAMS Growth and Yield Programm (Ed.) (2020): Electronic databases. Ontario Ministry of Natural Resources and Forestry. Ontario.
- Bertness, M. D.; Callaway, R. (1994): Positive interactions in communities. *Trends Ecol. Evol.* **9** (5): 191–193. DOI: 10.1016/0169-5347(94)90088-4.

- 301 Birchenko, I.; Feng, Y.; Romero-Severson, J. (2009): Biogeographical distribution of chloroplast
302 diversity in northern red oak (*Quercus rubra* L.). *Am. Midl. Nat.* **161** (1): 134–145. DOI: 10.1674/0003-
303 0031-161.1.134.
- 304 Bosela, M.; Redmond, J.; Kučera, M.; Marin, G.; Adolt, R.; Gschwantner, T. et al. (2016): Stem quality
305 assessment in European National Forest Inventories: an opportunity for harmonised reporting? *Ann.*
306 *For. Sci.* **73** (3): 635–648. DOI: 10.1007/s13595-015-0503-8.
- 307 Brown, D. (2016): Historical Climatology: North Bay, Ontario. Great lakes Integrated sciences +
308 Assessments. Available online at http://glisa.umich.edu/media/files/NorthBayCN_Climatology.pdf,
309 updated on 3/11/2016, checked on 11/30/2020.
- 310 Burkardt, K.; Annighöfer, P.; Seidel, D.; Ammer, C.; Vor, T. (2019): Intraspecific competition affects
311 crown and stem characteristics of non-native *Quercus rubra* L. stands in Germany. *Forests* **10** (10):
312 846. DOI: 10.3390/f10100846.
- 313 Dey, D. C.; Miller, G. W.; Kabrick, J. M. (2008): Sustaining northern red oak forests: managing oak
314 from regeneration to canopy dominance in mature stands. *USDA For Serv Pacific Northwest Res Sta*
315 *Gen Tech Rep 733* (PNW-733), 91.
- 316 DWD Climate Data Center-CDC (1988a - 2017): Annual grids of monthly averaged daily air
317 temperature (2m) over Germany. Edited by Deutscher Wetterdienst. Available online at
318 https://opendata.dwd.de/climate_environment/CDC/grids_germany/annual/air_temperature_mean
319 [/](https://opendata.dwd.de/climate_environment/CDC/grids_germany/annual/air_temperature_mean/), checked on 8/27/2019.
- 320 DWD Climate Data Center-CDC (1988b-2017): Annual sum of monthly precipitation grids over
321 Germany. Edited by Deutscher Wetterdienst. Available online at Jahressumme der Raster der
322 monatlichen Niederschlagshöhe für Deutschland unter Berücksichtigung der Klimatologie, checked
323 on 8/27/2019.
- 324 DWD Climate Data Center-CDC (1992a - 2018): Annual grids of pedunculate oak - autumn leave
325 colouring in Germany. Edited by Deutscher Wetterdienst. Available online at
326 https://opendata.dwd.de/climate_environment/CDC/grids_germany/annual/phenology/STEBV/BESC
327 [HREIBUNG_gridsgermany_annual_phenology_STEBV_de.pdf](https://opendata.dwd.de/climate_environment/CDC/grids_germany/annual/phenology/STEBV/BESC), checked on 12/4/2020.
- 328 DWD Climate Data Center-CDC (1992b -2018): Annual grids of pedunculate oak - beginning of
329 unfolding of leaves in Germany. Edited by Deutscher Wetterdienst. Available online at
330 https://opendata.dwd.de/climate_environment/CDC/grids_germany/annual/phenology/STEBV/,
331 checked on 8/27/2019.
- 332 Göhre, K.; Wagenknecht, E. (1955): Die Roteiche und ihr Holz. Berlin: Deutscher Bauernverlag.
- 333 Groninger, J. W.; Long, M. A. (2008): Oak ecosystem management considerations for central
334 hardwoods stands arising from silvicultural clearcutting. *North. J. Appl. For.* **25** (4): 173–179. DOI:
335 10.1093/njaf/25.4.173.
- 336 Hannah, P. R. (1988): The shelterwood method in northeastern forest types: A literature review.
337 *North. J. Appl. For.* **5** (1): 70–77. DOI: 10.1093/njaf/5.1.70.
- 338 Hegyi, F. (1974): A simulation model for managing jack-pine stands. J. Fries (Ed.): Growth Models for
339 Tree and Stand Simulations. Royal College of Forest. Stockholm, 74–90.

- 340 Hein, S. (2008): Knot attributes and occlusion of naturally pruned branches of *Fagus sylvatica*. *For.*
 341 *Ecol. Manag.* **256** (12): 2046–2057. DOI: 10.1016/j.foreco.2008.07.033.
- 342 Höwler, K.; Annighöfer, P.; Ammer, C.; Seidel, D. (2017): Competition improves quality-related
 343 external stem characteristics of *Fagus sylvatica*. *Can. J. For. Res.* **47** (12): 1603–1613. DOI:
 344 10.1139/cjfr-2017-0262.
- 345 Höwler, K.; Vor, T.; Seidel, D.; Annighöfer, P.; Ammer, C. (2019): Analyzing effects of intra- and
 346 interspecific competition on timber quality attributes of *Fagus sylvatica* L.—from quality assessments
 347 on standing trees to sawn boards. *Eur. J. For. Res.* **138** (2): 327–343. DOI: 10.1007/s10342-019-
 348 01173-7.
- 349 Johnson, P. S.; Shifley, S. R.; Rogers, R. (2002): The ecology and silviculture of oaks. Wallingford Oxon,
 350 New York: CABI.
- 351 Juchheim, J.; Annighöfer, P.; Ammer, C.; Calders, K.; Raunonen, P.; Seidel, D. (2017): How
 352 management intensity and neighborhood composition affect the structure of beech (*Fagus sylvatica*
 353 L.) trees. *Trees* **31** (5): 1723–1735. DOI: 10.1007/s00468-017-1581-z.
- 354 Kirk, C.; Berrill, J.-P. (2016): Second-log branching in multiaged Redwood and Douglas-Fir. Influence
 355 of stand, site, and silviculture. *Forests* **7** (12): 147. DOI: 10.3390/f7070147.
- 356 Kraft, G. (1884): Beiträge zur Lehre von den Durchforstungen, Schlagstellungen und Lichtungshieben.
 357 Hannover, Germany: Klindworth's.
- 358 Kretschmer, U.; Kirchner, N.; Morhart, C.; Spiecker, H. (2013): A new approach to assessing tree stem
 359 quality characteristics using terrestrial laser scans. *Silva Fenn.* **47** (5): 14. DOI: 10.14214/sf.1071.
- 360 Lavnyy, V.; Savchyn, V. (2017): Ukraine. In H. Hasenauer, A. Gazda, M. Konnert, K. Lapin, G. M. J.
 361 Mohren, H. Spiecker et al. (Eds.): Non-native tree species for european forests: experiences, risks and
 362 opportunities. joint volume. 3.th ed. Vienna (COST Action FP1403 NNEXT, Country Reports), 413.
- 363 Loftis, D. L. (1990): A shelterwood method for regenerating red oak in the Southern Appalachians.
 364 *For. Sci.* **36** (4): 917–929.
- 365 Macdonald, E. (2002): A review of the effects of silviculture on timber quality of Sitka spruce. *Forestry*
 366 **75** (2): 107–138. DOI: 10.1093/forestry/75.2.107.
- 367 Mäkinen, H.; Hein, S. (2006): Effect of wide spacing on increment and branch properties of young
 368 Norway spruce. *Eur. J. For. Res.* **125** (3): 239–248. DOI: 10.1007/s10342-006-0115-9.
- 369 Marschall, J. M.; Guyette, R. P.; Stambaugh, M. C.; Stevenson, A. P. (2014): Fire damage effects on
 370 red oak timber product value. *For. Ecol. Manag.* **320**: 182–189. DOI: 10.1016/j.foreco.2014.03.006.
- 371 Nagel, R. (2015): Die Roteiche (*Quercus rubra* L.). In Vor, T.; Spellmann, H.; Bolte, A.; Ammer, C.
 372 (Eds.): Potenziale und Risiken eingeführter Baumarten. Göttingen: Universitätsverlag Göttingen
 373 (Göttinger Forstwissenschaften, Band 7), 219–267.
- 374 Nicolescu, V.-N.; Vor, T.; Mason, W. L.; Bastien, J.-C.; Brus, R.; Henin, J.-M. et al. (2020): Ecology and
 375 management of northern red oak (*Quercus rubra* L. syn. *Q. borealis* F. Michx.) in Europe: a review.
 376 *Forestry* **93** (4): 481–494. DOI: 10.1093/forestry/cpy032.
- 377 NMELV (2004): Langfristige ökologische Waldentwicklung: Richtlinie zur Baumartenwahl. [Long-term
 378 ecological forest development. Guideline to species selection]. Schriftenreihe Waldentwicklung

- 379 Niedersachsen, **54**. Niedersächsisches Ministerium für den ländlichen Raum, Ernährung,
380 Landwirtschaft und Verbraucherschutz, Hannover.
- 381 Northeast Timber Exchange, L. L.C. (2021): March 2021 veneer log prices. Rockingham VT. Available
382 online at http://northeasttimberexchange.com/?page_id=3, checked on 3/19/2021.
- 383 NRCS (2002): Plant guide. northern red oak (*Quercus rubra* L.). Edited by USDA. NRCS National Plant
384 Data Center. Louisiana. Available online at http://plants.usda.gov/plantguide/pdf/cs_quru, checked
385 on 3/19/2021.
- 386 Von Oheimb, G.; Lang, A. C.; Bruelheide, H.; Forrester, D. I.; Wäsche, I.; Yu, M.; Härdtle, W. (2011):
387 Individual-tree radial growth in a subtropical broad-leaved forest: The role of local neighbourhood
388 competition. *For. Ecol. Manag.* **261** (3): 499–507. DOI: 10.1016/j.foreco.2010.10.035.
- 389 Paradis, D.; Vigneault, H.; Lefebvre, R.; Savard, M. M.; Ballard, J.-M.; Qian, B. (2016): Groundwater
390 nitrate concentration evolution under climate change and agricultural adaptation scenarios: Prince
391 Edward Island, Canada. *Earth Syst. Dynam.* **7** (1): 183–202. DOI: 10.5194/esd-7-183-2016.
- 392 Pederson, N.; Cook, E. R.; Jacoby, G. C.; Peteet, D. M.; Griffin, K. L. (2004): The influence of winter
393 temperatures on the annual radial growth of six northern range margin tree species.
394 *Dendrochronologia* **22** (1): 7–29. DOI: 10.1016/j.dendro.2004.09.005.
- 395 Rédei, K.; Csiha, I.; Keserű, Z.; Rásó, J.; Györi, J. (2010): Management of red oak (*Quercus rubra* L.)
396 stands in the Nyírség forest region (Eastern-Hungary). *Hung. Agric. Res.* **3**: 13-17.
- 397 Richards, W.; Daigle, R. (2011): Scenarios and guidance for adaptation to climate change and sea-
398 level rise - NS and PEI Municipalities. Edited by ACASA. Available online at
399 <http://www.gov.pe.ca/photos/original/ccscenarios.pdf>, checked on 12/1/2020.
- 400 Richter, C. (2010): Holzmerkmale Beschreibung der Merkmale, Ursachen, Vermeidung, Auswirkungen
401 auf die Verwendung des Holzes, technologische Anpassung. 3., updated and extended edition.
402 Leinfelden-Echterdingen: DRW-Verlag.
- 403 Rollinson, C. R.; Kaye, M. W.; Canham, C. D. (2016): Interspecific variation in growth responses to
404 climate and competition of five eastern tree species. *Ecology* **97** (4): 1003–1011. DOI: 10.1890/15-
405 1549.1.
- 406 RVR (2015): Rahmenvereinbarung für den Rohholzhandel in Deutschland (RVR. 2.th ed. Available
407 online at [http://www.rvr-](http://www.rvr-deutschland.de/docs/dynamisch/8302/rvr_gesamtdokument_2.auflage_stand_oktober_2015.pdf)
408 [deutschland.de/docs/dynamisch/8302/rvr_gesamtdokument_2.auflage_stand_oktober_2015.pdf](http://www.rvr-deutschland.de/docs/dynamisch/8302/rvr_gesamtdokument_2.auflage_stand_oktober_2015.pdf),
409 checked on 5/27/2019.
- 410 Schall, P.; Ammer, C. (2013): How to quantify forest management intensity in Central European
411 forests. *Eur. J. For. Res.* **132** (2): 379–396. DOI: 10.1007/s10342-013-0681-6.
- 412 Schmitz, F.; Polley, H.; Hennig, P.; Kroher, F.; Marks, A.; Riedel, T. et al. (2014): Der Wald in
413 Deutschland. Ausgewählte Ergebnisse der dritten Bundeswaldinventur. Edited by Bundesministerium
414 für Ernährung, Landwirtschaft und Forsten (BMEL). Bonn. Available online at
415 [https://www.bundeswaldinventur.de/fileadmin/SITE_MASTER/content/Dokumente/Downloads/BM](https://www.bundeswaldinventur.de/fileadmin/SITE_MASTER/content/Dokumente/Downloads/BMEL_Wald_Broschuere.pdf)
416 [EL_Wald_Broschuere.pdf](https://www.bundeswaldinventur.de/fileadmin/SITE_MASTER/content/Dokumente/Downloads/BMEL_Wald_Broschuere.pdf), checked on 5/21/2018.
- 417 Seidel, J.; Kenk, G. (2003): Wachstum und Wertleistung der Eichenarten in Baden-Württemberg. In
418 *AFZ* **1**: 28–31.

- 419 Sonderman, D. L.; Rast, E. D. (1988): Effect of thinning on mixed-oak stem quality. In *US For. Serv.*
420 *Res. Pap.*, 1–6.
- 421 Stängle, S. M.; Brüchert, F.; Kretschmer, U.; Spiecker, H.; Sauter, U. H. (2014): Clear wood content in
422 standing trees predicted from branch scar measurements with terrestrial LiDAR and verified with X-
423 ray computed tomography. In *Can. J. For. Res.* **44** (2): 145–153. DOI: 10.1139/cjfr-2013-0170.
- 424 Tardif, J. C.; Conciatori, F. (2006): Influence of climate on tree rings and vessel features in red oak and
425 white oak growing near their northern distribution limit, southwestern Quebec, Canada. *Can. J. For.*
426 *Res.* **36** (9): 2317–2330. DOI: 10.1139/X06-133.
- 427 Timbal, J.; Aussenac, G. (1996): An overview of ecology and silviculture of indigenous oaks in France.
428 *Ann. For. Sci.* **53** (2-3): 649–661. DOI: 10.1051/forest:19960243.
- 429 van der Zande, D.; Jonckheere, I.; Stuckens, J.; Verstraeten, W. W.; Coppin, P. (2008): Sampling design
430 of ground-based lidar measurements of forest canopy structure and its effect on shadowing. *Can. J.*
431 *Remote Sens.* **34** (6): 526–538. DOI: 10.5589/m08-070.
- 432 Vansteenkiste, D.; de Boever L.; van Acker, J. (2005): Alternative processing solutions for red oak
433 (*Quercus rubra*) from converted forests in Flanders, Belgium. Proceedings of the COST action E44
434 conference on broad spectrum utilization of wood at BOKU. Vienna, Austria, 13–26.
- 435 Ward, J. S. (2002): Crop tree release increases growth of mature red oak sawtimber. *North. J. Appl.*
436 *For.* **19** (4): 149–154. DOI: 10.1093/njaf/19.4.149.
- 437 Wilson, S.M.G.; Mason, W. L.; Savill, P.; Jinks, R. (2018): Alternative oaks (*Quercus* spp.). *Quart. J. For.*
438 **112** (2): 93–105.
- 439 Zobel, B. J.; Jett, J. B. (1995): Genetics of wood production. Berlin, Heidelberg: Springer (Springer
440 Series in Wood Science).
- 441

Tables 1-3:

Table 1. Study site information in Canadian (CAN) and German (GER) stands in the regions: LS: Lower Saxony, NRW: North Rhine-Westphalia, BW: Baden-Württemberg, THU: Thuringia, BR: Brandenburg, ON: Ontario, NS: Nova Scotia and PEI: Prince Edward Island. Latitude (Lat.), longitude (Long.), mean annual precipitation (Mean annual prec.), mean annual temperature (mean annual temp.), growing season length (Grow. season length), diameter at breast height (DBH) (mean diameter of the target trees, 10 in each stand) and tree basal area (calculated based on the 10 m radius around each target tree) on the study sites. With tree species ash (AS), black cherry (BC), balsam fir (BF), black spruce (BS), common birch (CB), horbeam (HB), ironwood (IW), large-tooth aspen (LA), northern red oak (RO), red maple (RM), red spruce (RS), sugar maple (SM), white birch (WB), eastern white pine (WP).

Country	Plot ID	Region	Stand Age (yrs)	Lat. (°N)	Long. (°)	Soil texture	Tree species (%)	Mean annual prec. [mm]*	Mean annual temp. [°C]*	Grow. season length [days]*	DBH (cm)	Tree density (trees /ha)	Tree basal area [m²]
CAN	1	ON	100	46.38	79.11 W	Loamy sand	RO 56.3%; RM 28.2%; SM 9.4%; WP 3.2%; BF 3.2%	1044	4.3	156	38.2	925	48.8
CAN	2	ON	107	46.65	79.16 W	Loamy sand	RO 20.3%; SM70.3%; IW 8.1%; BC 1.4%	1044	4.3	156	40.7	814	46.2
CAN	3	NS	89	44.52	65.41 W	Loamy sand	RO 40%, WP 16%, RM 7%, WB 4%, BF 4%, BS 4%, IA 4%, RS 1%	1327	8.5	198	30.4	502	27.1
CAN	4	NS	86	44.49	65.26 W	Loamy sand	RO 38%, WP 25%, RM 21%, WB 10%, BS 6%, IA, 4%	1330	8.5	198	31.2	976	37.6
CAN	5	PEI	115	46.27	63.11 W	Loamy sand	Data not available	1073	5.3	148	35.7	1014	44.3
GER	6	LS	67	51.78	9.59E	Loessssig loam	RO: 100%	1192	7.2	154	35.3	706	21.7
GER	7	LS	68	52.95	9.37 E	Loamy sand Gravell	RO: 100%	775	9.5	173	40.4	735	24.7
GER	8	NRW	59	51.54	6.49 E	y- , loamy sand	RO: 100%	813	10.8	181	36.5	418	27.8
GER	9	NRW	69	51.54	6.50 E	Loamy sand	RO: 100%	826	10.7	181	44.7	344	29.0

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GER	10	BW	68	48.45	7.86 E	Silty loam	RO: 90% AS: 10%	846	11.1	185	52.4	729	30.5
GER	11	BW	61	48.45	7.86 E	Silty loam	RO: 95% HB: 5%	846	11.1	185	51.7	550	29.8
GER	12	THU	58	50.76	11.73 E	sand	RO: 95% CB: 5%	668	8.8	167	37.0	415	32.7
GER	13	THU	83	50.77	11.64 E	sand	RO: 100%	656	8.9	168	33.7	612	32.1
GER	14	BR	64	52.45	13.07 E	sand sandy cov.	RO: 100%	592	9.8	174	25.1	731	21.7
GER	15	BR	68	52.38	13.10 E	Lay. o. bould. clay	RO: 100%	560	9.8	174	35.8	614	24.6

Climate Data in Germany are based on calculations of the Climate Data Center in Germany: (DWD Climate Data Center-CDC 1988b-2017, 1988a - 2017, 1992a - 2018, 1992b -2018), in North Bay, Ontario information is provided by local forest authorities, BAMS Growth and Yield Program (2020); and Brown (2016), data of Nova Scotia provided by local forest authorities and Richards and Daigle (2011), of Prince-Edward Island based on Paradis et al. (2016). Soil texture: Data acquisition based on the Harmonized World Soil Database v.1.2.. Stand information in Germany according to Burkardt et al 2019.

Table 2. Significance of the differences between the stem characteristics bark anomalies, stem non-circularity, bending and sweep in the sections 0 - 4 m and 4 - 8 m of both Canadian (N = 49) and German northern red oak trees (N = 94) according to the T-test and F-test.

Section	Bark anomalies [counts/m]	Stem non-circularity [m]	Bending [m]	Sweep [m]
0-4 m	$p = 0.052$	$p = 0.87$	$p < 0.01$	$p < 0.01$
4-8 m	$p < 0.01$	$p < 0.01$	$p = 0.03$	$p = 0.95$

P values < 0.05 are marked in italics.

Table 3. Relationship between the number of bark anomalies (Bark anom.) in the stem section 0 m – 4 m (N =143) and 4 m – 8 m (N = 142) as dependent variables, Heygi-Index (Heygi), and local climatic effects, namely countries (Country) and mean annual temperature (Temp.) as independent variables of the multiple linear regression model. Model equation (Model), adjusted R-squared (Adj. R²), Akaike Information Criterion of the model (AIC) and p - value for each independent variable, Country:Temp represent the p - value of the interaction term.

Stem characteristics	Model	Adj R ²	AIC	P-value
Bark anom [counts/m], section: 0 - 4 m	Y = -85.8 - 113.4 x Heygi + 917.6 x Country + 132.3 x Temp - 101.5 x Country x Temp	0.36	1987.0	Heygi: P < 0.001 Country: P < 0.001 Temp.: P < 0.001 Country:Temp.: P < 0.001
Bark anom. [counts/m], section: 4 - 8 m	Y = 577.9 - 76.4 x Heygi + 215.0 x Country - 0.17 x Prec.	0.26	1851.3	Heygi: P < 0.001 Country: P < 0.001 Prec.: P = 0.01

Figure 1. Schematic draft of the stem characteristics calculation based on the point clouds of the terrestrial laser scans. a, b, c and d were used to calculate lean and sweep according to Höwler et al. (2017). Grafical representation of an bark scar included in the calculation of the number of bark anomalies (Bark anom.).

Figure 2. Range of competition intensities (Hegyi-Index) on the 15 study sites with site ID 1 and 2: Ontario; 3 and 4: Nova Scotia; 5: Prince Edward Island; 6 and 7: Lower Saxony; 8 and 9: North-Rhine Westfalia; 10 and 11: Baden-Württemberg; 12 and 13: Thuringia; 14 and 15: Brandenburg.

127x101mm (300 x 300 DPI)

Figure 3. Range of the external stem characteristics: number of bark anomalies (bark anom.) (section 0 - 4 m (a), section 4 - 8 m (b)), stem non-circularity (SNC) (section 0 - 4 m (c), section 4 - 8 m (d)), sweep (section 0 - 4 m (e); section 4 - 8 m (f)) and bending (section 0 - 4 m (g), section 4 - 8 m (h)) between Canadian (CAN) and German (GER) northern red oak stands (N = 143, each). Figure a: the numbers 1 - 6 shows the values visualised by an boxplot; 1: minimum; 2: first quartile; 3: median; 4: third quartile; 5: maximum; 6: outlier of the values.