Beech provenance trail in Sweden

– growth and timber quality evaluation

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Master's Thesis • 30 credits

Swedish University of Agricultural Sciences, SLU
Southern Swedish Forest Research Centre
Alnarp, 2021

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Credits:	30 credits
Level:	A2E
Course title:	Master´s thesis in Forest Science
Course code:	EX0984
Course coordinating dept:	Southern Swedish Forest Research Centre
Place of publication:	Alnarp
Year of publication:	2021
Cover picture:	Lukáš Vaníček

Keywords: Beech, climate change, growth, provenance, Sweden, timber quality

Swedish University of Agricultural Sciences
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Southern Swedish Forest Research Centre

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Abstract

Provenance trails allow to test tree growth differences and meet current requirements for timber quality in a particular experimental site. The aim of this manuscript was to distinguish the differences in growth and timber quality features between European beech (*Fagus sylvatica* L.) provenances at its natural northern European margin – in southern Sweden. Data was obtained from a provenance experiment established in 1995 in Rånna to evaluate the growth and timber quality features of 36 European beech provenances. Statistical analysis was conducted using generalized and linear mixed models, and a *post-hoc* Tuckey´s test to check provenance differences on quantitative (diameter at breast height, tree basal area increment, height increment, total height) and qualitative features (crookedness, classification of stem morphology, spike knots above 0.5 meters and below 0.5 meters).

Results show, that the German provenance number 37 (Deister, Lower Saxony) reached the best growth outputs in following variables: diameter at breast height 2020, basal area increment, height increment and total height. German provenance number 39 (Seelzerthurm, Lower Saxony) shows the absolute best performance within classification of stem morphology and within spike knots below 0.5 meters abundance. Romanian Provenance number 150 (Sovata (25)) accomplished the best results within crookedness and spike knots above 0.5 meters abundance. German provenance number 51 (Eitorf 1502/262a – North-Rhine-Whestfalia) was evaluated worst in the following tree characteristics: crookedness, classification of stem morphology and spike knots below 0.5 meters abundance. Swedish and Danish beech provenances showed stable growth without any relevantly negative timber quality features, although they did not differ significantly from other provenances in their growth.

The results demonstrate that the genetic background of studied provenances has an important role in building stand development for numerous timber quality features. New provenance experiments establishment may better understand different provenances responses to the climate change as well as to determine the best provenance for high quality timber on the Swedish market.

Keywords: Beech, climate change, growth, provenance, Sweden, timber quality

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Abbreviations

DBH	Diameter at breast height. Measured by caliper at the height of 130 cm above the ground
HI	Height increment
BAI	Basal area increment
SE	Sweden
DE	Germany
DK	Denmark
HU	Hungary
SK	Slovakia
SI	Slovenia
UA	Ukraine
FR	France
RO	Romania
Long	Longitude
Lat	Latitude
Alt	Altitude
a. s. l.	above sea level

1. Introduction

1.1. European beech forests and climate change

The threat of predicted increasing temperature and higher occurrence of extreme events, that had been prognosticated by scientists (Mátyás *et al.* 2010), might negatively influence tree species resilience and composition in Europe. It is expected, that some tree species will not be able to adapt to ongoing climate change due to highly fragmented landscapes (Jump & Penuelas 2005) and low migration rate (Davis *et al.* 2005; Mátyás 2005).

Global warming might change set of environmental conditions in the natural range of European beech which could cause decline in its natural niche (Bellard *et al.* 2012). Eilmann *et al*. (2014) argue that climate change does not only cause a reduction of productivity of beech stands, but also elevate mortality rates in certain areas. Kramer *et al.* (2010) expect expansion of beech towards northern edge and decline in southern edge distribution. A tool for climate adaptation is a selective transfer of southern range margins provenances, which are heat- and drought-tolerant and use them in northern altitudes (Huber *et al*. 2014). For example, it is expected that drought in the Mediterranean region will cause changes in abundance and distribution of tree species typical for this region, such as cork oak (*Quercus suber*) and Aleppo pine (*Pinus halepensis*) (Ruiz-Labourdette *et al.* 2013). Further studies demonstrate higher assimilation rates of southern European beech provenances, therefore these provenances show higher photosynthesis rates and bigger mean annual increment (Robson *et al.* 2012). Populations from the southern range margin are expected to testify higher water-stress tolerance and faster growth rates (Wang *et al.* 2021).

Severe damages to the forest ecosystem, caused by biotic (pests and diseases) and abiotic (drought, frost, storms or fires) factors influence the physiology, stand development, inter- and intra- specific competition or spring phenology (Badeau & Bréda 2008). Forest management adaptation to climate change can be particularly developed by foresters, who can decide to plant mixtures, which have positive effects on biodiversity; choose optimal stocking density; doing proper interventions such as thinnings or to give a priority to manage forest for other than timber purposes. Attention should be paid to use proper planting material, which will meet current requirements appropriate to the forthcoming changes on the respective sites (Mátyás 2016; Kramer & Mátyás 2016). Proper quality forest reproductive material should meet the requirement of being well adapted to habitat conditions prevailing in sites to be restored (Bogunovic *et al.* 2020).

The reason to test different provenances of studied species is clear – rapid environmental changes could cause that original provenances might no more find their ecological optimum in amended conditions. Experimental trails, known as common garden experiments, should clarify, which provenance will respond the best towards sustainable forestry in affected environments. Cultivated selected provenances of the studied species would response to the site of provenance test; the provenances are adapted to the original seed source area and therefore should express differences in their growth in the experimental site (Petkova 2020). It is also desirable to develop rapid, inexpensive early testing procedures in order to determinate drought tolerant clones, provenances or families to be used in future climates (Dvorak 2012).

In Sweden, natural regeneration is widely used in forestry only for pine and beech (Agestam *et al.* 2006). If the proportion of beech increases, it would also be possible to abandon intensive clear-cut system and promote a more environmentally friendly approach to forest management, based on continuous cover forestry, or shelterwood system including natural regeneration, in accordance with Sustainable development goals number 15 "Life on land" and number 13 "Climate action" (United Nations 2021).

The history of beech forests in Sweden is dated back to the Middle Ages, when beech forests covered prevalent areas of Southern Sweden (Brunet 1995). 19th century meant a swift change in Swedish forest landscape: wood pastures were transformed into the expansion of dense conifer forests for timber purposes, reducing the broadleaves surface (Brunet *et al.* 2012). The percentage of beech stands in Sweden has fallen even further to the present (Brunet *et al*. 2012), where the percentage of European beech standing stock approaches 2.5 % (Corry & Nilson 2018). There is enormous potential to increase the beech production and compete with spruce timber on the market, which is now questioned in many European countries due to bark beetle outbreak.

Knoke *et al*. (2006) highlighted the main qualitative characteristics of beech timber, which reflect the final price of the timber on the market:

- The red heartwood: it is recommended to shorten the final felling age in order to minimize the formation of the heartwood

- Signs of overgrown old branches

- Signs of old felling damage

- Knobs/ Spike knots: indicators of former presence of branch

- The stem curvature (stem crookedness): deviation from vertical axis of the trunk

- The spiral grain: a helical course of timber fibres around the stem centre

- The growth stresses

- The roughness of bark: smooth/harsh

- Signs of "t-cancer" at the bark

As for quantitative characteristics, it usually applies that larger log diameter is awarded higher price per cubic meter.

The demand for beech forests in Sweden is not only requested for the purpose of high-quality timber, however, forest reserves (irrespective of provenances, but preferably of local beech) are needed to be enlarged to maintain forest biodiversity in Sweden – the core are nemoral, broadleaved forests with native species: *Fagus sylvatica* L.*, Quercus robur* L.*, Tilia cordata* Mill.*, Acer platanoides* L.*, and Fraxinus excelsior* L. (Andersson & Angelstam 2001). The remnants of old beech forests in Sweden have usually protective character and usually belong to some National Parks or forest reserves. These forests are the habitat for rare saproxylic species, which are dependent on slowly decomposing wood (Brunet *et al.* 2012).

1.2. European beech – the studied species

In the past, beech used to be the most important tree species in the hills and foothill areas throughout Central Europe. Its hard and well-workable wood was an important raw material used for the production of many supplies and aids, including charcoal (Barna *et al.* 2011). Its timber can be used for furniture, flooring and engineering purposes (Savill 2013). Beech is generally considered as a species with lower migration variability (Memišević *et al.* 2019), however, according to the poster by Memišević *et al.* 2019, the feature of beech is outstanding by its significant intra-population and inter-population variability. Recent research by Petrík *et al*. (2020) documents, that European beech provenances have shown high ratio of both adaptation and acclimation after transfer to new environmental conditions. Beech can reach the height of 35 – 40 m and diameter at breast height of 150 cm. The species performs high annual increment up to late ages. Beech usually lives up to 250 years in native forests (Wuhlisch 1984).

Beech is regarded as a dominant forest tree species of high economic as well as ecological relevance with a wide distribution range linking Scandinavia and the Mediterranean part of Europe (Sulkowska *et al*. 2011). Climate change predictions presuppose beech to lose habitats in the southern and south-eastern edge of current distribution (Stojnic *et al*. 2013). They report that strong selective pressures in last decades force Southern European margin of common beech (Jump *et al*. 2006; Piovesan *et al*. 2008; Varsamis *et al*. 2018). Phenological cycles of plants are changing; spring leaf phenology occurs earlier, autumn leaf phenology shows delay; which potentially result in a prolonged growing season and thus increasing forest net ecosystem productivity (Homero *et al*. 2019).

Scientists warn against denying negative effects of rapid climate change on European beech forest ecosystems, and recommend to use proper planting stock, which matches the local morphological and future climate conditions (Horváth *et al*. 2016). This is currently followed by European countries. Czech Republic has implemented stringent restrictions on the transfer of planting material between different natural forest areas/ provenances/ altitudes (Flora 2018). This step is to prevent the formation of unstable forests, which might not reach expected final felling age due to biotic and abiotic stressors. In Germany, forest owners are provided by recommendation of usage of different provenances of reproductive material in different regions, although the local provenance is recommended (Bayerisches Amt fur Waldgenetik, 2021).

Czajkowski *et al*. (2006a) suggested two possible options as a chance to mitigate negative effects of climate change by silviculture: first, to plant drought-adapted provenances, and second, to select naturally regenerated, local beech populations or provenances. They divided living conditions of a general species according to the degree of optimality / suitability of the species for local living conditions (Figure 1). The areas were set aside so that each additional one connects to the outer boundary of the previously inner one site. The internal (core) site “Optimum area” is surrounded by “Sub-optimum area”, then by “Limit/Border area” and by “Excision area” on the very edge. We can interlink this figure with the Figure of distribution of beech. Scandinavia and Mediterranean nowadays belongs to the “Limit/Border area” of beech distribution. However, as climate is changing, Southern Sweden might shift from the status of Limit/Border area to the status of Sub-optimum area of beech.

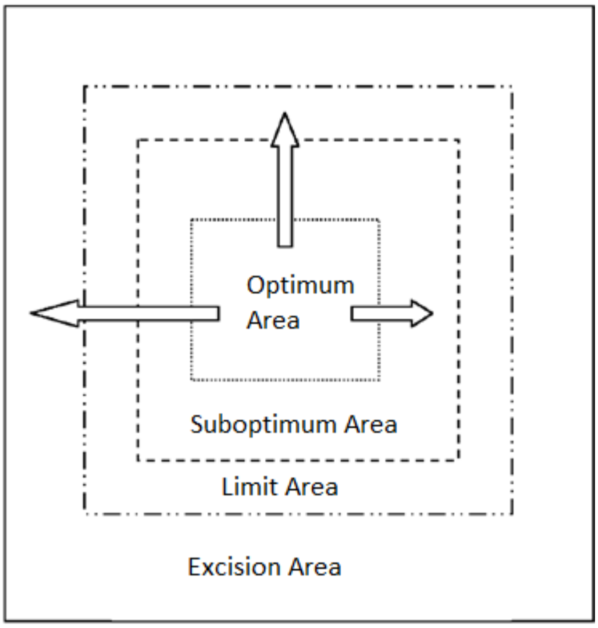


Figure 1: Optimal living conditions. Original figure by Czajkowski, T et al, 2006c modified by translation.

2. Objectives of the thesis

The main objective of this thesis is to evaluate which European beech (*Fagus sylvatica* L.) provenance is better adapted to Swedish conditions to increase growth and timber quality. We proposed to assess tree growth characteristic and timber quality between beech provenances from different European origins established in Southern Sweden.

The specific objectives are:

(1) To evaluate growth differences (tree basal area increment and height increment) among European beech provenances in comparison to the last inventory in 2008

(2) To compare timber quality between provenances, especially to evaluate spike knots abundance, crookedness and tendency of tree to fork

The following hypotheses were tested:

(1) The growth rate of south-eastern European beech provenances should be higher, since these provenances are adapted to harsher climate conditions, especially affected by higher altitude, and should therefore be well adapted to lower mean annual temperatures in the Nordic latitudes

(2) Swedish and Danish beech provenances should express better growth, since they are naturally adapted to Nordic latitudes

3. Material and Methods

3.1. Experimental design

The data was collected in March 2020, in the beech provenance experiment S21F9571256 located in Rånna, approximately 10 km north of the city of Skövde, Sweden. The exact coordinates are 58.4511892N, 13.8265236E, sited at 85 m a.s.l. The experiment contains 36 beech provenances, with European origin, including a wide range of varieties with their original features. This can be observed by their original latitude, longitude and altitude: the range includes origins from Sweden in the north to Slovenia in the south; from Germany in the west to Romania in the east (Figure 2). As well as altitudes, ranging from near to a bottom of a sea level (Germany, 25 m), up to mountain provenances originating from 1100 m a.s.l. in Slovenia, create unique vertical range, from which plasticity, diversity, adaptability and response to environmental climatic condition derive. Their detailed description is stated in Table 1 and Table 2.

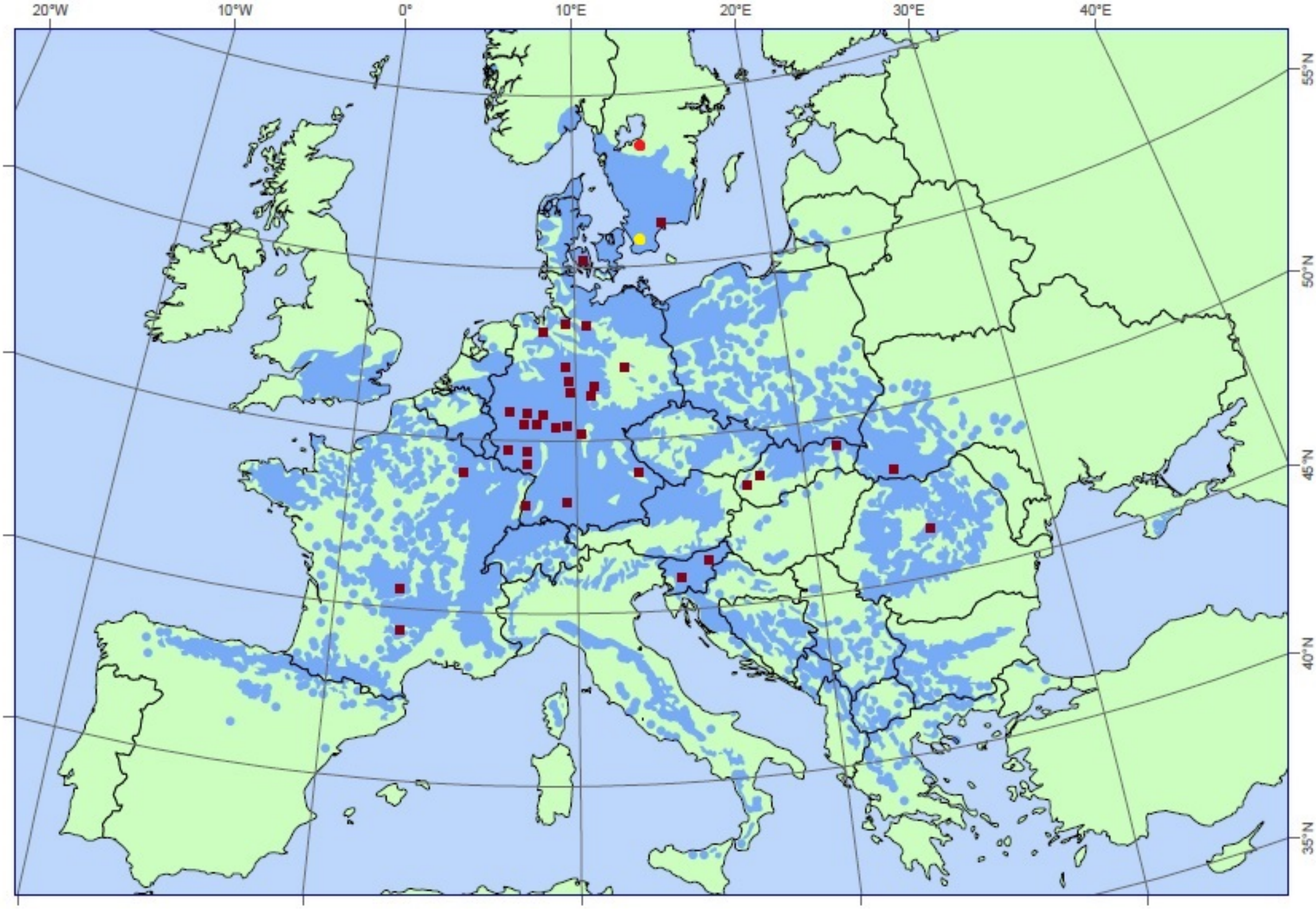


Figure 2: The current European beech distribution in Europe (source: EUFORGEN 2021), study site location and European beech provenances. The red dot indicates position of Rånna trail site. The yellow dot indicates the position of similar trail, established in 1998 in Trolleholm. Brown-purple squares indicate locations of the 36 provenances of beech evaluated in the experiment. Note: Provenances Büdingen Abteilung 762 and Büdingen Abteilung 763 are overlapping on the map, therefore only one square is visible for both of them: their coordinates are after rounding the same: 50.28 N, 9.12 E.

The provenance trail in Rånna was established in 1995 on former agricultural land, using two-year old bare-root seedlings. Planting stock was previously cultivated at the Institute for Forest Genetics and Forest Breeding in Grosshandorf, Germany. The provenance experiment was designed with randomized design and consist of three blocks, where each of them is compiled by 36 individual provenance plots. Each plot is described by a provenance number and plot number. Each plot had 50 individual seedlings with spacing 2 x 1 m at the year of establishment. Each plot has square shape, where the distance between square corners is 10 m. Each individual tree has own position characterized by block number, plot number, provenance number, row number and plant number. The outer edge of the trail is delimited by buffer trees so as to exclude possible edge effect (edge trees are characterized by different growth patterns caused by higher amount of available light). The trail was established on a fertile soil along a north slope (Skogforsk 2009). The stand is characterized by mean annual precipitation of 678 mm (SHMI 2021). The trend of increasing mean annual temperature for the Skövde climate station is shown in Figure 3.

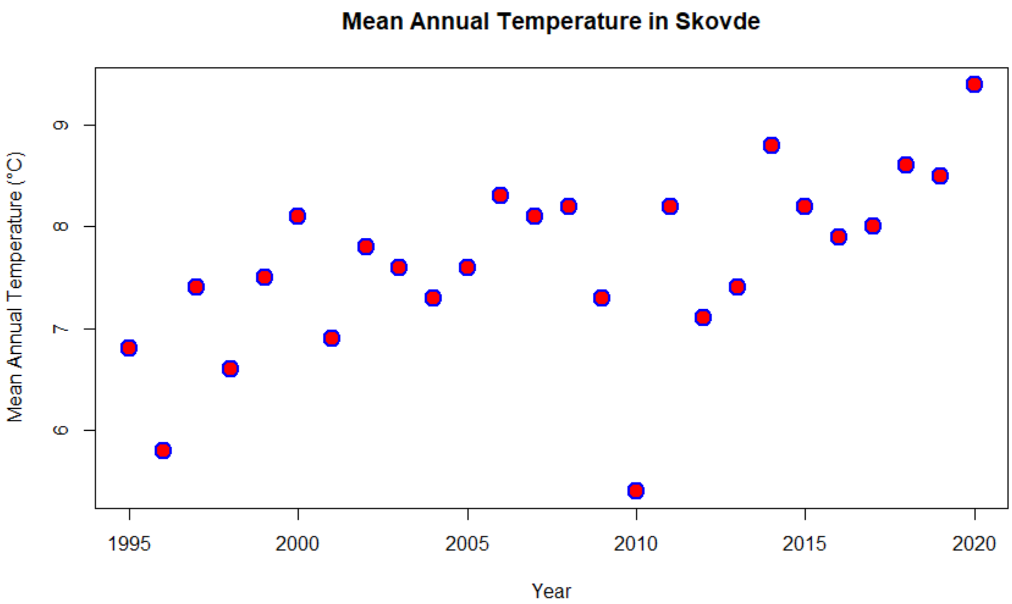


Figure 3: Mean Annual Temperature in the study site. Source: own elaboration from SHMI climate data.

While the mean annual temperature in 1995, when the provenance trail was established, was only 6,8 °C; after twenty-five years, it reached 9,4 °C. This is 2,6 °C increment for 25 years. Although it is not possible to state that the temperature would increase every following year, it is still possible to see the increasing pattern (except one colder year 2010). The data used to create Figure 3 are available online (Kapsi.fi, 2021).

The design of the experiment is depicted in Figure 4.

93	67	161	26	39	36			
18	137	94	51	38	11			
138	43	77	135	144	90			
14	69	88	99	129	87			
80	28	104	37	73	44			
70	92	130	150	66	40	88		
40	37	138	150	161	93	36	73	
38	130	26	129	44	70	137	77	11
92	80	51	94	90	28	99	66	39
43	18	69	144	104	14	67	87	
43	104	161	26	40	38	135		
130	44	36	67	73	11	39		
70	37	87	69	92	18			
144	138	88	93	51	99			
137	66	94	90	80	150			
14	135	129	77	28				

Figure 4: Experimental design. Each plot is represented by provenance number. Block 1 is in grey, block 2 is in orange and block 3 is in green.

Table 1: List of provenances established at Rånna trail site, sorted by provenance number

Prov no.	Name	Country (- region)	Number of trees sampled*	Long	Lat	Alt (m a.s.l.)
11	F.D des Charmettes	FR	32	45.60	2.68	900
14	F.D de Lagast	FR	45	44.15	2.63	850
26	Glorup	DK	32	55.18	10.68	70
18	F.D de Ligny en Barrois	FR	41	48.62	5.27	350
28	Ryssberget	SE	29	56.08	14.60	90
36	Osterholz-Scharmbeck	DE - Lower Saxony	49	53.23	8.80	25
37	Deister	DE - Lower Saxony	20	52.25	9.50	175
38	Harsefeld	DE - Lower Saxony	41	53.30	9.53	43
39	Seelzerthurm	DE - Lower Saxony	48	51.80	9.70	360
40	Bovenden	DE - Lower Saxony	51	51.50	9.83	375
43	Busschewald	DE - Lower Saxony	32	53.23	10.52	75
44	Oderhaus	DE - Lower Saxony	44	51.67	10.83	710
51	Eitorf 1502/262a	DE - North-Rhine-Whestf.	14	50.77	7.45	305
66	Dillenburg	DE – Hesse	33	50.73	8.27	500
67	Hadamar	DE – Hesse	38	50.45	8.07	218
69	Büdingen Abt. 762 (Standard)	DE – Hesse	34	50.28	9.12	198
70	Büdingen Abt. 763 (Standard)	DE – Hesse	57	50.28	9.12	225
73	Sinntal Abt. 414 A (Standard)	DE – Hesse	43	50.32	9.63	465
77	Eisenach	DE – Thuringia	38	50.08	10.08	615
80	Ebeleben	DE – Thuringia	37	51.33	10.50	315
87	Osburg	DE - Rhineland-Palatinate	46	49.68	6.82	540
88	Morbach	DE - Rhineland-Palatinate	28	50.75	7.00	660
90	Kirchheimbolanden	DE - Rhineland-Palatinate	33	49.67	8.02	400
92	Elmstein-Süd, Appenthal	DE - Rhineland-Palatinate	26	49.37	7.95	405
93	Montbaur	DE - Rhineland-Palatinate	37	50.43	7.83	313
94	Etterheim	DE - Baden-Wurtenberg	28	48.20	7.92	445
99	Ehingen	DE - Baden-Wurtenberg	30	48.40	9.50	620
104	Zwiesel	DE - Bavaria	37	49.02	13.23	755
129	Smolenice	SK	28	48.48	17.37	280
130	Trenčín	SK	32	48.88	18.00	200
135	Medzilaborce-Koškovce	SK	36	49.28	21.83	370
137	Postojna	SI	49	45.75	14.32	1100
138	Rogaska Slatina	SI	31	46.30	15.60	420
144	Rachiv	UA	38	48.04	24.17	520
150	Sovata (25)	RO	25	46.58	25.00	1015
161	Fläming	DE - Saxony-Anhalt	44	52.13	12.58	135

* The number of sampled trees represent all living trees in March 2020.

Table 2: Provenance stand characteristics: Number of stems per hectare (N/ha), Basal Area (BA) and Survival

Prov. no.	Name	Country (- region)	N/ha	BA (m^2/ha)	Survival (%)**
11	F.D des Charmettes	FR	1067	12.56	21.33
14	F.D de Lagast	FR	1500	14.76	30.00
26	Glorup	DK	1067	13.59	21.33
18	F.D de Ligny en Barrois	FR	1367	17.06	27.33
28	Ryssberget	SE	967	10.87	19.33
36	Osterholz-Scharmbeck	DE - Lower Saxony	1633	16.90	32.67
37	Deister	DE - Lower Saxony	667	13.50	13.33
38	Harsefeld	DE - Lower Saxony	1367	15.85	27.33
39	Seelzerthurm	DE - Lower Saxony	1600	22.68	32.00
40	Bovenden	DE - Lower Saxony	1700	19.21	34.00
43	Busschewald	DE - Lower Saxony	1067	12.11	21.33
44	Oderhaus	DE - Lower Saxony	1467	14.23	29.33
51	Eitorf 1502/262a	DE - North-Rhine-Whestf.	467	5.17	9.33
66	Dillenburg	DE - Hesse	1100	15.47	22.00
67	Hadamar	DE - Hesse	1267	14.85	25.33
69	Büdingen Abt. 762 (Standard)	DE - Hesse	1133	11.54	22.67
70	Büdingen Abt. 763 (Standard)	DE - Hesse	1900	20.88	38.00
73	Sinntal Abt. 414 A (Standard)	DE - Hesse	1433	16.17	28.67
77	Eisenach	DE - Thuringia	1267	14.45	25.33
80	Ebeleben	DE - Thuringia	1233	15.08	24.67
87	Osburg	DE - Rhineland-Palatinate	1533	16.19	30.67
88	Morbach	DE - Rhineland-Palatinate	933	12.79	18.67
90	Kirchheimbolanden	DE - Rhineland-Palatinate	1100	12.65	22.00
92	Elmstein-Süd, Appenthal	DE - Rhineland-Palatinate	867	11.12	17.33
93	Montbaur	DE - Rhineland-Palatinate	1233	12.72	24.67
94	Etterheim	DE - Baden-Wurtenberg	933	13.87	18.67
99	Ehingen	DE - Baden-Wurtenberg	1000	13.25	20.00
104	Zwiesel	DE - Bavaria	1233	10.00	24.67
129	Smolenice	SK	933	12.77	18.67
130	Trenčín	SK	1067	14.46	21.33
135	Medzilaborce-Koškovce	SK	1200	10.55	24.00
137	Postojna	SI	1633	17.62	32.67
138	Rogaska Slatina	SI	1033	10.02	20.67
144	Rachiv	UA	1267	13.83	25.33
150	Sovata (25)	RO	833	11.05	16.67
161	Fläming	DE - Saxony-Anhalt	1467	15.48	29.33

** Survival represents percentage of currently living trees out of initial 5000 trees per hectare planted in 1995. The stand was (pre-commercially) thinned twice and some trees also died spontaneously (self-thinning).

3.2. Data collection

Current data was collected in March 2020, that is, twelve years after the last inventory, and twenty-five years after the establishment. Stand plot measurements were recorded as listed below.

Diameter at breast height (DBH) and basal area increment (BAI)
DBH was measured for all living trees (n = 1306). BAI was calculated as a difference between individual tree basal areas in 2008 and 2020 divided by number of growing seasons between inventories.

Tree height (H) and height increment (HI). Tree height was measured for 108 randomly selected trees, including one tree per plot (three trees per provenance). Based on the H-DBH relationship, it was possible to estimate heights for all living trees.

Crookedness. Stem crookedness was evaluated from two perpendicular sides; the tree was classified using the following scale:

1 = straight, the tree was straight from both observation points

2 = slightly crooked; the stem was straight from one observation point and crooked from the second observation point

3 = significantly crooked; the tree was significantly crooked without any straightness seen from both observation points.

Classification of stem morphology. This parameter refers to the morphological appearance of a tree and to the tendency of a tree to branch and present bifurcated stems. We can distinguish 5 main classes:

class 1: straight (continuous) main stem
class 2: not continuous main stem but negligible reduction in height growth
class 3: bifurcated trunk with a bifurcation point above 1.3 m above the ground
class 4: bifurcated trunk with a bifurcation point below 1.3 m above the ground
class 5: bush- tree habitus with branches branched by the ground
class 6: wolf trees. Monumental trees that, by their appearance, height and volume, far exceed other trees.

Spike knots. Spike knots are appearing as a result of acutely angled branches. Branches, which were formed in a steep angle given on a stem, thus creating spike knots, might reduce the value of timber, since such timber is usually not suitable for peeling or some sawn products. Spike knots may also develop based on genetical predispositions of certain provenances. Spike knots are unwanted stem harm, which may lead to reduced quality and significantly reduced timber price on the market. Spike knots were divided into two categories: below 0.5 meters and above 0.5 meters. For each tree, the number of spike knots was counted (Interpine Innovation 2021).

3.3. Data preparation

Basal area increment

Based on pairwise comparison of values measured in 2008 and 2020, tree basal area increment (cm^2/year) was calculated (Table 3). The best random structure for the model resulted in plot nested to block effect (block/plot).

Height increment

Due to practical reasons and following common methods in the national forest inventories, height was measured only for approx. one tenth of all living trees. The individual tree height was estimated using a logarithmic regression model adjusted *ad-hoc*:

$$H20 = 81.587 * \ln(DBH20) – 259.86.$$

After calculating height of each remaining tree, it was possible to calculate height increment as a difference between the values H20 and H08 (heights in 2020 and 2008 respectively). Tree height annual increment was then obtained as height increment divided by the number of years between the inventories. The final model used for height reconstruction is also shown in Appendix 1 - Supplementary figure 1.

Crookedness

Stem crookedness evaluation was made out depending on level of predisposition of trees to be crooked, ranging on scale 1, 2 or 3. More detailed description is shown in chapter 3.2. For this variable, generalized linear mixed model comprising Poisson error distribution was used. Thus, differences among beech provenances were considered in the model and only block was represented in the random structure.

Classification of stem morphology

For this variable, Poisson distribution was used. It was decided to exclude class 6, since it was very rare in the experiment and was usually only found on the edge trees in buffer zone.

Spike knots above 0.5 m and spike knots below 0.5 m

Spike knots as indicator of timber quality were evaluated in the manuscript. For these variables, a generalized linear mixed model was used, including block as the unique random effect factor.

3.4. Statistical analysis

The response variables analyzed in this study are described in Table 3.

Table 3: Description of response variables evaluated

Dependent variable (y_{ijk})	Description	Abbreviation	Error distribution	Variable type
Basal area increment & DBH	cm^2/year & cm (2020)	BAI	Normal	Continuous
Height increment	cm/year	HI	Normal	Continuous
Stem crookedness	Range 1 – 3	Crook	Poisson	Count
Classification of stem morphology	Trees divided into 6 classes based on habitus	Class	Poisson	Count
Spike knots above 0.5 m	Amount of spike knots above 0.5 m	SpikeA	Poisson	Count
Spike knots below 0.5 m	Amount of spike knots below 0.5 m	SpikeB	Poisson	Count

Differences between European beech provenances on each of former variables were checked using Generalized (GLMM) or simple Linear Mixed Model (LMM). These models allow to consider spatial dependence of measurements via the use of random and fixed structure. The best random-effect structure was fitted by restricted maximum log-likelihood techniques (REML) and the goodness-of-fit of the different models was compared by means of Akaike information criterion (Zuur *et al.*, 2009). Nested random structures were used for plot nested in block. The fixed part of the model included provenance as unique explanatory variable and the final model was fitted by using REML. Differences between provenances for each response variable were evaluated using the following model:

$$\mathbf{y_{ijk} = \alpha_0 + \alpha_1 * Provenance + w_k + u_{jk} + \varepsilon_{ijk}}$$

where α_0 and α_1 are intercept and coefficient associated to each other provenance. Subscript and parameters are explained in Table 4.

Table 4: Model variable description

variable	Description
y_{ijk}	dependent variable
i	Tree
j	Plot
k	Block
Provenance	independent variable
$w \sim N(0, \sigma_k)$	block random effect
$u \sim N(0, \sigma_{jk})$	plot random effect
$\varepsilon_{ijk} \sim N(0, \sigma_e)$	error term

A Tuckey *post-hoc* analysis was used to identify pair provenances differences and obtain letters of significance for each studied response variables (Gramm *et al.* 2007).

Statistical analysis was conducted in RStudio version 4.1.1. (2021). Packages used for data evaluation were "multcomp" (Multiple Comparison package - Hothorn *et al*. 2008) and "nlme" (Non-linear Mixed Effects package - Pinheiro *et al*. 2015).

4. Results

DBH 2020

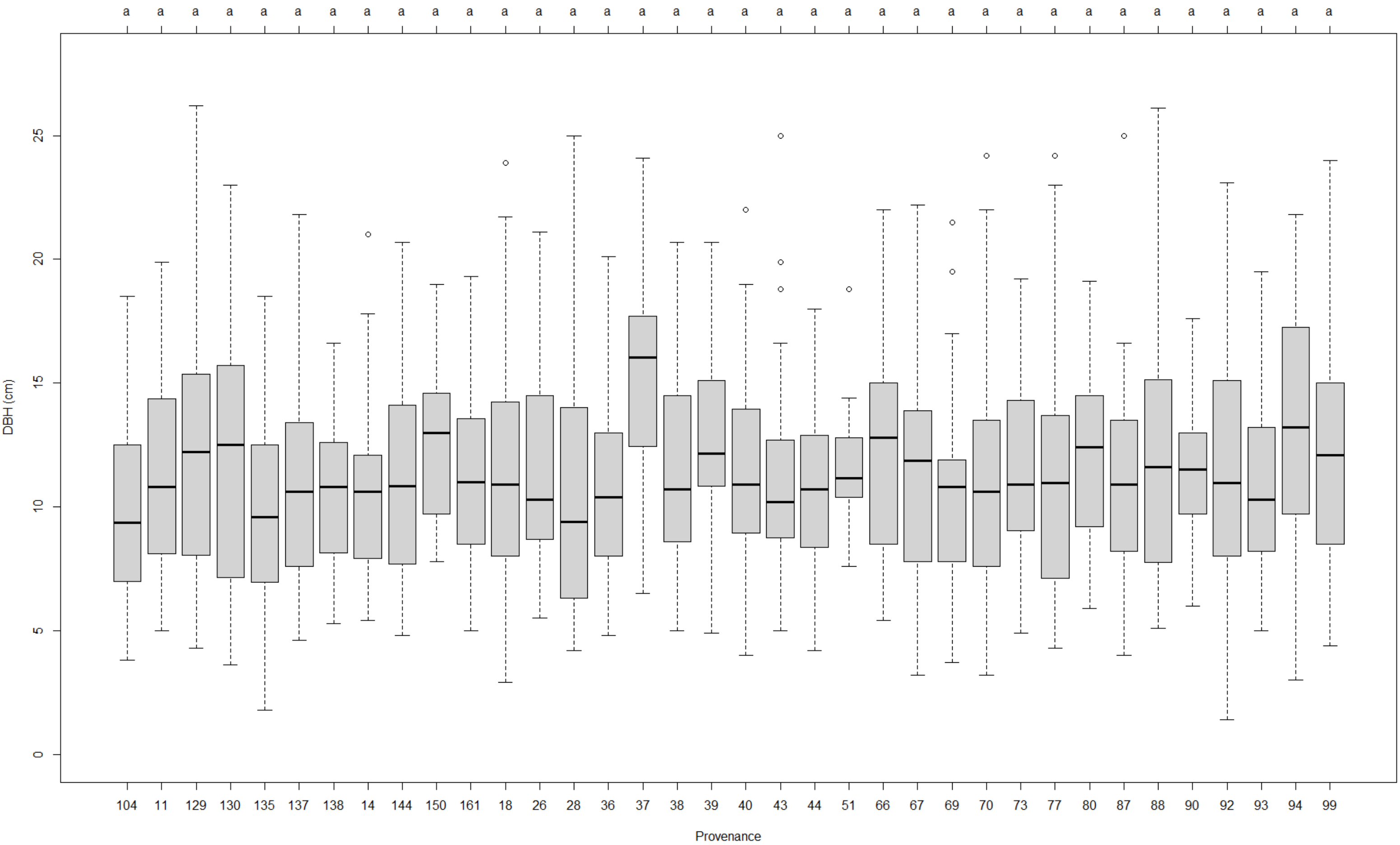


Figure 5: Diameter at breast height, 2020. Different letters denote significant differences at 0.05 significance level. The black lines indicate the mean value for the specific provenance

Highest average DBH 2020 was found within provenance number 37 (Deister – DE – Lower Saxony). Usually, mean tree DBH varied approximately in 10 cm, with extend between 7 and 13 cm (Figure 5). Minimal DBH was approx. 5 cm and, on the other hand, some trees exceeded DBH of 25 cm.

Basal area increment (cm²/year)

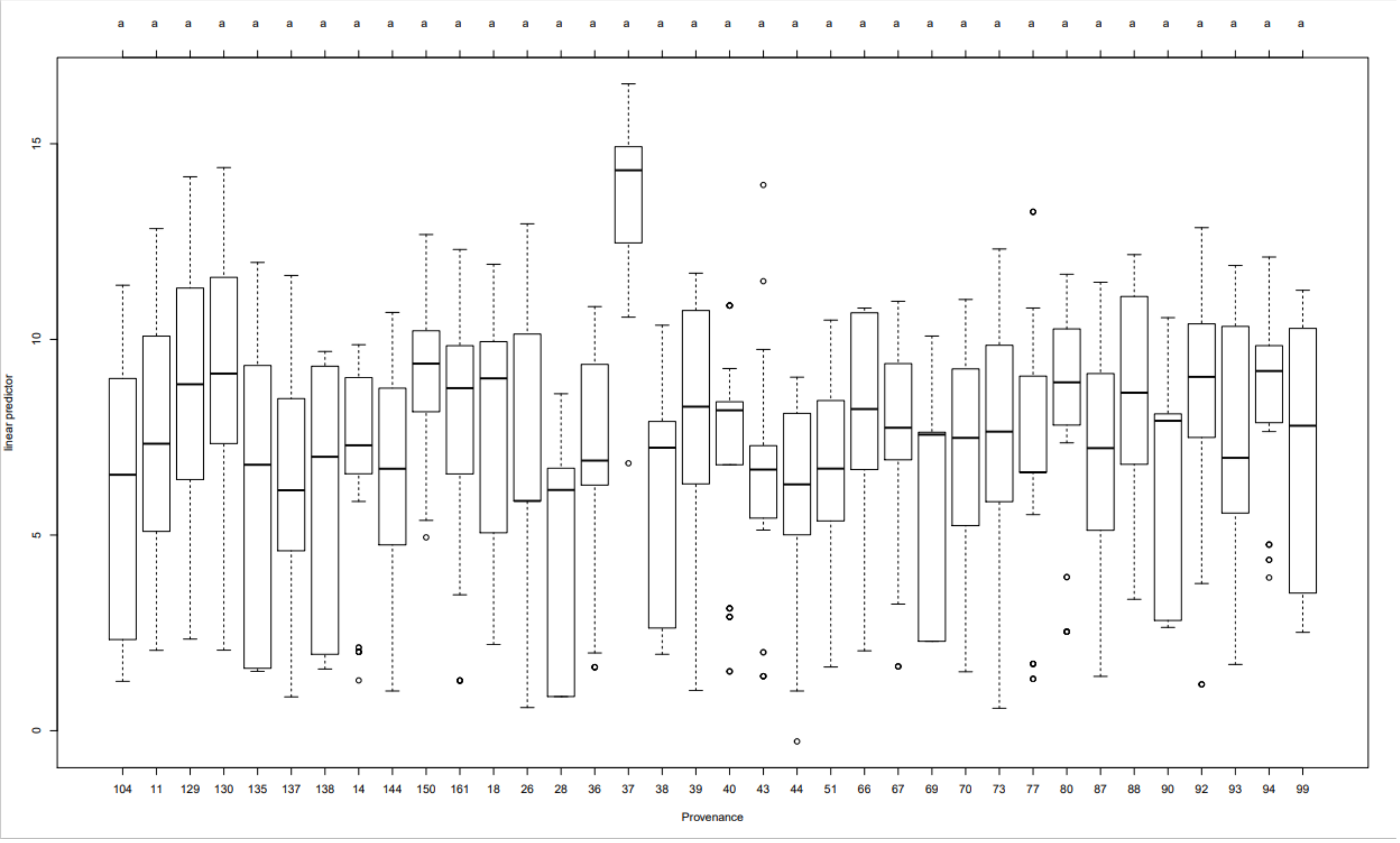


Figure 6: Basal area increment (cm²/year). Different letters denote significant differences at 0.05 significance level. The black lines indicate the mean value for the specific provenance. The linear predictor (y axis) indicates the values of BAI (cm²/year)

The only significant letter "a" confirms that no statistical differences in basal area increment were found (the confidence interval of all provenances overlaps). The mean value of BAI oscillates between 5 and 10 cm² per year (Figure 6). We can also observe a trend, that provenance number 37 (Deister – DE – Lower Saxony) has the highest BAI. Model results, i.e., coefficient and p-values can be consulted in Appendix 2 -Supplementary Table S1.

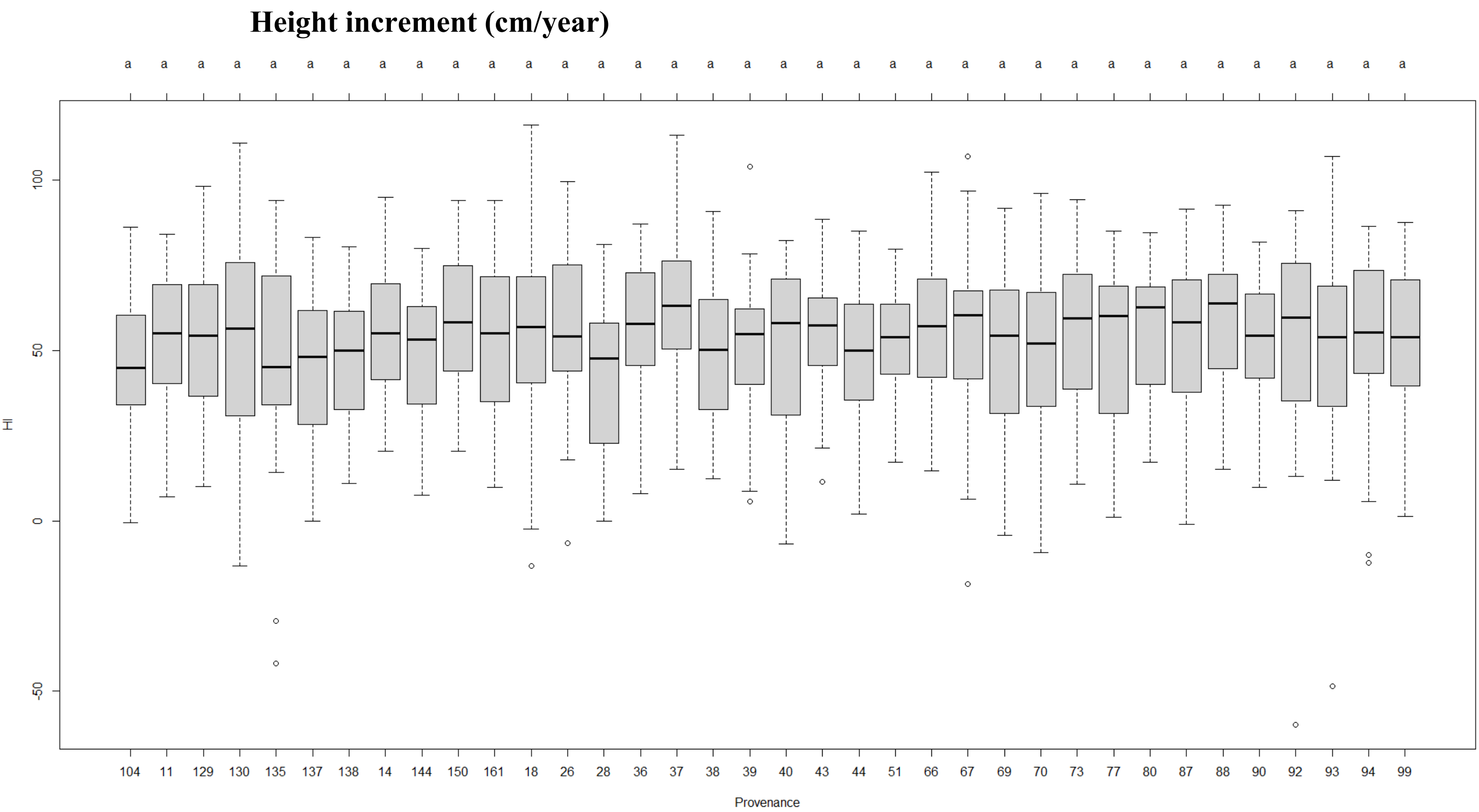


Figure 7: Height increment (cm/year). Different letters denote significant differences at 0.05 significance level. The black lines indicate the mean value for the specific provenance. The y axis indicates HI (cm/year)

Mean stand height for 2020 was 13.1 m (number of trees sampled = 108; Appendix 1 - Supplementary Figure S2). Mean annual tree height increment was 0.3 m per year (1995 – 2001) and 0.5 m per year in the time of 2002 – 2008 (Skogforsk 2009). Height increment between last two inventories was calculated by height-diameter relationship fitted model, which can be found in Appendix 1 – Supplementary figure S1. Height increment varied from 40 to 70 cm per year (Figure 7, Appendix 2 – Supplementary table S2). Only small differences between provenances were found, probably due to thinning interventions previously done. Lowest height increment was found by provenance number 28 (Ryssberget – SE); greatest height increment was found by provenance number 37 (Deister – DE – Lower Saxony).

Crookedness

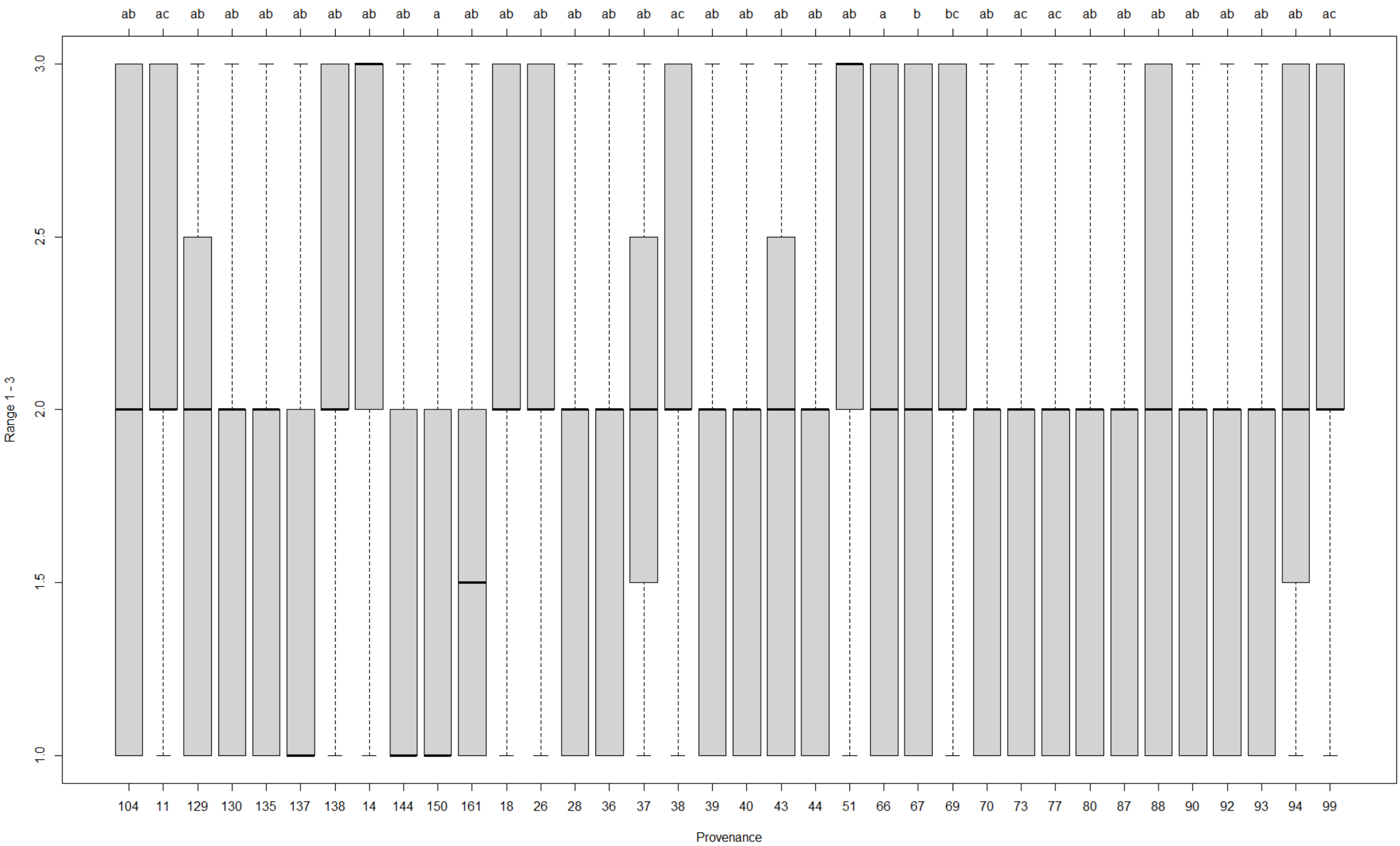


Figure 8: Crookedness. Different letters denote significant differences at 0.05 significance level. The black lines indicate the mean value for the specific provenance

High quality stems were found by southeastern European provenances 137 (Postojna – SI), 144 (Rachiv – UA) and 150 (Sovata (25) – RO). Most of the other provenances showed just somewhat fair quality, ranging between 1 and 2 (Figure 8, Appendix 2 – Supplementary Table S3). Only within provenances number 14 (F.D. des Charmettes - FR) and 51 (Eitorf 1502/262a – DE - North-Rhine-Whestf), most of trees are crooked from both sides.

Classification of stem morphology

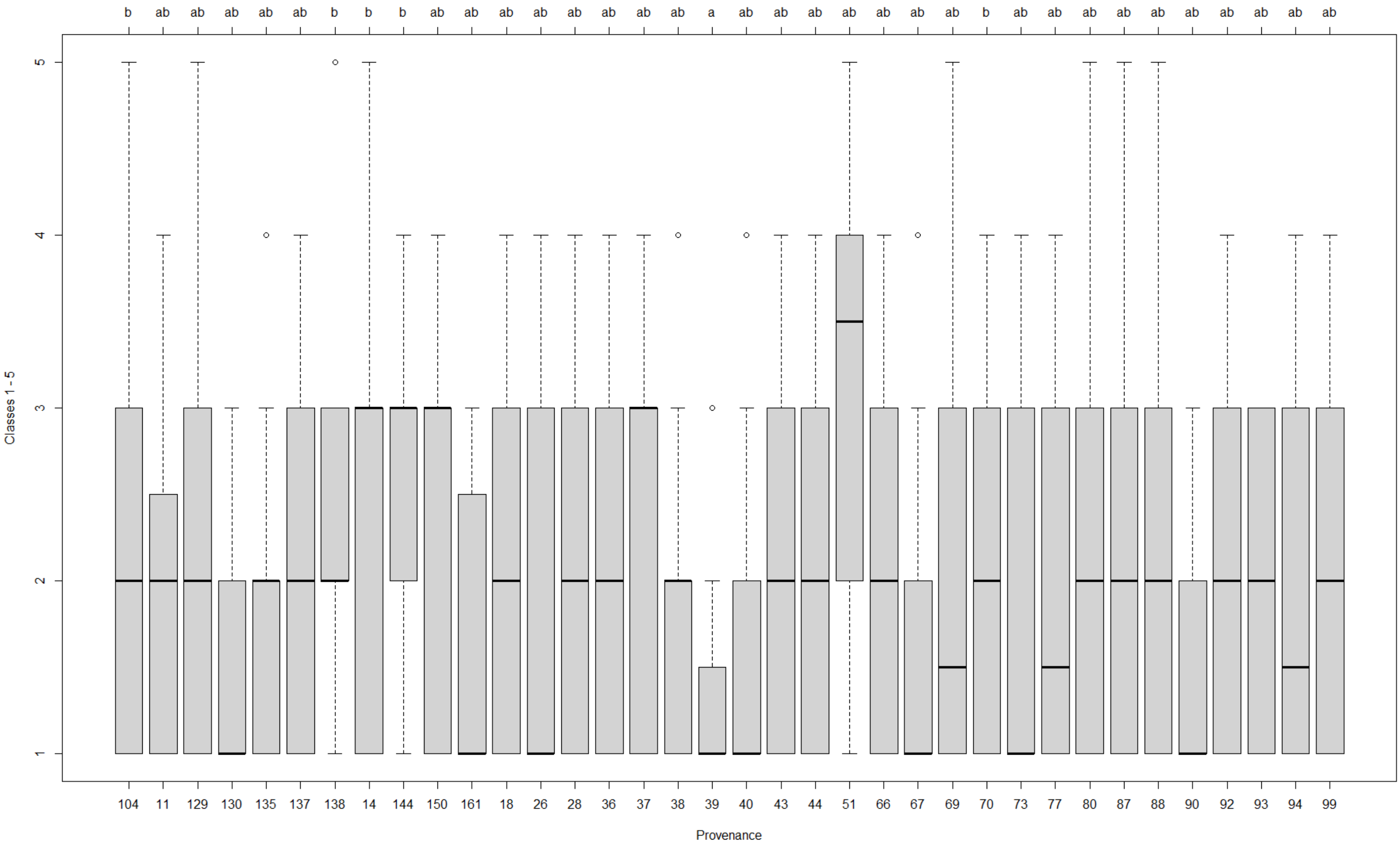


Figure 9: Classification of stem morphology. Different letters denote significant differences at 0.05 significance level. The black lines indicate the mean value for the specific provenance

The Figure 9 shows, that classification number 1 (straight (continuous) main stem), 2 (not continuous main stem but negligible reduction in height growth), and 3 (bifurcated trunk with a bifurcation point above 1.3 m above the ground) was mainly observed. For classification number 4 (bifurcated trunk with a bifurcation point below 1.3 m above the ground), rather rare samples were found. Provenance 39 (Seelzerthurm – DE – Lower Saxony) showed best results – only minority of trees were assigned to the classification number 2 and 3; on the contrary, most of the trees within provenance 39 belong to the class 1 (Appendix 2 – Supplementary Table S4). The worst class was found in case of provenance number 51 (Eitorf 1502/262a – DE - North-Rhine-Whestfalia), indicating shrubby trees or trees which are bifurcating under 1.3 meters above the ground.

Spike knots above 0.5 meters

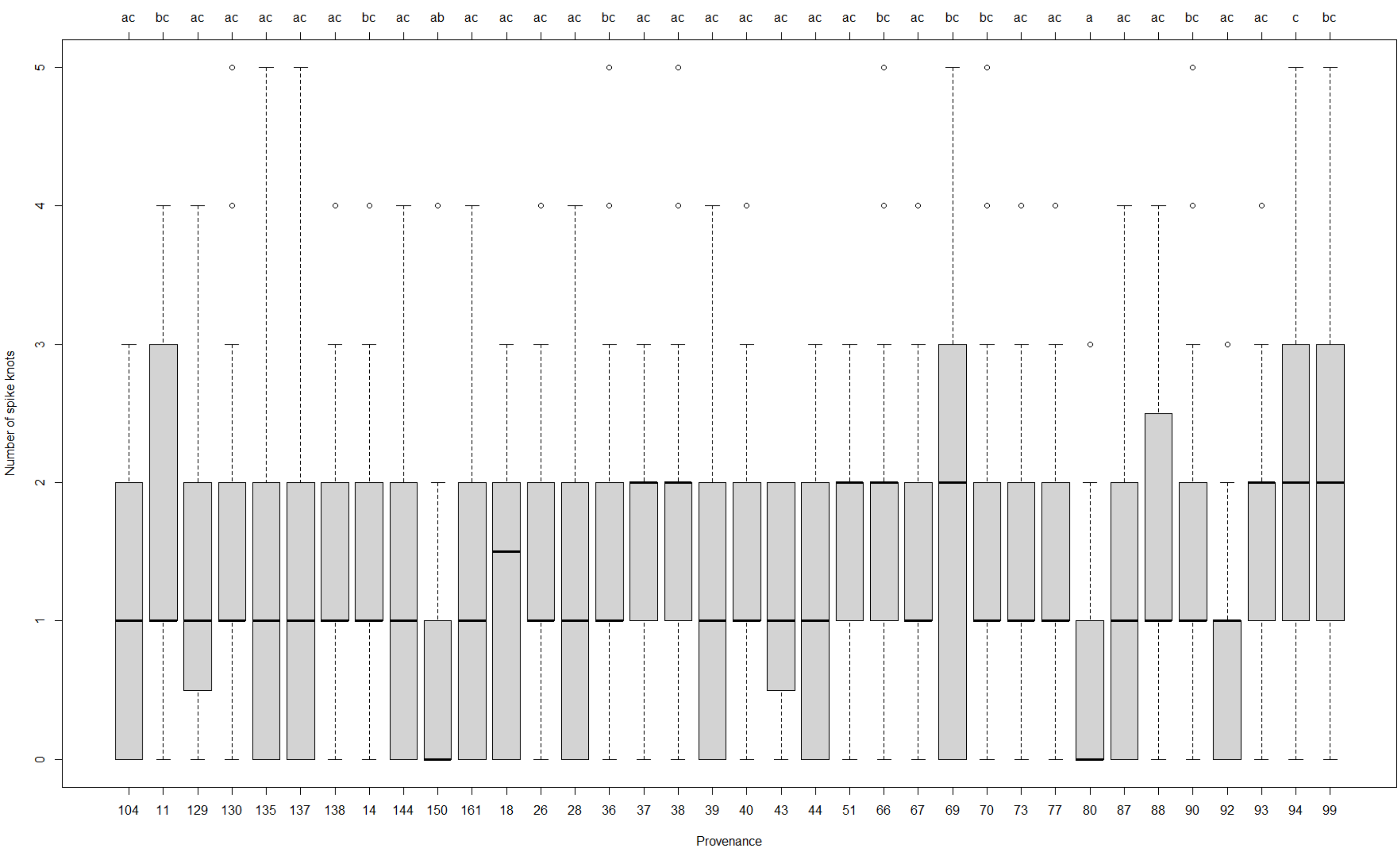


Figure 10: Spike knots above 0.5 meters. Different letters denote significant differences at 0.05 significance level. The black lines indicate the mean value for the specific provenance

Figure 10 shows, that provenance with lowest amount of spike knots was number 80 (Ebeleben, DE-Thuringia) and number 150 (Sovata – RO). These provenances differed from the rest because no tree with three and more spike knots above 0.5 m was found (Figure 10). Usually, trees showed similar patterns belonging to the spike knots quantity 1 to 2. Provenances number 11 (F.D des Charmettes – FR), 14 (F.D. de Lagast – FR), 66 (Dillenburg – DE-Hesse), 69 (Büdingen Abt. 762 – DE-Hesse), 70 (Büdingen Abt. 763 – DE -Hesse), 90 (Kirchheimbolanden – DE- Rhineland-Palatinate) and 99 (Ehingen – DE - Baden-Wurtenberg) were distinguished by higher quantity of spike knots. Provenance 94 (Ettreheim – DE – Baden-Wuttenberg) with the letter of significance “c” showed the worst possible qualitative characteristic of the evaluated variable (Appendix 2 – Supplementary Table S5).

Spike knots below 0.5 meters

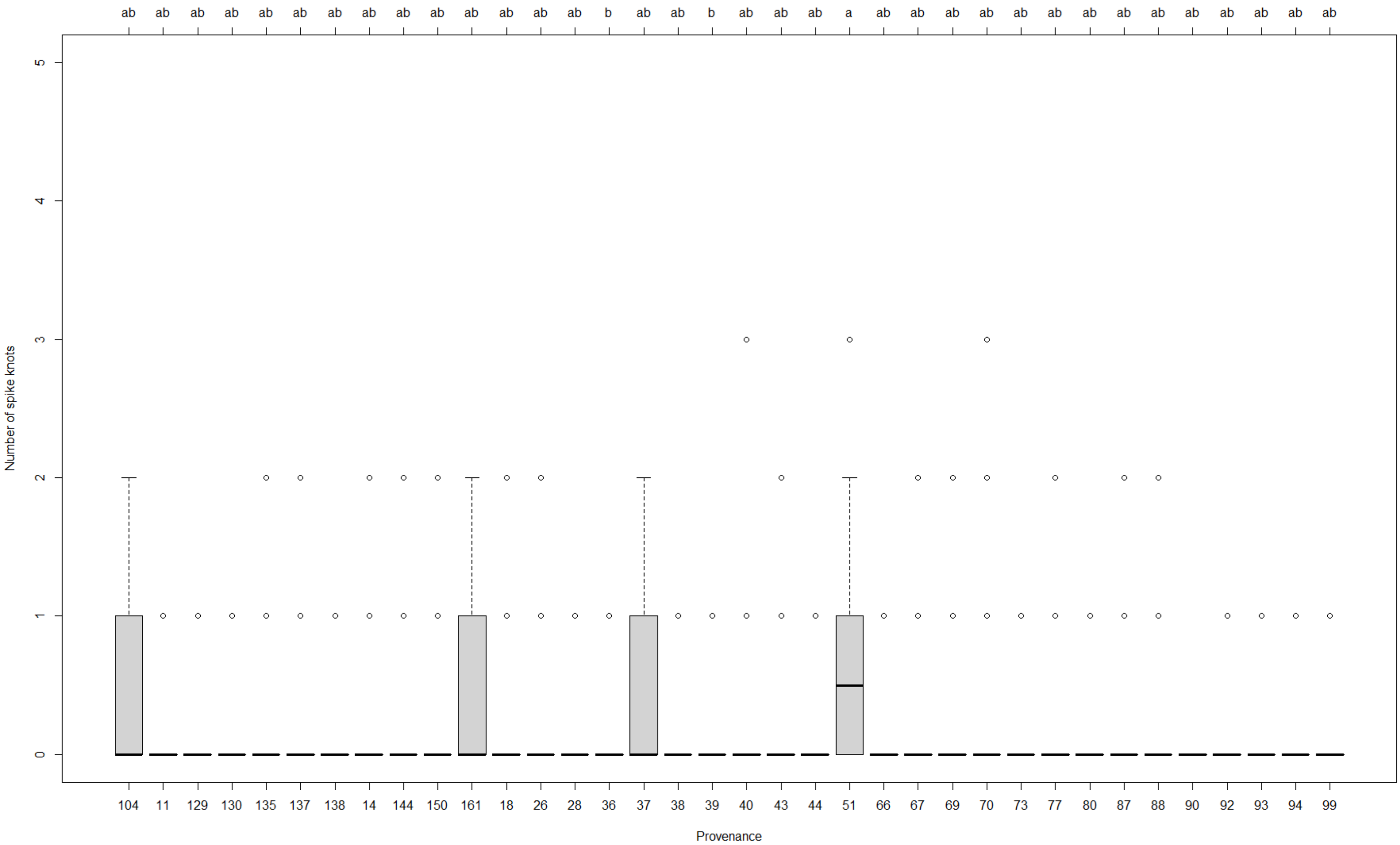


Figure 11: Spike knots below 0.5 meters. Different letters denote significant differences at 0.05 significance level. The black lines indicate the mean value for the specific provenance

Only four German provenances originating from different region of the country showed number of spike knots ranging between 0 and 1 (Figure 11). To be named: Provenance number 37 (Deister – Lower Saxony), 51 (Eitorf 1502/262a – North-Rhine-Whestfalia), 104 (Zwiesel –Bavaria) and 161 (Flaming - Saxony–Anhalt). Two provenances originating from Lower Saxony, Germany (number 36 – Osterholz-Scharmbeck and number 39 – Seelzenthurm), labelled by "b" significance letter, showed the best results of the evaluated variable (Appendix 2 – Supplementary Table S6). For the rest of provenances, almost no spike knots under 0.5 m was observed.

5. Discussion

In this study, we tested the tree growth and timber characteristics between several European beech provenances coming from a wide area of the European continent. We provided insights into the more adequate provenances to improve production and timber quality which could serve as guideline for designing forest management decisions in Sweden. We observed no significant differences between provenances in terms of tree basal area or height growth between the last two inventories. Therefore, our first and second hypothesis were rejected. We could not evidence any growth advantage for the southern European or local Swedish provenances. However, we observed that the German provenance number 37 (Deister, Lower Saxony) showed a higher growth trend for tree basal area, height increment and total height compared to the rest of provenances. We hypothesize that those differences could become greater and, hence, significant in future inventories. Thus, we may consider that provenance as the most interesting one with remarkable potential for future use in Sweden for a timber production proposal.

Results from other experimental provenance trials established in southern Sweden showed similar to those presented here. Bergkvist (2019) evidenced no difference in tree growth between European beech provenances in southern Sweden, but a good performance for native Swedish ones. Previous inventories for the same experimental site studied here, showed that German provenances presented higher basal area increment compared to the others (Skogforsk 2009). Accordingly, in the last inventory carried out in 2008, the German provenance number 39 showed the best performance regarding tree growth. Ježík *et al*. (2016) concluded that the lowest tree growth is commonly found for the provenance from the most oceanic climate and lowest altitude. In addition, site characteristic could influence tree height growth depending on provenance of origin (Stojnic *et al*. 2010). Future research and new stand inventories in the present experimental trial would be essential to provide a better understanding of the European beech provenances differences on tree growth characteristics.

Timber quality differences were observed between provenances regarding the second goal of the present work. South-eastern provenances were found to present the lowest crookedness and spike knots above 0.5 m, although central European ones were equally adequate in similar studies in Sweden (Bergkvist 2019). German provenances (number 39 and 37) showed good timber qualities such as the lowest tendency to develop double stems and spike knots below 0.5 m. However, the worst provenance according to timber quality was German too (number 51), which agree with similar studies in southern Sweden (Bergkvist 2019). It evidenced that even neighboring provenances could show more different adaptive traits compared to distant ones (Rau *et al*. 2015). Accordingly, a high genetic diversity within provenances has been frequently revealed (Muller *et al*. 2016). German provenance number 51 was observed economically the less valuable and might be mainly considered only for firewood use. Denser initial spacing may be recommended to reduce the likelihood of low branching and to promote height growth for that provenance. Native provenances from Sweden and Denmark showed generally good timber qualities compared to the rest of provenances. In this sense, Bergkvist (2019) evidenced that they rarely trend to bifurcation.

The experimental trial studied here might be used onwards to test the response of different European beech provenances to the ongoing climate change. Drought adaptation might play an important role for seedlings survival, tree growth and timber quality. This adaptation could limit growth and timber performance, since biomass distribution, leaf and root system morphology are evidently a core strategy of beech saplings to cope with water deficits (Knutzen *et al*. 2015). Provenances from continental to subcontinental climate, with higher probability of summer droughts occurrence, present several functional traits for a well drought adaptation compared to the sub-oceanic Central Germany (Rose *et al*. 2009). In this sense, we could expect a good drought adaptation for provenance number 40 (Boveden) in the experimental site studied here. A low drought response was also found in sandy soils for European beech (Buhk *et al*. 2016). It may be capable to face more frequent drought episodes from climate change by stomatal density changes (Stojnic *et al*. 2015), what would be interesting to compare the response of different European beech provenances in the future. Banach *et al*. (2015) evidenced that natural beech population growing in difficult environments showed better growing patterns in sites with arduous conditions such as higher altitudes. On the other hand, extreme winter frost from climate change could be similarly important than drought (Czajkowski *et al*. 2006b), what could be evaluated in future researches.

The results presented here may be limited by inherent features related with the experimental design. Stands were thinned two times after establishment. This could homogenize growth and timber features among provenances removing dominated and malformed trees, influencing also tree survival. Some standing trees were damaged accidentally by thinning treatment which could affect growth and timber quality. Strip roads might influence stem crookedness, enhancing growth of lateral branches and trunk tilt. Despite a buffer zone to avoid interactions from other factors unrelated with the experiment, the closeness to an adjacent old forest may affect in different way tree growth of provenances due to wind protection or sunlight interception. Differences in soil types and high mortality related to waterlogging (beech was replaced by natural regeneration of black alder- *Alnus glutinosa* (L.) Gaertn.) could affect observed results (Gömöry *et al*. 2011). Spike knots, especially those below 0.5 m, were hard to observed and, hence, to evaluate. There are no universal international restoration programs, so each region of provenance has different marketing rules (Auñon *et al*. 2011). Magagna *et al.* (2020) reminds, that foresters should pay attention to the forest management documentation, only then they can keep quality sources of reproductive planting material and separate them from malleable, low-quality sources.

Results of the manuscript provide a scientific basis to select the right provenance if the timber quality is the management goal. European beech promotion, to the detriment of Norway spruce in southern Sweden, may involve positive non-timber outcomes, such as enhance biodiversity via increasing broadleaved forest, recreational and other ecosystem services.

6. Conclusions

The aim of this thesis was to examine tree growth and timber quality differences among European beech provenances in Sweden. The study showed that, despite no significant differences on tree growth, German provenance number 37 (Deister, Lower Saxony) revealed an important potential for high quality timber production. In addition, German provenance number 39 (Seelzerthurm, Lower Saxony) had the lowest tendency to develop double stems and spike knots below 0.5 m. Another interesting provenance was a Romanian provenance number 150 (Sovata (25)) with the lowest values of crookedness and number of spike knots above 0.5 m. Swedish and Danish beech provenances, which were hypothesized to express high growth rates, since they are naturally adapted to Nordic conditions, did not differ significantly from other provenances.

The results of this study indicate that the genetic background of the studied provenances could have an important role on tree growth and timber quality features of European beech. However, more research and future inventories is needed to clarify the tree growth differences between provenances. In addition, the experimental design described here may be used to improve the current understanding of European beech adaptation to face the ongoing climate change in Southern Sweden.

References

Agestam E, Karlsson M, Nilsson U. 2006. Mixed forests as a part of sustainable forestry in Southern Sweden, Journal of Sustainable Forestry, 21:2-3, 101-117

Angelstam P, Andersson L. 2001. Estimates of the needs for forest reserves in Sweden, Scandinavian Journal of Forest Research, 16:S3, 38 51

Auñon F, Garcia del Barrio, Jose M, Mancha J, Ricardo A, Vries S. 2011. Regions of provenance of European Beech (*Fagus sylvatica* L.) in Europe

Banach J, Kubacki K, Skrzyszewska K, Smetek M. 2015. Evaluating the progeny of European beech (*Fagus sylvatica* L.) in the early years of growth. Forest Research Papers [online]. 2015, 76(1), 49-58 [cit. 2021-04-18]. ISSN 2082-8926

Barna M, Bublinec E, Kulfan J. 2011. Buk a bukové ekosystémy Slovenska: Beech and beech ecosystems of Slovakia. Bratislava: Veda, 634 p.

Bayerisches Amt fur Waldgenetik, 2021. Available online: http://www.stmelf.bayern.de/wald/asp/014927/index.php [cit. 2021-04-18]

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F. 2012. Impacts of climate change on the future of biodiversity. Ecology Letters 15: 365–377

Bergkvist J. 2019. Growth and timber quality evaluation of 33 European beech (*Fagus Sylvatica* L.) provenances from a site in Southern Sweden. Master thesis. Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre

Bogunović S, Bogdan S, Celepirovic N, Lanscak M, Ivankovic M. 2020. Use of a common garden experiment in selecting adapted beech provenances for artificial stand restoration. South-east European Forestry. 11. 10.15177/seefor.20-07

Bréda N, Badeau V. 2008. Forest tree responses to extreme drought and some biotic events: Towards a selection according to hazard tolerance? Comptes Rendus

Geoscience, Volume 340, Issues 9–10, 2008, Pages 651-662, ISSN 1631-0713Brunet J. 1995. Sveriges bokskogar har gamla rotter. Svensk Botanisk Tidskrift 89 (1995): –10

Brunet J, Felton A, Lindbladh M. 2012. From wooded pasture to timber production – changes in a European beech (*Fagus sylvatica* L.) forest landscape between 1840 and 2010. Scandinavian Journal of Forest Research 27.3 (2012): 245–254

Buhk C, Beierkuhnlein C, Jentsch A, Jungkunst H, Kämmer M, Kreyling J. 2016. On the influence of provenance to soil quality enhanced stress reaction of young beech trees to summer drought. Ecology and Evolution. 6:8276-8290

Czajkowski T, Bolte A. 2006a. Unterschiedliche Reaktion deutscher und polnischer Herkünfte der Buche (*Fagus sylvatica* L.) auf Trockenheit (Different reaction of beech (*Fagus sylvatica* L.) provenances from Germany and Poland to drought). Allgemeine Forst und Jagdzeitung. 177. 30-40

Czajkowski T, Bolte A. 2006b. Frosttoleranz deutscher und polnischer Herkünfte der Buche (*Fagus sylvatica* L.) und ihre Beeinflussung durch Trockenheit (Frost tolerance of German and Polish beech (*Fagus sylvatica* L.) provenances influenced by drought). Archiv für Forstwesen und Landschaftsökologie. 40. 119-126

Czajkowski T, Bolte A, Kompa T. 2006c. Zur Verbreitungsgrenze der Buche (*Fagus sylvatica* L.) im nordöstlichen Mitteleuropa (The distribution boundary of European beech (*Fagus sylvatica* L.) in north-eastern Europe). Forstarchiv. 77: 203-216

Davis ME, Shaw RG, Etterson JR. 2005. Evolutionary responses to climate change. Ecology 86 (7): 1704-1714

Dvorak WS. 2012. Water use in plantations of eucalypts and pines: a discussion paper from a tree breeding perspective. International Forestry Review. 14(1): 110–119

Eilmann B, Sterck L, Wegner S, MG DE Vries, G Von Arx, G M J Mohren, J Den Ouden, U Sass-Klaassen. 2014. Wood structural differences between northern and southern beech provenances growing at a moderate site. Tree Physiology 34: 882–893

EUFORGEN 2021. Current distribution map of European beech (*Fagus sylvatica* L.). Available online: http://www.euforgen.org/species/fagus-sylvatica/ [cit. 2021-05-05]

Flora M. 2018. Lesní zákon a některé související předpisy, stav ke dni 1.1.2018 (Forest act and some related regulations, status as of 1.1.2018. ISBN 978-80-906022-5-0

Gramm J, Guo J, Hüffner F, Niedermeier R, Piepho, H-P, Schmid R. 2007. Algorithms for Compact Letter Displays: Comparison and Evaluation. Computational Statistics & Data Analysis - CS&DA. 52

Gömöry D, Gömöryová E, Paule L. 2011. Effects of microsite variation on growth and adaptive traits in a beech provenance trial. Journal of Forest Science. 57. 192-199

Horváth A, Mátyás C. 2016. The decline of vitality caused by increasing drought in a beech provenance trial predicted by juvenile growth. South-east European forestry (SEEFOR). 7: 1-8

Hothorn T, Frank B, Westfall P. 2008. Simultaneous inference in general parametric models. Biometrical journal 50.3 (2008): 346-363

Huber G, Konnert M, Petkova K, Thiel, D. 2014. Transfer experiments with beech (*Fagus sylvatica* L.) to test adaptedness in a changing climate. Part I: Cultivation under strong varying climatic conditions. Allgemeine Forst- und Jagdzeitung. 185. 82-96

Interpine Innovation, 2021. Spike knots – What are They? Introduction into identifying and measuring spike knots. Available online: https://interpine.nz/spike-knots-what-are-they-introduction-into-identifying-and-measuring-spike-knots/ [cit. 2021-10-10]

Ježík M, Blazenec M, Ditmarová Ľ, Kučera J, Strelcova K. 2016. The response of intra-annual stem circumference increase of young European beech provenances to 2012-2014 weather variability. iForest - Biogeosciences and Forestry. 9: 1-10

Jump AS, Hunt JM, Penuelas J. 2006. Rapid climate change-related growth decline at the southern range edge of 876 *Fagus sylvatica* L. Global Change Biology. 12:2163–174

Jump AS, Penuelas J. 2005. Running to stand still: adaptation and the response of plants to rapid climate change. Ecology Letters 8 (9): 1010-1020

Kapsi.fi, 2021. Mean annual temperature in Skövde. Available online: https://mt.kapsi.fi/weather/se/station-5370-mean-temperature.html [cit. 2021-10-10]

Knoke T, Stang S, Remler N, Seifert T. 2006. Ranking the importance of quality variables for the price of high quality beech timber (*Fagus sylvatica* L.). Annals of Forest Science. 63. 399-413

Knutzen F, Leuschner Ch, Meier I. 2015. Does reduced precipitation trigger physiological and morphological drought adaptations in European beech (*Fagus sylvatica* L.)? Comparing provenances across a precipitation gradient. Tree Physiology. 35. 949-963

Kramer K, Buschbom J, Degen B, Hickler T, Thuiller W, Sykes MT, de Winter W 2010. Modelling exploration of the future of European beech (*Fagus sylvatica* L.) under climate change— range, abundance, genetic diversity and adaptive response. Forest Ecology and Management 259:2213–2222

Magagna B, Atkinson M, Goldfarb D, Koulouzis S, Martin P, Zhao Z. (2020). Data Provenance. In: Zhao Z., Hellström M. (eds) Towards Interoperable Research Infrastructures for Environmental and Earth Sciences. Lecture Notes in Computer Science, vol 12003. Springer, Cham.

Mátyás CS, Berki I, Czúcz B, Gálos B, Móricz N, Rasztovits E 2010. Future of beech in Southeast Europe from the perspective of evolutionary ecology. Acta Silvatica et Lignaria Hungarica 6: 91-110

Mátyás CS, Kramer K, 2016. Adaptive management of forests and their genetic resources in the face of climate change: Reference to the document: Climate change affects forest genetic resources: consequences for adaptive management. FORGER Policy Brief, Bioversity International, Rome, Italy, pp 1-8

Mátyás CS, 2005. Expected climate instability and its consequences for conservation of forest genetic resources. In: Geburek T, Turok J (eds) Conservation and management of forest genetic resources in Europe. Arbora Publishers, Zvolen, Slovakia, pp 465-476

Mátyás CS, 2016. Guidelines for the choice of forest reproductive material in the face of climate change. Forger Guidelines 2016, Biodiversity International, Rome, Italy, pp 1-8

Memišević HM, Ballian D. 2019. Morphological traits of common beech (*Fagus sylvatica* L.) in international provenance test. 10.13140/RG.2.2.24710.11848

Muller M, Reiner F. 2016. Genetic and adaptive trait variation in seedlings of European beech provenances from Northern Germany.Silvae Genetica [online]. 2016, 65(2), 65-73 [cit. 2021-04-18]. ISSN 2509-8934

Nilsson P, Cory N. 2018. Skogsdata. Current information about the Swedish forests from the national forest assessment. Swedish University of Agricultural Sciences, Department of Forest Resource Management, Umeå

Petkova K. 2020. Potential for adaptation of douglas-fir and common beech provenances to climate change. Doctoral thesis. University of forestry, Sofia

Petrík P, Bošeľa M, Fleischer P, Frýdl J, Konôpková A, Kurjak D, Petek A. 2020. Stomatal and Leaf Morphology Response of European Beech (*Fagus sylvatica* L.) Provenances Transferred to Contrasting Climatic Conditions. Forests. 11

Pinheiro J., *et al*. 2015. "R Core Team. 2015. nlme: linear and nonlinear mixed effects models. R package version 3.1-120." R package version (2015): 3-1

Piovesan G, Alessandrini A, Biondi F, Di Filippo A, Maugeri M. 2008. Drought-driven growth reduction in old 957 beech (*Fagus sylvatica L.*) forests of the central Apennines, Italy. Glob Change Biol (2008) 14:1–17

Rau HM, Rumpf H, Schönfelder E. 2015. New results from the Krahl-Urban provenance trials with European beech. Forstarchiv. 86. 27-41

Robson TM, Aranda I, Cano FJ, D San´Chez-Gómez. 2012. Variation in functional leaf traits among beech provenances during a Spanish summer reflects the differences in their origin. Tree Genetics and Genomes 8: 1111–1121

Rose L, Buschmann H, Köckemann B, Leuschner Ch. 2009. Are marginal beech (*Fagus sylvatica* L.) provenances a source for drought tolerant ecotypes? European Journal of Forest Research. 128. 335-343

Ruiz-Labourdette D, Pineda FD, Schmitz MF. 2013. Changes in tree species composition in Mediterranean mountains under climate change: Indicators for conservation planning. Ecological Indicators, 24: 310-323

Savill P. 2013. The silviculture of trees used in British forestry. University of Oxford, Oxford, UK. ISBN 9781780640266

Scribbr.com, 2021. Akaike information criterion. Available online: https://www.scribbr.com/statistics/akaike-information-criterion/ [cit. 2021-10-10]

SHMI, 2021. Skövde Climate station. Available online: https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer/#param=airTemperatureMinAndMaxOnceEveryDay,stations=all,stationid=83230 [cit. 2021-10-10]

Skogforsk, 2009. Study of survival, growth, external quality and phenology in beech provenance trail in Rånna, Sweden. Arbetsrapport NR 671 2009

Stojnic S, Orlović S, Pilipovic A, Kebert M, Sijacic/Nikolic M, Vilotić D. 2010. Variability of Physiological Parameters of European Beech Provenances in International Provenance Trials in Serbia. Acta Silvatica et Lignaria Hungarica. 6. 135-141

Stojnic S, Miljković D, Orlović S, Trudić B, Wuehlisch G, Zivkovic U. 2015. Phenotypic plasticity of European beech (*Fagus sylvatica* L.) stomatal features under water deficit assessed in provenance trial. Dendrobiology. 73. 163-173

Stojnic S, Eilmann B, Matović B, Sass-Klaassen U, Orlović S, (2013). Plastic growth response of European beech provenances to dry site conditions. IAWA Journal. 34. 475-484

Sulkowska M, Liesebach M, Wojcik J, Dobrowolska D. 2011. "Soil characteristics in the International Beech Provenance Experiments of 1993/95 and 1996/98" in proc. COST E52 Evaluation of beech genetic resources for sustainable forestry 4-6.5.2010. Burgos, Spain. Pp. 22 - 35

United Nations, 2021. Sustainable development goals. Available online: https://sdgs.un.org/goals [cit. 2021-10-10]

Varsamis G, Papageorgiou AC, Merou T, Takos I, Malesios C, Manolis A, Tsiripidis I, Gailing O. 2018. Adaptive diversity of beech seedlings under climate change scenarios. PeerJ Preprints 6:e27022v1

Wang F, David I, José A, Ramírez V, David SG, Ismael A, Pedro JA, Robson TM. Seedlings from marginal and core populations of European beech (*Fagus sylvatica* L.) respond differently to imposed drought and shade. Trees [online]. 2021, 35(1), 53-67 [cit. 2021-04-18]. ISSN 0931-1890

Wuhlisch G. 1984. Propagation of Norway Spruce cuttings free of fopophysis and fyrophysis effects. Silvae Genet. 215-219

Xiangdong L *et al*. 2009. "Individual height–diameter models for young black spruce (Picea mariana) and jack pine (Pinus banksiana) plantations in New Brunswick, Canada." The Forestry Chronicle 85.1: 43-56

Zuur A, Ieno E, Walker N, Saveliev A, Smith G. 2009. Mixed effect models and extensions in ecology with R. Springer, New York. ISBN: 978-0-387-87457-9

Acknowledgements

I would like to thank you, Jorge Aldea, for your never-ending professional support, encouragement and enthusiasm; for being my supervisor; for explanation of dozens of errors especially when creating R-codes. R would be hard to understand without your help. Your feedback always pushed the boundaries of my understanding.

Thank you, Mateusz Liziniewicz for your trust, cooperation and time we spent together in a forest or in your office. I appreciate your help with site navigation, past and ongoing experimental trails references and ongoing feedback.

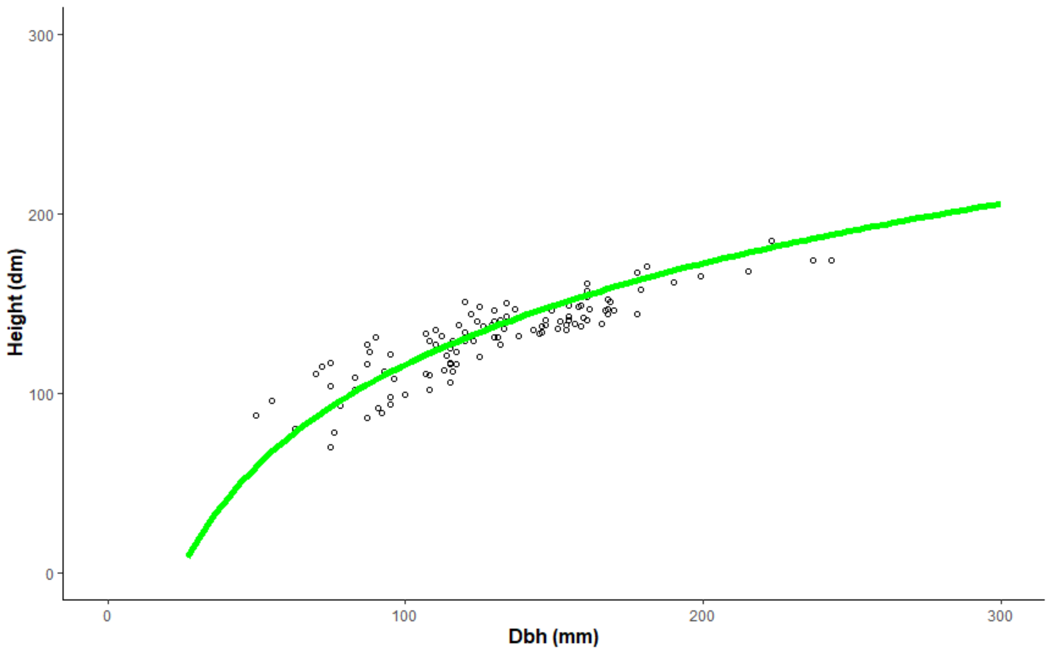
Thank you, Giulia Attocchi for your ongoing feedback, which led to the improvement of the manuscript. Your experiences in writing scientific papers allowed to find weaker sides of the study, which I would hardly recognize without your comments.

Thanks also belongs to Skogforsk and Partnerskap Alnarp for supplementary aid, measuring tools and material resources. The networking of this study was supported by Skogforsk (S21F9571256) and Partnerskap Alnarp (project number 1248 19).

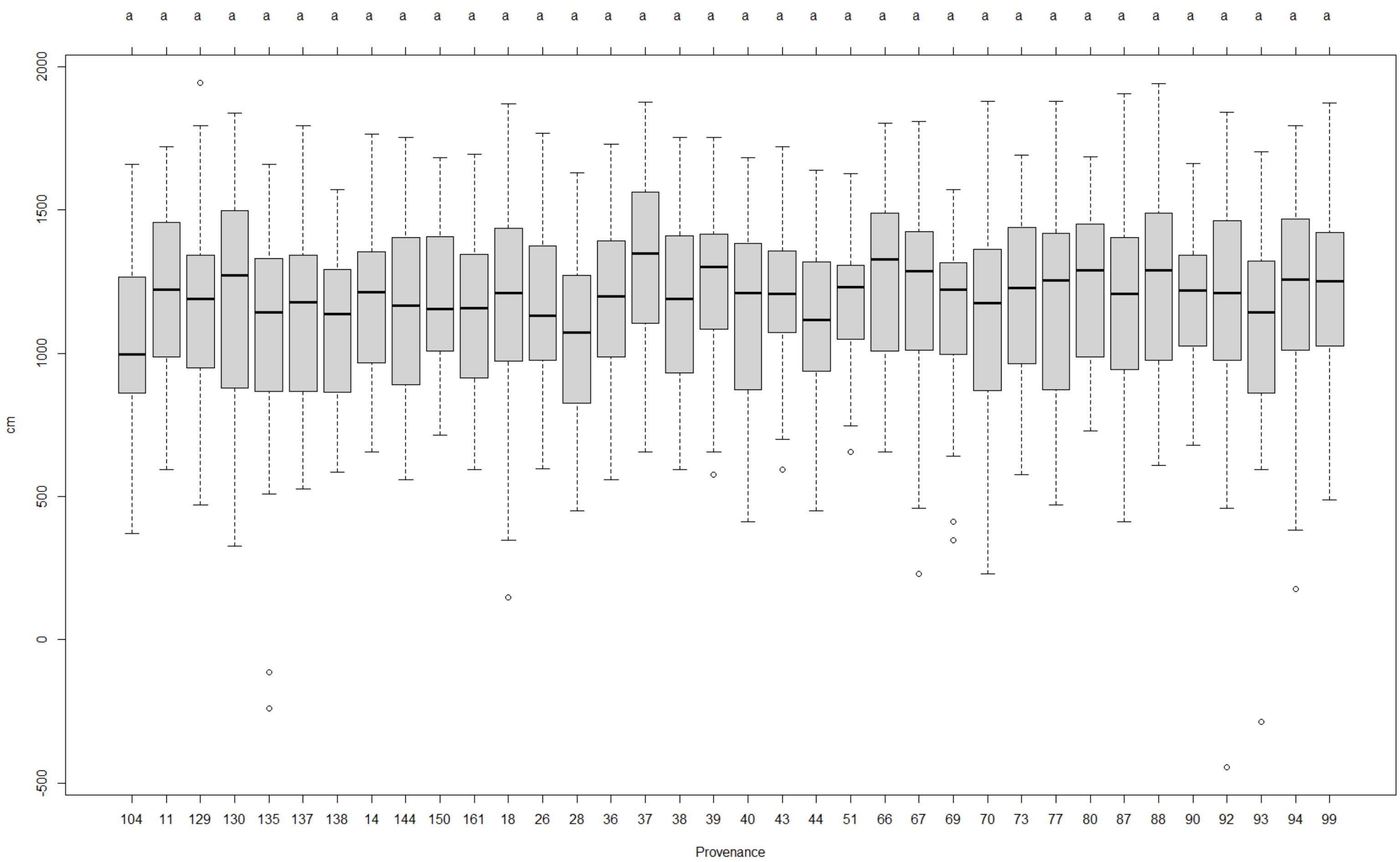
Last but not least, I would like to thank to my employer Jana Čacká, branch director of Forest Management Institute in Jablonec nad Nisou, Czech Republic, who encouraged me to complete university education.

It has been unique experience to be a part of Euroforester master program, which I appreciate.

Appendix 1 - supplementary figures



Supplementary Figure S1: The height - diameter relationship fitted model



Supplementary Figure S2: Total height, 2020

Appendix 2 – supplementary tables

Supplementary Table S1: Model-fitted coefficients for Basal Area Increment

Parameter	Coefficient	p-value
α_0 (Provenance 104)	5.576	0.0000
α_1 (Provenance 11)	0.717	0.4754
α_1 (Provenance 129)	1.746	0.0854
α_1 (Provenance 130)	1.854	0.0681
α_1 (Provenance 135)	0.266	0.7907
α_1 (Provenance 137)	-0.115	0.9082
α_1 (Provenance 138)	-0.385	0.7014
α_1 (Provenance 14)	-0.523	0.6026
α_1 (Provenance 144)	-0.407	0.6850
α_1 (Provenance 150)	0.410	0.6826
α_1 (Provenance 161)	0.159	0.8736
α_1 (Provenance 18)	1.130	0.2623
α_1 (Provenance 26)	1.169	0.2462
α_1 (Provenance 28)	-0.383	0.7023
α_1 (Provenance 36)	0.230	0.8188
α_1 (Provenance 37)	3.004	0.0037
α_1 (Provenance 38)	0.454	0.6512
α_1 (Provenance 39)	0.874	0.3852
α_1 (Provenance 40)	0.346	0.7300
α_1 (Provenance 43)	0.480	0.6323
α_1 (Provenance 44)	-0.910	0.3661
α_1 (Provenance 51)	-0.290	0.7725
α_1 (Provenance 66)	1.154	0.2522
α_1 (Provenance 67)	1.168	0.2469
α_1 (Provenance 69)	0.336	0.7377
α_1 (Provenance 70)	0.226	0.8214
α_1 (Provenance 73)	0.352	0.7256
α_1 (Provenance 77)	0.564	0.5741
α_1 (Provenance 80)	0.448	0.6555
α_1 (Provenance 87)	0.083	0.9335
α_1 (Provenance 88)	1.972	0.0526

α_1 (Provenance 90)	0.253	0.8006
α_1 (Provenance 92)	0.944	0.3481
α_1 (Provenance 93)	0.528	0.5990
α_1 (Provenance 94)	1.892	0.0627
α_1 (Provenance 99)	1.752	0.0843

Supplementary Table S2: Model-fitted coefficients for Height Increment

Parameter	Coefficient	p-value
α_0 (Provenance 104)	12.131	0.0000
α_1 (Provenance 11)	0.609	0.5439
α_1 (Provenance 129)	0.608	0.5446
α_1 (Provenance 130)	1.221	0.2261
α_1 (Provenance 135)	-0.047	0.9626
α_1 (Provenance 137)	-0.328	0.7438
α_1 (Provenance 138)	-0.098	0.9218
α_1 (Provenance 14)	1.240	0.2189
α_1 (Provenance 144)	0.225	0.8222
α_1 (Provenance 150)	2.021	0.0471
α_1 (Provenance 161)	0.812	0.4194
α_1 (Provenance 18)	0.949	0.3459
α_1 (Provenance 26)	1.624	0.1088
α_1 (Provenance 28)	-0.599	0.5509
α_1 (Provenance 36)	1.455	0.1499
α_1 (Provenance 37)	2.406	0.0188
α_1 (Provenance 38)	0.208	0.8352
α_1 (Provenance 39)	0.658	0.5123
α_1 (Provenance 40)	0.525	0.6009
α_1 (Provenance 43)	1.151	0.2534
α_1 (Provenance 44)	0.244	0.8073
α_1 (Provenance 51)	0.676	0.5010
α_1 (Provenance 66)	1.338	0.1850
α_1 (Provenance 67)	1.194	0.2363
α_1 (Provenance 69)	0.402	0.6888
α_1 (Provenance 70)	0.297	0.7673
α_1 (Provenance 73)	1.273	0.2072
α_1 (Provenance 77)	0.495	0.6221
α_1 (Provenance 80)	1.377	0.1727
α_1 (Provenance 87)	1.070	0.2880
α_1 (Provenance 88)	1.833	0.0711

α_1 (Provenance 90)	0.706	0.4821
α_1 (Provenance 92)	0.949	0.3455
α_1 (Provenance 93)	0.445	0.6576
α_1 (Provenance 94)	1.034	0.3044
α_1 (Provenance 99)	1.033	0.3049

Supplementary Table S3: Model-fitted coefficients for Crookedness

Parameter	Coefficient	p-value
α_0 (Provenance 104)	-1.024	0.3060
α_1 (Provenance 11)	-1.942	0.0521
α_1 (Provenance 129)	-1.028	0.3040
α_1 (Provenance 130)	-0.836	0.4032
α_1 (Provenance 135)	-0.435	0.6636
α_1 (Provenance 137)	1.063	0.2878
α_1 (Provenance 138)	-1.583	0.1134
α_1 (Provenance 14)	-2.705	0.0068
α_1 (Provenance 144)	2.512	0.0119
α_1 (Provenance 150)	2.010	0.0444
α_1 (Provenance 161)	0.774	0.4389
α_1 (Provenance 18)	-2.221	0.0263
α_1 (Provenance 26)	-1.775	0.0758
α_1 (Provenance 28)	0.016	0.9870
α_1 (Provenance 36)	-0.990	0.3222
α_1 (Provenance 37)	-1.191	0.2336
α_1 (Provenance 38)	-1.538	0.1240
α_1 (Provenance 39)	-0.336	0.7367
α_1 (Provenance 40)	-0.924	0.3553
α_1 (Provenance 43)	-1.107	0.2682
α_1 (Provenance 44)	0.378	0.7056
α_1 (Provenance 51)	-1.709	0.0873
α_1 (Provenance 66)	-1.192	0.2332
α_1 (Provenance 67)	-0.845	0.3983
α_1 (Provenance 69)	-2.349	0.0188
α_1 (Provenance 70)	-1.101	0.2707
α_1 (Provenance 73)	-0.779	0.4358
α_1 (Provenance 77)	0.305	0.7607
α_1 (Provenance 80)	-0.054	0.9565
α_1 (Provenance 87)	-0.383	0.7018
α_1 (Provenance 88)	-0.439	0.6605

α_1 (Provenance 90)	-0.663	0.5075
α_1 (Provenance 92)	-0.827	0.4084
α_1 (Provenance 93)	-1.252	0.2105
α_1 (Provenance 94)	-1.328	0.1840
α_1 (Provenance 99)	-2.084	0.0371

Supplementary Table S4: Model-fitted coefficients for Classification of stem morphology

Parameter	Coefficient	p-value
α_0 (Provenance 104)	-2.628	0.0085
α_1 (Provenance 11)	1.461	0.1440
α_1 (Provenance 129)	0.184	0.8536
α_1 (Provenance 130)	2.873	0.0040
α_1 (Provenance 135)	1.777	0.0756
α_1 (Provenance 137)	1.516	0.1295
α_1 (Provenance 138)	-0.363	0.7163
α_1 (Provenance 14)	0.449	0.6533
α_1 (Provenance 144)	-0.272	0.7852
α_1 (Provenance 150)	1.093	0.2743
α_1 (Provenance 161	2.806	0.0050
α_1 (Provenance 18)	0.697	0.4859
α_1 (Provenance 26	2.434	0.0149
α_1 (Provenance 28)	0.689	0.4907
α_1 (Provenance 36)	1.339	0.1804
α_1 (Provenance 37)	0.661	0.5085
α_1 (Provenance 38)	1.753	0.0796
α_1 (Provenance 39)	4.141	3.47e-05
α_1 (Provenance 40)	3.022	0.0025
α_1 (Provenance 43)	1.705	0.0882
α_1 (Provenance 44)	1.891	0.0586
α_1 (Provenance 51)	-0.899	0.3688
α_1 (Provenance 66)	1.365	0.1721
α_1 (Provenance 67)	2.225	0.0261
α_1 (Provenance 69)	1.971	0.0487
α_1 (Provenance 70)	0.958	0.3379
α_1 (Provenance 73)	2.348	0.0188
α_1 (Provenance 77)	2.018	0.0436
α_1 (Provenance 80)	1.685	0.0919
α_1 (Provenance 87)	0.791	0.4289

α_1 (Provenance 88)	0.783	0.4333
α_1 (Provenance 90)	2.074	0.0381
α_1 (Provenance 92)	1.281	0.2003
α_1 (Provenance 93)	1.467	0.1424
α_1 (Provenance 94)	1.884	0.0595
α_1 (Provenance 99)	1.144	0.2525

Supplementary Table S5: Model-fitted coefficients for Spike knots above 0.5 m

Parameter	Coefficient	p-value
α_0 (Provenance 104)	1.693	0.0905
α_1 (Provenance 11)	1.702	0.0888
α_1 (Provenance 129)	0.031	0.9753
α_1 (Provenance 130)	0.707	0.4792
α_1 (Provenance 135)	-0.018	0.9852
α_1 (Provenance 137)	-0.534	0.5932
α_1 (Provenance 138)	1.121	0.2623
α_1 (Provenance 14)	1.005	0.3147
α_1 (Provenance 144)	-1.275	0.2023
α_1 (Provenance 150)	-2.177	0.0294
α_1 (Provenance 161)	-1.110	0.2668
α_1 (Provenance 18)	0.067	0.9465
α_1 (Provenance 26)	0.172	0.8637
α_1 (Provenance 28)	-0.017	0.9861
α_1 (Provenance 36)	1.156	0.2474
α_1 (Provenance 37)	1.168	0.2428
α_1 (Provenance 38)	0.924	0.3554
α_1 (Provenance 39)	0.035	0.9717
α_1 (Provenance 40)	0.303	0.7620
α_1 (Provenance 43)	-1.146	0.2519
α_1 (Provenance 44)	-0.886	0.3754
α_1 (Provenance 51)	0.926	0.3542
α_1 (Provenance 66)	1.759	0.0786
α_1 (Provenance 67)	0.295	0.7676
α_1 (Provenance 69)	1.316	0.1880
α_1 (Provenance 70)	0.924	0.3553
α_1 (Provenance 73)	0.481	0.6302
α_1 (Provenance 77)	0.387	0.6985

α_1 (Provenance 80)	-2.887	0.0038
α_1 (Provenance 87)	-0.784	0.4329
α_1 (Provenance 88)	0.608	0.5431
α_1 (Provenance 90)	1.532	0.1256
α_1 (Provenance 92)	-1.379	0.1680
α_1 (Provenance 93)	0.670	0.5027
α_1 (Provenance 94)	2.378	0.0174
α_1 (Provenance 99)	1.566	0.1172

Supplementary Table S6: Model-fitted coefficients for Spike knots below 0.5 m

Parameter	Coefficient	p-value
α_0 (Provenance 104)	-3.427	0.0006
α_1 (Provenance 11)	-2.102	0.0355
α_1 (Provenance 129)	-0.991	0.3218
α_1 (Provenance 130)	-1.802	0.0714
α_1 (Provenance 135)	-0.115	0.9082
α_1 (Provenance 137)	-1.571	0.1162
α_1 (Provenance 138)	-1.904	0.0569
α_1 (Provenance 14)	-0.054	0.9570
α_1 (Provenance 144)	-1.552	0.1207
α_1 (Provenance 150)	0.509	0.6104
α_1 (Provenance 161)	0.076	0.9393
α_1 (Provenance 18)	0.154	0.8772
α_1 (Provenance 26)	-0.128	0.8978
α_1 (Provenance 28)	-0.319	0.7495
α_1 (Provenance 36)	-2.071	0.0383
α_1 (Provenance 37)	0.687	0.4920
α_1 (Provenance 38)	-1.391	0.1641
α_1 (Provenance 39)	-2.474	0.0133
α_1 (Provenance 40)	-1.394	0.1632
α_1 (Provenance 43)	-0.552	0.5809
α_1 (Provenance 44)	-1.739	0.0820
α_1 (Provenance 51)	2.369	0.0178
α_1 (Provenance 66)	-1.123	0.2616
α_1 (Provenance 67)	-0.593	0.5528
α_1 (Provenance 69)	-0.586	0.5579
α_1 (Provenance 70)	-0.152	0.8793
α_1 (Provenance 73)	-2.299	0.0214
α_1 (Provenance 77)	-1.092	0.2749
α_1 (Provenance 80)	-1.162	0.2453

α_1 (Provenance 87)	-1.368	0.1712
α_1 (Provenance 88)	0.094	0.9247
α_1 (Provenance 90)	-0.442	0.6584
α_1 (Provenance 92)	-0.475	0.6344
α_1 (Provenance 93)	-1.913	0.0557
α_1 (Provenance 94)	-1.276	0.2021
α_1 (Provenance 99)	-1.570	0.1163