Cent. Eur. For. J. 65 (2019) 67–80 sciendo DOI: 10.2478/forj-2019-0011

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

A comparison of different methods for assessing leaf area index in four canopy types

Cristina Ariza-Carricondo[1, *], Francesca Di Mauro[2], Maarten Op de Beeck[1], Marilyn Roland[1], Bert Gielen[1], Domenico Vitale[2], Reinhart Ceulemans[1, 3], Dario Papale[2]

[1] *University of Antwerp, Department of Biology, Research Center of Excellence on Plants and Ecosystems, Universiteitsplein 1, B–2610 Wilrijk, Belgium*

[2] *University of Tuscia, Department for Innovation in Biological, Agro-food and Forest systems (DIBAF), Via C. de Lellis, 01100 Viterbo, Italy*

[3] *CzechGlobe, SustES, Belidla 4a, CZ–603 00 Brno, Czech Republic*

Abstract

The agreement of Leaf Area Index (LAI) assessments from three indirect methods, *i.e.* the LAI–2200 Plant Canopy Analyzer, the SS1 SunScan Canopy Analysis System and Digital Hemispherical Photography (DHP) was evaluated for four canopy types, *i.e.* a short rotation coppice plantation (SRC) with poplar, a Scots pine stand, a Pedunculate oak stand and a maize field. In the SRC and in the maize field, the indirect measurements were compared with direct measurements (litter fall and harvesting). In the low LAI range (0 to 2) the discrepancies of the SS1 were partly explained by the inability to properly account for clumping and the uncertainty of the ellipsoidal leaf angle distribution parameter. The higher values for SS1 in the medium (2 to 6) to high (6 to 8) ranges might be explained by gap fraction saturation for LAI–2200 and DHP above certain values. Wood area index –understood as the woody light-blocking elements from the canopy with respect to diameter growth– accounted for overestimation by all indirect methods when compared to direct methods in the SRC. The inter-comparison of the three indirect methods in the four canopy types showed a general agreement for all methods in the medium LAI range (2 to 6). LAI–2200 and DHP revealed the best agreement among the indirect methods along the entire range of LAI (0 to 8) in all canopy types. SS1 showed some discrepancies with the LAI–2200 and DHP at low (0 to 2) and high ranges of LAI (6 to 8).

Key words: LAI–2200; SunScan; DHP; indirect methods; direct methods; Wood Area Index

Editor: Bohdan Konôpka

1. Introduction

Canopy leaf area is a crucial driver of light interception, and thus of photosynthetic carbon uptake and biomass production (GCOS 2011). Leaf area index (LAI), the metric of canopy leaf area, is commonly defined as half of the total leaf area per unit ground surface area (Chen & Black 1992). LAI is closely related to vegetation-atmosphere interactions as well as to gas exchange processes as photosynthesis and evapotranspiration (Duchemin et al. 2006). Being a key variable in ecological, hydrological and biogeochemical models and a reliable indicator of crop productivity, LAI is used to facilitate the understanding of dynamic vegetation changes and of the impact of climate change on ecosystems (Lin et al. 2016).

Unfortunately, the direct quantification of LAI requires a lot of manual labour as it implies the physical measurement of the area of leaves obtained from the destructive sampling of (parts of the) vegetation or by collecting leaf litter. The destructive sampling of evergreen, especially coniferous, species needs a very premeditated protocol. Morphological properties (e.g. specific leaf area) of needles differ along the vertical crown profile, among needles of different ages as well as among trees of different sizes due to competition pressure (Konôpka & Pajtík 2014). For tree genera that produce leaves at different time intervals during the growing season, as for example poplars, litter trap data represent an overestimation of the maximum LAI (Jonckheere et al. 2004). Destructive harvesting introduces a permanent disturbance to the canopy and is nearly impossible in forest canopies. It is furthermore not always possible to collect data along the entire season as the collection of leaf litter can only be used to estimate the seasonal LAI maximum and the pattern of LAI during leaf fall. It is therefore dif-

Corresponding author. Cristina Ariza-Carricondo, e-mail: Cristina.ArizaCarricondo@uantwerpen.be, phone: +32 3 265 17 07

ficult to assess the spatio-temporal dynamics of LAI using direct measurements.

To overcome these limitations a number of indirect methods have been developed, as described in some comprehensive reviews (Breda 2003; Jonckheere et al. 2004; Zheng & Moskal 2009). By indirect methods LAI is inferred from observations of a more easily measurable variable. Although in principle less accurate on a sample basis than direct measurements, indirect methods are frequently used since they are faster, allowing for a larger sample size and a higher spatial representativeness. Indirect methods are either based on light interception measurements, hemispherical photography, allometry or remote sensing. The latter approach is the most efficient method for large-scale LAI estimates, but it requires validation with ground truth data. The two first mentioned approaches infer LAI from measurements of the transmission of radiation through the canopy, making use of the radiative transfer theory (for details see Breda (2003) and references therein). They are here referred to as indirect optical methods. Besides hemispherical photography, alternative restricted-angle methods include 57° photography and zenith cover photography (Macfarlane et al. 2007; Alivernini et al. 2018). Some other recent methods include Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle (UAV) to estimate LAI in forestry (Chianucci et al. 2016; Woodgate et al. 2015).

Indirect optical methods are widely used to estimate LAI in a range of canopy types (forests, croplands, grasslands, etc.), but they have some limitations. First of all, they do not really measure LAI but rather plant area index (PAI), since radiation is intercepted by all light-blocking plant parts. In other words, these methods do not distinguish photosynthetically active (green) leaf tissue from non-green or woody plant parts as stems, branches or flowers. They hence tend to overestimate the true LAI in canopies where non-green plant parts are present (Weiss et al. 2004; Zheng & Moskal 2009). A second important concern is the clumping, *i.e.* the spatial aggregation of plant elements in the canopy. As leaves are not randomly distributed within a forest canopy, the clumping index describes the extent to which LAI retrieved from a random model of leaf placement differs from true LAI (Zhao et al. 2012). Although indirect methods are very useful and widely applicable, each one has its own inherent bias and errors, and is therefore more suited for particular conditions than other methods. To provide more reliable and more accurate LAI measurements with indirect methods, a range of techniques and correction procedures have been developed. These have been compared in a number of studies, on crops (Facchi et al. 2010, Fang et al. 2018), on rice (Fang et al. 2014), on forest stands (Macfarlane et al. 2007; Ryu et al. 2010b; Chianucci & Cutini 2013), on pine (Mason et al. 2012) and for different rice varieties (Sone et al. 2009). For a mix of canopies different – but only indirect – methods were compared (Woodgate et al. 2015). The current research of this manuscript differs in that these afore-mentioned studies focused either on the comparison of different instruments tested for the same canopy, or on the comparison of different canopies with the same instrument. The present study combines these factors, i.e. four canopies were studied, three different indirect methods were compared (LAI–2200 Plant Canopy Analyzer, SunScan Plant Canopy Analysis System and Digital Hemispherical Photography) and two direct methods were used to validate the results (litter fall collection and harvesting). This reflects the aim of the present study, i.e. assessing the agreement of the above-mentioned indirect methods to better understand their bias and to quantify the error terms for different canopy types.

2. Materials and methods

2.1. Description of sites and plant material

Four different canopy types – all located in Belgium – were selected for this study, *i.e.* a short rotation poplar coppice (SRC) plantation, a mature Scots pine stand, a mature Pedunculate oak stand, and a maize field. A brief summary of the site characteristics including location, vegetation type, year of most recent thinning or harvest, and planting density is presented in Table 1.

The short rotation coppice (SRC) plantation is located in Lochristi, province East of Flanders. In April 2010 an area of 14.5 ha was planted at a density of 8 000 trees ha^{-1} with dormant hardwood cuttings of 12 selected genotypes of *Populus deltoides, P. maximowiczii, P. nigra, P. trichocarpa* and interspecific hybrids. The genotypes were arranged in large (0.16 – 0.61 ha) mono-genotypic blocks of eight double rows wide, with alternating distances of 0.75 m and 1.50 m between the rows and 1.1 m between the individual trees within the row. The plantation was harvested for the first time in February 2012. From then on, trees continued to grow as a coppice culture with multiple shoots per stool in the following biennial rotation. The second harvest took place in February 2014. More detailed information about the site history, soil type, management procedures and productivity has been previously published (Broeckx et

Table 1. Main characteristics of the four canopy types and study sites selected for this study.

	Short Rotation Coppice	Scots pine	Pedunculate oak	Maize field
Location	Lochristi, East-Flanders	Brasschaat, Antwerp	Brasschaat, Antwerp	Wilrijk, Antwerp
Coordinates (deg. N, deg. E)	51.1122, 3.8505	51.3092, 4.5205	51.3092, 4.5205	51.1476, 4.4161
Species description	*Populus deltoides, P. maximowiczii, P. nigra, P. trichocarpa*	*Pinus sylvestris*	*Quercus robur*	*Zea mays, var GL Fantastic*
Density (trees ha^{-1}; seeds ha^{-1})	8 000	360	310	94 000
Thinning or Harvest	2014	2015	No recent data	2015

al. 2012; Verlinden et al. 2015; see also http://uahost.uantwerpen.be/popfull/).

The Scots pine (*Pinus sylvestris* L.) stand is located in the urban mixed forest 'De Inslag' (150 ha) in Brasschaat, province of Antwerp. The selected stand is about 1.7 ha with an overstory of Scots pine and an understory of mosses, grasses (*Molinia caerulea* [L.] Moench), *Betula pendula* Roth and young Scots pine seedlings (Curiel Yuste et al. 2005). It was originally planted in 1929 and regularly thinned and managed since then. In 2011 the stock density was 360 trees ha^{-1} while diameter at breast height and tree height were on average 33 cm and 21.4 m, respectively (Gielen et al. 2013). The stand canopy is sparse and according to assessments in 2007 the LAI was 1.31 $m^2 m^{-2}$ with only two needle age classes present (Op de Beeck et al. 2010). In August 2015 the stand was most recently thinned, reducing the number of trees with about one third (Gebauer et al. 2015). Both the SRC plantation and the Scots pine stand host eddy covariance monitoring stations that are part of the European ICOS infrastructure network (www.icos-etc.eu).

The Pedunculate oak *(Quercus robur* L.*)* stand is also located in the forest 'De Inslag', close to the Scots pine stand. The oaks were planted in 1936 with a current density of 310 trees ha^{-1}. The most recent assessments (2005) reported that canopy height was on average 26 m (Curiel Yuste et al. 2005). No thinnings were made in this stand.

The maize (*Zea mays* L.) field was located in Wilrijk, Antwerp. It was cultivated by a local dairy farmer for silage production. The maize crop (variety GL Fantastic) was sown on 5 May 2015 after application of manure (60 $m^3 ha^{-1}$) and ploughing the field to 25 cm depth. The date of seedling emergence was 20 May 2015. The planting design comprised an inter-row distance of 70 cm and an average distance between plants in the row of 14 cm. The sowing density was about 94,000 seeds ha^{-1} with a SW-NE row direction.

2.2. Indirect optical methods

Three widely applied instruments for indirect LAI measurements were used in this study, *i.e.* the LAI–2200 Plant Canopy Analyzer (LI–COR®, Lincoln, NE, USA), the SS1 SunScan ceptometer (Delta–T Devices Ltd, Cambridge, UK) and Digital Hemispherical Photography (DHP). The theory of leaf area index calculation has been explained in detail in the Appendix text 1. Theory of leaf area index calculation.

2.2.1 LAI–2200 Plant Canopy Analyzer

The LAI–2200 Plant Canopy Analyzer (LI–COR®, Lincoln, NE, USA), further referred to as LAI–2200, measures the canopy transmittance of diffuse light at five zenith angles, which is obtained from simultaneous measurements of diffuse light above and below the canopy with a fish-eye PAR sensor divided in five concentric rings. LAI is estimated by inverting the measured canopy transmittance (Eq. 1 in Appendix text 1) and taking into account the Apparent Clumping Factor (ACF) under the usual assumption that leaves are randomly (Poisson) distributed in the canopy (*cfr*. user manual of the LAI–2200 Plant Canopy Analyzer).

In this study the below-canopy measurements were manually taken with one LAI–2200 sensor, while above-canopy measurements were collected with another LAI–2200 sensor installed in a clearing close to the site. This sensor was set to automatically log incoming light readings at a 30 s interval during below-canopy measurements, which were afterwards matched to the closest readings in time. To avoid any influence from the operator the standard five ring configuration was used with a 45° view cap on both above- and below-canopy sensors. All LAI–2200 measurements were processed with the FV2200 software (v 1.0.0).

2.2.2 SS1 SunScan Plant Canopy Analysis System

The SS1 SunScan Plant Canopy Analysis System (Delta-T Devices, Cambridge, UK), further referred to as SS1, is a ceptometer that uses measurements of radiation transmittance through the canopy to provide LAI estimates by applying the Beer-Lambert extinction law (Eq. 3 in Appendix text 1) and taking into account other parameters as absorption and transmission of diffuse light, and zenith angles (*cfr*. user manual of the SunScan Canopy Analysis System version 3.3). This method requires simultaneous measurements of both incident and transmitted photosynthetically active radiation (PAR), a requirement that was met in different ways depending on the canopy type. For the SRC, the Scots pine and the Pedunculate oak stands, two instruments were used that independently collected above- and below-canopy measurements, similar to the methodology explained above for the LAI–2200. In the maize crop only one instrument was used. This instrument was radio connected to an external PAR sensor measuring incoming PAR, allowing for simultaneous above- and below-canopy PAR readings.

The SS1 SunScan ceptometer uses a specific term to define the Ellipsoidal Leaf Angle Parameter (ELADP). This parameter is modified depending on the canopy and characterizes the horizontal or vertical orientation of the leaves (*cfr*. user manual of the SunScan Canopy Analysis System version 3.3). Because site-specific ELADP values were not available, ELADP was set to 1 for the SRC and the Scots pine and Pedunculate oak stands, and set to 1.37 for the maize crop. The SS1 does not account for clumping.

2.2.3 Digital Hemispherical Photography (DHP)

With this method, which is also known as fish-eye photography and further referred to as DHP, LAI is derived with the inverted Poisson model (Eq. 2 in Appendix text 1) from the amount and the distribution of vegetation pixels on digital hemispherical pictures of the canopy. In this study, the hemispherical pictures were first transformed into binary black and white pictures using the Ridler-Calvard thresholding algorithm (Ridler & Calvard 1978). Gap fraction was estimated and LAI was calculated by inversion of the Poisson model as described by Thimonier et al. (2010), and by accounting for clumping using the logarithmic averaging method (Lang & Xiang 1986). All the above calculations are implemented in the HemiTool software, which is the standard processing protocol for hemispherical imagery as a standard LAI measurement method at all ecosystem stations of the ICOS research infrastructure (www.icos-etc.eu).

All hemispherical pictures were taken with a digital single-lens reflex camera (DSLR; Nikon D7100, Tokyo, Japan) in combination with a hemispherical lens (4.5 mm F 1:2.8 DC HSM Sigma Corporation, New York, USA). Following the ICOS measurement protocol, pictures were made in RAW format, using the auto-focus of the lens, a fixed aperture of 8, and the lowest shutter speed at which no overexposure occurred. The minimum camera-to-foliage distance was 15 cm from the closest leaf or 10 times the leaf length.

2.3. Sampling design

All LAI measurements with the three indirect methods were collected over the span of one full growing season, from spring 2015 to spring 2016. Measurement dates were selected to collect data over the full environmental range of LAI values for each canopy type, including the seasonal minima and maxima. Due to some instrument failure and periods of unfavourable weather conditions, it was unfortunately not possible to measure with all three indirect methods at all scheduled dates. All indirect measurements were done under fully overcast sky conditions, *i.e.* in the absence of direct sunlight. In the SRC and the maize field, also direct LAI measurements were collected.

2.3.1 Short rotation coppice poplar plantation

Measurements in the SRC plantation were carried out in three permanent plots of 3 m by 4 m inside each of eight selected blocks, each block representing a different poplar genotype. At each measurement date 12 below-canopy readings were made in each plot with the LAI–2200 and SS1, six parallel and six perpendicular to the rows (Fig. 1a).

Above-canopy readings for both instruments were taken in a nearby clearing. In each of the 3 × 8 plots two hemispherical pictures were taken parallel to the rows with the camera positioned as close to the ground as possible (Fig. 1a). Measurements were taken about every two weeks between the time of bud break and the end of leaf fall, as well as one measurement during the leafless period in winter.

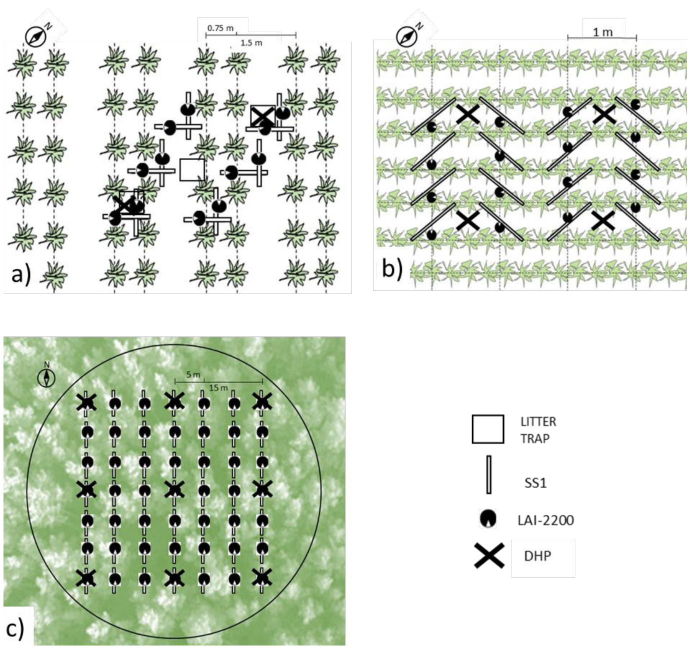

Fig. 1. Description of the sampling design in the different ecosystems. Measurements were performed in a short rotation coppice poplar plantation (a), in a maize field (b) and in a mature Scots pine and a mature Pedunculate oak stand (c). Location of the three indirect measurements (LAI–2200, SS1 and DHP) are reported in all ecosystems and litter trap positions in the short rotation coppice.

Direct LAI measurements in the SRC plantation were obtained with the gravimetric method (Daughtry 1990) from leaf litter collected at regular intervals from the start to the end of the leaf fall period, *i.e.* from late August to December 2015. In each plot, leaf litter was collected in three plastic litter traps (surface area of 0.22 m^2) installed along a diagonal transect (Fig. 1a). Collected leaves were transported to the laboratory, dried in a drying oven at 70 °C until constant weight and then weighed. Total leaf area (LA) was calculated from dry weight using specific leaf area (SLA), which was determined from a representative sample of nine leaves collected from each plot at the time of maximum LAI (LAI_{max}). SLA was calculated by dividing fresh leaf area of the sample by its dry weight. For each plot LAI was obtained by dividing the total LA by the total ground surface area of the three litter traps inside the plot (Broeckx et al. 2015).

2.3.2 Scots pine and Pedunculate oak forest stands

Indirect measurements in the Scots pine and the Pedunculate oak stands were carried out in a 25 m radius circular plot (Fig. 1c). At each measurement date 49 below-canopy measurements were made with both LAI–2200 and SS1, one measurement spaced 5 m apart from the other, and with the sensor always pointing to the South. Simultaneous above-canopy measurements were taken in a nearby clearing. Nine upward-facing hemispherical pictures were taken at 1.3 m above the ground, the upside of the picture placed to the North, with 15 m distance between each picture taken. No direct measurements of LAI were collected in these two forest stands.

2.3.3 Maize field

Indirect measurements in the maize field were taken in a 3 m by 3 m plot almost every two weeks. At each measurement date 16 measurements were taken with the LAI–2200 and SS1 in each plot, as well as four upward looking hemispherical pictures parallel to the row direction (Fig. 1b).

Direct LAI values were obtained from destructive harvesting during the summer period. In each plot 15 plants (five plants in three rows) were removed, and leaves and the stem of the fresh plants were separated. The height of each stem was measured with a ruler and the diameter measured with a calliper at 10 cm above the ground and at 2/3 of the total stem height. The hemi-surface area of each stem was derived from these measurements assuming a cylindrical stem shape. To calculate LA, total fresh weight of the leaves was first determined, and then the LA of a subsample of approximately 10% of these leaves was measured with a leaf area meter (LI–3100A, LI–COR®, Lincoln, NE, USA). This value was multiplied with the fresh weight ratio of the full sample to the subsample. The total hemi-surface area of the 15 harvested plants was obtained by summing the LA and the summed hemi-surface area of the stems. To obtain the direct LAI estimate, this value was multiplied with the ratio of the total number of plants in the plot to the number of harvested plants and then divided by the ground area of the plot.

2.4. Statistical analyses

The results from the three indirect methods and the direct method were pairwise compared for each of the four canopy types. The level of agreement between each pair of methods was assessed by means of robust statistical tools developed for method comparisons, and consisting in: (i) the regression approach of Passing & Bablok (1983) and (ii) the Tukey mean-difference plot popularised by Bland & Altman (1986) in analytical chemistry and biostatistics. More details about the statistical methods are to be found in the Appendix text 2.

3. Results

This section shows the results of each statistical analysis, i.e. Passing & Bablok (P–B), Bland and Altman (B–A), Bravais-Pearson correlation coefficient (r) and scatter plots. For reasons of simplicity, the LAI ranges were arbitrarily divided in the following order: low (0 to 2 $m^2 m^{-2}$), medium (2 to 6 $m^2 m^{-2}$) and high (6 to 8 $m^2 m^{-2}$) LAI range. The inter-comparison of the indirect methods (LAI–2200, SS1 and DHP) in the four canopies (SRC, Scots pine, Pedunculate oak and maize field) is first broken down (Fig. 2). Afterwards the comparison between the indirect and direct methods (litter fall and harvest) was performed for validation in SRC, and maize field only (Fig. 3).

3.1. Passing-Bablok regression results between indirect and direct methods

Focusing on the 95% CIs of the P-B regression terms for the comparison of indirect methods, the LAI–2200 and SS1 methods were the most comparable in the Pedunculate oak stand and the maize crop, as they provided similar LAI values based on the 95% CI of intercept and slope coefficients. The LAI–2200 and DHP methods agreed very well in the Scots pine stand and in the SRC. Compared with the direct method, LAI–2200 and DHP readings in the maize field provided unbiased LAI measurements (Table 2). For all other indirect methods there was either a constant bias (when the intercept differed significantly from 0), or a proportional bias (when the slope differed significantly from 1), or both biases were jointly detected (Fig. 2). These afore-mentioned results need, however, to be interpreted with care because the assumptions underlying the linear regression model were not always met.

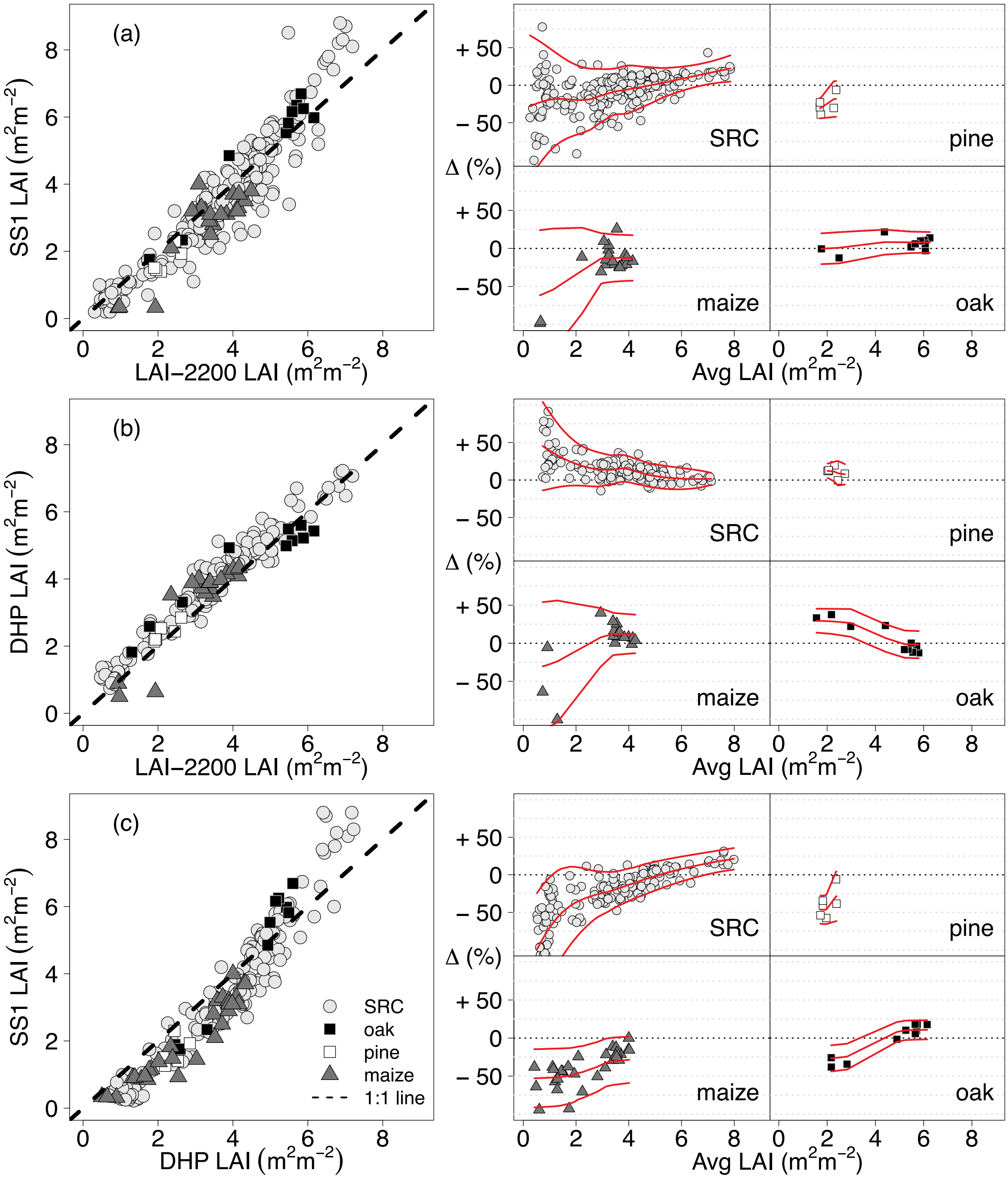

Fig. 2. Inter-comparison of indirect methods for leaf area index (LAI) estimations. Panels on the left (a–c) show the conventional x–y scatter-plots with LAI readings. Panels on the right show the Bland and Altman (B–A) plots separately for each canopy type and for each pair of methods. The horizontal axis in the B–A plots represents the averages of each pair of measurements, while the vertical axis indicates the percentage differences (Δ) for each pair of measurements, explaining an overestimation or underestimation if the percentage is positive or negative, respectively. Red smoothed lines denote the systematic error (bias) and limits of agreement. SRC: short rotation coppice.

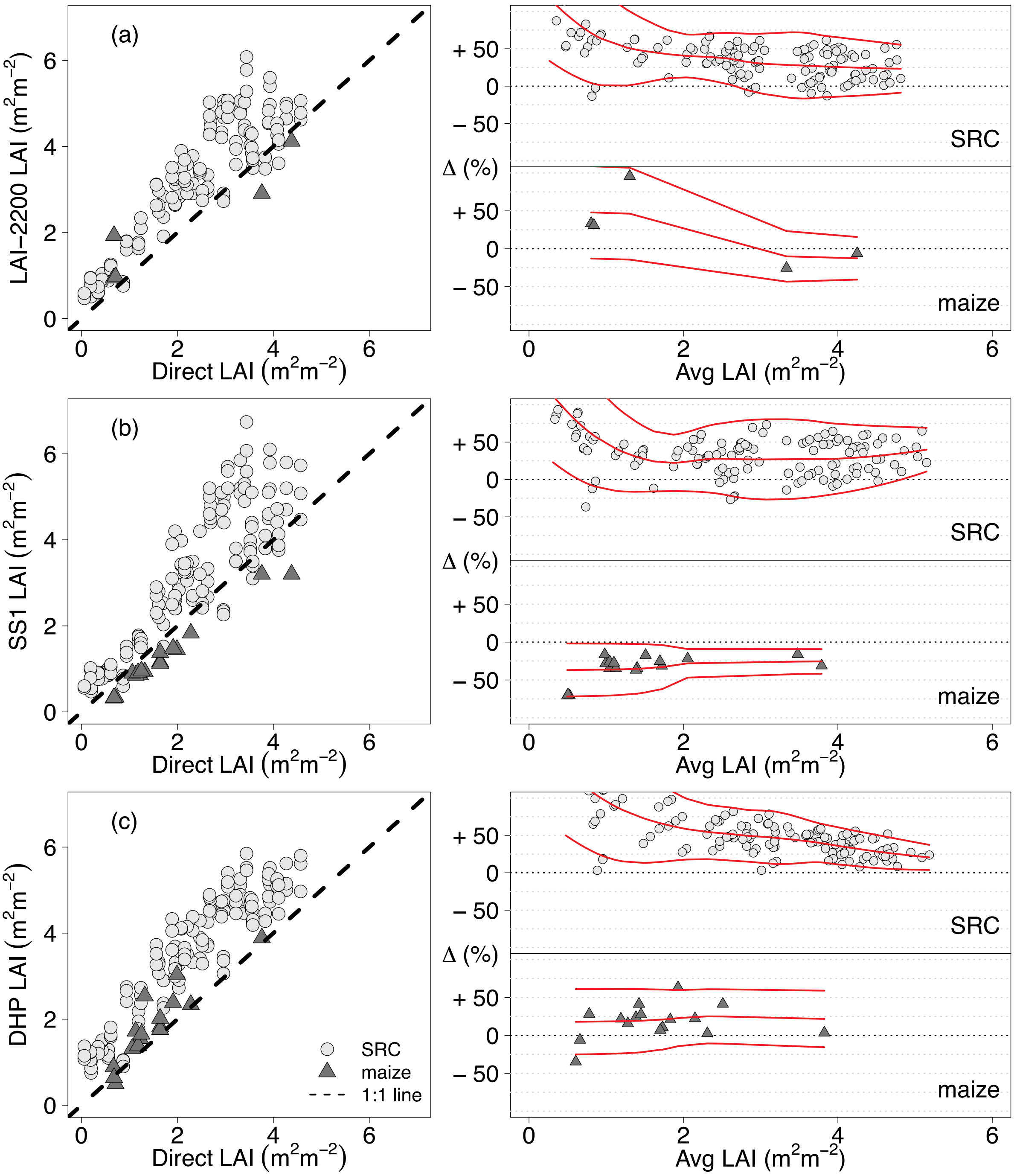

Fig. 3. Comparison of indirect *vs.* direct methods for leaf area index (LAI) estimations. Panels on the left (a–c) show the conventional x–y scatter-plots with LAI readings. Panels on the right show the Bland and Altman (B–A) plots separately for each canopy type and for each pair of methods. The horizontal axis in the B–A plots represents the averages of each pair of measurements, while the vertical axis indicates the percentage differences (Δ) for each pair of measurements, explaining an overestimation or underestimation if the percentage is positive or negative, respectively. Red smoothed lines denote the systematic error (bias) and limits of agreement. SRC: short rotation coppice.

Table 2. Results of the statistical analyses used for the inter-comparison between the three indirect methods and the comparison of the indirect with the direct methods (litter fall and harvest) in the four canopies studied (SRC, Scots pine, Pedunculate oak and maize field). The Bias column represents the constant (C) and proportional (P) systematic errors within their associated 95% confidence interval (CI) after judgement of the 0 and 1 values for the intercept and slope. N denotes the number of paired observations. Pearson's correlation (r) and intercept and slope coefficients of the simple linear regression $Y = a + bX$ were estimated through the Passing and Bablok (P–B) non-parametric procedure. Est, Low and Upp columns report the estimated, the lower and the upper 95% (CI), respectively, associated with intercept and slope. SRC: short rotation coppice.

X vs Y	Canopy	Bias	N	r	Intercept			Slope		
					Est	Low	Upp	Est	Low	Upp
LAI–2200 vs SS1	Short Rotation Coppice	C+P	251	0.94	−0.54	−0.70	−0.39	+1.15	+1.11	+1.20
	Scots pine	—	5	0.82	−0.91	n.a.	n.a.	+1.21	n.a.	n.a.
	Pedunculate oak	—	10	0.97	−0.40	−5.10	+2.02	+1.16	+0.71	+2.01
	Maize field	—	21	0.88	−0.53	−1.59	+0.75	+0.96	+0.64	+1.27
LAI–2200 vs DHP	Short Rotation Coppice	C	143	0.98	+0.49	+0.35	+0.63	+0.96	+0.93	+1.00
	Scots pine	—	6	0.88	+0.31	−2.50	+2.32	+0.97	+0.00	+2.41
	Pedunculate oak	C+P	10	0.96	+1.21	+0.58	+2.32	+0.72	+0.50	+0.88
	Maize field	—	17	0.91	+0.54	−0.64	+2.21	+0.93	+0.48	+1.28
DHP vs SS1	Short Rotation Coppice	C+P	171	0.96	−1.08	−1.24	−0.94	+1.21	+1.16	+1.27
	Scots pine	—	6	0.52	−0.87	n.a.	n.a.	+1.02	n.a.	n.a.
	Pedunculate oak	C+P	10	0.98	−2.41	−5.65	−1.16	+1.60	+1.29	+2.26
	Maize field	C	29	0.95	−0.53	−0.84	−0.25	+0.94	+0.84	+1.06
LAI–2200 vs Litter fall	Short Rotation Coppice	C+P	134	0.90	+0.47	+0.29	+0.61	+1.18	+1.08	+1.31
LAI–2200 vs Harvest	Maize field	—	5	0.93	+0.40	n.a.	n.a.	+0.80	n.a.	n.a.
DHP vs Litter fall	Short Rotation Coppice	C+P	133	0.93	+0.98	+0.84	+1.11	+1.12	+1.04	+1.20
DHP vs Harvest	Maize field	—		0.91	−0.16	−0.83	+0.29	+1.33	+0.96	+1.92

n.a. indicates not available value occurring when the procedure failed to converge because of small sample size.
r as well as the intercept and slope of the simple linear regression model were estimated according to the non-parametric P–B procedure.

3.2. X–Y scatter plot results between indirect and direct methods

The conventional x–y scatter plots for pairwise comparison of methods (left panels of both Figs. 2 and 3), showed some clear curvature. Among the indirect methods the best agreement was found between the LAI–2200 and DHP, as reflected by the data points close to the 1:1 line (Fig. 2b). The comparison of SS1 with the two other indirect methods yielded a more exponential curve, deviating from the 1:1 line (Fig. 2a and c). The comparison between the direct and the indirect methods showed a general overestimation in SRC and maize field canopies by all indirect methods, especially in the higher LAI range and in the SRC.

3.3. Bland and-Altman results between indirect and direct methods per canopy type

The B-A analysis for the inter-comparison of the indirect methods is depicted separately for each canopy type (right panels of Fig. 2). The main results are reported for each canopy type in terms of bias and of Limits of Agreements (LoA). Note that for low LAI values, small absolute differences resulted in high relative variations (in %), and consequently the LoA diverged.

First, in the SRC, the LAI measurements obtained with DHP and LAI–2200 agreed best, especially in the high LAI range, characterized by a low bias and narrow LoA. In the low-to-medium LAI range, however, DHP produced higher values than LAI–2200; some source of bias as well as diverging LoA were observed. SS1 yielded slightly lower values than LAI–2200 and DHP in the low and medium LAI ranges (up to 4–5 $m^2 m^{-2}$), but higher values in the high LAI range. Secondly, in the Pedunculate oak stand, a good level of agreement was observed between SS1 and LAI–2200 (low bias and relatively narrow LoA). Measurements with DHP in the low-to-medium LAI ranges were higher than the measurements obtained with SS1 and LAI–2200.

Thirdly, in the Scots pine stand, LAI–2200 and DHP were again in better agreement than compared to SS1, which produced lower values than the other two methods. Due to some instrument failure only few data were available for LAI–2200 in the low LAI range leading to a poor method comparability in the Pedunculate oak and in the Scots pine stands. Finally, in the maize field the three inter-comparisons showed the same tendency, *i.e.* that LoA diverged with decreasing LAI.

The B–A analysis was also performed for the comparison of the indirect and the direct methods in both the SRC and the maize field (Fig. 3, right panels). In the SRC all three indirect methods overestimated the direct method. The most biased indirect method was the SS1 method, showing a positive bias of 50% at low LAI values, which decreased to about 25% in the medium-to-high LAI range. On the contrary, LAI–2200 and DHP methods showed a decreasing bias when LAI increased. The bias in the indirect measurements corresponded to an average overestimation of the direct measurements with 0.5 to 2 $m^2 m^{-2}$.

In the maize field only few measurements were obtained with LAI–2200, showing a positive bias of more than 50% in the very low LAI range while for the medium LAI the LoA were closer to 0 as LAI increased. The DHP method only slightly overestimated the direct method (harvest), as shown by a small bias (Fig. 3c, right panel). On the other hand, SS1 underestimated the direct measurements by about 25% (Fig. 3b, right panel).

4. Discussion

Since direct measurements of LAI are destructive and labour-intensive, indirect methods to assess LAI offer an important alternative. All indirect methods are, however, affected by various factors, as the algorithms and approach used, radiation conditions and zenith angle at the time of measurements, canopy characteristics and clumping (Ryu et al. 2010a). In the current inter-comparison of three indirect methods to measure LAI the different outcome depended on the methods used and the canopy type studied.

4.1. Explaining the agreement and disagreement among canopy types

For all four canopy types, the DHP and LAI–2200 methods showed the best agreement, better than each of them compared with SS1. These findings are in line with a previous study (Fang et al. 2014), and may be explained by the similar approach for the clumping correction in both instruments. Differences between DHP and LAI–2200 in the low-to-medium range of LAI (similar to Homolová et al. 2007) may be explained by the gap fraction factor highly sensitive to canopy structure, by leaf distribution and leaf plasticity (Lopez-Lozano et al. 2007). This indicates that clumping at the shoot level might explain the differences between both instruments as documented for a mature Scots pine stand (Jonckheere et al. 2005).

A better agreement between all three indirect methods in the four canopy types was observed in the medium range of LAI. There was a discrepancy between SS1 and the two other indirect methods in both the low (underestimation) and high (overestimation) LAI ranges. The lower values obtained with the SS1 method in the low LAI range, can be explained by the fact that this method did not account for clumping, thus underestimating results (Jones 2014). Clumping factors calculated with the DHP and LAI–2200 methods varied between 0.85 and 0.96 depending on the canopy studied and the method used. These results were in agreement with a previous validation (Ryu et al. 2010a). The lack of a clumping correction in the SS1 method could, thus, only partly account for the observed differences. The higher values obtained with the SS1 method in the medium to high range were possibly related to the levelling-off effect at LAI 5-6 $m^2 m^{-2}$ in the LAI–2200 and DHP methods, caused by the gap fraction saturation (Gower et al. 1999; Leblanc et al. 2005). Finally, the discrepancy between the SS1 and the other indirect methods might also be due to the fact that the leaf angle distribution was *a priori* fixed in the SS1 method while it was calculated for each picture (DHP method) or for each set of measurements (LAI–2200 method).

4.2. Explaining the agreement and disagreement between indirect and direct methods

In the comparison of the indirect methods with the direct methods, the former overestimated the latter, with exception of SS1 in maize that showed an underestimation in the low-medium range of LAI. There was a clear difference between the two canopies tested, *i.e.* SRC and maize field. An exponential overestimation was found at the SRC (Fig. 3, right panels), which could be explained: (i) by the WAI in the SRC, and (ii) by the difference in the direct methods used. In the SRC the direct LAI was calculated from litter fall while in the maize field it was calculated from direct harvesting of all plant parts. In addition, the seasonal increment of the WAI in the SRC could explain the increasing difference between the indirect and direct methods. A previous study at the same site showed that the branch area increased with 0.60 m^2m^{-2} over three years (Broeckx et al. 2005). The systematic bias (of 25%) for the medium and high LAI values was in line with a previous report that woody material comprises 5% to 35% of the total PAI in forests (Gower et al. 1999).

The slight overestimations of the DHP method compared to the direct measurements in the maize crop agreed very well with earlier findings (Facchi et al. 2010) and might be explained by the presence of the large maize leaves. The underestimation of SS1 in maize was also observed in previous studies (*e.g.* Wilhelm et al. 2000) and was probably due to the lack of a clumping correction which explained the poor performance of SS1 at low LAI values and in row crops (Chiroro et al. 2006). The chosen ELADP for this canopy type may play an important role, and as the maize leaves change considerably along the growing season, the ELADP value may not have been accurate throughout the entire season (Fang, 2005).

5. Conclusions

Although indirect methods to estimate LAI have already been compared in previous studies, large uncertainties still remain. In the current study a standardized approach compared different indirect methods under contrasting canopies, and the results were validated with direct methods using more than one statistical analysis. The use of multiple instruments revealed, on the one hand, a considerable variability and thus, uncertainty in the measurements. On the other hand the approach helped to understand the factors determining LAI, such as the WAI and the degree of clumping, and how these factors differed among methods and canopies. It is, therefore, important to use more than one indirect method for measuring LAI. One suggestion for further research is that an improved hemispherical method is developed to indirectly measure LAI, which is able to simultaneously measure at different heights, providing information about clumping and leaf angle distribution. This improved method should furthermore enable to differentiate between non-green and woody parts of the canopy, by infrared techniques, as has been proposed (Jonckheere et al. 2004; Schaefer et al. 2015). For large-scale research infrastructures (as ICOS, LTER, ICP-Forests) a harmonized or standard protocol should enable LAI measurements that can be compared among canopy types, sites and temporal scales.

Acknowledgements

The research leading to the results of this study has received financial support of the Research Foundation-Flanders (FWO, contract # G0H3317N), of the University of Tuscia (Italy), of the Methusalem program of the University of Antwerp (Belgium) as well as of the European Commission's Horizon 2020 Research and Innovation Program ENVRIPLUS under grant agreement no. 654182. This study is part of the Ecosystem Thematic Center of the European ICOS infrastructure network. FDM acknowledges support from EU COST Action PROFOUND as a Short Term Scientific Mission under grant agreement FP1304.This study has formed the basis of the Master thesis of FDM under the supervision of DP and MODB. CAC and FDM collected and processed the data, and produced the various drafts of the manuscript contributing equally. All authors contributed in writing and revising the manuscript.

References

Alivernini, A., Fares, S., Ferrara, C., Chianucci, F., 2018: An objective image analysis method for estimation of canopy attributes from digital cover photography. Trees, 32:713–723.

Bland, J. M., Altman, D. G., 1986: Statistical methods for assessing agreement between two methods of clinical measurement. Lancet, 327:307–310.

Breda, N. J. J., 2003: Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. Journal of Experimental Botany, 54:2403–2417.

Broeckx, L. S., Verlinden, M. S., Ceulemans, R., 2012: Establishment and two-year growth of a bio-energy plantation with fast-growing *Populus* trees in Flanders (Belgium): effects of genotype and former land use. Biomass & Bioenergy, 42:151–163.

Broeckx, L. S., Vanbeveren, P. P. S., Verlinden, M. S., Ceulemans, R., 2015: First vs. second rotation of a poplar short rotation coppice: leaf area development, light interception and radiation use efficiency. iForest – Biogeosciences and Forestry, 8:565–573.

Carstensen, B., 2010: Comparing methods of measurement: Extending the LoA by regression. Statistics in Medicine, 29:401–410.

Chen, J. M. R., 1997: Leaf area index of boreal forests: Theory, techniques and measurements. Journal of Geophysical Research, 102:429–443.

Chen, J. M., Black, T. A., 1992: Defining leaf area index for non-flat leaves. Plant, Cell & Environment, 15:421–429.

Chen, J. M., Rich, P. M., Gower, S. T., Norman, J. M., Plummer, S., 1997: Leaf area index of boreal forests: Theory, techniques, and measurements. Journal of Geophysical Research: Atmospheres, 102:29429–29443.

Chianucci, F., Cutini, A., 2013: Estimation of canopy properties in deciduous forests with digital hemispherical and cover photography. Agricultural and Forest Meteorology, 168:130–139.

Chianucci, F., Disperati, L., Guzzi, D., Bianchini, D., Nardino, V., Lastri, C. et al., 2016: Estimation of canopy attributes in beech forests using true colour digital images from a small fixed-wing UAV. International Journal of Applied Earth Observation and Geoinformation, 47:60–68.

Chiroro, D., Milford, J., Makuvaro, V., 2006: An investigation on the utility of the SunScan ceptometer in estimating the leaf area index of a sugarcane canopy. Proceedings of the South African Sugar Technologists Association, 80:143–147.

Cleveland, W. S., 1979: Robust locally weighted regression and smoothing scatterplots. Journal of the American Statistical Association, 74:829–836.

Curiel, Y. J., Konôpka, B., Janssens, I. A., Coenen, K., Xiao, C. W., Ceulemans, R., 2005: Contrasting net primary productivity and carbon distribution between neighbouring stands of *Quercus robur* and *Pinus sylvestris*. Tree Physiology, 25:701–712.

Daughtry, C. S. T., 1990: Direct measurements of canopy structure. Remote Sensing Reviews, 5:545–60.

Duchemin, B., Hadriab, R., Errakib, S., Bouleta, G., Maisongrandea, P., Chehbounia, A. et al., 2006: Monitoring wheat phenology and irrigation in Central Morocco: On the use of relationships between evapotranspiration, crops coefficients, leaf area index and remotely-sensed vegetation indices. Agricultural Water Management, 79:1–27.

Facchi, A., Baroni, G., Boschetti, M., Gandolfi, C., 2010: Comparing optical and direct methods for leaf area index determination in a maize crop. Journal of Agricultural Engineering, 1:33–40.

Fang, F., 2005: The retrieval of leaf inclination angle and leaf area index in maize. Master of Science thesis, Geo-Information Science and Earth Observation for Environmental Modelling and Management program. University of Lund, Sweden, 64 p.

Fang, H., Li, W., Wei, S., Jiang, C., 2014: Seasonal variation of leaf area index (LAI) over paddy rice fields in NE China: Inter-comparison of destructive sampling, LAI-2200, digital hemispherical photography (DHP), and AccuPAR methods. Agricultural and Forest Meteorology, 198–199:126–14.

Gebauer, R., Cermak, J., Plichta, R., Spinlerova, Z., Urban, J., Volarik, D. et al., 2015: Within-canopy variation in needle morphology and anatomy of vascular tissues in a sparse Scots pine forest. Trees, 29:1447–1457.

Gielen, B., De Vos, B., Campioli, M., Neirynck, J., Papale, D., Verstraeten, A. et al., 2013: Biometric and eddy covariance-based assessment of decadal carbon sequestration of a temperate Scots pine forest. Agricultural and Forest Meteorology, 174–175:135–143.

Gower, S. T., Kucharik, C. J., Norman, J. M., 1999: Direct and indirect estimation of Leaf Area Index, f_{APAR}, and Net Primary Production of terrestrial ecosystems. Remote Sensing Environment, 70:29–51.

Homolová, L., Malenovský, Z., Hanuš, J., Tomášková, I., Dvořáková, M., Pokorný, R., 2007: Comparison of different ground techniques to map leaf area index of Norway spruce forest canopy. International Society for Photogrammetry and Remote Sensing (ISPRS), XXXVI, 499–504. [online] URL: http://www.isprs.org/proceedings/XXXVI/7-C50/papers/P95.pdf (accessed 15.01.2019).

Jonckheere, I., Fleck, S., Nackaerts, K., Muys, B., Coppin, P., Weiss, M. et al., 2004: Review of methods for in situ leaf area index determination. Part I: Theories, sensors and hemispherical photography. Agricultural and Forest Meteorology, 121:19–35.

Jonckheere, I., Muys, B., Coppin, P., 2005: Allometry and evaluation of in situ optical LAI determination in Scots pine: a case study in Belgium. Tree Physiology, 25:723–732.

Jones, H. G., 2014: Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology. Third edition, Cambridge University Press, NY, USA.

Konôpka, B., Pajtík, J., 2014: Similar foliage area but contrasting foliage biomass between young beech and spruce stands. Lesnícky časopis - Forestry Journal, 60:205–213.

Lang, A. R. G., Xiang, Y., 1986: Estimation of leaf area index from transmission of direct sunlight in discontinuous canopies. Agricultural and Forest Meteorology, 37:229–243.

Leblanc, S. G., Chen, J. M., Fernandes, R., Deering, D. W., Conley, A., 2005: Methodology comparison for canopy structure parameters extraction from digital hemispherical photography in boreal forests. Agricultural and Forest Meteorology, 129:187–207.

Lin, A., Zhu, H., Wang, L., Gong, W., Zou, L. 2016: Characteristics of long-term climate change and the ecological responses in central China. Earth Interactions, 20:1–24.

Lopez-Lozano, R., Baret, F., Chelle, M., Rochdi, N., España, M., 2007: Sensitivity of gap fraction to maize architectural characteristics based on 4D model simulations. Agricultural and Forest Meteorology, 143:217–229.

Mason, G. E., Diepstraten, M., Pinjuv, G. L., Lasserre, J-P., 2012: Comparison of direct and indirect leaf area index measurements of *Pinus radiate* D. Don. Agricultural and Forest Meteorology, 166–167:113–119.

Macfarlane, C., Hoffman, M., Eamus, D., Kerp, N., Higginson, S., McMurtrie, R. et al., 2007: Estimation of leaf area index in eucalypt forest using digital photography. Agricultural and Forest Meteorology, 143:176–188.

Op de Beeck, M., Gielen, B., Jonckheere, I., Samson, R., Janssens, I. A., Ceulemans, R., 2010: Needle age-related and seasonal photosynthetic capacity variation is negligible for modelling yearly gas exchange of a sparse temperate Scots pine forest. Biogeosciences, 7:199–215.

Passing, H., Bablok, W., 1983: A new biometrical procedure for testing the equality of measurements from two different analytical methods. Application of linear regression procedures for method comparison studies in clinical chemistry, Part I. Journal of Clinical Chemistry and Clinical Biochemistry, 21:709–720.

Ridler, T. W., Calvard, S., 1978: Picture thresholding using an iterative selection method. IEEE Transactions on System, Man and Cybernetics, 8:630–632.

Ryu, Y., Nilson, T., Kobayashi, H., Sonnentag, O., Law, BE., Baldocchi, D. D., 2010a: On the correct estimation of effective leaf area index: Does it reveal information on clumping effects? Agricultural and Forest Meteorology, 150:463–472.

Ryu, Y., Sonnentag, O., Nilson, T., Vargas, R., Kobayashi, H., Wenk, R. et al., 2010b: How to quantify tree leaf area index in an open savanna ecosystem: a multi-instrument and multi-model approach. Agricultural and Forest Meteorology, 150:63–76.

Schaefer, MT., Farmer, E., Soto-Berelov, M., Woodgate, W., Jones, S., 2015: Overview of ground based techniques for estimating LAI. In: Held, A., Phinn, S., Soto-Berelov, M. & Jones, S. (eds.): AusCover Good Practice Guidelines: A technical handbook supporting calibration and validation activities of remotely sensed data product, 88–118. Version 1.1. TERN AusCover, ISBN 978-0-646-94137-0.

Scrucca, L., 2011: Model-based SIR for dimension reduction. Computational Statistics & Data Analysis, 55:3010–3026.

Sone, C., Saito, K., Futakuchi, K., 2009: Comparison of three methods for estimating leaf area index of upland rice cultivars. Crop Science, 49:1438–1443.

Thimonier, A., Sedivy, I., Schleppi, P., 2010: Estimating leaf area index in different types of mature forest stands in Switzerland: a comparison of methods. European Journal of Forest Research, 129:543–562.

Verlinden, M. S., Broeckx, L. S., Ceulemans, R., 2015: First vs. second rotation of a poplar short rotation coppice: Above-ground biomass productivity and shoot dynamics. Biomass & Bioenergy, 73:174–185.

Webb, N., Nichol, C., Wood, J., Potter, E., 2013: User Manual for the SunScan Canopy Analysis System type SS1 Version: 3.0, Delta-T Devices Ltd. 37–39: 49–56. [online] URL: http://www.delta-t.co.uk/wp-content/uploads/2016/10/SS1-SunScan-User-Manual-v2-0.pdf (accessed 15.01.19).

Weiss, M., Baret, F., Smith, G. J., Jonckheere, I., Coppin, P., 2004: Review of methods for in situ leaf area index (LAI) determination. Part II: Estimation of LAI, errors and sampling. Agricultural and Forest Meteorology, 121:37–53.

Wilhelm, W., Ruwe, K., Schlemmer, M. R., 2000: Comparison of three leaf area index meters in a corn canopy. Crop Science, 40:1179–1183.

Woodgate, W., Jones, S. D., Suarez, L., Hill, M. J., Armston, J. D., Wilkes, P. et al., 2015: Understanding the variability in ground-based methods for retrieving canopy openness, gap fraction, and leaf area index in diverse forest systems. Agricultural and Forest Meteorology, 205:83–95.

Zheng, G. and Moskal, L. M., 2009: Retrieving Leaf Area Index (LAI) using remote sensing: theories, methods and sensors. Sensors, 9:2719–2745.

Other resources:

GCOS, 2011: Systematic Observation Requirements for Satellite-based Data Products for Climate. WMO, Switzerland. [online] URL:http://www.wmo.int/pages/prog/gcos/Publications/gcos-154.pdf (accessed 15.01.2019).

ICOS Ecosystem Thematic Center. [online] URL: http://www.icos-etc.eu/icos/ (accessed 15.01.2019).

LI-COR, 2009. LAI–2200 Plant Canopy Analyzer Instruction Manual. Lincoln, NE, USA. [online] URL: https://www.licor.com/documents/6n3conpja6uj9aq1ruyn (accessed 15.01.2019).

POPFULL Project. [online] URL: http://uahost.uantwerpen.be/popfull/ (accessed 15.01.2019).

Appendix text and tables

Appendix text 1. Theory of leaf area index calculation

In-situ indirect measurements of LAI with optical instruments are based on a statistical and probabilistic approach of the distribution and arrangement of foliar elements (or their complement, the gap fraction) in the canopy. Two theoretical approaches have been developed to infer LAI from optical measurements. With the first approach, LAI is estimated by inversion of the exponential expression of the gap fraction (Eq. 1), *i.e.* by solving the expression for L (Eq. 2):

$$P(\theta) = e^{-G(\theta,\,\alpha)\,\Omega\,(\theta)L/\cos\theta} \quad [1]$$

$$L = -(\ln P(\theta)\cos\theta) \,/\, G(\theta)\,\Omega\,(\theta) \quad [2]$$

where $P(\theta)$ is the gap fraction, L is the LAI, θ is the zenith angle of view, α is the leaf angle, $G(\theta,)$ corresponds to the fraction of foliage projected on the plane normal to the zenith direction, and $\Omega(\theta)$ is the clumping coefficient, which corrects for a deviation from the assumption of random (Poisson) distribution of canopy elements. When the foliage is randomly distributed within the canopy, $\Omega(\theta) = 1$, but as the foliage becomes more clumped, $\Omega(\theta) < 1$. The function $G(\theta, \alpha)$ depends on leaf angle distribution, which is generally not known a priori. The calculation of LAI therefore requires gap fraction measurements for a range of zenith angles of view.

The second approach is based on the Beer-Lambert extinction law expanded to plant canopies. This law expresses the attenuation of radiation in a homogenous turbid medium. In such a medium the flux is proportionally absorbed to the optical distance. Assuming a random (Poisson) distribution of leaves within the canopy:

$$I = I_0\, e^{(-kL)} \quad [3]$$

where I_0 is the incident radiation above the canopy, I is the radiation transmitted below the canopy, and k is the extinction coefficient, which depends on the leaf angle distribution and on the direction of the beam (*e.g.* $k = 1$ for entirely horizontal leaves). I/I_0 is theoretically equivalent to the gap fraction in Eq. 1*, i.e.* P(θ).

Whichever approach used, when applied to canopies with a significant woody-to-total plant area ratio, L represents an overestimation of LAI because of the presence of light-blocking non-leaf and non-green elements. Consequently L provides an estimation of PAI rather than of LAI. To obtain LAI, a woody element correction factor has been introduced (Chen 1997):

$$LAI = L\,(1 - \alpha) \quad [4]$$

where $0 \le \alpha \le 1$ is the proportion of woody-to-total plant area. Formally α = WAI/PAI where WAI is the wood area index, which can be estimated from destructive sampling by calculating the sum of the hemi-surface area of all branches and stems or taken from the literature, if available.

Appendix text 2. Statistical analyses

The Passing & Bablok (1983) regression is based on a robust, non-parametric model and is, unlike the Ordinary Least Squares (OLS) regression, not sensitive towards outliers. It assumes that measurement errors of both methods (direct and indirect) have the same distribution. The 95% confidence intervals (CI) of the intercept and slope terms of the Passing and Bablok regression equation $y = a + bx$ were interpreted to reveal a constant or a proportional bias. If the 95% CI for the intercept included the zero value, it could be concluded that there was no significant constant bias. If the 95% CI for the slope included 1 as a value, it could be concluded that there was no significant proportional bias. When both conditions were met, one could assume that $y = x$ and that there was no statistically significant difference between the two compared methods. In this latter case the two compared methods could be used interchangeably. In the present study the Passing and Bablok regressions were estimated through the PBreg function of the R MethComp package (Cartensen 2010).

The Bravais-Pearson correlation coefficient (r), which measures the strength of the linear relationship and which was calculated per canopy type, helped the understanding of the previous analysis. This method had to be carefully interpreted as the high r value was not a sufficient condition to affirm that two methods were in agreement; it simply showed the presence of a strong linear relationship between the two methods.

The Bland & Altman (1986) approach involves a graphical method (hereafter denoted as the B–A plot) consisting of a scatter plot where the difference between each pair of measurements is plotted against the average of each pair of measurements. The mean of the differences is shown on the plot as a reference line indicative of the systematic error (or bias). The 95% limits of agreement (LoA), which are calculated as the mean of the differences $\pm$1.96 standard deviation (SD) of the differences, quantify the range of variability (*i.e.* precision) between the two measurements. LoA can be evaluated or compared with pre-determined limits to enable the researcher to decide whether given techniques have an acceptable agreement or repeatability. Therefore, assuming a negligible bias, the smaller the LoA, the better the agreement is. In this study an approach based on regressing the relative (%) differences to the averages was used, and the resulting equation was used to evaluate both the bias and the LoA. The relation between the relative LAI differences and the averages of the differences was estimated through a locally weighted scatterplot smoothing (LOWESS, Cleveland 1979). This is a non-parametric method, which combines much of the simplicity of linear least squares regression with the flexibility of non-linear regression. Fitting is done locally, i.e. at each point x in the range of the data set a low-degree polynomial is fitted to a subset of the data using points in a neighbourhood of *x*, weighted by their distance from *x*. The LOWESS curve was computed through the *loees.sd* function implemented in the *msir R* package (Scrucca 2011).

Table A1. Abbreviations and symbols – in the main text

Abbreviation	Definition	Additional information
ACF	Apparent Clumping Factor	—
B–A	Bland and Altman	Statistical analysis
CI	Confidence Interval	Part of the Passing & Bablok statistical analysis
DHP	Digital Hemispherical Photography	Leaf area index indirect method used in this study
ELADP	Ellipsoidal Leaf Angle Parameter	—
LA	Total Leaf Area	—
LAI	Leaf Area Index	—
LAI–2200	LAI–2200 Plant Canopy Analyzer	Leaf area index indirect method used in this study
LAI_{max}	Maximum LAI	—
LoA	Limits of Agreement	Part of the Bland & Altman statistical analysis
PAI	Plant Area Index	—
PAR	Photosynthetically Active Radiation	—
P-B	Passing & Bablok	Statistical analysis
OLS	Ordinary Least Squares regression	Part of the Passing & Bablok statistical analysis
SLA	Specific Leaf Area	—
SRC	Short Rotation Coppice	—
SS1	SunScan Canopy Analysis System	Leaf area index indirect method used in this study
TLS	Terrestrial Laser Scanning	—
UAV	Unmanned Aerial Vehicle	—

Table A2. Abbreviations and symbols – in the Appendix text

Abbreviation	Definition	Additional information
C	Constant	—
$G(\theta, \alpha)$	Fraction of foliage projected on the plane normal to the zenith direction	—
I	Radiation transmitted	—
r	Bravais-Pearson correlation coefficient	—
I/I_0	Theoretically equivalent to the gap fraction	—
K	Extinction coefficient	—
L	The LAI	Represents LAI in the equation
P	Proportional	—
$P(\theta)$	The gap fraction	—
SD	Standard Deviation	—
Θ	The zenith angle of view	—
$\Omega(\theta)$	Clumping coefficient	—
α	The leaf angle	—

Cent. Eur. For. J. 65 (2019) 81–91 sciendo DOI: 10.2478/forj-2019-0006

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Analysis of natural-production conditions for timber harvesting in European North of Russia

Ilya Shegelman[1], Pavel Budnik[1, *], Vyacheslav Baklagin[2], Oleg Galaktionov[1], Ivan Khyunninen[1], Artem Popov[1]

[1] *Petrozavodsk State University, Lenin Str., 33, 185910, Petrozavodsk, Russia*
[2] *Northern Water Problems Institute of the Karelian Research Centre of the Russian Academy of Sciences, Aleksander Nevsky Str., 50, 185030, Petrozavodsk, Russia*

Abstract

Natural-production conditions determine operational efficiency of logging machines. This influence needs to be taken into account at different levels of forest management. It is necessary to allocate areas with similar natural-production conditions for effective forest management. It allows simplifying the decision making process for selecting logging technology and machines. The purpose of this study was to establish areas with similar natural and production conditions in the European North of Russia (ENR). In addition, for small enterprises, we recommend logging technologies and logging machines that can be used in established areas. We determined the indicators of the natural-production conditions of ENR regions and compared them. Cluster analysis was used to compare the indicators. We found that ENR can be divided into three main zones A, B, C and two subzones B1 and B2 with similar natural-production conditions. In the zones A, B and the subzones B1 and B2, small logging enterprises should use a harvester and a forwarder. In the zone C, the enterprises can use a logging system including a harvester and a forwarder or a logging system including a feller buncher, a skidder and a processor. The logging system should be based on the light class of logging machines for the zone A, the medium class or the heavy class for the zones B, C and the subzones B1, B2, the heavy class of machines for the zone C.

Key words: natural-production conditions; tree size; relief; soil conditions; timber volume; forest species composition, logging machines, cluster analysis

Editor: Tomáš Hlásny

1. Introduction

Natural and production conditions determine operational efficiency of logging machines (Häggström et al. 2016; Alam et al. 2014; Nurminen et al. 2006). This influence needs to be taken into account at different levels of forest management: operational, tactical and strategic.

In order to assess the influence of natural-production conditions it is necessary to define the factors of such impact. It can be performed based on analysis of studies regarding the impact of natural-production conditions on operational efficiency of logging machines.

The influence of timber volume per hectare (ha), sizes of trees on the efficiency of harvester has been studied rather thoroughly (Kormanek et al. 2018; Laitila et al. 2013; Jiroušek et al. 2007; Ovaskainen et al. 2005; Kärhä et al. 2004; Eliasson 1998; Glöde 1999). These studies indicate that harvester efficiency increases with the increase of tree size. However such increase is not endless. For certain models of machines there are specific tree sizes the increase of which leads not to efficiency improving, but – on the contrary – to its loss (McNeel & Rutherford 1994; Kärhä et al. 2004).

Numerous research works reveal that there is a growth of diesel fuel consumption with the increase of sizes of treated trees and their species (Kellogg et al. 1994; Ackerman et al. 2017).

Large-size tree trunks can be a severe restriction to logging with the use of logging machines. For example, large trees and small timber volume per ha is a serious problem for using harvesting machines in rainforests (Castro et al. 2016).

The influence of timber volume per ha and sizes of trees on the operation of forwarders has been extensively studied (Kellogg & Bettinger 1994; Tufts & Brinker 1993). The studies show that the efficiency of forwarders increases with the increase of timber volume per ha and sizes of trees.

*Corresponding author. Pavel Budnik, e-mail: budnikpavel@yandex.ru, phone: +79 535 281 068

When it comes to the efficiency of timber harvesting, soil conditions are often determinant (Proto et al. 2018; Rozītis et al. 2017). The speed of skidding machine depends on the quality of skidding road surface. When skidding or transporting wood on soils with low bearing capacity, a track appears fast thus increasing resistance to motion. It leads to decline in productivity, fuel consumption increase and growth of the load on transmission.

A lot of works give evidence of negative impact of logging machines on soil during the process of timber harvesting (Klaes 2016; Reza et al. 2009; Schack-Kirchner et al. 2007). The negative impact is expressed in tracking and soil panning, preventing further timber regeneration. Waterlogged soils are especially vulnerable to such harm.

Relief of the terrain markedly affects the efficiency of logging machines and imposes restrictions upon their use (Strandgard et al. 2017; Tiernan et al. 2004). For instance, excavator-based harvesters are uncommonly used in Finland and Russian north despite their advantages over harvesters with specialized chassis (Palander et al. 2012, Bergroth et al. 2006; Wang et al. 2002). This is mainly due to restrictions on the use of such machines, even on small slopes.

Species of wood have structure and development specifics that substantially influence operational efficiency of logging machines. Therefore, species composition of stands shall be considered when analyzing natural-production conditions. Besides, species composition determines economic value of a forest stand. Economic value of woods depends on a wide range of factors: structure of stand, age, conditions of habitat and others. In the European part of Russia coniferous forests are more valuable and spreading than deciduous. Economic value of forest stand defines a forest entrepreneur's possibilities to use more progressive machinery with the highest efficiency relating to performance and environmental safety at the expense of generated profits.

Peculiarities of species structure mostly influence operational efficiency of logging machines performing the following operations: felling, limbing, length bucking. Species' influence on operational efficiency of logging machines has been studies not so extensively as other earlier mentioned factors of natural-production conditions (Pētersons 2014). In general, many specialists have acknowledged that operation of logging machines is more productive and less problematic in coniferous forest stands than in deciduous forest stands.

Taking into account the influence of natural and production conditions of logging requires a high level of forest management. This implies the ability to analyze a large amount of information and make management decisions based on the analysis. In addition, a high degree of awareness of natural and production conditions of the forest resource base of the enterprise is required. Therewith it requires a wide fleet of logging machines, which gives the possibility to choose the most suitable logging machines for the specific area of the forest resource base.

This approach in forest management can be implemented in large enterprises. Small enterprises cannot take this approach. As a rule, they are contractors and their fleet includes one or two complexes. There is limited information on studies in substantiation of logging technology and logging machines for such enterprises. In Russia, the problem is complicated by the fact that small enterprises have to work in forest areas that are located in different subjects of the Russian region, and sometimes even in neighboring subjects of Russia. Thus, taking into account the size of the subjects of the Russia, enterprises operate in various natural and production conditions but are forced to use a limited fleet of logging machines.

We suppose that for small enterprises logging technology and logging machines should be universal and provide an opportunity to work in forest areas with a wide variety of natural and production conditions. However, at the same time, it is necessary to ensure that the technical characteristics of the logging machines are not excessive. For example, the use of logging machine in a small forest, which is designed to work in a large forest.

This approach can be implemented by solving the following tasks. First, territories with similar natural and production conditions should be allocated. At the same time, the allocated territories should be comparable in scale with forest areas, which the enterprises work. It allows simplifying the decision making process for selecting logging technology and machines. Secondly, the development of general recommendations on the applied logging technologies and logging machines for the allocated territories.

At the same time, we suppose that an objective approach to solving these problems can be the use of weighted average values that characterize the natural and production conditions of the allocated territories and variance of the values. This approach allows ensuring the universality of the selected technologies and logging equipment, as well as the use of logging machines with non-excessive technical characteristics.

The latest definition of territories with similar natural-production conditions in Russia was carried out in the eighties of the last century (Vinogorov 1986). The study was performed on the scale of the Soviet Union. Sizes of trees in forest stand and relief were the main indicators of natural-production conditions. However, the above research shows that it is necessary to take into account a greater number of natural-production conditions indicators. A number of other factors shall be also taken into account: soil conditions, timber volume per hectare, species composition of stands, location of merchantable forest and its accessibility. Besides, Vinogorov's work (1986) does not consider specific features of certain regions.

The purpose of this study was to establish areas with similar natural and production conditions in the European North of Russia (ENR). In addition, the aim of the study was to develop recommendations for the use of logging technologies and logging machines for the established areas.

2. Materials and methods

2.1. Study outline and methods

The researches have included the following steps: 1) collecting data for defining natural-production conditions indicators of ENR; 2) comparing of the indicators and identifying zones with similar the natural-production conditions; 3) confronting of technical characteristics of logging machines with natural-production conditions and development of recommendations for using logging machines in the identified zones.

The step 2 contained three sub-steps. We calculated the values of the indicators at the first sub-step. At the second sub-step, we combined indicators into sets describing various aspects of natural-production conditions. At the third sub-step, we compared the sets and based on this identified zones with similar natural-production conditions. Tree clustering analysis was applied in the third sub-step. We employed single linkage for the linkage rules and Euclidean distances (ED). Tree clustering analysis was performed using STATISTICA on a PC.

The step 3 contained four sub-steps. We collected data on the technical characteristics of logging machines and data on their application at the first sub-step. At the second sub-step, we determined the feasibility of using models of logging machines in conditions of the identified zones. At the third sub-step, we divided logging machines into classes depending on its technical characteristics. At the last sub-step, we have developed recommendations for using the models of logging machines in the identified zones.

Method of expert evaluation was used in the step 3. The method had two stages. At the first stage, we determined the possibility of using the models of logging machines in the conditions of identified zones. To do this, we compared the technical characteristics of logging machines models and the natural-production conditions of zones. We took into account the recommendations of the manufacturer of the models of logging machines and information about their application. At the second stage, experts were involved. The experts were logging foremen and operators of logging machines. Each expert was invited to evaluate and comment on the results obtained in the first stage. The results were then analyzed and summarized.

2.2. Study region

Study region is European North of Russia (Fig. 1). ENR includes: Murmansk Region, the Republic of Karelia, Arkhangelsk Region, Vologda Region, Komi Republic, Nenets Autonomous Area. More than 40% of forest resources of Russian European part are concentrated on the territory of ENR, and forest and woodworking industries are among the main ones in the economic structure.

Fig. 1. Location of the ENR regions.

This study has not considered Nenets Autonomous Area. The reason for this is that timber resources of 18.2 mln. m^3 are negligible in comparison with the other regions included into ENR. Besides Nenets Autonomous Area scarcely carries our works on timber harvesting. As reported by the Federal Forestry Agency felling volume in 2017 will be only 1.9 thous. m^3.

Fig. 2 shows comparative diagrams of timber resources and the intensity of timber harvesting in ENR regions.

More than half of timber resources in ENR are situated in Komi Republic – 3 114 mln. m^3 and Arkhangelsk Region – 2 688 mln. m^3 (Fig. 2A). However, in the context of timber harvesting and applied machines, it is reasonable to assess timber resources in mature and old growth forests, situated on the territory of merchantable forests. According to the RF legislation industrial harvesting are conducted in merchantable forests. In total timber resources of Komi Republic 65% fall to the share of mature and old growth forests in merchantable forests. In other ENR regions this share is less than 50%: Arkhangelsk Region – 46%, Vologda Region – 48%. In the Republic of Karelia only 29% fall to the share of mature and old growth forests in merchantable forests.

Utilization rate of timber resources can be evaluated based on felling volume and annual allowable cut use. Annual allowable cut is a scientifically grounded volume of sustainable yield.

According to the Federal Forestry Agency the largest wood volume in 2017 was harvested by Vologda and Arkhangelsk Regions – 15.6 mln. m^3 and 12.7 mln. m^3, respectively (Fig. 2B). Despite the greatest timber resources in mature and old growth forests in merchantable forests among other ENR regions, Komi Republic takes the third place in felling volume – 8.7 mln. m^3. It is basically explained by lower intensity of timber harvesting in the republic. Thus, when the share of annual allowable cut development in Arkhangelsk Region, Vologda Region and the Republic of Karelia is more than 50%, it is only 27% in Komi Republic (Fig. 2C). The Republic of Karelia has the highest percentage of annual allowable cut development – 64 %.

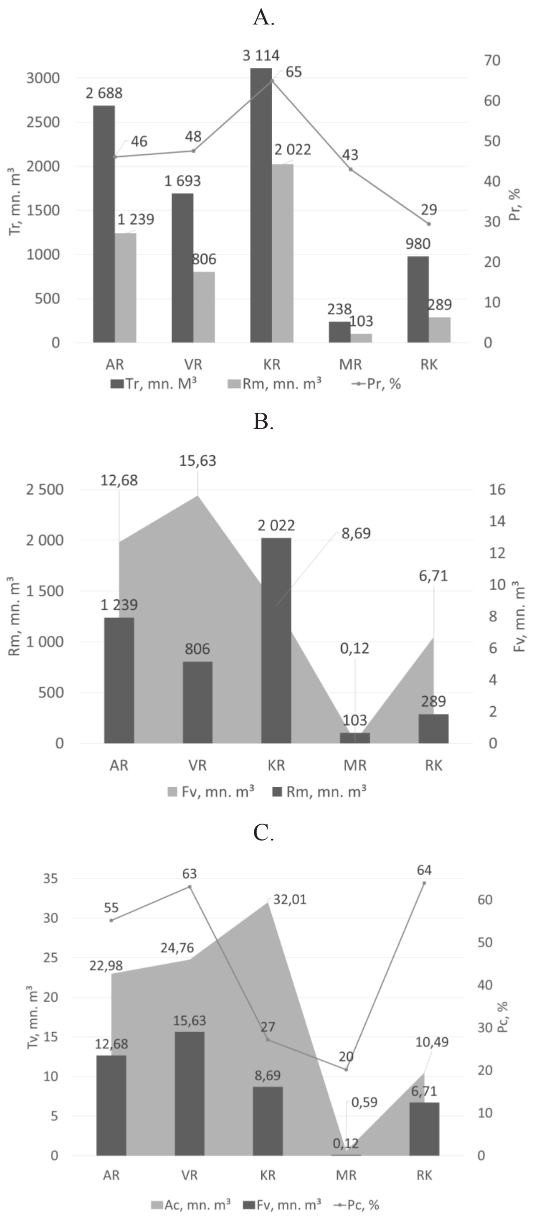

Fig. 2. Comparative diagrams of timber resources and the intensity of timber harvesting in ENR regions where A distribution of timber resources and resources of mature and old growth forests in merchantable forests, B distribution of resources of mature and old growth forests in merchantable forests and felling volumes in 2017, C distribution of resources of mature and old growth forests in merchantable forests and felling volumes in 2017, *Tr* timber resources, *Pr* percent of resources of mature and old growth forests in merchantable forests in timber resources, *Rm* resources of mature and old growth forests in merchantable forests, *Fv* felling volumes in 2017, *Tv* timber volume, *Pc* percent of reclaiming of annual allowable cut, *Ac* annual allowable cut, *AR* Archangelsk region, *VR* Vologda Region, *KR* Komi Republic, *MR* Murmansk region, *RK* The Republic of Karelia.

2.3. Indicators of natural-production conditions

We propose to compare natural-production conditions of ENR regions by comparing a number of indicators. Table 1 shows the list of indicators and their values for ENR regions. Table 2 shows sources of indicators data.

Table 1. The list of natural-production conditions indicators.

No	Indicator	Unit	Indicator values: Murmansk Region	The Republic of Karelia	Arkhangelsk Region	Komi Republic	Vologda Region
1	Average diameter of forest stands	[cm]	20	22	21	22	20
2	The most common class diameter		12	16	16	20	16
3	Maximum diameter class		48	56	52	56	52
4	Average volume of stem	[m³]	0.2	0.2	0.2	0.2	0.3
5	Maximum volume of stem		0.2	0.3	0.3	0.4	0.42
6	Minimum volume of stem		0.2	0.1	0.2	0.1	0.3
7	Average height of trees	[m]	18	21	21	21	25
8	Quality class		5	4	4	4	3
9	Slope ratios Up to 15 degrees	[%]	99.9	100	100	99.8	100
10	Slope ratios 16–25 degrees		0.1	0	0	0.2	0
11	Slope ratios 26 and more degrees		0	0	0	0	0
12	Ratios of class 1 of soil conditions		16	8	3	4	1
13	Ratios of class 2 of soil conditions		74	32	27	30	32
14	Ratios of class 3 of soil conditions		3	38	30	18	34
15	Ratios of class 4 of soil conditions		7	22	40	48	33
16	Timber volume per ha	[m³]	44	102	120	101	168
17	Minimal timber volume per ha		29	70	81	57	126
18	Maximal timber volume per ha		53	200	275	160	229
19	Proportion of pine in the stand	[%]	53.8	52.4	21.9	27.4	23.4
20	Proportion of spruce in the stand		34.7	35.9	65.1	66.5	26.8
21	Proportion of birch in the stand		11.5	9.9	10	0.2	36.1
22	Proportion of aspen in the stand		0	1.7	2.6	3.8	12.2
23	Proportion of other species in the stand		0	0.1	0.4	2.1	1.5
24	Automobile roads spacing, km of roads per 1 thous. ha of forest area		0.8	1.84	1.5	1.27	3.1

Average volume of stem (indicator 4) has been calculated based on forest taxation data of the forest areas included into the respective ENR regions according to the expression:

$$q_{av} = \sum_{i=1}^{n} \frac{Q_i \cdot q_{avi}}{\sum_{i=1}^{n} Q_i} \qquad [1]$$

where q_{av} – average volume of stem in the region, Q_i – timber resources in merchantable forest for the *i*-th forest area of the certain ENR region, q_{avi} – average volume of stem for the *i*-th forest area, *n* – total number of forest areas in the region.

Maximum volume of stem (indicator 5) is the largest value of q_{avi}. Minimum volume of stem (indicator 6) is lowest value of q_{avi}.

Mean height of forest stands (indicator 7) has been defined as per appraising scale applied in the RF, where, average site quality of forest and the determined felling age as per dominant coniferous species have been the input information. For this purpose data on the classification of stands in merchantable forests by site qualities and information about planned felling age have been collected and analyzed.

Table 2. Sources of natural-production conditions indicators.

No	Indicator name	Unit	Sources
1	Average diameter of forest stand	[cm]	Diameter distribution data given in Vinogorov's work (1972)
2	The most common class diameter		
3	Maximum diameter class		
4	Average volume of stem	[m^3]	Forest plans of the constituents of the RF, Komi Republic geoportal (gis.rkomi.ru)
5	Maximum volume of stem		
6	Minimum volume of stem		
7	Mean height of forest stands	[m]	—
8	Quality class		Freely available data of The Federal Forestry Agency of Russia
9	Slope ratios Up to 15 degrees	[%]	The data given in Lyumanov's work (1990) and specified according to the information from forest plans, physical, landscape and soil maps.
10	Slope ratios 16–25 degrees		
11	Slope ratios 26 and more degrees		
12	Ratios of class 1 of soil conditions		
13	Ratios of class 2 of soil conditions		
14	Ratios of class 3 of soil conditions		
15	Ratios of class 4 of soil conditions		
16	Timber volume per ha	[m^3]	Forest plans of the constituents of the RF
17	Minimal timber volume per ha		
18	Maximal timber volume per ha		
19	The proportion of pine in the stand	[%]	The schematic maps of forests distribution by dominant species, forest plans of the constituents of the RF
20	The proportion of spruce in the stand		
21	The proportion of birch in the stand		
22	The proportion of aspen in the stand		
23	The proportion of other species in the stand		
24	Automobile roads spacing, km of roads per 1 thous. ha of forest area		Allocation maps of leases of forest resources in forest areas, schematic maps of annual allowable cut use in forest areas, schematic maps of the current road networks, forest plans of the constituents of the RF

The indicators 12–15 shows ratios of soil conditions classes. Class 1 includes dry sands and stony soils. Under class 1 works on felling area can be performed throughout the year almost without restrictions. Class 2 includes sandy-loam soils and fine loam soils. Under the conditions of class 2 works in felling area are limited during spring and autumn time of impassable roads due to the decrease of bearing capacity of soils. Class 3 includes clayed soils, sand loams with clay courses. Such soils have high contents of moisture during whole warm season. Working under such conditions machines ruin surface soil fast and form track pits. Class 4 includes peat-bog and humus gley soils. They become impassable during the periods of steady rains, and have low bearing capacity during dry season.

Timber volume per ha (indicator 16) for ENR regions has been determined according to the expression:

$$SV = \sum_{i=1}^{n} Q_i \Big/ \sum_{i=1}^{n} S_i \qquad [2]$$

where SV – average timber volume per ha, S_i – area of the i-th forest area.

Indicator 17 is lowest value of timber volume per ha for i-th forest areas in the region. Indicator 18 is largest value of timber volume per ha for i-th forest areas in the region.

We conducted an analysis of the natural-production conditions by comparing sets of indicators. The description of the sets is given in Table 3.

Table 3. List of indicator sets.

Set name	Indicators	Description
NPS	all	The set characterizes the natural-production conditions on the basis of all indicators
ATD	4, 8, 16, 19–23	The set characterizes the average taxation data of forest stands (forest value)
TMed	1, 4, 7	The set characterizes the size of medium tree
TMax	3, 5, 7	The set characterizes the size of maximum tree
CLC	9–15	The set characterizes soil conditions and land form conditions
SC	19–23	The set characterizes species composition

2.4. Classification of timber harvesting machines

Two systems of logging machines are most common in Russia (Goltsev at al., 2011). The first system (HF) includes a harvester and a forwarder. The second system (FSP) includes a feller buncher, a skidder and a processor. Two types of skidders are used in Russia: with arch grapple and clambunk skidders. Excavator-based harvesters are often used as processors.

We separate three classes of logging machines: light (L), medium (M) and heavy (H). The technical characteristics of the classes are given in Table 4.

Logging machines on a wheeled chassis and on tracked chassis are used on forest harvesting. Logging machines on a wheeled chassis have 4×4, 6×6 and 8×8 axle configuration and can have antiskid chains. Some forest machines used in Russia have complicated cab leveling systems and system of self-propelled chassis active stabilization.

Table 4. Technical characteristics of logging machines classes.

Name of the timber harvesting machine	Technical characteristics		
	Light class	Medium class	Heavy class
Harvester	Gross power: 80–120 kW; Weight: 7–14 ton; Diameter processed tree up to: 50 cm e.g.: Sampo Rosenlew 1046 X, Logman 801, Logset 4H, Sampo Rosenlew 1066, John Deere 770D	Gross power: 120–160 kW; Weight: 14–20 ton; Diameter processed tree up to: 60 cm e.g.: Ponsse Beaver, Valmet 901, Logman 811H, Logest 5H, John Deere 1070D, Logset 6H; Ponsse Ergo, Ponsse Buffalo Dual; Valmet 911.3	Gross power: over 160 kW; Weight: over 20 ton; Diameter processed tree: over 60 cm e.g.: John Deere 1270, John Deere 1470E, John Deere 608L, Ponsse Scorpion, Ponsse Bear, Ponsse Fox, Volvo EC210BF, Daewoo Sola
Forwarder	Gross power: 80–120 kW; Lift capacities: up to 12 ton e.g.: Komatsu 835, Ponsse 10w, Ponsse Gazelle, John Deere 1010E; Gremo 950 F, HSM 208F 8,5t, Logset 5F	Gross power: 120–160 kW; lift capacities: 12–15 ton e.g.: Komatsu 855, Ponsse Elk, Ponsse Wisent, John Deere 1510E; Caterpillar 574; HSM 208F 14t, Logset 6F	Gross power: over 160 kW; Lift capacities: over 15 ton e.g.: Komatsu 895, Ponsse Elephant King, Ponsse Elephant, John Deere 1910E, Caterpillar 584, HSM 904F, Logset 10F; TimberPro TF830–B.
Feller buncher	Gross power: up to 120 kW; Weight: up to 15 ton; Diameter processed tree: up to 40 cm e.g.: DFM Compact Feller Buncher, Delfab DF703 Phoenix	Gross power: 120–180 kW; Weight: 15–20 ton; Diameter processed tree: up to 50 cm e.g.: John Deere 753J, John Deere 759J, Caterpillar 511, Valmet 415FX, John Deere PowerTech 6068H	Gross power: over 180 kW; Weight: over 25 ton; Diameter processed tree: over 50 cm e.g.: John Deere 853J, John Deere 903J, John Deere 959J, Caterpillar 521, Caterpillar 552, Valmet 445FXL, Tigercat 822C
Skidder	Gross power: up to 80 kW; Weight: 5–10 ton; Capacity clam bunk (arch grapple): up to 8 m^3 e.g.: Turboforest T42–C, Awassos MD–80	Gross power: 80–160 kW; Weight: 10–15 ton; Capacity clam bunk (arch grapple): 8–14 m^3 e.g.: John Deere 640L, John Deere 648L, Cat 525D, Cat 535D, Tigercat 610E, HSM 805 6WD	Gross power: over 160 kW; Weight: over 15 ton; Capacity clam bunk (arch grapple): over 14 m^3 e.g.: John Deere 948L, John Deere 848L, Cat 555D, Tigercat 620E, Tigercat 630E, TimberPro TS820–D, Clam Bunk, HSM 904 6WD
Processor	Gross power: 80–120 kW; Weight: up to 15 ton; Diameter processed tree: up to 50 cm e.g.: Hypro 755 VB, Hypro 450 XL, Hypro 300	Gross power: 120–160 kW; Weight: 15–30 ton; Diameter processed tree: up to 60 cm e.g.: John Deere 2154G, Prentice 2384C, 2484C, Komatsu PC200	Gross power: over 160 kW; Weight: over 30 ton; Diameter processed tree: over 60 cm e.g.: John Deere 803MH, 853MH, 859MH, 2654G, Tigercat 860C, Caterpillar H822D, LH822D

3. Results

3.1. Assessment of the similarity of natural-production conditions

Comparison of NPS sets (name set, see table 3) showed that the natural-production conditions of the Republic of Karelia are the closest to the natural-production conditions of Arkhangelsk region (ED 3.63). The most different are the natural-production conditions of Murmansk region and Vologda region (ED 9.91). The natural-production conditions of Komi Republic are closest to Arkhangelsk region (ED 4.96) and to the Republic of Karelia (ED 5.41). The natural-production conditions of Murmansk region and Vologda region are the most different from the natural-production conditions of other ENR regions. ED are in the range 6.45–9.91 for Murmansk Region and 5.94–9.91 for Vologda Region. Fig. 3 gives dendrogram of Euclidean distances between five studied regions calculated using cluster analysis based on NPS sets describing various aspects of natural-production conditions.

Comparison of ATD sets showed that the average taxation data of forest stands of Murmansk region and the Republic of Karelia are the most similar (ED 1.98). The average taxation data Arkhangelsk region are most similar to the average taxation data of the Republic of Komi (ED 2.08). The average taxation data of Vologda region is the most different from the average taxation data of other regions in particular Murmansk region (Fig. 4).

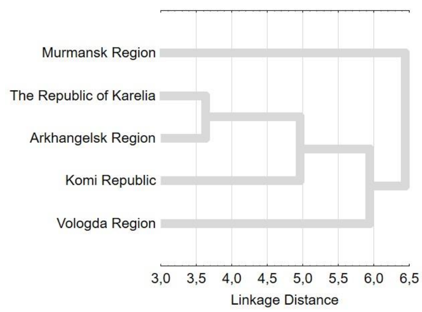

Fig. 3. Dendrogram of Euclidean distances between five studied regions calculated using cluster analysis based on NPS sets describing various aspects of natural-production conditions.

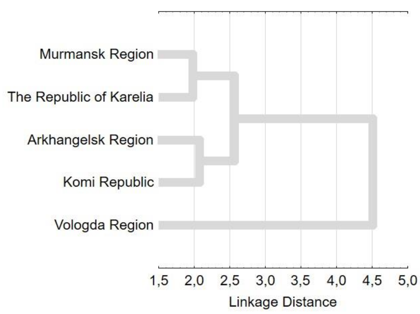

Fig. 4. Dendrogram of Euclidean distances between five studied regions calculated using cluster analysis based on ATD sets describing various aspects of natural-production conditions.

Fig. 5 gives the results of TMed sets comparison and Fig. 6 gives the results of TMax sets comparison.

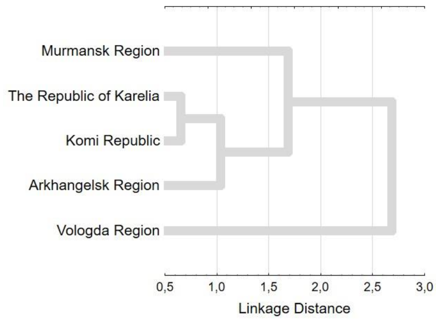

Fig. 5. Dendrogram of Euclidean distances between five studied regions calculated using cluster analysis based on TMed sets describing various aspects of natural-production conditions.

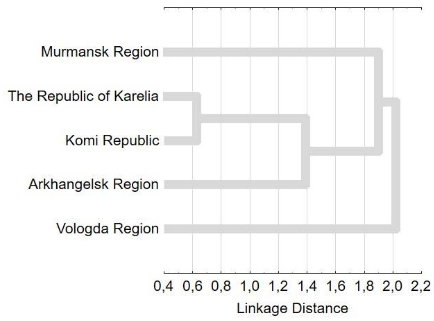

Fig. 6. Dendrogram of Euclidean distances between five studied regions calculated using cluster analysis based on TMax sets describing various aspects of natural-production conditions.

The sizes of maximum tree and medium tree are close in The Republic of Karelia and in Komi Republic (ED 0.63 and 0.65 respectively). From all ENR regions, sizes of trees are close in three regions (the Republic of Karelia, Komi Republic and Arkhangelsk Region). ED are in the range 0.6–1.07 for TMed sets and 0.63–1.79 for TMax sets. The sizes of maximum trees and medium trees in Vologda Region and in Murmansk Region are the most different from maximum and medium sizes of trees in other ENR regions. ED are in the range 1.9–3.91 for Murmansk Region and 2.02–3.91 for Vologda Region. Murmansk Region and Vologda Region differ most by these sets (ED 3.91).

Fig. 7 gives the results of CLC sets comparing. The soil conditions and the land form conditions are most similar in Arkhangelsk Region and Vologda Region (ED 0.67). The Republic of Karelia is approaching these regions by these conditions. The soil conditions and the land form conditions of Murmansk Region and Komi Republic are vary most considerably from other ENR regions. ED for Murmansk Region are greater than 3.9. ED for Komi Republic are greater than 3.3.

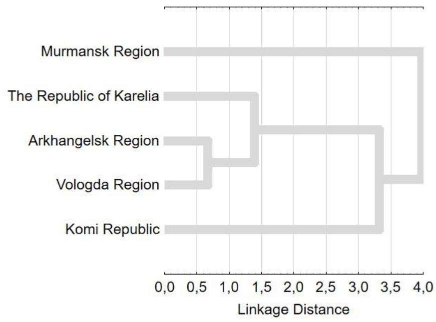

Fig. 7. Dendrogram of Euclidean distances between five studied regions calculated using cluster analysis based on CLC sets describing various aspects of natural-production conditions.

Fig. 8 gives the result of SC sets comparison. The forests of Murmansk region are similar to the forests of the Republic of Karelia by their species composition (ED 0.41). The forests of Arkhangelsk Region are similar to the forests of Komi Republic by their species composition (ED 2.01). The species composition of forests in Vologda region is very different from other ENR regions (ED > 3.6). The forests of Vologda region are most significantly different from the forests of Murmansk region in terms of species composition (ED 4.05).

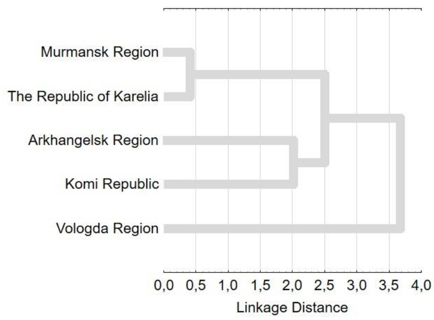

Fig. 8. Dendrogram of Euclidean distances between five studied regions calculated using cluster analysis based on SC sets describing various aspects of natural-production conditions.

Based on the results of cluster analysis in ENR, three zones of natural-production conditions can be identified (Fig. 9). Zone A includes Murmansk region. Zone B includes the Republic of Karelia, Komi Republic and Arkhangelsk Region. Zone C includes Vologda Region. Analysis of soil conditions and land form conditions and 9–15 indicators showed that it is advisable to allocate subzones B1 and B2. These subzones take into account the presence of undulating topography unusual for zone B. Zone B1 includes West Karelian upland. Zone B2 includes Northern Urals, Subpolar Urals, Polar Urals.

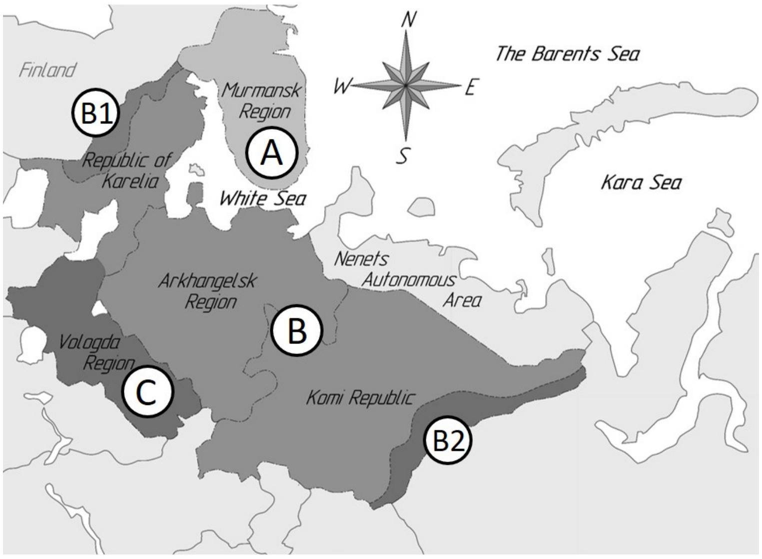

Fig. 9. Zones of natural-production conditions in ENR.

3.2. Comparison of technical characteristics of logging machines and natural-production conditions

The comparison of natural-production conditions and technical characteristics of logging machines allowed to make recommendations on the systems of logging machines that can be used in ENR regions. Table 5 summarizes the results of the comparison.

HF system is most applicable in all ENR regions for small logging enterprises. However, for zone A, HF system should be formed from L class of logging machines, for zone B from M or H class, for zone C from H class. FSP system can be used in Vologda Region, especially in its southern part.

Soil conditions of classes 3 and 4 predominate in ENR regions, except for Murmansk Region. High bogginess is typical for Komi Republic, The Republic of Karelia, Arkhangelsk and Vologda Regions. Therefore, in B and C zones (except for B1 and B2 subzones) it is necessary to use either logging machines on a tracked chassis or on a wheeled chassis with tracks for wheels and 6×6 or 8×8 axle configuration. In B1 and B2 subzones, the feasibility of using wheeled chassis with 6×6 or 8×8 axle configuration is explained by the need to ensure stability on slopes. Logging machines with 6x6 or 8x8 axle configuration have better stability. The use of tracks for wheels is explained by a decrease in the negative impact on the soil. Tracks for wheels are used to ensure passableness of logging machines in B and C zones.

Logging machines may be not equipped with cab leveling system and system of self-propelled chassis active stabilization in Vologda Region and Arkhangelsk Region and The Republic of Karelia (zones B and C except for B1 and B2 subzones) because relief on the forest areas of these regions is mainly characterized by slopes with less than 15° slope ratios. Areas of forest stands in zone A and subzones B1 and B2 (Murmansk Region and the part of Komi Republic and the part of The Republic of Karelia) are defined by the most rugged topography. Almost all the territory of Murmansk Region has an undulating land. In this region, logging machines must be equipped with cab leveling systems and system of self-propelled chassis active stabilization. Such systems should be equipped with machines used in the Western part of the Republic of Karelia (zone B1) and the Eastern part of Komi Republic (zone B2).

Table 5. Logging machines systems.

		Murmansk Region	The Republic of Karelia		Arkhangelsk Region	The Komi Republic		Vologda Region
Zone		A	B	B1	B	B	B2	C
Systems of logging machines		HF	HF	HF	HF	HF	HF	HF/FSP
Class of logging machines		L	M/H	M/H	M/H	M/H	M/H	H
Logging machines on a tracked chassis		—	+	—	+	+	—	+
Logging machines on a wheeled chassis	Axle configuration	6×6	8×8, 6×6	8×8, 6×6	8×8, 6×6	8×8, 6×6	8×8, 6×6	8×8, 6×6
	Tracks for wheels	—	+	+	+	+	+	+
Cab leveling systems and system of self-propelled chassis active stabilization		+	—	+	—	—	+	—

4. Discussion

Our results indicated high variability of natural-production conditions in the ENR regions. Except for Murmansk Region, ENR regions are similar in soil conditions and land form conditions. Species composition varies in ENR regions, however prevailing species are analogous. Sizes of trees in forest stands are the most considerable difference between ENR regions. Actually ENR regions can be divided into three groups by sizes of trees in forest stands. Murmansk Region refers to the first group which is characterized by the smallest sizes of trees. The second group described by middle-sized trees includes the Republic of Karelia, Komi Republic and Arkhangelsk Region. Vologda Region refers to the third group defined by the largest trees in forest stands.

The study evidence that in ENR there are several zones with the same natural-production conditions. The zones have special aspects that must be considered when choosing logging machines. Currently, the logger is trying to purchase heavy logging machines but the results indicate that all classes of logging machines can be used in ENR. Thus, the logging approach can be more flexible even for small enterprises.

In addition, the study showed that for small enterprises it is advisable to use HF system. This system is more universal for ENR than FSP system in ENR. As disadvantages of FSP system for ENR, experts noted machinery downtime associated with expectation of relocation. The sizes of cutting areas in ENR are small (10–15 hectares). FSP system has high productive so it processes the cutting area quickly. There is a need for frequent relocations. FSP system consists of three logging machines as against HF system that has two machines. The problem is complicated by the fact that in the most part of ENR has a low road density (indicator 24), and a relatively small hectare timber volume per ha (indicator 24). This leads to an increase in the relative cost of logging and machinery downtime. In general, FSP system requires a higher level of planning of logging operations under natural-production conditions of ENR. FSP system is advisable to use in Vologda region, where the forest is larger and higher level of road density. Disadvantages of FSP system for ENR are impossibility of strengthening skidding road with wood residues and contamination of wood while skidding.

These results are consistent with the results of Syunev et al. (2009), Goltsev et al. (2011) who presented a comparative appraisal of using logging system in Northwest of Russia.

For zones B and C, we do not recommend using logging machines with cab leveling system and system of self-propelled chassis active stabilization. This is because logging machines equipped with the systems tend to be more expensive than machines without such the systems and relief has relatively mild slopes (up to 15°) in the zones. Under such approach ergonomic working conditions of a logging machine operator deteriorate, but at the same time machine price and service charge will be considerably lower what is mostly important for small enterprises.

In our study, we used 46-year old data on diameter distribution given in Vinogorov (1972). The data were obtained from the measurement of 4.8 million trees. Conducting such a number of measurements is currently difficult. It is known from forest estimation that diameter distribution is subject to certain objective laws (Tyabera 1980; Picard et al. 2016). Conditions of habitat, species composition, age, density of stand, configuration of stand, economic activity in forest, environmental drivers, natural catastrophes, in particular fires, hurricanes, are the factors influencing diameter distribution in forest stand. Diameter distribution changes over time (Vacek et al. 2018).

According to Russian legislation, logging can only be carried out in forests that have reached a certain age. This age has not changed since the time of Vinogorov's research. Thus, we consider forests of the same age. We compared the data on the average volume of stem and the average timber volume per ha corresponding to the time of Vinogorov's research, with modern data. The data does not differ. Therefore, we consider it possible to use the Vinogorov's data for the present-day planning.

All conclusions are based on analysis, the available data and own sample observations. There are reasons that may limit the significance of the research results. First, it is reliability of the data used in the study. Secondly, it is limited number of the indicators used in the study that characterize natural and production conditions. In addition, the opinion of experts, whose objectivity is limited, was used in the development of recommendations on logging machines.

Small enterprises can use the results of the study in the planning of logging operations. In addition, the method of allocation of territories with similar natural-production conditions based on cluster analysis can be used by logging enterprises in the analysis of their own allocated timber supply area. Besides the researches findings are currently important for a buyer of logging machine allowing to make a well grounded choice of certain model among the whole variety of designs, and for a seller allowing to assess the characteristics of his models in the context of forest exploitation conditions of certain regions and make a commercial proposal based on the results of such assessment.

5. Conclusion

In consequence of the conducted study, it has been established that natural-production conditions in ENR regions are similar in relief and soil conditions. ENR regions vary most considerably in sizes of trees in forest stands and timber volume per ha. From the results, ENR can be divided into three main zones A, B, C and two subzones B1 and B2 with similar natural-production conditions. In the zones A, B and the subzones B1 and B2, small logging enterprises should use a harvester and a forwarder. In the zone C, the enterprises can use a logging system including a harvester and a forwarder or a logging system including a feller buncher, a skidder and a processor. The logging system should be based on the light class of logging machines for the zone A, the medium class or the heavy class for the zones B, C and the subzones B1, B2, the heavy class of machines for the zone C.

Acknowledgments

The researches have been performed within the frameworks of implementing grant of the President of the Russian Federation No MK-5321.2018.8.

References

Ackerman, S., F., Ackerman, P. ,Williams, C., Nathi, C., 2017: Diesel Consumption and Carbon Balance in South African Pine Clear-Felling CTL Operations: a Preliminary Case Study. Croatian Journal of Forest Engineering, 38:65–72.

Alam, M., Walsh, D., Strandgard, M., Brown, M., 2014: A Log-by-Log Productivity Analysis of Two Valmet 475EX Harvesters. International Journal of Forest Engineering, 25:14–22.

Bergroth, J., Palander, T., Kärhä, K., 2006: Excavator-based harvesters in wood cutting operations in Finland. Forestry Studies, 45:74–88.

Castro, G. P., Malinovski, J. R., Nutto, L., Malinovski, R. A., 2016: Harvesting Systems. Tropical Forestry Handbook. Springer, Berlin, Heidelberg, p. 2445–2485.

Eliasson, L., 1998: Analyses of single-grip harvester productivity. Doctoral thesis. Swedish University of Agricultural Sciences, Department of Operational Efficiency, Umeå, 24 p.

Glöde, D., 1999: Single- and double-grip harvesters – productive measurements in final cutting of shelterwood. Journal of Forest Engineering, 10:63–74.

Goltsev, V., Tolonen, T., Syunev, V., Dahlin, B., Gerasimov, Y. et al., 2011: Wood harvesting and logistics in Russia. Working Papers of the Finnish Forest Research Institute, 210 p. Available at: http://www.metla.fi/julkaisut/workingpapers/2011/mwp210.htm

Häggström, C., Lindroos, O., 2016: Human, technology, organization and environment – a human factors perspective on performance in forest harvesting. International Journal of Forest Engineering, 27:67–78.

Jiroušek, R., Klvac, R., Skoupý, A., 2007: Productivity and costs of the mechanised cut-to-length wood harvesting system in clear-felling operations. Journal of Forest Science, 53:476–482.

Kärhä, K., Rönkkö, E. & Gumse S.-I., 2004: Productivity and cutting costs of thinning harvesters. International Journal of Forest Engineering, 15:43–56.

Kellogg, L. D., Bettinger, P., 1994: Thinning productivity and cost for mechanized cut-to-length system in the Northwest Pacific coast region of the USA. Journal of Forest Engineering, 5:43–52.

Kellogg, L., D., Bettinger, P., 1994: Thinning Productivity and Cost for a Mechanized Cut-to-Length System in the Northwest Pacific Coast Region of the USA. Journal of Forest Engineering, 5:43–54.

Klaes, B., Struck, J., Schneider, R., Schueler, G., 2016: Middle-term effects after timber harvesting with heavy machinery on a fine-textured forest soil. European Journal of Forest Research, 135:1083–1095.

Kormanek, M., Baj, D., 2018: Analysis of Operation Performance in the Process of Machine Wood Harvesting with Fao Far 6840 Mini-Harvester. Agricultural Engineering, 22:73–82.

Laitila, J., Väätäinen, K., 2013: The cutting productivity in integrated harvesting of pulpwood and delimbed energy wood with a forestry-equipped peat harvesting tractor. Suo, 64:97–112.

Lyumanov, R., 1990: Mašinnaja valka lesa. Moscow, Timber industry, 280 p.

McNeel, J., F., Rutherford, D., 1994: Modeling harvester-forwarder system performance in a selection harvest. Journal of Forest Engineering, 6:7–14.

Nurminen T., Korpunen H., Uusitalo J., 2006: Time consumption analysis of the mechanized cut-to-length harvesting system. Silva Fennica, 40:335–363.

Ovaskainen, H., 2005: Comparison of harvester work in forest and simulator environments. Silva Fennica, 39:89–101.

Palander, T., Bergroth, J., Kärhä, K., 2012: Excavator technology for increasing the efficiency of energy wood and pulp wood harvesting. Biomass and Bioenergy, 40:120–126.

Pētersons, J., 2014: Productivity of harvesters in commercial thinnings in the forest stands of different composition of species. Research for rural development, 2:76–82.

Picard, D., Gasparotto, D., 2016: Liocourt's law for tree diameter distribution in forest stands. Annals of Forest Science, 73:751–755.

Proto, A. R., Macrì, G., Visser, R., Harrill, H., Russo, D., Zimbalatti, G., 2018: Factors affecting forwarder productivity. European Journal Forest Research, Available at: https://doi.org/10.1007/s10342-017-1088-6

Reza, N., Bagheri, I., Lotfalian, M., Setodeh, B., 2009: Rutting and soil displacement caused by 450C Timber Jack wheeled skidder (Asalem forest northern Iran). Journal of Forest Science, 55:177–183.

Rozītis, A., Zimelis, A., Lazdins,A., 2017: Evaluation of productivity and impact on soil of tracked ProSilva F2/2 forwarder in forest thinning. Research for Rural Development, 1:94–100.

Schack-Kirchner, H., Fenner, P., T., Hildebrand, E. E., 2007: Different responses in bulk density and saturated conductivity to soil deformation by logging machinery on a Ferralsol under native forest. Soil Use and Management, 23:286–293.

Strandgard, M., Mitchell, R., Acuna, M., 2017: Time consumption and productivity of a forwarder operating on a slope in a cut-to-length harvest system in a *Pinus radiata* D. Don pine plantation. Journal of Forest Science, 63:324–330.

Syunev, V., Sokolov, A., Konovalov, A., Katarov, V., Seliverstov, A., Gerasimov, Y. et al., 2009: Comparison of Wood Harvesting Methods in the Republic of Karelia. Working Papers of the Finnish Forest Research Institute, 120 p. Available at: http://www.metla.fi/julkaisut/workingpapers/2009/mwp120.htm

Tiernan, D., Zeleke, G., Owende, P., M., O., Kanali, C., L., Lyons, J., Ward, S., M., 2004: Effect of working conditions on for-warder productivity in cut-to-length timber harvesting on sensitive forest sites in Ireland. Biosystems Engineering, 87:167–177.

Tufts, R. A., 1997: Productivity and cost of the Ponsse 15-series, cut-to-length harvesting system in southern pine plantations. Forest Products Journal, 47:39–46.

Tyabera, A. P., 1980: Principy issledovanij stroenija drevostoev po tolščine derevjev. Forest Journal, 1:5–9.

Vacek, Z., Vacek, S., Bílek, L., Král, J., Ulbrichová, I., Simon, J., Bulušek, D., 2018: Impact of applied silvicultural systems on spatial pattern of hornbeam-oak forests. Central European Forestry Journal, 64:33–45.

Vinogorov, G. K., 1972:K metodike obosnovanija rasčetnych derevjev pri rešenii lesoekspluatacionnych zadač. Works of TSNIME, 122:52–64.

Vinogorov, G. K., 1986: Tipizacija prirodno-proizvodstvennych uslovij lesozagotoviteľnych rajonov. TSNIME, Ximki, 23 p.

Wang, J., Haarla, R., 2002: Production analysis of an excavator-based harvester: a case study in Finnish forest operations. Forest Product Journal, 52:85–90.

Cent. Eur. For. J. 65 (2019) 92–102 sciendo DOI: 10.2478/forj-2019-0010

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Growth variability of European beech (*Fagus sylvatica* L.) natural forests: Dendroclimatic study from Krkonoše National Park

Václav Šimůnek[1], Zdeněk Vacek[1, *], Stanislav Vacek[1], Ivo Králíček[2], Karel Vančura[1]

[1] *Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, CZ – 165 21 Prague 6 – Suchdol, Czech Republic*
[2] *University of Hradec Králové, Faculty of Science, Rokitanského 62, CZ – 500 03 Hradec Králové, Czech Republic*

Abstract
Long-term temporal development of beech stands in relation to climatic conditions is well documented by dendrochronological analyses. The study aims to identify and describe growth factors affecting natural European beech stands (*Fagus sylvatica* L.) on permanent research plots in the eastern Krkonoše Mountains, the Czech Republic. The paper focus on radial growth dynamics, frequency and cyclicity, and the effect of climatic factors on diameter increment of beech stands since 1850. The growth development of beech stands was significantly affected by air pollution load in 1977–1989, and increasingly frequent climate extremes in recent years (since 2010). Periodic increment events recurred in approximately 10–18 years' periods. Stands on research plots responded differently to climatic factors, the main limiting factor being low temperatures during the growing season, frost damages and extreme droughts. The positive influence of temperatures on beech increments was recorded in winter, early spring, and especially in July and August of the current year. Conversely, precipitation in the previous year had higher impact on radial increment, with prevailing negative correlation. The plots were negatively affected by the decrease in sum of precipitation in February and March, but it was the temperature that influenced the beech increment most significantly. Dendrochronological analysis of close-to-nature beech stands provides valuable information on radial forest growth in response to changing climatic conditions.

Key words: dendrochronology; tree-ring data; cyclical dynamics; temperature; precipitation; Central Europe

Editor: Bohdan Konôpka

1. Introduction

In terms of ongoing global climate change, European beech stands (*Fagus sylvatica* L.) show greater stability and resistance to water scarcity than Norway spruce stands (*Picea abies* [L.] Karst.) – (Dittmar et al. 2003; Zang et al. 2011, 2014; Hartl-Meier et al. 2018). Climate change has long been forcing forestry management to change its approach to tree species composition in favour of deciduous tree species. Confirming the trend, the Czech Republic has witnessed an increasing percentage of European beech (1% increase since 2010) (Ministry of Agriculture 2017). Supposedly, the numbers will increase continually. As a result, European beech will partially substitute languishing stands of Norway spruce (Lindner et al. 2010; Holuša et al. 2018). Some studies, however, point out European beech sensitive response to long-lasting drought (Jump et al. 2006; Geßler et al. 2007; Granier et al. 2007; Cavin & Jump 2017). In comparison to spruce stands, beech stands show greater success of natural regeneration (occurrence, density, growth) and adaptability to air pollution (Králíček et al. 2017; Slanař et al. 2017). The higher resilience and plasticity of the beech compared to spruce is caused by the annual replacement of the assimilation apparatus. However, during the long-term impact of pollution load the forest damage increased through the soil due to increased acidification, disruption of the sorption complex and decrease of mycorrhizal roots (Ling et al. 1993; Power & Ashmore 1996). In response to climate change, beech stands increase the frequency of seed years (Övergaard 2010). Growth processes of the tree species are also affected, its mortality increasing with increasing drought at lower altitudes, yet with the effect of prolongation of its lifetime cycle (Filippo et al. 2012).

As soon as the beginning of the 20th century, the first national parks began to emerge in Europe, together with increasing preferences for ecological approach to forests, which led to greater interest in close-to-nature forestry

**Corresponding author. Zdeněk Vacek, e-mail: vacekz@fld.czu.cz*

(Christensen et al. 2005). National parks, including our area of interest in the Krkonoše Mountains, took over the beech stands with their noteworthy history. From the 17th to the 19th century the beech stands were used as forest pastures and source of cattle feed – beech nuts (Nožička 1961; Lokvenc 1978). For many centuries, beech stands were also used for fuel wood and production of charcoal (Peters 1997). In recent decades, the health status and development of forest stands were damaged by synergic effects of air pollution load (acidification, ozone effect) and climate stress (extreme fluctuations, frosts, droughts, wind storms) (Bytnerowicz et al. 2007; Paoletti et al. 2010; Vacek et al. 2013, 2015a).

Together with industrial development and increasing air pollution after World War II, the first macroscopically visible large-scale damage to forest stands in the Czech Republic occurred (Materna 1989). Consequently, the most significant air pollution loads caused by high concentrations of SO_2 were recorded in the Krkonoše Mountains in the 1970s–1990s (Bridgman 2002; Matějka et al. 2010; Vacek et al. 2010; Král et al 2015; Vacek et al. 2017). Since the 1990s, NO_X and O_3 air pollution have also been perceived as a problem (Hůnová & Schreiberová 2012; Vacek et al. 2015a). Mankind has influenced forests throughout history, and on this basis it was found that 85% of beech stands developed in regeneration cycles of 15–25 years, with high-level regeneration in subdominant trees (Schütz 2001).

The Krkonoše Mountains stands were affected not only by air pollution loads but also by climatic factors such as ground frosts in 1977, wind disturbances in 2007 and 2008, or in increasingly frequent extreme droughts in recent years (Trnka et al. 2015; Bošeľa et al. 2016; Brázdil et al. 2017, 2018). Damaged by air pollution, forests were consequently infested with beech scale (*Crypotococcus fagi* /Baer./ Dougl.), followed by gummosis and more than often also by bark canker (Vacek 1988). Canker and necroses in beeches are most frequently induced by *Nectria*, *Ophiostoma*, *Phomopsis* and *Verticillium* pathogens, or some species of *Phytophtora*, fungi causing vast damage throughout Europe (Motta et al. 2003; Cicák et al. 2006). Among other pests in the Czech Republic we can name beech-leaf gall midge (*Mikiola fagi* Htg.), *Bucculatrix ulmella* Zeller and *Ectoedemia liebwerdella* Zimm. (Urban 2000; Mihál et al. 2014). All these abiotic and biotic factors affect the growth conditions of European beech stands on the research plot. Last studies bringing results of long-term research of natural beech stands in the eastern Krkonoše Mts. were published in 2010 and 2015, focusing on the European beech stand structure and the effects of air pollution (Špulák & Souček 2010; Vacek et al. 2015b), but no research on dendrochronological development of these unique forest stands has been published yet.

This study explores the potential of the cyclical dynamics of European beech in stands left to spontaneous development in conditions of the climate change and uses a dendrochronological analysis that combines the evaluation of frequency dynamics of the lower and higher "bandpass filtering" of dendrochronological series (Bunn & Mikko 2018a, 2018b). The study also evaluates the effect of monthly temperatures and precipitation on radial growth to differentiate responses to climate during a particular season (Biondi & Waikul 2004). Particular attention is given to clarification of the influence of climate change on natural beech stands in the eastern part of the Krkonoše Mountains National Park, which was left to spontaneous development in 1963.

2. Material and methods

2.1. Study area

The studied area of Boberská stráň (Rýchory Hills) is situated in the east of the Krkonoše Mountains National Park near the town of Žacléř, close to Poland frontier. Studied three permanent research plots (PRP 30, 31, 32) with similar growth conditions are composed by dominant European beech (99.8–100.0%) and admixed sycamore maple (*Acer pseudoplatanus* L.; 0.0–0.2%). Research areas are in the first zone of protection of the Krkonoše National Park at an altitude of 740–790 m a.s.l. on a northeast facing slope. The predominant soil type is the Cambisol with meta-diabase subsoil. The climate at the site is characterized by temperatures oscillating around 5.2 °C with an annual total precipitation of 870 mm. The growing season lasts about 120 days with an average temperature of 11.9 °C and a total precipitation of 640 mm. In Köppen's classification, this is a damp continental climate with warm summers (Dfb) – (Tolazs 2007). Phytosociology defines the area as *Fagion sylvaticae* Luquet 1926, *Eu-Fagenion* Oberdorfer 1957 suballiance and *Dentario enneaphylli-Fagetum* Oberdorfer ex W. et A. Matuszkiewicz 1960 plant association. In 1963, natural beech stands on the PRPs were left to spontaneous development.

The studied PRPs of 50 × 50 m (area of 0.25 ha) were established by Forestry and Game Management Research Institute, Forest Research Station at Opočno in 1980 to monitor long-term factors affecting the forest environment (Vacek 1988). Several measurements by technology Field-Map (Institute of Forest Ecosystem Research – Monitoring and Mapping Solutions Ltd.; IFER 2017) were carried out on these PRPs, studies of which were published (Vacek et al. 2010; Vacek et al. 2015b). This technology was used for repeated measurements of the positions of tree layer, dead wood and natural regeneration, tree heights, heights of the live crown base and crown projection areas together with the diameters at breast height (DBH). Fig. 1 illustrates the localization of natural beech forest stands on PRPs and Table 1 shows the basic site and stand characteristics of PRPs.

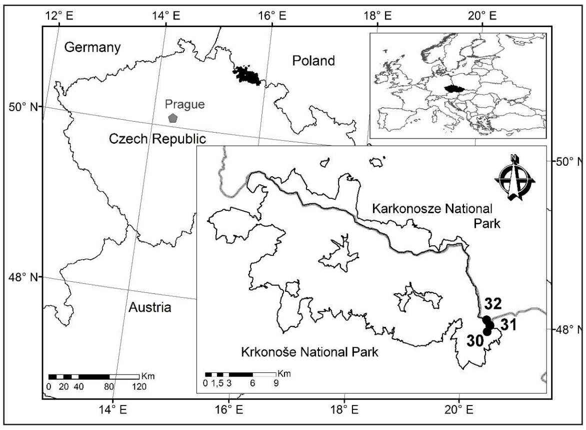

Fig. 1. Location of European beech forest stands on permanent research plots 30, 31 and 32 in the Krkonoše Mountains.

2.2. Data collection

For dendrochronological analysis, increment cores were taken from the European beech using the Pressler auger, perpendicularly to the stem axis, in the down-the-slope direction. Trees were randomly selected using the RNG selection (MS Excel); a total of 72 cores (24 per PRP) were taken from trees with DBH > 250 mm. The analysis required 67 samples: 23 from PRP 30, 21 from PRP 31, and 23 from PRP 32. Cores were measured by an Olympus microscope on a LINTAB measurement table (RINNTECH). The samples were measured from the bark to the heartwood, perpendicularly to the centre of the stem so that each ring was measured perpendicularly to the axis of the stem with an accuracy to hundredths of millimetres. Subsequently, the increment cores were crossdated in CDendro program (Cybis Dendrochronology), with the CC > 25.

Climate data (monthly air temperatures and sum of precipitation) were taken from the nearest meteorological station of Pec pod Sněžkou (Czech Hydrometeorological Institute, Prague), 11 km from research areas at an altitude of 816 m a.s.l. (50°41‘30.480“N, 15°43‘43.320“E). The range of climate data surveyed was set to the 1976–2017 period. Data on average annual temperatures, growing season temperatures, temperatures out of the growing season, temperatures in particular months and annual sum of precipitation, sum of precipitation in the growing season, precipitation out of the growing season, precipitation in particular months in 1976–2017 were used to describe the development of temperature and precipitation conditions. The meteorological data source was provided by operator Czech Hydrometeorological Institute. Climatic data was archived by the National Climatic Data Center.

2.3. Data analysis

Dendrochronological analysis data were processed in the R (R Core Team 2018) program, using negative exponential detrending to remove the age trend of analysed increment cores with an inserted spline of 1/3 sample age. Consequently, the values were averaged by the chron function (Bunn & Mikko 2018b). To generate information for each chronological curve signal, dplR-packages for R and signal were used. A graph of single high-pass filter spectrum signal was created in period ranges of 1 to 20 years. Splines from 4, 8, 16, 32, 64 to 128 years were inserted to the average data curve to show significant events (Bunn & Mikko 2018a; Team R Core 2018). DendroClim 2002 (DendroLab) was used for the analysis of dendrochronological curves with monthly climatic conditions, utilizing the response and correlation function in the months from May to September (Biondi & Waikul 2004).

Data from the evaluation of diameter increment of beech in relation to climate factors were statistically processed by the Statistica 12 program (Statsoft, Tulsa). To determine the combined effect of average annual temperature and annual sum of precipitation on radial growth of beech, the regression quadratic model was used. The principal component analysis (PCA) was run in CANOCO 5 program (Lepš & Šmilauer) to assess the relation between the radial growth of beech forest stands, sum of precipitation and average temperatures all the year round, in the growing season (from April to September), out of the growing season (from October of the previous year to March of the current year), in June to July and in January to March of the current and previous year. Prior to the analysis the data were logarithmized and standardized. The results of multivariate PCA were visualized in an ordination diagram.

Table 1. Overview of basic site and stand characteristics of permanent research plots (according to the Forest Management Plan).

PRP	GPS coordinates	Altitude [m]	Exposure	Slope [°]	Tree species	Age of tree layers [years]	Height [m]	DBH [cm]	Volume [m^3 ha^{-1}]	Forest type*
30	50°39’52”N 15°53’01”E	790	NE	24	beech	182/22	31	49	420	6D
					sycamore		28	40	38	
31	50°40’04”N 15°52’57”E	740	NE	23	beech	165/23	29	43	398	6B
					sycamore		27	39	40	
					spruce		31	40	20	
32	50°40’13”N 15°52’48”E	760	NE	35	beech	149/71/24	26	41	313	5B
					sycamore		26	35	34	

Notes: *Forest site type classification: 6D – *Piceeto-Fagetum acerosum diluvium* (Enriched-colluvial spruce-beech), 6B – *Piceeto-Fagetum eutrophicum* (Nutrient-rich spruce-beech), 5B – *Abieto-Fagetum eutrophicum* (Nutrient-rich fir-beech) – (Viewegh et al. 2003).

3. Results

3.1. Dynamics and frequency of radial growth

Detrended radial growth data series (Fig. 2) show that each stand on the studied PRPs developed differently. On PRP 30, no substantial drops in production were detected. This finding is also related to the fact that only five climatically significant years (12) were documented on the PRP until 1973. PRP 31, though, witnessed the highest number of climatically significant years (13) in terms of radial growth, and the increment varied significantly throughout the years. PRP 32 showed the most substantial cyclicity of radial growth and revealed five climatically significant years.

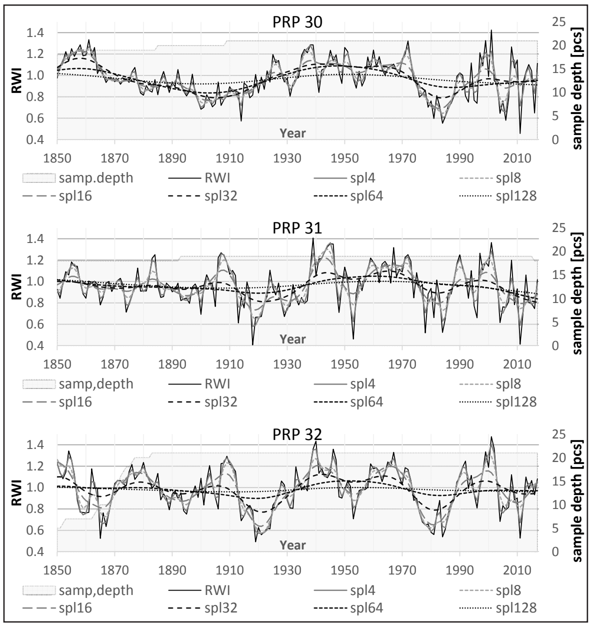

Fig. 2. Standardized ring-width chronologies of European beech on permanent research plots 30, 31 and 32 with added splines and sample depth (RWI – ring-width index, spl4 – spline 4 years, spl8 – spline 8 years, spl16 – spline 16 years, spl32 – spline 32 years, spl64 – spline 64 years, spl128 – spline 128 years).

On Boberská stráň, beech stands generally show great plasticity of radial growth (Fig. 2). The analysis of climatically significant years since the mid-19th century for all PRPs shows major significances as late as in 2011, 2016 and 2017. During the 3th to 8th May in 2011 the temperature was −8 °C, which these extreme late spring frosts damaged the fresh budding leaves and negatively affected whole growth of European beech in season 2011. The year of 2016 was specific for frost damage of the assimilation apparatus, serious infestation with beech-leaf gall midge and a significantly low precipitation of about 1 000 mm (300 mm below an average).

Forest stands on each PRP developed differently, while the longest, 17-year periodic growth cycle of beech occurred in PRP 31; the following cycles repeated every 2, 5, 6 and 7 years (Fig. 3). In PRP 30, the cycles repeated mostly in periods from 10 to 16 years. PRP 32 witnesses small cycles from 2 years and significant periods from 6–7, 10 and 18. Overall, in all PRPs, periods from 10 to 18 years prevail (Fig. 3).

3.2. Effects of temperature and precipitation on radial growth

In term of monthly air temperatures in relation to the average annual radial growth of beech, the growth responds positively in May of the previous year, where significant ($P<0.05$) values ($r = 0.30 – 0.37$) were found for PRP 30 and 31 (Fig. 4). Other significant months are January and February of the current year, when PRP 31 and 32 are significant ($r = 0.23 – 0.42$) and PRP 30 ($r = 0.24$) shifts the relation to February and March (i.e. by one month). In August of the current year, all stands on the PRPs ($r = 0.28 – 0.44$) responded significantly, with a longer response in PRP 32 – from July to August. In total, PRP 32 responds most significantly, followed by PRP 30, where a minor trend is apparent during growing periods, depending on the linear curve. All PRP stands show a rising positive trend of temperature effects in individual months (Fig. 4).

The effect of monthly sum of precipitation on the PRPs stands varies during vegetation periods (Fig. 5). The first significant month is August of the previous year,

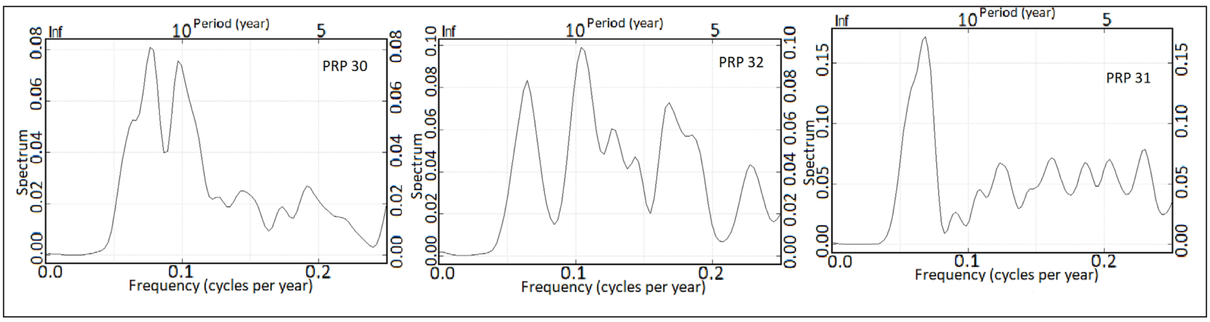

Fig. 3. Single spectral analysis of the indexed ring-width chronology for permanent research plot 30, 31 and 32, with middle pass filtering from 1 to 20 years cycles.

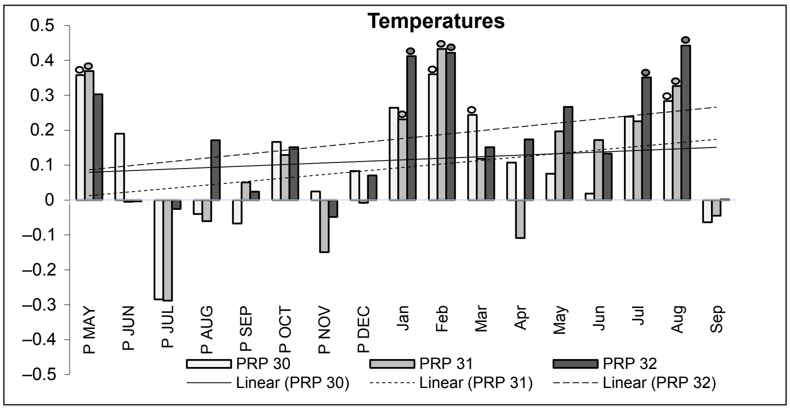

Fig. 4. The values of correlation coefficients of the regional residual index tree-ring chronology of European beech with the monthly temperatures from May of the previous year (P) to September of the current year for the period of 1976–2017 for. Values are statistically significant ($\alpha = 0.05$) and marked with round symbol and linear excel function is calculated for each PRP.

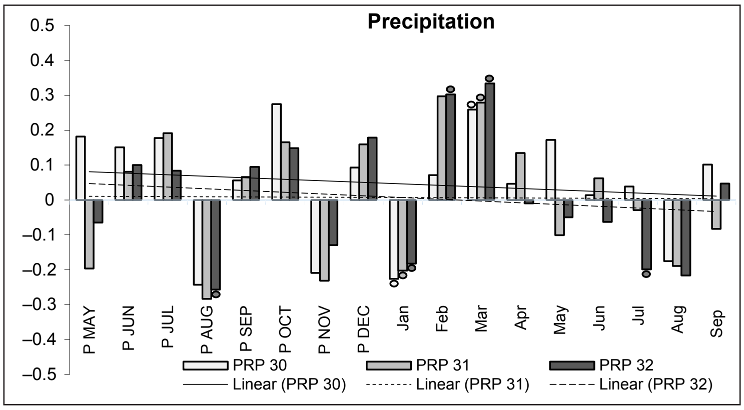

Fig. 5. The values of correlation coefficients of the regional residual index tree-ring chronology of European beech with the monthly precipitation from May of the previous year (P) to September of the current year for the period of 1976–2017. Values are statistically significant ($\alpha = 0.05$) and marked with round symbol and linear excel function is calculated for each PRP.

when the negative correlation was significant only in PRP 32 (r = −0.26). January of the current year is another significant month, when the negative relationship in the stands on all PRPs was significantly demonstrated (r = 0.18 – 0.23). Positive correlation was found in March of the current year in stands on all PRPs (r = 0.28 – 0.33) and in February of the current year in the stand on PRP 32 (r = 0.30). Another significant negative correlation was found in July of the current year (r = 0.20). Overall, the growing season shows an increasing negative influence of precipitation on radial growth of European beech (linear curve of all the plots; Fig. 5).

The main factor influencing the diameter increment of European beech in the study area according to regression quadratic model was the temperature (Fig. 6). Annual average temperature had significantly higher effect on radial growth compared to an annual sum of precipitation. Diameter increment only slightly increased with increasing precipitation, while optimal growth was observed in the range of annual air temperature from 5.5 to 6.5 °C.

3.3. Interactions between radial growth and climate

In terms of relationships between climate and radial growth presenting by PCA, the first ordination axis explains 32.7% of data variability, the first two axes together explain 50.0% and the first four axes 72.2% (Fig. 7). The x-axis illustrates the radial growth of beech with temperature parameters and the second y-axis represents the prevailing precipitation amount. Ring width index was positively correlated with temperature in January to March, out of the growing season and in the growing season of the current year, while temperature in the previous year had low effect on diameter increment. In terms of precipitation, the highest positive correlation of radial growth with precipitation was observed from January to March and out of the growing season of the current year, but these precipitations had small explanatory variable in the ordination diagram. Overall, the effect of temperature on increment was more significant than that of precipitation. Comparing similarity of growth on particular PRPs, diameter increment of beech on PRP 30

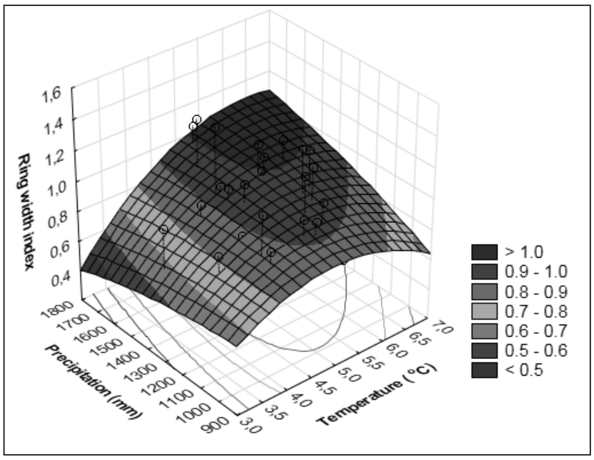

Fig. 6. Response of mean ring width index of European beech to annual sum of precipitation and annual mean temperature for all stands (regression quadratic model, years 1976–2017).

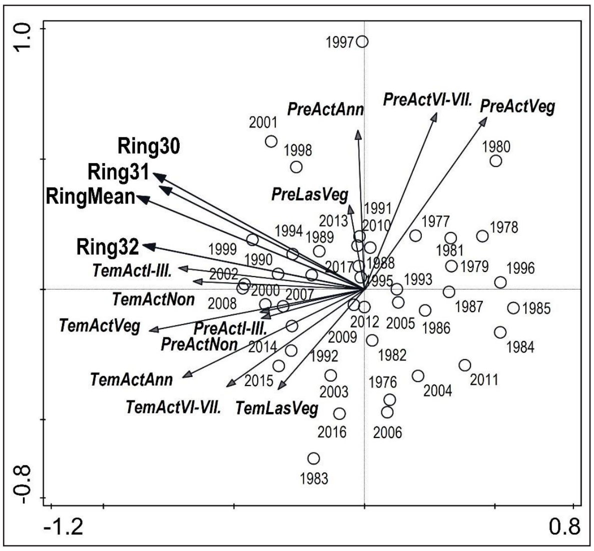

Fig. 7. Ordination diagram of PCA showing relationships between climate data (Tem – mean temperature, Pre – sum of precipitation, Act – current year, Las – previous year, Veg – growing season, NonVeg – out of growing season, I–III, VI–VII – months) and radial growth (Ring – tree-ring width index) of beech forest stands (PRP 30, 31, 32 and Mean); codes ○ indicate years 1976–2017.

and 31 was very close to each other compared to PRP 32. Species diversity diagram showed that years 2007, 2014, 2015 and 2016 brought the highest values.

4. Discussion

A standard dendrochronological analysis suggests that all studied PRPs showed increments of 0.4 to 1.4 RWI, which is close to the results obtained from the nearby Orlické hory Mountains, where the index reached similar values 0.4 – 1.6 RWI (Králíček et al. 2017). Foreign studies also show a similar range of values. For example, in southern Sweden, RWI ranges from 0.4 to 1.6 (Bolte et al. 2010).

The development of studied stands was affected by intensive thinning interventions in 1953 (on PRP 31 and 32) and 1954 (on PRP 30), in response to severe frost damage of the stands (beech crown breakage) at the end of winter 1952–1953. The ring series on studied PRPs also show a significant decrease in radial growth during 1975–1989, caused by effect of air-pollution load. Between 1980–1986 average SO_2 deposition from the EPO II thermal power plant in Poříčí reached to 59 μg m^{-3}, respectively seventeen times higher concertation than nowadays (Samec & Vránová 2005; Tesař et al. 2011). Air pollution impact on radial growth is well documented in Norway spruce in the Krkonoše Mountains and the whole Sudeten system (Kroupová 2002; Rydval & Wilson 2012; Vacek et al. 2013; Kolář et al. 2015), less in European beech (Vacek & Hejcman 2012; Králíček et al. 2017). In early spring 1981, beech crowns were heavily damaged by ice-load and, consequently, the assimilation apparatus of the trees suffered from frost. The air-pollution calamity in 1984 was followed by strong infestation with beech scale (*Cryptococcus fagi*) and beech-leaf gall midge (*Mikiola fagi*) (Vacek 1988). Furthermore, lower temperatures during the winter period in 1996 combined with the reverberating pollution load led to beech scale outbreak, recorded in other mountain regions of the Czech Republic as well (Králíček et al. 2017). A similar situation occurred in Europe in 1976 when beech scale along with extreme drought caused considerable damage and decreased radial growth of European beech (Wainhouse et al. 1988). Negative impact of beech scale on beech growth was also recorded in America (Gavin & Peart 1993; Kasson & Livingston 2009, 2012). To a lesser extent, ice-load induced crown damage repeated in winter 2004–2005. Above mentioned types of damage on many PRPs in the Krkonoše Mountains was reported by Vacek et al. (2007). Assimilation apparatus was severely damaged at the beginning of the vegetation period in 2011 and, less severely, in 2016. In respect to the economic function of studied beech stands until 1963, their development on all PRPs was different, which has also been confirmed (Kooijman et al. 2000).

A spectral dendrochronology analysis shows, in all PRP stands, 10 – 18 years' cycles occurring in the largest frequency spectrum. Short, mostly 2-year cycles are usually rationalized by fructification and seed-year cyclicity (Övergaard 2010; Nussbaumer et al. 2018) or local climate particularities associated with fructification of European beech (Drobyshev et al. 2010) or other events such as spring late frosts (Vacek & Hejcman 2012). More significant cycles occur in 10 – 18 years' periods, mainly due to repeated extensive harvesting or climatic extremes in given periods (Mausolf et al. 2018). However, detailed studies on cyclical growth of European beech in the Sudeten system are yet to be carried out.

The relation of European beech radial growth to monthly sum of precipitation was similar in all stands on the PRPs. Negative correlations were recorded in August of the previous year and in January of the current year. Positive correlations were observed in February and March of the current year. Statistically significant negative correlations were also documented in July and August of the current year. The results are comparable with Králíček et al. (2017), who present similar positive correlations until March and negative impact of precipitation on radial growth in July. In Sweden, European beech does not suffer from the lack of precipitation as much as in our country, but a minor positive effect of precipitation in early spring is detectable (Drobyshev et al. 2010).

The relation of radial growth of European beech to average monthly temperatures suggest the prevailing positive influence of temperatures, except in July of previous year. In rare cases, however, extreme frosts negatively affected radial growth in late spring (in 1996, 2011 and 2016). Similar events are reported by Vacek & Hejcman (2012) from the western parts of Krkonoše. In our study, the most significant month influencing radial growth was August in current year, similarly such as in beech forests in Balkan (Tegel et al. 2014). A comparison of our results and the study of European beech from the Orlické hory Mountains (Králíček et al. 2017) shows that our results from the Krkonoše Mts. differ in these correlations by two months earlier. Also, the results of a study carried out in Turkey show a similar trend of a shift in *Fagus orientalis* (Köse & Güner 2012). In contrast to the Swedish growth conditions (Drobyshev et al. 2010), the correlation we have found is significantly positive.

The main climatic factor affecting the growth of beech trees in the studied montane localities is the positive effect of temperature. This was also observed by Vacek & Hejcman (2012) in beech stands at higher altitudes of the Krkonoše Mountains. On the contrary, at lower altitudes of the Czech Republic high temperatures were a limiting factor of growth, especially in the growing season (Remeš et al. 2015). The altitude significantly supports the influence of climatic factors on radial growth; the positive effect of temperature on radial growth increases with the altitude, especially in June and July (Meyer & Bräker 2001; Andreassen et al. 2006; Hauck et al. 2012). A similar situation is reported from Germany and Italy, where the temperature had significant positive influence in May in montane areas (1560 m a.s.l.), while in the lowlands (420–450 m a.s.l.) the temperature in June had a negative impact on the radial growth of the beech (Skomarkova et al. 2006). In contrast, Opała-Owczarek et al. (2018) documented that the temperature from April to June is decisive for the radial growth in the mountainous parts of the Sudetes. The diameter increment is a slightly less influenced by precipitation, as described by regression quadratic model and PCA or foreign references (Ježík et al. 2016; Rohner et al. 2016). It can be assumed that the global warming and lack of precipitation will bring growth decline at lower altitudes and growth increase at higher altitudes in the centre of the beech distribution range (Penuelas et al. 2007; Kramer et al. 2010; Dulamsuren et al. 2017; Ruosteenoja et al. 2018). The trend is confirmed by gradual expansion of natural regeneration of beech in montane areas in recent years (Vacek et al. 2015c; Janík et al. 2016). Similarly, global climate change may lead to rapid decline in the growth of range-edge populations, consequent retreat of the beech distribution in southern Europe and conversely it spread to the north (Sykes & Prentice 1996; Jump et al. 2006). On the base of modern species distribution models, the ecological consequences of the range contractions would lead to serious nature conservation and forest management in future (Dyderski et al. 2018).

5. Conclusion

Growth and development of beech stands in the Krkonoše National Park is influenced by several abiotic (late frosts, droughts), biotic (beech scale, beech-leaf gall midge) and anthropogenic factors (extensive harvesting, air pollution load). The climatically significant years show that radial growth of the stands on the PRPs responded differently, but low temperatures during the growing season and lack of precipitation at the beginning of the year were the most important limiting factors. The overall effect of the average temperature on the beech diameter increase was significantly higher compared to precipitation. As regards the radial growth period, 2-year cycles were most often followed by cycles ranging from 10 to 18 years. Dendrochronological analyses of close-to-nature beech stands show us possible trends of their development in the ongoing global climate change, as European beech is considered to be one of the most important tree species in the Czech Republic.

Acknowledgement

This study was supported by the Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences (No. IGA B03/18).

References

Andreassen, K., Solberg, S., Tveito, O. E., Lystad, S. L., 2006: Regional differences in climatic responses of Norway spruce (*Picea abies* L. Karst) growth in Norway. Forest Ecology and Management, 222:211–221.

Biondi, F., Waikul, K., 2004: DENDROCLIM2002 AC+ + program for statistical calibration of climate signals in tree-ring chronologies. Computers & Geosciences, 30:303–311.

Bolte, A., Hilbrig, L., Grundmann, B., Kampf, F., Brunet, J., Roloff, A., 2010: Climate change impacts on stand structure and competitive interactions in a southern Swedish spruce-beech forest. European Journal of Forest Research, 129:261–276.

Bošeľa, M., Štefančík, I., Petráš, R., Vacek, S., 2016: The effects of climate warming on the growth of European beech forests depend critically on thinning strategy and site productivity. Agricultural and Forest Meteorology, 222:21–31.

Brázdil, R., Trnka, M., Miksovský, J., Tolasz, R., Dobrovolný, P., Rezníckova, L. et al., 2017: Drought events in the Czech Republic: past, present, future. In: 19th EGU General Assembly, proceedings from the conference held 23–28 April, 2017 in Vienna, Austria, 19285 p.

Brázdil, R., Stucki, P., Szabó, P., Řezníčková, L., Dolák, L., Dobrovolný, P. et al., 2018: Windstorms and forest disturbances in the Czech Lands: 1801–2015. Agricultural and Forest Meteorology, 250:47–63.

Bridgman, H. A., Davies, T. D., Jickells, T., Hunova, I., Tovey, K., Bridges, K. et al., 2002: Air pollution in the Krusne Hory region, Czech Republic during the 1990s. Atmospheric Environment, 36:3375–3389.

Bunn, A., Korpela, M., 2018a: Time Series Analysis in dplR, 14 p.

Bunn, A., Korpela, M., 2018b: Chronology Building in dplR, 13 p.

Bytnerowicz, A., Omasa, K., Paoletti, E., 2007: Integrated effects of air pollution and climate change on forests: A northern hemisphere perspective. Environmental Pollution, 147:438–445.

Cavin, L., Jump, A. S., 2017: Highest drought sensitivity and lowest resistance to growth suppression are found in the range core of the tree *Fagus sylvatica* L. not the equatorial range edge. Global Change Biology, 23:362–379.

Christensen, M., Hahn, K., Mountford, E. P., Ódor, P., Standovár, T., Rozenberger, D. J. et al., 2005: Dead wood in European beech (*Fagus sylvatica*) forest reserves. Forest Ecology and Management, 210:267–282.

Cicák, A., Mihál, I., Tsakov, H., Petkov, P., 2006: Actual status of the beech bark necrotic disease in North Western Bulgaria. Journal of Forest Science, 52:226–232.

Dittmar, C., Zech, W., Elling, W., 2003: Growth variations of Common beech (*Fagus sylvatica* L.) under different climatic and environmental conditions in Europe—a dendroecological study. Forest Ecology and Management, 173:63–78.

Drobyshev, I., Övergaard, R., Saygin, I., Niklasson, M., Hickler, T., Karlsson, M. et al., 2010: Masting behaviour and dendrochronology of European beech (*Fagus sylvatica* L.) in southern Sweden. Forest Ecology and Management, 259:2160–2171.

Dulamsuren, C., Hauck, M., Kopp, G., Ruff, M., Leuschner, C., 2017: European beech responds to climate change with growth decline at lower, and growth increase at higher elevations in the center of its distribution range (SW Germany). Trees - Structure and Function, 31:673–686.

Dyderski, M. K., Paź, S., Frelich, L. E., Jagodziński, A. M., 2018: How much does climate change threaten European forest tree species distributions? Global Change Biology, 24:1150–1163.

Filippo, A. D. I., Biondi, F., Maugeri, M., 2012: Bioclimate and growth history affect beech lifespan in the Italian Alps and Apennines. Global Change Biology, 18:960–972.

Gavin, D. G., Peart, D. R., 1993: Effects of beech bark disease on the growth of American beech (*Fagus grandifolia*). Canadian Journal of Forest Research, 23:1566–1575.

Geßler, A., Keitel, C., Matyssek, R., Seiler, W., Rennenberg, H., 2007: Potential risks for European beech (*Fagus sylvatica* L .) in a changing climate Potential risks for European beech (*Fagus sylvatica* L .). Trees, 21:1–11.

Granier, A., Reichstein, M., Bréda, N., Janssens, I. A., Falge, E., Ciais, P., 2007: Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003. Agricultural and Forest Meteorology, 143:123–145.

Hartl-Meier, C., Zang, C., Büntgen, U., Esper, J., Rothe, A., Göttlein, A. et al., 2018: Uniform climate sensitivity in tree-ring stable isotopes across species and sites in a mid-latitude temperate forest. Tree Physiology, 35:4–15.

Hauck, M., Zimmermann, J., Jacob, M., Dulamsuren, C., Bade, C., Ahrends, B. et al., 2012: Rapid recovery of stem increment in Norway spruce at reduced SO_2 levels in the Harz Mountains, Germany. Environmental Pollution, 164:132–141.

Holuša, J., Lubojacký, J., Čurn, V., Tonka, T., Lukášová, K., Horák, J., 2018: Combined effects of drought stress and Armillaria infection on tree mortality in Norway spruce plantations. Forest Ecology and Management, 427:434–455.

Hůnová, I., Schreiberová, M., 2012: Ambient ozone phytotoxic potential over the Czech forests as assessed by AOT40. iForest-Biogeosciences and Forestry, 5:153.

IFER 2017: Field-Map Software & Hardware Catalogue – www.fieldmap.com. IFER – Monitoring and Mapping Solutions, Ltd., Jílové u Prahy, 51 p.

Janík, D., Král, K., Adam, D., Hort, L., Samonil, P., Unar, P. et al., 2016: Tree spatial patterns of *Fagus sylvatic*a expansion over 37years. Forest Ecology and Management, 375:134–145.

Ježík, M., Blaženec, M., Kučera, J., Střelcová, K., Ditmarová, L., 2016: The response of intra-annual stem circumference increase of young European beech provenances to 2012–2014 weather variability. IForest, 9:960–969.

Jump, A. S., Hunt, J. M., Penuelas, J., 2006: Rapid climate change-related growth decline at the southern range edge of *Fagus sylvatica*. Global Change Biology, 12:2163–2174.

Kasson, M. T., Livingston, W. H., 2009: Spatial distribution of Neonectria species associated with beech bark disease in northern Maine. Mycologia, 101:190–195.

Kasson, M. T., Livingston, W. H., 2012: Relationships among beech bark disease, climate, radial growth response and mortality of American beech in northern Maine, USA. Forest Pathology, 42:199–212.

Kolář, T., Čermák, P., Oulehle, F., Trnka, M., Štěpánek, P., Cudlín, P. et al., 2015: Pollution control enhanced spruce growth in the "Black Triangle" near the Czech–Polish border. Science of the Total Environment, 538:703–711.

Kooijman, A. M., Emmer, I. M., Fanta, J., Sevink, J., 2000: Natural regeneration potential of the degraded Krkonoše forests. Land Degradation and Development, 11:459–473.

Köse, N., Güner, H. T., 2012: The effect of temperature and precipitation on the intra-annual radial growth of *Fagus orientalis* Lipsky in Artvin, Turkey. Turkish Journal of Agriculture and Forestry, 36:501–509.

Král, J., Vacek, S., Vacek, Z., Putalová, T., Bulušek, D., Štefančík, I., 2015: Structure, development and health status of spruce forests affected by air pollution in the western Krkonoše Mts. in 1979–2014. Lesnícky časopis - Forestry Journal, 61:175–187.

Králíček, I., Vacek, Z., Vacek, S., Remeš, J., Bulušek, D., Král, J. et al., 2017: Dynamics and structure of mountain autochthonous spruce-beech forests: Impact of hilltop phenomenon, air pollutants and climate. Dendrobiology, 77:119–137.

Kramer, K., Degen, B., Buschbom, J., Hickler, T., Thuiller, W., Sykes, M. T. et al., 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.

Kroupová, M., 2002: Dendroecological study of spruce growth in regions under long-term air pollution load. Journal of Forest Science, 48:536–548.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J. et al., 2010: Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management, 259:698–709.

Ling, K. A., Power, S. A., Ashmore, M. R., 1993: A survey of the health of *Fagus sylvatica* in southern Britain. Journal of Applied Ecology, 30:295–306.

Lokvenc, T., 1978: Toulky krkonošskou minulostí. Kruh, Hradec Králové, 267 p.

Matějka, K., Vacek, S., Podrázský, V., 2010: Development of forest soils in the Giant Mts. in the period 1980–2009. Journal of Forest Science, 56:485–504.

Materna, J., 1989: Air pollution and forestry in Czechoslovakia. Environmental Monitoring and Assessment, 12:227–239.

Mausolf, K., Wilm, P., Härdtle, W., Jansen, K., Schuldt, B., Sturm, K. et al., 2018: Higher drought sensitivity of radial growth of European beech in managed than in unmanaged forests. Science of the Total Environment, 642:1201–1208.

Meyer, F. D., Bräker, O. U., 2001: Climate response in dominant and suppressed spruce trees, *Picea abies* (L.) Karst., on a subalpine and lower montane site in Switzerland. Ecoscience, 8:105–114.

Mihál, I., Cicák, A., Tsakov, H., 2014: Selected biotic vectors transmitting beech bark necrotic disease in Central and South-Eastern Europe. Folia Oecologica, 41:62–74.

Ministry of Agriculture, 2017: Zpráva o stavu lesa a lesního hospodářství České republiky v roce 2016. Praha, 132 p.

Motta, E., Annesi, T., Pane, A., Cooke, D. E. L., Cacciola, S. O., 2003: A new Phytophthora sp. causing a basal canker on beech in Italy. Plant Disease, 87:1005–1005.

Nožička, J., 1961: Vývoj krkonošských lesů na Vrchlabsku a Maršovsku. Práce VÜLHM, 18:161–228.

Nussbaumer, A., Waldner, P., Apuhtin, V., Aytar, F., Benham, S., Bussotti, F. et al., 2018: Impact of weather cues and resource dynamics on mast occurrence in the main forest tree species in Europe. Forest Ecology and Management, 429:336–350.

Opała-Owczarek, M., Błaś, M., Owczarek, P., Sobik, M., Godek, M., 2019: A dendroclimatological study of east- and west-facing slopes in mountainousareas subjected to strong air pollution (the Sudetes, Central Europe), Physical Geography, 40:186–208.

Övergaard, R., 2010: Seed Production and Natural Regeneration of Beech (*Fagus sylvatica* L .) in Southern Sweden. Swedish University of Agricultural Sciences, 74 p.

Peters, R., 1997: Beech Forests. Kluwer Academic Publishers , Dordrecht, The Netherlands, p. 39–40.

Paoletti, E., Schaub, M., Matyssek, R., Wieser, G., Augustaitis, A., Bastrup-Birk, A. M. et al., 2010: Advances of air pollution science: from forest decline to multiple-stress effects on forest ecosystem services. Environmental Pollution, 158:1986–1989.

Penuelas, J., Ogaya, R., Boada, M., S. Jump, A., 2007: Migration, invasion and decline: changes in recruitment and forest structure in a warming-linked shift of European beech forest in Catalonia (NE Spain). Ecography, 30:829–837.

Power, S. A., Ashmore, M. R., 1996: Nutrient relations and root mycorrhizal status of healthy and declining beech (*Fagus sylvatica* L.) in southern Britain. Water, Air, and Soil Pollution, 86:317–333.

Remeš, J., Bílek, L., Novák, J., Vacek, Z., Vacek, S., Putalová, T., Koubek, L., 2015: Diameter increment of beech in relation to social position of trees, climate characteristics and thinning intensity. Journal of Forest Science, 61:456–464.

Rohner, B., Weber, P., Thürig, E., 2016: Bridging tree rings and forest inventories: How climate effects on spruce and beech growth aggregate over time. Forest Ecology and Management, 360:159–169.

Ruosteenoja, K., Markkanen, T., Venäläinen, A., Räisänen, P., Peltola, H. ,2018: Seasonal soil moisture and drought occurrence in Europe in CMIP5 projections for the 21st century. Climate Dynamics, 50:1177–1192.

Rydval, M., Wilson, R., 2012: The impact of industrial SO_2 pollution on north Bohemia conifers. Water, Air, & Soil Pollution, 223:5727–5744.

Samec, P., Vránová, V., 2005: Bioindication of soil sorption properties in the substitute tree stands at submontane conditions. In: Šimková, P.: MendelNet 2005, Contemporary state and development trends of forest in cultural landscape. Brno, Mendelova univerzita v Brně, p. 113–119.

Schütz, J. P., 2001: Der Plenterwald. Parey Buch- verlag, Berlin, 207 p.

Skomarkova, M. V., Vaganov, E. A., Mund, M., Knohl, A., Linke, P., Boerner, A. et al., 2006: Inter-annual and seasonal variability of radial growth, wood density and carbon isotope ratios in tree rings of beech (*Fagus sylvatica*) growing in Germany and Italy. Trees, 20:571–586.

Slanař, J., Vacek, Z., Vacek, S., Bulušek, D., Cukor, J., Štefančík, I. et al., 2017: Long-term transformation of submontane spruce-beech forests in the Jizerské hory Mts.: Dynamics of natural regeneration. Central European Forestry Journal, 63:212–224.

Sykes, M. T., Prentice, I. C., 1996: Climate change, tree species distributions and forest dynamics: a case study in the mixed conifer/northern hardwoods zone of northern Europe. Climatic Change, 34:161–177.

Špulák, O., Souček, J., 2010: The Sibyla model and development of beech forests affected by air pollution. Central European Journal of Biology, 5:317–383.

Team R Core, 2018: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Tegel, W., Seim, A., Hakelberg, D., Hoffmann, S., Panev, M., Westphal, T., Büntgen, U., 2014: A recent growth increase of European beech (*Fagus sylvatica* L.) at its Mediterranean distribution limit contradicts drought stress. European Journal of Forest Research, 133:61–71.

Tesař, V., Balcar, V., Lochman, V., Nehyba, J., 2011. Přestavba lesa zasaženého imisemi na Trutnovsku. Brno, Mendelova univerzita v Brně, 177 p.

Tolazs, R., 2007: Atlas podnebí Česka. Praha a Olomouc, 256 p.

Trnka, M., Brázdil, R., Možný, M., Štěpánek, P., Dobrovolný, P., Zahradníček, P. et al., 2015: Soil moisture trends in the Czech Republic between 1961 and 2012. International Journal of Climatology, 35:3733–3747.

Vacek, S., 1988: Dynamics of the defoliation of beech forest stands under the influence of air pollution. In: 3. IUFRO Buchensymposium. Zvolen, 3. 6. – 6. 6. 1988. Zvolen, VŠLD, p. 377–388.

Vacek, S., Matějka, K., Simon, J., Malík, V., Schwarz, O., Podrázský, V. et al., 2007: Zdravotní stav a dynamika lesních ekosystémů Krkonoš pod stresem vyvolaným znečištěním ovzduší. Folia forestalia Bohemica, Kostelec nad Černými lesy, Lesnická práce, 4:216 p.

Vacek, S., Nosková, I., Bílek, L., Vacek, Z., Schwarz, O., 2010: Regeneration of forest stands on permanent research plots in the Krkonoše Mts. Journal of Forest Science, 56:541–554.

Vacek, S., Hejcman, M., 2012: Natural layering, foliation, fertility and plant species composition of a *Fagus sylvatica* stand above the alpine timberline in the Giant (Krkonoše) Mts., Czech Republic. European Journal of Forest Research, 131:799–810.

Vacek, S., Bílek, L., Schwarz, O., Hejcmanová, P., Mikeska, M., 2013: Effect of Air Pollution on the Health Status of Spruce Stands Effect of Air Pollution on the Health Status of Spruce Stands. Mountain Research and Development, 33:40–50.

Vacek, S., Hůnová, I., Vacek, Z., Hejcmanová, P., Podrázský, V., Král, J., 2015a: Effects of air pollution and climatic factors on Norway spruce forests in the Orlické hory Mts. (Czech Republic) 1979–2014. European Journal of Forest Research, 134:1127–1142.

Vacek, S., Černý, T., Vacek, Z., Podrázský, V., Mikeska, M., Králíček, I., 2017: Long-term changes in vegetation and site conditions in beech and spruce forests of lower mountain ranges of Central Europe. Forest Ecology and Management, 398:75–90.

Vacek, Z., Vacek, S., Bílek, L., Remeš, J., Štefančík, I., 2015b: Changes in horizontal structure of natural beech forests on an altitudinal gradient in the Sudetes. Dendrobiology, 73:33–45.

Vacek, Z., Vacek, S., Podrázský, V., Bílek, L., Štefančík, I., Moser, W. K. et al., 2015c: Effect of tree layer and microsite on the variability of natural regeneration in autochthonous beech forests. Polish Journal of Ecology, 63:233–246.

Viewegh, J., Kusbach, A., Mikeska, M., 2003: Czech forest ecosystem classification. Journal of Forest Science, 49:85–93.

Wainhouse, D., Gate, I. M., Lonsdale, D., 1988: Beech Resistance to the Beech Scale: A Variety of Defenses. In: Mattson, V. J., Levieux, J., Bernard-Dagan, C. (eds.): Mechanisms of Woody Plant Defenses against Insects. Springer, New York, NY, p. 277–293.

Urban, J., 2000: Beech gall midge (*Mikiola fagi* Htg.) and its natural enemies. Journal of Forest Science, 46:543–568.

Zang, C., Hartl-Meier, C., Dittmar, C., Rothe, A., Menzel, A., 2014: Patterns of drought tolerance in major European temperate forest trees: Climatic drivers and levels of variability. Global Change Biology, 20:3767–3779.

Zang, C., Rothe, A., Weis, W., Pretzsch, H., 2011: Zur baumarteneignung bei klimawandel: Ableitung der trockenstress- anfälligkeit wichtiger waldbaumarten aus jahrringbreiten. Allgemeine Forst- und Jagdzeitung, 182:98–112.

Cent. Eur. For. J. 65 (2019) 103–120 sciendo DOI: 10.2478/forj-2019-0009

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Forest management scenarios modelling with morphological analysis – examples taken from Podpoľanie and Kysuce

Rudolf Navrátil[1, 2] *, Yvonne Brodrechtová[1], Róbert Sedmák[1], Ján Tuček[1]

[1] *Technical University in Zvolen, Faculty of Forestry, T. G. Masaryka 24, SK – 960 53 Zvolen, Slovak Republic*
[2] *Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 1176, CZ – 165 21 Praha 6 – Suchdol, Czech Republic*

Abstract
Scenarios modelling offers to forest management an option how to envision complex future associated with various natural, social, or economic uncertainties. The challenge is what modelling method to choose as many methodological approaches to scenario building exists. Morphological analysis is a basic modelling method for structuring and analysing a whole set of relationships existing in multi-dimensional, non-quantifiable, and complex topics. Especially, its application is relevant when abstract policy or market-driven challenges need to be investigated. In this study, we demonstrated the usefulness of the morphological analysis with an example case taken from forest management in Slovakia. The use of the method has enabled, from a number of uncertain futures, to identify three possible, plausible and consistent future scenarios of possible forest management direction in the regions of Podpoľanie and Kysuce. Additionally, the future scenario modelling as prognostic method of qualitative research supported by quantitative models or forestry DSS could introduce participation and more dimensions into forest management modelling. Thus, the future scenarios modelling offers new methodological possibilities to how to deal with increasing uncertainties associated with increasing demands for various ecosystem services or negative impacts of climate change, that forest management in Slovakia will face in the near future.

Key words: forest management; future variations; coherence of scenarios; consistency matrix; cluster map

Editor: Róbert Marušák

1. Introduction

Although the term "scenario" comes from the field of dramatic art, from a prognostic point of view, it is a method of predictive analysis to forecasting the future pioneered by Kahn (Glenn & Gordon 2009). Future scenarios, originally developed for military planning purposes and later adapted by business world, have emerged since the late 1990s as an important tool in environmental analysis and policy formulation (Evans et al. 2008). Scenarios offer an excellent option for how to deal with uncertain future for which we have to make decisions today. They do no forecast the future-the most probable one- but rather search for multiple plausible futures.

Scenarios have been also used in assessing future forest management, which faces uncertainties mainly associated with changing the climate, socio-economic conditions, or technological developments (Hoogstra et al. 2017). Therefore, in the forest management, the scenarios could be used for illustration of the trade-off between ecosystem services, evaluation of different forest management practices, and/or assessment of potential future developments (e.g. Nordström et al. 2013; Korosuo et al. 2014; Albert et al. 2015; Carlsson et al. 2015; Hengeveld et al. 2017). Future scenarios method is often used also as a means of communication in initiating discussions with the public and stakeholders (Gaßner & Steinmüller 2004). Wollenberg et al. (1999, 2000) identified future scenarios as a tool encouraging the cooperation of forest owners, managers and stakeholders. The scenarios can be implemented in a participatory manner as a workshop-based activity with the participation of forest owners, decision makers and other stakeholders. The method stimulate dialogue in the searching for barriers and driving forces of further development as well as in planning processes (Evans et al. 2008). In recent years, the forestry sector in Slovakia has to deal with changing climatic and environmental conditions and higher demands of the public for forest products and ecosystem services. So, future scenarios implemented by a participatory approach could be an

**Corresponding author. Rudolf Navrátil, e-mail: navratil@fld.czu.cz*

appropriate response to the ever-increasing public call for sustainable forest management. What is also confirmed by the fact that public participation in sustainable forestry in Slovakia is still very formal and difficult (Kovalčík et al. 2012; Sarvašová et al. 2014; Sarvašová 2016).

The challenge for the scenarios modelling is how to capture the complexity of the world. In order to inspire and influence the decision making, scenarios must be sufficiently reliable and consistent. Many different methodological approaches to how to deal with scenarios modelling exist (e.g. Bishop et al. 2007; Amer et al. 2013), also with various application in the field of forest management (e.g. Hoogstra et al. 2017). Bishop et al. (2007) described eight general categories (types) of scenario modelling techniques including those that deal with dimensions of uncertainty - GBN matrix (Schwartz 1991) and morphological analysis. By applying of these techniques, the scenarios are constructed by first identifying the sources of uncertainty that are the basis for alternative futures, depending on how the uncertainties play out. While GBN matrix of four cells represents alternatively the four combinations of the poles of the two uncertainties, the morphological analysis matrix contains any number of uncertainties and any number of alternative states for each uncertainty. Morphological analysis allows to narrow down all possible combinations by deciding which combinations of uncertainties (factors) and alternatives (variations) are plausible and important in modelling consistent scenarios for the future (Heinecke 2006).

Although a large number of possible combinations can be considered as a disadvantage of morphological analysis, there are several sophisticated software tools overcoming the problem. Some of the best-known tools in the field of morphological analysis and future scenarios modelling are Morphol (Godet & Roubelat 1996), Casper (Eriksson & Ritchey 2002) Godet Toolbox (2003), Scenario Analysis Tool Suite (Dilek 2009) or Parmenides EIDOS tool suite provided by Parmenides Foundation.

The goal of this paper is to present an application of future scenario modelling technique – morphological analysis in the development of forest management scenarios in two Slovak regions of Podpoľanie and Kysuce. The uncertainties - drivers and barriers affecting forest management in both regions were derived with the help of participatory manner by in-person interviews and structural analysis presented in previous papers (Navrátil et al. 2016; Brodrechtová et al. 2018). In this paper we present the method of examining possible, credible and plausible future alternatives of these derived uncertainties. Attention is paid to the process of assessing the overall consistency and coherence of scenarios implemented with the strong support of analytical functions of Parmenides EIDOS tool suite. As the result, three possible future scenarios of forest management presented in a short description were developed for each region.

2. Morphological analysis in general

The general morphological analysis is a basic, conceptual (non-quantified) modelling method for structuring a conceptual problem space - called a morphospace - and, through a process of existential combinatorics, synthesising a solution space (Ritchey 2018). More precisely, the goal of the method is in identifying and structuring all possible factors and solutions for non-reducible, complex problem spaces that often include human behaviour and political aspects (Johansen 2018).

The morphological process characterized by repeated sequences of analysis and synthesis generally moves ahead in five distinct steps (Johansen 2018). The first one is based on the detailed formulation of the problem while acknowledging that a precise definition of the issue might be unlikely. Within the second step, the defined problem is split into factors that set boundaries to it. Each factor must be carefully selected and characterized by a set of possible variations. The third step is crucial as the morphological box is designed. This box also called multidimensional matrix represents all combinations of the factors and their variations. As some combinations are inconsistent or impossible-called also a problem space-, in the fourth step this space needs to be reassessed. In the search for a solution space, the consistency of the combinations is checked. Generally, consistency is assessed according to two criteria: (1) logical consistency- internal relations of the factors cannot be contradictory, and (2) empirical consistency- solution should not be empirically impossible (Amer et al. 2013; Johansen 2018). In the final fifth step the remaining solution space is surveyed and the best solutions - scenarios are selected.

Overall, Ritchey (2018) pointed the advantage of morphological analysis in recognizing new relationships or configurations, which may not be so evident and which we might have overlooked by less systematic methods. Importantly, it encourages the identification and investigation of boundary conditions, i.e. the limits and extremes of different contexts and factors.

3. Application of morphological analysis

3.1. Definition of the problem

As it is difficult to describe a future forest management in a holistic way, scenarios modelling has to focus on specific factors and omit issues that might be of relevance in other research contexts. In this respect it was essential to define the time horizon, the scenario-space via thematic coverage and the geographical scope (Greeuw et al. 2000; van Notten et al. 2003).

In the study we were concerned with assessment of possible future direction of forest management in the regions of Podpoľanie and Kysuce. Both case study areas (CSAs) represent traditional agricultural-forest regions in Slovakia with more than 50% of forest cover.

The territories have varied forms of land use such as forests, arable land, meadows, wetlands and dispersed as well as concentrated settlements. Significant parts of both regions belong to the network of protected areas. The forest ownership structure, health status, and current structure of forest stands are the biggest contrasts between the two CSAs. Considering the similarities and differences, the territories were chosen for application of future forest management scenarios modelling. Specifically, we described the forested landscape future and the development of the path from the present (2010) to the future forest management in 2040 while considering the influence of ecological, socioeconomic and political factors. Taking into account the comparatively slow-changing system of forests the time horizon of 30 years can be considered as a short- or medium-term approach. The task was to create three possible, credible and mutually different future scenarios indicating possible forestry development over the next 30 years in each CSA.

The process was supported by Parmenides EIDOS tools suite offering several tools for analysis and scenarios building. The tool suite is used globally by public institutions in decision-making and strategic decisions, especially for complex processes requiring a multidisciplinary approach.

3.1.1 Case study area Podpoľanie

Case study area is located in the central part of Slovakia within Detva district. Podpoľanie is traditional agricultural-forest region with specific cultural landscape development characterized by dispersed rural settlements and traditional land use (e.g. small private owners). Due to very favourable climatic conditions, Podpoľanie region is one of the most productive forest areas in Slovakia. Especially upper part covered by beech, fir-beech and spruce forests is very productive. Forest stands are relatively healthy and stable with predominance of original tree species composition, but there are also stands with artificially inserted spruce. State forest ownership dominates (almost 85%), so State enterprise Forests of the SR is the strongest forestry entity in the CSA. From non-state subjects the biggest share has communal (8%), private and church ownership (3%), while the proportion of municipal forests is very small. The northern mountain area of the region dominated by the massif of Poľana Mt. is part of the Carpathian Arc. Due to the richness of fauna and flora (nearly 2700 species), this part of CSA is under the Poľana Protected Landscape Area. Moreover, more than half of territory (57%) is covered by NATURA 2000 network. As the drink water reservoir Hriňová, located in CSA supplies drinking water to the surrounding cities, the water management function of the surrounding forest stands is equally important. Thanks to the Protected Game Area Poľana, providing a coordinated ecological and large-scale management of the game, the region is known for its hunting tradition. The case study area is also intensively used for recreational activities such as hiking, mushroom picking, cycling as well as winter sports. For more information see also Navrátil et al. (2016) and Brodrechtová et al. (2018).

3.1.2 Case study area Kysuce

Case study area located in north-western Slovakia completely covers two districts – Čadca and Kysucké Nové Mesto. The rural population (56%) prevails in the region, inhabiting 37 mostly rural municipalities. The region represents an agricultural and forest landscape forested by coniferous forests (84%) mainly concentrated in the higher positions of the northern part of the territory. Almost half of the CSA belongs to the Kysuce Protected Landscape Area covering the northwest and northeast parts of the region. In the past the tree species composition in Kysuce has been significantly affected by the establishment of spruce monocultures. However, in the last decades the health of spruce forests in Kysuce has declined (e.g. Konôpka 2004; Kulla 2009) due to intensive and widespread necrosis (Hlásny et al. 2010; Bošeľa et al. 2014). This unfavourable situation causes frequent calamities, so the Kysuce belongs to the Slovak regions with highest volume of incidental felling (Vakula 2011). This situation mainly affects smaller non-state forest owners, as the forest ownership in Kysuce is highly fragmented with a large proportion of non-state owners (46%). The largest share has the private ownership (33%), followed by state (20%) and communal (13%). In addition, there is a large area of forests with unsettled ownership due to still ongoing restitution process (34%). For more information see also Navrátil et al. (2016) and Brodrechtová et al. (2018).

3.2. Characteristics of key factors and their variations

Identification and selection of key factors for the selected CSAs were based on the results of studies done by Riemer et al. (2013), Navrátil et al. (2016) and Brodrechtová et al. (2018). Within these studies, a wide group of drivers and barriers of forest management have been created at first. From this group, the set of relevant factors were identified and finally, key factors were isolated for each CSA.

The drivers and barriers have been analysed at the local level of CSAs, as well as at the national and EU levels. Their identification was based on primary data (structured in-person interviews) and secondary data (output of qualitative analysis of national and European documents). Brodrechtová et al. (2018) identified via 50 in-person interviews with forest owners, managers and other relevant stakeholders from Podpoľanie and Kysuce 22 drivers and barriers shaping forest management in the future from the local perspective. More precisely, biophysical conditions and attributes of the community, including the political and economic context, institutions, and discourses, were among the significant drivers affecting forest owners and managers, and their interactions and decisions concerning forest management in the Podpoľanie and Kysuce (Brodrechtová et al. 2018). Secondary data were analysed in the form of desktop research. An extensive review of existing national documents (e.g. strategic and prognostic documents related to forestry, rural economy and the nature protection) resulted in the isolation of subset of 28 drivers and barriers, including bio-physical conditions and attributes of the community, political and economic contexts, and institutions that can potentially determine decisions concerning forest management in Slovakia (national level) (Navrátil et al. 2016). In addition, an extensive review of existing national documents and EU documents resulted into the isolation of 35 drivers and barriers representing EU level (Riemer et al. 2013).

From the group of 85 local, national and EU drivers and barriers Navrátil et al. (2016) identified 20 relevant factors for each CSA. Reduction was completed within an expert workshop (10 experts from Technical University in Zvolen and National Forest Centre). From the list of 85 factors, every expert chose 20 factors considered the relevance for the further development of forest management in the CSAs and sorted all factors by importance. To facilitate the listing procedure the factors were structured according to STEEP analysis that provides a useful framework to assist experts in the consideration of factors external environment (Zanoli 2012). Finally, the factors were evaluated by the frequency analysis, taking into account the frequency and ranking of the factors. The set of 20 relevant factors for each CSA was subsequently grouped according to STEEP categories (‘Society’, ‘Technology’, ‘Economy’, ‘Ecology’ and ‘Politics’) (Navrátil et al. 2016).

For the purpose of scenarios creation, it was necessary to reduce number of relevant factors. Thus, the key factors were identified first, from which the final factors used to construct scenarios were selected. For the isolation of key factors, the method of structural analysis (Glenn and Gordon 2009) supported by Parmenides EIDOS were applied within participatory scenario-building workshops (forest owners, stakeholders from CSAs, national level) conducted in each CSA. As result of the workshops a set of nine key factors crucial for the future forest management in Podpoľanie and eight key factors in Kysuce were isolated (Navrátil et al. 2016).

Based on the results of the above studies and the key factors isolated, the research team chose final key factors used for designing the scenario space in each CSA. More detailed analysis of key factors, assessment of their individual character, similarity and the possibility of mutual aggregation resulted in selection of 8 final key factors in Podpoľanie and 7 final key factors in Kysuce (Table 1). According to STEEP categories the policy, economic and ecological key factors prevailed within scenarios spaces in both CSAs. Based on the information collected during the previous phases of the research, a description of each factor was drawn up (Table A1, Table A2 in Appendix A).

The key factors were split into two groups by its nature: G – Given (factors considered as unchanged and stable in the future) and U – Uncertain (factors for which at least two possible future variations are suggested). Furthermore, for each factor the possible, plausible and alternative future variations for the next 30 years were created by research team. Three basic requirements were taken into account: (i) the future variations should integrate the results of the structural analysis and the available scientific information on the individual key factors, (ii) the future variations should be as plausible as possible, and (iii) the future variations should differ in a meaningful way. Total set of 20 possible future variations of factors for Podpoľanie and 18 variations for Kysuce has been created. Description and characteristics of created variations are provided in Appendix A of this paper (Table A3, Table A4).

3.3. Design of morphological box

3.3.1 Weights and probability of occurrence

Derived sets of key factors and their possible future variations represented individual dimensions of the future space of 30-years scenarios for Podpoľanie and Kysuce. Morphological boxes were derived by the research team in Parmenides EIDOS. The morphological box for Podpoľanie contained 8 factors and their 20 future variations (Fig. 1) while scenario’s space matrix for Kysuce was represented by 7 factors and 18 variations (Fig. 2).

Table 1. Final key factors (with STEEP categories) selected for constructing of scenarios for Podpoľanie and Kysuce.

8 factors in CSA Podpoľanie: 7 uncertain factors U1–U7, 1 given factor G1							
U1 State of forests Ecology	U2 Policies and legislation Policy	U3 Timber/Bioenergy market Economy	U4 Forest owner’s economic situation Economy	U5 Non-wood ecosystem services Ecology	U6 Innovation and technology Technology	U7 Codes of conduct Society	G1 Forest ownership Policy
7 factors in CSA Kysuce: 7 uncertain factors U1–U7							
U1 State of forests Ecology	U2 Forest ownership Policy	U3 Subsidies Policy	U4 Forest owner’s economic situation Economy	U5 Timber market Economy	U6 Innovation and technology Technology	U7 Population Society	

The significance of the individual factors for future forest management in CSAs was assessed by research team members via the weighting factors (numbers in the top row) and the probability of occurrence of each variation was expressed in percentage (numbers in lighter boxes). The significance of the individual key factor was expressed by assigning the appropriate weights to each factor with the sum of weights being 100. The process was carried out in the framework of the discussion, using the expertise and knowledge base of the expert team, characteristics of factors and findings from previous research steps.

Each future factor's variation was associated with probabilities of its occurrence in the future, based on the assessment how probable a variation is compared to the other alternatives in the scenarios space. Within the discussion research team members answered the question: *What is the probability that a given variation occurs over the next 30 years*? Then the probability of its occurrence in percentage was attributed to each variation, while the sum of the percentages of all variations within the factor was 100%. Due to its nature the given factor G1 – Forest ownership (in CSA Podpoľanie) was associated with a 100% probability, as it was assumed that the owner's structure would not change.

3.3.2 Consistency matrix

Within the created scenarios spaces the coherence of variations was assessed by defining relationships between the variations on the basis of internal consistency. The consistency was assessed by research team members during several brainstorming sessions with the support of Consistency Matrix tool of Parmenides EIDOS. The consistency matrix measures the logical fit of two variations. A higher consistency level indicates better coexistence of the two alternatives. A lower consistency rating indicates a greater degree of friction between the variations. Research team discussed and evaluated each variations pair by answering the questions: *Do the two variations make sense together*? *How well or poorly do they fit together*? The evaluation scale by Parmenides EIDOS was used (Table 2).

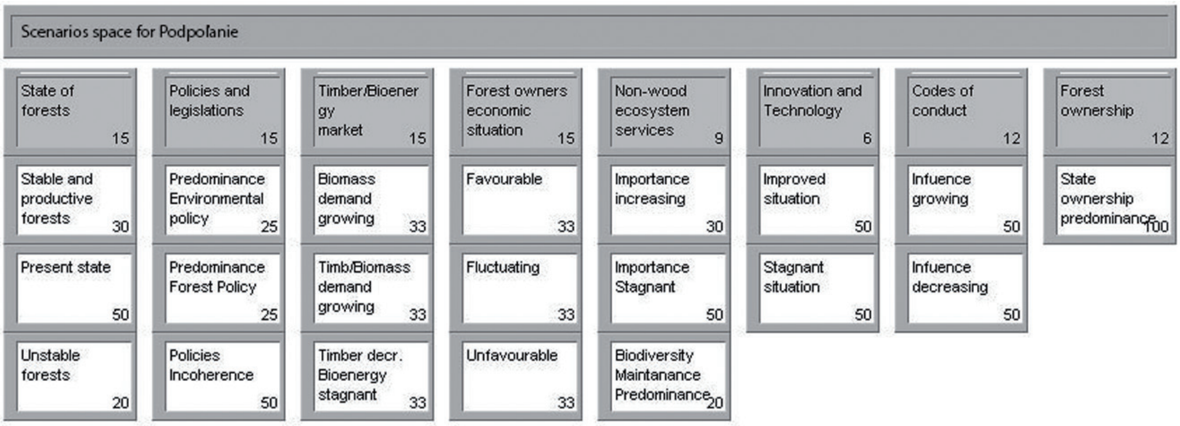

Fig. 1. Morphological box for Podpoľanie.

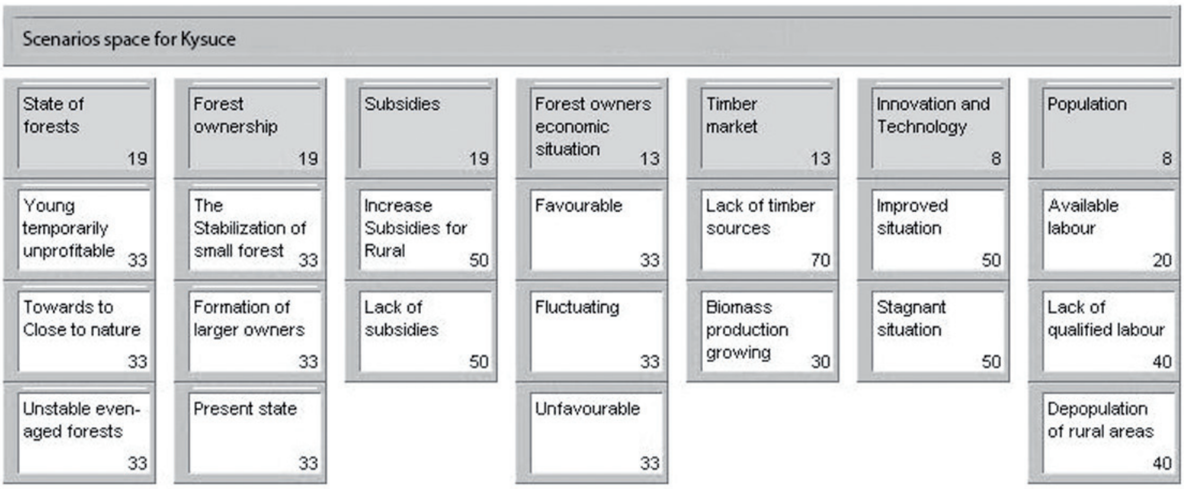

Fig. 2. Morphological box for Kysuce.

Table 2. Consistency evaluation scale used for filling the consistency matrix.

−3	*Complete inconsistency.* Both projections exclude each other absolutely and cannot go together in a plausible scenario.
−2	*Strong partial inconsistency.* Both projections strongly contradict each other. Their common appearance affects the credibility of a scenario strongly.
−1	*Light partial inconsistency.* Both projections contradict each other easily. Their common appearance lightly affects the credibility of a scenario.
0	*Neutrally or independently of each other.* Both projections do not influence each other and their common appearance does not influence the credibility of a scenario.
+1	*Light mutual support.* Both projections can coexist easily in a scenario.
+2	*Strong mutual support.* Both projections can go together rather well.
+3	*Very strong mutual support.* The common appearance of both projections supports the strong credibility of the scenario.

The consistency values for each pair of variations were determined as a consensus after the discussion. In the case where was really difficult to assess relationships of the variations, the neutral dependency was assigned (value 0). The consistency for all combinations of variations was assessed by filling the matrices for both CSAs (Fig. 3, 4). The direction of impact does not have to be taken into consideration, thus it was sufficient to fill the area above the diagonal in the matrix. The consistency calculation was carried out by means of Parmenides EIDOS. The software calculates with a full enumeration all possible scenarios combinations with their internal consistencies. In consistency matrices in both CSAs, the

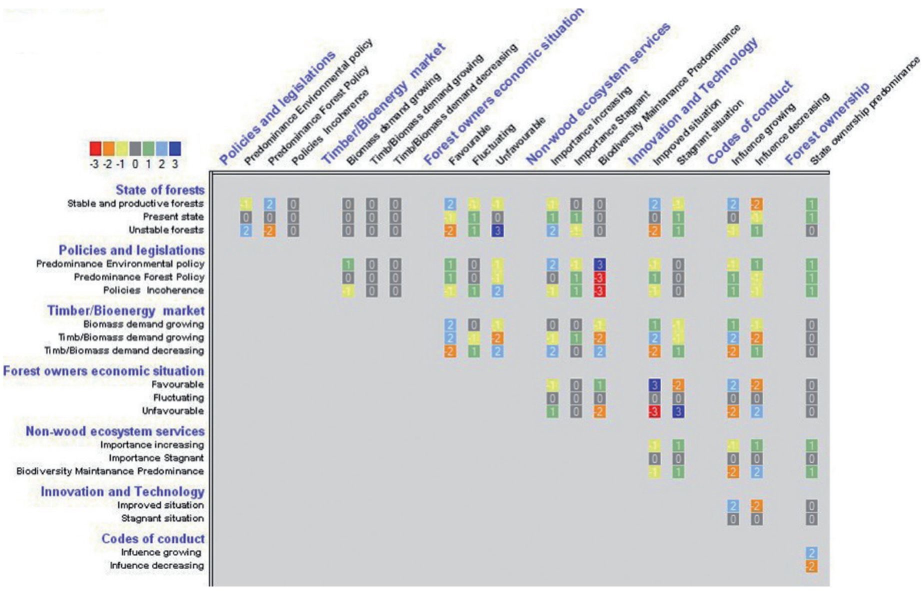

Fig. 3. Consistency matrix for Podpoľanie (−3 complete inconsistency, +3 strong consistency).

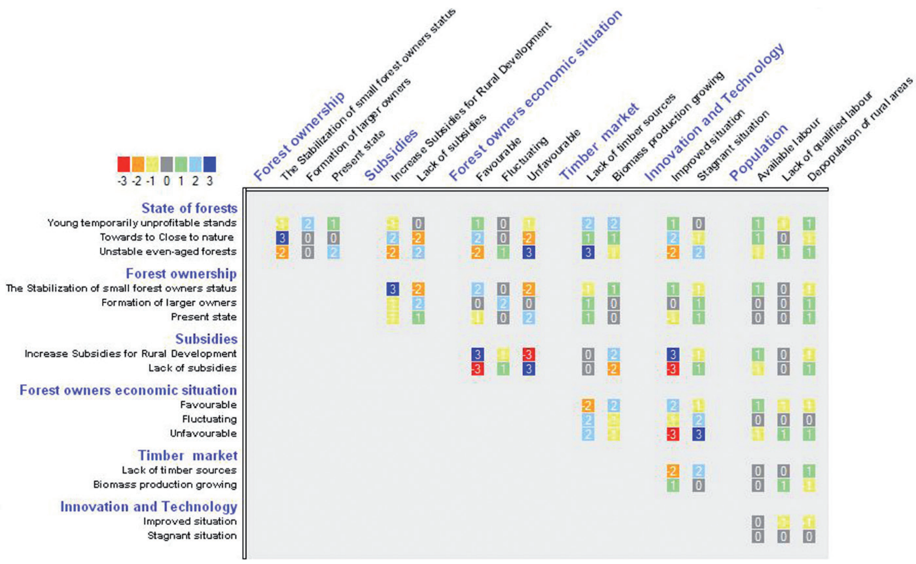

Fig. 4. Consistency matrix for Kysuce (−3 complete inconsistency, +3 strong consistency).

most commonly assigned consistency value was 0 (37% in Podpoľanie, 25% in Kysuce), followed by +1 (20% in Podpoľanie, 22% in Kysuce) and −1 (18% in Podpoľanie, 21% in Kysuce). The predominance of combinations 'neutrally or independently' (value 0) meant frequent occurrence of projections that do not affect each other but also the fact that it had often been difficult to assess the relationships of the variations.

3.3.3 Cluster map

Subsequently, clustering of coherent combinations of possible variations (scenarios) was carried out by Cluster Map tool of Parmenides EIDOS. The calculation was based on the number of factors and their assigned weights, a number of variations, their probabilities and consistency degrees assigned in consistency matrix. The cluster map displayed generated scenarios in two-dimensional distribution built up on their similarity and overall consistency. The cluster view is based on a complex projection algorithm and shows the 100 most consistent scenarios on a cluster map pooling single scenario (shown as circles) to clusters according to their similarity. The closer the circles that represent scenarios are, the more similar are the scenarios; the farther they are apart, the more different they are.

Internal consistency of scenarios is expressed by size of the circle in the map. The larger circle, the more internally consistent scenario and vice versa the small circle means a scenario with a small internal consistency. Calculation of overall degrees of consistency of individual scenarios was done by Parmenides EIDOS using scaled pairwise consistency assessment, where a weighting function assigns numerical values to the Likert-levels and the average of the consistency values of the involved tuples is calculated (Kempf 2015). Degrees of consistency (dimensionless numbers) represented overall

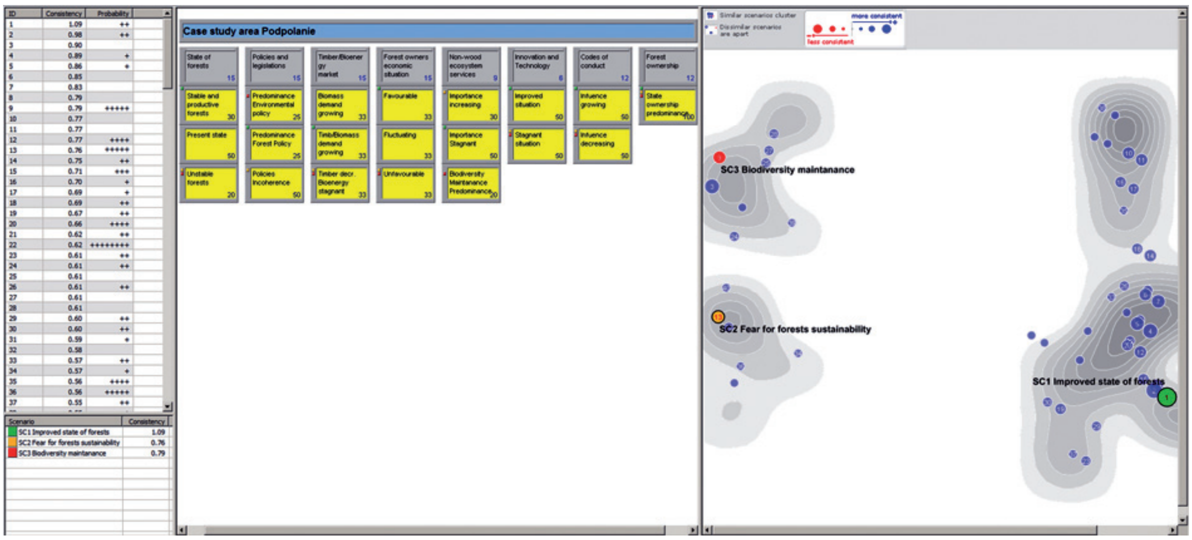

Fig. 5. Cluster map, morphological box, consistency degrees, probabilities and marked selected scenarios for Podpoľanie.

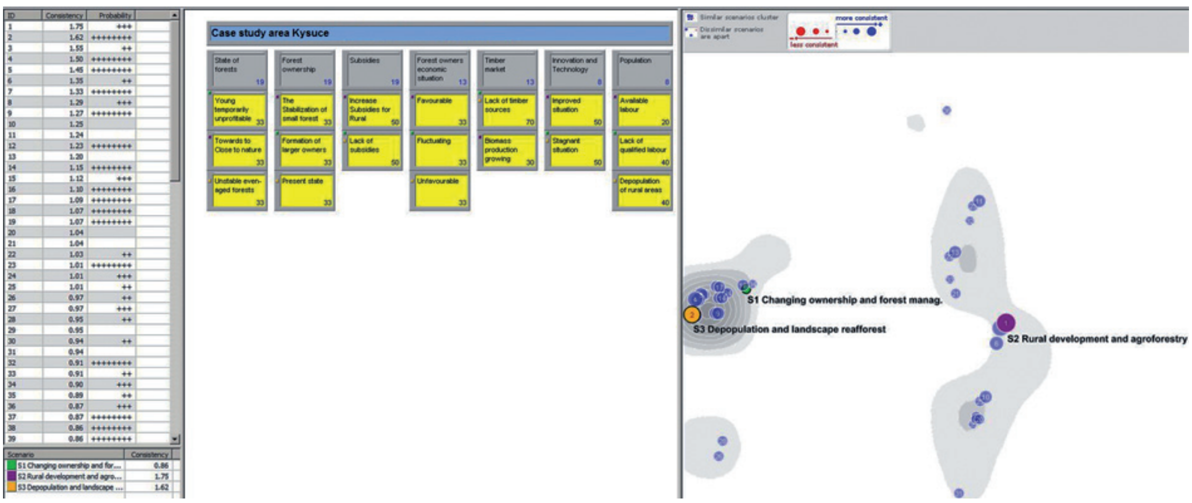

Fig. 6. Cluster map, morphological box, consistency degrees, probabilities and marked selected scenarios for Kysuce.

internal consistency of individual scenarios and helped in selecting scenarios, since scenarios of greater consistency are of interest.

The probability of occurrence of the scenarios was carried out by Parmenides EIDOS using the probabilities of the individual variations defined in the morphological box. The scenario probability was expressed by the number of "+" marks associated with the scenario. A range of 0 (lowest probability) to 8 (highest probability) marks has been used.

From 8 factors and their 20 variations, a set of 972 possible future scenarios have been derived for *Podpoľanie*. It can be clearly identified in the cluster map (Fig. 5) that all possible scenarios are redistributed into four main groups of clusters. Scenarios concentrated close together in a cluster were meaningfully similar to each other. Since the goal was to select mutually different scenarios, the focus was mainly on different groups of clusters. A ranking procedure by degrees of consistency was applied to identify scenarios which are particularly consistent. Calculated consistency degrees of scenarios ranged from 0.1 (lowest consistency) to 1.09 (highest consistency). Most of the 972 scenarios had a low degree of consistency, with only 65 had the consistency degree greater than 0.5.

In Kysuce, a combination of 7 elements and their 18 manifestations, resulted in a set of 648 possible future scenarios (Fig. 6). At least five main groups of clusters could be identified in the map. Probabilities of occurrence, as well as consistency degrees, reached higher values compared to Podpoľanie. The consistency ranged in 0.2 to 1.75 and 25 scenarios had consistency degree greater than 1.0.

3.3.4 Selection of final forest management scenarios

The final selection of scenarios for both CSAs was done by the research team during several brainstorming sessions. As the result, the three scenarios of possible future development of forest management in Podpoľanie and Kysuce regions were selected (Table 3, 4). The process was supported by Parmenides EIDOS but the decision was reached by a consensus of team members. The choice of scenarios was determined by three criteria: consistency, diversity and plausibility. Cluster maps displaying the scenarios in a cluster view were used to ease the selection. To avoid selecting several scenarios that are simply slight variations on the same theme, distinct clusters were identified at first. This has ensured the diversity criterion to select scenarios each other meaningfully distinguished. Then we looked for the most consistent scenarios in the cluster. The more consistent scenarios were, the bigger they were displayed in the cluster map. The ranking by consistency degrees showed scenarios with the high consistency, but the order itself was not a decisive criterion because it does not take into account diversity of scenarios. That's why the combination of cluster map visualisation and consistency degrees was used for the selection. To obtain reasonably likely scenarios the probability of their occurrence over the next 30 years was considered. Scenarios marked with 0 or 1 "+" were excluded from the selection. We have focused particularly on scenarios with 4 and more "+". But, as can be seen (Table 3, 4) the most consistent scenarios in both CSAs had a probability of only 2 "+" or 3 "+" respectively. Considering the highest consistency and focus of these scenarios, the lower probability was accepted by the research team. This shows that despite strong software support, the final decision was on the research team that took into account all the information gathered during the all research phases.

4. Features of selected forest management scenarios

As a result of the morphological analysis process, three selected scenarios of possible future development of forest management were identified for each CSA. These scenarios meet the requirement of internal consistency, are meaningful, probable and mutually different. Each scenario was created by combining selected variations that define the scenario itself (Table 5, 6). For scenarios, the brief basic descriptive features that are presented in this chapter have been created.

Table 3. Selected scenarios for Podpoľanie.

Name of scenario	Consistency degree	Order by consistency (from 972 scenarios)	Probability of occurrence
Scenario 1: Improved state of forests and increased wood demand	1.09	1.	++
Scenario 2: Fear for forest sustainability	0.76	13.	+++++
Scenario 3: Biodiversity maintenance – Growing societal demand for nature conservation	0.79	9.	+++++

Table 4. Selected scenarios for Kysuce

Name of scenario	Consistency degree	Order by consistency (from 648 scenarios)	Probability of occurrence
Scenario 1: Transformation of ownership and change of the forest management objectives	0.86	38.	++++++++
Scenario 2: Rural development and agro-forestry landscape use	1.75	1.	+++
Scenario 3: Depopulation and landscape afforestation	1.62	2.	++++++++

4.1. Selected scenarios for CSA Podpoľanie

Table 5. Final scenarios for Podpoľanie – selected combinations of future variations of key factors.

Factors / Scenarios	U1 State of forests	U2 Policies and legislation	U3 Timber/Bioenergy market	U4 Forest owner's economic situation	U5 Non-wood ecosystem services	U6 Innovation and technology	U7 Codes of conduct	G1 Forest ownership
Sc. 1.	U1a Stable and productive forests	U2b Predominance forest policy	U3b Timber/Bioenergy demand growing	U4a Favourable	U5b Importance Stagnant	U6a Improved situation	U7a Influence growing	G1a State ownership predominance
Sc. 2.	U1c Unstable forests	U2c Policies incoherence	U3c Timber decreasing Bioenergy stagnant	U4c Unfavourable	U5a Importance increasing	U6b Stagnant situation	U7b Influence decreasing	G1a State ownership predominance
Sc. 3.	U1c Unstable forests	U2a Predominance environmental policy	U3c Timber decreasing Bioenergy stagnant	U4c Unfavourable	U5c Dominance of biodiversity maintenance	U6b Stagnant situation	U7b Influence decreasing	G1a State ownership predominance

Table 6. Final scenarios for Kysuce – selected combinations of future variations of key factors.

Factors / Scenarios	U1 State of forests	U2 Forest ownership	U3 Subsidies	U4 Forest owner's economic situation	U5 Timber market	U6 Innovation and technology	U7 Population
Sc. 1.	U1a Young temporarily unprofitable stands	U2b Formation of larger owners	U3b Lack of subsidies	U4b Fluctuating	U5a Lack of timber sources	U6b Stagnant situation	U7b Lack of qualified labour
Sc. 2.	U1b Towards to Close to nature	U2a Stabilisation of small forest owner's status	U3a Increased subsidies for rural development	U4a Favourable	U5b Biomass production growing	U6a Improved situation	U7a Available labour
Sc. 3.	U1c Unstable even-aged forests	U2c Present state	U3b Lack of subsidies	U4c Unfavourable	U5a Lack of timber sources	U6b Stagnant situation	U7c Depopulation of rural areas

Scenario 1: Improved state of forests and increased wood demand

Full use of the natural production potential of forests in Podpoľanie is predicted. Such maximal utilization will also be supported by the application of short-term rotation forestry under preservation of the sustainability and ecological stability of forests with less emphasis on the provision of other ecosystem services. Lessening the impact of climate change and ecological disturbance is awaited. Health conditions and ecological stability of forests will stay on the current level, respectively will be improved. Strong political enforcement of the economic interests of forest owners over the interests of nature conservation is expected. Despite a harmonization of environmental and forestry policies, the forest law will be more strongly enforced as a law on nature conservation. Growing wood demand is estimated due to new investments in timber processing capacities and/or due to increased support of energy from renewable resources, particularly from biomass. Lower societal demands for the fulfilment of other ecosystem services are expected. It will lead to a reduction in the extent of forest protection and biodiversity conservation.

Scenario 2: Fear for forest sustainability

Applying measures to systematically enhance the sustainability and ecological stability of forest stands in Podpoľanie is expected. The measures will be applied in combination with strengthening the provision of selected non-production ecosystem services (water, recreation, hunting, research function), which will be complemented by secondary wood and biomass production. Increasing the negative impact of climate change and ecological disturbances on forest stands are anticipated. Effective forest management, mainly focused on the production function, in practice will not be possible or will be significantly limited. Increased efforts by forest owners for income outside the forest are foreseen. The incoherence of forestry and environmental policy will persist, but as a result of social pressures, the importance of sustainable management is expected to increase, which, on the other hand, will enhance the protection of nature and biodiversity.

Scenario 3: Biodiversity maintenance – Growing societal demand for nature conservation

The dominance of nature and biodiversity protection, expanding the provision of certain non-production ecosystem services (recreation, water, research) is foreseen in Podpoľanie. Passive forest management is expected, coupled with strong restrictions on any active interventions (minimizing the provision of production functions and hunting). The strong demand and interest of society will lead to the strengthening of nature conservation legislation in favour of the economic interests of existing forest owners. Misunderstandings between foresters and environmentalists in the region will be resolved in favour of the environmentalists. The state will either completely purchase forest land from small owners or will be willing to pay full compensation for the restriction of forest management.

4.2. Selected scenarios for CSA Kysuce

Scenario 1: Transformation of ownership and change of the forest management objectives

In the 30-year time horizon, the existence of large areas of even-aged mixed coppices formed naturally is expected as a result of the predicted collapse of large complexes of unnatural spruce stands in Kysuce. Ecological stability of dense and even-aged forest stands may not be fully satisfactory due to the increasing cost of stands tending. At the same time, the revenues from timber production will be significantly reduced due to the unfavourable situation in the domestic and foreign markets. It is assumed that small private forest owners will sell their land to bigger investors because the income from the forests will be significantly lower and no more subsidies are expected to be provided. In addition, due to rising forest management costs of forest land of unknown owners as well as due to growing political and social pressure, the state will be forced to address the issue of forest land of unknown owners. The same or rising demand for pulp and new biomass requirements for energy purposes are foreseen.

Scenario 2: Rural development and agroforestry landscape use

Expansion of the rural development policy, supported by a sufficient amount of subsidies is expected in Kysuce. It is supposed that this will lead to the preservation of the fragmented forestry agrarian landscape. The number of subsidies will be sufficient for the preservation and development of agricultural activities, as well as on developing the use of biomass in the forest sector. The fragmented nature of the land ownership will be preserved, because of forest owners regardless of the situation on in timber and biomass trade, will be financially motivated to maintain the current forestry agrarian character of the landscape. It is expected the adoption of new legislation promoting the production of biomass and forest management. Biomass from increased production areas will be effectively exploited the growing bioenergy sector. Furthermore, these processes supported by subsidies will lead to job creation and to meeting the demands for skilled labour.

Scenario 3: Depopulation and landscape afforestation

Lack of subsidies and limited timber production will further increase the depopulation of the Kysuce and cause a massive reduction in non-economic agrarian and forestry activities. Extending the successive development of ecosystems on abandoned agricultural land and self-development of forest stands is envisaged. Lack of resources for forest management, low income from timber and biomass production as well as lack of subsidies will lead to a fall in investment and job losses. Big investors will not be interested in buying forest land of small owners due to rising costs for tending of naturally regenerated even-aged mixed forest stands, lack of qualified labour and need for technological innovation. This will result in the conversion of fragmented forestry agrarian landscape to large complexes of fields, meadows and pastures overgrown with pioneer tree species. Due to high management costs, lack of subsidies and poor sales, the necessary tending of forest stands will also be neglected. The stability and health status of forest stands will further deteriorate. A shift towards close to nature management will also be problematic because such a transformation of forests requires time and investment in the necessary technology.

5. Discussion and conclusions

The future forest management could be driven by many factors and their variations, yet their combinations would deliver many scenarios. The morphological analysis offers systematic approach and helps to deal with the complexity that consists of a set of relationships, multidimensional and non-quantifiable problems challenging forest management. In this study, we have shown its applicability in forest management scenario modelling with an example taken from forest management in two traditional agricultural-forest Slovak regions. This specific qualitative approach of prognostic method of future scenarios was used for the prediction of forest management development probably for the first time in the conditions of the Slovak forestry.

In the paper, the created scenarios are presented in the form of a brief description of the situation that can occur in 30 years. These scenarios can serve as a driving scenarios for further steps toward the final decision scenarios. Schoemaker (1995) called these scenarios Learning scenarios that help outline the boundaries of further development and identify themes that are strategically relevant in each case study area. They become the basis for further research to organize the possible outcomes and trends around these themes. While the Podpoľanie region was particularly concerned with the possible implementation of the forestry or nature conservation paradigms, the scenarios in the Kysuce region were mainly concerned with the topic of the ownership structure and its impact on forest ecosystems.

As learning scenarios are results of qualitative approach, the further research could be focused on quantitative models' implementation or evaluation of stakeholder's behaviours in given scenarios. By implementing forestry Decision Support Systems or growth simulators e.g. Silva (Pretzsch et al. 2002), Sibyla (Fabrika 2007), Heureka (Heureka 2010) or Optimal (Marušák 2015) to the trends set in the individual scenarios, it is possible, for example, to quantify the fulfilment of ecosystem services in forest ecosystems in each region. The modelling can include simulated behaviour of forest owners and stakeholders, and various forest management measures correlating with the theme of the scenarios. The quantification of the consequences of various scenarios significantly enhances the credibility of the scenarios and allows them to be further extended as narrative scenarios into stories. Such scenarios can be further used in decision-making processes, for example, using the backcasting method (Wilson et al. 2006) exploring the feasibility of desirable futures set in scenarios.

Implementation of the whole scenario modelling process has been a challenge for the research team. Our experience has shown that the method cannot be realized by an individual, but the process requires experienced team capable of assessing socio-economic, technological and environmental or policy aspects of forestry issues. The steps of scenarios' consistency and credibility assessment were carried out in a number of iterations, using the brainstorming, discussion and consensus. Evans et al. (2008) called this process as a mental exercises to consider plausible, future situations, imagine potential outcomes and explore contingencies. Parmenides EIDOS toll suite was very helpful throughout the modelling process. The software provided flexible tools for scenario's spaces management and visualisation that facilitated and clarified the whole process. However, like suggested by Gausemeier et al. (2009) the choice of final scenarios was supported by software, but not determined by it.

In the study, we used the participatory approach in particular in the initial phases of modelling scenarios; in-person interviews and structural analysis involving forest owners and stakeholders helped to isolate the crucial factors that later became the basis for scenarios. Based on our findings, it is advisable to involve forest owners and other stakeholders also in the process of consistency assessment itself. The process could be done by adding another participatory workshop where participants would jointly assess the morphological box, fill out the consistency matrix and judge the created set of scenarios. Stakeholders would discuss and evaluate the consistency of each variation pair. Weccard (2012) suggested to display on a screen two newspapers with a different top headline, that are the names of a variations from the variation pair and ask participants *How do the two headlines make sense together*? By using attractive visualization tools of Parmenides EIDOS, stakeholders could discuss and identify their preferred scenarios or scenarios they would like to avoid. Through joint consensus, they would be involved in planning the future direction of forest management in their region. The selection of workshop participants is crucial in order to achieve relevant results. It is important to involve relevant decision makers, experienced and informed owners and stakeholders with the relation to the region representing all relevant stakeholder groups. Engaging the same stakeholders as in earlier steps of the scenario making process can guarantee their interest in issues of forest management in their region. Beside this, the whole research team must also be involved in this kind of workshop, with the facilitator's role in managing the productive discussion very important.

Our experience demonstrated that the morphological analysis supported by Parmenides EIDOS is a useful method for forest management modelling challenged by many factors (e.g., forest policy, forest owner's behaviour) that by their nature are not applicable for analysis via deterministic or probabilistic methods (e.g. Ritchey 2011, 2015). As scenario studies concerning forest management have rather quantitative, non-participatory, or single factor in nature character (Hoogstra et al. 2017), an application of qualitative future scenarios method enriched by a quantitative model can introduce the use of the mixed-methods and participation into forest management scenarios modelling in Slovakia. Such forest management scenarios modelling carried out in a participatory manner may be considered a means to improve collaboration and promote dialogue among forest owners, other forestry stakeholders and the general public as well. Additionally, participatory scenario modelling workshops might increase the stakeholders' interest in engaging in forest management planning processes, as this method is systematic, interesting and productive.

Acknowledgements

This research study has received funding from the EU's Seventh Programme for research, technological development and demonstration under grant agreement No. 282887.

References

Albert, M., Hansen, J., Nagel, J., Schmidt, M., Spellmann, H., 2015: Assessing risks and uncertainties in forest dynamics under different management scenarios and climate change. Forest Ecosystems, 2:14.

Amer, M., Daim, T. U., Jetter, A., 2013: A review of scenario planning. Future, 46: 23–40.

Bishop, P., Hines, A., Collins, T., 2007: The current state of scenario development: an overview of techniques. Foresight, 9:5–25.

Bošeľa, M., Sedmák, R., Sedmáková, D., Marušák R., Kulla, L., 2014: Temporal shifts of climate-growth relationships of Norway spruce as an indicator of health decline in the Beskids, Slovakia. Forest Ecology and Management, 325:108–117.

Brodrechtová, Y., Navrátil, R., Sedmák, R., Tuček, J., 2018: Using the politicized IAD framework to assess integrated forest management decision making in Slovakia. Land Use Policy, 79:1001–1013.

Carlsson, J., Eriksson, L. O., Öhman, K., Nordström, E. M., 2015: Combining scientific and stakeholder knowledge in future scenario development - a forest landscape case study in northern Sweden. Forest Policy and Economics, 61:122–134.

Dilek, C., 2009: The Scenario Analysis Tool Suite: A User's Guide. Joint Operations Division Defence Science and Technology Organisation Canberra, 24 p.

Eriksson, T., Ritchey, T., 2002: Scenario Development using Computerised Morphological Analysis. Swedish Defence Research Agency Stockholm, 8 p.

Evans, K., Cronkleton, P., de Jong, Wil., 2008: Future Scenarios as a Tool for Collaboration in Forest Communities. Sapiens. 1. 10.5194/sapiens-1-97-2008.

Fabrika, M., 2007: Implementation of GIS and model SIBYLA in a special decision support system for forest management. In: Kappas, M., Kleinn, C., Sloboda, B. (eds.), 2007: Global Change Issues in Developing and Emerging Countries, Proceedings of the second Göttingen GIS and Remote Sensing Days. Göttingen, Germany, Universitaetsverlag Göttingen, p. 61–72.

Gaßner, R., Steinmüller, K., 2004: Scenarios that tell a story; Normative Narrative Scenarios – An efficient tool for participatory innovation-oriented foresight. In: Proceedings of the EU-US Scientific Seminar: New Technology Foresight, Forecasting & Assessment Methods in Seville, Spain, p. 31–37.

Gausemeier, J., Plass, C., Wenzelmann, C., 2009: Zukunftsorientierte Unternehmensgestaltung: Strategien, Geschäftsprozesse und IT-Systeme für die Produktion von morgen. München, Hanser, p. 404–405.

Glenn, J. C., Gordon, T. J. (eds.), 2009: The Millennium Project: Futures Research Methodology. Version 3.0. (CD-ROM).

Godet, M., Roubelat, F., 1996: Creating the future: The use and misuse of scenarios. Long Range Planning, 29:164–171.

Greeuw, S. C. H., van Asselt, M. B. A., Grosskurth, J., Storms, Ch. A. M. H., Rijkens-Klomp, N., Rothman, D. S., Rotmans, J., 2000: Cloudy Crystal Balls: An assessment of recent European and global scenario studies and models, European Environment Agency, 113 p.

Heinecke, A., 2006: Die Anwendung induktiver Verfahren in der Szenario-Technik. In: Falko E. P. Wilms (ed.), Szenariotechnik: Vom Umgang mit der Zukunft, Bern, Haupt Verlag, p. 183–213.

Hengeveld, G. M., Schüll, E., Trubins, R., Sallnäs, O., 2017: Forest Landscape Development Scenarios (FoLDS) – a framework for integrating forest models, owners' behaviour and socio-economic developments. Forest policy and economics. 85:245–255.

Hlásny, T., Sitková, Z. (eds.), 2010: Spruce forests decline in the Beskids. National Forest Centre – Forest Research Institute Zvolen & Czech University of Life Sciences Prague & Forestry and Game Management Research Institute Jíloviště – Strnady, 184 p.

Hoogstra-Klein, M. A., Hengeveld, G. M., de Jong, R., 2017: Analysing scenario approaches for forest management – One decade of experiences in Europe. Forest Policy and Economics, Elsevier, 85:222–234.

Johansen, I., 2018: Scenario modelling with morphological analysis. Technological Forecasting and Social Change, 126:116–125.

Kempf, J., 2015: Visualizing general morphological analysis via multidimensional scaling. Bachelor Thesis, University of Passau, 89 p.

Konôpka, J., 2004: Hynutie lesov, najmä smrečín na Slovensku v druhej polovici 20. storočia a opatrenia na zlepšenie situácie. In: Zúbrik, M. (ed.): Hynutie lesov, najmä smrečín na Slovensku v druhej polovici 20. storočia a opatrenia na zlepšenie situácie. Zvolen, NLC, 52 p.

Korosuo, A., Sandström, P., Öhman, K., Eriksson, L. O., 2014: Impacts of different forest management scenarios on forestry and reindeer husbandry. Scandinavian Journal of Forest Research, 29:234–251.

Kovalčík, M., Sarvašová, Z., Schwarz, M., Moravčík, M., Oravec, M., Lásková, J., Tutka, J., 2012: Financial and socio-economic impacts of nature conservation on forestry in Slovakia. Journal of Forest Science, 58:425–435.

Kulla, L., Merganič, J., Marušák, R., 2009: Analysis of natural regeneration in declining spruce forests on the Slovak part of the Beskydy Mts. Beskydy, 2:51–62.

Marušák, R., Kašpar, J., Vopěnka, P., 2015: Decision Support Systems (DSS) Optimal – A Case Study from the Czech Republic. Forests, 6:163–182.

Navrátil, R., Brodrechtová, Y., Sedmák, R., Smreček, R., Tuček, J., 2016: Structural analysis of the drivers and barriers of forest management in the Slovak regions of Podpoľanie and Kysuce. Forestry Journal, 62:152–163.

Nordström, E. M., Holmström, H. and Öhman, K., 2013: Evaluating continuous cover forestry based on the forest owner's objectives by combining scenario analysis and multiple criteria decision analysis. Silva Fennica, 47:22.

Pillkahn, U., 2008: Using Trends and Scenarios as Tools for Strategy Development: Shaping the Future of Your Enterprise. Erlangen, Publicis Corporate Publishing, 452 p.

Pretzsch, H., Biber, P., Durský, J., 2002: The single tree-based stand simulator SILVA: construction, application and evaluation. Forest Ecology and Management, 162:3–21.

Riemer, A., Betuch, H., Zhirkova, I., Winkler, J., Wappler, S., Storch, S., 2013: Impact of selected structural factors on the forest-based sector in the European Union, Fraunhofer MOEZ, Leipzig, 61 p.

Ritchey, T., 2009: Morphological Analysis. Futures Research Methodology 3.0 (CD-ROM).

Ritchey, T., 2011: Wicked Problems – Social Messes. Decision Support Modelling with Morphological Analysis. Springer-Verlag, Berlin, Acta Morphologica Generalis, 2:1–8.

Ritchey, T., 2015. Principles of cross-consistency assessment in morphological modelling. In: Acta Morphological Generalis, vol. 4.

Ritchey, T., 2018: General morphological analysis as a basic scientific modelling method. Technological Forecasting and Social Change, 126:81–91.

Sarvašová, Z., Dobšinská, Z., Šálka, J., 2014: Public participation in sustainable forestry: The case of forest planning in Slovakia. iForest – Biogeosciences and Forestry, 7:414–422.

Sarvašová, Z., Dobšinská, Z., 2016: Provision of ecosystem services in mountain forests – case study of experts' and stakeholders' perceptions from Slovakia. Journal of Forest Science, 62:380–387.

Schoemaker, P., 1995: Scenario Planning: A Tool for Strategic Thinking. Sloan Management Review, 36:25–40.

Schwartz, P., 1991: The Art of the Long View. Planing for the Future in an Uncertain World, New York, 272 p.

Tuček, J., Navrátil, R., Sedmák, R., Brodrechtová, Y., Smreček, R., 2015: Participatory scenarios and backcasting in strategic planning of forest management. Zvolen, Technical University in Zvolen, 332 p.

Vakula, J., 2011: State of Forest Health and Appearance of Harmful Factors in the Regions of Slovakia according to inspectors of Forest Protection Service for 2010. LOS.sk, [online 20. September 2015] URL: http://www.los.sk/zil.html

van Notten, P. W. F., Rotmans, J., van Asselt, M. B. A., Rothman, D. S., 2003: An updated scenario typology. Futures, 35:423–443.

Weccard, E. N., 2012: Future scenarios for the derivation of material requirements – the automobile interior 2030. University of Twente, NIKOS, Technische Universität Berlin, 91 p.

Wilson, C., Tansey, J., LeRoy, S., 2006: Integrating backcasting & decision analytic approaches to policy formulation: a conceptual framework. Integrated Environmental Assessment and Management, 6:143–164.

Wollenberg, E., Edmunds, D., Buck, L., 1999: Using scenarios to make decisions about the future: Anticipatory learning for the adaptive co-management of community forests. Landscape Urban Plan, 47:65–77.

Wollenberg, E., Edmunds, D., Buck, L., 2000: Anticipating change: scenarios as a tool for adaptive forest management: a quide. Bogor, Indonesia, Centre for International Forestry Research, 38 p.

Zanoli, R., Gambelli, D., Vairo, D., 2012: Scenarios of the organic food market in Europe. Food Policy, 37: 41–57.

Appendix A: Characteristics of key factors and their variations for Podpoľanie and Kysuce

Table A1. Key factors used for designing the scenario space for CSA Podpoľanie.

Code	Key factor	Factor description
U1	State of forests	Up to 90% of forest stands in CSA represent mixed forests of temperate climate zone. Tree species composition is made up mainly of spruce (61.9%), beech (30.7%), fir (1.5%) and oak (0.5%) (Tuček et al. 2015). Due to very favourable climatic conditions, the CSA is one of the most productive forest areas in Slovakia. It is dominated by intensely-cultivated even-aged stands in which mainly shelterwood silvicultural system with an emphasis on natural regeneration is applied. Despite the occurrence of calamity felling in the CSA, forest stands are relatively healthy and stable. The original tree species composition is predominant, but there are also forest stands with artificially inserted spruce.
U2	Policies and legislation	There are several strategic documents in Slovakia and two laws are of strategic significance for the forestry legislation: Act No 326/2005 Coll. on Forests and Act No 543/2002 Coll. on Nature and Landscape Protection. Implementation of the aforementioned laws causes forest management problems (e.g. dense network of various protected areas limits ownership rights by environmental restrictions; NATURA 2000 partially overlaps with protected areas of the national level). The policies incoherence situation is significant in Podpoľanie, where a state forest ownership structure prevails and large protected areas exist (Brodrechtová et al. 2018). Compensations for financial loss due to nature protection restrictions is also problematic.
U3	Timber/Bioenergy market	The wood sale is the most important source of income in the forestry sector in Slovakia (including CSA). Trends in the wood processing industry thus significantly influence forestry enterprises and the forest management as well. The processing capacity problems are encountered in Slovakia concerning the processing of deciduous round timber (e.g., beech and oak). As the beech is considered to be the predominant tree species in CSA, this problem is significant to forestry income (Tuček et al. 2015). In contrast, the bioenergy market and biomass demand are growing in Slovakia and in CSA as well. A number of municipalities, towns or companies and industrial plants with biomass heating plants is growing. Moreover, a strong interest in fuelwood biomass among the population in the form of fuelwood and wood waste pellets remains in CSA.
U4	Forest owner's economic situation	The economic situation of forest owners is significantly influenced by the forest management costs associated with forest management and its planning. There are several types of costs that affect the economic situation of forest owners in CSA. Firstly, the costs associated with the inconsistency of policies and the bureaucracy directly affecting forest management measures. In the CSA, where more than 50% of the area is under the nature and landscape protection, the inconsistency and contradiction of forestry and environmental legislation are well demonstrated. Unclear procedures for liquidation of various calamities in forests (especially in protected areas), restrictions on the implementation of silvicultural measures create additional costs for forest management. Forest stands surrounding the drink water reservoir Hriňová requires other additional costs related to special treatment for ensuring a purity of the water source. In addition, forestry enterprises are faced too often bureaucracy in relation to state administration. Disproportionate paperwork is a time-consuming factor, which reduces the productivity of enterprises and increases costs. This also applies to the process of financial compensations for the restriction in forest management due to nature protection. Next, there are operating costs associated with the practical implementation of silvicultural and forestry measures in forest stands. Forest owners sensitively perceive a gradual increase in total operating costs (Tuček et al. 2015).
U5	Non-wood ecosystem services	The main important non-wood ES in CSA are Biodiversity Maintenance, Water Regulation/Clean Water, Recreation/Tourism and Hunting. The richness of the fauna and flora of CSA represents nearly 2700 species, of which 310 are protected by national legislation. The 174 bird species were identified and 128 nested in the territory. 32% of the region is part of the Poľana Protected Landscape Area and 62% belongs to the NATURA2000 protected areas network (Tuček et al. 2015). Drink water reservoir Hriňová, located in CSA serves as a reservoir of drinking water for the water supply system of surrounding cities. Thus, the most of the surrounding forest stands fall within the category of Special purpose forests with prevalent water management function. Management of such forests requires special treatment in order to ensure purity of the water source. The CSA is well known for its hunting tradition. The Protected Game Area of Poľana (area of more than 20 000 ha) provides a coordinated ecological and large-scale management of the game. In addition, forests are used intensively for picking mushrooms and berries. Recreational activities, including hiking, cycling and winter sports, are also popular. Environmental restrictions significantly affect the forest owners and have a rather braking effect.
U6	Innovation and technology	Lack of financial resources is the main obstacle to the innovation process in forestry in Slovakia. Most forestry enterprises use subcontractors for silvicultural and harvesting operations. Due to short-term contracts, subcontractors face problems in fleet and mechanization renewal through loans, leasing, and so on. It affects the quality of the works carried out. The usage of obsolete machinery for working in forests has a negative impact on the environment as well. Due to the lack of funds, some forest enterprises do not perform silvicultural measures what may negatively affect the stability of forest ecosystems. Insufficient investments in the development and maintenance of forest road network influence the usability of felling-transport technologies and the overall cost. Overall, the innovation process in forestry stagnates and the transfer of the latest knowledge and research results into practice is still missing. The innovation cycle is too long, there is a lack of productive cooperation between research institutions and practice.
U7	Codes of conduct	In contrast to formal institutions (e.g., laws, regulations, standards, norms, rules), changes in informal institutions are going slower, are more problematic and resistant to adjustments of legislative measures. Impact of informal institutions is widespread across the society, as well as in the forestry sector, wood processing industry and the protection of the environment. It emerges by the struggle for influence in this sector, promoting of interests of financial groups through political parties, political lobbying, clientelism, the occupation of political nominees into management functions, abusing of personal contacts and by non-transparent business practices. An unsuccessful fight against corruption, a slow shift in the culture of society and codes of conduct may negatively affect the institutions and state administration and the society as a whole.
G1	Forest ownership	Ownership of the forest land in CSA is split between state and non-state forestry entities. State enterprise Forests of the SR manages almost 85% of forests in the CSA. Thus, it is the strongest forestry subject in CSA. The largest share of non-state forest owners has communal (8.3%) and private (3.2%) ownership types. There is only a small part of municipal forests, church forests or forests still in the restitution process (unsolved ownership).

Table A2. Key factors used for designing the scenario space for CSA Kysuce.

Code	Key factor	Factor description
U1	State of forests	Kysuce belongs to the Slovak territories with high forest cover and prevalence of the spruce. In the past, large spruce monocultures were established in the region, often even in places not suitable for spruce. Such stands have a low degree of ecological stability as well as of resistance to harmful factors. Lately, the area had been extensively affected by widespread necrosis of spruce stands (Kulla et al. 2009, Bošeľa et al. 2014) due to various abiotic, anthropogenic and biotic harmful factors such as honey fungus (Armillaria) and aggressive species of bark beetles (Hlásny & Sitková 2010). These factors caused, that in 2010, the region was the area with the largest volume of calamity felling in Slovakia (Vakula 2011).
U2	Forest ownership	Forest land ownership in CSA is characterized by very high fragmentation: state forest owners (19%), forests still in restitution process (unknown owners) managed by State enterprise Forests of the SR (34%), and non-state forest owners including private, communal, municipal and church owners (46%) (Navrátil et al. 2016). The restitution process, which began in 1991 has not yet been completed. Although the management of such forests is provided by state foresters, this situation causes many problems. For instance, highly fragmented forest ownership structure means a divergent interest of forest owners, various expertise and experience, management approaches, traditions, different financial options, human qualities or relationship to the forest.
U3	Subsidies	Most financial instruments for agriculture and forestry originate from EU Rural Development policies. Specifically, via Rural Development Programme in SR for periods 2007–2013 and 2014–2020 should be achieved: (I.) improvement of the competitiveness of agriculture, food industry and forestry by promoting restructuring, modernization, development and innovation, (II.) improving the environment and the quality of life in rural areas, and (III.) promoting diversification of economic activity. Financial resources from the EU Structural Funds are also an important financial instrument for innovations. These resources are almost unattainable for many small private forest owners in CSA due to bureaucracy and administrative burden. They sensitively perceive the incoherence of forestry and environmental legislation as well as unclear legislation on subsidies and financial compensation (Tuček et al. 2015).
U4	Forest owner's economic situation	The economic situation of forest owners is significantly influenced by the forest management costs associated with forest management and its planning. There are several types of costs that affect the economic situation of forest owners in CSA: (1.) Costs associated with the critical health status of spruce forests in the region, the effects of harmful factors and spreading of bark beetles. The high proportion of incidental felling, on one hand, increases a one-off income of forest owners. However, the income is lower because the wood is sold at lower quality. At the same time, problems are expected in the future, because of the lack of forest stands for logging. (2.) Total operating costs associated with the practical implementation of forestry measures. (3.) Costs associated with the inconsistency of forestry and environmental policies and legislation (e.g. unclear procedure for the liquidation of various calamities in forests located in protected areas).
U5	Timber market	Due to the high rate of calamity felling, excessive logging and high demand for wood in recent years, it is expected that the total felling volume in CSA will be reduced by 2030 due to lack of wood. Since the sale of wood is the most important source of income for the forestry sector, it will have a significant impact on the regional forestry enterprises, wood-processing companies, the overall forest management and measures in CSA. Additionally, economic performance will depend on the demand for fuelwood and biomass as well as on political development.
U6	Innovation and technology	In the majority of forestry enterprises in CSA, machinery equipment for the mechanization of harvesting and wood transportation does not correspond to still increasing demands for the reduction of negative environmental impacts. This is also reflected in the loss of the logged timber and poorer quality of assortments, which in turn leads to increased operating costs and reduced income. A high proportion of calamity felling has another significant impact on applied harvesting technologies. Insufficient density and quality of forest road network causes an increase of skidding distance, what determines the usability of felling-transport technologies and affects the overall cost. By the majority of forest managers, the lack of financial sources is perceived as a main barrier in the innovation process. There is a mutual interaction between technological equipment and the level and quality of forestry measures implementation.
U7	Population	Demographic development of last decades in Slovakia mirrors the EU trend of decreasing birth rates and a decline in mortality. In CSA, the population census in 2011 showed population decline for the first time in census history (−1.2% in Čadca district and −1.6% in Kysucké Nové Mesto district). The decline is due to an increased share of older people in the population while reducing the proportion of young people and people of working age. In Žilina region the ageing index increased in period 2001−2011 from 52.9 to 74.9 and for Kysucké Nové Mesto district rose to 76.3 (Tuček et al. 2015). Since the trend in demographic transition and ageing is likely to continue, it will bring challenges concerning the availability of a qualified workforce in the region. The reasons behind are twofold. First, the employment in agriculture, forestry and fisheries at the national and regional level is becoming less attractive. Second, in the population engaged in agriculture and forestry higher average age and lower qualifications dominate.

Table A3. Variations of key factors used for designing the scenario space for CSA Podpoľanie.

	Key factor U1: State of forests
U1a	*Stable and productive forests* • The stabilisation of changes in climate characteristics associated with a decrease in their variability. • Slight changes in tree species composition. • The predominance of the principles of shelterwood silvicultural system with a special emphasis on natural forest regeneration. • Possible formation of reliable plans in the strategic timeframe of rotation age.
U1b	*Present state* • The trend of changes in climatic characteristics mirrors those of last years. • Continuing strong influence of harmful factors, a high proportion of incidental felling and changes in tree species composition. • Reliable planning is possible utmost for the tactical time frame (decade).
U1c	*Unstable forests* • Unprecedentedly rapid changes of climate factors accompanied by the high frequency of occurrence of various extreme weather events (drought, heat waves, windstorms). • The strong influence of the entire spectrum of harmful factors and a high proportion of incidental felling. • Significant changes in tree species compositions. Non-native forest stands are decaying and even the original forests are changing. • Reliable tactical and strategic planning is practically impossible.
	Key factor U2: Policies and legislation
U2a	*Predominance environmental policy* • Strong societal demands lead to enforcement of legislation favouring entire societal interests for nature conservation over the economic interests of current forest owners. • Introduction of legislation significantly increasing financial resources for nature protection management. • Forest management activities of state and non-state forests owners are limited. • Compensation for financial loss due to nature protection restrictions entirely paid to forests owners.
U2b	*Predominance forest policy* • Strong political enforcement of the economic interests of forest owners over the interests of nature conservation. Despite partial harmonization of policies, forest law takes over nature protection law. • The forestry paradigm based on multi-purpose sustainable forest management, aimed at maximizing the volume production, even-flow and sustainable felling by sustaining other non-productive functions of forests is politically enforced.
U2c	*Policies incoherence* • Discrepancies between foresters and environmentalists are even getting worse. • Consistent lack of finances for protected areas management and compensation for financial loss due to nature protection restrictions. The State's obligation to compensate financial losses to forests owners thus remains declarative.
	Key factor U3: Timber/Bioenergy market
U3a	*Biomass demand growing* • Rapidly growing demand for biomass due to rising prices of basic fuels and energy. • Growing number of municipalities and companies equipped with biomass heating systems. • Introduction of legislation fostering the biomass production on unused agricultural land and the establishment of energetic forest stands.
U3b	*Timber/Bioenergy demand growing* • Growing timber demand due to the renaissance of wood processing and pulp/paper industry. • Fostering the green economy (green buildings; higher use of wood beams; improvements in the use of composite materials) is driven by the higher support of innovations and competitiveness. • The persisting strong interest in biomass among the population and a growing number of municipalities with biomass heating systems.
U3c	*Timber decreasing and Bioenergy stagnant* • The price of input resources is increased twice as faster as production price causing pressure on the effectiveness of the wood processing industry. • As banks perceive the wood processing industry as risky investment sector, no new investments are planned and lack of wood processing capacities expected. • Stagnant demand for biomass due to stagnant fuels and energy prices and weak legislative and subsidies support for biomass.
	Key factor U4: The Forest owners' economic situation
U4a	*Favourable* • Better availability of subsidies through Rural Development policies as well as new supporting schemes introduced. • The positive trends in timber and biomass markets result in increased income for forest owners. • Better accessibility of compensation for financial loss due to nature protection restrictions and/or fulfilment of other ecosystem services.
U4b	*Fluctuating* • Fluctuating trends timber and biomass markets cause unstable income for forest owners. • Stagnant improvements in policy coherence and/or continuing only declarative character of Rural Development policies. • Unclear subsidies scheme insecure forest managers and do not allow longer-term financial planning.
U4c	*Unfavourable* • Income from timber and biomass production is limited. • Increased incoherency of forest and environmental policies and persisting absence of mutual cross-sectorial coordination. • Weak accessibility to EU structural funds due to bureaucracy and administrative complexity.
	Key factor U5: Non-wood ecosystem services
U5a	*Importance increasing* • Increased broad societal pressure to foster sustainable forest management, greater emphasis on non-production ES and also to enhance the biodiversity and nature protection as a whole. • Non-wood ES becoming more attractive to forest owners, as a potential source of diversified income. • Growing importance of clean water as a strategic resource causes the spreading of special purpose forests around the water reservoirs Hriňová and Málinec.
U5b	*Importance stagnant* • Importance of ES reflects the present situation as there is a weak societal demand to change. • The tourist infrastructure development is very weak, so the region's tourist potential is more-less stagnant.
U5c	*The dominance of biodiversity maintenance* • Policy instruments fully enforce the environmental paradigm that the natural evolution of the ecosystems is homeostatic and the best way of ensuring the ecological stability of the forests is the strengthening of their biodiversity. Production ES are subdued and the preference is given to nature conservation. • Passive forest management is associated with the strong limiting of any active forest management measures. • Compensations for financial loss due to environmental restrictions are entirely paid to forest landowners.

	Key factor U6: Innovation and technology
U6a	*Improved situation* • Large investments in technology fleet renovation, the building of forest roads and other forestry infrastructure are emerging. This positively affects the quality of forest management measures. • More effective cooperation between researchers and practitioners bringing the utilisation of procedures and facilities significantly affecting the quality and efficiency of forest management measures.
U6b	*Stagnant situation* • General lack of financial sources is still the main barrier of technology innovations and is reflected in the overall stagnation and unfavourable situation in the field of innovation and technology. • Transfer of the latest knowledge and research results into practice stagnate and the innovation cycle is still too long. Cooperation between researchers and practitioners is weak.
	Key factor U7: Codes of conduct
U7a	*Influence growing* • Growing struggle for influence in the forestry. Particularly, diverse political power affects the governmental and administrative authorities in forestry as well as in agricultural and environmental sector. Persisting impact of informal institutions and influence of financial groups in form of relying on the inherited system and on networking.
U7b	• Influence decreasing • The pressure from the EU on institutional changes, transparency and the fight against corruption leads to the recovery of the entire society as well as the forestry sector. • Decreasing in the impact of politicians, financial groups, lobbyists as well as informal institutions.
	Key factor G1: Forest ownership
G1a	State ownership predominance • No remarkable and comprehensive changes expected in the ownership structure. • State enterprise Forests of the SR is still the most important forestry entity in the CSA Podpoľanie.

Table A4. Variations of key factors used for designing the scenario space for CSA Kysuce.

	Key factor U1: State of forests
U1a	*Young temporarily unprofitable stands* • The occurrence of large areas of even-aged mixed young forests incurred mainly by natural regeneration after the collapse of large complexes of non-native spruce stands. • Tree species composition of a new forest generation is generally more suitable, the mixed stands more correspond to the site and climatic conditions of the region. On the other hand, forest stands have even-aged structure and due to natural regeneration and high production potential of sites in the region, the density of forests is very high. • The high intensity of tending is necessary to maintain the ecological stability of even-aged and dense forests. Despite the relatively high silviculture costs, the ecological stability of forests is satisfactory.
U1b	*Towards to Close to nature* • The occurrence of large areas of even-aged mixed young forests incurred mainly by natural regeneration after the collapse of large complexes of non-native spruce stands. • Due to the availability of subsidies, the numerous forest stands are under conversion from the even-aged structure, managed by clear-cut or shelterwood system, to uneven-aged structure managed by more close-to-nature management (ideally by selection system). • The ecological stability of forest stands with suitable species composition is guaranteed.
U1c	*Unstable even-aged forests* • The occurrence of large areas of even-aged mixed young forests incurred mainly by natural regeneration after the collapse of large complexes of non-native spruce stands. • Due to lack of subsidies and fragmented ownership structure, the tending measures or conversions of young even-aged forest stands are not performed. Thus, the ecological stability and health status of stands are getting worse. • Fulfilment of production, economic and ecological management goals is strongly limited due to high management costs and lack of income.
	Key factor U2: Forest ownership
U2a	Stabilization of small forest owner's status • The strengthening of the rural state policy supported by subsidies helps to maintain fragmented agroforestry landscape. • Private forest owners have no effort to sell their forests, although their forest stands are currently unprofitable. Due to subsidies, their motivation to maintain the current agroforestry landscape character is increased. Subsidies help them to bridge an unfavourable period caused by loss of incomes from timber sales and to focus on other non-productive functions and/or on biomass production.
U2b	*Formation of larger owners* • Smaller private and communal owners sell their forest land. It is caused by the unfavourable state of forests that are currently unprofitable. Significantly smaller income from the young forests stands is insufficient to meet the essential tending costs. • Major strategic investors taking the opportunity to buy forest land at low prices are emerging. Financially strong investors are able to cover current higher costs for forest stands tending as in the long-term they expect rising productivity of the forests. • The regional municipalities and towns try to transfer the unknown owner forests into their ownership.
U2c	*Present state* • Continuation of fragmented forest ownership structure is expected in CSA. Despite some changes, the situation more or less reflects the current state. • Large investors are not very interested in buying forest land. Smaller forest owners would like to sell/rent their unprofitable forest stands but the buyers/renters are missing.
	Key factor U3: Subsidies
U3a	*Increased subsidies for rural development* • Strengthening of EU rural development policy in agriculture and forestry serve as a platform for economic diversification in rural communities. • Adoption of New National Strategic Plan of Rural Development based on the evaluation of rural development programmes and increasing spending on forestry and agriculture. • Significant increase and availability of financial instruments such as forest subsidy schemes appear. • Compensations for financial loss due to environmental restrictions are entirely paid to forest landowners.

U3b	*Lack of subsidies* • Stagnant and weak EU and national rural development policies reflected in the limited support of agricultural, forestry, biomass production or agro-tourism. • Lack of financial instruments such as forestry subsidy schemes and low accessibility of compensation for financial loss due to nature protection restrictions and/or fulfilment of other ecosystem services.
	Key factor U4: The Forest owners' economic situation
U4a	*Favourable* • Better availability of subsidies through Rural Development policies as well as new supporting schemes introduced. • Missing income from timber production is subsidized by income from biomass production as well as via new supporting schemes. • New opportunities and entry of capital providing the additional income to the forest enterprises to conduct and improve their forest management measures.
U4b	*Fluctuating* • Stagnating situation due to unmovable improvements in policy coherence and continuing declarative character of Rural Development policies. • Fluctuating trends timber and biomass markets cause unstable income for forest owners. • Unclear subsidies scheme insecure forest managers and do not allow longer-term financial planning.
U4c	*Unfavourable* • Young forest stands are unprofitable and require increased tending costs. Thus, profit from timber sale is limited regardless of the situation on the domestic and foreign timber markets. • The situation is also aggravated by the incoherence of forest and environmental policies and weak mutual cross-sectoral coordination. • Minimal accessibility to EU structural funds for the majority of non-state forest owners due to bureaucracy and administrative complexity.
	Key factor U5: Timber market
U5a	*Lack of timber sources* • Limited timber supplies due to excessive harvesting in past and recent years. Unstable even-aged and young forests lead to temporarily limited supplies of quality timber. • Despite the growing timber demand, limited timber supplies (especially coniferous round-wood) in CSA endangers both forest owners and sawmills in the region. • Persisting interest in fuelwood and biomass among the population, municipalities and companies with biomass heating systems.
U5b	*Biomass production growing* • Biomass production is supported by the adoption of new legislation in the field of renewable energy production. In particular, the legislation supporting wood biomass production on fallow agricultural land (e.g. short-term forestry) and the establishing of energy forests among others are introduced. • Strong interest in fuelwood and biomass among the population, municipalities and companies with biomass heating systems.
	Key factor U6: Innovation and technology
U6a	*Improved situation* • Large investments in technology fleet renovation, the building of forest roads and other forestry infrastructure are emerging. This positively affects the quality of forest management measures. • Appropriate mechanization of works in young forest stands together with better forest stands accessing multiply the utilization of the production potential of biomass for energy purposes. Additionally, capacities for biomass processing are built in the region.
U6b	*Stagnant situation* • General lack of financial sources is still the main barrier to technology innovations. • Since the investments in forestry are deeply undersized, the vehicle fleet is obsolete, forest roads network is uneven and neglected the utilised tending and felling-transport methods are inappropriate. It also brings obstacles to the utilization of the production potential of biomass for energy purposes.
	Key factor U7: Population
U7a	*Available labour* • The improved situation in rural development thanks to supporting of forestry and agricultural activities, agro-tourism as well as the support of renewable energy production mainly from biomass. • There are new employment opportunities, improved infrastructure of villages, protection and development of social capital and the rural cultural heritage, and availability of raw biomass materials for the implementation of renewable energy policies. • Raising attractiveness of the majority of rural settlements causing stabilisation of rural population and increased interest in employment in forestry and agriculture.
U7b	*Lack of qualified labour* • Weak support in the rural development, forestry and agricultural activities, agro-tourism as well as the support of renewable energy production from biomass. • Low interest in employment in forestry and agriculture and migration of young people from the countryside in some areas resulting in reducing of availability of qualified available labour. There is a predominance of older and less qualified workers in forestry and agricultural in CSA.
U7c	*Depopulation of rural areas* • No support in the rural development, forestry and agricultural activities, agro-tourism as well as the support of renewable energy production from biomass. • Migration of young people from the countryside reduces the availability of qualified labour and create unfavourable demographic structure. Along with the population ageing it causing the depopulation of the region.

Cent. Eur. For. J. 65 (2019) 121–128 sciendo DOI: 10.2478/forj-2019-0012

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Assessment of phenotypic plasticity of spruce species *Picea abies* (L.) Karst. and *P. obovata* (Ledeb.) on provenances tests in European North of Russia

Elena Nakvasina[1, *], Nadezhda Demina[2], Nadezhda Prozherina[3], Natalia Demidova[2]

[1] *Northern (Arctic) Federal University of M. V. Lomonosov, Department of Forestry and Forest Management Severnaya Dvina emb. 17, 163002, Arkhangelsk, Russia*
[2] *Northern Research Institute of Forestry, Nikitova 13, 163062, Arkhangelsk, Russia*
[3] *N. Laverov Federal Center for Integrated Arctic Research, Laboratory of Population Ecology, Severnaya Dvina emb. 23, 163000, Arkhangelsk, Russia*

Abstract
Phenotypic plasticity of 22 spruce provenances in three test plots located in the European North of Russia was studied. Parent spruce stands are located within the Russian Plain and are represented by *Picea abies* (L.) Karst., *P. obovata* (Ledeb.) and two introgressive hybrids. In the test plots located in the middle and southern taiga subzones *P. abies* provenances are tested northward of its distribution area and *P. obovata* provenances are tested within the distribution area and nearby its boundaries. phenotypic plasticity of the spruce provenances was assessed. Straight-line regression coefficient based on survival, diameter, and height was calculated. All provenances are divided into two groups: plastic and non-plastic provenances. High plasticity is observed more often for *P. abies* and hybrids forms with properties of *P. abies*. Plastic provenances based on three parameters grow in the Leningrad, Pskov, Vologda, Kostroma and Karelia. Area of parent stands growing is quite small-size and lies between 56º30´ – 61º40´ N and 30º30´ – 42º30´ E. Adaptive provenances of *P. obovata* and its related hybrids forms grow in the North-Eastern part of the Russian Plain that could be consequence of its distribution in Holocene. *Picea abies* being the more adaptive species would be more responsive to climate changes in terms of survival and growth rate than *P. obovata*. Therefore, in case of sustainable climate warming in the Northern areas of the Russian Plain, the further propagation and major distribution of *P. abies* with further competitive replacement of *P. obovata* can be expected.

Key words: *Picea*; provenance test; survival; growth; phenotypic plasticity

Editor: Dušan Gömöry

1. Introduction

Provenance tests have more value in gen-ecological studies. Provenance trials contain large-scale genetic resources *ex situ* concentrated within small-size areas. They are objects of genetic monitoring (Iroshnikov 2002) providing multivariate stationary studies and assessment of provenances adaptive capacity based on their age and ecological stability (Rone 1979).

At present, it is considered that provenance trials can be used not only for provenances selection for the purpose of reforestation in certain regions as well as for seeds transfer. These experiments can be used for study of species history and their distribution within a certain territory (Lindgren & Persson 1995), for study genetic variations and migration (Potokina et al. 2015). A provenance trial can be used as a model for prediction of climate changes impact on species productivity and survival is of a special interest (O'Neill et al. 2008; Gömöry et al. 2012; Kapeller & Schüler 2012). Natural climate warming (shift towards south) or cooling (shift towards north) is simulated in provenance test when we use seeds from the parent stands from the north or to the south of a test plot. In new conditions, wide range of genetic variations of a species demonstrating its genetic differentiation and environmental sustainability can be observed (Petrov 1987). In the opinion of I. I. Kamalova (Nakvasina et al. 2008), it can take place because of genotype frequency shift from homeostasis in the areas of parent stands growing.

To study different adaptation of tree provenances to climate changes various parameters are used. For spruce provenances, height of trees of different ages (Beaulieu

Corresponding author. Elena Nakvasina, e-mail: nakvasina@yandex.ru, phone: +7818 2216174

& Rainville 2005; Gömöry et al. 2012; Kapeller et al. 2012) or diamter growth (Suvanto et al., 2016) were used. We carried out the similar studies on Scots pine and spruce provenances response to climate change in terms of growth rate and seeds production (Nakvasina 2003, 2014; Nakvasina et al. 2008, 2016).

Study of intraspecific variability and phenotypic plasticity related to population origin and growing conditions is considered of higher priority (Mátyás 2006; Garzón et al. 2011; Kapeller et al. 2012; Suvanto 2016).

In wide sense, plasticity means biological ability of species to adapt to environmental conditions. Phenotypic plasticity means ability of an organism to change its phenotype in response to changes in the environment without genetic change (Gienapp et al. 2008; Price et al. 2003). Plasticity is based on homeostatic responses. Phenotypic plasticity provides stability of large populations, such as spruce populations (Gomez-Mestre & Jovani 2013).

However, species tests beyond its natural distribution area is of specific interest (Kapeller & Schüler 2012), as species response to climate changes can be explained by species distribution history, its migration from the distribution area center (Kapeller et al. 2012). For *P. abies* such opportunity is provided by provenance tests established in Russia. The eastern boundary of this species distribution area goes just within the Russian Plain area. Here, the species comes in contact with *P. obovata* and forms an introgressive hybridization zone.

We studied provenances of *Picea abies* (L.) Karst. and *P. obovata* (Ledeb.) in provenance trials located in the European North of Russia within the natural distribution area of *P. obovata*. *Picea abies* provenances grow in provenance trials beyond the distribution area of this species. Environmental conditions of the taiga zone considerably differ from optimal growing conditions for this species in the distribution area and therefore, it would make it possible to assess its phenotypic plasticity in extreme growth conditions. We can also compare phenotypic plasticity of *P. abies* and *P. obovata*. Provenances of *P. obovata* are tested in optimal growing conditions for this species or in simulated climate warming conditions.

2. Materials and methods

In the European North of Russia spruce provenances were tested in three test plots (Fig. 1) located in the southern taiga subzone (the Vologda Region, "Vologda" test plot, and in the middle taiga subzone (the Arkhangelsk Region, "Plesetsk" test plot, Komi Republic, "Komi" test plot). These plots make a part of the State Provenance Trial Network of the USSR established in 1970s (Rodin & Prokazin 1996, 1997; Shutyaev 1990). Geographical and environmental characteristics of the test plots are given in Table 1. Latitude difference of the test plots is 2.5–3.5° N, longitude difference is up to 14° E. In the Arkhangelsk and Vologda Regions climate is continental, in Komi Republic climate is strong continental result from proximity of the Urals. Provenances are grown on podsolic soils in spruce-blueberry shrub forest type.

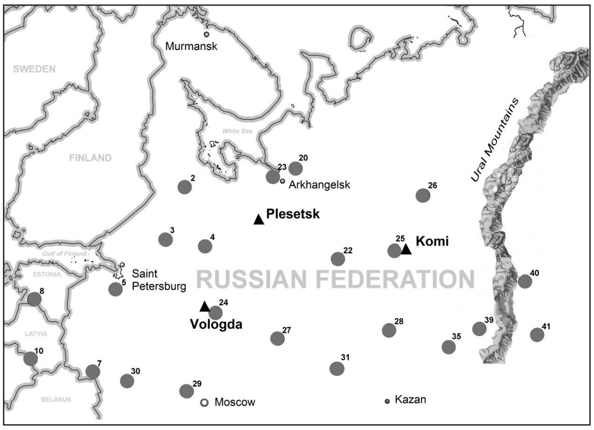

Fig. 1. Location of tested populations and spruce test plots in the European North of Russia (triangle – test plots location, dark circles – provenance location).

Table 1. Characteristics of geographic coordinates and climatic parameters of the experimental plots.

Parameters	Plesetsk	Vologda	Komi
Age [years]*	31/34	31/34	33/36
Latitude, [°N]	62°54’	59°15’	61°41’
Longitude, [°E]	40°24’	37°20’	51°31’
Vegetation period [days]	148	160	141
Sum of temperatures above +5 °C	1810	2020	1720
Annual mean temperature, [°C]	1	2.3	−0.1
Mean temperature in January, [°C]	−12	−12	−15
Mean temperature in July, [°C]	10.0	17.5	16.0
Annual rainfall [mm]	530	580	550
Climate continentality, [%]	45.0	48.0	50.0

* – The age of plantation / the biological age of trees at the time of study.

Provenance trials were established in 1977. For tree planting 3-year seedlings were used for planting. Plant spacing: 0.75 m, row spacing: 2.5 m. Average block area – 0.25 ha, number of planted trees is about 400 in 3–6 replications. Supervisor of the test plots (Northern Research Institute of Forestry, Arkhangelsk, Russia) carries on regular observations.

For study of spruce provenances, the generally accepted Russian method of provenance tests of the main forest-forming species (Prokazin 1972) approved by the Basic Research Council on Forest Genetics, Selection, and Seed Production was used. For each provenance diameter (DBH) was measured at least for 100 randomly selected plants with accuracy of 0.1 cm. Average tree height for the provenance was determined using a height profile developed based on diameter and height values measured for at least 25 plants of different diameter classes in each variant. Survival was determined (in per cent) by number of survived trees against total number of trees initially planted out in blocks.

In our research 22 spruce provenances growing in each test plot were chosen. Geographical coordinates and forest types of their parent stands and taxation parameters of tested provenances are given in Table 2. List of tested provenances includes provenances from the northern, middle, and southern taiga subzones and mixed forest zone located within the Russian Plain (Fig. 1). Seven from 22 provenances are represented by *P. obovata* (L.) Karst., and six are represented by *P. abies* (Ledeb.). The rest provenances are represented by their introgressive hybrid forms distinguished by scale edges of mature macrostrobiles (Pravdin 1975; Orlova & Egorov 2010). Provenances represented by hybrid forms are of two types: hybrids with *P. obovata* characters (4 provenances) and hybrids with *P. abies* characters (6 provenances).

For ecological plasticity calculation the method developed by S. Eberhart and W. Russel (1966) in S. A. Petrov (1984) interpretation was used. The method is used in system experiments when the same provenances (at least three) are cultivated in different environmental conditions. The method by S. Eberhart and W. Russell (1966) is widely use in Russia and other countries for assessment of agricultural field and fruit sorts and species crop capacity (Scapim et al. 2000; Besedina et al. 2014; Gulnyashkin et al. 2014; Krasnova et al. 2014). This method was used in provenance trials for forest species plasticity assessment (Shutyaev & Giertych 1997, 2000; Nakvasina et al. 2008).

According to the method (Eberhart & Russell 1966), total variability (plasticity) of a provenance under test conditions is characterized by linear regression coefficient (b_i). Provenances with $b_i > 1$ are characterized by high plasticity and easily adapt to cultivation conditions; in case of cultivation conditions improvement better results can be expected. Provenances with $b_i < 1$ have low

Table 2. Location, survival (%) and mean diameters and tree heights of spruce provenances.

No	Provenance area and location	Spatial coordinates	Forest vegetation subzone, zone	Plesetsk			Vologda			Komi		
				Sv	DBH	H	Sv	DBH	H	Sv	DBH	H
			Picea obovata (Ledeb.)									
20	Arkhangelsk Pinega	64°45' 43°14'	NT	81.3	7.5	8.0	82.4	7.8	8.3	51.9	4.5	4.8
23	Arkhangelsk Kholmogy	64°14' 41°38'	NT	81.3	7.3	7.8	85.5	8.0	8.5	28.5	3.6	3.7
25	Komi Kortkerosskii	61°41' 51°31'	MT	75.2	8.3	9.5	76.7	8.8	9.7	67.9	8.2	8.5
26	Komi Sosnogorskii	63°27' 53°55'	MT	68.4	8.3	9.9	81.6	8.6	9.6	46.6	7.3	7.9
40	Sverdlovsk Karpinsk	59°51' 60°00'	MT	60.5	7.7	7.7	81.8	8.5	9.1	42.4	7.5	7.7
39	Perm Dobrjanka	58°16' 56°25'	ST	62.7	7.2	8.4	75.2	9.5	10.3	50.5	4.8	5.1
41	Sverdlovsk Nizhnij Tagil	57°54' 60°00'	ST	60.5	7.1	7.7	68.8	8.9	10.1	50.5	5.1	5.7
			Hybrid forms with properties of *Picea obovata* (Ledeb.)									
2	Karelia Segezha	63°40' 34°23'	MT	68.7	7.1	8.3	78.0	8.9	9.5	54.8	5.3	5.4
22	Arkhangelsk Kotlass	61°15' 46°54'	MT	75.7	8.1	9.9	79.6	8.6	9.5	61.2	5.4	5.8
28	Kirov Slobodskoj	58°49' 50°06'	ST	71.3	7.0	8.3	77.9	9.8	10.2	51.8	5.6	5.9
35	Udmurtia Izhevsk	56°50' 53°10'	ST	51.3	6.2	7.7	71.0	8.6	9.7	50.7	3.7	4.1
			Hybrid forms with properties of *Picea abies* (L.) Karst.									
3	Karelia Prjazha	61°40' 33°33'	MT	70.9	8.9	9.8	81.1	8.8	9.6	42.0	4.3	4.7
4	Karelia Pudozh	61°40' 36°40'	MT	78.0	7.6	9.4	79.5	9.1	9.8	47.9	6.0	6.3
24	Vologda Cherepovets	59°07' 37°57'	ST	61.9	9.5	10.1	84.5	10.0	10.7	44.7	4.1	4.4
27	Kostroma Galich	58°24' 42°20'	ST	68.7	7.0	8.6	78.7	9.5	11.4	32.4	3.2	3.4
31	Nizhnii Novgorod Sharanga	57°11' 46°39'	MF	48.4	6.1	7.0	77.9	9.2	9.8	32.6	5.9	6.2
			Picea abies (L.) Karst.									
5	Leningrad Tosno	59°30' 30°52'	ST	70.9	8.5	10.7	84.5	10.3	11.5	24.8	4.5	4.6
7	Pskov Velikie Luki	56°23' 30°30'	MF	54.9	8.7	10.0	84.4	10.2	11.0	15.7	4.9	5.4
30	Tver Nelidovo	56°14' 32°48'	MF	62.2	7.3	8.8	63.5	9.5	10.8	36.7	6.2	6.5
8	Estonia Viljandi	58°24' 25°38'	MF	56.1	7.6	9.6	71.6	9.5	10.2	31.2	6.7	7.4
10	Latvia Daugavpils	56°10' 26°30'	MF	53.2	7.7	10.3	69.9	9.5	10.5	28.0	5.9	6.2
29	Moscow Solnechnogorsk	56°10' 36°58'	MF	66.6	8.7	10.6	61.6	8.8	9.8	31.5	5.5	6.0

No – provenance identification number; area and location as in the State Register; NT – northern taiga, MT – middle taiga, ST – southern taiga, MF – mixed forest; Sv – survival [%], DBH – diameter at breast height [cm], H – height [m].

phenotypic plasticity and weak response to environmental conditions change; on cultivation conditions improvement better results are not expected. At the same time, in case of condition decline, results would not downgrade considerably. Provenances with $b_i = 0$ are in intermediate position (with average plasticity). This makes it possible to assess spruce provenances both in terms of their use for forest cultivation and in terms of their adaptation to climate changes.

The method makes it possible to calculate environmental condition index intended for assessment of differentiation of provenance cultivation conditions (Eberhart & Russell 1966; Petrov 1984).

The present study is based mainly on Eberhart and Russell (1966) model. Wricke's ecovalence (1962) evaluate genotype stability and complements the Eberhart and Russell (1966) regression analysis. According to Kang et al. (1987) Wricke's ecovalence is equivalent to Shukla (1972) and gives similar results for genotype ranking. A high value of Wricke's ecovalence (W_i^2) is considered as an indicator of low stability, while $W_i^2 = 0$ gives the most stability. The regression coefficient of Eberhart and Russell (b_i) and the Wricke's ecovalence (W_i^2) were calculated for each genotype and compared by correlation analysis.

Phenotypic plasticity was estimated based on three parameters: survival, diameter, height. For estimation of growth parameters of phenotypic plasticity we used average increment calculated as height and diameter divided by biological age of a spruce because the differences in years of observations and stands ages.

ANOVA (SPSS v 22.0, GLM procedure) with groups of plasticity and spruce species on survival and growth parameters of spruce provenances as fixed factors was used to test differences in survival and growth parameters, and interactions between them. For the statistical data analysis, correlation analysis was used. Significant value was accepted at the $P < 0.05$ level.

3. Results

Differences in growth conditions in the spruce test plots in the taiga zone of the Russian Plain are proved by environmental condition indices determined using the S. Eberhart & W. Russell (1966) method (Table 3). The best conditions when the index has positive value, the worst conditions when the index has negative value (Korzun & Bruilo 2011). In the test plots Plesetsk and Vologda environmental conditions of spruce growth are quite favorable; in the test plot Komi growth conditions are worse. Environmental conditions impact spruce provenance survival rather than diameter and height of survived trees.

Survival and growth rate of 22 spruce provenances in different test plots differ but have common behavior related to spruce age. Spruce provenances from low-latitudes *(P. abies)* have worse survival during first years after planting out. In this period northern provenances represented by *P. obovata* have better resistance to environmental conditions (Nakvasina et al. 1990; Tarkhanov 1998). They maintain better survival also later. In most cases, survived *P. abies* trees have higher growth rate than *P. obovata* (Nakvasina & Gvozdukhina 2005; Faizulin et al. 2011; Demina et al. 2013).

Table 3. Environmental indices in spruce test plots.

Parameters	Plesetsk	Vologda	Komi
Survival	+4.203	+15.430	−19.633
Height	+2.726	+5.212	−7.938
DBH	+0.119	+0.534	−0.653

Table 4 shows the parameters of the phenotypic plasticity of the origin of spruce: Eberhart and Russell's b_i and Wricke's W_i^2. Provenances of plastic and non-plastic groups ($b_i > 1$ and $b_i < 1$) by growth and survival occur among *P. obovata, P. abies* and their hybrid forms. Grouping of provenances by plasticity does not agree in some parameters. Plasticity grouping by survival and growth is the most similar in two biometrical indices (DHB and height), correlation ratio *r* is 0.7258 (significant at $P = 0.05$). Wricke's ecovalence (W_i^2) is an indicator of genotype stability. A high value shows the low genotype stability, while $W_i^2 = 0$ gives the greatest stability. In our experiment, W_i^2 had the more variations in survival (from 2.68 to 456.49) and lower in DBH and height (0.09 – 4.98 and 0.32 and 6.96). This is close to variability of Eberhart and Russell's liner regression parameter b_i.

Correlation coefficients (Table 5) were important for estimating mean values of and Eberhart and Russell's coefficient (b_i) and Wrick's ecovalence (W_i^2), as well as pair combinations between them. The correlation between the coefficients was significant for survival (0.417). The same indicator has a significant correlation between mean values and Eberhart and Russell's coefficient (b_i). Correlations between the other pairs of combinations were not significant. It can be assumed that with a larger number of tested genotypes this effect can be stronger (Becker 1981).

4. Discussion

For practical purposes it is important to select genotypes that will respond to a changed environment and give the best results. Such a possibility is provided by the approach of Eberhart and Russell (1966), which proposes to evaluate the plasticity by the coefficient b_i. Therefore, according to the linear regression indicator, the tested genotypes were divided into two groups: Group 1 – ($b_i > 1$) – plastic populations; Group 2 – ($b_i < 1$) – non-plastic.

Among *P. obovata* and its hybrid forms, the most provenances are assigned by survival and growth to Group 2 ($b_i < 1$), i.e. non-plastic. It is especially typical

Table 4. Phenotypic plasticity of spruce parameters by survival (Sv), height (H) and diameter (DBH).

No	Provenance area	Means			Eberhart and Russell's b_i			Wricke's W_i^2		
		Sv	DBH	H	Sv	DBH	H	Sv	DBH	H
20	Arkhangelsk	71.9	6.6	7.0	0.93	0.93	0.86	51.45	0.62	0.35
23	Arkhangelsk	65.1	6.3	6.7	1.72	1.18	1.06	456.49	0.94	0.34
25	Komi	73.3	8.4	9.2	0.26	0.26	0.51	352.62	5.21	5.09
26	Komi	65.5	8.1	9.1	0.99	0.44	0.63	2.68	2.98	3.30
40	Sverdlovsk	61.6	7.9	8.2	0.67	1.20	1.11	51.06	4.13	6.41
39	Perm	62.8	7.2	7.9	1.07	0.34	0.44	81.48	0.58	0.57
41	Sverdlovsk	59.9	7.0	7.8	0.51	0.99	0.93	160.34	0.09	1.24
2	Karelia	67.2	7.1	7.7	0.65	0.94	0.94	81.06	0.15	0.08
22	Arkhangelsk	72.2	7.4	8.4	0.54	0.90	0.98	139.51	0.42	0.96
28	Kirov	67.0	8.4	9.2	0.76	1.06	0.95	40.19	1.00	0.55
35	Udmurtia	57.7	6.2	7.2	0.49	1.24	1.15	276.56	0.79	0.97
3	Karelia	64.7	7.3	8.0	1.13	1.26	1.18	14.33	2.68	1.69
4	Karelia	68.5	7.6	8.5	0.96	0.84	0.90	48.62	0.31	0.32
24	Vologda	63.7	7.9	8.4	1.07	1.60	1.40	65.27	4.98	3.36
27	Kostroma	59.9	6.6	7.8	1.35	1.59	1.57	94.37	3.31	6.96
31	N. Novgorod	53.0	7.1	7.7	1.19	0.81	0.75	167.75	2.52	3.32
5	Leningrad	60.1	7.8	8.9	1.74	1.52	1.52	369.42	2.40	4.95
7	Pskov	51.7	7.9	8.8	1.91	1.40	1.26	567.11	1.54	1.16
30	Tver'	54.1	7.7	8.7	0.81	0.86	0.96	56.54	0.77	0.68
8	Estonia	53.0	7.9	8.1	1.14	0.75	0.78	15.95	1.05	1.16
10	Latvia	50.4	7.7	9.0	1.17	0.95	1.08	26.18	0.15	0.42
29	Moscow	53.2	7.7	8.8	0.95	0.95	1.04	138.28	0.89	1.70

Table 5. Correlation coefficients between of spruce growth and survival and genotype stability parameters.

Parameters	Survival			Diameter			Height		
	Means	b_i	W_i^2	Means	b_i	W_i^2	Means	b_i	W_i^2
Means	1.000	−0.498*	−0.167	1.000	−0.252	0.370	1.000	−0.047	0.206
b_i	—	1.000	0.417*	—	1.000	0.145	—	1.000	0.321
W_i^2	—	—	1.000	—	—	1.000	—	—	1.000

* Significant at 0.05 level.

for survival. Provenance No 23 (*P. obovata*, Arkhangelsk Region, Kholmogory District) from the Northern taiga subzone is different as can be assigned to Group 1 by three indices. Three more provenances have high plasticity index (b_i> 1) for certain parameters: for survival (*P. obovata*, Sverdlovsk Region, No 40) and for height (*P. obovata*, Perm Region, No 39 and hybrid form with properties of *Picea obovata*, Udmurtia, No 35).

For *P. abies* and its hybrid forms the high index (b_i > 1) is observed more often and represents high plasticity of the species. It is especially typical for survival. Five provenances of *P. abies* and its hybrid forms characterize by high plasticity both in survival and growth. These are provenances from Leningrad (No 5), Pskov (No 7), Vologda (No 24), Kostroma (No 27) Regions, Karelia Republic (No 3). They are located in different zones and taiga subzones: in the middle and southern taiga subzones and mix forest zone. However, the area of initial stand habitats of these provenances is quite local and is restricted by 56º30´ – 61º40´ N and 30º30´ – 42º30´ E.

The genotype survival has a clear differentiation (P < 0.05) by selected groups of plasticity and by species and forms of spruce (Table 6). The stability of the provenances in the new environmental conditions during the testing of spruces genotypes can be considered as priority in the practical genotypes assessment. Growth (height and diameter) is less impacted by the environment. The provenances maintain hereditarily fixed growth parameters and implement them when the growing conditions change in accordance with the reaction norm.

Table 6. Fisher values (F) and statistical significances (P-values) of main effects of groups of plasticity and spruce species on survival and growth parameters of spruce provenances (one-way ANOVA), F_{crit}=4.351.

Parameters	Spruce species and forms, df = 3		Groups of plasticity, df = 1	
	F	P	F	P
Survival	3.188	0.049	4.558	0.045
Diameter	0.431	0.733	0.223	0.642
Height	0.946	0.439	0.098	0.757

Plastic provenances of *Picea abies* and its hybrid forms are concentrated near the western boundaries of the Russian Plain (Fig. 2). It can be a result of closeness of the spruce refugium located in the territory of Belovezhskaya Pushcha from where spruce migration towards north-east has occurred (Dering & Levandovski 2007).

At the same time, plastic provenances of *Picea obovata* and its hybrid forms are dispersed all over the north-western part of the Russian Plain that can be a result from *P. obovata* propagation to the Russian Plain from Siberia via the Polar Urals (Popov 2005). In the North-Eastern part of the Russian Plain plastic spruce provenances mixed with provenances close to plastic ones, i.e. they are not plastic in all studied parameters (they can be named as partly plastic). Such genomic clustering of parent populations is typical of Eurasian spruce species (Melnikova et al. 2012).

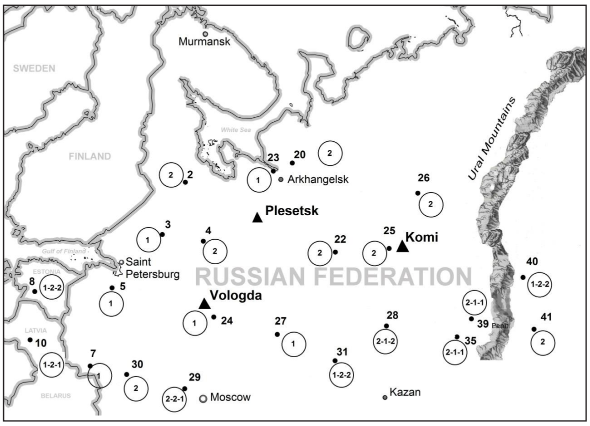

Fig. 2. Spruce provenance plasticity by survival, diameter and height, their location in the Russian Plain (numbers in a circle: 1 – plastic, 2 – non-plastic; three numbers in a circle: rank of plasticity by survival, diameter and height).

According to Garzón et al. (2011), different response to climatic changes can be expected for species and provenances with different phenotypic plasticity. In general, *Picea abies*, due to its better plasticity, would be more responsive to climatic changes in production properties (survival and growth). *Picea obovata* is a more conservative species and would poorly respond to climatic changes. It agrees with a general conclusion made by Kapeller et al. (2012) for *Picea abies*, that southern spruce species from a zone with higher temperatures and less precipitation would be more suitable for use in new environmental conditions.

Gömöry et al. (2012) noted that high-latitude spruce provenances are more resistant and low-latitude spruce provenances are more sensitive to climate change. Persson (1998) considers it as a result of decrease of required cold resistance under climate warming.

In this case, in future, with climate warming in the Northern areas of the Russian Plain, we can expect further *Picea abies* dispersion and its suppression on *Picea obovata*. For species adaptation to climate warming several species generations will required (Beaulieu et al. 2005). It should be taken into consideration that forest ecosystems have high tolerance providing their high resistance to unfavorable environmental impact. In addition, so called adaptive delay (for about 100 years) of species response to climate changes takes place (Savolainen et al. 2004). Therefore, *P. abies* dispersion over the Russian Plain would be slow and first it would cause extension of introgressive hybridization zone. It can cause decrease of *P. abies* phenotypic plasticity due to hybridization with less plastic *P. obovata*.

5. Conclusions

Picea abies (L.) Karst. provenances have better phenotypic plasticity, including the response to the climate changes. In future, on sustainable climate warming, this species could predominate in the Russian Plain and start to force out *P. obovata* (Ledeb.).

Variability of phenotypic plasticity observed for populations of spruce species (*Picea abies* (L.) Karst. and *P. obovata* [Ledeb.]) and for their hybrids forms occurring in the contact zone proves necessity in further study of certain provenances. Selection based on provenances phenotypic plasticity would make it possible to solve some production problems related to adaptation of forest-forming species to climate changes.

Acknowledgements

The authors are grateful to the Northern Research Institute of Forestry, N. V. Ulissova, and D. Kh. Faizulin for contributed field data on provenance observation. A.G. Volkov for help in statistical analysis. The work by N. A. Prozherina was carried out within the framework of the State Task AAAA-A18-118011690221-0 of the N. Laverov Federal Center for Integrated Arctic Research.

References

Beaulieu, J., Rainville, A., 2005: Adaptation to climate change: Genetic variation is both a short- and a long-term solution. The Forestry Chronicle, 81:704–709.

Becker, H. C., 1981: Correlation among some statistical measures of phenotypic stability. Euphytica, 30: 835–840.

Besedina, T. D., Tutberidze, Ts. V., Dobezhina S. V., 2014: Ecological characteristics of the introduced cultivars of *Actinidia deliciosa* in Russian humid subtropics. Nauchnyj zhurnal KubGAU, 100:1275–1286. [in Russian].

Demina N. A., Faizulin D. Kh., Nakvasina, E. N., 2013: Specification of the boundaries of forest seeding of spruce in the European North. Lesnoj Vestnik, 2:23–28. [in Russian].

Dering, M., Lewandowski, A., 2007: Postglacial re-colonization of Norway spruce (*Picea abies* [L.] Karsten) in Poland based on molecular markers In: Conference session abstracts "Norway Spruce in the Conservation of Forest Ecosystems in Europe", September 3–5, 2007, Warszawa, 37 p.

Eberhart, S. A., Russell, W. A., 1966: Stability parameters for comparing varieties. Crop Science, 6:36–42.

Faizulin, D. Kh., Artemjeva, N. R., Senkov, A. O., 2011: Pine and spruce provenance tests in the middle and southern subzones of the taiga of the European part of the Russian Federation. In: Results of scientific research work of "SevNIILKh" for 2005–2009. Arkhangelsk, p. 23–27. [in Russian].

Garzón, M. B., Alía, R., Robson, T. M., Zavala, M. A., 2011: Intra-specific variability and plasticity influence potential tree species distributions under climate change. Global Ecology and Biogeography, 20:766–778.

Gienapp, P., Teplitsky, C., Alho, J. S., Mills, J. A., Merila, J., 2008: Climate change and evolution: disentangling environmental and genetic responses. Molecular Ecology, 17:167–178.

Gomez-Mestre, I., Jovani, R., 2013: A heuristic model on the role of plasticity in adaptive evolution: plasticity increases adaptation, population viability and genetic variation. Proceedings of the Royal Society B: Biological Sciences, https://doi.org/10.1098/rspb.2013.1869.

Gömöry, D., Longauer, R., Hlásny, T., Pacalaj, M., Strmeň, S., Krajmerová, D., 2012: Adaptation to common optimum in different populations of Norway spruce (*Picea abies* Karst.). European Journal of Forest Research, 131:401–411.

Gulnyashkin, A. V., Anashenkov, S. S., Varlamov, D. V., 2014: Study results of ecological adaptability of new early ripening hybrids of maize grain farm in Russia. Zernovoe Khozyajstvo Rossii, 4:31–36. [in Russian].

Iroshnikov, A. I. 2002: On the concept and the program of genetic monitoring of forest woody plant populations. Lesovedenie, 1:58–64. [in Russian].

Kang, M. S., Miller, J. D., Darrah, L. L., 1987: A note on relationship between stability variance and ecovalence. Journal of Heredity, 78:107.

Kapeller, S., Lexer, M. J., Geburek, T., Hiebl, J., Schueler, S., 2012: Intraspecific variation in climate response of Norway spruce in the eastern Alpine range: Selecting appropriate provenances for future climate. Forest Ecology and Management, 271:46–57.

Kapeller, S., Schüler, S., 2012: Alternative, adapted seed sources handbook & map of trans-alpine provenance regions. Federal Research and Training Centre for Forests, Natural Hazards and Landscape, Vienna, 8 p.

Krasnova, Y. S., Shamanin, V. P., Petukhovsky, S. L., Kirilyuk, L. M., 2014: Ecological plasticity of grades of the soft springwheat in the conditions of the southern forest-steppe of Western Siberia. Sovremennye Problemy Nauki i Obrazovaniya. 6:1633. [in Russian].

Korzun, O. S., Bruilo, A. S., 2011: Adaptive features of plant breeding and seed crops. GSAU, Grodno, 140 p. [in Russian].

Lindgren, D., Persson, A., 1995: Vitalization of results from provenance tests. In: Pälvinen, R., Vanclay, J., Minna, S. (eds.): Caring for the Forest: Research in a Changing World. IUFRO XX World Congress, August 6–12 1995, Tampere, Finland, 249 p.

Mátyás, Cs., 2006: Migratory, genetic and phenetic response potential of forest tree populations facing climate change. Acta Silvatica et Lignaria Hungarica, 2:33–46.

Melnikova, M. N., Petrov, N. B., Lomov, A. A., la Porta, N., Politov, D. V., 2012: Testing microsatellite primer with different populations of Eurasian spruces *Picea abies* (L.) Karst. and *Picea obovata* (Ledeb.). Russian Journal of Genetics, 48:562–566.

Nakvasina, E. N., Yudina, O. A., Prozherina, N. A., Kamalova, I. I., Minin, N. S., 2008: Provenance test in gene-ecological studies in the European North. Arkhangelsk, 307 p. [in Russian].

Nakvasina, E. N., 2003: Provenance tests of Scots pine (*Pinus sylvestris* L.) as a natural model of imitation of climatic changes. Vestnik Pomorskogo Universiteta, 2:48–53. [in Russian].

Nakvasina, E. N., 2014: Changes in the generic sphere of Scots pine in the imitation of climate warming. Izvestiya Sankt-Peterburgskoj Lesotekhnicheskoj Akademii, 209:114–125. [in Russian].

Nakvasina, E. N., Tarkhanov, S. N., Ulissova, N. V., Sizov, I. I., Bedritskaya, T. V., 1990: Northern forests: state, dynamics, anthropogenic impact. In: Pisarenko, A. I. (ed.): Proceedings of international conference Arkhangelsk, (Russia): USSR State Forest Agency, 2:131–140. [in Russian].

Nakvasina, E. N., Gvozdukhina, O. A., 2005: An assessment of the state and growth of pine and spruce provenance tests in the Arkhangelsk Region. Problems of Forest Science and Forestry. Proceedings of conference Arkhangelsk (Russia): AGTU, p. 58–63. [in Russian].

Nakvasina, E. N., Yudina, O. A., Pokatilo, A. V., 2016: Growth and reproductive reactions *Picea abies* (L.) Karst. × *P. obovata* Ledeb. in simulated climate warming. Arctic Environmental Research, 1:89–96. [in Russian].

O'Neill, G. A., Hamann, A., Wang, T., 2008: Accounting for population variation improves estimates of the impact of climate change on species growth and distribution. Journal of Applied Ecology, 45:1040–1049.

Orlova, L. V., Egorov, A. A., 2010: By taxonomy and geographical distribution of Finnish spruce (*Picea fennica* (Regel) Kom., Pinaceae). Novosti Sistematiki Vysshykh Rastenij, 42:5–23. [in Russian].

Persson, B., 1998: Will climate change affect the optimal choice of *Pinus sylvestris* provenances? Silva Fennica, 32:121–128.

Petrov, S. A., 1984: Recommendations for the use of genetic and statistical methods in the selection of forest species on productivity. Voronezh, 43 p. [in Russian].

Petrov, S. A., 1987: Genetic resources of forest-forming species, ways of their formation and rational use. Lesorazvedenie i lesomelioratsiya, 1:1–30. [in Russian].

Popov, P. P., 2005. Spruce European and Siberian. Science, Novosibirsk, 231 p. [in Russian].

Potokina, E. K., Kiseleva, A. A., Nikolaeva, M. A., Ivanov, S. A., Uljanich, P. S., Potokin, A. F., 2015: Analysis of polymorphism of organelle DNA to elucidate the phylogeography of Norway spruce in the East European Plain. Russian Journal of Genetics: Applied Research, 5:430–439.

Pravdin, L. F., 1975: Norway spruce and Siberian spruce in the USSR. Science, Moscow, 176 p. [in Russian].

Price, T. D., Qvarnström, A., Irwin, D. E., 2003: The role of phenotypic plasticity in driving genetic evolution. Proceedings of the Royal Society B: Biological Sciences, 270:1433–1440.

Prokazin, E. P., 1972: Program and methods of work. The study of available and creation of new provenance trial. VNIILM, Pushkino, 52 p. [in Russian].

Rodin, A. R., Prokazin, A. E. 1996: About study problems of provenance trial of basic forest species. Lesnoe khozjajstvo, 4:16–18. [in Russian].

Rodin, A. R., Prokazin, A. E., 1997: Study of geographic variation of the main forest-forming species. In: Kharin, O. A. (ed.): Forest use and reproduction of forest resources, Moscow, p. 70–75. [in Russian].

Rone, V. M., 1979: Methods of genetic analysis and selection in populations of spruce. Doctoral Thesis in Biology, Institute of General Genetics of USSR Academy of Sciences, Moscow, 36 p. [in Russian].

Savolainen, O., Bokma, F., Garcia-Gil, R., Repo, T., 2004: Genetic variation in cessation of growth and frost hardiness and consequences for adaptation of *Pinus sylvestris* to climatic changes. Forest Ecology and Management, 197:79–89.

Scapim, C. A., Oliveira, V. R., Brassini, A. de L., Cruz, C. D., de Bastos Andrade, C. A., Gonçalves Vidigal, M. C., 2000: Yield stability in maize (*Zea mays* L.) and correlations among the parameters of the Eberhart and Russell, Lin and Binns and Huehn models. Genetics and Molecular Biology, 23:387–393.

Shukla, G. K., 1972: Genotype stability analysis and its application to potato regional trails. Crop Science, 11:184–190.

Shutyaev, A. M., 1990: Basics forest seeds zoning. In: Veretennikov, A. V. (ed.): Increased productivity, sustainability and the protective role of forest ecosystems. Voronezh, Russia, p. 62–66. [in Russian].

Shutyaev, A. M., Giertych, M., 1997: Height growth variation in a comprehensive Eurasian provenance experiment of (*Pinus sylvestris* L.). Silvae Genetica, 46:332–349.

Shutyaev, A. M., Giertych, M., 2000: Genetic subdivisions of the range of Scots pine (*Pinus sylvestris* L.) based on a transcontinental provenance experiment. Silvae Genetica, 49:24–38.

Suvanto, S., Nöjd, P., Henttonen, H. M., Beuker, E., Mäkinen, H., 2016: Geographical patterns in the radial growth response of Norway spruce provenances to climatic variation. Agricultural and Forest Meteorology, 222:10–20.

Tarkhanov, S. N., 1998: Variability of spruce in the provenance tests of the Komi Republic. Ekaterinburg, 194 p. [in Russian].

Wricke, G., 1962. Über eine Methods zur Erfassung der ökologisches Streubreite in Feldversuchen. Zeitschrift für Pflanzenzüchtung, 47:92–96.

Cent. Eur. For. J. 65 (2019) 129–144 sciendo DOI: 10.2478/forj-2019-0013

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Adaption of Norway spruce and European beech forests under climate change: from resistance to close-to-nature silviculture

Zdeněk Vacek[1, *], Stanislav Vacek[1], Jiří Slanař[1], Lukáš Bílek[1], Daniel Bulušek[1], Igor Štefančík[2], Ivo Králíček[3], Karel Vančura[1]

[1] *Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, CZ – 165 21 Prague 6 - Suchdol, Czech Republic*

[2] *National Forest Centre, Forest Research Institute, T. G. Masaryka 2175/22, SK – 960 01 Zvolen, Slovak Republic*

[3] *University of Hradec Králové, Faculty of Science, Rokitanského 62, CZ – 500 03 Hradec Králové, Czech Republic*

Abstract

In time of climate change, close-to-nature silviculture is growing in importance as a tool for future forest management. The paper study the tree layer and natural regeneration of monospecific Norway spruce (*Picea abies* [L.] Karst.), trough mixed spruce-beech to dominant European beech (*Fagus sylvatica* L.) forests in Jizerské hory Mts., the Czech Republic. In the locality, shelterwood and selection system have been applied since 2000. The research objectives were to evaluate production parameters, structural diversity, species richness, natural regeneration dynamics and radial growth of individual tree species in relation to climatic factors and air pollution. The stand volume on permanent research plots amounted to 441 – 731 m^3 ha^{-1} in initial stage of transformation. Natural regeneration showed high expansion of beech and decrease of spruce compared to mature tree species composition. Radial growth of spruce was in significant negative correlation with SO_2 and NO_X concentrations compared to no effect on beech increment. Moreover, spruce was more sensitive to significant years with extreme low radial growth. Beech was more stable in radial growth. Spruce was more resistant to air pollution and climatic stress in mixed stands. Low temperature was limiting factor of radial growth together with climate extremes (such as strong frosts and more frequent droughts) and biotic factors (bark beetle, beech scale). Close-to-nature management supporting admixed tree species should lead in future to diversification of stand structure toward higher species, spatial and age structure to mitigate negative effect of climatic change.

Key words: natural regeneration; forest transformation; stand structure; forest dynamics; air pollution; Czech Republic

Editor: Bohdan Konôpka

1. Introduction

Pure and mixed forest stands of European beech (*Fagus sylvatica* L.) were the most widespread forests in the Middle Age in Europe (Packham et al. 2012). In the course of centuries intensive forest management has changed their original species composition and stand structure in many localities (von Oheimb 2005; Petritan et al. 2015). For example in the Czech Republic, beech was represented by 40.2% in natural forests, currently it is represented by 8.4% (MZe 2018). Forests of the temperate zone have usually undergone greater changes than other forest ecosystems (Terek & Dobrovic 2013). In Central Europe, natural forest ecosystems were mostly affected and constrained by unfavourable anthropogenic factors (Jantsch et al. 2013; Bošeľa et al. 2016) as a result of dense human population (Barna & Bosela 2015). In Central Europe, due to anthropic impacts, spruce monocultures take up a large portion of forest land (Spiecker et al. 2004). These stands have been repeatedly affected by disturbances in the last decades (Hlásny & Sitková 2010; Briner et al. 2013) and consequently their long-term sustainability is questioned (Grodzki 2010).

Currently, crucial factors influencing forest ecosystems in Central Europe are climate extremes (winter desiccation, summer drought, wind storm), pollutants (SO_2, NO_x, O_3), bark beetle disturbances, excessive damage by ungulates (browsing, bark stripping) or inappropriate management (Flechard et al. 2011; Krejčí et al. 2013; Vacek et al. 2017a; Putalová et al. 2019). As in the last

**Corresponding author. Zdeněk Vacek, e-mail: vacekz@fld.czu.cz*

years gradual changes have occurred in forest management approaches in Central Europe, there has been a shift from the preference of coniferous monocultures to the support of mixed stands, natural regeneration and broadleaved species in general (Petritan et al. 2009; Slanař et al. 2017). Close-to-nature and sustainable forestry management practices have been increasingly applied (FAO 2006; Barbati et al. 2014). These alternative management strategies usually avoid a clear-cutting system while small-scale management and creation of mixed and structurally diversified forest stands is preferred (Schütz 1999; Tesař et al. 2004; Puettmann et al. 2015). Increasing the proportion of deciduous tree species and optimizing age and spatial composition of forest stands follows these management objectives and is therefore one of the key objectives of the modern forestry (Schütz 2002; Bílek et al. 2011; Puettmann et al. 2015). Target trees should be composed of at least 30% share of the original tree species composition and its close-to-nature structure differentiation is recommended (Poleno et al. 2009). This trend is also a result of recent conferences on forest conservation in Europe (MCPFE 2015) and at the same time it has become a dominant forestry paradigm in many countries (Butler & Koontz 2005). The application of these modern principles should lead to an increase in stand resistance to disturbances and to an improvement in the ability of individual trees to survive (Jönsson et al. 2012; Neuner et al. 2014; Vacek et al. 2015). This is particularly important in areas with increasing extent of forest disturbances (Hlásny et al. 2017). Taking into account this trend, foresters try to reduce a difference in structural variability between natural and commercial forests and to establish a balance between ecological and socioeconomic functions of forest (Cardinall et al. 2004; Urli et al. 2017). In this context Vacek et al. (2014b) and Remeš et al. (2015) state that the stands that would undergo the process of transformation toward close-to-nature forests would fulfil ecological, environmental and socioeconomic functions of forest in a substantially better way.

European beech as one of the most important broadleaved species in Europe (Packham et al. 2012; Chianucci et al. 2016) plays a crucial role in this trend of sustainable forest management (Bolte et al. 2007; Barna & Bosela 2015). It is very important from both economic (Shahverdi et al. 2013) and ecological aspects (Drobyshev et al. 2014). In Central Europe, beech represents a potentially dominant species of natural vegetation in humid to moderately dry areas of submontane zones under current climatic conditions (Ellenberg 1996). Nevertheless, the expected climate changes (Lorz et al. 2010; Bilela et al. 2012; Machar et al. 2017) can worsen its vitality and competitiveness (Fotelli et al. 2003). The expected regional warming and the related decreasing water availability are considered as a significant negative factor with an impact on vitality and productivity of forest ecosystems in Central Europe (IPCC 2007). On the other hand, beech is a relatively resistant tree species, especially at the centre of its distribution range, with regard to global climate change (Bolte et al. 2010; Bošeľa et al. 2016; Králíček et al. 2017). Králíček et al. (2017) or Kolář et al. (2017) concluded that European beech show higher stability and resistance in relation to climate changes (especially to droughts) compared to Norway spruce. Nevertheless, Gessler et al. (2007) showed also potential risks for this tree species in relation to climate change. Close-to-nature management strategies should solve both ecological risks and related economic risks (Seidl et al. 2014; Schelhaas et al. 2015).

The purpose of present paper is to assess the possibilities of stabilization of spruce monocultures in the process of their transformation by gradual increase of beech and structural differentiation of the forest stands in Jizerské hory Mts. For the research, mixed (spruce-beech) forest stands were selected with different proportions of beech at the initial stage of the transformation, focusing on the area where the beech is the only one prospective ameliorating and stabilising tree species in relation to ungulate browsing and climatic change. The study evaluates the structure and dynamics of spruce-beech forest stands in the 40-year transformation phase toward close-to-nature structure with emphasis on production, ecological stability and biodiversity under ongoing global climate change. The main objectives were:

- to define production parameters, structure and biodiversity (vertical, horizontal, species and complex) of forest stands at the initial stage of forest transformation including dead wood characteristics,
- to quantify dynamics of diameter increment and resistance of European beech and Norway spruce on air pollution (SO_2, NO_X, O_3), climatic factors (temperature, precipitation) and climate change,
- to estimate relationship among radial growth, tree species composition, climate and air pollution load in relation to forest stability,
- to quantify changes in structural diversity and species composition of natural regeneration compared to mature stand and the role of game damage in the process of transformation.

2. Materials and methods

2.1. Study area

The research was conducted on four permanent research plots (PRP) in the Jedlový důl area in the Protected Landscape Area Jizerské hory Mts. and Bird Conservation Area CZ0511008 Jizerské hory Mts., northern part of the Czech Republic (Fig. 1). The bedrock is composed of porphyritic medium-grained granite and granodiorite. Prevailing soil is Cambisols and Cryptopodzols (Vacek et al. 2003).

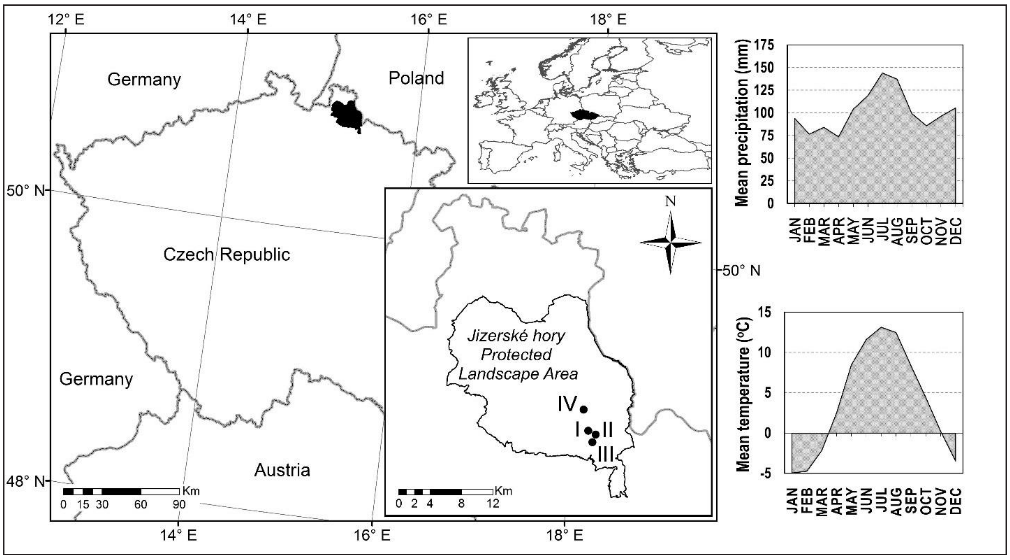

Fig. 1. The localization of spruce-beech forest stands on permanent research plots I – IV in the Jizerské hory Mts. with climatic characteristics (1960–2016).

The mean annual temperature was around 3.8 °C and the mean annual sum of precipitation reached 1 220 mm with minimum temperature in January (−5.0 °C), resp. precipitation in April (73 mm) and maximum in July (13.1 °C, 144 mm) in 1960–2016 (Fig. 1). During this period, the sum of precipitation average decreased by 77 mm and temperature increased by 1.8 °C under climate change. On all PRP the growing season lasts for about 131 days, average temperature in the growing season was around 10.7 °C with sum of precipitation 646 mm. The study territory belongs to humid continental climate characterised by hot and humid summers and cold to severely cold winters (classification symbol Dfb) according to Köppen climate classification (Köppen 1936).

From the aspect of environmental pollution, SO_2 concentrations had increased since 1970s in connection with the operation of large coal firing power station Turów in Poland (Vacek et al. 2003). The quantity of emissions increased there more than ten times in the course of two decades (45,000 tons of SO_2 in 1957, 500,000 tons of SO_2 in 1980) – (Jirgle et al. 1983). Currently, a substantial decrease in SO_2 concentrations from 28 to 3 μg m^{-3} was reached since 1972. Average concentrations of NO_X are around 7 μg m^{-3} and the O_3 exposure index AOT40F is 27,000 ppb h^{-1}.

The studied territory is covered by spruce-beech forests with individual admixture of sycamore maple (*Acer pseudoplatanus* L.), silver fir (*Abies alba* Mill.), rowan (*Sorbus aucuparia* L.) and silver birch (*Betula pendula* Roth; Table 1). Silver fir was introduced into these stands in the 80s and 90s of the 20th century through group underplantings. At the end of the 1970s and during the 1980s in connection with the air pollution load, gradual release of suppressed beech trees started in declining spruce forest stands. Substantial care for the mature beech crowns contributed to their future fertility and natural regeneration. These silviculture practises have begun the initial transformation of spruce stands in study area of the Jizerské hory Mts. (Vacek & Cipra 1979). On PRP forest transformation based on the principles of shelterwood and selection system has been applied since 2000. In terms of phytocoenology PRP belong to acidophilous beech forests (the association *Luzulo-luzuloidis-Fagetum sylvaticae* Meusel 1937, *Calamagrostio villosae-Fagetum* Mikyška 1972) and partly forms of herb-rich beech forests (the association *Dentario enneaphylli-Fagetum* Oberdorfer ex W. et A. Matuszkiewicz 1960).

Table 1. Basic site and stand characteristics of permanent research plots I, II, III and IV according to forest management plan.

PRP	GPS coordinates	Altitude [m]	Exposition	Slope [°]	Forest site type[1]	Tree species	Age [y]	Stand volume [m^3 ha^{-1}]
I	50°46′53′′ N 15°15′15′′ E	715	SW	12	6S	FS, PA, BP	129/12	438
II	50°46′42′′ N 15°15′46′′ E	730	SE	15	6S (6A)	FS, PA	166/12	512
III	50°46′28′′ N 15°15′40′′ E	640	SE	22	6S (6A)	FS, PA, SA,	164/12	532
IV	50°47′48′′ N 15°15′41′′ E	810	SE	15	6S	FS, PA, AA, AP	168/12	327

Notes: [1]6S – *Piceo-Fagetum oligomesotrophicum* represent vegetation associations of *Calamagrostio villosae-Fagetum* Mikyška 1972, 6A – *Aceri-Piceeto-Fagetum lapidosum* represent vegetation associations of *Aceri-Fagetum* J. et M. Bartsch 1940; tree species FS – *Fagus sylvatica*, PA – *Picea abies*, AA – *Abies alba*, SA – *Sorbus aucuparia*, AP – *Acer pseudoplatanus*, BP – *Betula pendula*.

2.2. Data collection

FieldMap technology (IFER-Monitoring and Mapping Solutions Ltd.) was used to determine the structure of the tree layer, dead wood and natural regeneration in 2015–2016 on four PRP of 50 × 50 m in size. The position of all individuals of the tree layer with diameter at breast height (DBH) ≥ 4 cm and crown projections were localized, minimally at 4 directions perpendicular to each other. DBH of the tree layer were measured with a metal calliper (accuracy 1 mm) and tree heights and heights of live crown base were measured with a Vertex laser hypsometer (accuracy 0.1 m; Haglöf, Sweden).

In 15 dominant and co-dominant trees of each main tree species (spruce and beech) on each PRP (only spruce on PRP 3), increment sample cores at DBH (130 cm) perpendicular to the axis of the tree along the slope and against the slope were taken by the Pressler's borer. Annual ring widths were measured with an Olympus binocular magnifier (accuracy 0.01 mm) on the LINTAB measuring table (Rinntech) and recorded by TSAPWIN (Registograph).

For naturally regenerated individuals with DBH < 4 cm and height ≥ 150 cm these characteristics were measured on the whole PRP: position, height, height of live crown base, crown width (with a height measuring pole to the 1 cm) and damage by ungulate (branch browsing, bark stripping). For standing and lying dead wood (diameter ≥ 7 cm, length ≥ 1 m) the position, tree species and volume according to the Harmon et al. (1986) method were determined.

2.3. Data analysis

Based on measured dendrometric data of tree layer, stand volume (Petráš & Pajtík 1991), stocking (stand density index – SDI) and canopy density (crown closure and crown projection area) were computed. For natural regeneration and tree layer species diversity by the following indices were evaluated: species richness *D* (Margalef 1958), species heterogeneity *H´* (Shannon 1948) and species evenness *E* (Pielou 1975). Structural and total diversity was evaluated by Arten-profile index *A* (Pretzsch 2006), diameter TM_d and height TM_h differentiation index (Füldner 1995), index of non-randomness α (Mountford 1961), aggregation index *R* (Clark & Evans 1954) and total diversity index *B* (Jaehne & Dohrenbusch 1997) using the software Sibyla (Fabrika & Ďurský 2005). Ten criteria were implemented in order to characterize forest status (Table 2).

Characteristics describing the horizontal structure of individuals within the plot were calculated using software PointPro 2.2 (Zahradník & Puš 2010). The test of significance of differences from values expected for the random layout of points was carried out by Monte Carlo simulations. Mean values of the *L*-function were estimated as means of *L*-functions calculated for 1999 randomly generated point structures. The spatial relations of natural regeneration and tree layer were evaluated by the cross-type pair correlation function *G(r)* using software R (R Project). Layout maps were created in the ArcGIS (Esri).

The annual rings series were individually cross-dated (error correction of missing rings) using statistical tests in the PAST application program (SCIEM) and, subsequently, subjected to visual inspection by Yamaguchi (1991). If a missing annual ring was found, a ring of 0.01 mm was inserted in its place. Individual curves from a PRP were age detrended by the 100 years spline and used to create the average annual-ring series in the ARSTAN program (Laboratory of Tree-Ring Research). Negative significant pointer years were analyzed for each tree and subsequently for all PRP and tree species according to Schwein-Gruber et al. (1990). These pointer years were tested as an extremely narrow annual ring reaching less than 40% of the mean diameter increment of tree in 4 preceding years. It was proven if such a strong reduction in radial growth occurred in at least 20% of the trees on the plot. Average annual ring series of the PRP were correlated with climatic data (precipitation, temperatures 1961–2015 from Bedřichov Station – 777 a.s.l.) and with air pollution data (SO_2 1975–2015, NO_X 1992–2012 and AOT40F 1996–2012 from Desná-Souš Station – 772 a.s.l.). Both stations are located in the Jizerské hory Mts. within an 8-km range of the PRP. DendroClim software (DedroLab) was used to model the diameter increment in relation to climatic characteristics.

Table 2. Overview of indices describing the stand diversity and their common interpretation.

Criterion	Quantifiers	Label	Reference	Evaluation
Species diversity	Richness	*D* (Mai)	Margalef (1958)	minimum D = 0, higher D = higher values
	Heterogeneity	*H´* (Si)	Shannon (1948)	minimum H´ = 0, higher H´ = higher values
	Evenness	*E* (Pii)	Pielou (1975)	range 0 – 1; minimum E = 0, maximum E = 1
Vertical diversity	Arten-profile index	*A* (Pri)	Pretzsch (2006)	range 0 – 1; balanced vertical structure A < 0.3; selection forest A > 0.9
Structure differentiation	Diameter dif.	TM_d (Fi)	Füldner (1995)	range 0 – 1; low TM < 0.3; very high differentiation TM > 0.7
	Height dif.	TM_h (Fi)		
Horizontal structure	Index of non-randomness	α (P&Mi)	Mountford (1961)	mean value α = 1; aggregation α > 1; regularity α < 1
	Aggregation index	*R* (C&Ei)	Clark & Evans (1954)	mean value R = 1; aggregation R < 1; regularity R > 1
	Index of cluster size	*CSI* (D&Mi)	David & Moore (1954)	mean value ICS = 0; aggregation ICS > 0; regularity ICS < 1
Complex diversity	Stand diversity	*B* (J&Di)	Jaehne & Dohrenbusch (1997)	monotonous structure B < 4; uneven structure B = 6 – 8; very diverse structure B > 9

Statistical analyses were processed in the Statistica 12 (StatSoft, Tulsa). Radial growth dataset with air pollution and climatic factors were tested by the Pearson correlation coefficient. Unconstrained principal component analysis (PCA) in Canoco 5 (Šmilauer & Lepš 2014) was used to analyse relationships between growth of beech and spruce on PRP, climate factors and air pollution data in 1975–2015. Data were log-transformed, centred and standardized before the analysis.

3. Results

3.1. Production parameters and structure of tree layer

Tree density ranged from 272 to 416 trees ha^{-1} (in European beech 40 – 212 trees ha^{-1} and in Norway spruce 10 – 328 trees ha^{-1}) with SDI 0.51 – 0.74 (Table 3). The stand volume reached 441 – 731 m^3 ha^{-1}, while beech accounted for 0 – 544 m^3 ha^{-1} and spruce for 166 – 442 m^3 ha^{-1}. The highest stand volume (731 m^3 ha^{-1}) was found out on PRP III, and the lowest on PRP I (441 m^3 ha^{-1}). Spruce-beech stands had dominant representation of Norway spruce on PRP I, II and III (60.7 – 99.9%), only on PRP IV European beech was dominant tree species (76.8%). The basal area was in the range of 36.0 – 50.4 m^2 ha^{-1} (in beech 0.1 – 34.9 m^2 ha^{-1} and in spruce 13.0 – 35.9 m^2 ha^{-1}). Periodic annual increment of stands ranged from 5.0 to 7.0 m^3 ha^{-1} y^{-1} and mean annual increment was 3.4 – 4.5 m^3 ha^{-1} y^{-1}. Canopy closure was 57.6 – 92.0% and crown projection area ranged between 0.86 and 2.52 (Table 3).

Spruce-beech stands on PRP were two or three-storeyed stands. The trees on PRP reached the mean DBH of 35.3 – 45.1 cm, in beech it was 6.0 – 45.8 cm and in spruce 37.3 – 50.2 cm. On PRP I, III and IV the occurrence of diameter classes 32 – 36 and 36 – 40 cm was the highest, only on PRP II the class >56 cm was prevailing (Fig. 2). On PRP I–III beech prevailed in the small classes while on PRP IV it was spruce. The tallest individuals of beech and spruce on PRP reached the height of 33 – 37 m and 38 – 43 m, respectively. The heights of live crown base were highly variable both in beech and spruce. In the

Table 3. Stand characteristics of spruce-beech stands on permanent research plots in 2016.

PRP	Species	Age [y]	dbh [cm]	h [m]	v [m^3]	N [trees ha^{-1}]	BA [m^2 ha^{-1}]	V [m^3 ha^{-1}]	PAI [m^3 ha^{-1}y^{-1}]	MAI [m^3 ha^{-1}y^{-1}]	CC [%]	CPA [ha]	SDI
I	Spruce	130	37.3	29.8	1.345	328	35.9	441	5.0	3.39	55.2	0.80	0.51
	Beech	16	6.0	5.3	0.003	40	0.1	0	0.0	0.00	5.3	0.05	0.00
	Total	130	35.3	27.1	1.199	368	36.0	441	5.0	3.39	57.6	0.86	0.51
II	Spruce	160	50.2	34.0	2.765	160	31.6	442	3.9	2.76	59.8	0.91	0.40
	Beech	164	36.8	22.5	1.637	112	11.8	183	2.0	1.12	63.0	1.00	0.20
	Total	161	45.1	29.2	2.301	272	43.4	626	6.0	3.89	85.1	1.91	0.60
III	Spruce	165	39.0	32.6	1.626	272	32.4	442	4.1	2.68	67.1	1.11	0.45
	Beech	160	40.0	25.7	2.002	144	18.0	288	2.9	1.80	75.5	1.41	0.29
	Total	163	39.3	30.2	1.756	416	50.4	731	7.0	4.48	92.0	2.52	0.74
IV	Spruce	162	39.4	25.9	1.537	108	13.0	166	1.6	1.02	26.1	0.30	0.18
	Beech	161	45.8	32.1	2.568	212	34.9	544	5.1	3.38	80.8	1.65	0.53
	Total	161	43.7	30.0	2.220	320	48.0	710	6.7	4.41	85.9	1.96	0.72

Notes: Age – average stand age; dbh – mean quadratic breast height diameter; h – mean height; v – average tree volume; N – number of trees; BA – basal area; V – stand volume; PAI – periodic annual increment; MAI – mean annual increment, CC – canopy closure, CPA – crown projection area, SDI – stand density index.

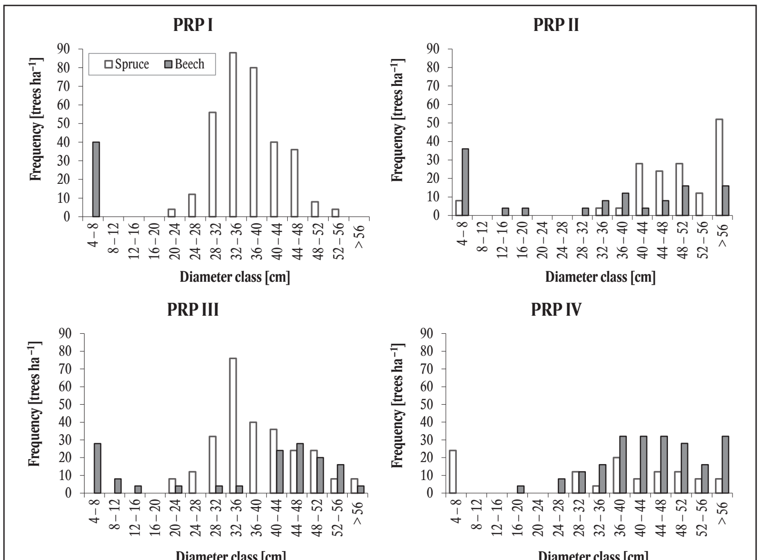

Fig. 2. Histogram of diameter classes by main tree species in a mixed stands on permanent research plots in 2016.

understorey it was mostly 1 – 3 m and in the overstorey 7 – 19 m.

The occurrence of dead wood ranged from 4.3 to 31.8 m^3 ha^{-1} (on average 16.4 m^3 ha^{-1}). The volume of lying dead wood was 0.0 – 18.2 m^3 ha^{-1} and standing dead wood was in range 2.7 – 22.6 m^3 ha^{-1}. Comparing total stand volume on PRP, volume of dead wood (lying DW 30.2%, standing DW 69.8%) formed 2.6% and stand volume of living trees 97.4%.

3.2. Biodiversity of tree layer

Vertical structure according to the Arten-profile index *A* was medium to highly diversified (0.395 – 0.725; Table 4). Diameter differentiation TM_d was low to medium (0.238 – 0.375), such as height differentiation TM_h (0.180 – 0.341). Species richness *D* was low (0.166 – 0.178). Species heterogeneity expressed by entropy *H´* indicated minimum to low biodiversity (0.009 – 0.283). According to species evenness *E*, biodiversity on PRP I was low (0.030) while biodiversity on the other PRP was very high (0.844 – 0.944). Total diversity according *B* indicated even structure on PRP IV (5.909) and uneven structure on the other PRP (6.219 – 6.457).

Horizontal structure of the tree layer of mixed stands with dominant representation of European beech and Norway spruce was regular on all PRP (significantly according to *R* and *CS* indices; Table 4, Fig. 3). Conversely the mostly random pattern of tree layer individuals according to their distance (spacing) was indicated by Ripley's *L*-function. Regular horizontal structure was observed on PRP at small spacing in distance from tree stem to 3 – 4 m.

Table 4. Stand biodiversity indices of mixed stands on permanent research plots in 2016.

PRP	D (Mai)	H´ (Si)	E (Pii)	A (Pri)	TM_d (Fi)	TM_h (Fi)	α (P&Mi)	R (C&Ei)	CS (D&Mi)	B (J&Di)
I	0.169	0.009	0.030	0.395	0.238	0.188	0.802*	1.245*	−0.421*	6.219
II	0.178	0.254	0.844	0.664	0.375	0.341	0.816	1.228*	−0.259*	6.295
III	0.166	0.283	0.940	0.725	0.306	0.204	0.995	1.265*	−0.344*	6.457
IV	0.173	0.254	0.844	0.512	0.310	0.180	0.929	1.274*	−0.343*	5.909

Notes: D – species richness index; H´ – species heterogeneity index (entropy); E – species evenness index; A – Arten-profile index; TM_d – diameter differentiation index, TM_h – height differentiation index, α – index of non-randomness, R – aggregation index, CS – index of cluster size, B – total diversity index.
* statistically significant (p>0.05) for horizontal structure (in all cases regularity).

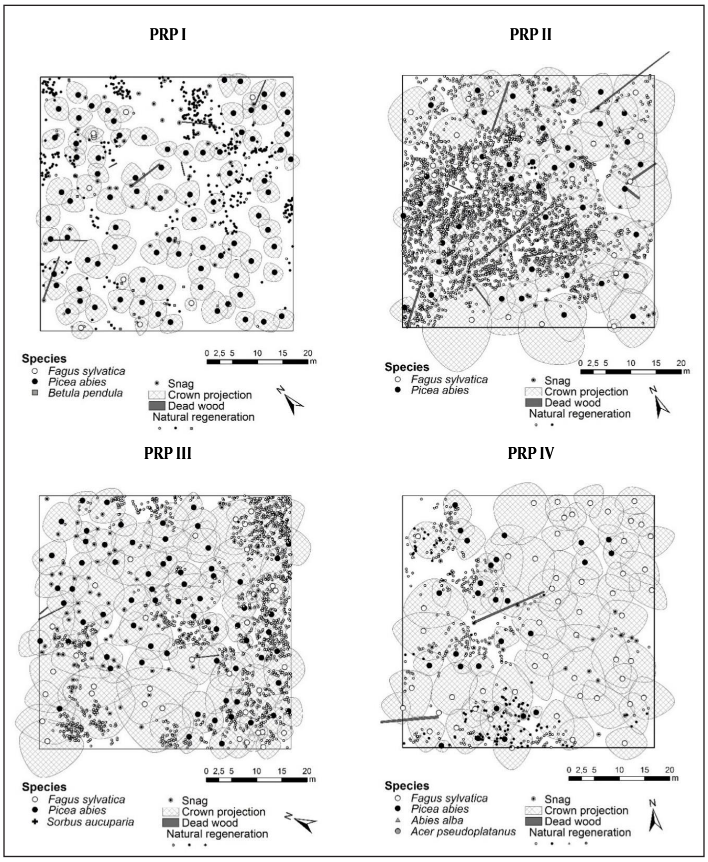

Fig. 3. Horizontal structure of mixed stands on permanent research plots in 2016.

3.3. Radial growth of European beech and Norway spruce

Dynamics of Norway spruce showed very strong growth depression in 1979–1987 with pronounced minimum growth in 1980–1982 that was caused by an interaction of air pollutants (SO_2), climate stress and bark beetle feeding (Fig. 4). This trend was not observed on PRP 8 where spruce is only admixed tree species. In spruce, years 1980, 1981, 1982 and 2004 were observed as the strong incidence of beech scale (*Cryptococcus fagi*). In beech, years 1997 and 2012 were observed as the negative pointer years with extreme low radial growth (Fig. 4). Higher balance of radial growth was manifested in beech (SD ± 0.14) compared to spruce (SD ± 0.22). Average diameter increment of spruce on PRP I, II, III and IV in 1960–2015 was in positive correlation with temperatures in April of the preceding year and current year (r = 0.26 – 0.22). Besides, radial growth showed a positive correlation with rainfall in May of the preceding year (r

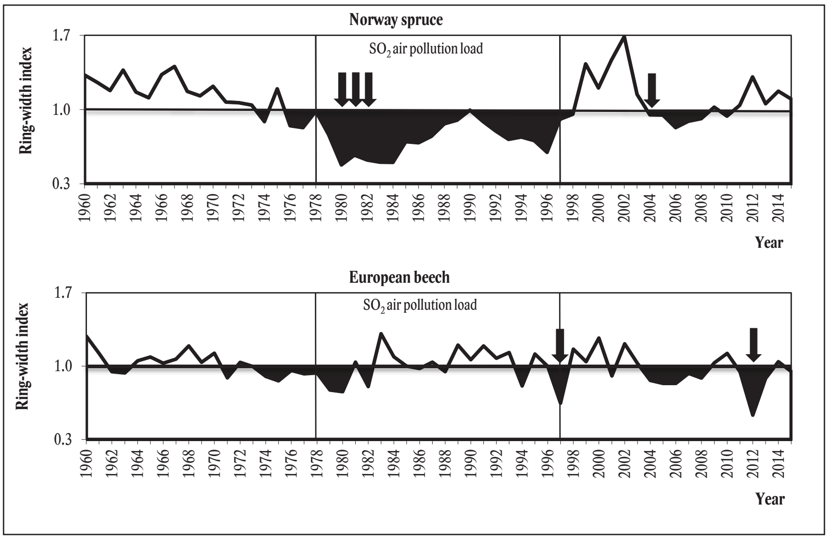

Fig. 4. Standardized mean chronology of Norway spruce and European beech in 1960–2015 expressed by the tree ring index (in 1960 used 100% of tree cores; the oldest tree rings dated back to 1852); arrows indicate significant negative pointer years with extreme low radial growth reaching less than 40% of the mean diameter increment in previous 4 years and occurred in at least 20% of the trees.

negative pointer years with extreme low radial growth. Generally, the highest variability in ring-width index was observed on PRP I and II (SD ± 0.25) with the highest share of spruce, while the relatively balanced radial growth of spruce was observed on beech dominated PRP IV (SD ± 0.16).

Growth depressions of European beech on PRP II, III and IV was observed in 1979, 1980 and 1982 with pronounced minimum growth in 1980 that were caused by the synergism of air pollutants, climate extreme and = 0.25) and a negative correlation with precipitation in November of the preceding year (r = −0.23) and April of current year (r = −0.23; Fig. 5).

Average diameter increment of beech on PRP II, III and IV in 1960–2015 was in positive correlation with temperatures in July and August of the preceding year (r = 0.33 – 0.22) and in April of the current year (r = 0.32). In addition, radial growth showed a positive correlation with precipitation in May of the current year (r = 0.23) and a negative correlation with precipitation in July of the

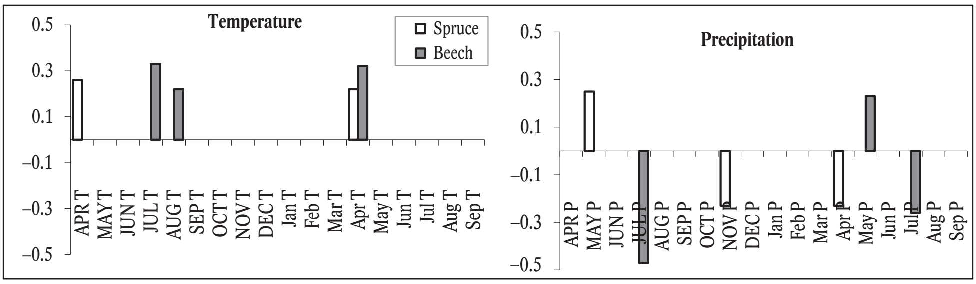

Fig. 5. Correlation coefficients of the regional residual tree-ring index chronology of Norway spruce and European beech with the monthly temperature (left) and precipitation (right) from April to December of the preceding years (capitals) and from January to September of the current year (lower case) summary for all permanent research plots in 1960–2015. Only correlation coefficients of statistically significant values are presented (α = 0.05%).

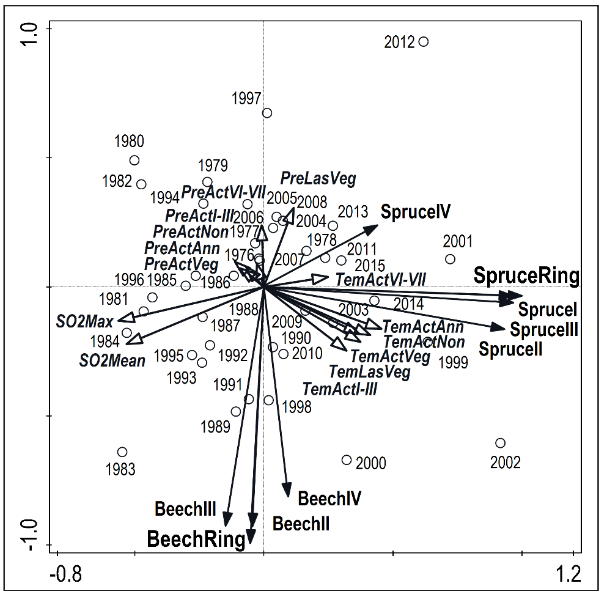

Fig. 6. Ordination diagram of PCA showing relationships between climate data (Tem – mean temperature, Pre – sum of precipitation, Act – current year, Las – preceding year, Veg – growing season, NonVeg – non-growing season, I–III, VI–VII – months), SO_2 concentrations (mean – mean annual concentration, max – maximum concentration) and tree-ring width (Ring – mean tree-ring width) for beech and spruce on permanent research plots I, II, III and IV; codes ○ indicate years 1977–2015.

preceding year ($r = -0.48$) and current year ($r = -0.26$; Fig. 5).

Interactions among radial growth of beech and spruce, climate factors and SO_2 concentrations are presented in an ordination diagram of PCA (Fig. 6). The first ordination axis explains 43.2% of data variability, the first two axes together explain 82.2% and the first four axes 97.4%. The x-axis illustrates the radial growth of spruce stands and the y-axis represents the radial growth of beech. SO_2 concentrations (average and maximum ones) were negatively correlated with spruce radial growth while there was no effect on growth of beech. Spruce increment was in positive correlation with temperature, especially with average annual temperature and temperature in June and July of the current year. Beech increment was negatively correlation with precipitation. Overall, the effect of temperature on diameter increment was more significant in comparison with very low influence of precipitation. In the period of the 80s and 90s of the 20th century the radial growth was affected especially by high SO_2 concentrations while in the second half of the studied period (after 2000) there was a closer correlation between growth and air temperature.

The radial growth increment of spruce showed a significantly negative correlation with the mean annual and maximum daily ($r = -0.53, -0.56$; $p < 0.001$) SO_2 concentrations (Table 5). Specifically, the highest negative effect of SO_2 concentrations was observed in July and February ($r = -0.58, -0.51$; $p < 0.001$). The lowest effect of SO_2 was observed on PRP IV with dominant beech ($r = -0.44$, $p < 0.01$). Mean annual NO_X concentrations had also negative effect on spruce increment ($r = -0.43$; $p < 0.05$). Ozone exposure had no effect on diameter increment of spruce. Spruce was significantly positively influenced by annual temperature and temperature in the growing season ($r = 0.46, 0.41$; $p < 0.01$), while the lowest non-significant effect was observed again on PRP IV ($p > 0.05$).

Generally, beech showed higher resistance to air pollutants load and was less influenced by summary climatic variables. O_3, NO_X, and SO_2 concentrations had no significant effect on radial growth of beech, such as temperature and precipitation during the year and in the growing season (Table 5).

3.4. Structure and diversity of natural regeneration

The number of natural regeneration (height ≥ 1.5 m) on PRP ranged from 1,800 (PRP IV) to 13,356 (PRP II) recruits ha^{-1} (Table 6). Beech on PRP accounted for 7 – 100%, spruce for 0 – 89%, silver fir 0 – 1% and silver

Table 5. Correlation matrix describing interactions between the radial growth of spruce and beech, precipitation and temperature (1975–2015) and concentrations of SO_2 (1975–2015), NO_X (1992–2012) and AOT40F (1996–2012). Significant correlations are designated by * ($p < 0.05$) and ** ($p < 0.01$).

Ring width index	SO_2 mean	SO_2 max.	NO_X mean	NO_X max.	AOT40F	Temp ActAnn	Temp ActVeg	Prec ActAnn	Prec ActVeg
Beech stands	0.22	0.14	0.07	−0.03	0.22	0.14	0.15	−0.09	−0.04
Spruce stands	−0.53**	−0.56**	−0.43*	−0.37	−0.06	0.46**	0.41**	−0.13	−0.09

Notes: SO_2(NO_X) mean – mean annual SO_2 (NO_X) concentration, SO_2(NO_X)max – maximum SO_2 (NO_X) concentrations, AOT40F – ozone exposure, TempActAnn – mean annual temperature of the given year, TempActVeg – mean temperature in the growing season of the given year, PrecActAnn – annual sum of precipitation of given year, PrecActVeg – sum of precipitation in the growing season of the given year.

Table 6. Mean height of natural regeneration and its density per hectare from registration height of 1.5 m according to tree species.

PRP	Spruce		Beech		Fir		Rowan		Birch		Sycamore		Total	
	[ind.]	[cm]	[ind.]	[cm]	[ind.]	[cm]	[ind.]	[cm]	[ind.]	[cm]	[ind.]	[cm]	[ind.]	[cm]
I	1,608	190.0	120	262.0	0	—	0	—	72	285.8	0	—	1,800	198.6
II	24	273.3	13,332	227.9	0	—	0	—	0	—	0	—	13,356	228.0
III	4	155.0	6,248	216.5	0	—	12	170.0	0	—	0	—	6,264	216.3
IV	440	203.5	1,420	215.8	20	186.0	0	—	0	—	4	215	1,884	212.6

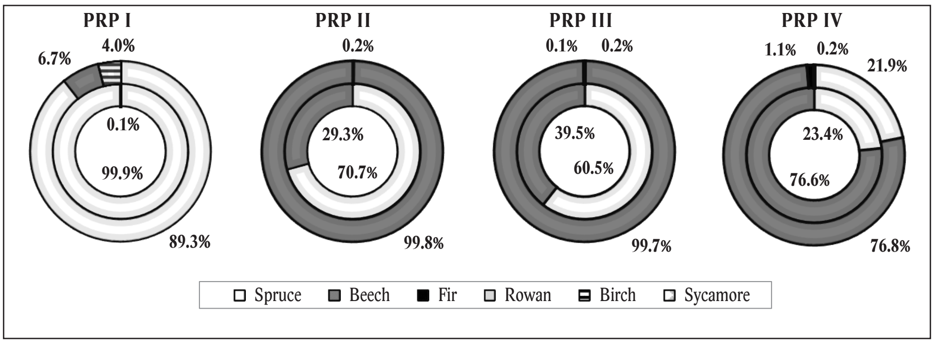

Fig. 7. Percentage proportions of tree species composition of natural regeneration (height ≥ 150 cm and DBH < 4 cm) according to number of individuals (outer circle), and trees (DBH ≥ 4cm) according to stand volume in m³ (inner circle).

birch 0 – 4%. Comparing tree species composition of natural regeneration to tree layer, significant expanse of beech regeneration was observed on all PRP (increase up to 71%) to the detriment of spruce and occurrence of admixed tree species (silver fir, sycamore maple, silver birch, rowan).

Evaluating species diversity of natural regeneration, species richness *D* was low on PRP I–III (0.105 – 0.229) and medium on PRP IV (0.398; Table 7). Entropy *H´* index showed minimum species heterogeneity on PRP II and III (0.013 – 0.019) and medium diversity on PRP I and IV (0.410 – 0.614). Species evenness *E* was minimum on PRP II and III (0.018 – 0.019) and medium on PRP I and IV (0.373 – 0.443). Height differentiation TM_h was medium on PRP I and IV (0.340 – 0.483) and high on PRP II and III (0.502 – 0.558). Comparing natural regeneration and tree layer, higher diversity in natural regeneration was in species richness (+ 45%) and height differentiation (+ 106%), while species evenness was higher (+212%) in tree layer due to low occurrence of tree species. The spatial pattern of natural regeneration was significantly aggregated on all plots (Table 7). The clumpy pattern of recruits according to their distance (spacing) was indicated by Ripley's *L*-function. Higher aggregation of recruits was proved in beech compared to spruce.

Table 7. Indices describing the diversity of natural regeneration on permanent research plots.

PRP	D (Mai)	H´ (Si)	E (Pii)	TMh (Fi)	α (P&Mi)	R (C&Ei)	CS (D&Mi)
I	0.267	0.410	0.373	0.483	4.159*	0.612*	9.507*
II	0.105	0.013	0.019	0.558	10.515*	0.701*	26.248*
III	0.229	0.019	0.018	0.502	16.169*	0.545*	24.846*
IV	0.398	0.614	0.443	0.340	27.872*	0.546*	10.290*

Notes: D – species richness index, H´ – species heterogeneity index (entropy), E – species evenness index, TM_h – height differentiation index, α – index of non-randomness, R – aggregation index, CS – index of cluster size.

* statistically significant (p>0.05) for horizontal structure (in all cases aggregation).

The mean height of recruits from 1.5 m was comparable on all plots, showing a left-skewed distribution. Mean height of natural regeneration ranged from 199 to 228

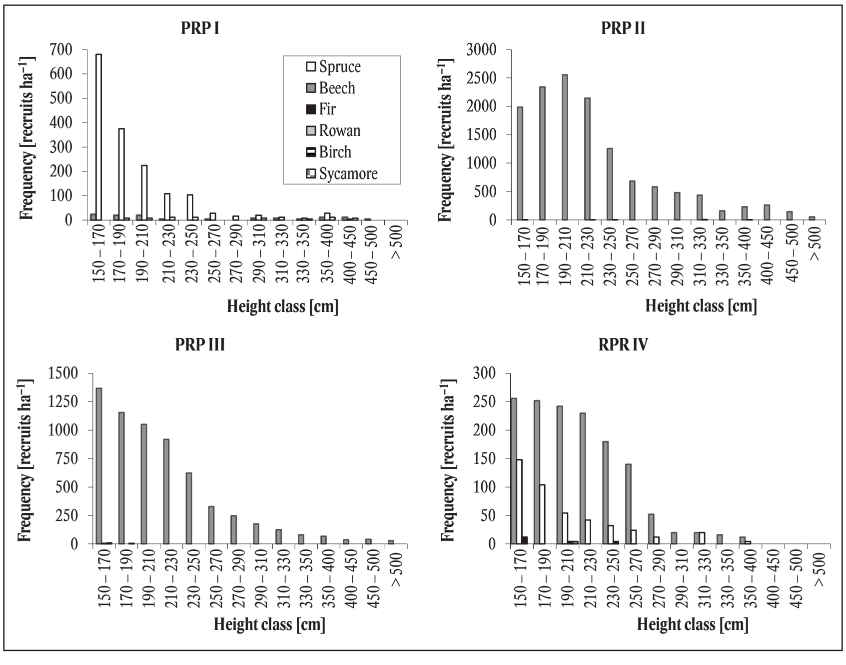

Fig. 8. Histogram of the height structure of natural regeneration according to tree species on permanent research plots in 2016.

cm, for beech it was from 216 to 262 cm, in spruce 155 – 273, in fir 186 cm, sycamore maple 215 cm and rowan 170 cm. The growth pattern of heights reached by natural regeneration according to tree species was similar on all plots. On all PRP the most frequent was first height class (150 – 170 cm) except advanced natural regeneration on PRP II (Fig. 8).

Mean damage by browsing and bark stripping caused by red deer (*Cervus elaphus* L.) was low on natural regeneration on PRP (< 5%), especially in spruce (2%) and in beech (6%). However, the opposite situation was in admixed tree species, the browsing of the leading shoot in silver fir amounted to 68%, in rowan to 82% and growth of sycamore maple was completely eliminated by game (damage 100%).

In relation to mature stands, the spatial relationships between natural regeneration and tree layer expressed by the pair correlation function was as random at distances longer than 2 m, only on PRP I it was so from 5 m. At shorter distances the pattern was significantly regular on all PRP that it indicated a negative influence of the tree layer on natural regeneration (Fig. 9).

4. Discussion

In recent years, relatively few studies have been published in Central Europe that deal with close-to-nature silviculture and forest transformation according to the guidelines of shelterwood or selection management system (Schütz 2001; Sterba & Zingg 2001; Souček 2002; Švec et al. 2015). Stand transformations are very important for sustainable forestry and contribute indirectly to faster adaptation to the climate change (Schelhaas et al. 2015). Mixed and structurally diversified stands compared to monospecific stands with homogenous stand structure are more resistant to disturbances (Metz et al. 2016). Moreover, diversification of silvicultural measures should allow both achieving production targets and maintaining biological and ecological diversity (Bergeron et al. 1999).

In studied PRP in the initial stage of transformation, the stand volume ranged from 441 to 731 m^3 ha^{-1}, while beech and spruce were dominant tree species. Similar stand volume was reported from mountain forest in Central Europe (von Oheimb et al. 2005; Bulušek et al. 2016; Králíček et al. 2017). On the other hand, significantly higher stand volume (up to 1,237 m^3 ha^{-1}) was reported from Uholka Ukrainian beech virgin forest (Trotsiuk et al. 2012). The volume of dead wood on study plots reached on average 16 m^3 ha^{-1}. E.g. Hobi et al. (2015) and Kucbel (2012) reported the average volume of dead wood 136 m^3 ha^{-1}, resp. 169 m^3 ha^{-1}.

Biodiversity as an important factor plays a key role in all ecosystem components (Pimm et al. 2014; Bílek et al. 2016; Schulze et al. 2016). The results documented the medium- to very strongly diversified vertical structure of investigated stands. Complex stand diversity showed a mostly uneven structure while species richness was low. Natural regeneration reached higher values instead of species heterogeneity. Among the particular plots, PRP I differed by the presence of beech only in small diameter classes due to initial stage of transformation of monospecific spruce forest stand, and low biodiversity unlike the other PRP. These results are generally consistent with Gao et al. (2014), who demonstrated that old stands with multi-layered structure usually have higher species diversity. Mölder et al. (2008) or Barbier et al. (2009) considered the effects of several factors like age, canopy density and species composition as biodiversity determinants. Bílek et al. (2016) stated that biodiversity is influenced by forest management while Heinrichs and Schmidt (2009) directly confirmed an increase in stand diversity after a tending treatment contrary to stands without management.

The horizontal structure of the tree layer in our study was moderately regular, especially at short distances. Random pattern of trees was evident at higher distances,

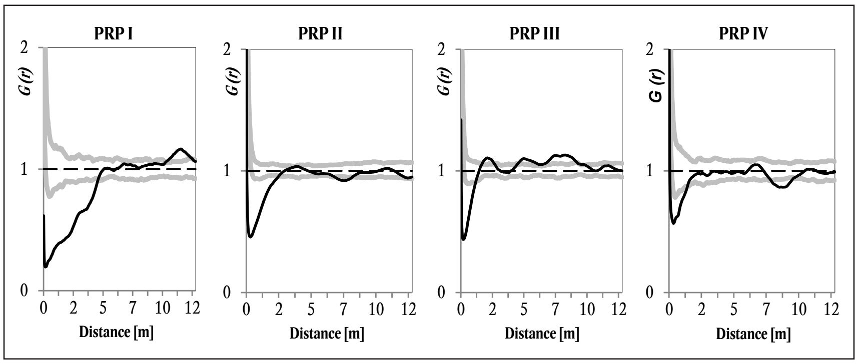

Fig. 9. Spatial distribution of natural regeneration in relation to mature trees on particular permanent research plots expressed by the cross-type pair correlation function; the bold black line represents real distances of individuals; the dashed black line on the level of $G(r) = 1$ represents the mean course for random spatial distribution of trees and the two grey curves 95% confidence interval; when the observed value exceeds the upper (lower) limit of the simulation interval, it indicates significant aggregation – positive relationship (regularity – negative relationship).

such a prevailing random pattern in spruce-beech forest in Orlické hory Mts. (Králíček et al. 2017). However, in some studies clumpy pattern was reported (von Oheimb et al. 2005), that is usually the result of extreme sites conditions or growth of natural regeneration in canopy gaps (Sefidi et al. 2007; Bulušek et al. 2016). In our research aggregated horizontal structure of regeneration prevailed similar to studies of Ambrož et al. (2015) and Králíček et al. (2017).

Average tree-ring width on the studied PRP was nearly the same in spruce (1.4 – 1.6 mm) and in beech (1.3 – 1.6 mm). Radial increment of spruce and beech from 0.5 to 1.5 mm was similar in the Orlické hory Mts. (Králíček et al. 2017). Higher radial increment of spruce compared to beech in spruce-beech stands was reported in southern Sweden (Bolte et al. 2010). The dominant diameter increment of spruce has decreased in the last 50 years, but in beech it has been relatively balanced. The growth depression of spruce particularly from 1980 to 1982 was caused by the synergism of air pollutants (especially SO_2 concentrations), climate and bark beetle outbreaks. In fact, 1980 was the coldest year within the cold period 1960–2016 (2.3 °C, mean 3.8 °C) followed by the extreme dry year 1982 (795 mm, mean 1 220). There were strong attacks of bark beetles in 1992–1997 with subsequent high radial increment due to better light availability. In beech decrease of radial growth in 1997 and 2012 was the effect of damage to beech crowns by icing and wet snow in the winter seasons 1996/1997 and 2011/2012. In April 1997 mean temperature reached −0.3 °C (mean in 1960–2016 2.6 °C). In spring 2012 the assimilating organs were damaged by late frost and by the subsequent mass outbreak of gall midge (*Mikiola fagi*). These results were confirmed also by other authors (Alles 1994; Vacek et al. 2015a; Králíček et al. 2017). A decrease in the radial growth of spruce in 2004–2015 in comparison with the years 1999–2003 was a result of precipitation decrease and increased temperatures. Generally, spruce was more sensitive to negative pointer years with extreme low radial growth compared to beech. Radial growth of spruce was also in significant negative correlation with SO_2 and NO_X concentrations (no effect in beech), such as in other studies (Hauck et al. 2012; Králíček et al. 2017; Putalová et al. 2019). Moreover, spruce was damaged by insect pests and fungal pathogens to a larger extent (Bolte et al. 2010; Maaten-Theunissen & Bouriaud 2012). The competitiveness of beech in relation to spruce is higher. In our study, spruce was more resistant to air pollution and climatic stress in mixed beech dominant stand on PRP IV compared to spruce monospecific PRP I. Similarly, both species showed higher increment and resistance in mixtures compared to monocultures in Germany (Pretzsch et al. 2014).

Natural regeneration as an important component of close-to-nature management (Šticha et al. 2010; Bílek et al. 2014; Vacek et al. 2017b) was evaluated on all PRP. The number of recruits was in the range of 1,800 – 13,400 recruits ha^{-1}, that it is as higher density compared to spruce-beech forest in Orlické hory Mts. (Vacek et al. 2014b) or in north-eastern Germany (von Oheimb et al. 2005). The abundance of natural regeneration is mainly influenced by the quantity of seeds from the seed bank, successful germination and subsequent survival and growth of seedlings (Sagnard et al. 2007; Wagner et al. 2010). However, many factors are essential for subsequent survival and growth of natural regeneration in forest stands; among them, decreased stand canopy, sufficient light and favourable climatic conditions are the most important (Klopcic & Boncina 2010; Vacek et al. 2015b). Natural regeneration of spruce has similar requirements when spruce requires more light than beech (Úradníček et al. 2009). It coincides with the negative influence of the tree layer on spatial pattern of natural regeneration confirmed by our study in at short distances lower than 2 to 5 m. Similar conclusions were drawn by Králíček et al. (2017) and Slanař et al. (2017), but in extreme conditions the influence of tree layer may be positive (Vacek & Hejcman 2012; Bulušek et al. 2016).

In terms of tree species, natural regeneration shows significant increase of beech and decrease of spruce compared to mature tree species composition in study sites. Expansion of beech regeneration was also observed at higher altitudes (Dulamsuren et al. 2017; Vacek et al. 2017b). Not only changing climatic conditions, but also game pressure significantly influence tree species composition in natural regeneration. Game damage is one of the main factors driving species composition of naturally regenerated forests (Roth 1996; Weisberg & Bugmann 2003; Bernard et al. 2017). Although 90 – 120 ungulates are hunted in a study forestry section, regeneration of silver fir (68%), rowan (82 %) and especially sycamore maple (100 % damage) was heavily or completely eliminated by red deer. On the contrary, the lowest browsing damage was caused to spruce (2%) and beech (6 %). Thus, in the study area, beech is the only one perspective deciduous tree species that is able to escape strong pressure of ungulates. Considerable silviculture care of the beech crowns has had a positive impact in terms of beech masting and natural regeneration. Unlike the beech, this type of management has not had a real impact on sycamore and fir due to decimation of natural regeneration by ungulates. The attractiveness of fir, rowan and sycamore for game was also confirmed in other part of Czechia (Vacek et al. 2014a, b, 2018), Slovakia (Konôpka & Pajtík 2015), Germany (Ammer 1996) and Italy (Motta 2003). The recommendation for limiting the game damage and protection of valuable admixed tree species is reduction of still increasing ungulate population, building of overwinter preserve, feeding of game in selected localities, reliable fencing of stands, establishing of fields for game or reintroduction of predators (Vrška et al. 2001; Konôpka et al. 2015; Cukor et al. 2017; Vacek 2017; Cukor et al 2019).

5. Conclusions

Forest managers should make use of the possibilities of adaptation on climatic change with maximum involvement of natural processes. These modern silvicultural approaches should be directed at sustainable, ecologically and socio-economically acceptable forest development in the future. This study shows that beech is at altitudes of 640 – 810 m a.s.l. generally more resistant tree species than spruce. Spruce is more resistant to unfavourable environmental conditions (pollution and climatic extremes) in admixtures compared to monospecific stands. In terms of climate change, it is necessary to support resistance of forest to extreme climate evens by increasing structural diversity and retaining species richness. It must be outlined that the studied forest stands are at the beginning of forest transformation with emphasis on production, ecological stability and biodiversity under ongoing global climate change. Based on our results the set silvicultural strategy leads despite the considerable pressure of ungulates to the formation of stable mixed forests able to mitigate climate change.

Acknowledgments

This study was supported by the Ministry of Agriculture of the Czech Republic (NAZV No. QK11910292) and by the Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences (IGA No. B03/18).

References

Ambrož, R., Vacek, S., Vacek, Z., Král, J., Štefančík, I., 2015: Current and simulated structure, growth parameters and regeneration of beech forests with different game management in the Lány Game Enclosure. Central European Forestry Journal, 61:78–88.

Ammer, C., 1996: Impact of ungulates on structure and dynamics of natural regeneration of mixed mountain forests in the Bavarian Alps. Forest Ecology and Management, 88:43–53.

Barbati, A., Marchetti, M., Chirici, G., Corona, P., 2014: European forest types and forest Europe SFM indicators: tools for monitoring progress on forest biodiversity conservation. Forest Ecology and Management, 321:145–157.

Barbier, S., Chevalier, R., Loussot, P., Bergès, L., Gosselin, F., 2009: Improving biodiversity indicators of sustainable forest management: Tree genus abundance rather than tree genus richness and dominance for understory vegetation in French lowland oak hornbeam forests. Forest Ecology and Management, 258:176–186.

Barna, M., Bošeľa, M. 2015: Tree species diversity change in natural regeneration of a beech forest under different management. Forest Ecology and Management, 342:93–102.

Bergeron, Y., Harvey, B., Leduc, A., Gauthier, S., 1999: Forest management guidelines based on natural disturbance dynamics: stand- and forest-level considerations. Forestry Chronicle, 75:49–54.

Bernard, M., Boulanger, V., Dupouey, J. L., Laurent, L., Montpied, P., Morin, X., et al. 2017: Deer browsing promotes Norway spruce at the expense of silver fir in the forest regeneration phase. Forest Ecology and Management, 400:269–277.

Bílek, L., Remeš, J., Podrázský, V., Rozenbergar, D., Diaci, J., Zahradník, D., 2014: Gap regeneration in near-natural European beech forest stands in Central Bohemia – the role of heterogeneity and microhabitat factors. Dendrobiology, 71:59–71.

Bílek, L., Remeš, J., Zahradník, D., 2011: Managed versus unmanaged. Structure of beech forest stands" *Fagus sylvatica* L." after 50 years of development, Central Bohemian. Forest Systems, 1:122–138.

Bílek, L., Vacek, S., Vacek, Z., Remeš, J., Král, J., Bulušek, D., Gallo, J., 2016: How close to nature is close-to-nature pine silviculture? Journal of Forest Science, 62:24–34.

Bilela, S., Dounavi, A., Fussi, B., Konnert, M., Holst, J., Mayer, H. et al., 2012: Natural regeneration of *Fagus sylvatica* L. adapts with maturation to warmer and drier microclimatic conditions. Forest Ecology and Management, 275:60–67.

Bolte, A., Czajkowski, T., Kompa, T., 2007: The northeastern distribution range of European beech – a review. Forestry, 80:413–429.

Bolte, A., Hilbrig, L., Grundmann, B., Kampf, F., Brunet, J., Roloff, A., 2010: Climate change impacts on stand structure and competitive interactions in a southern Swedish spruce–beech forest. European Journal of Forest Research, 129:261–276.

Bošeľa, M., Štefančík, I., Petráš, R., Vacek, S., 2016: The effects of climate warming on the growth of European beech forests depend critically on thinning strategy and site productivity. Agricultural and Forest Meteorology, 222:21–31.

Briner, S., Elkin, C., Huber, R., 2013: Evaluating the relative impact of climate and economic changes on forest and agricultural ecosystem services in mountain regions. Journal of Environmental Management, 129:414–422.

Bulušek, D., Vacek, Z., Vacek, S., Král, J., Bílek, L., Králíček, I., 2016: Spatial pattern of relict beech (*Fagus sylvatica* L.) forests in the Sudetes of the Czech Republic and Poland. Journal of Forest Science, 62:293–305.

Butler, K. F., Koontz, T. M., 2005: Theory into practice: implementing ecosystem management objectives in the USDA Forest Service. Environmental Management, 35:138–150.

Cardinall, D., Hammond, H., Holt, R., Moore, K., Beese, B., Ruitenbeek, J. et al., 2004: Ecosystem-Based Management Planning Handbook. Coast Information Team, Victoria, BC, 80 p.

Chianucci, F., Salvati, L., Giannini, T., Chiavetta, U., Corona, P., Cutini, A., 2016: Long-term response to thinning in a beech (*Fagus sylvatica* L.) coppice stand under conversion to high forest in Central Italy. Silva Fennica, 50:1549–1558.

Clark, P. J., Evans, F. C., 1954: Distance to nearest neighbour as a measure of spatial relationship in populations. Ecology, 35:445–453.

Cukor, J., Havránek, F., Rohla, J., Bukovjan, K., 2017: Stanovení početnosti jelení zvěře v západní části Krušných hor. Zprávy lesnického výzkumu, 62:288–295.

Cukor, J., Vacek, Z., Linda, R., Vacek, S., Marada, P., Šimůnek, V., Havránek, F., 2019: Effects of bark stripping on timber production and structure of Norway spruce forests in relation to climatic factors, Forests, 10:320.

Drobyshev, I., Niklassona, M., Mazerolled, M. J., Bergeron, Y., 2014: Reconstruction of a 253-year long mast record of European beech reveals its association with large scale temperature variability and no long-term trend in mast frequencies. Agricultural and Forest Meteorology, 192–193:9–17.

Dulamsuren, C., Hauck, M., Kopp, G., Ruff, M., Leuschner, C., 2017: European beech responds to climate change with growth decline at lower, and growth increase at higher elevations in the center of its distribution range (SW Germany). Trees – Structure and Function, 31:673–686.

Ellenberg, H., 1996: Vegetation Mitteleuropas mit den Alpen, 5th edition. Ulmer, Stuttgart, 1095 p.

Fabrika, M., Ďurský, J., 2005: Algorithms and software solution of thinning models for SIBYLA growth simulator. Journal of Forest Science, 51:431–445.

FAO, 2006: Global Forest Resource Assessment 2005 - Progress Towards Sustainable Forest Management. FAO Forestry Paper 147.

Flechard, C. R., Nemitz, E., Smith, R., Fowler, D., Vermeulen, A. T., Bleeker, A. et al., 2011: Dry deposition of reactive nitrogen to European ecosystems: a comparison of inferential models across the NitroEurope network. Atmospheric Chemistry and Physics, 11:2703–2728.

Fotelli, M. N., Rennenberg, H., Holst, T., Mayer, H., Gessler, A., 2003: Carbon isotope composition of various tissues of beech (*Fagus sylvatica*) regeneration is indicative of recent environmental conditions within the forest understorey. New Phytologist, 159:229–244.

Füldner, K., 1995: Strukturbeschreibung in Mischbeständen. Forstarchiv, 66:235–606.

Gao, T., Hedblom, M., Emilsson, T., Nielsen, A. B., 2014: The role of forest stand structure as biodiversity indicator. Forest Ecology and Management, 330:82–93.

Gessler, A., Keitel, C., Kreuzwieser, J., Matyssek, R., Seiler, W., Rennenberg, H., 2007: Potential risk of European beech (*Fagus sylvatica* L.) in a changing climate. Trees, 21:1–11.

Grodzki, W., 2010: The decline of Norway spruce *Picea abies* (L.) Karst. stands in Beskid Śląski and Zywiecki: Theoretical koncept and reality. Beskydy, 3:19–26.

Harmon, M. E., Franklin, J. F., Swanson, F. J., Sollins, P., Gregory, S. V., Lattin, J. D. et al., 1986: Ecology of Coarse Woody Debris in Temperate Ecosystems. Advances in Ecological Research, 15:133–302.

Hauck, M., Zimmermann, J., Jacob, M., Dulamsuren, C., Bade, C., Ahrends, B. et al., 2012: Rapid recovery of stem increment in Norway spruce at reduced SO_2 levels in the Harz Mountains, Germany. Environmental pollution, 164:132–141.

Heinrichs, S., Schmidt, W., 2009: Short-term effects of selection and clear cutting on the shrub and herb layer vegetation during the conversion of even-aged Norway spruce stands into mixed stands. Forest Ecology and Management, 258:667–678.

Hlásny, T., Sitková, Z. (eds.), 2010: Spruce forests decline in the Beskids. National Forest Centre-Forest Research Institute Zvolen, Czech University of Life Sciences Prague, Forestry and Game Management Research Institute Jíloviště-Strnady, Zvolen, 182 p.

Hlásny, T., Barka, I., Rößiger, J., Kulla, L., Trombik, J., Sarvašová, Z. et al., 2017: Conversion of Norway spruce forests in the face of climate change: a case study in Central Europe. European Journal of Forest Research, 136:1013–1028.

Hobi, M. L., Commarmot, B., Bugmann, H., 2015: Pattern and process in the largest primeval beech forest of Europe (Ukrainian Carpathians). Journal of Vegetation Science, 26:323–336.

Hopkins, B., Skellam, J. G., 1954: A new method for determining the type of distribution of plant individuals. Annals of Botany, 18:213–227.

IPCC, 2007: Climate change 2007: the physical science basis. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B. et al. (eds.): Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 996 p.

Jaehne, S. C., Dohrenbusch, A., 1997: Ein Verfahren zur Beurteilung der Bestandesdiversität. Forstwissenschaftliches Centralblatt, 116:333–345.

Jantsch, M. C., Fischer, H. S., Winter, S., Fischer, A., 2013: How are plant species in central European beech (*Fagus sylvatica* L.) forests affected by temperature changes? Shift of potential suitable habitats under global warming. Annals of Botany, 4:97–113.

Jirgle, J., Kučera, J., Tichý, J., Materna, J., 1983: Poškození lesů v Jizerských horách imisemi. Zprávy lesnického výzkumu, 28:16–24.

Jönsson, A. M., Schroeder, L. M., Lagergren, F., Anderbrant, O., Smith, B., 2012: Guess the impact of *Ips typographus* – an ecosystem modelling approach for simulating spruce bark beetle outbreaks. Agricultural and Forest Meteorology, 166–167:188–200.

Klopcic, M., Boncina, A., 2010: Patterns of tree growth in a single tree selection silver fir–European beech forest. Journal of Forest Research, 15:21–30.

Kolář, T., Čermák, P., Trnka, M., Žid, T., Rybníček, M., 2017: Temporal changes in the climate sensitivity of Norway spruce and European beech along an elevation gradient in Central Europe. Agricultural and Forest Meteorology, 239:24–33.

Köppen, W., 1936: Das Geographische System der Klimate, Handbuch der Klimatologie. Gebrüder Borntraeger, Berlin.

Konôpka, J., Kaštier, P., Konôpka, B., 2015: Teoretické východiská a praktické opatrenia na harmonizáciu záujmov lesného hospodárstva a poľovníctva na Slovensku. Lesnícky časopis - Forestry Journal, 61:114–123.

Konôpka, B., Pajtík, J., 2015: Why was browsing by red deer more frequent but represented less consumed mass in young maple than in ash trees?! Journal of Forest Science, 61:431–438.

Králíček, I., Vacek, Z., Vacek, S., Remeš, J., Bulušek, D., Král, J. et al., 2017: Dynamics and structure of mountain autochthonous spruce-beech forests: impact of hilltop phenomenon, air pollutants and climate. Dendrobiology, 77:121–139.

Krejčí, F., Vacek, S., Bílek, L., Mikeska, M., Hejcmanová, P., Vacek, Z., 2013: The effects of climatic conditions and forest site types on disintegration rates in *Picea abies* occurring at the Modrava Peat Bogs in the Šumava National Park. Dendrobiology, 70:35–44.

Kucbel, S., Saniga, M., Jaloviar, P., Vencurik, J., 2012: Stand structure and temporal variability in old-growth beech-dominated forests of the northwestern Carpathians: A 40-years perspective. Forest Ecology and Management, 264:125–133.

Lorz, C., Fürst, C., Galic, Z., Matijasic, D., Podrázký, V., Potocic, N. et al., 2010: GIS-based probability assessment of natural hazards in forested landscapes of central and south-eastern Europe. Environmental Management, 46:920–930.

Machar, I., Vlčková, V., Buček, A., Voženílek, V., Šálek, L., Jeřabková, L., 2017: Modelling of climate conditions in forest vegetation zones as a support tool for forest management strategy in European beech dominated forests. Forests, 8:82–99.

Margalef, D. R., 1958: Information theory in ecology. International Journal of General Systems, 3:36–71.

Metz, J., Annighöfer, P., Schall, P., Zimmermann, J., Kahl, T., Schulze, E.-D. et al., 2016: Site-adapted admixed tree species reduce drought susceptibility of mature European beech. Global Change Biology, 22:903–920.

Ministerial Conference on the Protection of Forests in Europe, 2015: Madrid Ministerial Declaration 25 years together promoting Sustainable Forest Management in Europe. Madrid 20–21 October 2015, 156 p.

Ministerstvo zemědělství 2018: Zpráva o stavu lesa a lesního hospodářství České republiky v roce 2017. Ministerstvo zemědělství, Praha, 118 p.

Mölder, A., Bernhardt-Römermann, M., Schmidt, W., 2008: Herb-layer diversity in deciduous forests: raised by tree richness or beaten by beech? Forest Ecology and Management, 256:272–281.

Mountford, M. D., 1961: On E. C. Pielou's index of non randomness. Journal of Ecology, 49:271-275.

Motta, R., 2003: Ungulate impact on rowan (*Sorbus aucuparia* L.) and Norway spruce (*Picea abies* (L.) Karst.) height structure in mountain forests in the eastern Italian Alps. Forest Ecology and Management, 181:139–150.

Neuner, S., Albrecht, A., Cullmann, D., Engels, F., Griess, V. C., Hahn, W. A. et al., 2014: Survival of Norway spruce remains higher in mixed stands under a dryer and warmer climate. Global Change Biology, 21:935–946.

Packham, J. R., Thomas, P. A., Atkinson, M. D., Degen, T., 2012: Biological Flora of the British Isles: *Fagus sylvatica*. Journal of Ecology, 100:1557–1608.

Petráš, R., Pajtík, J., 1991: Sústava česko-slovenských objemových tabuliek drevín. Lesnícky časopis, 37:49–56.

Petritan, I. C., Commarmot, B., Hobi, M. L., Petritan, A. M., Bigler, C., Abrudan, I. V. et al., 2015: Structural patterns of beech and silver fir suggest stability and resilience of the virgin forest Sinca in the Southern Carpathians, Romania. Forest Ecology and Management, 356:184–195.

Petritan, A. M., von Lüpke, B., Petritan, I. C., 2009: Influence of light availability on growth, leaf morphology and plant architecture of beech (*Fagus sylvatica* L.), maple (*Acer pseudoplatanus* L.) and ash (*Fraxinus excelsior* L.) saplings. European Journal of Forest Research, 128:61–74.

Pielou, E.C., 1975: Ecological Diversity. Wiley, New York, 165 p.

Pimm, S. L., Jenkins, C. N., Abell, R., Brooks, T. M., Gittleman, J. L., Joppa, L. N. et al., 2014: The biodiversity of species and their rates of extinction, distribution, and protection. Science, 344:987.

Poleno, Z., Vacek, S., Podrázský, V., Remeš, J., Štefančík, I., Mikeska, M. et al., 2009: Pěstování lesů III. Praktické postupy pěstování lesů. Kostelec nad Černými lesy, Lesnická práce, 952 p.

Pretzsch, H., 2006: Wissen nutzbar machen für das Management von Waldökosystemen. Allgemeine Forstzeitschrift/Der Wald, 61:1158–1159.

Pretzsch, H., Rötzer, T., Matyssek, R., Grams, T. E. E., Häberle, K. H., Pritsch, K. et al., 2014: Mixed Norway spruce (*Picea abies* [L.] Karst) and European beech (*Fagus sylvatica* [L.]) stands under drought: from reaction pattern to mechanism. Trees, 28:1305–1321.

Puettmann, K. J., Wilson, S. M., Baker, S. C., 2015: Silvicultural alternatives to conventional even-aged forest management – what limits global adoption? Forest Ecosystems, 2:8.

Putalová, T., Vacek, Z., Vacek, S., Štefančík, I., Bulušek, D., Král, J., 2019. Tree-ring widths as an indicator of air pollution stress and climate conditions in different Norway spruce forest stands in the Krkonoše Mts. Central European Forestry Journal, 65:21–33.

Remeš, J., Bílek, L., Novák, J., Vacek, Z., Vacek, S., Putalová, T. et al., 2015: Diameter increment of beech in relation to social position of trees, climate characteristics and thinning intensity. Journal of Forest Science, 61:456–464.

Roth, R., 1996: The effect of deer on the natural regeneration of mixed forests. Zeitschrift fur Jagdwissenschaft, 42:143–156.

Sagnard, F., Pichot, C., Dreyfus, P., Jordano, P., Fady, B., 2007: Modelling seed dispersal to predict seedling recruitment: recolonization dynamics in a plantation forest. Ecological Modelling, 203:464–474.

Sefidi, K., Marvi Mohadjer, M. R., Zobeiri, M., Etemad, V., 2007: Investigation on dead trees effects on natural regeneration of Oriental beech and hornbeam in a mixed beech forest. Iranian Journal of Forest and Poplar Research, 15:365–373.

Seidl, R., Schelhaas, M. J., Rammer, W., Verkerk, P. J., 2014: Increasing forest disturbances in Europe and their impact on carbon storage. Nature Climate Change, 4:806–810.

Shahverdi, M., Dashti, H., Taghiyari, H. R., Heshmati, S., Gholamiyan, H., Hossein, M. A., 2013: The Impact of red heartwood on drying characteristics and mass transfer coefficients in beech wood. Austrian Journal of Forest Science, 130:85–101.

Shannon, C. E., 1948: A mathematical theory of communications. Bell System Technical Journal, 27:379–423.

Schelhaas, M. J., Nabuurs, G. J., Hengeveld, G., Reyer, C., Hanewinkel, M., Zimmermann, N. E. et al., 2015: Alternative forest management strategies to account for climate change-induced productivity and species suitability changes in Europe. Regional Environmental Change, 15:1581–1594.

Schulze, E. D., Aas, G., Grimm, G. W., Gossner, M. M., Walentowski, H., Ammer, C. et al., 2016: A review on plant diversity and forest management of European beech forests. European Journal of Forest Research, 135:51–67.

Schütz, J. P., 1999: Close-to-nature silviculture: is this concept compatible with species diversity? Forestry, 72:359–366.

Schütz, J. P., 2001: Opportunities and strategies of transforming regular forests to irregular forests. Forest Ecology and Management, 151:87–94.

Schütz, J. P., 2002: Silvicultural tools to develop irregular and diverse forest structures. Forestry, 75:329–337.

Slanař, J., Vacek, Z., Vacek, S., Bulušek, D., Cukor, J., Štefančík, I. et al., 2017: Long-term transformation of submontane spruce-beech forests in the Jizerské hory Mts.: dynamics of natural regeneration. Central European Forestry Journal, 63:212–224.

Souček, J., 2002: Conversion of forest managed under systems involving coupes to a selection forest on an example of the Opuky research area. Journal of Forest Science, 48:1–7.

Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J. P., Sterba, H., von Teuffel, K., 2004: Norway spruce conversion – options and consequences. Brill, Leiden.

Sterba, H., Zingg, A., 2001: Target diameter harvesting – a strategy to convert even-aged forests. Forest Ecology and Management, 151:95–105.

Šmilauer, P., Lepš, J., 2014: Multivariate analysis of ecological data using CANOCO 5. Cambridge university press, 361 p.

Švec, O., Bílek, L., Remeš, J., Vacek, Z., 2015: Analysis of operational approach during forest transformation in Klokočná Range, Central Bohemia. Journal of Forest Sciences, 61:148–155.

Šticha, V., Kupka, I., Zahradník, D., Vacek, S., 2010: Influence of micro-relief and weed competition on natural regeneration of mountain forests in the Šumava Mountains. Journal of Forest Science, 56:218–224.

Terek, J., Dobrovič J., 2013: Ecologically active surface, the basis for the study and evaluation of ecological functions. In: 4th International Conference „To Protect Our Global Environment of Future Generation", Obuda University, Budapest, p. 149–157.

Tesař, V., Klimo, E., Kraus, M., Souček, J., 2004: Dlouhodobá přestavba jehličnatého lesa na Hetlíně – kutnohorské hospodářství. Brno, MZLU v Brně, 60 p.

Trotsiuk, V., Hobi, M. L., Commarmot, B., 2012: Age structure and disturbance dynamics of the relic virgin beech forest Uholka (Ukrainian Carpathians). Forest Ecology and Management, 265:181–190.

Úradníček, L., Maděra, P., Tichá, S., Koblížek, J., 2009: Dřeviny České republiky. Lesnická práce, Kostelec nad Černými lesy.

Urli, M., Thiffault, N., Barrette, M., Bélanger, L., Leduc, A., Chalifour, D., 2017: Key ecosystem attributes and productivity of boreal stands 20 years after the onset of silviculture scenarios of increasing intensity. Forest Ecology and Management, 389:404–416.

Vacek, S., Cipra, Z., 1979: Struktura porostů v biocentru Jedlový důl. Zpráva pro CHKO Jizerské hory. VS Opočno a SCHKO Jizerské hory, 18 p.

Vacek, S., Vančura, K., Zingari, P.C., Jeník, J., Simon, J., Smejkal, J., 2003: Mountain forests of the Czech Republic. Ministry of agriculture of the Czech Republic, Prague, 320 p.

Vacek, S., Hejcman, M., 2012: Natural layering, foliation, fertility and plant species composition of a *Fagus sylvatica* stand above the alpine timberline in the Giant (Krkonoše) Mts., Czech Republic. European Journal of Forest Research, 131:799–810.

Vacek, S., Vacek, Z., Podrazský, V., Bílek, L., Bulušek, D., Štefančík, I., 2014a: Structural Diversity of Autochthonous Beech Forests in Broumovské Stěny National Nature Reserve, Czech Republic. Austrian Journal of Forest Science, 131:191–214.

Vacek, S., Hůnová, I., Vacek, Z., Hejcmanová, P., Podrázský, V., Král, J. et al., 2015a: Effects of air pollution and climatic factors on Norway spruce forests in the Orlické hory Mts. (Czech Republic), 1979–2014. European Journal of Forest Research, 134:1127–1142.

Vacek, S., Černý, T., Vacek, Z., Podrázský, V., Mikeska, M., Králíček, I., 2017a: Long-term changes in vegetation and site conditions in beech and spruce forests of lower mountain ranges of Central Europe. Forest Ecology and Management, 398:75–90.

Vacek, S., Vacek, Z., Kalousková, I., Cukor, J., Bílek, L., Moser, W. K. et al., 2018: Sycamore maple (*Acer pseudoplatanus* L.) stands on former agricultural land in the Sudetes-evaluation of ecological value and production potential. Dendrobiology, 79:61–76.

Vacek, Z., Vacek, S., Bílek, L., Král, J., Remeš, J., Bulušek, D. et al., 2014b: Ungulate Impact on Natural Regeneration in Spruce-Beech-Fir Stands in Černý důl Nature Reserve in the Orlické Hory Mountains, Case Study from Central Sudetes. Forests, 5:2929–2946.

Vacek, Z., Vacek, S., Podrázský, V., Bílek, L., Štefančík, I., Moser, W. K., 2015b: Effect of tree layer and microsite on the variability of natural regeneration in autochthonous beech forests. Polish Journal of Ecology, 63:233–246.

Vacek, Z., 2017: Structure and dynamics of spruce-beech-fir forests in Nature Reserves of the Orlické hory Mts. in relation to ungulate game. Central European Forestry Journal, 63:23–34.

Vacek, Z., Bulušek, D., Vacek, S., Hejcmanová, P., Remeš, J., Bílek, L. et al., 2017b: Effect of microrelief and vegetation cover on natural regeneration in European beech forests in Krkonoše national parks (Czech Republic, Poland). Austrian Journal of Forest Science, 134:75–96.

van der Maaten-Theunissen, M., Bouriaud, O., 2012: Climate–growth relationships at different stem heights in silver fir and Norway spruce. Canadian Journal of Forest Research, 42:958–969.

von Oheimb, G., Westphal, C., Tempel, H., Härdtle, W., 2005: Structural pattern of a near-natural beech *(Fagus sylvatica*) forest (Serrahn, North-east Germany). Forest Ecology and Management, 212:253–263.

Vrška, T., Hort, L., Odehnalová, P., Adam, D., Horal, D., 2001: Boubín virgin forest after 24 years (1972–1996) – Development of tree layer. Journal of Forest Science, 47:439–456.

Wagner, S., Madsen, P., Ammer, C., 2009: Evaluation of different approaches for modelling individual tree seedling height growth. Trees – Structure and Function, 23:701–715.

Weisberg, P. J., Bugmann, H., 2003: Forest dynamics and ungulate herbivory: from leaf to landscape. Forest Ecology and Management, 181:1–12.

Yamaguchi, D. K., 1991: A simple method for cross-dating increment cores from living trees. Canadian Journal of Forest Research, 21:414–416.

Zahradník, D., Puš, V., 2010: Program PoinPro Version 2.2. Czech University of Life Sciences, Prague.