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Uneven-aged silviculture of Scots pine in Bohemia and Central Spain: comparison study of stand reaction to transition and long-term selection management

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Abstract: The achievement of sustainable forest management requires the incorporation of ongoing environmental changes into long-term planning. Moreover, in time of climatic change and changing company demands, importance of Scots pine (*Pinus sylvestris* L.) is still increasing at the expense of other tree species due to its low ecological requirements. The aim of the study was to compare the structure and production of Scots pine stands managed under different silvicultural systems on four research plots, assess the structural and diversity indices, and analyse the increment structure using tree-ring dating in the Czech Republic and Spain. Area of study was Western Bohemian and Guadarrama Mountain range in Central Spain. The results indicate that stand volume on the investigated plots ranged from 231 to 441 $m^3 \cdot ha^{-1}$ with tree density 276–996 $trees \cdot ha^{-1}$. Intensively managed (uneven-aged) permanent research plots showed increased growth on basal area. The difference was evident also for older trees. The transition to uneven-aged forest does not negatively influence stocking and wood production and provide higher benefits for diversity and structural complexity in comparison to regular stands.

Keywords: *Pinus sylvestris* L.; close-to-nature silviculture; uneven-aged stands; forest structure; tree-ring dating

The first silvicultural measures were driven by the lack of wood and the need of sustainable wood production in future (Mustian 1978; Lautenschlager 2000; Schmidt 2012). Subsequently, various silvicultural systems evolved, with differences in inputs, rotation and regeneration periods and following differences in structure and function of forest stands (Kenk 1995). The silvicultural systems based on this principle are variable and can be grouped under a common term 'close-to-nature silviculture' (Haveraaen 1995). In the past decades, not only wood production, but socio-economic and biodiversity needs have become an importance (Šišák et al. 2013). Subsequently, the rebuilding of even-aged stands to uneven-aged silviculture started to take place as a consequence of close-to-nature silviculture approach (Guldin 1996; Vacek et al. 2019a). It is a viable model to reach more complex structure for Scots pine stands (Švec et al. 2015; Bílek et al. 2016).

The attention to more ecological forestry in larger scale has been drawn relatively recently (Gillis 1990; O'Hara 2002), however, the methods have been

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long known: Liocourt (1898) derived the curve of diameter quantity for optimal stocking in selection forest (Kerr 2013). The idea of shelterwood system and selection forests was intended almost exclusively for shade-tolerant species, particularly silver fir (*Abies alba* Mill.), partly also for Norway spruce (*Picea abies* [L.] Karst.), European beech (*Fagus sylvatica* L.), and Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) (Schütz 1989; Korpeľ, Saniga 1993; Vacek et al. 2015) and diverse species mixtures are considered as one of the common features of selection forests (Kelty 2006; Slanař et al. 2017). Nevertheless, there are examples of monospecific uneven-aged stands of Scots pine (García-Abril et al. 2007), and we can assume that depending on site conditions, positive reaction of sun light increment after gap release could be found also in species considered as pioneer, or sun-demanding.

Importantly, even though the structure is considered as more close-to-nature than other silvicultural systems, the balanced and production-convenient structure is not determined by natural processes, but it is the result of intentional activity of forest manager (Schütz 2002). There are few examples of uneven-aged stands of Scots pine in Central Europe (Bílek et al. 2016), more studies come from the Mediterranean regions (Barbeito et al. 2009; Ponce et al. 2017).

Although the indigenous stands of Scots pine in the Czech Republic are scarce: the autochthonous pine is rather individually distributed at extreme and relict sites (Musil, Hamerník 2007), it is the second commercially most important forest tree species (Ministry of Agriculture 2014), after Norway spruce. In addition, large disturbances and decline of Norway spruce have occurred due to air pollution load (Král et al. 2015; Králíček et al. 2017) and ongoing climate change (Cukor et al. 2019a; Putalová et al. 2019). Scots pine as a tree species that is adapted to a wide range of climatic conditions, having particularly high tolerance to soil moisture, from drying-up sites to waterlogged sites, it has a prerequisite for resisting climatic extremes (Mátyás et al. 2004).

Therefore, Scots pine can serve as a stabilizing part of forest ecosystem, on both nutrient poor and rich sites (Vacek et al. 2016; Vacek et al. 2017). Historically, Scots pine had been planted on extensive areas on poor, sandy sites, where often the removal of litterfall for the purpose of collecting bedding material, resulted in occurrence of non-productive forest cultures; as it is known from the region of Pilsen (Czech: Plzeň), around the municipality Plasy, Western Bohemia (Mikeska et al. 2008). On many sites, wrong provenience had a negative impact on the quality of the cultures; on other sites, many valuable local cultural types were exerted (Musil, Hamerník 2007).

In Spain, Scots pine is forming mountain stands between 800–2,000 m AMSL, the optimum is between 1,600–1,700 m (Serrada et al. 2008). In the Central system of Spain, *Pinus sylvestris* var. *iberica* (Svoboda) is distinguished (Amaral 2015; Serrada et al. 2008; Serrada 2011; López-Sáez et al. 2013) from all other populations, and also all the Spanish populations are genetically significantly different from other European populations (Prus-Glowacki, Stephan 1994; Alía et al. 2001).

Up to now, knowledge about stand mixtures with Scots pine show that there is a strong potential of wood production increase (Del Río, Sterba 2009), and potential for establishing more favourable stand structure in comparison with pine monoculture, with the maintenance of stand stability (Pretzsch et al. 2013a; Sharma et al. 2017, 2019).

The problems with artificial regeneration of Scots pine are often related to human factor during planting (delayed budflush, bad growth and high mortality after planting resulting from insufficient morphological and physiological quality of planting stock), as well as to environmental conditions, which in case of Scots pine are relatively high temperatures and low precipitation in lowland regions of Central Europe – with a precondition to short-term drought (Martincová 1998) and the combination of drought and fungi disease (Nárovcová 2010; Nárovec et al. 2012). Similarly, in European forests there are documented changes leading to subsequent dying of light-demanding (and relatively drought-tolerant) pines and oaks (Morán-López et al. 2014), probably because of ever dryer and warmer climate in the recent years.

Therefore, the possibilities of natural regeneration through the use of selection silvicultural system (Korpeľ, Saniga 1993) or system of clear-cut borders (Bílek et al. 2018) deserve an increased focus. In case of clear-cutting system, different methods of site preparation should be considered, as they have various impact on natural regeneration (Aleksandrowicz-Trzcińska et al. 2014; Aleksandrowicz-Trzcińska et al. 2017). Older monocultural stands are more threatened by *Ips acumina-*

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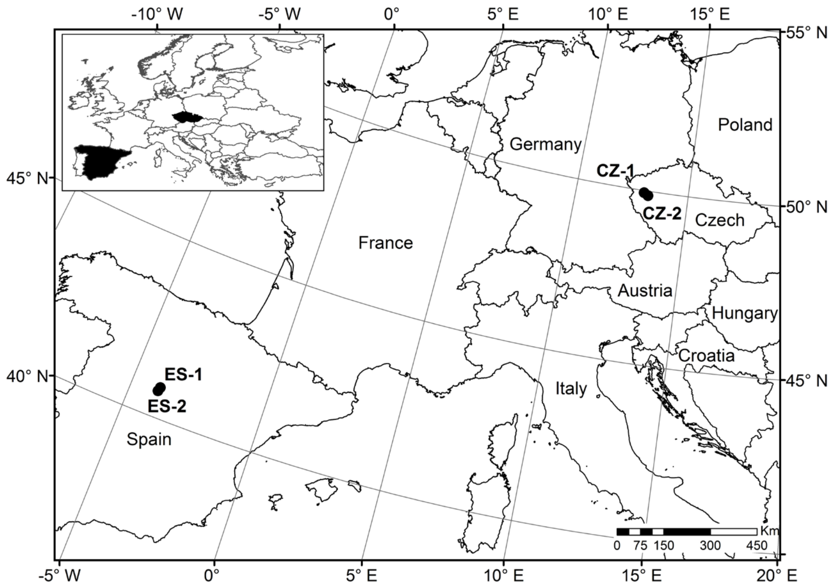

Figure 1. Localization of pine forests on permanent research plots in the Czech Republic (CZ-1, CZ-2) and in the Spain (ES-1, ES-2)

tus (Colombari et al. 2012) and by fungi associated with it (Jankowiak 2012; Davydenko 2017).

Selection forest is a model of biological automatization and autoregulation of forest ecosystem, regulated by forester (Schütz 1989). With respect to site conditions, it is stated that on rich sites, selection system can be used for its production advantages, while on poor sites, it should be used as a matter of priority, or even obligatory (Ammon 1946). Kern (1966) described that the slenderness coefficient was lower, and the mechanical stability higher in selection forest in comparison to regulated forest. The crucial interval is in DBH dimensions 12–20 cm, i.e. trees of medium layer, where the acceleration of growth is expected. It is the differentiated structure and relations of small groups that creates the conditions of stability. The selection silvicultural system involves the four main intentions: tending, structure formation, regeneration and harvesting (Leibundgut 1951). The sustainability and continuity of regeneration processes in selection forest was initially considered as matter of course, but in many cases this assumption was not fulfilled (Korpeľ, Saniga 1993).

Objective of the study was to determine the structural and growth characteristic of pine forest stand with differentiated multi-aged structure and compare it with the situation in pine forest stand, which is under transformation into differentiated structure. At each site, one plot with even-aged structure is included for comparison. Alongside comparing forest structure on each of the experimental plots, basic hypothesis was that the intensively managed (uneven-aged) plots would exhibit an increased growth as reaction to release cuts. We hypothesize that even older trees show a positive growth reaction to such measure.

MATERIAL AND METHODS

Study area. Four squared permanent sample plots (PRP) of size 50×50 m (0.25 ha) were established; two in the Western Bohemia, the Czech Republic (CZ-1, CZ-2), and two in the Community of Madrid, Spain (ES-1, ES-2) (Figure 1). The permanent research plots were chosen in natural (autochthonous) Scots pine-dominated forest stands of following characteristics: CZ-1: unmanaged for at least 30 years with regular structure; CZ-2: managed stand in transition from even-aged to uneven-aged stand, ES-1: regular stand with low intensity intervention; ES-2: irregular stand with low intensity intervention. All plots are regenerated by natural regeneration under the shelter of mature parental stand. CZ-1 and CZ-2 are Scots pine dominated stands with admixture of Norway spruce (CZ-1, CZ-2) and silver birch (*Betula pendula* Roth.) (CZ-1), ES-1 and ES-2 are pure Scots pine stands without admixture. Cutting frequency on the three managed plots was 5–10 years.

General description of the plots is summarized in Table 1. Geological and soil conditions on plots are characterized as poor acidic kaolinite-clayed Carboniferous sandstone with acidic soils that

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Table 1. Overview of the main site characteristics of permanent research plots

Parameter	Plots			
	CZ-1	CZ-2	ES-1	ES-2
Longitude	49.9099036N	49.9055694N	40.8229028N	40.8224694N
Latitude	13.1998936E	13.2062422E	3.9202889W	3.9206583W
Elevation (m)	600	590	1,710	1,710
Age	142	145	140	140
Exposure	-	E	N	N
Gradient (°)	0	5	15	15
Average precipitation (mm)	550	550	1,300	1,300
Average temperature (° C)	7.4	7.4	6.5	6.5

are heavily compacted (CZ-1, CZ-2), and poor acidic gneiss with silicate-clayed soil (ES-1, ES-2). Climatic conditions according to nearest meteorological stations are characterized by mean annual temperature of 7.4 °C and precipitation of 500–550 mm for CZ; and 6.5 °C and 1,300 mm for ES plots.

Data collection. Measurements were done in 2014 and 2015. Positions of all trees of diameter of the breast height (DBH) above 8 cm and structural parameters of tree layer were registered by Field-Map. Trees with DBH less than 8 cm and with height above 150 cm were counted as natural regeneration. The tree-crown diameter was measured minimally at 4 directions perpendicular to each other. Tree heights and crown bases of were live crown were measured by Vertex III hypsometer with accuracy to 0.1 m and DBH were measured with a metal calliper with accuracy to 1 mm.

On every PRP, the Pressler's borer was used to register at least 3 healthy trees in each DBH class for tree core analysis. The core analysis required in total 263 dendrochronological samples of Scots pine from 4 sample plots (2 in Czech Republic and 2 in Spain). On each PRP, the number of sample cores in range from 36 to 83 pcs was taken based on number of DBH classes (CZ-1: 75, CZ-2: 69, ES-1: 36, ES-2: 83). The samples were bored in breast height (130 cm) to the stem axis up- and downslope. The core samples were measured with measuring table. The measurements were done by binocular microscope with accuracy to 0.01 mm.

Data analysis. Structural indices and indices of diversity were calculated in SIBYLA growth simulator (Fabrika, Ďurský 2005). To evaluate structural, species and total diversity of the pine forest stand, the following indices were determined: vertical Arten-Profil index (Pretzsch 2006), diameter and height differentiation index (Füldner 1995), index of species heterogeneity (Shannon 1948), index of species evenness (Pielou 1975), stand diversity index (Jaehne, Dohrenbusch 1997), and the *L*-function (Ripley 1981).

Horizontal structure of tree layer was evaluated using Clark-Evans index (Clark, Evans 1954) and the *L*-function (Ripley 1981). The PointPro 2 programme (Zahradnik, Pus) was used for the computation of horizontal structure. The test of significance of deviations from the values expected for the random pattern of points was done by Monte Carlo simulations (999 randomly generated points). Calculation of individual structural and diversity indices is detailed in the study by Vacek et al. (2019c).

Stand volume was calculated using volume equations published by Petráš, Pajtík (1991) for the Czech Republic and by Carpenter, Alfonso (1967) for Spain. Height curves were constructed using the Näslund height-diameter function (Näslund 1936). The relative stand density index (Reineke 1933), the crown closure (Crookston, Stage 1999) and the crown projection area were observed for each PRP. The measured core samples were cross dated in software CDendro (Cybis Dendrochronology), with the correlation coefficient (CC > 23) to the mean reference stack. Dendrochronological data are with age trend (without age detrendation). Basal area was analysed by 5-year moving average, which was calculated as average from increment values of the particular year and two earlier and two following years. Situational maps were created in ArcMap 10.2.

RESULTS

Stand structure. Mean DBH was relatively equal on CZ-1 and CZ-2 (Table 2). The ES-1 plot was a mature compartment of regular forest, and there-

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Table 2. Stand parameters of Scots pine forests on the permanent research plots

PRP	DBH (cm)	*h* (m)	*f*	*v* (m^3)	*N* ($trees \cdot ha^{-1}$)	*G* ($m^2 \cdot ha^{-1}$)	*V* ($m^3 \cdot ha^{-1}$)	HDR	CC (%)	CP (ha)	SDI
CZ-1	27.2	17.80	0.483	0.501	488	28.3	245	65.6	68.6	1.16	0.56
CZ-2	24.9	15.80	0.566	0.434	552	26.8	240	63.3	65.2	1.06	0.55
ES-1	45.9	20.08	0.480	1.596	276	45.7	441	43.7	70.9	1.23	0.74
ES-2	20.7	9.05	0.761	0.232	996	33.4	231	43.7	79.6	1.59	0.74

DBH – mean quadratic breast height diameter; *h* – mean height; *f* – form factor; *v* – average tree volume; *N* – number of trees per hectare; *G* – basal area; *V* – stand volume; HDR – height to diameter ratio; CC – canopy closure; CP – crown projection area; SDI – stand density index

fore featured the highest DBH of all plots. In comparison with ES-2, the ES-1 could not be considered as basic functional unit of forest management as it did not contain all DBH classes. ES-2, on the other hand features all DBH classes which reduces the mean DBH. The absolute site quality was lower on the CZ plots in comparison to ES, as can be seen on the mean height on even-aged plots (CZ-1 vs. ES 1). Horizontal structure depicts the distribution of individual trees, crown projections, dead wood and regeneration (Figure 2). Stems lying on the ground were marked as black sticks: they were present on CZ-1 and CZ-2, not on ES-1 neither on ES-2. Regeneration clusters was marked as black triangle: it

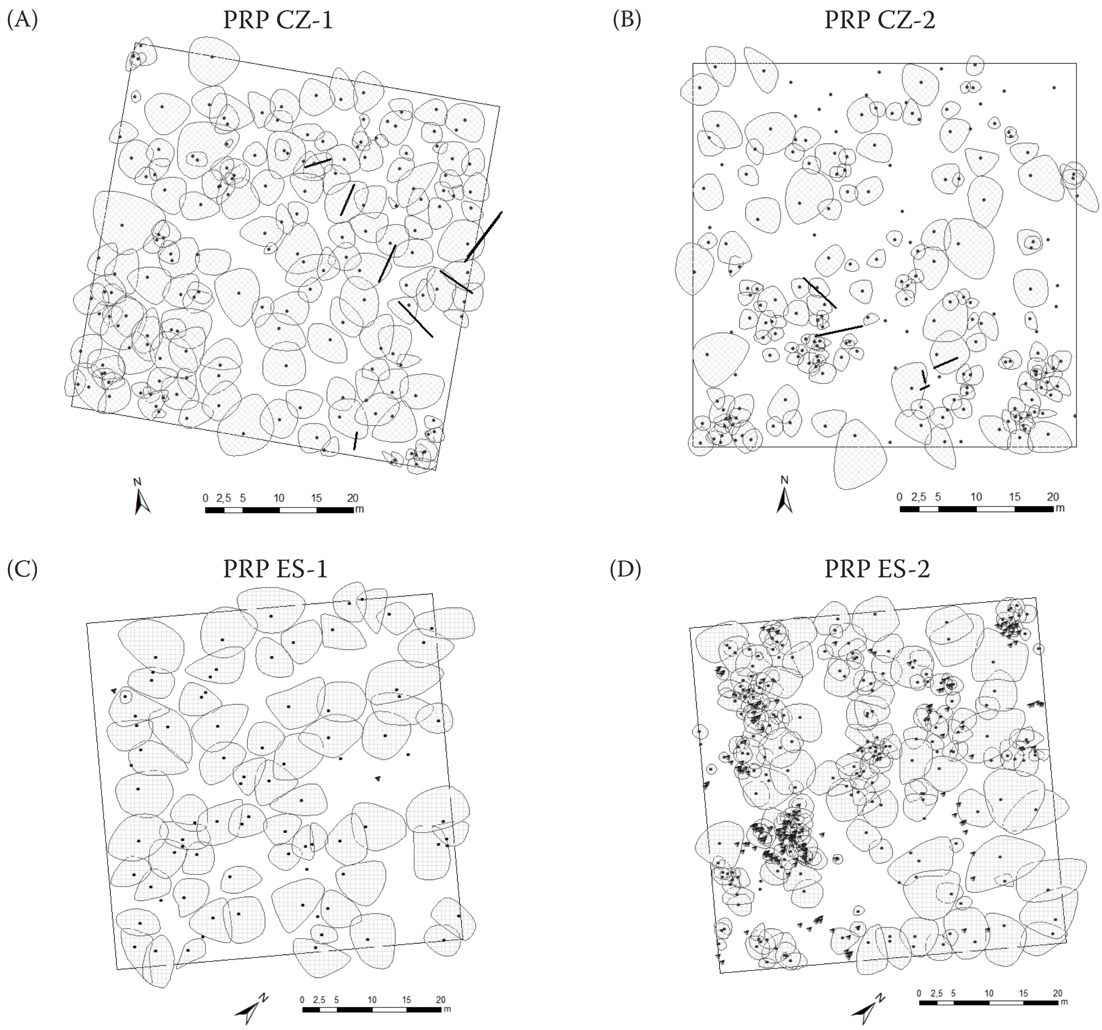

Figure 2. Horizontal structure of Scots pine forests on permanent research plots: CZ-1, CZ-2, ES-1 and ES-2

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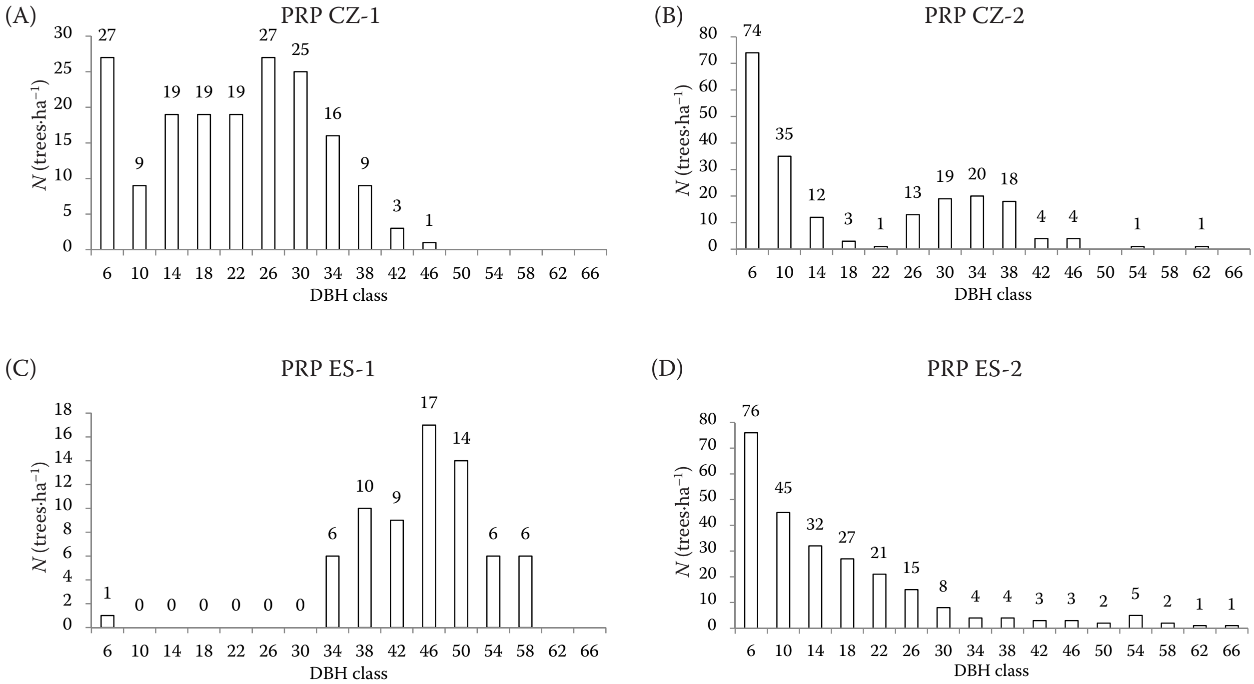

Figure 3. Distribution of DBH classes of Scots pine forest stands on permanent research plots

was missing on both CZ-1 and CZ-2, scarcely present on ES-1, and most abundant on ES-2. Canopy closure was highest on ES-2, stand with most irregular structure, followed by ES-1. CZ-1 – stand with lower intensity management showed higher canopy closure CC compared to CZ-2 with high intensity selection harvest. Canopy closure followed the same trend on all plots. Stand density index was comparable within the individual forest areas.

The distribution of trees in DBH classes on all plots is shown in Figure 3. CZ-1 can be considered as relatively close to regular structure, however, but with elevated number of trees in thin DBH class. In CZ-2, continual measures were applied for the transition to irregular stand, which is illustrated by most trees of small dimensions and decreasing trend of abundance, however, with some major problems in following DBH classes, which have insufficient numbers of individuals. ES-1 had relatively regular DBH structure, shifted in favour of larger dimensions, typical for mature compartment. ES-2, on the contrary, had selection (irregular) structure of distribution of trees among DBH classes.

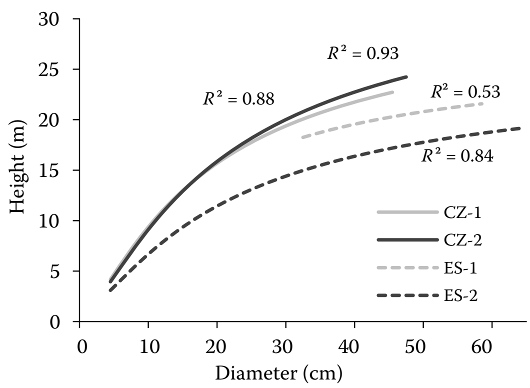

Figure 4. Relation between diameter at breast height and tree height of Scots pine on permanent research plots; R^2: coefficient of determination

Figure 4 depicts the comparison of the relation between height and DBH class on all plots using Näslund function. From the lowest DBH classes, CZ-1 and CZ-2 had higher value of the h: DBH ratio. The comparison could not be fully demonstrated in case of ES-1, because of its shift to higher DBH classes.

Diversity of tree layer. Table 3 shows the indices of horizontal structure and diversity of tree layer. Since the Clark and Evans aggregation index, R (C&Ei), describing the distribution of individuals, can reach values from 0 to 2.15, the most aggregated structure was found in irregular forest (ES-2). ES-1 was very close to value 1 (fully random distribution) and the two Bohemian plots were slightly more of a regular distribution, although still far from fully regular.

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Table 3. Indices of horizontal structure and diversity of tree layer on investigated plots

PRP	R (C&Ei)	A (Pi)	B (J&Di)	TM_d (Fi)	TM_h (Fi)	H´ (Si)	E (Pii)
CZ-1	1.170	0.375	**7.121**	0.324	0.225	**0.184**	**0.236**
CZ-2	**1.229**	0.386	5.576	0.275	0.208	0.005	0.017
ES-1	1.041	0.415	5.846	0.166	0.083	0.000	0.000
ES-2	0.790	**0.981**	6.287	**0.405**	**0.323**	0.000	0.000

R – Clark and Evans aggregation index; A – Arten Profil index; B – total diversity index; TM_d – diameter differentiation index; TM_h – height differentiation index; H´ – index of species heterogeneity; E – index of species evenness; in bold – the highest values of each index

The Arten Profil Index of vertical structure A (Pi) reaches values from 0 to 1; when more than 0.9, the stand can be considered as selection forest in terms of diverse vertical structure. Therefore, the plot ES-2 was an adequate example of selection forest. It can be noted, that the continuing transition of structure form regular to irregular at plot CZ-2 has not yet secured the vertical differentiation form regular plot CZ-1.

Total diversity index B (J&Di) is an aggregation of partial diversity components: the highest value was found in unmanaged regular forest CZ-1. The second highest value was in selection forest ES-2. CZ-2 and ES-1 had similar values.

Diameter differentiation TMd (Fi) and height differentiation TMh (Fi) were medium on ES-2, and low on all the other plots.

On even-aged plots (CZ-1, ES-1), the spatial distribution of trees was predominantly random (CZ-1), or random bound to regular (ES-1), while the horizontal structure of the tree layer was aggregated on the more irregular plots (CZ-2, ES-2) according to *L*-function (Figure 5).

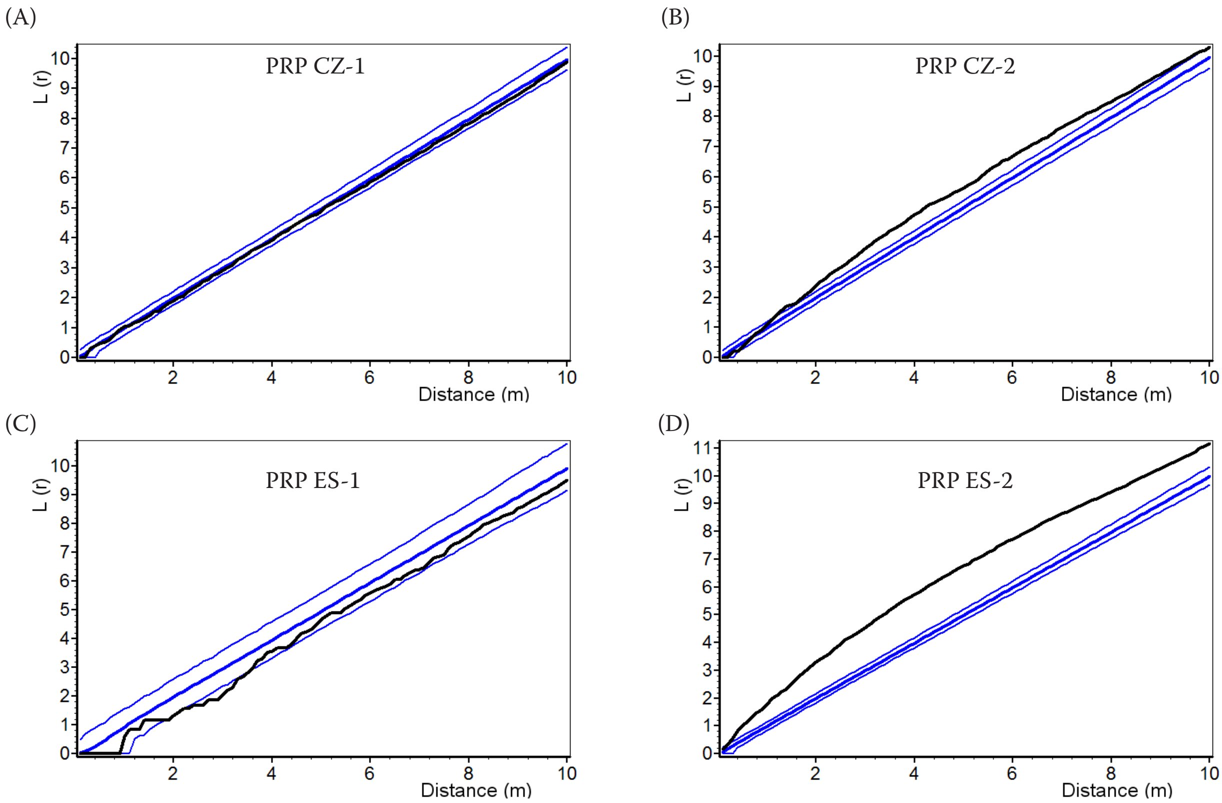

Figure 5. Horizontal structure of pine tree individuals on permanent research plots expressed by the *L*-function; the bold blue line represents the mean course for random (Poison) spatial distribution of trees and the two thinner central blue curves represent 95% interval of reliability; when the black line of measured tree distribution on PRP is below this interval, it indicates a tendency of trees toward regular distribution, and if it is above this interval, it shows a tendency toward aggregation

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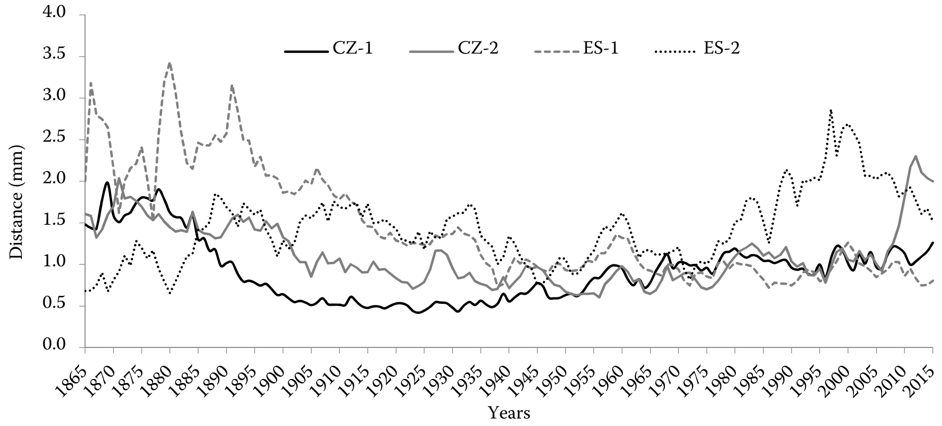

Figure 6. Increment of Scots pines on permanent research plots during the rotation according to core analysis

Annual rings analysis. The historic course of mean annual core increment is shown in Figure 6. The mean annual core increment (also mean periodical increment) in the period of 150 years (1865–2015) was 0.92 mm on plot CZ-1, 1.11 mm on CZ-2, 1.44 and 1.43 on ES-1 and ES-2, respectively. The development roughly resembled U letter – after initial (relatively) rapid growth, mean annual increment decreased, and again rose in the last decades.

In the last 10 years (2006–2015) it was 1.12 and 1.72 for CZ-1 and CZ-2, respectively, and the mean of the last 30 years reached 1.05 and 1.27 for CZ-1 and CZ-2, respectively. The mean increments therefore differed by 0.20 mm, 0.22 mm, and 0.60 mm for those 150, 30, and 10-year periods.

For the last 10 years, the mean annual increment was 0.88 on ES-1 and 1.84 on ES-2, and it accounted for 0.90 and 2.04 on ES-1 and ES-2, respectively, in the period 1986 – 2015 (last 30 years).

Figure 7. Shows clear reaction of trees on plot CZ-2 to release cutting in the last 7 and especially 5 years. The mean annual core increment of trees above 20 cm of DBH showed similar general dynamics as when all trees were considered. The previously faster-growing trees of DBH 20+ on CZ-1 were outperformed by CZ-2 from 2010 on (Figure 8).

The analysis of basal area increment using 5-year moving average confirmed the results of analysis of annual rings (Figure 9). The more intensively managed plots showed increased production, independently on geographical position. For Spanish plots, the difference was more long-term, corresponding to long-term diversification. On Czech plots, the trees' growth response to the transition to multi-age stand was clearly observed for the last 5 years.

DISCUSSION

Advantages of uneven-aged, and particularly selection silviculture systems are the attainment of elevated number of large diameters stems for veneer processing, continuous cover forestry with no

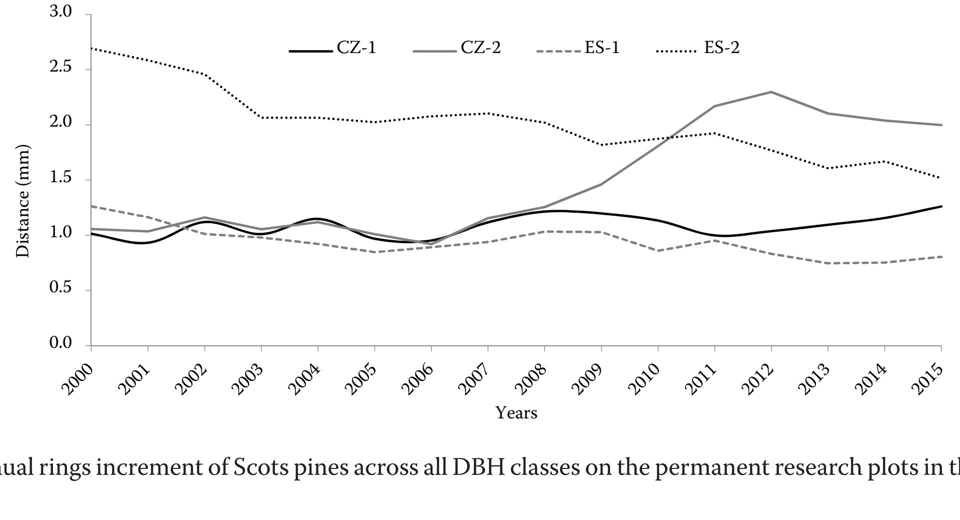

Figure 7. Annual rings increment of Scots pines across all DBH classes on the permanent research plots in the last 15 years

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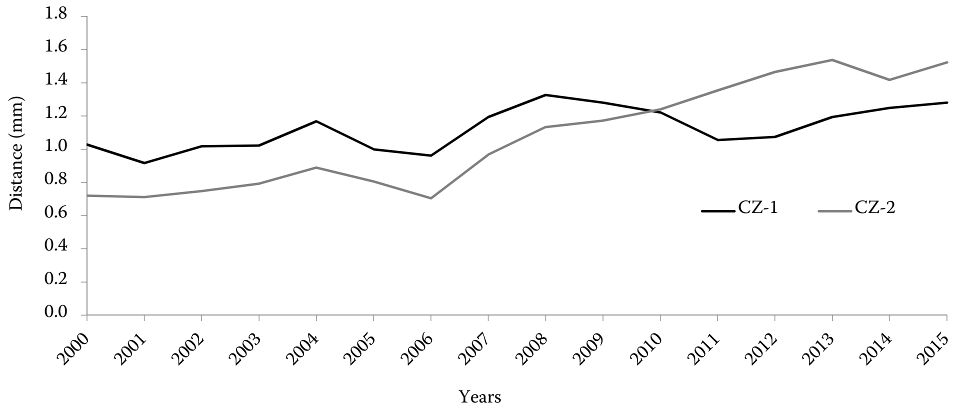

Figure 8. Annual rings increment of Scots pines with DBH > 20 cm on the permanent research plots CZ-1 and CZ-2 in the last 15 years

temporal loss of forest environment, which subsequently leads to balanced diversity and stand structure (Guldin 1996; Diaci et al. 2011). Uneven-aged forest stands require consistent silvicultural interventions every 5–10 years. Longer pause of intervention causes the loss of stratification and 2-etage stand begins to form. The model can be applied also in Scots pine, such as in our study, where differentiated structure is desirable as an alternative (Bílek et al. 2016).

Long-term examples of uneven-aged silviculture of coniferous and coniferous-broadleaved mixtures are common from Switzerland (Hanewinkel 2002) or France (Buongiorno et al. 1995). Mixed forests are commonly recommended as more stable, diverse, and natural (Pretzsch et al. 2013b; Sharma et al. 2016; Vacek et al. 2019b). Nevertheless, we present an example of Scots pine selection forest that fulfil protection, as well as production function. The advantage of producing larger diameter assortments is documented in our study. The stand volume ranged between 240–245 $m^3 \cdot ha^{-1}$ in Czech PRP, and respectively 231–441 $m^3 \cdot ha^{-1}$ for Spain PRP. Comparable stand volume (151–511 $m^3 \cdot ha^{-1}$) of uneven-aged forest stands was observed in other localities in Czech Republic and Poland (Bílek et al. 2016; Vacek et al. 2017). This is consistent with the results of study from north-eastern Spain, where stand volume of uneven-aged pine forest does not exceed value of 500 $m^3 \cdot ha^{-1}$ (Trasobares et al. 2004). Development of slenderness coefficient was similar within locations regardless of management, which is in accordance with other studies (Dušek et al. 2011; Dušek et al. 2012), however, thinning especially in early stage can have a positive effect on stem diameter and stand volume (Abetz, Chroust 2004; Dušek et al. 2010).

In the Guadarrama Mountain range of Central Spain, Scots pine forests are traditionally managed as even-aged by shelterwood silvicultural system (Montes et al. 2005). This can be viewed as relatively drastic by the public, especially on steep slopes

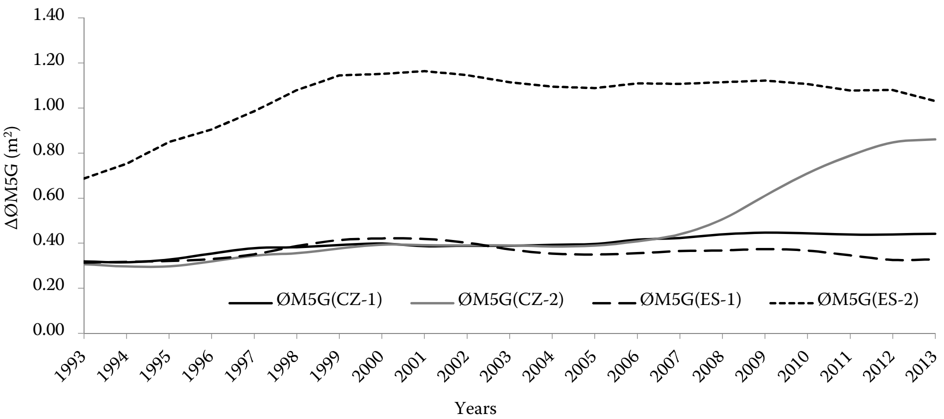

Figure 9. 5-year moving averages of basal area increment (ØM5G) 1993–2013 on permanent research plots

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where protection functions are a priority, depending on the intensity of opening thinning. On the other hand, leaving the forests unmanaged for 'conservation' purposes leads to accumulation of standing volume, lack of natural regeneration and ultimately increases the potential of large-scale forest fires (de Rigo et al. 2017). Eventually the contrary is achieved: more threats to endangered species like cinereous vulture, soil erosion, loss of retention function etc. In this context, the suggestion of uneven-aged silviculture serves as an alternative, proportionally fulfilling all the desired services.

The trees had lower HDR ratio on ES plots compared to CZ plots, i.e. Spanish pines were thicker. This is an important trait of increased stand stability (Korpeľ, Saniga 1993; Schütz 1999). On even-aged plots (CZ-1, ES-1), the spatial distribution of trees was predominantly random (CZ-1), or random bound to regular (ES-1), while it was aggregated on the more irregular plots (CZ-2, ES-2) according to *L*-function. The prevailing random distribution with tendency to aggregation was also observed in other uneved-aged pine forest stands in Central Europe (Bílek et al. 2016; Vacek et al. 2017), while horizontal structure of even-aged pine forest with clear-cut management was significantly regular (Vacek et al. 2016).

In regard to mean core increments, it was examined, whether different silvicultural measures caused a reaction in growth performance. CZ-1 was a regular forest plot with low intensity management, while CZ-2 was in the process of transition into uneven-aged stand with high intensity interventions in recent years. Since the dynamics when comparing all sampled trees and trees above 20 cm of DBH of mean annual core increment on plots CZ-1 and CZ-2 resulted similar, it can be assumed that mature trees positively reacted to release cutting. Such difference in growth performance-reaction could not be expected on ES-1/ES-2. Even though the silvicultural systems used are different, the practical intervention resulted in similar cutting intensity in recent periods: individual tree cutting, which made up the preliminary cutting (as part of small-scale shelterwood silvicultural system) on ES-1, and individual mature trees harvest on ES-2, as practical implementation of the four united intentions in single tree selection silvicultural system (harvesting and regeneration in the first place, followed by structure formation and stand tending).

In regard to the researched plots, some principal suggestions could be derived: in the conditions of municipality Plasy, the forest ecosystems are close to its limits. A transition to more close-to-nature uneven-aged forest is favourable for the decrease of inputs and for the increase of overall stand stability (Vacek et al. 2019a). It is necessary to mention the problems with natural regeneration caused by browsing damages that could be partially solved by gradual change of tree species composition together with transition to irregular stand (Vacek et al. 2014). Sufficient quantity of natural regeneration is of essential importance. This can be limiting in forests, where forest pasture takes place (common in Spain), and also in forests heavily browsed by deer (problem in the Czech Republic – Vacek 2017; Vacek et al. 2018). Similar problem is described for the conditions of mountain Scots pine forests in Spanish Central system, however, caused by traditional forest pasture (Pardo, Gil 2005). But it didn't seem to be of such crucial importance as it was in case of Sika deer (*Cervus nippon*Temminck) damages in the Bohemian forests (Dvořák, Čermák 2008; Cukor et al. 2019b). On the other hand, selection forest is not necessarily the only scheme of uneven-aged stand, as documented by Moser et al. (2002) who proposes two-phase regeneration or Bílek et al. (2018), who suggests clear-cut borders as a possible alternative.

CONCLUSIONS

Close-to-nature silviculture is a viable management model for creating more complex forest structure and sustainable wood production in Scots pine forest stands together with better adaptation on ongoing environmental changes, especially climatic extremes, fire risk and requirements of society. Increased production as well as strong reaction to silvicultural measures was found in structurally more diverse Scots pine stands. Our results showed that stand volume ranged from 231 to 441 $m^3 \cdot ha^{-1}$, depending on management type. Intensively managed forest stands showed increased production characteristics. The transformation to uneven-aged forest stands does not negatively affected stand and wood production and provide higher benefits for structural complexity and diversity when comparison to homogenous stands. Conditions between localities were different in terms of climatic factors. The results generally showed that selection thinning caused higher diameter of mean stem and also higher stand volume. Selection system also allows

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the production of larger diameter logs for veneer, and at the same time represents so called continuous cover forestry, and therefore we expect no loss of forest environment in any moment of the existence of the stand. Less structurally diverse stands, on the other hand, required less input to maintain its structure and stability.

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