

Root system development in Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) on fertile sites

O. MAUER, E. PALÁTOVÁ

Department of Forest Establishment and Silviculture, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic

ABSTRACT: The paper analyses the root system development in the artificially established stands of Douglas fir aged 10, 20, 30, 60 and 80 years on aerated soils (Cambisols) without skeleton. On these sites, the Douglas fir develops a uniform root system of substitute taproots and anchors, which has great predispositions to assure the good mechanical stability of trees as well as its resistance to sudden changes in upper soil horizons. Several anchors growing in positive geotropic direction shoot from the stem base, several slant anchors shooting from the side of the stem base turn into the positive geotropic direction of growth. In humus horizons, horizontal skeletal roots shoot from the stem base, which turn into lower soil horizons in an “elbow-pipe” manner and from which shoot positively geotropically growing anchors. Trees of Douglas fir develop this type of root system already at an age of twenty years.

Keywords: Douglas fir; root system; fertile sites

Douglas fir is the most important introduced tree species for the Czech forestry. Conditions favourable for its growth occur in the country on an area of over 1 million hectares (ŠIKA et al. 1988). At present, the species is cultivated on 4,400 ha, which represent mere 0.17% of the forestland (KANTOR et al. 2010). The current standing volume of Douglas fir stands is ca 1,076,980 m³ (NOVOTNÝ, BERAN 2008). In respect of forestry, Douglas fir is considered a prospective species and its share in the long-term species composition of forest stands was recommended to be 2% of the forest stand area in the long-term concepts and even up to 4% of the forest stand area in the ÚHÚL study from 1994 mentioned by BERAN and ŠINDELÁŘ (1996). There are plenty of references in literature on the production potential and silvicultural characteristics of Douglas fir (e.g. ŠIKA, VINŠ 1980; HUSS 1996; KANTOR 2006, 2008; MARTINÍK, KANTOR 2006, 2007 and others). Much fewer data exist on the root system of this tree species.

Douglas fir usually develops a primary taproot whose growth into depth ends at about 10 years

of its age (HENGST 1958). The slow-down of its growth has to do with the development of lateral roots, which begin to establish as taproot branches already during the first or second vegetation period (EIS 1974). Older trees feature the original taproot supplemented with branches from the main lateral roots, which penetrate the soil at a sharp angle and are rarely absolutely vertical (MCMINN 1963). The root system depth in Douglas fir is determined primarily by the soil structure and texture. On permeable soils with favourable moisture conditions, the roots may reach down to 60–100 cm but they may penetrate even deeper (HERMANN 2005).

Superficial lateral roots seldom remain in the organomineral soil layer along their entire length but would quite gradually penetrate deeper into the soil with the increasing distance from the stem (EIS 1974). The total length of roots increases with the increasing tree age. According to KÖSTLER et al. (1968), a root system with the missing far-reaching main lateral roots is characteristic of Douglas fir. WAGENKNECHT (ex KÖSTLER et al. 1968) informed

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about a tight correlation between the crown diameter and the root system diameter. However, KUIPER and COUTS (1992) did not corroborate the correlation between the crown size and the root system size. On well-aerated soils, they found roots reaching up to one metre beyond the crown perimeter and the area occupied by roots with a diameter up to 0.5 cm being 1.3-times larger than the crown projection.

The branching of the taproot and lateral roots results in a heart-shaped root system with regular, hemispherical rooting under the stump (KÖSTLER et al. 1968; EIS 1987; POLOMSKI, KUHN 1998; HERMANN 2005). KREUTZER (1961) described two more or less separated circles of main roots in the Douglas fir root system. The upper circle is formed by roots of oval (elliptical) cross-section and spreads right under the soil surface while the internal fringe of roots is branched, inclined downwards and occupies a hemispherical space under the crown.

Although the initial development of the root system is genetically controlled, it becomes soon modified (especially in depth) by the soil structure and density, moisture and nutrient contents, temperature, by the competition of other roots and canopy (HERMANN 2005). On aerated fresh and deep soils, Douglas fir would establish its species-specific heart-shaped root system. On drought-prone soils and soils with a high groundwater table, the species develops plate-shaped root systems (HERMANN 2005). WILPERT (1986 ex HERMANN 2005), who studied the root system of Douglas fir on *Pseudogleys*, claimed that the root system formation depends on the water regime type. Soils under a long-term influence of groundwater were observed to give rise to flat root systems of shallow rooting depths while soils under an influence of short-term waterlogging contained heart-shaped root systems with deep penetrating roots.

The formation of the root system in Douglas fir is affected not only by soil conditions but also by the social status of the tree. With respect to a considerably ample branching, the roots of neighbouring

trees considerably intertwine also in the intensively rooted middle part of the root system, especially in high-density Douglas fir stands (MCMINN 1963). According to the author, long and sparsely branching “pioneer” roots were common only in stands aged up to 10 years. KÖSTLER et al. (1968) found out that Douglas firs with narrow crowns growing in a dense canopy had distinctly weaker rootage. Dense canopy does not restrain only the lateral distribution of roots but even the rooting depth is low and the root system is weak in general. Dominant trees have a more symmetrical root system and more abundant lateral roots than co-dominant and intermediate trees although their rooting depths are similar (EIS 1974).

The disparity of data on the development of the root system in Douglas fir resulted from the fact that the comparison was made with Douglas firs of different age, established by both artificial and natural regeneration, growing on different sites and in different stand situations. The objective of this paper, which is the first in a series of articles, is to analyse in a time series the development of the root system in Douglas fir growing on fertile sites without the skeleton.

MATERIAL AND METHODS

The analysed pure Douglas fir groups aged 10–80 years were situated on plots under management of the Training Forest Enterprise in Křtiny, MENDELÚ in Brno (detailed characteristics of stands see Table 1). The number of root systems analysed in each stand was six (with the exception of Stand 10 and Stand 20 with analysed 10 and 8 root systems, respectively). All root systems were lifted manually using the archaeological method. The analyses included only vital co-dominant trees growing within the stand. All analysed stands were established by planting and their genetic origin is unknown. Parameters studied after the lifting and cleaning of the root systems were as follows:

Table 1. Characteristics of the analysed stands

Stand age (years)	Stand No.	Stand denoted as (years)	FT/ Stocking	Douglas fir share (%)	Terrain	Soil type	Soil subtype	Soil variety	Forest floor	Parent rock
9	130A10	10	3B 1	100	flatland	cambisol	haplic	mesotrophic	semimull	granodiorite
17	370A1a	20	2H 1	100	flatland	cambisol	haplic	mesotrophic	semimull	granodiorite
34	130B3	30	3H 1	100	flatland	cambisol	psephitic	mesotrophic	mull moder	granodiorite
64	136C7	60	2B 1	100	flatland	cambisol	haplic	mesotrophic	mull moder	granodiorite
81	137C8	80	3B 1	100	flatland	cambisol	haplic	mesotrophic	semimull	granodiorite



Fig. 1. Root system of Douglas fir at the age of 30 years



Fig. 2. Root system of Douglas fir at the age of 60 years

- length of the aboveground part of the tree and stem diameter at breast height (1.3 m),
- root system type,
- horizontal skeletal roots (all lateral roots with diameter at the stem > 10 mm); monitored was their number, diameter (at 20 cm and 60 cm from the stem), length (from the stem to the root tip), number and diameter of lateral roots with diameter > 4 mm, rooting depth (perpendicular distance from the soil surface to the lower part of the measured root at a distance of 20 cm from the stem and on the root tip),
- horizontal non-skeletal roots (all lateral roots with diameter at the stem 4–10 mm); monitored was their number, diameter (at a distance of 20 cm from the stem), length (from the stem up to the root tip), number and diameter of lateral roots with diameter > 4 mm),
- non-skeletal roots from the stem base (all roots shooting from the stem base whose diameter was < 4 mm) and their number,
- perpendicular anchors from the stem base (all roots shooting from the lower stem base with positively geotropic growth direction); monitored was their number, diameter, rooting depth (perpendicular distance from the soil surface to the anchor tip), number and diameter of lateral roots with diameter > 4 mm,
- slanted anchors from the stem base (all roots shooting from the stem base side with horizontal or slant growth direction, which rapidly turn into positive geotropic direction); parameters monitored were the same as in the perpendicular anchors from the stem base,

- anchors from horizontal skeletal roots (all roots shooting from horizontal skeletal roots with positively geotropic growth direction); parameters monitored were the same as in the perpendicular anchors from the stem base,
- diameter of all anchors was measured 5 cm from the point of their setting; diameter of all lateral roots was measured 2 cm from the point of their setting (elimination of buttresses at the point of setting),
- distribution of horizontal skeletal roots in the circular network was evaluated according to the largest detected angle between two neighbouring horizontal skeletal roots,



Fig. 3. Root system of Douglas fir at the age of 80 years

- the measured values were used to calculate Index p (I_p), which is to express the relation between root system size and aboveground part of the tree; it is calculated as a ratio of root cross-sectional areas at the measured point (in mm^2) to the aboveground part of the tree (in cm); the higher the I_p value, the larger the tree's root system,
- each root and stem base were cut lengthwise and analysed for possible rots at the cut; each root and stem base were also subjected to visual check for damage by biotic factors,
- the volume of fine roots ($< 2 \text{ mm}$) was measured due to high labour consumption only in Stand 20 and Stand 80 (two trees in each of the stands; in the root system, separately assessed were fine roots shooting from horizontal roots and fine roots shooting from all anchors (tables of results include absolute values found in the analysed trees),
- statistical significance of measured results was tested by t -test at a level of significance $\alpha = 0.05$; in the tables of results (parameters are characterized by arithmetic mean and standard error), the test results are marked graphically with all values in which no significant difference was detected as compared with Stand 80 being in bold case.

RESULTS

On fertile sites, all analysed Douglas firs developed one and the same type of root system (in Table of results denoted as Type 1). The taproot was missing in the root system, several positively geotropically growing anchors were shooting from the stem base and several slant anchors were shooting from the sides of the stem base, which turned into the positively geotropic growth direction. Horizontally growing roots of diverse diameters were shooting from the upper part of the stem base (in humus horizons) and positively geotropically growing anchors were shooting from the horizontal skeletal roots (Table 2).

Horizontal skeletal roots. All analysed trees developed a nearly identical number of horizontal skeletal roots, which did not significantly differ at the age of twenty and eighty years. The average length of these roots did not reach beyond the crown projection and although it was increasing with the increasing age, no significant length increase was observed from the age of 30 years. The longest horizontal skeletal root reached only slightly beyond the crown projection, its length increasing with the increasing age of trees; however,

from 60 years of age no significant differences were observed compared with the length at 80 years of age. The horizontal skeletal roots showed very large diameters at the stem (elliptical, often even tabular cross-section). With the increasing length, their diameter rapidly decreased and from the age of thirty years, the diameter of horizontal skeletal roots did not significantly increase at a distance of 20 and 60 cm from the stem and remained more or less the same as that of 80-years-old trees. The horizontal skeletal roots did not branch and the number of relatively small-diameter and short lateral roots shooting from them was very low. The number of lateral roots did not increase with the increasing age unlike their diameter. Not all horizontal skeletal roots grew parallelly to the soil surface but from a distance of ca 40 cm from the stem, some of them penetrated into the lower soil horizons. From the age of thirty years, no significant differences were found in the maximum rooting length as measured on their tips. Although the horizontal skeletal roots did not cover the circular network at a uniform pattern, differences in the maximum angle between two horizontal skeletal roots were insignificant in the analysed stands.

Horizontal non-skeletal roots. All analysed trees developed a nearly identical number of horizontal non-skeletal roots; from the age of twenty years, differences among the stands were insignificant (10-years-old stand did not exhibit this type of roots). Average length of these roots was by ca 25–50% lower than the length of horizontal skeletal roots; from the age of 30 years, the differences among the stands in the length of non-skeletal roots were insignificant. The diameter of roots was increasing with the increasing age of stands; from the age of sixty years, differences in diameters among the stands were insignificant. The horizontal non-skeletal roots did not branch and the amount of small-diameter and short-length lateral roots shooting from them was low. Differences in the number of lateral roots were insignificant from the age of 60 years; from the age of 30 years, the same applied also to differences in their diameter.

Non-skeletal roots from the stem base. The number of non-skeletal roots shooting from the stem base was by up to 100% higher than the sum of horizontal skeletal and horizontal non-skeletal roots. Their number was increasing with the increasing age of the stands and from 30 years of age, differences in their number among the stands were insignificant.

Horizontal skeletal + horizontal non-skeletal roots. The horizontal skeletal and the horizontal

Table 2. Root system parameters and traits

Parameters, traits	Stand designation				
	10	20	30	60	80
Number of analysed trees (pcs)	10	8	6	6	6
Length of aboveground part (cm)	387 ± 25	1061 ± 69	2147 ± 78	3190 ± 28	3375 ± 148
Stem diameter at d1.3 (mm)	64 ± 9	117 ± 9	209 ± 12	312 ± 24	340 ± 13
Root system type 1 (% of trees)	100	100	100	100	100
Horizontal skeletal roots					
– number (pcs)	4.3 ± 1.5	5.4 ± 0.5	6.0 ± 2.0	5.0 ± 1.4	6.1 ± 1.1
– diameter at 20 cm (mm)	11.3 ± 5.4	31.1 ± 12.2	53.1 ± 21.8	79.6 ± 31.1	110.4 ± 57.2
– rooting depth at 20 cm (cm)	8.2 ± 2.1	12.4 ± 3.1	13.6 ± 2.8	12.7 ± 3.3	14.6 ± 2.9
– diameter at 60 cm (mm)	–	10.7 ± 6.1	25.5 ± 10.9	49.2 ± 24.2	62.8 ± 25.4
– max. rooting depth on the tip (cm)	–	21.5 ± 4.2	37.4 ± 5.1	34.4 ± 5.1	38.5 ± 5.5
– length (cm)	58.2 ± 20.1	88.5 ± 15.4	152.7 ± 15.4	146.2 ± 66.1	169.3 ± 47.8
– length of the longest root (cm)	79.7 ± 28.6	105 ± 22.2	187 ± 49.9	252.5 ± 10.6	235.0 ± 35.5
– number of lateral roots (pcs)	1.6 ± 0.9	4.6 ± 1.4	4.0 ± 1.1	2.5 ± 0.7	2.7 ± 1.0
– diameter of lateral roots (mm)	4.8 ± 1.1	6.8 ± 2.6	7.7 ± 2.1	13.4 ± 5.6	12.5 ± 5.6
– maximum angle between HSR ¹ (deg.)	130 ± 34	104 ± 24	122 ± 47	145 ± 49	115 ± 21
Horizontal non-skeletal roots					
– number (pcs)	–	3.3 ± 1.7	4.5 ± 1.0	3.5 ± 0.7	4.5 ± 0.7
– diameter (mm)	–	8.4 ± 1.4	14.9 ± 3.1	18.9 ± 4.3	18.2 ± 2.8
– length (cm)	–	63.9 ± 12.1	95.8 ± 11.6	90.4 ± 18.2	87.7 ± 8.1
– number of lateral roots (pcs)	–	3.2 ± 0.9	3.7 ± 1.1	5.7 ± 1.4	5.6 ± 0.9
– diameter of lateral roots (mm)	–	4.6 ± 0.9	5.7 ± 1.3	6.5 ± 1.5	6.5 ± 1.3
Number of non-skeletal roots from the stem base (pcs)	12.0 ± 2.6	16.5 ± 2.4	21.2 ± 9.2	22.5 ± 6.3	26.0 ± 4.2
Skeletal + non-skeletal horizontal roots					
– number (pcs)	4.3 ± 1.5	8.7 ± 1.4	10.5 ± 1.9	8.5 ± 2.2	10.6 ± 0.7
– number of lateral roots (pcs)	1.6 ± 0.9	7.8 ± 0.8	7.7 ± 0.8	8.2 ± 1.0	8.3 ± 0.8
Perpendicular anchors from the stem base					
– number (pcs)	2.3 ± 1.1	2.3 ± 0.8	3.3 ± 1.2	4.2 ± 2.1	4.0 ± 1.4
– diameter (mm)	13.7 ± 4.3	52.0 ± 24.2	45.8 ± 16.9	86.0 ± 40.9	78.6 ± 25.2
– rooting depth (cm)	58.6 ± 17.1	91.7 ± 15.2	94.8 ± 29.2	108.1 ± 15.7	107.5 ± 23.2
– max. rooting depth (cm)	81.0 ± 31.4	98.6 ± 8.7	108.5 ± 5.6	122.0 ± 5.6	151.2 ± 7.1
– number of lateral roots (pcs)	2.2 ± 0.9	4.3 ± 1.5	4.6 ± 1.5	4.4 ± 2.1	4.6 ± 0.9
– diameter of lateral roots (mm)	5.4 ± 1.9	11.9 ± 5.6	13.9 ± 6.4	25.6 ± 12.2	22.8 ± 8.6
Slant anchors from the stem base					
– number (pcs)	3.0 ± 1.0	2.3 ± 1.3	4.1 ± 1.8	4.0 ± 2.8	3.2 ± 1.4
– diameter (mm)	14.1 ± 4.4	32.8 ± 11.2	54.6 ± 19.3	83.6 ± 21.3	123.0 ± 43.7
– rooting depth (cm)	57.6 ± 24.7	50.8 ± 13.0	68.4 ± 15.5	92.1 ± 17.1	122.2 ± 23.2
– number of lateral roots (pcs)	2.1 ± 0.6	3.7 ± 1.1	4.4 ± 1.2	4.2 ± 0.9	5.9 ± 1.0
– diameter of lateral roots (mm)	4.8 ± 0.9	6.6 ± 2.2	14.1 ± 6.2	22.6 ± 10.5	30.1 ± 9.8
Anchors from HSR ¹					
– number (pcs)	–	2.1 ± 0.8	4.5 ± 2.1	6.2 ± 2.8	8.9 ± 2.8
– diameter (mm)	–	15.9 ± 5.7	27.7 ± 12.4	41.3 ± 10.1	51.2 ± 20.6
– rooting depth (cm)	–	36.2 ± 13.8	46.1 ± 10.8	57.4 ± 15.5	61.4 ± 19.4
– number of lateral roots (pcs)	–	2.9 ± 0.9	3.8 ± 1.3	3.2 ± 0.6	4.1 ± 1.1
– diameter of lateral roots (mm)	–	5.1 ± 1.2	9.3 ± 4.4	14.5 ± 4.6	16.2 ± 7.0

Table 2 to be continued

Parameters, traits	Stand designation				
	10	20	30	60	80
All anchors					
– number (pcs)	5.3 ± 2.1	6.7 ± 1.4	11.9 ± 4.3	14.4 ± 2.1	16.1 ± 2.8
– diameter (mm)	13.9 ± 4.2	29.2 ± 9.3	46.9 ± 24.4	66.5 ± 30.3	71.6 ± 38.1
– number of lateral roots (pcs)	4.1 ± 0.7	10.9 ± 1.2	12.8 ± 1.3	11.8 ± 1.1	14.6 ± 1.0
Ip values					
– Ip of the whole root system	4.3 ± 1.0	14.4 ± 3.8	24.2 ± 6.8	35.8 ± 3.5	41.2 ± 4.2
– Ip of all horizontal roots	1.5 ± 1.1	5.5 ± 1.3	8.6 ± 2.7	9.9 ± 1.5	7.5 ± 2.1
– Ip of all perpendicular anchors from the base	1.1 ± 0.2	5.1 ± 2.1	7.0 ± 3.5	7.6 ± 0.1	9.0 ± 5.3
– Ip of all slant anchors from the base	1.7 ± 0.8	2.7 ± 0.8	6.4 ± 2.0	14.5 ± 5.9	15.6 ± 4.1
– Ip of all anchors from HSR	–	1.1 ± 0.9	2.2 ± 1.4	3.8 ± 1.9	9.1 ± 2.8
Root rots (% of trees)	0	0	0	0	0
Infestation of roots by biotic agents (% of trees)	0	0	0	0	0
Volume of fine roots					
– from horizontal roots (in % of the whole root system)	ND ²	45, 52	ND	ND	32, 36
– from anchors (in % of the whole root system)	ND	55, 48	ND	ND	68, 64
– whole root system (100 % = stand age 20)	ND	100, 100	ND	ND	520, 560

¹HSR – horizontal skeletal roots, ²ND – not detected, all values in which no significant difference was detected as compared with Stand 80 being in bold case

non-skeletal roots balance out in the root network. If we should evaluate the two types of roots at the same time, we would find out that no significant differences were found from the twenty years of the stand age in their numbers or in the number of lateral roots shooting from them (in other parameters, the roots could not be evaluated because of their different diameters and lengths).

Perpendicular anchors from the stem base. All analysed trees developed the almost identical number of anchors from the stem base. Although their number was slightly increasing with the increasing age, the differences were insignificant from the age of 30 years. However, the increasing stand age was markedly reflected in their increasing diameter; the differences in diameter were no more significant from the stand age of 60 years. From the age of twenty years, the average rooting depth reached to ca 1 m and detected differences were insignificant. The greatest rooting depth (the analyses included only the deepest reaching root of each tree) was different though; the largest rooting depth was growing with the increasing age of stands and reached 150 cm in the stand aged 80 years. There were short lateral, mostly slant roots shooting from the per-

pendicular anchors; in spite of the fact that no significant differences were detected in their number from the stand age of twenty years, their diameter was increasing with the increasing stand age.

Slant anchors from the stem base. All analysed trees developed almost the identical number of slant anchors from the base; the differences were insignificant from the stand age of 30 years. Nevertheless, their diameter and depth was increasing with the increasing stand age as well as the number and diameter of lateral roots shooting from them.

Anchors from horizontal skeletal roots. The number, diameter and rooting depth of anchors shooting from horizontal skeletal roots were markedly increasing with the increasing stand age. Although no larger difference in the number of lateral roots growing from them was detected (differences became insignificant from the age of 30 years), their diameter was markedly increasing with the increasing age.

All anchors. Similarly like horizontal roots, anchors also balanced out in the root system architecture. Evaluating all anchors together (in parameters that can be assessed together), we concluded that the number and diameter of anchors and the number of

lateral roots shooting from the anchors were significantly increasing with the increasing stand age.

Ip values. An exact view on the root system architecture in the analysed stands can be obtained also by Ip values. Ip of the whole root system markedly grows with the increasing stand age (the assessment included all roots in the root system). Ip of all horizontal roots was slightly growing until the stand age of twenty years (the assessment included only all horizontal roots); the differences were however no more significant from the stand age of thirty years. This indicates that the share of horizontal roots in the Ip value of the whole root system decreases with the increasing stand age because the value was about 35% at the stand age of up to thirty years, 27% at the age of sixty years and only 18% in stands aged 80 years. A similar pattern was shown by the perpendicular anchors from the stem base in which the difference in Ip values was insignificant up to thirty years of stand age with their absolute values being similar to the values of all horizontal roots and their share in the Ip values of the whole root system being therefore similar. The Ip values of the whole root system increasing with the growing age of stands resulted from the markedly increasing Ip values of slant anchors from the stem base (whose share in the Ip value of the whole root system was 26% at the age of thirty years, 40% at the age of sixty years and 37% at the age of eighty years) and anchors from the horizontal skeletal roots (whose share in the Ip value of the whole root system was 9% at the age of thirty years, 10% at the age of sixty years and 22% at the age of eighty years of the stands).

Root system injury. Root rots, the occurrence of honey fungus or other biotic agents were not observed in any of the analysed trees.

Volume of fine roots. Fine roots shoot from all horizontal and anchor roots. Because of the high consumption of manpower (complete root systems were analysed), fine roots were determined only in two trees in 20-year old stands and in two trees in the stand aged 80 years. The analyses revealed that at the age of eighty years, a tree has by about 5.2 times more fine roots than a tree aged twenty years. This indicates that the share of fine roots increases with the increasing stand age more than the share of the whole root system (Ip values of the whole root system were by 2.8 times higher at the age of eighty years than at the age of twenty years). Trees aged 20 years had ca 50% of the volume of fine roots on the horizontal roots and the same proportion on the anchors. At the age of 80 years, ca 35% of the fine root volume occurred on the horizontal roots and ca 65% of the fine root volume occurred on the anchors.

DISCUSSION

The root system anchors the tree in the soil, absorbs water and nutrients and serves for the storage of carbohydrates. Its type, size and efficiency are conclusive for the competitive potential of individual trees and for the success of the tree species in the given environment. Knowledge of the root system structure and development is vital for understanding ecological requirements of individual forest tree species (EIS 1974). In spite of the fact that the initial evolution of each root system is controlled genetically, with the increasing age its architecture is increasingly determined by soil characteristics, root competition and social status of trees. As the root system provides for the interconnection between the tree and the soil, it is necessary to know for the forest management how the soil can influence the root system since the root system size and shape reflect not only in the production but also in the stability of trees and entire forest stands. However, the response of the Douglas fir root system to soil conditions has not been perfectly known so far (CURT et al. 2001). ŠIKA et al. (1988) claimed that Douglas fir should be grown in the Czech Republic on mesotrophic sites of fresh hornbeam-oak up to fir-beech woods and this is why stands on fertile sites (mostly growing on Haplic Cambisols) were chosen for our analyses of root systems.

Most tree species establish a taproot at the juvenile stage of their evolution (BOLTE et al. 2003), which maintains its dominant position during the life of the tree or is overgrown by lateral roots. In Douglas fir, the taproot remains preserved only in the first years and disappears after the tenth year of the tree life (HENGST 1958). However, ČERMÁK and NADĚŽDINA (2009) described a taproot in a Douglas fir of DBH 38.6 cm, which reached a depth of 1.7 m and the authors deduced from its diameter and growth direction that it would have reached even deeper. EIS (1963) found out by the analysis of stumps of Douglas firs aged 31–102 years that all trees used to have originally a well-developed taproot, which had grown rapidly in the first years and reached 50% and 90% of its final depth at the age of 3–5 and 6–8 years, respectively. According to the author, the taproot was surprisingly longer in shallow stony soils than in deep permeable soils. Exactly, even on the deep soils the taproot was splitting close to its base into several branches of more or less equable diameter, which retained their positively geotropic character. Their growth was however usually slower than that of non-split taproots. The analysed stands grew on deep soils without skeleton and none of the analysed root systems exhibited a

taproot. McMINN (1963) reported the occurrence of the taproot as a juvenile form of the root system in the suppressed trees aged 30–40 years whose root systems showed only low branching. The trees analysed by us were in the main level, which may be another reason to explain why we did not find a taproot in any of them. Yet another reason for the absence of the taproot may be the fact that the analysed stands originated from artificial regeneration in which the mechanical pruning of roots gives rise to the development of substitute taproots; however, taproots were not found even by analysing root systems of trees from natural regeneration (MAUER, PALÁTOVÁ 2010).

The penetration of Douglas fir roots into depth is affected primarily by soil structure and texture. According to HERMANN (2005), the species root system usually reaches a depth of 60–100 cm on loose soils with favourable water regime on which the trees analysed by us occurred. On the other hand, SMITH (1964) recorded a rooting depth of 182 cm in coastal Douglas fir. In vertical direction, Douglas fir occupies the available space with perpendicular and slant anchors shooting from the stem base relatively early and according to EIS (1974) it reaches the final configuration of the root system at about 10 years. Analysing root systems in a time series in identical habitats we observed that the average rooting depth of perpendicular anchors from the base reached 60% at the age of 10 years and from 20 years of age it did not change any more. In spite of this, we identified one perpendicular anchor in each tree, which grew further into depth and at the age of 60 years it was 1.5 times longer than at 20 years with further growth to be expected in the next years. This type of root, reaching into a depth larger than 1.7 m, was observed by ČERMÁK and NADĚŽDINA (2009), who denoted it as a taproot. Slant anchors from the stem base and anchors from horizontal skeletal roots extend their growth with the increasing age. CURT et al. (2001) recorded on Cambisol without obstacles (the same soil type as that on which the trees analysed by us occurred) a rooting depth to ca 120 cm in Douglas firs aged 30–40 years with the density of roots decreasing at a greater depth. This rooting depth fully corresponds with results of our analyses of the stands of equable age. In line with KÖSTLER et al. (1968), we can state that the share of vertically growing roots in the total mass of the root system was higher than the share of horizontally growing roots. The difference increases with the increasing age and in these habitats, the Douglas fir develops a deep-reaching root system.

The root system starts expanding in the horizontal direction upon the taproot branching, which occurs already in the first and second year of growth (EIS 1987). The number of main lateral roots (horizontal skeletal roots) of trees analysed by us did not change significantly with age and corresponded to the range of 3–8 lateral roots mentioned by EIS (1974). HALTER and CHANWAY (1993) found eight lateral roots in planted Douglas firs aged 11 years while the number of lateral roots in trees of the same age from natural regeneration was higher.

In the 80-years-old stand analysed by us, the horizontal skeletal roots reached to a distance of ca 170 cm from the stem while McMINN (1963) observed in a 10-years-old stand and in a 25-years-old stand the average maximum reach of roots with diameters > 1 cm 0.4 m and 2.5 m, respectively. Similarly like McMINN (1963), we found out that the length of horizontal roots did not reach beyond the crown projection. Nevertheless, in each tree we recorded one or two roots reaching beyond the crown projection. According to HENGST (1958), such a pattern of roots might signal adaptation to the conditions of nutrition. On poor sandy soils where humus-rich mounds were created, the author detected part of roots penetrating to a distance of 1.5–2.5 m beyond the crown projection. The trees analysed by us occurred on a homogeneous fertile site and the reason for their greater length of roots and set growth direction was apparently different and remained hidden to us. ČERMÁK and NADĚŽDINA (2009) also found horizontal roots reaching to a distance of 6 m from the stem in a tree with DBH 38.6 cm.

The distribution of horizontal skeletal roots in the trees analysed by us was not entirely regular but was not connected with crown asymmetry or vicinity of other trees, which is in agreement with the conclusions of EIS (1974). The network of horizontal roots includes also non-skeletal roots, which fill the space among the horizontal skeletal roots. Assessing the distribution pattern of these two types of horizontal roots together, we find out that the distribution of horizontal roots is nearly regular.

Anchors establish on the horizontal skeletal roots and in vertical direction, the root system is complemented with slant anchors. Some horizontal skeletal roots suddenly change their growth direction in an “elbow-pipe” manner from horizontal to positively geotropic (changing into anchors). Then, a new horizontally growing skeletal root develops on the upper part of the elbow turn, which further continues in the growth direction of the original root. The horizontal root diameter before the elbow turn

(before the anchor) is substantially larger than behind the turn while the diameter of the horizontal root before the turn (before the anchor) is identical to the diameter of the anchor. New slant anchors do not shoot from the stem base but rather from the upper part of the already developed anchor and rapidly turn to the positively geotropic growth direction. The original anchor and the newly developed anchor grow near each other.

A species-specific type of root system develops through the gradual branching and growth of roots. Most authors who analysed root systems both overseas (McMINN 1963; SMITH 1964; EIS 1974) and in Europe (KÖSTLER et al. 1968) agreed that Douglas fir develops a heart-shaped root system with hemispherical branching pattern under the stump. In our analyses, we did not find out the vertically growing roots (anchors) to turn beneath the stem axis but rather to grow in positive geotropic direction (in parallel and at a short distance from the stem). Regarding the fact that their lateral branches are relatively short, the root system does not form a hemisphere but rather a cylinder. Therefore, the developed root system can be denoted as the root system of substitute taproots and anchors. In his classification of root systems, HENGST (1958) ranked the root system of Douglas fir between the heart-shaped and flat root systems because he observed two more or less distinctly separated circles of main roots on Douglas fir root systems. The upper circle, formed of initially large-diameter oval roots, spread near the soil surface and reached to the crown perimeter. Roots of the inner circle were inclined downwards and branched soon. It follows from our research that the maximum depth at which some horizontal skeletal roots grow is considerably greater than the thickness of humus horizons – these roots grow slightly inclined downwards. If we assess the rooting depth of these roots at their tip, we may have an impression that they grow in two horizontal planes. The reason is that some horizontal roots begin to turn and reach a greater rooting depth already at a short distance from the stem; however, very frequent is the incidence of elbow-shaped roots that after the second turn grow horizontally in lower soil layers.

As to the uptake of water and nutrients, most important are the fine roots. As mentioned by KÖSTLER et al. (1968), the penetration of fine roots is very intensive. Fine roots develop not only on the horizontal roots but also on all vertical roots. The abundance of fine roots at a relatively short length of structural roots in the root system is made possible by the fact that the fine roots grow out in peculiar small tufts (resembling vine grapes). The tufts grow

not only on end roots but also they shoot from very thick primary horizontal roots or anchors.

CONCLUSIONS

The paper brings an analysis of the root system development of newly established Douglas fir stands at the age of 10, 20, 30, 60 and 80 years on aerated soils (Cambisols) without skeleton. Root systems were lifted manually using the archaeological method and at least 6 trees were analysed in each stand. Measured parameters of the root systems were compared statistically. Main conclusions derived from the comparison of partial analyses are as follows:

- on the given sites, Douglas fir develops a nearly uniform, deep-reaching system of substitute taproots and anchors with a high potential to ensure the good mechanical stability of the tree as well as its resistance to sudden changes in the upper soil horizons;
- horizontal skeletal roots and horizontal non-skeletal roots create a regular network of horizontal roots (maximum angle up to 70 degrees); from 20 years of the stand age, no significant differences exist in their total number or in the number of lateral roots shooting from them;
- with the increasing age, the number and the diameter of perpendicular and slant anchors shooting from the stem base and anchors shooting from horizontal skeletal roots as well as the number of lateral roots shooting from them are increasing;
- with the increasing age, the size of the root system as a whole is markedly increasing as compared with the aboveground part of the tree (Ip increasing from 4.3 to 41.2). However, the share of horizontal skeletal roots and perpendicular anchors from the stem base in the root system size is decreasing with the increasing age while the share of slant anchors from the stem base and perpendicular anchors from the horizontal skeletal roots is increasing;
- fine roots: grow on all roots; with the increasing age, a greater volume of fine roots is recorded on anchors (ca 60%) than on horizontal roots (ca 40%); the fine roots grow in tufts;
- no root rots and stem base rots or infestation by biotic agents were observed.

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Corresponding author:

Doc. EVA PALÁTOVÁ, Ph.D., Mendel University in Brno, Faculty of Forestry and Wood Technology, Department of Forest Establishment and Silviculture, Zemědělská 3, 613 00 Brno, Czech Republic
e-mail: evapal@mendelu.cz
