Comparison of the root system architecture between windthrown and undamaged spruces growing in poorly drained sites

P. Štofko, M. Kodrík

Faculty of Forestry, Technical University in Zvolen, Zvolen, Slovakia

ABSTRACT: In the locality Hnilé Blatá (High Tatras Mts.) the parameters of root plates and the number, length and diameter of the individual root branches in windthrows and standing Norway spruces (*Picea abies* [L.] Karst.) were measured. Individual root branches were classified to 12 diameter classes according to their diameter measured in the middle of the root branch length. Using random sampling, 21 windthrows were selected. In their neighbourhood, another 21 undamaged trees were selected on the basis of their similarity in aboveground parameters and they were uprooted by a tractor winch. We found out significantly higher mean values of the vertical radius, the average width and theoretical surface of root plates in undamaged spruces. Mean values of root branch frequency in the first six diameter classes (up to 6 cm) were higher in undamaged spruces, but mean values of root branch frequency in the last five diameter classes (12.1–30.0 cm) were higher in windthrows. Mean values of the root branch length in the first six diameter classes were higher in undamaged spruces. Similarly, mean values of the total root branch length were higher in the first six diameter classes in undamaged spruces, but the mean values of the total root branch length were higher in the last six diameter classes (9.1–30.0 cm) in windthrows.

Keywords: Norway spruce; stability; root system; windthrow

Wind damage of forest stands belongs to actual problems of forest protection. In general, the following parameters of tree growth have the biggest influence on tree stability: proportions and character of the crown (width, length, shape), stem (height, diameter, habit and strength) and root system (depth, width and way of anchorage) (Konôpka 1978). In Slovakia, the wind effect on the stability of spruce was investigated by Kodrík and Konôpka. But the majority of the papers has studied the aboveground parts of trees and the question of root systems has been studied less. Besides, the problem has been studied to a lesser extent in poorly drained sites characterized by specific soil properties which influence the root development.

Kodrík (1998) reported the groundwater level to have the highest influence on the root system formation. Köstler et al. (1968) stated that the spruce formed an extremely shallow root system in poorly drained sites. According to Konôpka (2003) the roots need not or cannot penetrate through deeper soil horizons and a shallow and unstable root system is formed. Similarly, Polomski and Kuhn (2001) reported that forest stands in poorly drained sites were threatened mainly by wind. Ray and Nicoll (1998) tested the stability on 46-years-old Sitka spruce trees growing on gleyed soils. Their results indicated that intensive drainage of peaty gleys would increase the rooting depth and resistance to overturning. Similarly, Nicoll et al. (2006) found out that the anchorage of Sitka spruce was the strongest on peat and the poorest on gleyed mineral soil and a deep rooting increased the critical turning moments by 10–15% compared with the trees of equivalent mass with

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shallower roots. Stokes et al. (1996) mentioned that the depth and length of roots in the soil were dominant factors influencing pull-out resistance. Coutts et al. (1999) concluded that the values of root-soil plate area decreased with increasing values of the root-soil plate depth. Cucchi et al. (2003) found out that the linear regression analyses between critical bending moment and (H × dbh^2), with regard to soil conditions, showed no significant differences in uprooting resistance between the trees growing on wet lands and those growing on dry lands. Fourcaud et al. (2003) studied the mechanical structure of root system in 50-years-old maritime pine (*Pinus pinaster* Ait). Their results show that root architecture may explain a half of the sensitivity to uprooting.

In Slovakia an extensive research of the tree root system has been done by Kodrík (2002), who investigated root systems of the main forest trees in terms of static stability. Konôpka (2001, 2002) compared the root systems of trees with respect to soil drainage. Kodrík (2005) analyzed the root biomass of forest trees in view of productive ecology.

The belowground biomass inventory methods were comprehensively described by Köstler et al. (1968), Kolesnikov (1972), Böhm (1979) and recently by Smit et al. (2000). For rough root research of trees, the excavation method is the most common when roots are exposed from the soil by digging. The use of trees which are naturally uprooted from the soil, e.g. by wind or by winch, is also effective.

MATERIAL AND METHODS

The belowground parts were measured on Norway spruces in the locality Hnilé Blatá (the High Tatras Mts.). This site is uneven-aged, with the overstorey 90 years old, southern exposure, 5–10% slope, altitude is about 950 m a.s.l. The management set of forest type is waterlogged fir-spruce stand. The site consists of the following forest types: peaty fir-spruce (50%) that belongs to the group of forest type *Abieto-Piceetum*, birch-alder on fluvio-glacial (40%) that belongs to the group of forest type *Betuleto-Alnetum* and bilberry-spruce with fir (10%) that belongs to the group of forest type *Piceetum abietinum* higher stage (Križová 1995). The spruce is a dominant tree species in the site, but the birch and alder are also quite abundant. The soil is rather sloppy with a low incidence of peats.

At first, the aboveground parameters of static stability were measured in windthrown spruces. In their neighbourhood, the aboveground parameters of undamaged spruces were measured. We compared differences in the aboveground parameter between windthrows and undamaged spruces growing in this locality. No significant differences in the aboveground parameters were found out between windthrows and undamaged spruces. The results of this research were published by Štofko (2006). Because we did not find any differences in the aboveground parts, we decided to analyze the architecture of the root systems of spruces growing in this locality.

Altogether, 21 windthrown spruces were selected. These windthrown spruces were scattered in the stand. In their neighbourhood, one undamaged tree to each windthrow was selected on the basis of its similarity in the aboveground parameters and they were uprooted by a tractor winch. These selected stand-up spruces were overturned in the same direction as the windthrown spruces (in the direction of blowing wind).

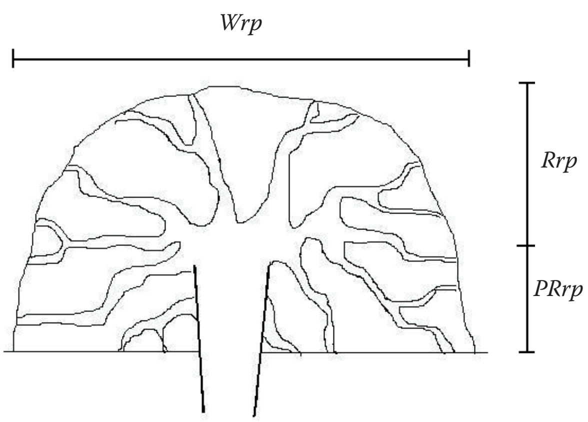

Fig. 1. Measurement of the root-soil plate: width of root plate (*Wrp*), distance from the stem centre to the windward edge (*Rrp*), distance from the stem centre to the hinge (*PRrp*)

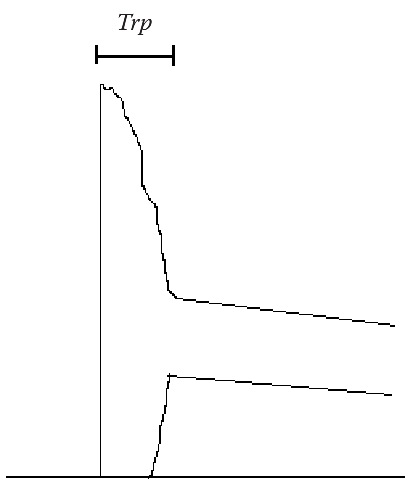

Fig. 2. Measurement of the root-soil plate thickness across the plate (*Trp*)

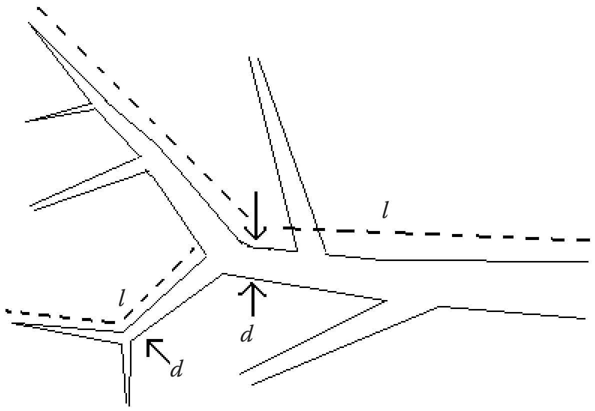

Fig. 3. Measurement of diameter (*d*) and length (*l*) of individual root branches

For the belowground biomass the following parameters were measured: horizontal width of the root plate (*Wrp*), vertical radius of the root plate (*Rrp*), partial vertical radius of the root plate (*PRrp*) and thickness of the root plate (*Trp*) (see Figs. 1 and 2). The average width of root plate (*AWrp*) was calculated according to the formula: $AWrp = (Wrp + 2\ Rrp)/2$. The theoretical surface of the root plate was calculated according to the formula: $St = \pi(AWrp/2)^2$ and the root plate surface of measured root branches was calculated according to the formula: $Smrb = (\pi(AWrp/2)^2)/2 + Wrp \times PRrp$. The mean values of all belowground biomass characteristics were calculated. The mean values of root plate parameters were compared between the windthrows and undamaged spruces by Student's *t*-test. The correlation analysis was used to evaluate the relationships between root plate parameters.

The root plates of analyzed spruces were cleaned of soil with hand tools. After cleaning the root plates, the parameters of root branches were measured. The number, the length and the diameter of individual root branches were measured according to Fig. 3. The individual root branch is defined as the strongest continual root branch from which the other individual root branches are forked. The length of indi-

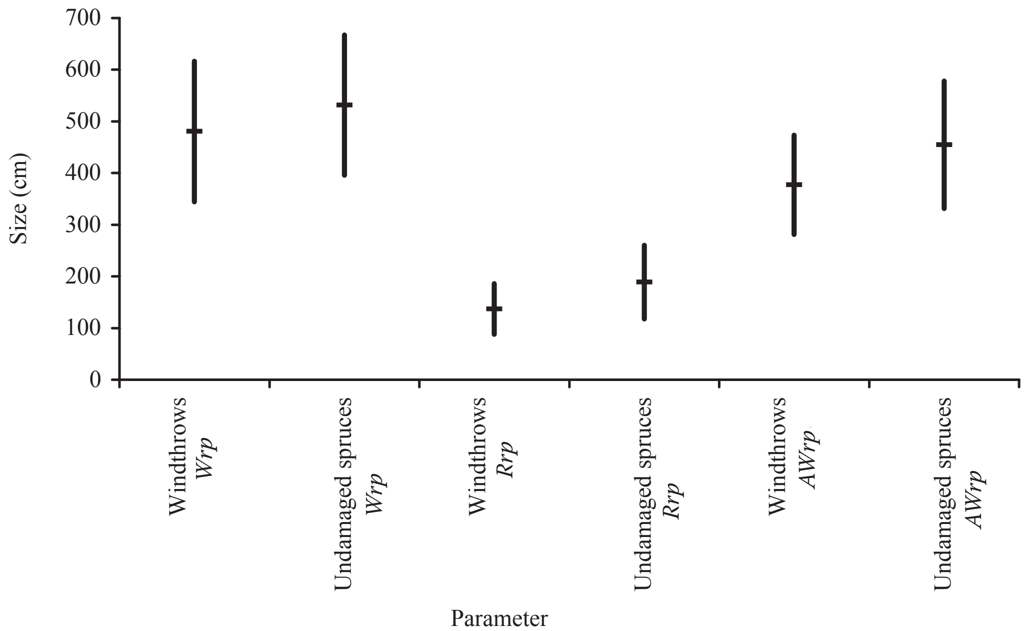

Fig. 4. Comparison of root plate parameters of uprooted and undamaged trees (mean value ± standard deviation)

Table 1. Comparison of aboveground parameters of uprooted and undamaged spruces (mean value ± standard deviation)

Parameter	Stem diameter at breast height* dbh (cm)	Tree height *H* (m)	Crown length *L* (m)	Crown proportion index $Cpi = (L/H) \times 100$ (%)
Windthrows	31.29 ± 6.32	22.38 ± 1.79	16.04 ± 2.81	71.69 ± 8.31
Undamaged spruces	31.00 ± 6.62	22.71 ± 2.36	16.55 ± 3.17	72.83 ± 10.27

*measured at 130 cm from the ground level vidual root branches was measured as a real distance from the point where the root branch is emerging from the other root branch up to the tip of the root branch. Individual root branches were classified to twelve diameter classes according to their diameter measured in the middle of the root branch length: 0.2–1.0 cm, 1.1–2.0 cm, 2.1–3.0 cm, 3.1–4.0 cm, 4.1–5.0 cm, 5.1–6.0 cm, 6.1–9.0 cm, 9.1–12.0 cm, 12.1–15.0 cm, 15.1–20.0 cm, 20.1–25.0 cm and 25.1–30.0 cm. The number and length of individual root branches in the first diameter class (0.2–1.0 cm) were estimated only so these data are only approximate. Mean values of the number and length of root branches were calculated in each diameter class. Mean values of the number and length of root branches in each root diameter class were compared between the windthrows and undamaged spruces.

RESULTS

The mean values of aboveground parameters of analyzed spruces are shown in Table 1. Because we selected undamaged spruces on the basis of their similarity in aboveground windthrow parameters, the mean values of aboveground parameters for windthrows and undamaged spruces are almost the same and the differences are statistically insignificant.

The mean values of root plate parameters are shown in Table 2 and Fig. 4. We found out considerable differences in root plate parameters between windthrows and undamaged spruces. Mean value of *Wrp* in windthrows was 480 cm and in undamaged spruces it was 531 cm. Mean value of *Rrp* in windthrows was 137 cm and in undamaged spruces it was 189 cm while these differences were statistically significant tested on a 5% significance level. Mean values of *PRrp* in windthrows and undamaged spruces were almost identical. We found out small differences in mean values of *Trp* between windthrows and undamaged spruces. Mean value of *Trp* in windthrown spruces was 28.62 cm and in undamaged spruces it was 29.57 cm, but the differences were not significant. We found out a significant difference in *AWrp* between windthrows and undamaged spruces. Mean value of *AWrp* in windthrows was 377 cm and in undamaged spruces it was 455 cm. Mean value of the theoretical surface of root plate was considerably smaller in windthrown spruces (11.89 m^2). Mean value of *St* was 17.43 m^2 in undamaged spruces. These differences were statistically significant. Mean value of the surface of measured root branches was 9.30 m^2 in windthrows and 12.54 m^2 in undamaged spruces.

Table 2. Comparison of root plate parameters of uprooted and undamaged trees (mean value ± standard deviation)

Parameter	Width of root plate *Wrp* (cm)	Radius of root plate *Rrp* (cm)	Partial radius of root plate *PRrp* (cm)	Thickness of root plate *Trp* (cm)	Average width of root plate *AWrp* (cm)	Theoretical surface of root plate *St* (m^2)	Surface of measured root branches *Smrb* (m^2)
Windthrows	480.48 ± 135.77	136.90 ± 48.73	68.10 ± 27.80	28.62 ± 4.99	377.14 ± 96.00	11.89 ± 5.97	9.30 ± 4.36
Undamaged spruces	531.43 ± 135.66	189.05 ± 71.14*	67.86 ± 31.11	29.57 ± 3.35	454.76 ± 123.3*	17.43 ± 9.78*	12.54 ± 6.29

*statistically significant difference (tested on a 5% significance level)

Table 3. Values of correlation coefficients of linear dependence between root plate parameters

Parameter	Windthrows			Undamaged spruces		
	Wrp	*Rrp*	*Trp*	*Wrp*	*Rrp*	*Trp*
Wrp	1			1		
Rrp	0.337	1		0.576*	1	
Trp	–0.156	–0.151	1	0.068	0.021	1

*statistically significant correlation coefficient tested on a 95% level of confidence probability

The values of correlation coefficients between individual root plate parameters are shown in Table 3. We found out a higher degree of significant correlation only between the width of root plate and the vertical radius of root plate in undamaged spruces. No correlation was found out between the thickness of root plates and the width and vertical radius of root plates. The graphical representations of 3-dimensional linear correlations between individual root plate parameters are shown in Figs. 5 and 6. After insertion of linear plane into the graphs it is apparent that the values of root plate thickness decrease with increasing values of root plate radius. The values of root plate thickness increase with decreasing values of root plate width in windthrows. On the other hand, the values of root plate thickness decrease with decreasing values of root plate width in undamaged spruces.

Mean values of the length and frequency of root branches according to particular diameter classes are shown in Table 4. Mean values of root branch frequency of the first six diameter classes are higher in undamaged spruces except for the second diameter class (1.1–2.0 cm) (Figs. 7 and 8). Interestingly, mean value of root branch number was smaller in the second diameter class in undamaged spruces, but the mean value of root branch length was higher in this diameter class in undamaged spruces. Relatively low values of root branch frequency were found out in the highest diameter classes. It is interesting that the mean values of root branch frequency in the last five diameter classes are higher in windthrows. Mean values of root branch length in the first six diameter classes are higher in undamaged spruces except for the first diameter class. Similarly, mean values of the total root branch

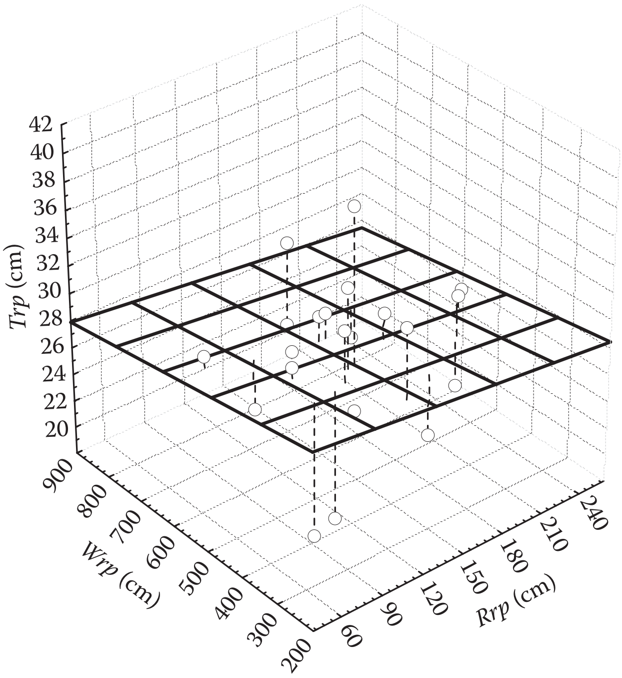

Fig. 5. Representation of 3-dimensional linear correlation between the width of root plates (*Wrp*), radius of root plates (*Rrp*) and thickness of root plates (*Trp*) in windthrows

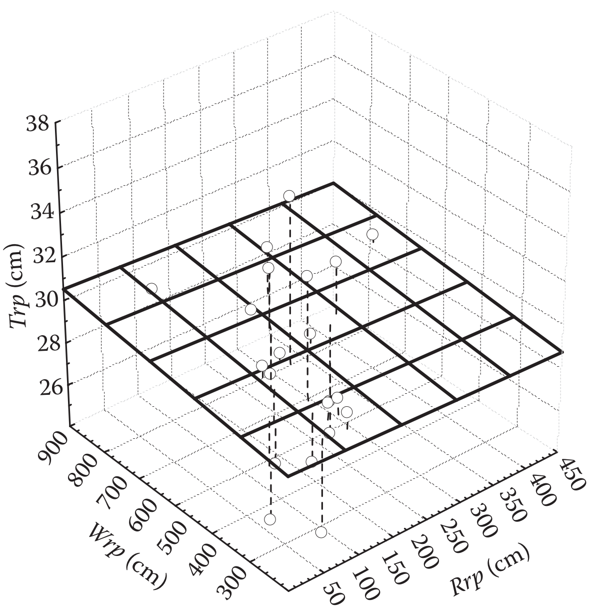

Fig. 6. Representation of 3-dimensional linear correlation between the width of root plates (*Wrp*), radius of root plates (*Rrp*) and thickness of root plates (*Trp*) in undamaged spruces

Table 4. Mean values of frequency and length of root branches according to individual diameter classes in windthrows and undamaged spruces

Diameter class (cm)	0.2–1.0	1.1–2.0	2.1–3.0	3.1–4.0	4.1–5.0	5.1–6.0	6.1–9.0	9.1–12.0	12.1–15.0	15.1–20.0	20.1–25.0	25.1–30.0
Windthrows												
n (p)[1]	226.00	39.18	16.00	5.82	4.18	2.09	3.36	1.82	0.82	1.09	0.64	0.27
n (%)[2]	75.02	13.01	5.31	1.93	1.39	0.69	1.12	0.60	0.27	0.36	0.21	0.09
n without 0.2–1.0 (%)[3]	–	52.05	21.26	7.73	5.56	2.78	4.47	2.42	1.09	1.45	0.85	0.36
l (cm)[4]	36.43	75.88	99.47	94.19	134.34	113.87	172.28	152.92	96.67	165.50	165.50	156.00
$n \times l$ (cm)[5]	8,232.86	2,973.12	1,591.52	548.01	561.79	238.09	579.48	278.03	79.09	180.55	105.32	42.55
Undamaged spruces												
n (p)[1]	449.09	34.73	19.55	7.09	4.45	2.36	3.36	1.18	0.64	0.36	0.18	0.09
n (%)[2]	85.85	6.64	3.74	1.36	0.85	0.45	0.64	0.23	0.12	0.07	0.03	0.02
n without 0.2–1.0 (%)[3]	–	46.93	26.41	9.58	6.02	3.19	4.55	1.60	0.86	0.49	0.25	0.12
l (cm)[4]	28.86	90.61	109.54	120.85	157.43	195.50	108.33	167.00	122.50	172.00	169.50	143.00
$n \times l$ (cm)[5]	12,962.40	3,146.74	2,140.95	856.94	701.29	462.09	364.39	197.36	77.95	62.55	30.73	13.00

[1]average number of root branches, [2]relative average number of root branches, [3]relative average number of root branches without the first root diameter class, [4]average length of root branches, [5]total average length of root branches

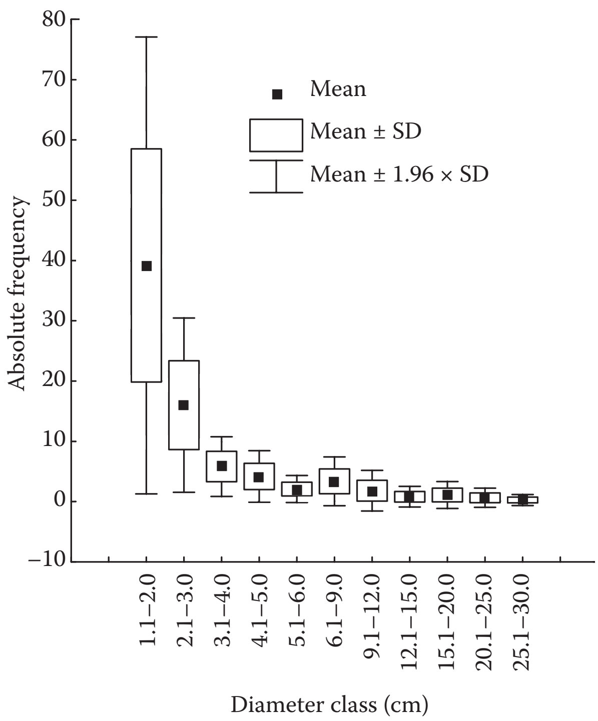

Fig. 7. Representation of average values of root branch frequency in individual diameter classes in windthrows

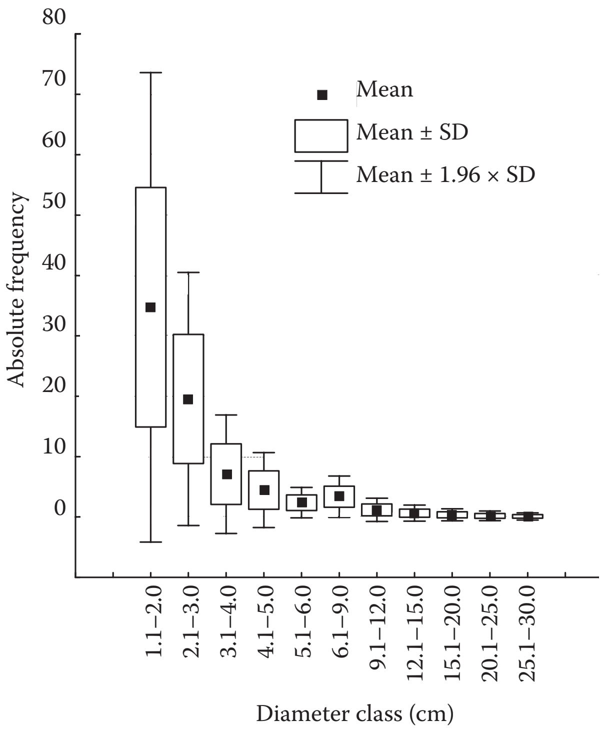

Fig. 8. Representation of average values of root branch frequency in individual diameter classes in undamaged spruces

length were higher in the first six diameter classes in undamaged spruces. On the other hand, the mean values of total root branch length were higher in the last six diameter classes in windthrows (Figs. 9 and 10). Mean value of the relative number of root branches in the first diameter class was higher in undamaged spruces (85% of total root number vs. 75% in windthrows). On the other hand, mean values of the relative number of root branches in the other diameter classes were higher in windthrows. Mean value of the relative number of root branches without the first diameter class was higher in the second diameter class in windthrows (52% vs. 47% in undamaged spruces). Mean values of the relative number of root branches without the first diameter class were higher in diameter classes 3.1 to 9.0 cm and lower in diameter classes 9.1–30.0 cm in undamaged spruces compared to windthrows.

DISCUSSION

We found out the extremely wide and shallow root plates of spruces growing in poorly drained sites. The mean value of root plate thickness was only 29 cm in windthrows. Similarly, Konôpka (2001, 2002) found out the wide and shallow root systems of Norway spruces growing in poorly drained sites in the High Tatras Mts. However, he found out deeper (mean value 45 cm) and narrower (mean value 315 cm) root plates. Similar results were obtained by Rottmann (1986), who claimed that permanently waterlogged sites do not allow tree roots to penetrate to deeper horizons due to insufficient oxidation. This type of shallow root system, even though broad, is unstable. Mattheck et al. (2003) reported that the smaller diameter of root plate led to a smaller amount of transmittable moments into the surrounding soil. Ray and Nicoll (1998) found out that the maximum resistive turning moment increased with plate thickness in Sitka spruce.

We observed significant differences in the radius of root plates between windthrows and undamaged spruces. These findings have obvious relevance to the understanding of the anchorage of shallow root system. Mean value of the root plate radius was by 52 cm higher in undamaged spruces. These observations suggest that the expansion of root plate width on the windward side increases the stability of spruces growing in poorly drained sites. Coutts (1983) suggested that the shear would begin at the edge of the rigid soil-root plate and move rapidly towards the centre as a tree started to overturn.

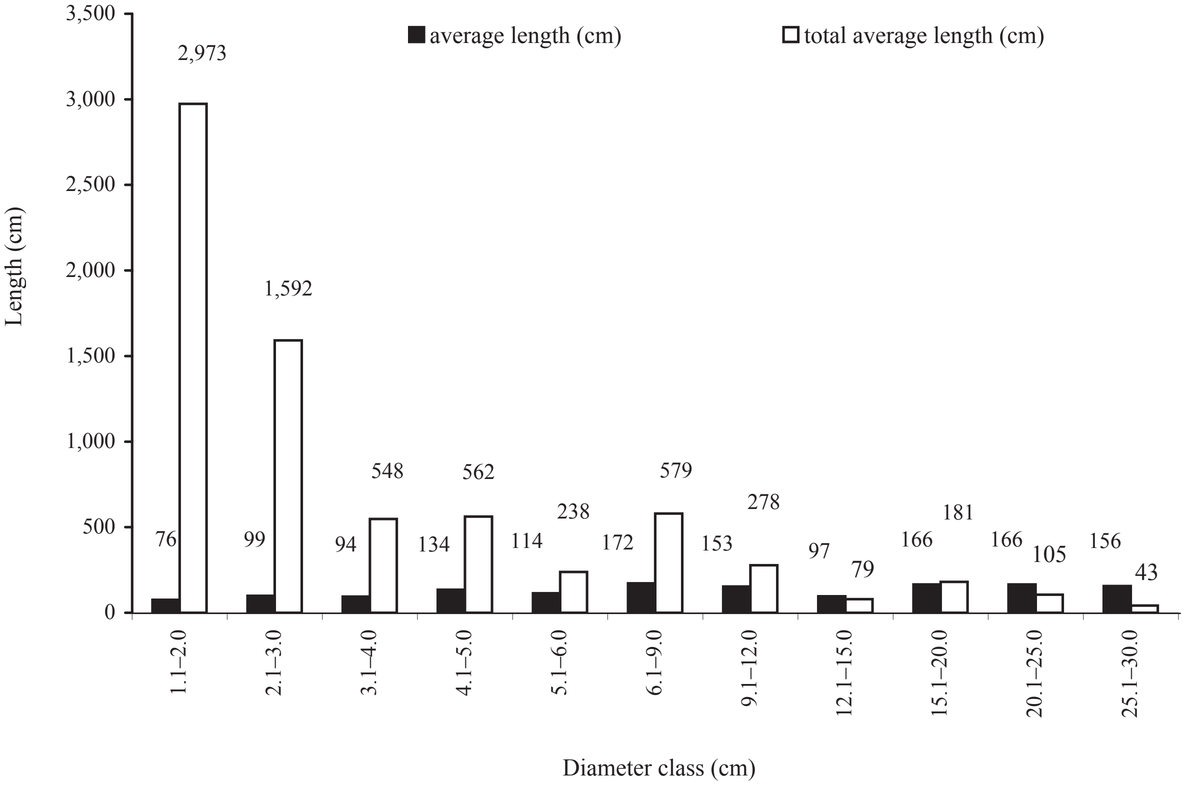

Fig. 9. Representation of average values of root branch lengths according to individual diameter classes in windthrows

In such a system the calculated turning moment to the fracture of the soil-root plate was six times greater than the observed turning moment of flexible plates. Measurements of soil displacement while the turning moment was applied to a thin, flexible soil-root plate showed that the soil sheared first under the plate close to the centre of the stem on the windward side, spreading quickly outwards towards the edge of the soil-root plate (Coutts 1983, 1986). Significant differences in the average width and theoretical surface of root plate are taken to mean that a large surface of shallow root plate, despite its shallowness, may support the stability of spruce. Smit et al. (2000) suggested that in plants which have a broad, spreading root system with many horizontal lateral roots and some vertical sinkers, three components of anchorage may be identified: the resistance of the leeward hinge to bending, the resistance of the windward side to uprooting and the weight of the root-soil plate. Significantly larger surface of root plates in undamaged spruces supports the concept that the weight of the root-soil plate is a very important component of anchorage of spruces growing in poorly drained sites.

Ray and Nicoll (1998) showed that anchorage in 46-years-old Sitka spruce was related to the rigidity of the plate, a factor which had an important effect on the resistance to failure in the soil. Rigidity also extends the distance from the stem to the point of bending on the lee side, conferring a mechanical advantage onto the root system. But we found out that the mean value of the partial radius of root plates in windthrows and in undamaged spruces was almost the same. These observations suggest that the rigidity of root plates in windthrows and in undamaged spruces was the same, as mean distances from the stem to the point of bending on the lee side were almost identical.

Interestingly, a significant correlation between the width and the radius of root plates in undamaged spruces may point out to the balanced parameters of root plates and can indicate the more symmetrical root plates in undamaged spruces. No correlation between the width and the thickness of root plates indicates that root plates of spruces growing in poorly drained sites spread only in the horizontal direction. Nicoll and Ray (1996) found a direct relationship between the root-soil plate area and depth in 46-years-old Sitka spruce on peaty gley soil, with the shallowest plates having the largest areas.

The results of comparison of the root branch structure suggest that the number and length of

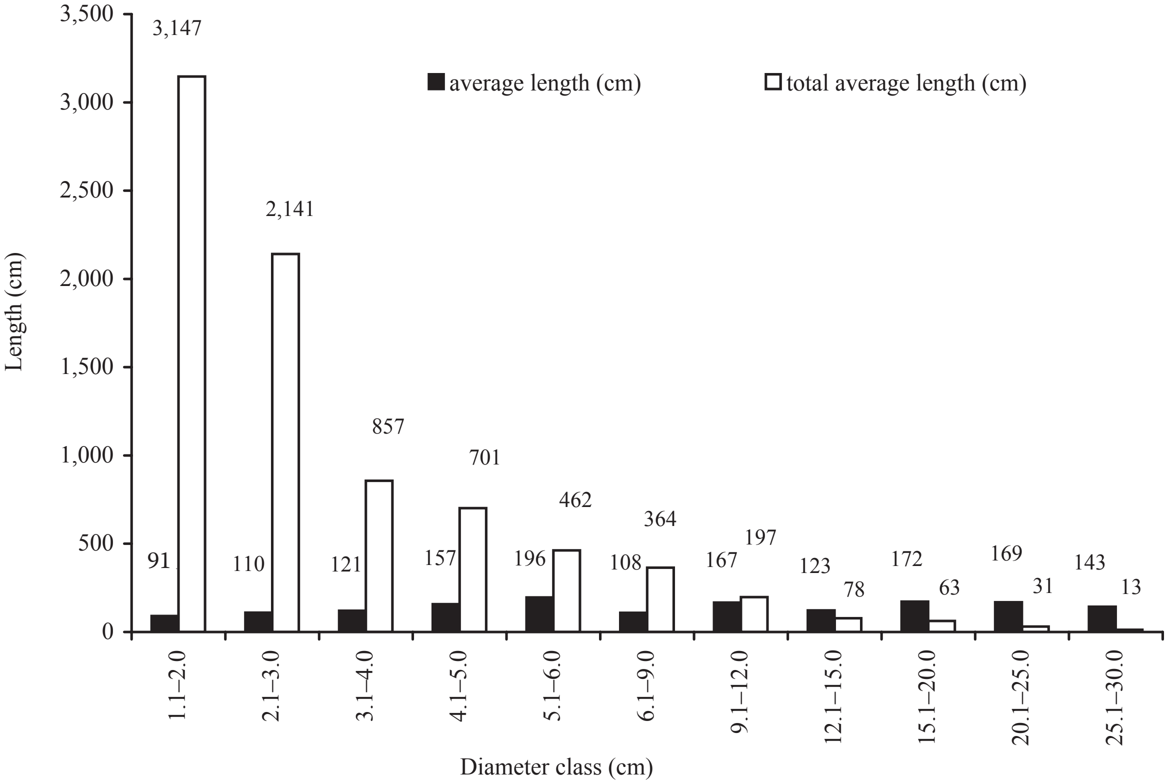

Fig. 10. Representation of average values of root branch lengths according to individual diameter classes in undamaged spruces

root branches up to the 6-cm root branch diameter has a major effect on stability of spruces growing in poorly drained sites. The higher number of root branches on the windward side corresponds to the results by Fourcaud et al. (2003). They reported that one of the structural features the resistance to uprooting depended on was a large windward network of roots. Kodrík and Kodrík (2002) stated that the number of roots 3–10 cm in diameter was an important factor of the tree static stability and that the roots over 10 cm in diameter were the most important for tree stability. Kodrík (2002) found out that the relative amount of roots below 3 cm in diameter was 59.5%, with diameter 3.1–9.0 cm it was 28% and with diameter over 10 cm it was only 12.5% of the total root number in windthrown spruces. He found out a different situation with standing spruces. In this case, the relative amount of roots with diameter below 3 cm was 46.6%, with diameter 3.1–9.0 cm it was 32.5% and with diameter over 10 cm it was 20.9% in Norway spruces growing in well-drained sites. It seems that his results are not usable in poorly drained sites. We found out almost the same relative amount of roots below 3 cm among windthrows and undamaged spruces. On the other hand, we found out a considerably smaller relative amount of roots over 10 cm in diameter of the total root number in undamaged spruces in comparison with windthrows. Fourcaud et al. (2003) reported that undamaged trees of maritime pine had more sinkers in the zone of rapid taper (ZRT) (25% of root volume vs. 17% in windthrows) and a larger East chuck (7% of root volume vs. 3.5% in windthrows).

We cannot exactly compare our results with the results of Sereda (1983), who stated that namely the fine roots several mm in diameter only formed a reinforced matrix and that they were important for static stability. We found out a higher amount of root branches in the first diameter class in undamaged spruces, but these observations are not quite accurate. However, such a rough estimate of the number of fine roots obtained in this way may support the results of Sereda and can give a certain view on the spruce root system architecture.

CONCLUSIONS

The results described here have pointed out the importance of the root plate size in relation to the stability of spruces growing in poorly drained sites. The width and the surface of spruce root plate are very important factors of spruce stability in waterlogged sites. Moreover, a large windward network of roots improves the anchorage of these spruces. In general, permanent water logging (high water table) negatively influences the root system depth of Norway spruce and the shallower the root system, the more susceptible the spruces to uprooting. Silvicultural measures (e.g. thinning) in spruce stands growing in poorly drained sites can probably improve the root system width and resistance to uprooting due to the support of the root plate expansion in horizontal direction.

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Porovnanie architektúry koreňových systémov medzi vetrom vyvrátenými a stojacimi smrekmi rastúcimi na podmáčaných stanovištiach

ABSTRAKT: V lokalite Hnilé Blatá (Vysoké Tatry) boli merané parametre koreňových balov ako aj počet, dĺžka a hrúbka jednotlivých koreňových vetiev na vetrom vyvrátených a stojacich smrekoch (*Picea abies* [L.] Karst.). Jednotlivé koreňové vetvy boli zatrieďované do dvanástich hrúbkových tried podľa ich hrúbky meranej v polovici dĺžky koreňovej vetvy. Náhodným výberom bolo vybratých 21 vetrom vyvrátených stromov. V ich susedstve bolo vybratých ďalších 21 stojacich smrekov na základe ich podobnosti v nadzemných parametroch a tie boli vyvrátené traktorovým navijakom. Zistili sme významne vyššie stredné hodnoty vertikálneho polomeru, priemernej šírky a teoretického povrchu koreňových balov pri stojacich smrekoch. Stredné hodnoty početností koreňových vetiev v prvých šiestich hrúbkových triedach (do hrúbky 6 cm) boli vyššie pri stojacich smrekoch, ale stredné hodnoty početností koreňových vetiev v posledných piatich hrúbkových triedach (12,1–30,0 cm) boli vyššie pri vetrom vyvrátených smrekoch. Stredné hodnoty dĺžok koreňových vetiev v prvých šiestich hrúbkových triedach boli vyššie pri nepoškodených smrekoch. Podobne stredné hodnoty celkovej dĺžky koreňových vetiev boli vyššie v prvých šiestich hrúbkových triedach pri stojacich smrekoch, ale stredné hodnoty celkovej dĺžky koreňových vetiev boli vyššie v posledných šiestich hrúbkových triedach (9,1–30,0 cm) pri vývratoch.

Kľúčové slová: smrek obyčajný; stabilita; koreňový systém; vývrat

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Corresponding author:

Ing. Peter Štofko, Technická univerzita vo Zvolene, Lesnícka fakulta, T. G. Masaryka 20, 960 53 Zvolen, Slovensko
tel.: + 421 455 206 257, fax: + 421 455 332 654, e-mail: stofko@vsld.tuzvo.sk

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