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Physiological aspects of European beech (*Fagus sylvatica* L.) health condition in Slovakia

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ABSTRACT: The health status of beech (*Fagus sylvatica* L.) in Slovakia has not developed positively in the past ten years. The health status has especially deteriorated in young beech stands originating from natural regeneration, whereby the beech forests of Central Slovakia are mostly affected. We measured the parameters of the fast kinetics of chlorophyll *a* fluorescence – F_0, F_m, F_v, F_v/F_m, T_m, Area on selected sample trees at two localities with different levels of pollution load during the vegetation seasons 1996 and 1997. Simultaneously, assimilatory organs were collected and the concentrations of chlorophylls *a* and *b* were determined spectrophotometrically. On the basis of the selected physiological and biochemical parameters (especially chlorophyll fluorescence parameters) we can observe a deteriorated physiological state of the young beech trees at the more polluted locality even at the stage of latent (hidden) damage.

Keywords: European beech; stress; chlorophyll fluorescence; pigments

Beech (*Fagus sylvatica* L.) is an indigenous tree species of the Slovak mountain forests. Traditionally it has been our most frequent tree. The representation of beech in the forested area of Slovakia was 30.2 % in 1995 (HLADÍK 1996).

The knowledge of the state of damaged forest stands and their future development is the requirement to plan the forest management precautions in pollution areas. In professional literature beech belongs to the group of moderately tolerant tree species to pollution. It is necessary to study its standard behaviour in real ecological conditions and at the same time to study symptomatic deviations in the growth and development under pollution influence. The tree damage is not caused only by pollution but also by a number of other abiotic factors (drought, frost) and biotic factors (insect, parasitic fungi mainly the genus *Nectria* Fries). Since pollution acts in combination with the above-mentioned factors of the environment, the definition of beech tolerance is complicated (VACEK 1989). During the last 20 years the beech stand die-back has occurred very rarely in Slovakia (HEINRICH et al. in SUROVEC 1990). Since 1989 at health (sanitary) status controls it has regularly been indicated that all beech age categories showed a decline, even the

young natural stands under optimal conditions. The most likely primary reason of this disease is the high pollution stress in the followed areas, permanent deficit of available soil water, and injuries by late frost or hail. Insects can also play a substantial role in spreading the disease: mainly galls and mites but also some species of herbivorous insects. There is also a possibility of infection by a seed transfer (SUROVEC 1990).

The effects of stress factors on tree species are manifested by visible or hidden physiological damage. Visible damage is the consequence of a total collapse of leaves or long-term chronic injury. The loss and yellowing of assimilatory organs are the basic indicators of the visible injury of tree species. In addition to the evaluations of a loss of assimilatory organs, different methods are used to avoid errors. There is a certain lack of confidence in visual evaluation. Questions arise as to what extent the crown transparency of a tree can be considered a measure of defoliation and how the defoliation evaluation is affected by a tree habitus, which in turn is influenced by site conditions and other circumstances. The observer has to consider all visible effects from tree to tree. It has been confirmed that consideration of only visible injury symptoms can be a reason of delayed deci-

sions and the improvement steps are very expensive (RAČKO et al. 1994). The beech average defoliation expressed in percentage was 21% (ČABOUN 1996) in 1996.

In the case of latent (hidden) damage, life functions of tree species, especially physiological processes (photosynthesis, respiration, transpiration) and biochemical characteristics (chloroplast and enzyme activities, the assimilation pigments and proteins content) are negatively affected. Consequently, the biomass production decreases (MASAROVIČOVÁ 1988).

For the identification of the symptoms of hidden damage and the factors which cause this kind of damage (but mainly for a possibility to forecast what are the consequences of an injury for tree growth and survival, as well as the functioning of whole forest stands) we started to investigate the tolerance and damage dynamics of young beech stands at two localities under different pollution loads.

MATERIAL AND METHODS

Five individual beech trees at the age of about 12 years were chosen on both localities (in 1996). The sample trees were growing under the canopy shelter. We excluded trees growing on the edge of the stand and close to footpaths. We sampled assimilatory organs from both localities always on the same day and separately from individual sample trees of beech during the vegetation periods 1996 and 1997. A beech tree growing on a clearcut area was also chosen to measure the mentioned parameters on sun exposed leaves in 1997 (Table 1).

Photosynthetic pigment content determination: We carried out the sampling for quantitative analysis of chlorophyll a and b using the disc method. One sample for the analysis always contained 10 discs. Analysis of chloro-

phylls was made in 80% (v/v) acetone after leaf-sample homogenization. The total chlorophyll and chlorophyll a and b of the extracts were determined spectrophotometrically (SPEKOL – 211) according to LICHTENTHALER (1987). We also analyzed the dry matter by drying up to 105°C to a constant weight.

Chlorophyll a fluorescence measurement: We measured the chlorophyll fluorescence on two branches of each individual (after that one branch was used for pigment analysis and the next fluorescence measurement was carried out on the second branch). Measurements were carried out on an upper and lower leaf side. To determine the parameters of the fast kinetics of chlorophyll a fluorescence (F_0, F_m, F_v, F_v/F_m, Area, T_m – nomenclature according to KOOTEN, SNEL 1990), a portable fluorometer was used (Plant Efficiency Analyser – PEA, Hansatech Ltd., Kings Lynn, UK). A recording interval of 1 second was chosen. Leaves were dark adapted in leaf clamp cuvettes for 30 minutes prior to measurement. During measurements there was a 50% level of light energy saturating intensity (2,100 μmol/m^2 per s).

RESULTS AND DISCUSSION

On the basis of the evaluation of the concentration dynamics of chlorophylls a and b, we can state that along with the development and growth of the assimilatory organs the corresponding concentration increased. The decrease occurred in autumn (sampling on September 16 and October 4, 1996, September 30 and October 16, 1997).

The years 1996 and 1997 can be considered as years with high precipitation totals. There were no long periods without precipitation which could considerably interact with other stress factors. Water is a very important

Table 1. Basic characteristics of research plots

Characteristic	Research plot	
	EES Kováčová	VMP Žiar nad Hronom
Location	Kremnické vrchy Mts.	Štiavnické vrchy Mts.
Exposition	West	Northwest
Altitude (m a.s.l.)	450–475	400
Stand age (years)	12	12
Stocking	0.0–0.5	0.6
Area	0.15	0.21
Parent rock	dark pyroxene andesites, volcanic sandstones, tuffs	rhyolitic agglomerates
Soil type	Cambisol with high content of skeleton	Luvic Pseudogleyic Cambisol
Group of forest types	*Fagetum pauper*	*Querceto-Fagetum*
Average annual temperature (°C)	6.8	7.6
Average annual precipitation (mm/year)	778	750
Distance from emmission source (km)	18	1.5

EES – ecological experimental stationary plot, VMP – research monitoring plot

Fig. 1. Parameter of the chlorophyll fluorescence F_v/F_m – locality Žiar nad Hronom (adaxial side of leaf – 1996)

factor for beech. However, it must be emphasized that the precipitation deficit from preceding years remains quite high.

We consider the phenomenon of generally higher concentrations of chlorophylls a and b at the locality in the Žiarska dolina valley, which is under a strong pollution load, to be important. In some samplings these differences are negligible but sometimes they are larger. This indicates a possibility of stimulation effect of pollution compounds on chlorophyll concentrations. However, there is also a question of missing interaction between the polluted environment, drought and high temperatures during the observation period.

The values of the other parameter – chlorophyll a to b ratio – are not so clearly high at the Žiar nad Hronom locality. There is preliminary information that this ratio increases in the case of the deteriorated physiological state of assimilatory organs (more data about this ratio is available in association with *Picea abies* needles). This is valid for the Žiar locality especially in 1996. On the other hand, the values of this parameter are more or less equal for 1997 measurements.

The analysis of variance of photosynthetic pigments (Table 2) proved that there is a significant difference in chlorophyll a concentration as well as total chlorophyll ($a+b$) concentration between the localities with a 99% probability. However, variance components indicate a quite low influence of locality on the investigated plastid pigment parameters, which confirms a low specificity of this physiological and biochemical marker.

The year of sampling does not exhibit any significant influence on the measured values, which indicates that the courses of weather in 1996 and 1997 were very similar. On the contrary, significant differences ($\alpha = 0.001$) were found between the days of sampling within the year and the variance component values confirm dynamic

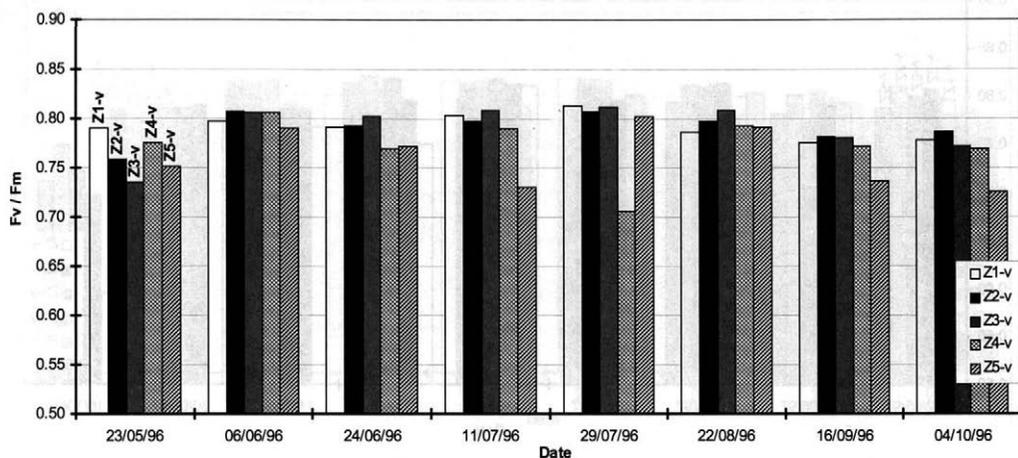Fig. 2. Parameter of the chlorophyll fluorescence F_v/F_m – locality Kováčová (adaxial side of leaf – 1996)

Fig. 3. Parameter of the chlorophyll fluorescence F_v/F_m – locality Žiar nad Hronom (adaxial side of leaf – 1997)

changes of particular concentrations during the vegetation period. A low specificity of the photosynthetic pigment parameters in association with the physiological state is indicated by a considerable effect of unknown factors on the measured variables as well.

The dynamics of the selected parameters of fast kinetics of chlorophyll fluorescence (F_v/F_m, Area) shows a better physiological state of assimilatory organs and consequently, of the observed beech trees on the EES Kováčová locality.

The average values of F_v/F_m from all sample trees on all sampling dates are higher at the Kováčová locality. This ratio even decreases below the threshold of physiological distortion (0.725) in two cases at the Žiar locality in 1996. This parameter is especially unfavourable in October sampling (October 16) as can be seen in the figures with an indicated critical level in 1997. It is partially caused also by temperature extremes in autumn at this

locality. At the Kováčová plot, i.e. outside the range of the direct pollution influence, the ratio F_v/F_m drops below the threshold of physiological distortion only once during two years of observation. It is interesting that the higher values of this parameter were found on the bottom sides of assimilatory organs at both localities.

The course of another parameter of chlorophyll a fluorescence – Area (which is the area above the induction curve of fast kinetics) indicates that, especially in 1997, the capacity for the electron transport in primary photosynthetic processes (between the primary electron acceptor Q_A and the intrathylakoid plastoquinone and/or photosystem I) is potentially higher in leaf samples from the Žiar locality. This is valid for the values from the upper as well as bottom sides of assimilatory organs. This bigger quantity of primary electron acceptors is probably related to higher chlorophyll a and b concentrations found in the leaves from this locality. The potentially

Fig. 4. Parameter of the chlorophyll fluorescence F_v/F_m – locality Kováčová (adaxial side of leaf – 1997)
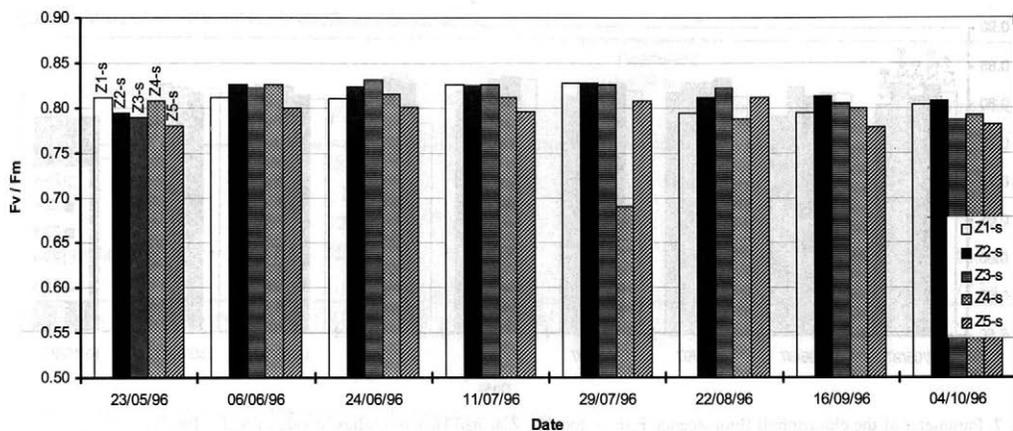
Fig. 5. Parameter of the chlorophyll fluorescence F_v/F_m – locality Žiar nad Hronom (abaxial side of leaf – 1996)

higher capacity for electron transport is not, however, fully utilized in photosynthetic processes due to negative environmental conditions. This is confirmed by the two preceding chlorophyll fluorescence parameters. The 'Area' values are clearly lower on the bottom sides of leaves at both localities, which is associated with the beech leaf anatomy.

For the parameters F_v/F_m and 'Area' a significant difference on a probability level of 99.9% was found between the localities (Table 3). The values of variance components confirm a considerable effect of the locality on the recorded values (except Area).

We would like to draw attention to statistically significant differences between individual trees within the sample plot, the upper and the bottom side of assimilatory organs, years of sampling and the sampling dates within one vegetation period. These factors confirm the relevance of measurements of chlorophyll a fast kinetics parameters in association with the evaluation of the physiological state of young beech trees in different pollution and environmental conditions even before they manifest any damage symptoms.

For the evaluation of correlations between individual parameters we used Spearman's rank correlation coefficient (Table 4). There is a clear and logical significant negative correlation between the basic fluorescence F_0 and the chlorophyll a, b and $a+b$ concentrations. F_v/F_m ratio is positively correlated with the chlorophyll a concentration. There is an evident positive correlation between the Area parameter and the chlorophyll a, b and $a+b$ concentrations.

Due to their important role in plant metabolism, plastid pigments occur in various hypotheses about the forest decline. If we suppose that the pollution compounds directly affect the plastids, various mechanisms of pigment damage can be expected depending on the pollutant type.
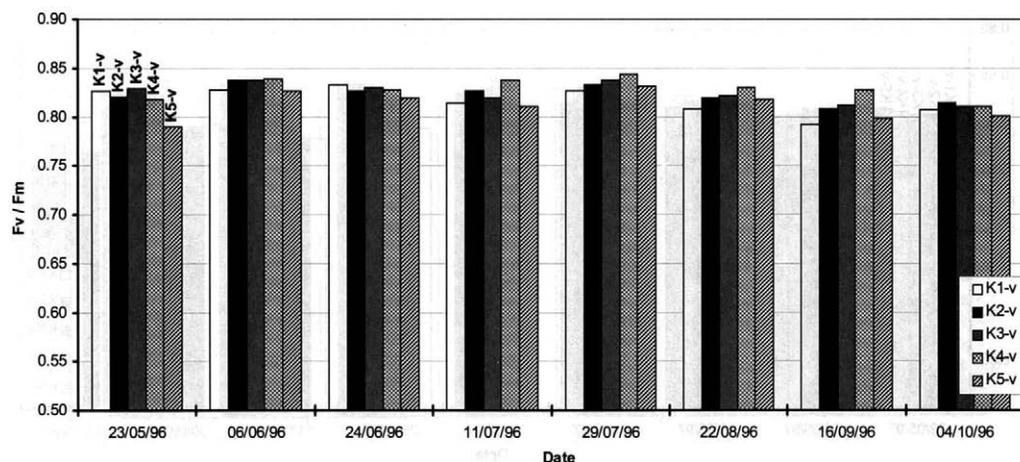

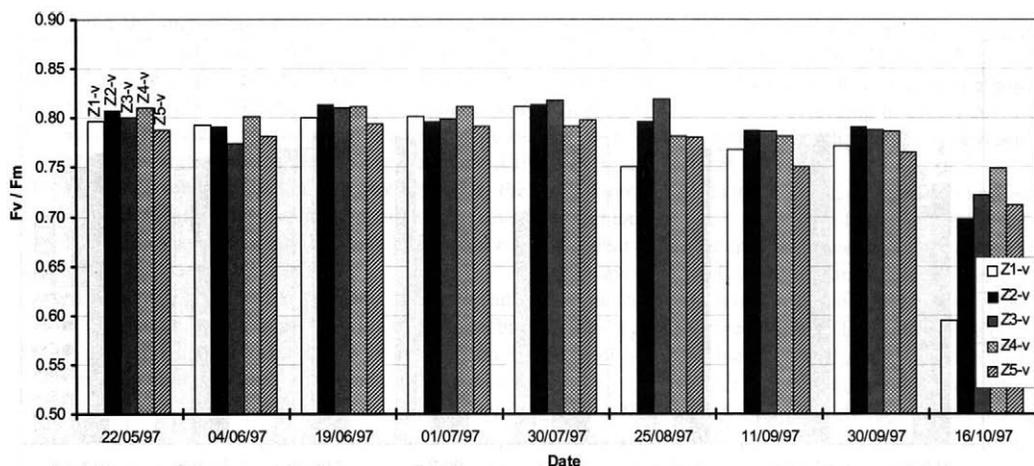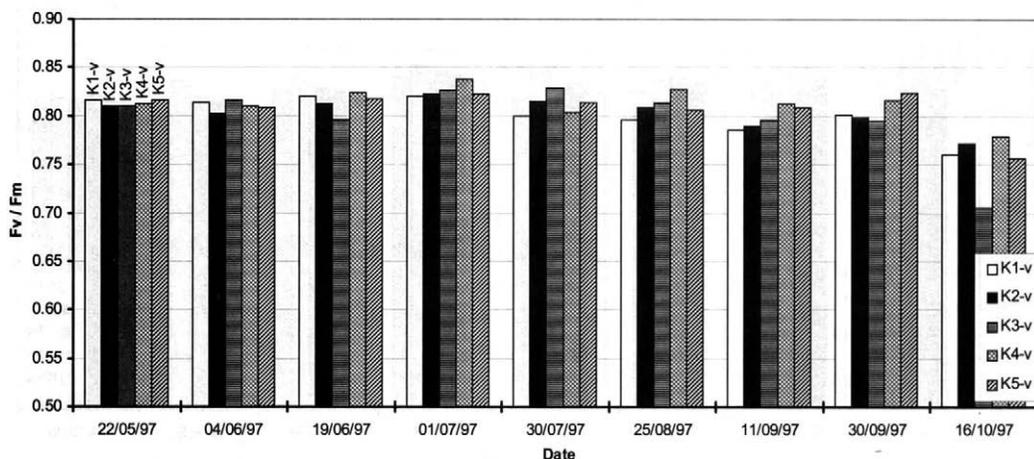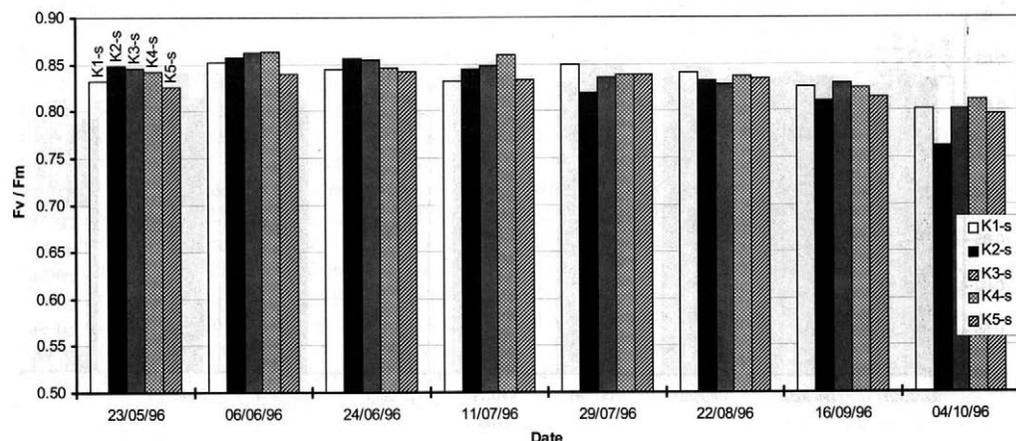Fig. 6. Parameter of the chlorophyll fluorescence F_v/F_m – locality Kováčová (abaxial side of leaf – 1996)
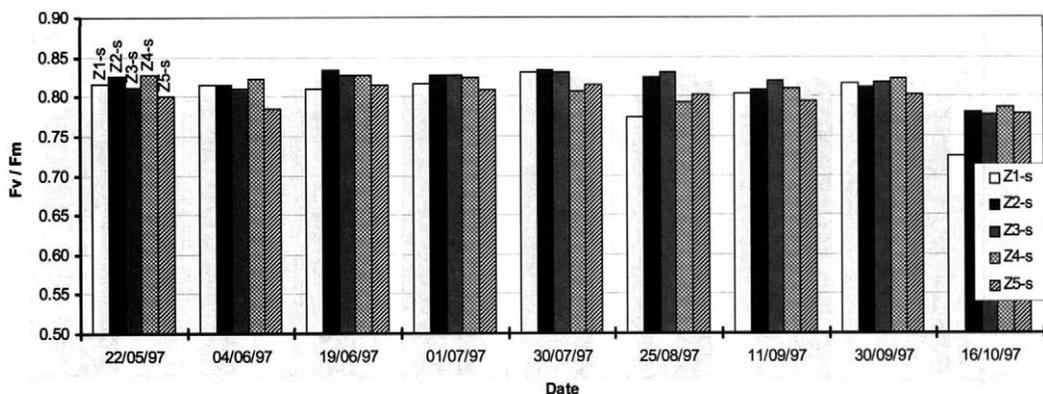
Fig. 7. Parameter of the chlorophyll fluorescence F_v/F_m – locality Žiar nad Hronom (abaxial side of leaf – 1997)

Sulphur dioxide (SO_2) and the subsequently arising HSO_3^- anion are suspected to degrade chlorophyll to phaeophytin due to their acid effect (ZIEGLER in PFEIF-HOFER, GRILL 1987). Furthermore, there is an evidence on the induction of the reactions of radical chains by SO_2 and ozone leading to lipid peroxidation, cooxidation and pigment degradation.

The results of the investigations on the effect of the toxic fluorine on pigments indicate a probable distortion of chlorophyll synthesis and their degradation. The observed effect could result from changes in the organelle and protein structure and the membrane integrity. Chloroplasts, in contrast to other organelles, accumulate considerable amounts of fluorine – even 20% of the total content in leaves – which may cause their destruction (HOLUB 1977).

Our results show that chlorophyll a and b concentrations represent an unspecific biomarker of the physiological state of beech leaves. At the Žiarska dolina valley locality even higher values were recorded than at the less loaded locality at the EES Kováčová. The chlorophyll a to b ratio presents a different picture.

As it was stated by MASAROVIČOVÁ (1988), changes in chlorophyll concentrations in oak leaves confirmed a different reaction and a different operation mechanism of environmental factors on the photosynthetic apparatus. A decrease in chlorophyll content in *Quercus cerris* leaves was followed by increasing chlorophyll a to b ratio due to a higher sensitivity of chlorophyll b to environmental changes. The changes in chlorophyll concentrations in spruce needles depended on the degree of damage by SO_2 pollution (KRATOCHVÍLOVÁ in MASA-ROVIČOVÁ 1988). The author found that spruce needles originating from less damaged localities exhibited higher chlorophyll concentrations that the control locality. A decrease in chlorophyll concentrations was recorded only in spruces from highly damaged localities.

It seems probable that the stability and the associated mutual relationships of plastid pigments (i.e. the proportions of their contents) will depend on whether the phy-

Fig. 8. Parameter of the chlorophyll fluorescence F_v/F_m – locality Kováčová (abaxial side of leaf – 1997)

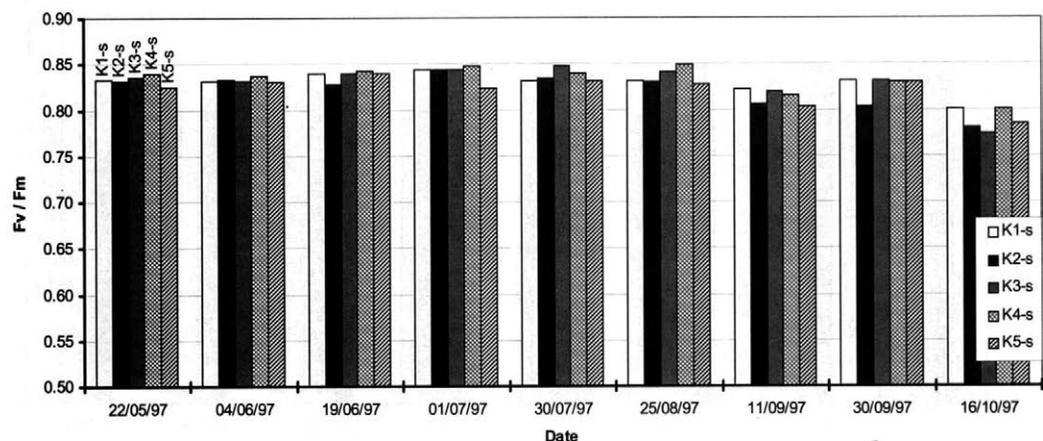Table 2. Analysis of variance of chlorophyll concentrations

Source of variation	D. F.	Chl a		Chl b		Chl a/b	
		F-ratio	Variance component	F-ratio	Variance component	F-ratio	Variance component
Locality	1	25.08***	11.51	1.97	0.17	1.73	0.50
Tree within locality	9	1.00	0.00	3.00**	3.30	1.17	0.85
Year	1	3.90	0.00	1.64	0.00	3.85	0.00
Sampling date within year	15	12.71***	47.35	2.79***	14.50	3.36***	18.80
Error	148		41.14		82.03		79.84

*significant at $P < 0.05$; **significant at $P < 0.01$; ***significant at $P < 0.001$

Table 3. Analysis of variance of chlorophyll fluorescence parameters

Source of variation	D. F.	F_v/F_m		Area	
		F-ratio	Variance component	F-ratio	Variance component
Locality	1	140.90***	19.92	59.61***	6.50
Tree within locality	9	16.73***	11.15	6.59***	3.71
Leaf side	1	108.54***	18.53	458.11***	58.66
Year	1	5.06*	0.00	21.33***	3.62
Sampling date within year	15	18.38***	25.59	8.20***	8.14
Error	307		24.80		19.38

*significant at $P < 0.05$; **significant at $P < 0.01$; ***significant at $P < 0.001$

totoxic compounds affect only the process of pigment biosynthesis or if the compounds' influence is so strong that it causes a direct destruction of pigments (CICÁK 1978).

According to HASPELOVA-HORVATOVIČOVA and PE-LIKÁNOVÁ (in HOLUB 1977), the differences are most easily seen if the yellowing occurs when the tissues still contain a high proportion of water in contrast to a sudden withering and a big reduction of water content in tissues. Yellow leaves contain only a negligible amount of chlorophyll. Suddenly withered leaves are almost completely green at the beginning since the water shortage hinders the physiological degeneration of chlorophylls as well as their postmortal decay. The necessity of water for the postmortal decay is manifested in brown leaves where the water content is still high but the chlorophyll concentration decreases very rapidly within a short time interval. The cited authors, like the majority of other authors, observed a greater stability of chlorophyll a. This means also the decease in chlorophyll a to b ratio, but only in cases of postmortal decay, especially leaf browning. In living tissues this ratio was preserved, even increased. The more complicated task is the evaluation of these parameters at the stage of latent (hidden) damage of assimilatory organs. Therefore, supplementary analyses of the content of damaging compounds in leaves (fluorine, sulphur) should help in the future. Also, the determination of magnesium content, since this element occupies a central position in the chlorophyll molecule, is important. Attention should also be paid to carotenoid concentrations, which play an important role in the photosynthetic process as well.

The dynamics of the course of chlorophyll fluorescence parameters during the vegetation seasons 1996 and 1997 shows that the physiological state of leaves and, subsequently, beech trees is better on the EES Kováčová sample plot. The thylakoid membrane is very sensitive to stress: pollution, high temperatures, frost, drought, excessive radiation. Therefore, a close correlation was found between the photosynthesis inhibition and the decrease in the F_v/F_m ratio (BOLHAR-NORDENKAMPF, GÖTZL 1992). The photochemical capacity PSII is not completely identical with the photosynthetic capacity. However, it is sure that the decreased F_v/F_m ratio is followed by an equivalent decrease in the amount of fixed CO_2. The measurement of the F_v/F_m ratio is a means for the determination of the theoretical photosynthetic capacity in view of the limits of electron transport capacity chain (area). The photochemical capacity determined by this relationship decreases steeply especially with the

Table 4. Spearman correlation coefficients between chlorophyll fluorescence and pigment content of European beech (*Fagus sylvatica* L.) leaves

	Chl *a*	Chl *b*	Chl tot	Chl *a/b*
F_0	−0.287***	−0.257***	−0.291***	−0.057
F_m	−0.119	−0.163*	−0.136	−0.034
F_v	−0.106	−0.160*	−0.124	−0.022
F_v/F_m	0.024	−0.090	−0.005	0.031
T_m	−0.230**	−0.131	−0.207**	−0.025
Area	0.106	0.130	0.135	−0.117

*significant at $P < 0.05$; **significant at $P < 0.01$; ***significant at $P < 0.001$

occurrence of strong frost periods which, however, have not occurred in our case.

A close correlation of the fluorescence emission spectrum of leaves with the concentration of pigments (especially chlorophyll *a*) and assimilatory tissue ultrastructure is well known. The fluorescence decreases with the increasing chlorophyll concentration (LICHTENTHALER et al. 1986). Along with the increasing chlorophyll *a* concentration in leaves the absorption within the entire visible-light range increases. This is most clearly seen within the red chlorophyll maximum at the wave length of 680 nm and at blue light with the wave length below 500 nm, which is absorbed by carotenoids and chlorophylls. The composition and concentration of pigments in assimilatory organs determines their fluorescence characteristics. It is also important that the fluorescence emitted from the bottom leaf side is always more intensive that the fluorescence emitted from the upper leaf side (LICHTENTHALER et al. 1986) and the F_v/F_m ratio is higher on the bottom side that on the upper side which is evident even in our samples. Attention must also be paid to the measurements of chlorophyll fluorescence of sunny and shaded leaves of beech. According to LICHTENTHALER et al. (1986), shaded leaves exhibit a higher fluorescence intensity than sunny leaves. It is, however, necessary to emphasize that the existence of a mathematical relationship as such is not yet a proof of the existence of a causal relationship. It allows surely to formulate the hypotheses about the underlying physiological mechanisms and to explain the observed relationship, but it does not represent a confirmation of these hypotheses (GÖMÖRY 1998).

According to CICÁK et al. (1998), the productive claim of beech leaves increases along with the increasing pollution load. When comparing beech leaves from a polluted plot with a control one, they found that in polluted regions the regulatory system of stomatal as well as cuticular water discharge of leaves is distorted (reduced efficiency of the opening and closing of stomata and damage to the cutinized surface, respectively). An increased water discharge associated with pollution was proved also by other authors.

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Fyziologické aspekty zdravotného stavu buka (*Fagus sylvatica* L.) na Slovensku

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ABSTRAKT: Zdravotný stav buka (*Fagus sylvatica* L.) sa na Slovensku za obdobie posledných desať rokov nevyvíja priaznivo. Veľmi nepriaznivý je zdravotný stav mladých bukových porastov z prirodzeného zmladenia, pričom najviac postihnuté sú bučiny stredného Slovenska. V priebehu vegetačného obdobia 1996 a 1997 sme merali na vybraných vzorníkoch buka na dvoch lokalitách s rozdielnym imisným zaťažením parametre rýchlej kinetiky fluorescencie chlorofylu a – F_0, F_m, F_v, F_v/F_m, T_m, Area. Súčasne boli odoberané asimilačné orgány a spektrofotometricky určené koncentrácie chlorofylu a, b. Na základe vybraných fyziologicko-bichemických markérov (predovšetkým parametrov fluorescencie chlorofylu) môžeme konštatovať zhoršený fyziologický stav mladých jedincov buka na lokalite s väčším imisným zaťažením už v štádiu latentného (skrytého) poškodenia.

Kľúčové slová: buk lesný; stres; fluorescencia chlorofylu; pigmenty

Buk lesný (*Fagus sylvatica* L.) je pôvodná drevina horských lesov Slovenska. V minulosti bol – a i v súčasnosti je – najrozšírenejšou drevinou. Z plošnej rozlohy lesov Slovenska zastúpenie buka v roku 1995 predstavovalo 30,2 % (HLADÍK 1996). Pri kontrole zdravotného stavu bukových porastov na našom území sa pravidelne od roku 1989 zisťuje, že chradnutím trpia všetky vekové stupne buka, dokonca aj nárasty z prirodzeného zmladenia v optimálnych podmienkach. Pravdepodobnou primárnou príčinou tejto epifytócie je vysoké imisné zaťaženie v sledovaných oblastiach, stále pretrvávajúci vlahový deficit v pôde, časté poškodzovanie neskorými mrazmi. Rozhodujúcu úlohu pri šírení choroby môže mať aj hmyz. Sú to najmä vošky, roztoče, ale aj niektoré druhy listožravého hmyzu. Nevylučuje sa ani možnosť prenosu infekcie semenami (SUROVEC 1990).

Pre poznanie symptómov skrytého poškodenia a faktorov, ktoré ho spôsobujú, ale hlavne pre možnosť prognózy, aké bude mať poškodzovanie následky pre rast i prežitie stromov a funkcií celých porastov, pristúpili sme od roku 1996 k výskumu tolerancie a dynamiky poškodenia mladých bukových porastov na dvoch lokalitách s rozdielnym imisným zaťažením (lokalita Kováčová – bez priameho imisného vplyvu a lokalita Žiar nad Hronom – pásmo ohrozenia A, kyslý imisný typ).

V práci uvádzame dvojročné výsledky v sledovaní vybraných fyziologicko-biochemických parametrov na týchto lokalitách (koncentrácia asimilačných pigmentov, meranie parametrov rýchlej kinetiky fluorescencie chlorofylu a – F_0, F_m, F_v, F_v/F_m, T_m, Area – nomenklatúra podľa KOOTENA, SNELA 1990). Z *F*-testu analýzy variancie fotosyntetických pigmentov je zrejmé, že medzi lokalitami je štatisticky veľmi významný rozdiel v koncentrácii chlorofylu a, sumy chlorofylov $a+b$ na hladine významnosti 99,9 %. Percentuálne vyjadrenie komponentov variancie však ukazuje, že vplyv lokality je na zistené parametre plastidových pigmentov veľmi malý. Pomocou analýz pigmentov môžu byť dokázané negatívne vplyvy prostredia už vtedy, keď ešte nie je možné makroskopicky stanoviť žiadne poškodenie. Na druhej strane použitie pigmentových analýz na diagnostické účely je zmysluplné iba v kombinácii s ďalšími fyziologicko-biochemickými postupmi (predovšetkým súčasne s meraním výmeny plynov, fluorescencie chlorofylu a, obsahu minerálnych látok a pod.). Výsledky mnohých výskumných prác (ako aj táto práca) potvrdili, že meranie fluorescencie chlorofylu je jednou z tých metód, ktoré umožňujú rýchle zistenie fyziologického stavu stromu. Tieto poznatky sú podložené na jednej strane koreláciou fotochemickej kapacity s niektorými parametrami indukčnej krivky fluorescencie chlorofylu, na druhej strane vysokou citlivosťou fotosyntetického reťazca reakcií voči mnohým stresorom. Okrem stanovištne špecifickej vzorky stresorov sa vždy musí skúmať tiež fyziológia stromu, aby sme mohli stanoviť vzťah medzi zaťažením, reakciou, kompenzáciou a zotavením. V našich výsledkoch pri parametroch F_v/F_m a Area bol zistený signifikantný rozdiel medzi lokalitami na hladine významnosti 99,9 %. Hodnoty komponentov variancie ukazujú tiež, že vplyv lokality na namerané údaje (okrem Area) je veľký.

Z doterajších výsledkov výskumu je zrejmé, že pre celkové zhodnotenie príčin zhoršeného zdravotného stavu bukových porastov je v súčasnosti potrebná široká paleta zisťovania. Stanovenie fyziologicko-biochemických parametrov na popísanie stresového zaťaženia je odkázané na poznanie veľkého počtu prirodzených

a antropogénnych stresorov, bez ktorých v súčasnosti nie je možné urobiť definitívne závery o príčinách stresového zaťaženia. Potvrdzuje sa, že odumieranie lesných drevín je fyziologický dôsledok ťažkých porúch látkových a energetických tokov, ako aj autoregulácie v rozličných lesných ekosystémoch.

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Nitrogen transformation in soil and nutrition conditions of young spruce stands in the Moravian-Silesian Beskids

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ABSTRACT: The study evaluates the effect of density of a young Norway spruce stand and reclamation liming on nitrogen transformations in soil and the level of nitrogen nutrition of spruce stands in the ridge part of the Moravian-Silesian Beskids. The area is affected by acid industrial air pollutants and, therefore, it was reclaimed by liming in 1983, 1985 and 1987. The concentration of ammonium and nitrate nitrogen in soil during the growing season considerably fluctuated. On the basis of the results from 1999, nitrogen in ammonium form predominated in soil, the content of nitrate nitrogen was lower and nitrite nitrogen was detected only sporadically. Nitrogen concentrations in needles of the first generation were below the limit of sufficient nutrition. For the given intensity of tending measures, the effect of stand density on nitrogen transformation in soil has not been found. The effect of reclamation liming on nitrogen transformations in soil 12 years after the last application has not been proved either.

Keywords: Norway spruce; nitrogen; stand nutrition

Issues of nitrogen in forest ecosystems appear to be a generally discussed problem. In forest ecosystems saturated with nitrogen, relations between NO_3^- immobilization processes and nitrification can be expressed by a value of < 0.01 and in the case of NH_4^+ immobilization/mineralization by a value of < 0.50, i.e. increased nitrogen outputs from saturated ecosystems, particularly in the form of nitrates, will influence the quality of groundwater. A number of authors (KREUTZER 1981; RASMUSSEN 1987) pointed out the fact of leaching nitrates and decreasing the quality of groundwater under conditions of nitrogen saturation. On the other hand, a great deal of forest ecosystems is limited by nitrogen which results in the decreased increment of forest biomass. In ecosystems limited by nitrogen, it is possible to express relations between NO_3^- immobilization/nitrification and NH_4^+ immobilization/mineralization by a value close to 1.0. Differences between nitrogen saturated and nitrogen limited ecosystems are summarized in detail by ABER and FEDERRER (1992).

In stands of boreal forests and temperate zone forests, about 90% nitrogen are concentrated in soil (COLE, RAPP 1981). Forest soils of mountain areas of the Czech Republic have a thick layer of organic matter particularly below Norway spruce monocultures. The influence of acid spruce litter with high C/N ratio and industrial air pollution show often negative effects on the decomposition of organic matter (ULRICH 1981; LOHM 1984).

Large amounts of nitrogen and other nutrients are fixed in the organic humus matter. From the humus reserve, nitrogen should be replenished into the soil solution in a mineral form to be assimilated by forest stands again. Impaired decomposition conditions prevent, however, the process.

Ammonification is a primary process of the organic matter mineralization. In a number of ecosystems such as e.g. wetlands or boreal forests, nitrogen is mineralized to some extent only (ÚLEHLOVÁ 1989). Ammonia nitrogen is the main source of nitrogen available to plants in acid forest soils of Europe (NIHGARD 1985) being preferentially taken by conifers (CARLYLE, MALCOM 1986; REUSS, JOHNSON 1986; GIJSMAN 1991; SARJALA 1993; ARNES et al. 1995). It is a dominant form of nitrogen available to plants in soils of mountain forests (ATKIN et al. 1993; ATKIN, CUMMINS 1994).

Industrial air pollution and soil acidification can differently affect ammonification intensity. BROWN (1985) proved significantly negative effects of acid precipitation on the process of ammonification, LOHM et al. (1984) did not find any statistically significant effects of forest soil acidification on the process of ammonification. According to PERSSON (1988), due to soil acidification the amount of ammonium nitrogen in soil can increase as a result of mineralization of dead soil microorganisms.

A number of forest ecosystems was repeatedly limed to eliminate the effects of industrial acid air pollutants.

By means of liming of forest ecosystems the decomposition of organic matter is usually accelerated. POD-RÁZSKÝ (1994) pointed out favourable effects of experimental liming of Norway spruce plantations in air-polluted areas of the Orlické and Jizerské hory Mts. from the viewpoint of height increment, lower needle losses and lower occurrence of the chlorotic coloration in assimilatory tissues. PODRÁZSKÝ (1992) also proved marked intensification of mineralization processes after liming and stressed the importance of monitoring the impact of the chemical treatment on the dynamics of organic substances and nitrogen in soil.

Nitrogen mineralization increases, however, in soils sufficiently rich in nitrogen only. It decreases in soils of ecosystems limited in nitrogen because the intensive growth of microbial communities results in intensive immobilization of nitrogen into soil organic matter (PERSSON 1988). According to KULHAVÝ (1992), liming resulted in marked decrease of ammonium nitrogen concentration in forest soils. According to NÔMNIK (1979), nitrogen mineralization in humus layers after liming is higher only if the C/N ratio is < 30. It decreases if the ratio is higher when most of nitrogen is consumed by soil microorganisms.

With respect to the fact that mineral soil layers are affected by liming only after several years, growth of forest stands was subsequently many times retarded after the liming (PERSSON 1988). LHOTSKÝ, VINŠOVÁ (1981) pointed out increased amounts of ammonium and nitrate forms of nitrogen on limed plots. According to LETTL (1991), the effect of forest soil liming can be modified by ground vegetation. Due to liming, intensity of nitrification and leaching of nitrates into groundwater increase (POD-RÁZSKÝ 1992; KULHAVÝ1992; MOHAMED et al. 1993).

Effects of various rates of liming on particular components of spruce ecosystems in air-polluted areas at higher altitudes of the Moravian-Silesian Beskids were studied by VAVŘÍČEK and BETUŠOVÁ (1995). In the Moravian-Silesian Beskids, the content of total nitrogen in soil decreased already in the fourth year after application of the dolomitic limestone (VAVŘÍČEK 1990). A decrease in nitrogen was the cause of organic matter mineralization in the forest floor and subsequent nitrification.

At present, the level of spruce stand nutrition is often assessed on the basis of a number of physiologically important elements in needles of the first generation according to criteria published by HÜTTL (1991). On the basis of these criteria, growth of spruce in the Moravian-Silesian Beskids was limited by nitrogen and magnesium (KLIMO, KULHAVÝ 1996).

MATERIAL AND METHODS

The research was carried out on limed FD and FS plots of different stand density which are part of the experimental area of the Institute of Landscape Ecology, Academy of Sciences of the Czech Republic at Bílý Kříž, the Moravian-Silesian Beskids and on the FK plot situated in the area of Bílý Kříž which was not reclaimed by liming in the past.

On all the plots, moderate humus podzol with mor/moder form of humus predominated. Basic differences between the experimental plots are given in Table 1.

In the soil profile, Ol, Of+h, Ae, Ep, Bh, Bs and Cd horizons were differentiated on all the plots. The characteristics of particular horizons, the content of total and available nutrients and adsorption complex characteristics are described in detail in papers of KULHAVÝ et al. (2000) and FORMÁNEK (2000).

From the viewpoint of climatic characteristics, mean annual temperature in the area is 5°C, mean annual total

Table 1. Field experimental plots

Characteristics	FD	FS	FK
Forest area	40 – Moravian-Silesian Beskids	40 – Moravian-Silesian Beskids	40 – Moravian-Silesian Beskids
Management set of stands	55	55	55
Vegetation zone	5 – fir/beech	5 – fir/beech	5 – fir/beech
Forest type group	*Abieto-Fagetum*	*Abieto-Fagetum*	*Abieto-Fagetum*
Number of trees/ha	2,600	2,100	2,600
Stand age (years)	21	21	21
Species composition	100% Norway spruce	100% Norway spruce	100% Norway spruce
Slope (°)	13.5	13.5	15
Altitude (m)	908	908	890
Parent rock	sandy flysch sediments	sandy flysch sediments	sandy flysch sediments
Soil type	moderate humus podzol	moderate humus podzol	moderate humus podzol D37
Surface humus form	mor – moder	mor – moder	mor – moder
Terms of liming	1983, 1985, 1987	1983, 1985, 1987	–
Dose of dolomitic limestone (kg/ha)	3,000	3,000	–

Note for Tables 1–5: FD – dense stand, FS – open stand, FK – control plot (without liming)

precipitation amounts to 1,400 mm, mean number of days with snow cover is 160 (JANOUŠ 1990).

To monitor seasonal dynamics in nitrogen forms mixed soil samples were taken from Ol, Of+h, Ae and Ep horizons. Soil sampling started on 31 May 1999 and finished on 17 November 1999. The mixed samples were taken from each of the horizons separately and always from 10 places on each of the plots. The samples taken into PE bags were stored at 4°C, subsequently homogenized and sieved using a coarse screen. Ammonium nitrogen was determined in soil extracts using 1% K_2SO_4 by a modified indophenol method (ZBÍRAL et al. 1997). Nitrate nitrogen was determined after extraction of soil samples with demineralized water using capillary electrophoresis (KUBÁŇ et al. 1999) and the results were compared with values determined after the extraction of soil samples with 1% K_2SO_4 using a manual spectrometric method with sulphosalicylic acid (Standard ČSN ISO 7890-3). Nitrite nitrogen was determined by capillary electrophoresis only after the extraction of soil samples with demineralized water.

Total C and N were analysed using a LECO CNS 2000 analyser, calibration was carried out for sulphamethazin LECO 242-298, C and N drift for the same, used gases were He, O_2 and air (ZBÍRAL et al. 1997). Actual soil reaction (pH/H_2O) and exchangeable soil reaction (pH/KCl) were determined with a potentiometer. To determine the level of nutrition by nitrogen, needle samples of the first generation from selected 8 trees were taken monthly (the same trees during the whole period) from the insolated part of crowns. In 1999, the level of nutrition of spruce stands was determined on limed plots FD and FS only, sampling started on 28 April and finished in mid-December. The content of nitrogen was determined using the LECO CNS 2000 automatic analyser with calibration and drift for the certified standard LECO alfaalfa 502-273 for S and N at a temperature of 1,100°C or 1,350°C.

RESULTS

Results of the study show that the C/N ratio is relatively high in particular horizons of all plots exceeding nearly always the value 20 (Table 2). Soil reaction on the plots is acid. Owing to reclamation liming, higher values of pH/H_2O and pH/KCl occurred in the layer of forest floor despite of the 12-year interval from the last application as compared with control plot (Table 3). In the forest floor layer, the pH/H_2O value was 0.73–1.07 higher and the pH/KCl value was 0.54–1.13 higher.

From the viewpoint of the concentration of mineral forms of nitrogen in particular soil layers it is evident that the highest concentrations of ammonium nitrogen were found in forest floor (Ol and Of+h layers) where its concentration ranged from 6.47–9.94 (FD), 9.58–9.66 (FS) and 10.56–12.92 mg/kg DM (dried matter) (FK). With increasing depth ammonium nitrogen concentrations decreased. Mean concentrations of nitrate nitrogen

Table 2. The content of total carbon, nitrogen and the C/N ratio (1999)

Plot	Soil horizon	Ct (%)	Nt (%)	C/N
FD	Ol	38.8	1.47	26.4
	Of+h	22.5	1.0	22.5
	Ae	6.1	0.3	23.4
	Ep	4.0	0.2	23.6
FS	Ol	39.2	1.4	27.4
	Of+h	21.6	1.0	22.5
	Ae	7.8	0.4	21.7
	Ep	4.4	0.2	23.4
FK	Ol	45.2	1.71	26.4
	Of+h	24.9	1.2	20.8
	Ae	6.8	0.4	19.3
	Ep	3.3	0.15	21.7

Table 3. Soil reaction on experimental plots (1999)

Plot	Soil horizon	pH/H_2O	pH/KCl
FD	Ol	4.28	3.84
	Of+h	4.88	4.17
	Ae	4.30	3.20
	Ep	4.03	3.10
FS	Ol	4.41	3.92
	Of+h	4.71	3.71
	Ae	3.85	2.83
	Ep	3.81	2.82
FK	Ol	3.34	2.79
	Of+h	3.98	3.17
	Ae	3.60	2.70
	Ep	3.97	3.13

were lower nearly on all plots and in all horizons as compared with ammonium forms of nitrogen the difference being particularly evident in the forest floor. Occurrence of the nitrite form of nitrogen was found only sporadically. Main concentrations of the total mineral nitrogen (ammonium + nitrate nitrogen) decreased with depth. Within all horizons under study, the concentration reached the value 2.69–12.48 (FD), 2.04–12.44 (FS) or 2.66–16.13 mg/kg DM (FK) (Table 4). The ratio of mineral nitrogen concentration to total nitrogen was small in particular soil layers or horizons (Table 5). The mean ratio of mineral nitrogen to total nitrogen (N_{min}/N_t) reached the value 0.077–0.24% (FD), 0.087–0.152% (FS) and 0.094–0.177% (FK) being usually higher in mineral soil (Ae, Ep).

Figs. 1–3 show seasonal variations in the concentration of ammonium and nitrate forms of nitrogen in the Of+h horizon in 1999. The horizon was characterized by

Table 4. Mean concentrations of ammonium, nitrate and total mineral nitrogen (1999) (mg/kg DM)

Plot	Soil horizon	$NH_4^+ - N$	$NO_3^- - N$	N_{min}
FD	Ol	9.94	2.54	12.48
	Of+h	6.47	1.24	7.71
	Ae	3.75	2.50	6.25
	Ep	1.90	0.79	2.69
FS	Ol	9.66	2.78	12.44
	Of+h	9.58	0.96	10.54
	Ae	3.30	2.16	5.46
	Ep	0.61	1.43	2.04
FK	Ol	12.92	3.21	16.13
	Of+h	10.56	1.92	12.48
	Ae	2.84	2.30	5.14
	Ep	1.98	0.68	2.66

Table 5. Mean proportion of the concentration of ammonium and nitrate form of nitrogen as related to total nitrogen (1999)

Plot	Soil horizon	$NH_4^+ - N/Nt$ (%)	$NO_3^- - N/Nt$ (%)	N_{min}/Nt (%)
FD	Ol	0.068	0.017	0.085
	Of+h	0.065	0.012	0.077
	Ae	0.144	0.096	0.240
	Ep	0.112	0.046	0.158
FS	Ol	0.068	0.019	0.087
	Of+h	0.096	0.010	0.105
	Ae	0.092	0.060	0.152
	Ep	0.032	0.075	0.107
FK	Ol	0.076	0.019	0.094
	Of+h	0.088	0.016	0.104
	Ae	0.081	0.066	0.147
	Ep	0.132	0.045	0.177

Fig. 1. Seasonal variations in the concentration of ammonium and nitrate nitrogen in the Of+h horizon on plot FD – 1999
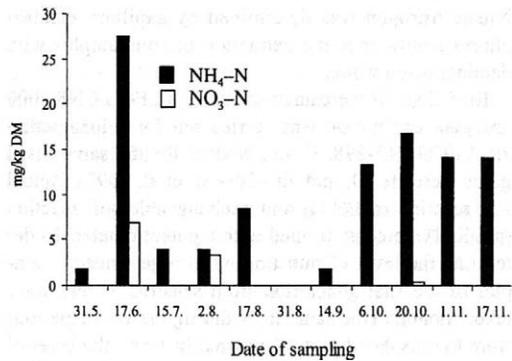
Fig. 2. Seasonal variations in the concentration of ammonium and nitrate nitrogen in the Of+h horizon on plot FS – 1999

a depth of 7–8 cm and contained the largest number of roots. On all the plots, seasonal variations in the concentration of ammonium and nitrate forms of nitrogen in the Of+h layer were very irregular and ammonium nitrogen dominated. Statistically significant differences between the plots were not found.

On the FD plot (dense stand), concentrations of the ammonium form of nitrogen ranged from 0 to 16.63 mg/kg DM with a mean value of 6.47 mg/kg DM and coefficient of variation 107.1%. In the case of nitrate form the concentrations seasonally varied from 0 to 5.83 mg/kg DM and coefficient of variation was 140.32%. At the end of May, only nitrate forms of nitrogen were found on the plot and in mid-July, nitrate nitrogen concentrations were higher than those of ammonium nitrogen. From November, the occurrence of mineral nitrogen in the Of+h horizon, plot FD, was not found (Fig. 1).

On the FS plot (open stand), in the course of the season concentrations of the ammonium form of nitrogen ranged from 0 to 27.52 mg/kg DM with a mean value of 9.58 mg/kg DM and coefficient of variation 83.8%. In the case of nitrate form the concentrations varied from 0 to 6.91 mg/kg DM with a mean value of 0.96 mg/kg DM and coefficient of variation 218.8%. The ammonium form of nitrogen always predominated over the nitrate form. The nitrate form of nitrogen was found only in three out of eleven samplings during the season (Fig. 2). At the end of August, the occurrence of mineral nitrogen in the Of+h horizon was not found.

On the FK plot (non-limed plot), concentrations of ammonium forms of nitrogen in the Of+h layer reached a value of 0–45.55 mg/kg DM with a mean value of 10.56 mg/kg DM and coefficient of variation 123.1% and in the case of nitrate form 0–9.36 mg/kg DM with a mean value of 1.92 mg/kg DM and coefficient of variation 142.7%. With the exception of sampling carried out at the end of August ammonium nitrogen concentrations were always higher than those of nitrate forms (Fig. 3).

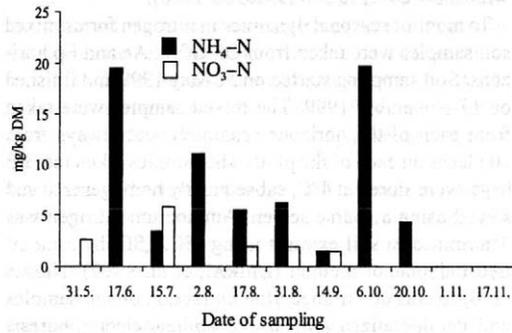The content of nitrogen in needles in the course of the year was typical by its dynamics (Fig. 4). After the initial
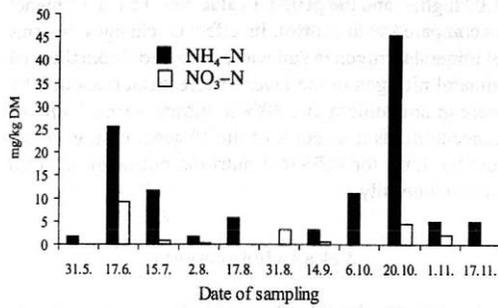
Fig. 3. Seasonal variations in the concentration of ammonium and nitrate nitrogen in the Of+h horizon on plot FK – 1999
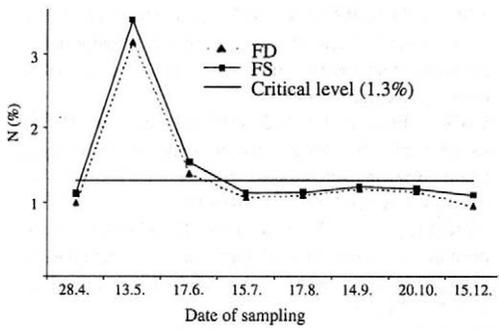

Fig. 4. Nitrogen concentration in needles of the 1ˢᵗ generation (1999)

increase in nitrogen concentration in the spring season and following decrease in biomass its concentration in needles of the first generation stabilized below the level which is considered to be critical for the growth of spruce stands. Nitrogen concentrations in needles of the first generation reached a value of 1.14% (plot FD) in the October sampling or 1.18% (plot FS) and in the sampling from mid-December a value of 0.96% (plot FD) or 1.09% (plot FS). No statistically significant differences were found between FD and FS plots.

DISCUSSION

Concentrations of total nitrogen in soil are considered to be a relatively stable property which is not in correlation with the intensity of net mineralization (BIELEK 1998). These concentrations in the ecosystems under study exceeded 1% in the layer of the forest floor which was near to values found by KLIMO (1982) or GRUNDA and VOREL (1996) in acid Cambisols beneath spruce monocultures. The actual supply of mineral forms of nitrogen is, however, important for plants. Processes of organic matter mineralization occur in soil as a result of the activity of very numerous and various microflora. Ammonification is a primary process of the organic matter mineralization. It is evident that ammonium nitrogen was a seasonally predominating form in soils beneath young Norway spruce ecosystems of the Moravian-Silesian Beskids, which is typical of these ecosystems (HARMSEN, KOLENBRADER 1965; CARLYLE, MALCOM 1986; ÚLEHLOVÁ 1989; TIETEMA et al. 1992; ZÁHORA 1999). Nitrate nitrogen occurred in lower quantities than those in podzols and Cambisols beneath young Norway spruce stands in the Krušné hory Mts. (KULHAVÝ, FORMÁNEK, unpublished). Nitrite forms of nitrogen were found only sporadically, which corresponded to the results of EMMER (1999) in forest soils of the Krkonoše Mts. A release of ammonia into the environment occurs because in the course of ammonification the microflora is able to build in into its body only a certain amount of nitrogen per unit amount of carbon and any surplus of nitrogen is released into the environment. We suppose, therefore, that the C/N ratio in the decomposing organic matter is often decisive. The higher the amount of nitrogen in decomposing organic matter, the higher the amount of ammonium nitrogen released into the environment (BIELEK 1984). In podzols studied by our laboratory, the C/N ratio was rather high (> 20) in all soil layers. It is an indicator of reduced decomposition because it is indirectly proportional to the intensity of mineralization. Our study also shows that podzols generally rank among the soils with a low level of mineralization (BIELEK 1998). The concentration of ammonium nitrogen in the forest floor roughly corresponded to the values found by ZÁHORA (1993) on sites of the Moravian-Silesian Beskids reforested by Norway spruce plants and with the initial formation of ground cover.

The proportion of mineral nitrogen as related to the total nitrogen in soil is low (COLE, RAPP 1981) being lower particularly in the forest floor layer that was found by PELÍŠEK (1974) in humus horizons of podzols. The ratio, as compared with the values found by ZÁHORA (1992), was much lower than in the case of floodplain forest Fluvisols.

A number of factors affects the relatively low amount of mineral nitrogen in podzols beneath spruce stands of the Moravian-Silesian Beskids. One of the factors could be the potential competition of heterotrophic microorganisms and plants for ammonia ions (KILLHAM 1990). Fluctuations in nitrogen uptake during the growing season and relation to moisture conditions (STEPHEN, FIRESTONE 1991) and temperature (KOWALENKO, CAMERON 1976; HARMSEN, KOLENBRADER 1965) could play an important role. Leaching of nitrates can be a very important phenomenon changing the amount of mineral nitrogen in the localities or the shift of mineral nitrogen particularly of nitrate form into lower soil horizons could be one of the consequences of previous liming the effect of which could show in lower soil horizons after 12 years (LETTL 1991). The low content of mineral nitrogen in soils of the ecosystems could also be caused by long-

term changes accompanying the decomposition of humus substances (ULRICH 1983). Losses of mineral nitrogen could also be caused by denitrification which can be of interest for such ecosystems impoverishing them by up to 30% nitrate nitrogen as found by EMMER (1999) in forest soils of the Krkonoše Mts. or losses of nitrogen during proper nitrification (ŠIMEK 1998) which can be related to the lower pH value of soils (MARTIKAINEN 1985). Another factor, from the viewpoint of nitrogen transformation, is biological fixation of atmospheric nitrogen which, however, based on data published by other authors, appears to be negligible under given conditions (WEBER, SUNDMAN 1986). Mineral nitrogen also enters the soils in atmospheric depositions and its input in throughfall in the localities under study in 1999 amounted to 12.34 kg/ha per year on plot FD and 8.76 kg/ha per year on plot FS (FORMÁNEK 2000). As a matter of fact, the mineral nitrogen level in soil is not always and only decisive but the rate, i.e. ammonification and nitrification. Moreover, nitrogen mineralization is affected by considerable time and spatial variability which could be given by the variability of moisture (SIERA 1997), temperature, basic ion content and soil reaction (MARTIKAINEN 1985) on the sites. From the viewpoint of area and time, nitrate nitrogen variability was very high and a lot of other studies pointed out this fact (RAISON et al. 1987; DAVIDSON et al. 1992; FORMÁNEK, GRUNDA 2000). Liming and thinning had no significant effects on the seasonal dynamics of mineral nitrogen, ammonium nitrogen was a prevailing form on all the plots. In our experiments, we did not find a marked decrease in the concentration of ammonium and total mineral nitrogen after liming as reported by PERSSON (1988); LETTL (1991) or KULHAVÝ (1992). The differences in the content of nitrates between limed plots and control plot were not significant either as reported by PODRÁZSKÝ (1992). The main cause in the given ecosystems could consist in the higher C/N ratio (NÔMNIK 1979).

According to our results, nitrogen concentrations in needles of the first generation were below the limit for sufficient nutrition, being much lower than those found in 1999 in the case of 21–50-year-old spruce stands in the Krušné hory Mts. (KULHAVÝ, FORMÁNEK, unpublished). Our findings confirm the results published by KLIMO and KULHAVÝ (1996) that under certain conditions the growth of trees in the Moravian-Silesian Beskids is limited by nitrogen.

CONCLUSIONS

In podzols of the Moravian-Silesian Beskids beneath Norway spruce stands of the second generation, seasonal concentrations of ammonium and nitrate nitrogen considerably fluctuated in 1999. Although we do not know how the soil reaction, adsorption complex and mineralization of organic matter were affected immediately after liming, 12 years after the last application of dolomitic limestone the pH/H$_2$O value in the forest floor was 0.73–

1.07 higher and the pH/KCl value was 0.54–1.13 higher as compared with control. Its effect on changes in forms of mineral nitrogen in soil was not proved. From the total mineral nitrogen in the layer of forest floor, about 80% were in ammonium and 20% in nitrate forms. Nitrogen concentrations in needles of the 1st generation were below the limit for sufficient nutrition not being affected by stand density.

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Transformace dusíku v půdě a stav výživy mladých smrkových porostů Moravskoslezských Beskyd

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ABSTRAKT: Studie hodnotí vliv hustoty mladého porostu smrku a melioračního vápnění na přeměny dusíku v půdě a zároveň dusíkaté výživy smrkových porostů v hřebenové části Moravskoslezských Beskyd. Lokalitu ovlivňují kyselé průmyslové imise, proto byla v letech 1983, 1985 a 1987 meliorována vápněním. Koncentrace amonného i nitrátového dusíku v půdě během sezony značně kolísala. Na základě výsledků z roku 1999 v půdě převažoval dusík v amonné formě, nitrátového dusíku bylo méně a nitritový dusík byl detekován pouze sporadicky. Koncentrace dusíku v jehličí 1. ročníku byla pod hranicí pro dostatečnou výživu. Při dané intenzitě výchovného zásahu nebyl zjištěn vliv hustoty porostu na přeměny dusíku v půdě. Rovněž vliv melioračního vápnění s odstupem 12 let od poslední aplikace na přeměny dusíku v půdě nebyl prokázán.

Klíčová slova: smrk; dusík; výživa porostů

Problematika dusíku v lesních ekosystémech byla a stále zůstává obecně diskutovaným problémem. V této souvislosti můžeme na jedné straně mluvit o ekosystémech dusíkem nadměrně saturovaných, na straně druhé dusíkem limitovaných. Lesní půdy horských oblastí České republiky mají zvláště pod smrkovými monokulturami silnou vrstvu organické hmoty. Vliv kyselého opadu smrku s vysokým C/N a průmyslové imise mají často negativní vliv na rozklad organické hmoty. V organické humusové hmotě je poutáno množství dusíku a ostatních živin. Z této humusové zásoby by měl být dusík doplňován do půdního roztoku v minerální formě, aby mohl být lesními porosty opět asimilován. Zhoršené rozkladné podmínky však tomu brání.

Studie hodnotí vliv hustoty mladého smrkového porostu a melioračního vápnění na přeměny dusíku v půdě a výživu porostů v roce 1999.

Experimenální práce probíhaly na plochách s rozdílnou hustotou 21letého smrkového porostu (plocha FD 2 600 jedinců na ha a plocha FS 2 100 jedinců na ha), které jsou součástí objektu Ústavu ekologie krajiny AV ČR na Bílém Kříži v Moravskoslezských Beskydech a byly v letech 1983, 1985 a 1987 meliorovány vápněním. Plocha kontrolní (plocha FK 2 600 jedinců na ha) není součástí tohoto objektu a nebyla v minulosti vápněna. Půdním typem je na všech plochách mírný humusový podzol s mor-moderovou formou humusu. Směsné půdní vzorky byly během sezony odebírány z vrstev Ol,

Of+h, Ae a Ep. Amonný dusík byl stanoven v extraktech půd 1% K $_2$SO$_4$ upravenou indofenolovou metodou, dusík nitrátový byl po extrakci půdních vzorků demineralizovanou vodou stanoven kapilární elektroforézou a výsledky byly srovnány s hodnotami stanovenými po extrakci půdních vzorků 1% K $_2$SO$_4$ manuální spektrometrickou metodou s kyselinou sulfosalicylovou. Nitritový dusík byl stanoven pouze kapilární elektroforézou po extrakci půdních vzorků demineralizovanou vodou. Celkový C a N byl analyzován na analyzátoru LECO CNS 2000, aktuální a výměnná půdní reakce byly stanoveny potenciometricky. Pro stanovení úrovně výživy dusíkem byly měsíčně odebírány vzorky jehličí 1. ročníku z osmi stromů z osvětlené části koruny. Úroveň výživy smrkových porostů byla v roce 1999 stanovena pouze na vápněných plochách FD a FS, koncentrace dusíku byla stanovena na analyzátoru LECO CNS 2000.

V podzolech Moravskoslezských Beskyd pod studovanými porosty smrku ve druhé generaci sezonní koncentrace amonného a nitrátového dusíku v roce 1999 značně kolísala. Přestože nevíme, jakým způsobem byla na studovaných lokalitách ovlivněna půdní reakce, sorpční komplex a mineralizace organické hmoty bezprostředně po vápnění či s odstupem následujících let, po 12 letech od poslední aplikace dolomitického vápence byla v nadložním humusu hodnota pH/H$_2$O vyšší přibližně o 0,73–1,07 a pH/KCl přibližně o 0,54–1,13 v porovnání s kontrolou a nebyl prokázán její vliv na změny forem minerálního dusíku v půdě. Poměr C/N byl v jednotlivých půdních horizontech na všech plochách poměrně vysoký a téměř vždy přesahoval hodnotu 20. Podíl koncentrace minerálního dusíku k dusíku celkovému (N$_{min}$/N$_t$) činil v nadložním humusu kolem 0,1 % a v minerální půdě byl zpravidla vyšší. Z celkového minerálního dusíku bylo ve vrstvě nadložního humusu přibližně 80 % ve formě amonné a 20 % ve formě nitrátové. Koncentrace dusíku v jehličí 1. ročníku byla za daných podmínek pod hranicí pro dostatečnou výživu a nebyla ovlivněna hustotou porostu.

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Forest maps, their development and present accuracy

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ABSTRACT: Forest Act No. 289/1995 sets down the geodetical accuracy of plotting permanent units of the spatial division of forests on forest maps 0.0004 × M where M is the scale number of a map. For the basic forest map of 1:5,000, it means ± 2m. Cadastral or (derived) state maps at a scale of 1:5,000 are a mandatory map background for the preparation and creation of forest maps. In many cases, however, the accuracy of the maps is lower than 2 m. With respect to errors occurring in forest mapping, errors resulting from the insufficient stabilization of boundaries of the permanent units of forest division as well as overlapping the boundaries by tree crowns in using methods of photogrammetry, the fulfilment of the law requirements appears to be rather problematic.

Keywords: mapping; forest map; accuracy

According to Forest Act and related Regulation No. 84/1996 on forest management planning, working plans (WP) or forest management schemes (FMS) are prepared for all forests in the Czech Republic. Forest maps are the obligatory part of the WP and FMS.

The regulation exactly defines what the forest map is, which scale is used for the map, the content of the maps and which of the maps are an obligatory part of the WP and FMS.

Forest maps represent all timber land, non-stocked forest land and other land (Forest Act, § 3 1 b)). Timber land is classified into units of the spatial arrangement of a forest. These units are as follows: compartment, subcompartment, stand, stand part and storey while the basic unit of the forest division is a stand. Boundaries of compartments and subcompartments are designed with respect to distinct boundaries in the terrain.

Cadastral or (derived) state maps at a scale of 1:5,000 are an obligatory map background for the preparation of forest maps. According to the above-mentioned regulation, forest maps are prepared and mapped in the geodetical reference system of the Unified Trigonometric Cadastral Network (UTCN). In mapping of higher units of the spatial division of a forest, i.e. compartments and subcompartments (§ 6), geodetical accuracy of 0.0004 × M (m) is used where M (m) is the map scale.

The purpose of the paper is to evaluate the present state of forest maps, to assess legal requirements for accuracy and to find what measures will be necessary to comply with the law.

The accuracy of existing forest maps is affected by original maps and by the accuracy of geodetical and photogrammetric methods used in forest mapping.

(a) In using a cadastral map the following points are decisive for accuracy:
 – when the cadastral measurement was carried out;
 – what survey methods, instruments and aids were used, whether the locality was affected by a land reform, accuracy of surveying newly established plots.

(b) In using a (derived) state map at a scale of 1:5,000:
 – proximity of the contact of boundaries of neighbouring cadastral regions (the contact of boundaries of cadastral regions manifests itself particularly negatively in maps of fathom scales);
 – professional level of persons preparing the derived state maps 1:5,000.

(c) Present forest mapping uses predominantly methods of aerial photogrammetry and here, the accuracy is affected by:
 – the number and accuracy of reference points;
 – visibility of surveyed lines;
 – large height differences of the terrain relief;
 – instrumentation and computer equipment of the workplace.

The first evidence of forest mapping in the territory of this country is in the Rožmitál 'Land and Duties Regis-

ter', where the names of surveyors who surveyed and taxed the estates of lords of Rožmberk in 1369–1373 are given. As stated in archival materials, forests were given a special attention in the surveying. In the 16th century, the first management maps originated in the Rožmitál and Mirošov domains. In 1587, Jan Dětřich of Jáchymov drew up a map of the Hluboká domain where forests, forest glades, ponds and villages were depicted.

According to Vladislav's decree of 1500, a surveyor of the Czech kingdom (*mensor publicus*) was appointed at the state board administered by the highest chamberlain and the Czech chamber had its own emperor assistant in the art of geometry.

A marked progress in forest management planning and thus also in forest mapping occurred in the second half of the 18th century. Forest maps as part of forest management plans (working plans) were prepared nearly regularly in larger forest units and also owners of smaller forest units had their forests surveyed by private surveyors in many cases. For example, forests of the Town of Brno had the first instruction of regulated forest management and the first maps for the Vohančice, Deblín and Lažánky Forest Districts as early as 1736. General mapping of forests of the Town of Brno was carried out in 1772 based on the decision of its municipality and the mapping was accomplished by the statutory engineer Václav Štoček.

The development of forest mapping progressed simultaneously with the development of cadastral measurements. In the former Austria-Hungary, cadastral measurements were carried out in 1817–1862 on the basis of a trigonometric network constructed by means of directly measured bases. End-points of the bases were determined by rectangular and geographical co-ordinates. Full use of cadastral maps was, however, limited by a non-uniform cadastre and also by the purpose for which the maps were prepared. The purpose was not geodetical but it was to be a basis for determining the land tax. Cadastral Act No. 177 of 1927 represented an increased importance of cadastral maps for forest mapping. The law removed main faults in the field of a cadastre and cadastral maps as well as Cadastral Edict No. 70 046-36-III 6a of 1936 on unified geodetical operations which unified cadastral works in the whole territory of the Czechoslovak Republic. Both legislative measures eliminated faults in operating and using cadastral maps and thus also reasons preventing their full use in mapping the forest.

A great progress in forest management planning and thus also in forest mapping came after World War II. A 'forest inventory' was carried out to determine the real state of forests. Within the operations, a 'basic forest map' of all forests in the Czechoslovak Republic was created. As maps of many forest units were destroyed or lost by war events, Dr. K. Matějů, a guarantor for forest mapping in the Institute of Forest Management, Brandýs nad Labem, determined three methods of forest mapping with direct or indirect use of cadastral maps.

The methods were as follows:
– new measurements completing copies of cadastral maps. Measurements of a 'forest detail' were only a forestry matter not being subject to a surveyor's authorization. Therefore, it did not serve as a background for completing cadastral maps;
– new measurements completing copies of cadastral maps and at the same time constructing a separate forest map. In these cases, own measurements by means of local triangulation connected to a cadastral trigonometric network were often carried out. Although the measurement complied with cadastral directives from the aspect of its accuracy, it was not incorporated and used by the cadastre and the areas of permanent units of forest division often had to be fitted to the erroneous condition of the cadastre;
– new measurements of forests by the renewal of the land cadastre. In the case of more extensive inaccuracies of cadastral maps, 'authenticity cadastral procedures' were applied in some cases resulting in the preparation of a new cadastral map. During the procedure, permanent units of spatial division of the forest were surveyed and plotted in the map. In these localities, the most accurate basic forest maps were drawn up.

The proposal of Dr. Matějů was included in an 'instruction' forming the basis of forest mapping after World War II. During the period, a nation-wide map work was prepared according to uniform working procedures of the Institute of Forest Management, Brandýs nad Labem, representing all forests of this republic at a uniform scale of 1:5,000 with a uniform content. This map, also called 'basic forest map', formed a background for a management map and other special-purpose forest maps. It contained cadastral and permanent forest planimetry complemented continuously in renewals of working plans by records of changes carried out in the cadastre as well as by changes in a forest detail. The map also contained positions of points of point fields taken from geodetical documentation as well as points from own measurements.

Although forest mapping used nearly always the cadastre, it has to carry out complementing measurements of the peculiarities as well as measurements of both the permanent and variable forest details (because we express technical and biological relations of forest ecosystems in forest maps). Due to these reasons, photogrammetric methods and methods of remote sensing appeared to be useful and were also fully used. Modern photogrammetric methods facilitate quick, economically profitable and sufficiently accurate mapping of forests and completing forest maps by all changes in the forest detail. If technological procedures of the Institute of Forest Management (IFM) for forest mapping by means of photogrammetric methods are followed, the topographic accuracy of ± 0.4 mm should be ensured after a cartographic adjustment which corresponds to ± 2 m for maps at a scale of 1:5,000. This value corresponds to the present legal requirement.

The accuracy of mapping the boundaries of permanent units of spatial division of the forest can be negatively

affected by the width of tree crowns of old and particularly broadleaved stands occurring above the boundary. In these cases, the topographical accuracy of forest maps (as given by technological procedures of the IFM from 1981) can range from ± 0.4 to ± 1.4 mm, i.e. 2–7 m for a map scale of 1:5,000.

The accuracy of maps can also be unfavourably affected by large height differences of topography increasing the radial distortion along the projection line in applying single-image photogrammetry (GÁL 1965).

Forest mapping by photogrammetric methods carried out by the IFM, Brandýs n. L., uses the existing points of the positional point field and points determined by the method of analytical aero-triangulation in a common block (AATB).

To map points of a point field as well as points of a forest detail, the GS mapping system (according to Křovák) was used. Points and subsequently boundaries of a forest detail were drawn on unshrinkable 'astralone' sheets into a frame corresponding to the map layout SMO 1:5,000 i.e. 2 × 2.5 km.

Into the frame, it was possible to draw all later measurements expressed in the map co-ordinates. Calculations of the co-ordinates of detailed points of a forest detail were carried out by the method of analytical photogrammetry and the obtained co-ordinates were then incorporated into map sources (SMO 1:5,000 or miniatures of cadastral maps).

According to the quality of map sources, differences occurred between measured data and these sources. The largest differences were at the contact of particular models and particular map sheets. Arisen errors were adjusted on the graphical sources. This fact also negatively affected accuracy.

PRESENT STATE OF FOREST MAPPING

Also at present, aerial photogrammetry appears to be the fundamental method of forest mapping. As compared with the past, the method makes huge progress particularly in methodology and technology. It is enabled by satellite sensing, new photogrammetric instruments and powerful computers. Changes in technology are enabled by using microprocessor electronics which particularly in photogrammetry changes traditional methods of obtaining and evaluating image data. Numerical as well as graphical data processing is carried out in the IFM, Brandýs nad Labem, by the TOPOTAX software.

Forest maps as part of forest management plans (working plans) were prepared by the IFM, Brandýs n. L., till 1997. Since that year, forest management plans (FMP) and forest management schemes (FMS) can be prepared by forest inventory bureaux authorized for the activity by the CR Ministry of Agriculture.

The majority of FMP and FMS is processed in a digital form. The largest administrator of forests in this republic – Lesy ČR, s.p. (Forests of the CR, state enterprise) financed digital processing of FMP from its own sources in the last years. At present, it is possible to obtain financial means for the activity.

In the digital processing of forest maps, interconnection with numerical data of FMP should be established, i.e. it is necessary to create bases of a geographical information system (GIS). The interconnection forms an integrated information system including forest ecosystems, permanent units of the spatial division of a forest and also the smallest unit of forest division – 'part of a stand' (delimited in regenerated stands only where part of the original stand is delimited from the regenerated one). Both FMP /FMS data and data of management records can be referred to the area providing the possibility to monitor the fulfilment of FMP tasks. Results of the system can be used by administration, forest owners and statistics.

The TOPOL program with special supplements for some operations is a program for data processing in the field of GIS.

According to legal directives, the (derived) state map 1:5,000 remains the basis for drawing up forest maps. Due to imperfections in the directives, discrepancies occur in many cases between the map groundwork, written part and forest management data. However, another complication will occur in the next period consisting in the possibility to draw up FMP and FMS by various forest inventory bureaux. A problem will occur when several cruising bureaux operate in a working-plan area (WPA) at the same time and without uniform preparation for the whole WPA. In these cases, various input materials will be transformed so that different mapping of boundary lines will appear. In order to prevent the complications it would be suitable and useful to authorize one of the bureaux to draw up the boundary lines. Results of the mapping would be obligatory for other bureaux.

INSTRUMENTS AND METHODS VERIFYING THE ACCURACY OF FOREST MAP DRAWING

On the basis of existing work with input materials serving for forest mapping (cadastral maps and derived state maps 1:5,000) and knowledge of their faults, check-out measurements were carried out of point fields, groundwork maps and points of a forest detail on several randomly selected localities. Control measurements were carried out in the same co-ordinate system as forest maps, i.e. S-JTSK.

a) Verification of the accuracy of a point field and control points for photogrammetric measurements

For the verification, a modern and progressive method of GPS (Global Positioning System) was used carried out by the Wild GPS system 200 satellite installation, product of Leica Co., Heerbrugg, Switzerland. The instrument was lent by the Department of Geodesy, Faculty of Civil Engineering, University of Technology, Brno. The installation made it possible to receive and process satellite signals on both frequencies from max. 9 satellites simultaneously. Thus, it referred to a 9-channel two-frequency GPS allowing to process both code and phase measurements, i.e. an apparatus suitable even for accurate geodetical applications.

Table 1. Positional deviations of points of the basic positional point field (BPPF) used as identical points for co-ordinate transformation

Point number	Positional deviation between BPPF points determined by terrestrial methods and by GPS (interp. transf. key) op (m)	Positional deviation between BPPF points determined by terrestrial methods and by GPS (trad. transf. key) op (m)
55 (3316)	0.026	0.001
58 (3316)	0.026	0.019
3 (3317)	0.045	0.018
10 (3317)	0.017	0.021
13 (3317)	0.046	0.020

The advantage of the apparatus during measuring in the forest consisted in a small weight of the sensor and controller, easy operation and also suitable software installed in a PC computer. The main function of the program consisted in the conversion of co-ordinates carried out by the GPS apparatus in the WGS 84 co-ordinate system into the S-JTSK co-ordinate system.

It referred to the conversion of a spatial (three-dimensional) co-ordinate system into a plane (two-dimensional) system of the given cartographic image with a possible relation to height. It was because co-ordinates of points in national networks are related to another ellipsoid than WGS 84. In the CR, there is Bessel's ellipsoid for S-JTSK and Krasovsky's ellipsoid for S-42. Two different methods of calculation were used for the transformation of particular points (by reason of check-up):

1. by means of a classical transformation key calculated using the similarity transformation where the procedure of calculation consists in the transformation of two identically orientated Cartesian co-ordinate systems with the various angular displacement of axes and with various scales;
2. by means of an interpolation method based on the model of affined transformation using the principle of collocation for the determination of a systematic component of adjustment.

Comparisons of point determination by traditional terrestrial methods (existing co-ordinates of the points) with measurements using GPS are given in Tables 1 and 2.

Accuracy analysis was discussed in another paper of DOUŠEK (1996).

b) Verification of the accuracy of drawings on forest maps

The accuracy of drawings of the permanent units of forest division on forest maps was assessed from the difference of co-ordinates displaced on a forest map and co-ordinates obtained by a direct measurement, see § (a) and accuracy of obligatory map sources, see § (b).

Accuracy of drawings on forest maps

The accuracy was assessed in the Working-Plan Area at Lomnice locality, subcompartment 113 D, from the difference of co-ordinates displaced on a forest map and co-ordinates obtained by a direct measurement (DOUŠEK 1996).

The measurement was carried out using polygonal traverses measured by an electronic theodolite PENTAX PCS – 1s. It referred to polygonal traverses connected and orientated on both sides and calculated by approximate adjustment.

A difference was assessed between the area calculated from the co-ordinates from direct measurements and the area in the working plan. The situation is given in Fig. 1:

area calculated from the co-ordinates   95,812 m²
area given in the working plan   96,200 m²
difference in the areas   388 m²

The actual difference reaches a value of 0.4% and if we do not take into consideration the position of a subcompartment to neighbouring units of forest division, it shows a very good quality of surveying.

Table 2. Positional deviations in newly determined points calculated by the comparison of a traditional terrestrial measurement with adjustment by the method of least squares (LSM) and measurements by the GPS method

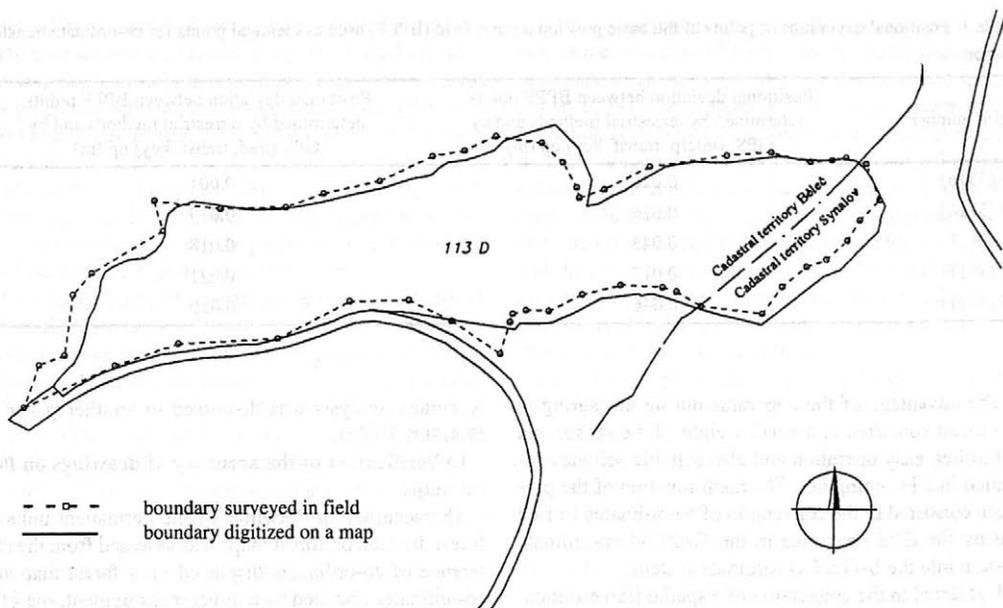| Point number	Positional deviation between points calculated by LSM and GPS (interp. transf. key) op (m)	Positional deviation between points calculated by LSM and GPS (traditional transf. key) op (m)
520	0.008	0.028
521	0.003	0.025
542	0.020	0.037
543	0.025	0.025
544	0.016	0.000
590	0.025	0.037
592	0.033	0.041

Fig. 1. Verification of drawing subcompartment 113D, Forest District Tišnov
On forest contour map 1:5,000 Bystřice nad Pernštejnem 4–5

In order to be able to evaluate also the accuracy of position a difference was assessed between the drawing of subcompartment 113 D on a forest map and the drawing obtained from the co-ordinates of polygon measurement.

Differences in transverse displacement reached a value of max. 24 m, in a forest road forming one of the subcompartment boundaries up to 16 m. The values exceed the geodetical accuracy of forest maps given by Regulation 84/1996 and it will be necessary to meet the legislative requirements when renewing the working plan.

The size of a mean absolute deviation between the actual state in the terrain (field) and situation on a forest map is $dx = 10.0$ m, standard deviation of a compared distance is $sx = \pm 12.2$ m.

In mapping subcompartment 113 D, a cadastral boundary going through the eastern part of the subcompartment was also mapped.

The deviation did not exceed a given limit of ± 2 m and, therefore, it is possible to suppose that errors in drawing the subcompartment boundaries originated in forest mapping. It is possible to assume that incorrect determination of boundaries on a forest map does not consist only in surveying methods and their accuracy but also in the insufficient stabilization of the boundaries.

It is evident that if we want to achieve accuracy given by the regulation we have to stabilize and survey boundary points by terrestrial methods in overgrown and shaded localities or to release the points for photogrammetric measurements. It is also wrong to think that the bound-

ary stabilization will be ensured by means of marks on trees in the proximity of the boundary.

(c) Verification of the accuracy of obligatory original map sources used for drawing up forest maps

In these cases, the accuracy was assessed of the cadastral boundary drawing, the accuracy of the contact of particular map sheets and the accuracy of drawing particular plots.

1. To verify the accuracy of a cadastral boundary, the Rašov-Šerkovice cadastral boundary was randomly selected. The boundary was drawn on a map at a scale of 1:2,880 (in a 'fathom scale'). The situation is given in Fig. 2. Landmarks were found on the cadastral boundary in the field and these were accurately surveyed using an electronic theodolite and electrooptical distance meter. The map drawing was transformed by means of similarity transformation into the S-JTSK system. In total 28 distance deviations were calculated between the boundary points. Mean absolute size of the deviation reached a value of $dx = 2.6$ m, standard deviation $sx = \pm 4.0$ m.

2. The accuracy of drawing the cadastral boundary is documented on a map sheet in a fathom scale, and the contact of cadastral boundaries between the cadastral areas Malá Morávka and Podlesí is depicted on the same map sheet. Differences in the boundary drawing depicted by a solid and dashed line amount to a value of max. ± 5 m (Fig. 3). The inaccuracy of drawing the map sheet frame originates from assigning the draw-
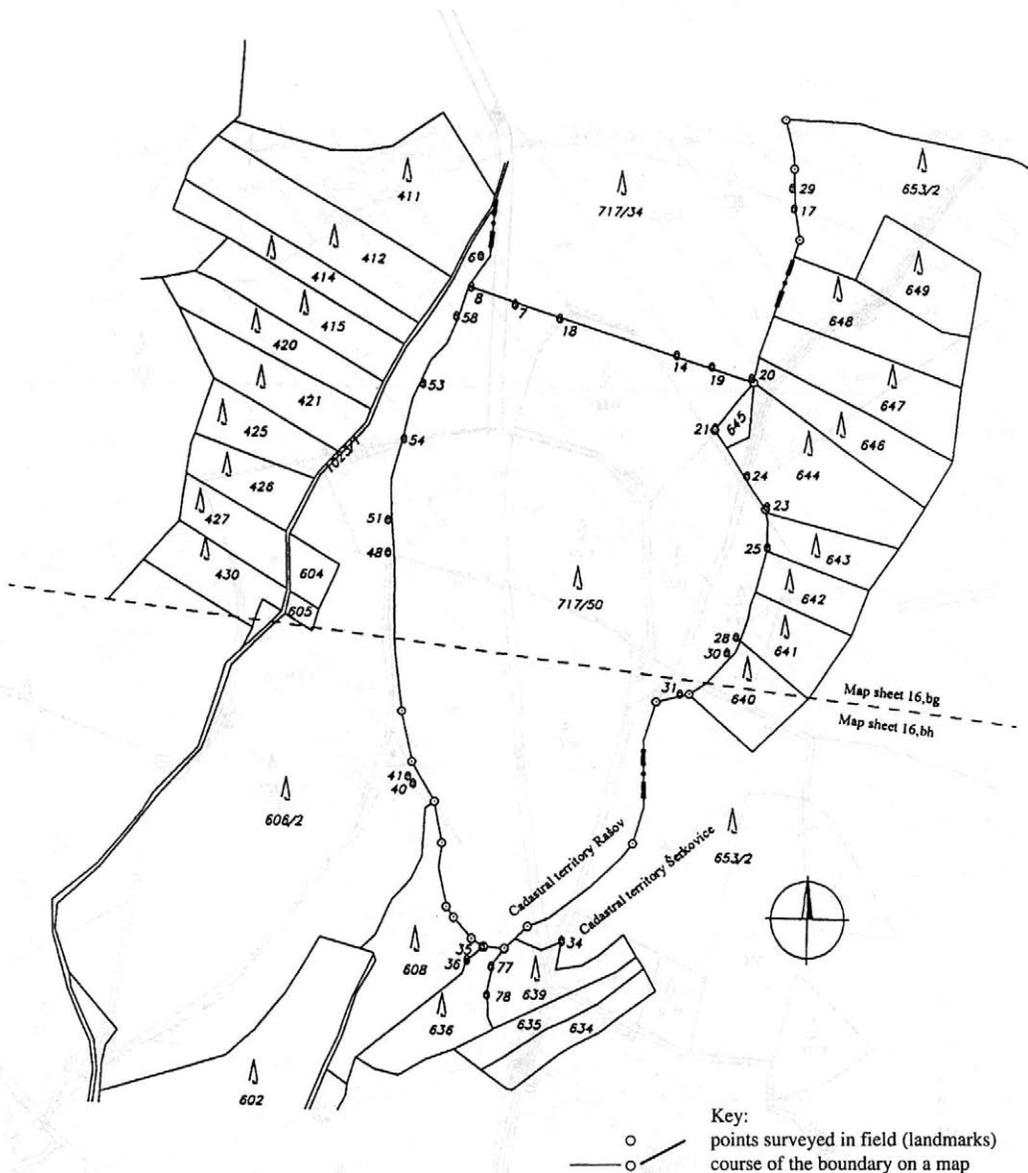
Fig. 2. The sketch of a marked out boundary (scale 1:5,000)

Key:

○ ╱   points surveyed in field (landmarks)

──○╱   course of the boundary on a map

ing of the neighbouring map sheet (depicted by a dashed line) and corresponds to a value of ± 5 m. Deviations are caused by the deformation of previously used paper map sheets and lower graphical accuracy of drawing in the proximity of the map sheet frame resulting from the method of forward intersection (plane-table method).

Extraordinarily large differences were found between the boundary drawing of particular forest plots on a cadas-

tral map and reality, and there were also differences in drawings at the contact of neighbouring map sheets in laying out forest plots by a geodetical bureau in Opava in border regions of northern Moravia (Fig. 4). In an exemplary case, differences in the plot drawing and drawing of neighbouring map sheets approach the value of ± 10 m.

The results show that the accuracy of drawing of original map sources is lower in some cases than accuracy required by legislation for forest maps.

Fig. 3. Discrepancy in the drawing of the cadastral area boundaries on the land cadastre maps

Fig. 4. Discrepancy between the drawing of the map sheet frame and drawing of the boundaries on the land cadastre maps

CONCLUSION AND PROPOSALS FOR SOLVING THE PROBLEMS

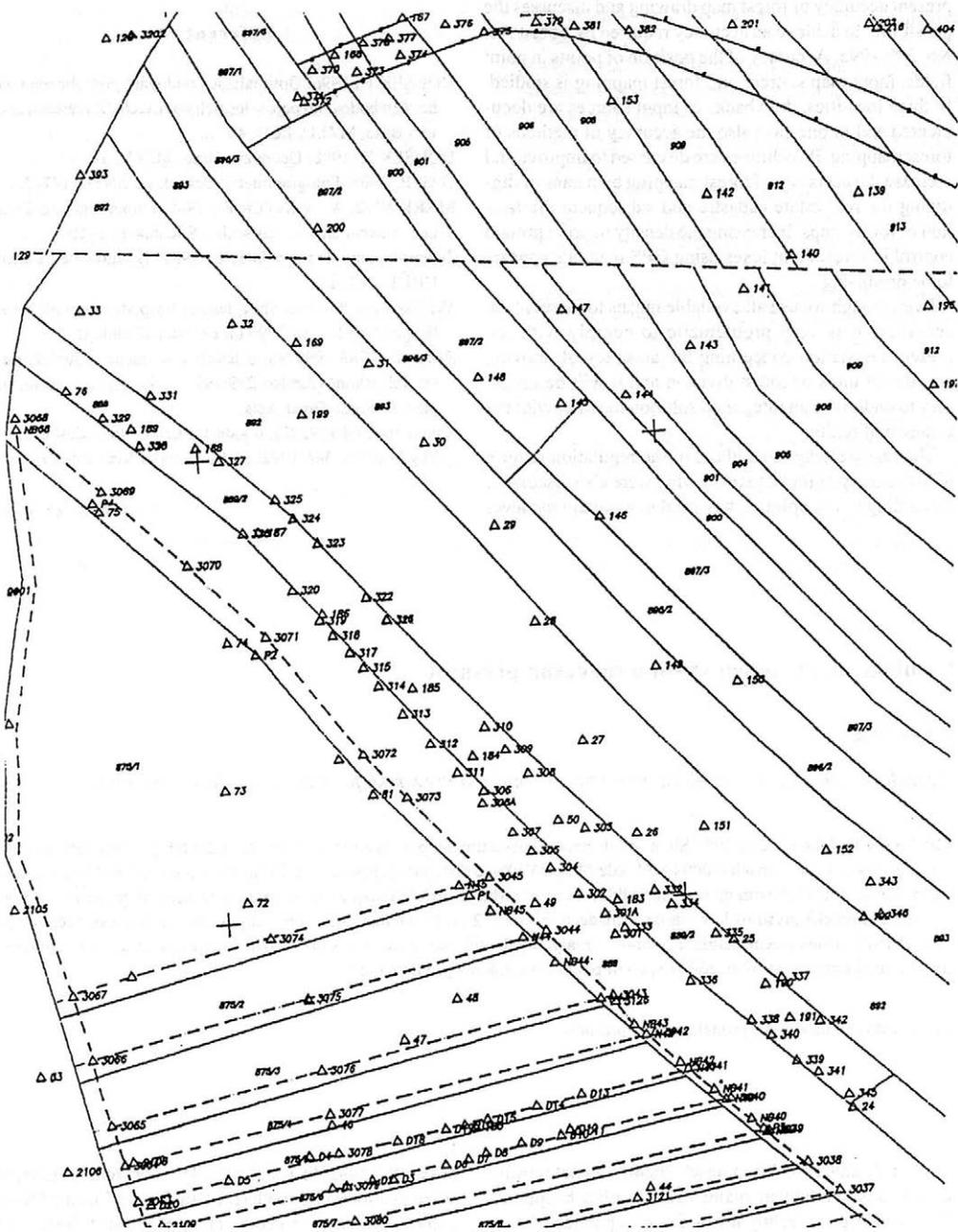The present paper deals with the development and present accuracy of forest map drawing and discusses the possibility to achieve an accuracy required by Forest Act No. 289/1995. Accuracy of the position of points in point fields, input map sources and forest mapping is studied. In three localities, drawbacks of input sources are documented and in one case also the accuracy of methods of forest mapping. Possibilities are discussed to improve and increase the accuracy of forest mapping by means of digitizing the real estate cadastre and subsequent digitization of forest maps. Increasing the density of point ground control in forest complexes using GPS methods appears to be promising.

Even though we use all available means to increase the accuracy, it is very problematic to comply with the present legislation concerning the accuracy of drawing permanent units of forest division and it will be necessary to undertake an integrated solution together with the cadastre of realty.

The reasons why the authors of the regulation require high accuracy of forest map drawing were also discussed. According to my opinion they tried to maintain the level of accuracy of forest maps even under situations when forest management plans and forest management schemes are prepared by various physical and legal entities which obtained a licence for these activities.

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Lesnické mapy, jejich vývoj a současná přesnost

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ABSTRAKT: Zákon č. 289/1995 Sb. o lesích stanovil geodetickou přesnost kresby trvalých jednotek prostorového rozdělení lesa na lesnických mapách 0,0004 × M, kde M je měřítkové číslo mapy. Pro základní lesnickou mapu 1 : 5 000 to znamená ± 2 m. Závazným výchozím mapovým podkladem pro tvorbu lesnických map je mapa katastrální nebo státní mapa 1 : 5 000 – odvozená, jejichž přesnost je v mnoha případech nižší než 2 m. Připočítáme-li k tomu chyby vzniklé při lesnickém mapování, chyby z nedostatečné stabilizace hranic trvalých jednotek rozdělení lesa a při použití fotogrammetrických metod překrytí hranic korunami stromů, zdá se splnění požadavku zákona problematické.

Klíčová slova: mapování; lesnická mapa; přesnost

Zákon č. 289/1995 Sb. o lesích stanovil vyhotovování lesních hospodářských plánů nebo lesních hospodářských osnov pro všechny lesy v České republice. Povinnou součástí těchto plánů a osnov jsou lesnické mapy. Závazným mapovým podkladem pro tvorbu lesnických map je mapa katastrální nebo státní mapa 1 : 5 000 – odvozená. Lesnické mapy se zpracovávají a zobrazují v geodetickém referenčním systému Jednotné trigonometrické sítě katastrální (S-JTSK). Při zobrazení vyšších jednotek prostorového rozdělení lesa, kterými jsou oddělení a dílec, se pracuje s geodetickou přesností 0,0004 × M, kde M je měřítkové číslo mapy. To znamená pro základní lesnickou mapu 1 : 5 000 přesnost zobrazení ± 2 m.

Vyhláška přesně definuje, co se rozumí pod pojmem lesnické mapy, v jakém měřítku se vyhotovují, které z těchto map jsou povinnou součástí lesních hospo-

dářských plánů a které lesních hospodářských osnov. Lesnické mapy zobrazují veškerou půdu porostní, bezlesí a jiné pozemky (§ 3, odstavec l, písmeno b lesního zákona). Půda porostní se zařazuje do jednotek prostorového rozdělení lesa, což je oddělení, dílec, porost, porostní skupina a etáž, přičemž základní jednotkou tohoto rozdělení je porost, který musí být vždy vylišen.

Veškeré lesnické mapy až do roku l997 vyhotovovali pracovníci Ústavu pro hospodářskou úpravu lesů v Brandýse nad Labem. Jednotky prostorového rozdělení lesa byly určovány převážně metodami fotogrammetrie a dálkového průzkumu Země. Při dodržení technologických postupů ÚHÚL pro lesnické mapování a při stabilizaci hranic měřených jednotek měla být po kartografické úpravě zajištěna polohová přesnost ± 0,4 mm, což se pro mapu měřítka 1 : 5 000 rovná ± 2 m.

Přesnost kresby hranic může být ale negativně ovlivněna korunami starých, zvláště listnatých stromů nacházejících se nad touto hranicí, a v tomto případě polohová přesnost kresby, jak uvádějí technologické postupy ÚHÚL (1981), se pohybuje od ± 0,4 mm až do ± 1,4 mm, tj. od dvou do sedmi metrů. Přesnost také negativně ovlivňují velké výškové rozdíly terénu, které zvětšují radiální zkreslení ve směru promítacího paprsku.

Na základě práce s lesnickými mapami se autor článku domníval, že jejich přesnost nesplňuje v mnoha případech legislativní požadavky a pro ověření této domněnky náhodně vybral několik lokalit, kde provedl přesná ověřovací měření vstupních mapových podkladů i lesnických map. Na základě těchto měření byl dokázán vliv na přesnost lesnických map:

- z chyb vzniklých nedostatečnou stabilizací hranic – označením stromů v blízkosti hranice není tato dostatečně fixována,
- z chyb použitého mapového podkladu, který v mnoha případech překračuje požadovanou legislativní přesnost lesnických map,
- z chyb vzniklých stykem hranic sousedních katastrálních území,
- z chyb z nepřesnosti rámu mapového listu,
- z chyb vzniklých překrytím hranice vyšší jednotky prostorového rozdělení lesa korunami stromů.

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Přesnost lesnických map je možné mj. také zvýšit převzetím hranic jednotlivých lesních parcel, případně dalších prvků polohopisu, z digitalizovaného katastrálního operátu (DKM – digitální katastrální mapa nebo KM-D – katastrální mapa – digitalizovaná). Data KM-D bude ale nutné transformovat pomocí vybraných identických bodů do souřadnicového systému S-JTSK.

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Economic evaluation of bark stripping by red deer on the basis of analysis on a time growth series of spruce stands in the Hrubý Jeseník Mts.

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ABSTRACT: An analysis was carried out on the time growth series of Norway spruce stands (both stripped and non-stripped) from the region of the Hrubý Jeseník Mts. aimed at the following aspects: (1) differences in the values of biometric and mensurational variables of stripped and non-stripped stands and (2) the extent of potential economic losses caused by red deer stripping in a felling age. It has been proved that the high 60–100% red deer stripping of trees causes a decrease in basic mensurational values of stands and particularly in standing volume by 20–30% with reference to the rotation period. Using assortment structure from generalized values of the region and price relations usual in the region it is possible to state that losses in wood price at the roadside in stands damaged by bark stripping amount to CZK 266,000 per hectare on average. The data support a requirement for the permanent minimization of losses due to bark stripping caused by red deer depending both on game stock and management strategy in forestry in relation to the natural environment and methods of game management. The method of evaluation is effective both in forest practice and in the field of research.

Keywords: red deer; bark stripping; stripping losses; economic evaluation; analysis; time growth series; spruce stands; Hrubý Jeseník Mts.

Problems of damage due to bark stripping caused by red deer are often a very discussed matter particularly from the beginning of changes in socio-economic conditions in the Czech Republic. The aspect is quite logical if we take into account the fact that according to official statements of the CR Ministry of Agriculture (1998), in 1979–1988 damage caused by bark stripping was found on a reduced area of 6.4% of the CR area of forests. Thus the effect of such great damage to trees on production, stability of stands and generally their prosperity is indisputable. For example NYMBURSKÝ (1992) mentions that due to bark stripping and browsing, growing stock quality is reduced by 20–30% and quantity by 10%. The problem was generally assessed also by other Czech authors, e.g. by HENŽLÍK (1989, 1995). Abroad, it was TURČEK (1962), DABURON (1963), WAGENKNECHT (1965), EIBERLE (1966), SZUKIEL (1986), EIBERLE and KLOTZLI (1968), PAGAJDA (1968), HANNAN and WHELAN (1989), etc. Data on the evaluation of the degree of damage are usually derived from forest management plans. Concrete studies comprehensively analysing the problems in selected regions during a long-term period are, however, missing.

THE DEVELOPMENT OF RED DEER STOCK

Reconstruction of the development of game stock in a longer period (about 150 years) in the present organizational or administrative limits is a very difficult problem particularly for the following reasons. On the one and, in such a long period organizational units and thus also units of records were changed and on the other hand, the quality of records was different. In the last 50 years, the information basis was not quite objective and unfortunately, this fact often outlasts. With respect to reasons for the CR (from the viewpoint of the paper particularly the region of the Hrubý Jeseník Mts.), it is possible to speak usually only about generalized information. BEDNÁŘ et al. (1963) and BÁLEK (1995) mentions that in the course of World War 1, the red deer population reached 5–10 animals per 1,000 ha. According to MINX (1995), the last 60 years have been characterized by the consid-
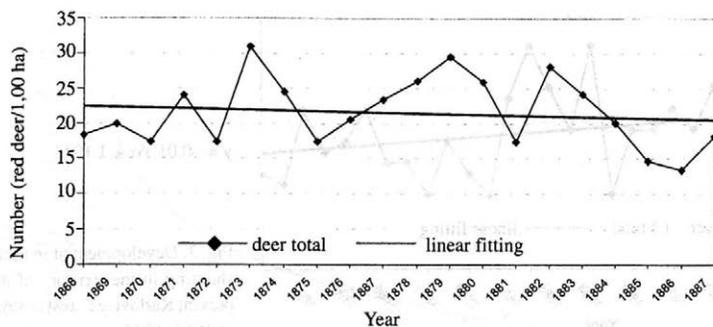
$y = -0.0988x + 22.597$

Fig. 1. Development of red deer population in the territory of the present Karlovice Forest District in 1868–1887

erable increase in hoofed game stock. The facts were confirmed by BABIČKA et al. (1995), who mentioned the region of the Jeseníky Mts., where in 1978 the red deer population was estimated to be 40 animals per 1,000 ha and these game populations increased to 50–60 deer per 1,000 ha in the 80s. The statement can also be supported by data on bags. MLČOUŠEK (1995) mentions for example an increase in bags by 410% (converted) in the Jeseníky Mts. in 1968–1990. For similar conditions, an experimental plot at an altitude of 800–1,491 m in the region of the Hrubý Jeseník Mts., KOUBEK et al. (1995) give an increase in kill from 12 to 27 deer per 1,000 ha in the last two years. Similarly, in the official report of the CR Ministry of Agriculture (1998), increased shooting by 140% (converted) is stated in the years 1980–1991 which is related to the trend of decreasing populations of particular species of hoofed game.

The most difficult task is to determine game stocks from historically distant periods (within the reference interval the end of the last century). For the region of the Karlovice Forest District which is undoubtedly in the forefront of interest during discussions on the problem in the Czech Republic, the data were collected and processed by the Institute of Forest Management, Olomouc Branch Office (Figs. 1–3). It is necessary to thank the workers of the Institute, namely Ing. A. NAVRÁTIL and Ing. I. ZATLOUKAL, for their work in this respect.

MATERIAL AND METHODS

Studies were carried out in 1999 in the selected parts of the Suchá Rudná and Praděd Forest Districts, Forest Administration Karlovice on the time series of pure even-aged Norway spruce stands classified into the forest type group 6 K (management set of stands – HS 53). The correspondence of natural, production and economic conditions was taken into consideration. Plots for analyses (of about 1 ha) were in particular stands of the time series (with a 10-year step) selected in duplicate. The choice was carried out on the basis of assessing the fitted series of mean stand height values for both the stripped and non-stripped sets, fitting was carried out by Mikhailov's growth function in the form:

$$h = A \cdot e^{-\frac{k}{t}}$$

with the following test of statistical significance and deviating values. To determine deviating values, probability zones were used. The package of programs of the Department of Forest Management, Faculty of Forestry and Wood Technology Mendel University of Agriculture and Forestry in Brno was used. Basic characteristics of stands of the time series (stripped and non-stripped) are given in Table 1. Detailed measurements of stands were carried out by standard mensurational methods (ZACH et al. 1994; DRÁPELA 2000;
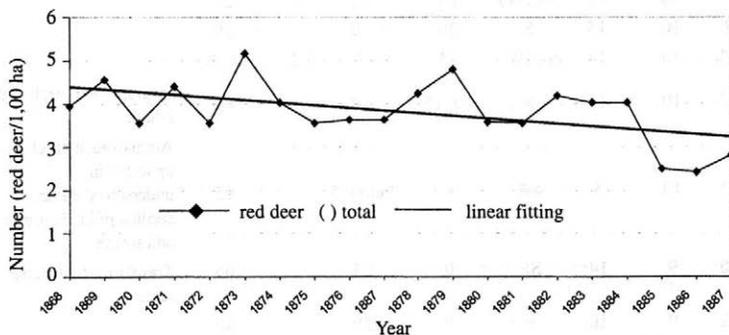
$y = -0.0611x + 4.4484$

Fig. 2. Development of red deer population in the territory of the present Karlovice Forest District in 1868–1887
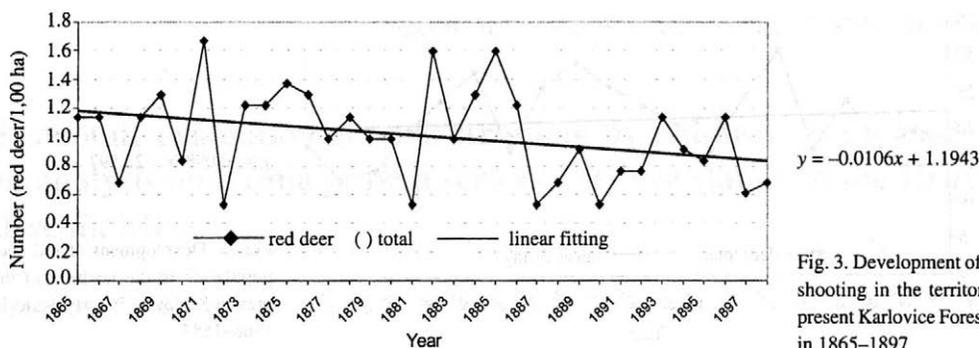
$$y = -0.0106x + 1.1943$$

Fig. 3. Development of red deer shooting in the territory of the present Karlovice Forest District in 1865–1897

ŠMELKO 2000). The output of the analysis is an assortment structure comparing stripped and non-stripped stands (according to long-term standards from the region) with the calculation of prices of different assortments for evaluating the economic effect of bark stripping by deer.

RESULTS

RED DEER STOCK

The development of the red deer stock and red deer shooting in 1865–1898, i.e. in the period when stands of

Table 1. Basic characteristics of stands of a time series

| Stand part	Serial No.	Forest type group	Spruce propor- tion	Age	Stocking	Slope (°)	Aspect	Stripping Browsing (%)	Top breaks (%)	Dead standing trees (%)	Cover (%)	Note
701 C1	3	6K	100	6–7	10	12	E	0	–	–	100	Interspersed birch
702 B1	7	6K	100	5	10	7	SW	0	–	–	100	
714 A1	21	6K	100	6	10	7	SE	10	–	–	100	
705 B2	20	6K	100	17	10	14	SE	60–70	–	–	0	
701 C2x	1	6K	100	29	10	12	E	50–60	–	–	0	Probably from natural regeneration
701 C3x	4	6K	100	31	10	5	E	100	–	1	0	Neglected tending
718 D4	10	6K	100	40	10	9	SE	95	20	–	5	
702 A4	8	6K	100	45	10	14	SE	95	10	5	10	Neglected tending
702 B4	11	6K (6S)	100	55	10	16	SE	40	10	–	20	Transition to a richer series
705 A6	17	6K	100	58	10	12	S	100	5	3	5	
702 B4	9	6K	100	64	10	4	SE	25	15	1	15	
702 A6	5	6K	100	68	9	8	SE	95	10	–	60	Neglected tending
705 A8	16	6K	100	82	10	12	SW	90	–	2	15	Interspersed larch
705 A8	18	6K	100	83	8–9	10.5	SW	60	40	–	40	
704 A9x	13	6K	100	85	10	12	S (SW)	60	30	5	20	
714 C10	15	6K	100	92	10	15	S	20	10	–	20	
705 A10	19	6K	100	103	10	14	S (SW)	15	5	2	45–50	
703 B11	12	6K	100	112	10	14	E	10–15	10	–	40	Interspersed birch and beech
702 A12	6	6K	100	112	10	5	SE	0	below 5	–	95	Admixture of beech up to 5% in understorey; natural seeding of birch, rowan and spruce
715 A12	14	6K (6S)	100	120	9	14	SE	0	25	–	65	Transition to a richer series
719 A14	2	6K	100	122	9	10	E	0	30	–	95	

$$y = -945.13\text{Ln}x + 5{,}086.2$$
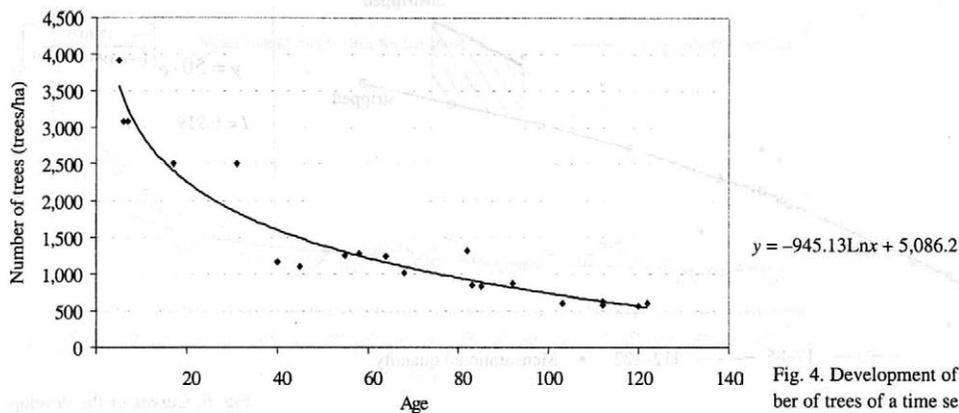
Fig. 4. Development of the number of trees of a time series

the non-stripped part of the time series were established, is given in Figs. 1–3. The diagrams show that the game population reached about 20 deer per 1,000 ha. However, red deer shooting amounting to about 1 deer per 1,000 ha is more significant. With reference to literature data, it is possible to consider 5–10 deer per 1,000 ha in the period of World War 1 and as much as 60 deer per 1,000 ha in the 80s of the twentieth century. The given data unequivocally prove the well known fact of the fluctuating game stock and its marked increase in the 50s to the 90s. The fact can also be documented using the values of shooting.

BIOMETRIC CHARACTERISTICS OF STANDS OF THE TIME SERIES

The development of the number of trees of the time series and exemplary curves of the development of mean heights and diameters with the mathematical formulation for the part of series of stripped stands is given in Figs. 4–6. The development of the number of trees of the stripped and non-strip parts is analogous, however, there is a marked difference in the values of mean diameter and height where is an evident and significant deficit, i.e. increment loss. The development is also illustrated in

$$y = 40 \cdot e^{\left[\frac{21.8771}{(1-1.8841)\,t^{1.8841-1}}\right]}$$

$$I = 0.919$$
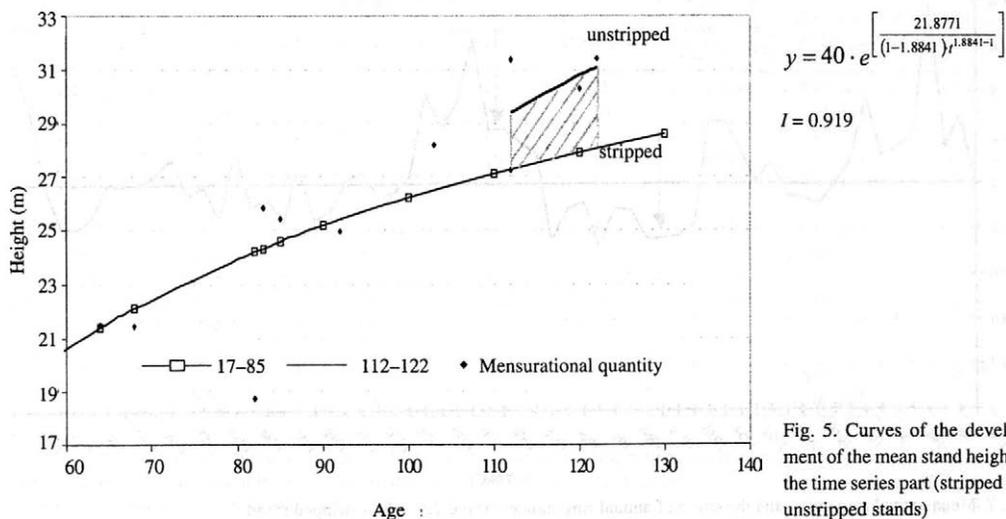
Fig. 5. Curves of the development of the mean stand height of the time series part (stripped and unstripped stands)

$$y = 50 \cdot e^{\left[\frac{17.1075}{(1-1.8364)t^{1.8374-1}} \right]}$$

$I = 0.919$
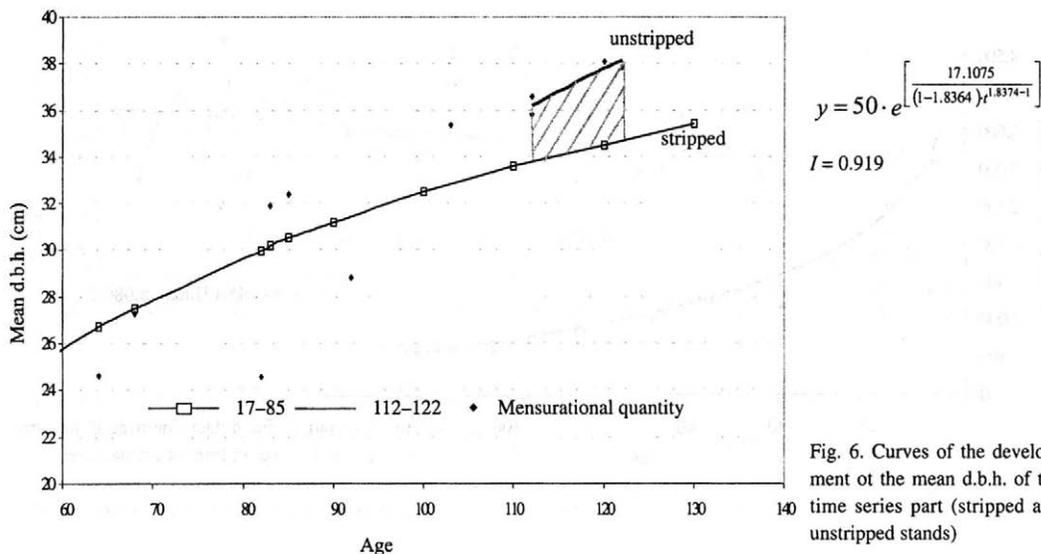
Fig. 6. Curves of the development ot the mean d.b.h. of the time series part (stripped and unstripped stands)
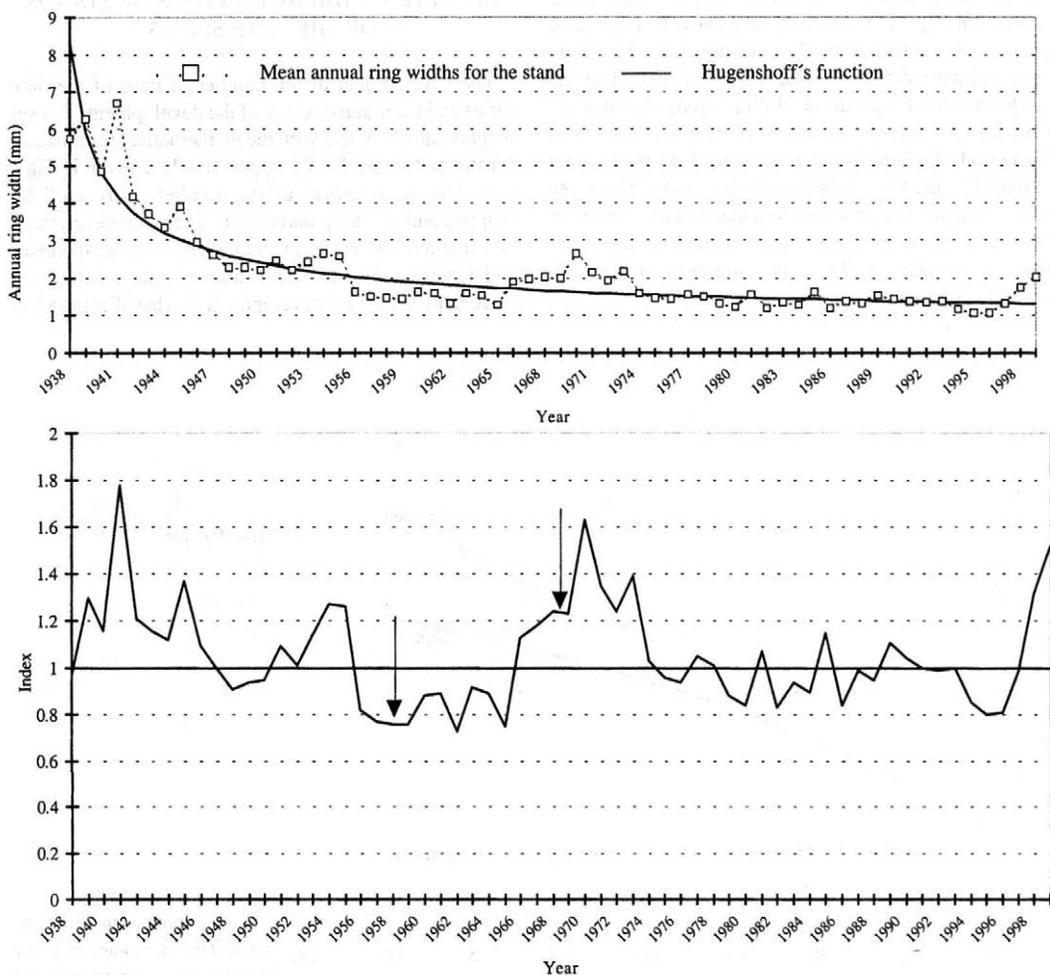

Fig. 7. Mean annual ring curve and the curve of annual ring indices (stand 702 A6) – stripped stand
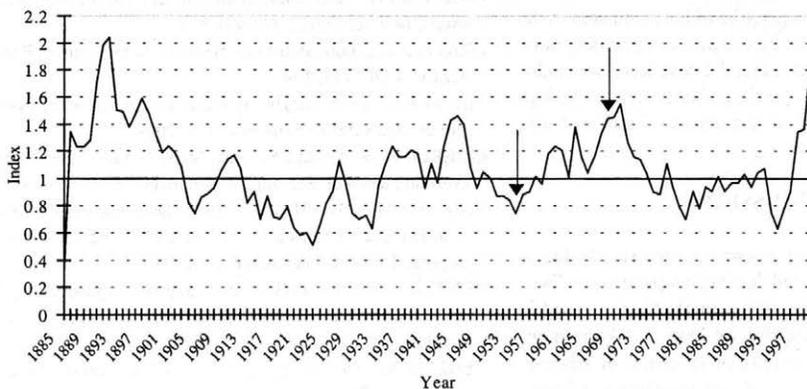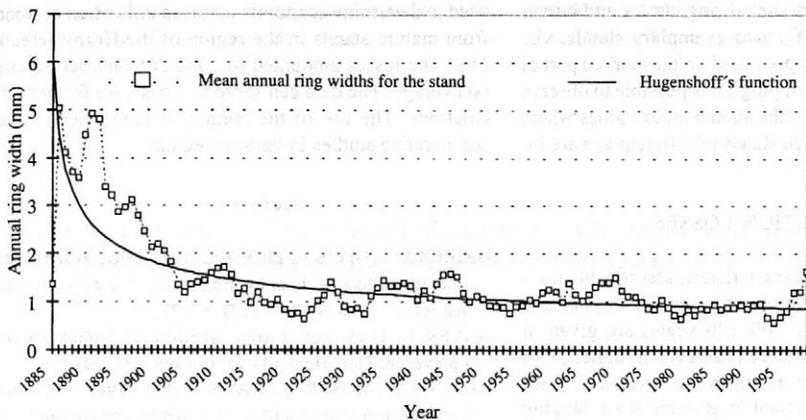
Fig. 8. Mean annual ring curve and the curve of annual ring indices (stand 715 A12) – unstripped stand

Table 2. Basic biometric characteristics, assortment structure and economic comparisons of sets of stands stripped (above) and unstripped by red deer (Forest District Karlovice)

Age	d (cm)	h (m)	v (m³)	N (trees/ha)	V/ha share (m³)	Assortment	Assortment share (%)	Price of assortments (CZK/m³ i.b.)	Total price (CZK/ha)	Price difference (CZK/ha)
100	32	26	1.00	730	730	IIIa	25	1,940	935,640	260,362
	34	28	1.20		876		30		1,196,002	
105	33	26.5	1.08	690	745.2	IIIb	35	1,605	954,865	250,694
	35	28.5	1.28		883.2		35		1,205,559	
110	33.5	27	1.16	640	742.4	V	25	779	951,020	254,539
	36	29	1.38		883.2		25		1,205,559	
115	34	27.5	1.18	600	708	fuelwood	15	268	910,006	264,152
	37	29.5	1.43		858		10		1,174,158	
120	34.5	28	1.21	550	665.5				845,922	300,930
	37.5	30	1.52		836				1,146,852	

Note:
– in the stripped set, calculations are carried out taking into account about 2 m of the stem base,
– price calculations carried out by the Czech Statistical Office, time horizon X. 2000
  (costs at the roadside not included)

Mean difference
in prices
(CZK/ha)
ca. 266,000

Figs. 7–8 showing mean annual ring curves and curves of annual ring indices for two exemplary stands, viz. a stripped and a non-stripped stand. In the marked part of curves (period of bark stripping), it is possible to observe quite a different course of the annual index values which should be similar although stands of different age are involved (climatic factor).

PRODUCTION LOSSES

Basic mensurational characteristics, assortment structure and economic calculations of the part of stripped and non-stripped stands (age 100–120 years) are given in Table 2. In all the stands there is an evident deficit, loss in all biometric parameters, from the economic point of view being most important in growing stock ranging from 20 to 30%. After sorting, differences in prices at the roadside without the calculation of costs amount to CZK 266,000 on average per 1 ha of the stand area in the rotation age. The data can be considered as an economic loss with respect to the fact that the cost items are analogous and the total disproportion of costs related to logging activities in parts of the series of stripped and non-stripped stands is not high.

DISCUSSION

Problems of damage to Norway spruce stands due to bark stripping caused by red deer are a topical issue. Even though we admit that the damage markedly decreased in the course of the last decades we have to take into account that there is an extensive spectrum of stripped stands and the stands will gradually approach the felling age when the economic losses are incurred. In other words, what we obtain by harvesting of wood and bark exhibits a deficit as compared with the condition that would exist if the phenomenon of bark stripping did not occur. These facts clearly show the necessity to keep damage on a minimum level. It is also evident that the game stock is not the only fundamental factor of the origin of damage. Silvicultural practices and strategy of forest management in relation to the condition of the natural environment and game management belong among other factors.

As for the degree of damage (determined by the above method), it is possible to say that the values do not exhibit any large differences as compared with data determined by summarization from working plans and inventories (e.g. NYMBURSKÝ 1992; HENŽLÍK 1995).

It is of course evident that the obtained data are of local validity. However, it is possible to conclude that the method is fully utilizable for the purpose and can be a very good tool both in forest practice and research.

CONCLUSION

The method of analysis on the time growth series of Norway spruce stripped and non-stripped stands was used to determine economic losses in utilization of wood from mature stands in the region of the Hrubý Jeseník Mts. The losses amounted to CZK 266,000 per hectare on average. The data can serve as a basis for further calculations. The use of the method is recommended for comparative studies in various regions.

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Ekonomické hodnocení ztrát loupáním vysokou zvěří na základě analýzy na časové růstové řadě smrkových porostů z oblasti Hrubého Jeseníku

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ABSTRAKT: Na časové růstové řadě smrkových porostů (loupaných a neloupaných) z oblasti Hrubého Jeseníku byla provedena analýza zaměřená na následující aspekty: (1) rozdíly hodnot biometrických a taxačních veličin loupaných a neloupaných porostů, (2) výše případných ekonomických ztrát loupáním vysokou zvěří v mýtním věku. Bylo prokázáno, že výrazné 60–100% loupání stromového inventáře způsobuje snížení hodnot základních dendrometrických veličin porostů, nejvýrazněji zásoby porostu o 20–30 % k referenčnímu období doby obmýtí. Při využití sortimentace ze zobecněných hodnot z území a při využití cenových relací obvyklých z regionu lze konstatovat, že ztráty na ceně dříví na odvozním místě u loupaných porostů činí průměrně 266 000 Kč/ha. To jednoznačně podporuje požadavek na permanentní minimalizaci škod loupáním, která jistě závisí na stavech zvěře, ale i na hospodářské strategii v lesnictví, v konkrétním kontextu na stavu přírodního prostředí, a na technologiích chovu zvěře. Využitá metoda hodnocení je efektivní v praktické oblasti i v oblasti výzkumných prací.

Klíčová slova: loupání vysokou zvěří; ztráty loupáním; ekonomické hodnocení; analýza; časová růstová řada; smrkové porosty; Hrubý Jeseník

Od změny společensko-ekonomických podmínek v ČR se stala problematika škod loupáním vysokou zvěří často diskutovanou záležitostí. Vezmeme-li v úvahu oficiální zprávy Ministerstva zemědělství ČR (z roku 1998), které uvádějí poškození lesních porostů loupáním na redukované ploše 6,4 % z celkové výměry lesů ČR za období 1979–1988, je tento trend zcela logický.

Velice problematické je zrekonstruování vývoje stavů jelení zvěře na zájmovém území v delším časovém horizontu, a to zejména v období před první světovou válkou, což je způsobeno především změnami organizačních, a tím i evidenčních jednotek. Vývoj stavů vysoké zvěře na území současné LS Karlovice v letech 1868–1887 udávají obr. 1–3.

Na časové růstové řadě stejnorodých a stejnověkých smrkových porostů (loupaných a neloupaných) zařa-

zených do souboru lesních typů 6K (HS 53) v oblasti Hrubého Jeseníku (LS Karlovice, revíry Suchá Rudná a Praděd) byla provedena analýza zaměřená na následující aspekty:

– rozdíly hodnot biometrických a taxačních veličin loupaných a neloupaných porostů,
– výše případných ekonomických ztrát loupáním vysokou zvěří v mýtním věku.

Jednotlivé rozdíly v základních biometrických veličinách, podílech sortimentů a jejich celkových cen jsou uvedeny v tab. 2.

Tyto údaje jednoznačně podporují požadavek na permanentní minimalizaci škod loupáním, která závisí na stavech zvěře, ale i na hospodářské strategii v lesnictví, v konkrétním kontextu na stavu přírodního prostředí a na technologii chovu zvěře.

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Wear coefficients for the non-solid roadways of forest roads

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ABSTRACT: The wear coefficients k_u are the result of long-term monitoring (up to 15 years) of roadway wear on forest roads. The wear process was evaluated for a consideration of the roadway deflection and its change during the time of roadway use. The roadway deflection was measured by a lever deflectometer every year in the spring season. The results indicated that the wheel traffic, thickness and quality of bituminous surface influence the wear process first of all. Therefore the seasonal coefficients were divided into four groups and they are presented numerically and graphically. The wear coefficients were included in the method *Diagnostics of the condition and overlay of non-solid roadways on forest roads*. These coefficients allow to quantify the gradual roadway wear (degradation) and decrease in the operating performance of the roadway. They also allow to determine the remaining service life of the roadway and to effectively plan major repair (overlay) of the roadway already 15 years in advance.

Keywords: forest roads; roadway wear; wear coefficients; practical importance

ROADWAY WEAR

Generally it can be said that at present a considerable attention is paid to road building materials in this country as well as in foreign countries.

The material wear is a complicated phenomenon and therefore it is difficult to define it exactly and uniformly. Some authors define the wear as a loss of strength by repeated material stress. The other authors prefer a more detailed definition and they emphasize the qualitative aspect of this phenomenon. They define the material wear as a process of structural degradation of material in time which is stressed at one or at several points by repeated loading or by repeated forced deformations.

The wear of building materials for roadway construction was studied mainly in bituminous compounds under laboratory conditions, which is easier and quicker but it is very often discussed whether the results correspond with the real conditions on the roadway.

The material, built in the roadway construction, is under steady influence of different stress and deformation combinations. Considering the used materials and possible climatic conditions of the surroundings and water relations of subsoil they can be influenced by many factors, for example by the axle loading of moving vehicles, their speeds, tyre compression, temperature and moisture. The wear process can also be influenced by varied subsoil properties, temperatures of layers varying during the day, month and year, the rest time when the traffic is limited (at night, seasonal variability of

traffic) or temporarily stopped when the bituminous compound is recovered and it is more resistant to the wear. The roadway wear is also influenced by after compacting of layers during traffic which increases the compound strength and formation of cracks on the roadway surface.

Therefore it is almost impossible in laboratory conditions to simulate exactly conditions on the roadway especially for forest roads where the conditions are even more varied than on public (state) roads.

Generally the roadway wear is a function of several variables:

$$u = f \cdot (I; t; g; k \dots)$$

where: u – roadway wear,
f – function,
I – wheel traffic,
t – time of roadway use,
g – quality of road building materials,
k – climatic conditions (temperature, moisture, solar radiation),
$\dots$ – other influences are as follows: subsoil type, line of road alignment (forest, unstocked forest land), asphalt ageing, mechanical effects and other factors which are able to influence the roadway wear.

This article is a continuation of already published papers in which are gradually published partial results of roadway wear from individual experimental sections (ZELINKA 1995, 1996, 1998, 1999) which formed the basis for the compilation of "wear coefficients".

Table 1. Wear coefficient k_u on the non-solid roadway of forest road in dependence on wheel traffic, surface and time of the roadway use in years

No.	Group of loading, number of standard axles after 24 h	Type and thickness of surface	Environment (forest, unstocked forest land)	Correlation index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
					Time of the roadway use in years (k_u)														
1.	I. group of loading to 3	PAH to 10 cm	irrelevant	0.98	1.00	1.19	1.40	1.61	1.84	2.08	2.34	2.61	2.89	3.19	3.50	3.82	4.16	4.55	4.95
		OK 8–10 cm	irrelevant	0.75	1.00	1.06	1.13	1.19	1.26	1.33	1.40	1.47	1.54	1.62	1.70	1.78	1.85	1.93	2.01
2.	II. group of loading 3–6	PAH; OK (12–15 cm)	irrelevant	0.91	1.00	1.11	1.22	1.34	1.45	1.56	1.66	1.76	1.86	1.95	2.04	2.13	2.21	2.29	2.39
3.	III. group of loading 6–10	PAH; OK (15–20 cm)	irrelevant	0.94	1.00	1.14	1.27	1.41	1.55	1.70	1.84	1.99	2.13	2.28	2.43	2.58	2.73	2.89	3.05
4.	Low – quality new roadways (especially newly built ones)	PAH; OK (10–12 cm)	irrelevant	0.69	1.00	1.02	1.05	1.08	1.11	1.14	1.18	1.22	1.26	1.31					

Table 2. Coefficients of regression equation and basic statistical characteristics for resultant wear coefficients k_u

No.	Intensity of roadway loading, number of standard axles after 24 hours	Surface	Thickness of surface	A_o	A_1	A_2	Square deviation	Residual variance	Correlation index
				Coefficients of regression equation					
1.	I. group of loading to 3	PAH	10	0.831	0.168	0.0067	0.872	0.028	0.98
		OK	8–12	0.944	0.057	0.0009	1.168	0.026	0.75
2.	II. group of loading 3–6	PAH OK	15–20	0.863	0.126	0.0017	1.109	0.027	0.91
3.	III. group of loading 6–10	PAH OK	15–20	0.866	0.134	0.0007	0.013	0.0006	0.94
4.	For insufficiently compacted roadways	PAH OK	10–12	0.956	0.018	0.0013	0.274	0.010	0.69

METHOD

The wear process is complicated and so for its long-time monitoring it was necessary to select the method which must not be changed during monitoring of wear process. First of all, the measuring apparatus and time interval during all periods (years) were not to be changed to eliminate subjective errors in most measurements.

The method of wear process monitoring was based on the roadway deflection which was measured every year in the spring season after the subsoil defreezing. The occurrence of pot-holes, cracks and other damage was also followed. The roadway deflection was measured by a lever deflectometer.

The principle of measurement by a lever deflectometer was already published by the author in greater detail (ZELINKA 1981). The reversible roadway deflection was measured under the back axle of vehicle which was loaded about 100 kN. At the same time the temperature of bituminous compound was measured. This method basically corresponds with the research program of American Association of State Highway Officials – AASHO (POLIAČIK 1971) which is known as AASHO Road Test.

As to wheel traffic which is one of the decisive factors influencing the course of wear, forest roads (sections) which had even-tempered wheel traffic during all year were studied. According to wheel traffic there were created categories of the roads (sections) with approximately the same wheel traffic expressed by the number of standard axles – ŠN/24 h (Tables 1, 2), and so reciprocal comparison of the individual roadway deflections.

22 experimental sections belong to the evaluated file. The average length of sections was 0.3 km but it was longer in single cases (2.2 km). The total length of experimental sections was 13.7 km.

The studied file included the pavements of forest roads with different structure and quality of surface and subgrade layers, with different bearing capacity of subsoil, wheel traffic, line of road alignment, roadway age, climatic conditions, surface properties. The other characteristics of experimental sections were already published in the above mentioned articles.

RESULTS

WEAR COEFFICIENTS – COMPILATION

These main effects which can influence the roadway wear were taken into consideration for compilation of wear coefficients:
– wheel traffic (effects of vehicles),
– time of the roadway use,
– climatic conditions (temperatures and water regime, frost index),
– bearing capacity of subsoil (frost sensitivity),

Legend:

——— I. group – Loading to 3 ŠN/24 h – PAH surface (to 10 cm)

— — – OK surface (8–10 cm)

—■— II. group – Loading 3–6 ŠN/24 h – PAH, OK surfaces (15–20 cm)

— ·· III. group – Loading to 6–10 ŠN/24 h – PAH, OK surfaces (15–20 cm)

- - - - IV. group – Insufficient compaction of roadway – loading 1–6 ŠN/24 h

·········· – assumed development of wear

Explanatory notes:
OK – Covered bituminous stone
PAH – Penetration asphalt macadam
ŠN – Number of standard axles
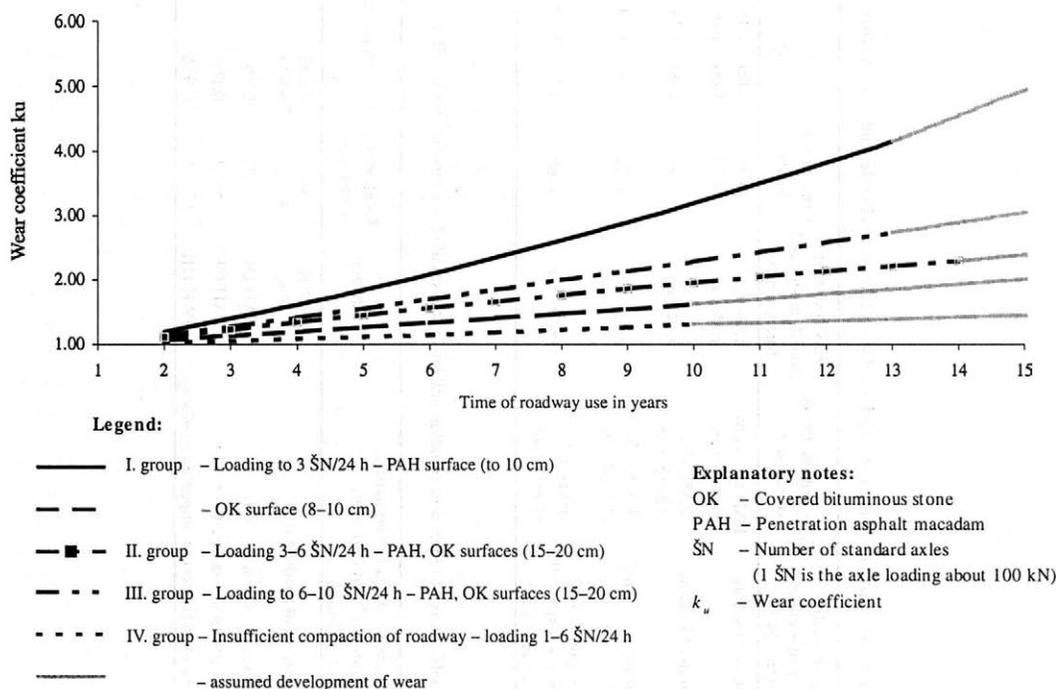(1 ŠN is the axle loading about 100 kN)
k_u – Wear coefficient

Fig. 1. The wear coefficients k_u in dependence on wheel traffic expressed by the number of standard (100 kN) axles after 24 hours, roadway surface (PAH, OK) and time of the roadway use (in years)

– material properties (base and surface layers and their thickness).

Complementary criteria were:
– location of road alignment (forest, unstocked forest land, exposure),
– surface properties (evenness).

After statistical processing of all tested alternatives it was found that the wear process (degradation) was influenced mainly by:
– wheel traffic during the time (years) of roadway use,
– type and thickness of surface layer.

As another factor that is statistically significant is the quality of the roadway (underwork), especially on new roads, namely their insufficient compaction.

Following this, four basic groups of forest roads with their wear coefficients were compiled. The other investigated possible dependences were so little statistically important that it was not necessary to create any other more detailed groups of the wear coefficients.

The resultant wear coefficients are listed in Table 1 or in graphic form in Fig. 1.

Note: The wear coefficient k_u which is presented in Fig. 1 is the graphic form (evaluation) of Table 1. The procedure of k_u determination according to Fig. 1 is as follows: k_u value is determined for the respective group of wheel traffic and time of roadway serviceability, which is next used in formula No. 1 (forecast of roadway wear) or in formula No. 2 (determination of the remaining service life of roadway).

SHORT EVALUATION OF WEAR COEFFICIENTS

We can see from Table 1 that the roadway wear of forest roads was divided into four groups. In the first three groups (I, II, III), the wear process is dependent mainly on wheel traffic and thickness of bituminous surface. The last group (IV) is defined for low-quality roadways, mainly for nonconsolidated newly built ones in which it is difficult to determine if the wear process is influenced either by wheel traffic, low-quality building works (mainly compaction) or by thickness and type of bituminous surface.

On the individual groups of wear coefficients

Group I of wear coefficients for roadway loading to 3 standard axles after 24 hours (to 3 ŠN/24 h)

These coefficients are divided into two subgroups – for penetration asphalt macadam (PAH) and covered bituminous stone (OK). It follows from the wear coefficients for PAH surface that these coefficients show the highest increase. It confirms that the roadways of forest roads with PAH surface about thickness to 10 cm are relatively quickly degraded and after the limit state is attained (ZELINKA 1998), major repair is necessary (overlay of the roadway). The wear coefficients for OK bituminous surface confirm (under the same conditions) that the wear process is slower on this surface, which confirms the advantage of OK surface (in quality) over PAH surface.

Group II of wear coefficients for roadway loading 3–6 standard axles after 24 hours (3–6 ŠN/24 h)

In this group it was not necessary to divide the wear coefficients into subgroups like in the previous group (I). The higher thickness of PAH surface – 15 cm (in two layers) decreases the difference between OK and PAH (this difference between PAH and OK was not statistically significant). The wear coefficients in this group are lower than on PAH surface in the first group but they are higher than on OK surface. It indicates that the wheel traffic begins to substantially influence the wear (degradation) process of the roadway.

Group III of wear coefficients for roadway loading 6–10 standard axles after 24 hours (6–10 ŠN/24 h)

For the compilation of wear coefficients it was not necessary to distinguish the type of bituminous surface (PAH and OK) like in the previous groups. The wheel traffic was decisive here. Although the thickness of bituminous surface is higher, the wear (degradation) process is faster in this group, which indicates the importance of wheel traffic again.

Group IV of wear coefficients – the roadway loading was not exactly specified (1–6 standard axles after 24 hours)

This group comprises mainly new roads which are of insufficiently good quality, first of all as for the compaction of the individual layers in roadway construction. On these roads the consolidation of the road bed takes approximately the first three years of the traffic, but some roads have higher bearing capacity. The wear process begins in the third year of the traffic during simultaneous consolidation of the road bed, which complicates the compilation of wear coefficients – the low value of correlation index (0.69).

We found that at the same time the consolidation of the road bed is parallel to the wear process here, which was reflected in relatively low values of wear coefficients and in the low value of correlation index (0.69) – immature roadways.

STATISTICAL ANALYSIS OF WEAR COEFFICIENTS

It was found in all cases that it is simple non-linear correlation (polynomial of degree II) which has this general relation for determination of regression equations for the individual loading groups:

$$k_u = A_o + A_{1x} + A_{2x}^2$$

where: k_u – wear coefficient,
A_o, A_1, A_2 – regression coefficients,
x – time of the roadway use in years.

Coefficients of the regression equation and the basic statistical characteristics for individual wear coefficients are presented in Table 2.

Note: The whole file for the calculation of regression coefficients presented 6,576 measurements. In individual groups it was: 1st group – 2, 250, 2nd group – 1,767, 3rd group – 1,312, 4th group – 1,247.

SUMMARY OF THE RESULTS AND IMPORTANCE OF WEAR COEFFICIENTS

The compilation of wear coefficients is a result of long-term monitoring of the roadway bearing capacity on forest roads.

The importance of wear coefficients can be summarized into the following points:
- they enable to forecast the roadway degradation (decrease in the operating performance) up to 15 years in advance,
- they enable to calculate the remaining service life of the roadway.

The advantage of "OK" surface over "PAH" was confirmed, mainly when the thickness of bituminous surface was about 10 cm (2×5 cm OK). Wheel traffic, and then thickness of bituminous surface are decisive for the roadway wear (degradation process). The other variables were not important. The course of roadway wear is nonlinear and it gradually moderately increased with the time (years) of roadway use.

1. Prognosis of the roadway deflection increase

For prognosis (quantification) of the roadway wear the following relation was used:

$$Y_p = Y_j \cdot k_u \qquad (1)$$

where: Y_p – prognosis of the deflection value (1–15 years in advance)
Y_j – spring deflection of the roadway,
k_u – wear coefficient for a selected group of loading and year (Table 1).

For a consideration of the calculated Y_p we can quantify the operating performance of the roadway. It is quantified by the method *Diagnostics of the condition and overlay of non-solid roadways on forest roads* which was already published (ZELINKA 1989c). By this method we can follow the course of the roadway wear (degradation) namely by quantification of a decrease in the traffic of standard (draft) axles for individual years. We can also estimate in advance the limit bearing capacity of the roadway and plan its major repair (overlay).

2. Determination of the remaining service life of the roadway

The following relation was used to determine the remaining service life of the roadway:

$$k_z = \frac{Y_d}{Y_j} \qquad (2)$$

where: k_z – coefficient of the remaining service life of the roadway,
Y_d – permissible deflection (ZELINKA 1989),
Y_j – spring deflection.

Note: Concrete value of permissible deflection Y_d is published in the method *Diagnostics of the condition and overlay of non-solid roadways on forest roads* (ZELINKA 1989c). This method enables to determine permissible deflection Y_d for the range of wheel traffic 0.3–300 ŠN/24 h with annual increase in traffic from 0 till 10 % for the service life of the roadway from 1 to 20 (respectively 35) years.

After k_z calculation the remaining service life of the roadway is given by comparison of the coefficient of remaining service life – k_z with the wear coefficient k_u (Table 1). Then we determine for the respective group of loading the number of years when the service life of the roadway is ended.

THE PRACTICAL INSTRUCTION FOR THE USE OF WEAR COEFFICIENTS

Example No. 1: Determination of the remaining service life of the roadway

Given parameters:
- average wheel traffic – 4 ŠN/24 h (or approximately 1,500 ŠN/year), 1 ŠN is the axle loading about 100 kN,
- thickness of bituminous surface – 13 cm OK,
- Y_j (spring deflection) = 1.82 mm,
- Y_d (permissible deflection) = 2.00 mm (it is determined by ZELINKA's method 1989a,b).

Method of the calculation:

a) Determination of k_z (coefficient of remaining service life)

$$k_z = \frac{Y_d}{Y_j} = \frac{2.00}{1.82} = 1.37 \qquad (3)$$

b) Determination of the remaining service life

We determine the remaining service life of the roadway according to Table 1. For group II of wheel traffic it is four years at $k_z = 1.37$.

Conclusion

After four years of the traffic, the service life of the roadway is ended (the limit state is attained) and major repair (overlay) of the roadway is necessary. (Overlay process is published by ZELINKA 1989c in *The diagnostics of the condition and overlay of non-solid roadways on the forest roads*.)

Example No. 2: Evaluation of the actual condition and/or determination of the remaining service life of the roadway

It is given:
- average wheel traffic is 5 ŠN/24 h (or 1,800 ŠN/year),
- thickness of bituminous surface is 10 cm PAH + 6 cm OK,
- spring deflection $Y_j = 2.40$ mm,
- permissible deflection $Y_d = 1.90$ mm,
- there are linear and square cracks, pot-holes and ruts on the roadway.

Method of the calculation:

a) Determination of k_z coefficient

$$k_z = \frac{Y_d}{Y_j} = \frac{1.90}{2.40} = 0.79 \qquad (4)$$

b) Determination of the remaining service life of the roadway

Table 3. The roadway wear quantified by the number of ŠN/24 hours respectively ŠN/year in dependence on time of use (in years) and change in deflection

Time of roadway use in years	Deflection in mm (deflection × k_u)	Operating performance Number of standard axles		Note
		after 24 h	after year	
1	1.50 × 1.00 = 1.50	15.0	5,475	
2	1.50 × 1.19 = 1.78	7.5	2,737	
3	1.50 × 1.40 = 2.10	3.6	1,278	
4	1.50 × 1.61 = 2.40	1.8	675	overlay
5	1.50 × 1.84 = 2.76	1.1	402	
6	1.50 × 2.08 = 3.12	0.6	219	
7	1.50 × 2.34 = 3.51	0.4	146	
8	1.50 × 2.61 = 3.91	< 0.3	110	
9	1.50 × 2.89 = 4.33	< 0.3	< 110	
10	1.50 × 3.19 = 4.78	< 0.3	< 110	overlay

It was found according to Table 1 for group II of the wheel traffic that when $k_u = 0.79$, the roadway is after the time of service life.

Conclusion

The roadway already attained the limit state of bearing capacity (approximately 2 years ago), the permanent and non-reversible deformations are in the roadway construction and therefore immediate overlay of the roadway is necessary (method is the same as in the previous example).

Example No. 3: Quantification of the roadway wear by the number of standard axles (ŠN) after 24 hours (respectively after a year) in dependence on the time of use and determination of the optimum time of major repair (overlay)

It is given:
– wheel traffic is about 2 ŠN/24 h (730 ŠN/year),
– surface of roadway is made of 10 cm PAH,
– initial spring deflection is 1.50 mm.

Method of the calculation:
a) The deflection change is determined by k_u (Table 1 – group I of loading).
b) The operating performance is calculated by the deflection (ZELINKA 1981).
c) Calculation of the wear is in Table 3.

Conclusion: At the relatively high initial value of deflection (1.50 mm) the roadway attains the limit state after 4 years of the traffic and its overlay is necessary.

DISCUSSION AND CONCLUSION

No similar results which are presented in this article with regard to wear coefficients of the roadways generally (state, special purpose communications) are reported in available literature. It is possible to compare our results only partly with the results of the AASHO test (POLIAČIK 1971) which however lasted only 2–3 years while the wear coefficients presented in this article evaluate the wear process during 15 years of the roadway monitoring.

AASHO test supposed (theoretically) the balanced deflection (null roadway wear) from the beginning of the use time and intense to steep increase in the roadway deflection (wear) to the end of service life. The continuous wear increase was observed on forest roads during the time of roadway use.

Despite the difficulty and complexity of this problem, the compilation of "wear coefficients" is the qualitative step forward in the roadway management. The results represent the knowledge of roadway behaviour from the long-term point of view and they expand the knowledge of the roadway geomechanics not only on forest roads but also generally.

Our results are also a practical contribution because from the knowledge of the wear process (wear coefficients) we can determine with the precision 1 year when the service life of the roadway is ended and when it is necessary to plan major repair. By this method various forest organizations can plan and compile the schedule of pavement repairs and so effectively spend the financial means.

This problem is still investigated and the results from the next 10 years of wear process monitoring will be known in 2001.

SUMMARY

The material built in the roadway construction is under steady influence of various stress and deformation combinations. Considering the used materials, climatic conditions and roadway loading by wheel traffic it is difficult and almost impossible to simulate the mentioned conditions in laboratory. Therefore the roadway wear was followed directly (*in situ*) on forest roads.

The results which are presented in this article are a follow-up of the partial results which the author already published. He summarized them in the most important parts of "wear coefficients" for forest roads.

So as the results were the most objective possible, the method of wear process monitoring and instrumental equipment were not changed during the whole period (15 years). The monitoring of roadway wear was based

on the value of roadway deflection which was measured every year in the spring season with a lever deflectometer. 22 experimental sections were included in the investigated file. The length of sections was 0.3–2.2 km according to the conditions. The whole length of experimental sections was 13.7 km.

At the final compilation of "wear coefficients" the following possible factors were taken into consideration which can expressively affect the roadway wear: wheel traffic, time of the roadway use, climatic conditions, bearing capacity of subsoil, properties of building materials for the roadway construction.

After statistical evaluation it was found that the wear process is a nonlinear correlation (polynomial of the second degree). The roadway wear is caused by the wheel traffic on forest roads first of all and by the different quality and thickness of bituminous (asphalt) surface.

Following this the wear coefficients were compiled which were divided into the groups according to the wheel traffic expressed by the number of standard (100 kN) axles – ŠN after 24 hours and according to the thickness (in cm) and type of bituminous surface.

The wear coefficients are expressed either numerically (Table 1) or graphically (Fig. 1) and they are divided into four independent groups.

The first group is represented by roadways with the wheel traffic to 3 ŠN/24 h, thickness of bituminous surface PAH about 10 cm and OK about 8 cm. The second group comprises forest roads with wheel traffic 3–6 ŠN/24 h, thickness of bituminous surface (PAH, OK) about 12–15 cm; the third group is represented by forest roads with wheel traffic 6–10 ŠN/24 h and thickness of bituminous surface 15–20 cm (PAH; OK); the fourth group is new forest roads where consolidation of the road bed by the wear process is in progress – immature roadways.

The most intensive wear process was found on the roadways of forest roads which belong to the first group of loading with less valuable PAH surface and to the third group where the wheel traffic is the main factor (Table 1).

The wear coefficients are also of practical importance because using these coefficients we can quantify the wear process of the roadway 15 years in advance and plan the optimal time of the roadway repair (overlay), as well as to determine the remaining service life of the roadway.

The wear coefficients were included in the method *The diagnostics of condition and overlay of non-solid roadways on forest roads* (ZELINKA 1989c). From the theoretical aspect, the knowledge of the roadway geomechanics has been expanded.

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Únavové koeficienty pre netuhé vozovky lesných ciest

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ABSTRAKT: Únavové koeficienty k_u sú výsledkom dlhodobého sledovania (až 15-ročného) únavy vozoviek lesných ciest. Proces únavy bol hodnotený na základe priehybu vozovky a jeho zmeny počas doby používania vozovky a meral sa pákovým priehybomerom každoročne v jarnom období. Výsledky ukázali, že na proces únavy a jeho veľkosť má rozhodujúci vplyv: intenzita dopravy, hrúbka a kvalita živičného krytu. Na základe toho boli sezónne koeficienty zoradené do štyroch skupín a sú uvedené v číselnej i grafickej podobe. Koeficienty únavy boli zapracované do metódy *Diagnostika stavu*

a zosilovanie netuhých vozoviek lesných ciest. Význam koeficientov spočíva v tom, že nám umožňujú vyčísliť postupujúcu únavu (degradáciu) vozovky a tým aj znižovanie prevádzkovej výkonnosti vozovky. Taktiež nám umožňujú určenie zostatkovej životnosti vozovky a tým naplánovanie zásadnej opravy (zosilnenia) vozovky až na 15 rokov dopredu.

Kľúčové slová: lesné cesty; únava vozovky; koeficienty únavy; praktický význam

Únava materiálov je zložitý jav, pretože je ťažké ju presne a jednoznačne definovať. Niektorí autori definujú únavu ako stratu pevnosti vyvolanú opakovaným namáhaním materiálu, iní autori dávajú prednosť podrobnejšej definícii a väčšiu váhu kladú na kvalitatívnu stránku javu, potom je únava materiálu definovaná ako proces štrukturálnej degradácie postupujúci s časom, ktorý pozorujeme na materiáli namáhanom v jednom alebo niekoľkých bodoch opakovaným zaťažovaním alebo opakovanými nútenými deformáciami.

Materiál zabudovaný v konštrukcii vozovky je totiž pod neustálym vplyvom rôznych kombinácií napätia a pretvorenia. Tie môžu byť, vzhľadom k použitým materiálom a možným klimatickým podmienkam okolia a vodného režimu podložia, ovplyvňované mnohými faktormi.

Z týchto dôvodov je takmer nemožné v laboratórnych podmienkach presne navodiť pomery na vozovke v teréne, zvlášť u lesných ciest, kde sú pomery ešte zložitejšie oproti verejným cestám. Z týchto dôvodov bola únava vozovky sledovaná *in situ*.

Vo všeobecnosti únava vozovky je funkciou viacerých premenných a pre tento predpoklad sa môže uviesť všeobecný vzťah:

$$u = f. \ (I; \ t; \ g; \ k \ ...)$$

kde: u – únava vozovky,
  f – funkcia,
  I – intenzita dopravy,
  t – čas používania vozovky,
  g – kvalita cestných stavebných materiálov,
  k – klimatické podmienky (teplota, vlhkosť, slnečné žiarenie),
  .... – ďalšie predpokladané vplyvy, ako sú: druh podložia, vedenie trasy cesty (les, bezlesie), starnutie asfaltu, mechanické účinky opotrebenia vrstvy a ďalšie iné faktory, ktoré by mohli mať vplyv na únavu vozovky.

Článok nadväzuje na už publikované príspevky, kde boli postupne uvádzané dielčie výsledky únavy vozovky z jednotlivých pokusných úsekov (ZELINKA 1995, 1996, 1998, 1999), ktoré tvorili základ pre zostavenie „únavových koeficientov" a tým sa v podstate završuje niekoľkoročné sledovanie únavového (degradačného) procesu na netuhých vozovkách lesných ciest.

Metodika sledovania únavového procesu bola založená na veľkosti priehybu vozovky, ktorý sa meral každoročne v jarnom období, po roztopení podložnej zeminy vozovky. Ďalej sa sledoval výskyt výtlkov, prasklín a iných porúch. Priehyb vozovky sa meral pákovým priehybomerom. Aby boli výsledky čo najobjektívnejšie, metodika sledovania únavového procesu a prístrojová technika sa po celú dobu (15 rokov) nemenili.

Princíp merania pákovým priehybomerom už autor podrobnejšie popísal (ZELINKA 1981). V krátkosti uvádzam: meral sa vratný priehyb vozovky pod zadnou nápravou nákladného auta, zaťaženou 100 kN. Súčasne sa merala teplota živičnej zmesi. Uvedený postup je v podstate zhodný s výskumným programom American Association State Highway Officialis – AASHO (POLIAČIK 1971), ktorý je známy pod názvom AASHO Road Test.

Vyhodnotený súbor predstavuje 22 pokusných úsekov o priemernej dĺžke 0,3 km, v ojedinelých prípadoch i dlhších (2,2 km). Celková dĺžka pokusných úsekov bola 13,7 km.

V sledovanom súbore boli zastúpené vozovky lesných ciest rôzneho zloženia v krytových i podkladových vrstvách vozovky a jeho kvality, únosnosti podložia, intenzity dopravy, vedenia trasy, veku vozovky, klimatických podmienok, povrchových vlastností.

Pri zostavení koeficientov únavy boli do úvahy brané nasledujúce hlavné vplyvy, ktoré môžu pôsobiť na únavu vozovky: dopravné zaťaženie, doba používania vozovky, klimatické podmienky (teplotný a vodný režim, index mrazu), únosnosť podložia (citlivosť na mráz), vlastnosti materiálu (podkladové vrstvy, krytové vrstvy a ich hrúbky). Ako doplňujúce kritérium bolo umiestnenie trasy cesty (les, bezlesie, expozícia), povrchové vlastnosti (rovnosť a pod.).

Celkový súbor pre výpočet regresných koeficientov predstavoval 6 576 meraných bodov. Po štatistickom spracovaní vyšlo, že únavový proces má nelineárnu závislosť (polynóm II. stupňa) a na jeho proces má predovšetkým vplyv intenzita dopravy a kvalita i hrúbka krytovej (živičnej) vrstvy. Ostatné faktory nepotvrdili takú štatistickú významnosť, ktorá by musela byť zohľadnená.

Únavové koeficienty sú vyjadrené číselne (tab. 1) alebo graficky (obr. 1) a sú rozdelené do štyroch samostatných skupín.

1. skupinu tvoria vozovky s intenzitou dopravy do 3 ŠN/24 h o hrúbke živičného krytu 10 cm PAH, resp. 8 cm (2 × 4 cm) OK.

2. skupinu tvoria lesné cesty s intenzitou dopravy 3–6 ŠN/24 h a hrúbkou živičného krytu PAH, OK 12–15 cm.

3. skupinu tvoria lesné cesty s intenzitou dopravy 6–10 ŠN/24 h o hrúbke živičného krytu 15–20 cm.

4. skupinu tvoria novovybudované lesné cesty, kde ešte dochádza ku konsolidácii cestného telesa dopravou ako

dôsledok nedostatočného hutnenia. Klasický proces únavy sa začína prejavovať po 2 rokoch prevádzky. Každá vozovka (pokusný úsek) tejto 4. skupiny vykazovala veľmi rozdielny priebeh únavy a bolo veľmi obtiažne vyjadriť vhodné závislosti, o čom svedčia nízke hodnoty indexu korelácie.

Z uvedených skupín najväčší nárast únavy vozovky majú vozovky lesnej cesty 1. skupiny o hrúbke živičného krytu 10 cm PAH pri relatívne nízkej intenzite dopravy. Tieto vozovky musia byť približne po 8–12 rokoch zosilnené, pretože dosiahli medzný stav únosnosti. Potom nasleduje skupina vozoviek zaradených do 3. skupiny, kde proces únavy začína ovplyvňovať predovšetkým vyššie dopravné zaťaženie (6–10 ŠN/24 h) pri pomerne dosť vysokej hrúbke živičného krytu (2 × 10 cm PAH alebo 3 × 5 cm OK).

Praktický význam „únavových koeficientov" spočíva v tom, že umožňujú vyčísliť proces únavy vozovky na 15 rokov dopredu a tým si naplánovať optimálnu dobu opravy (zosilnenia) vozovky, resp. umožňujú určiť zostatkovú životnosť vozovky.

Únavové koeficienty boli zapracované do metódy *Diagnostika stavu a zosilňovanie netuhých vozoviek lesných ciest* (ZELINKA 1989c).

Napriek obtiažnosti a zložitosti problematiky zostavenie „únavových koeficientov" predstavuje kvalitatívny krok dopredu v systéme hospodárenia s vozovkami. Výsledky prezentujú poznatky o správaní sa vozovky z dlhodobého pohľadu a tým rozširujú poznatky z geomechaniky vozovky nielen u lesných ciest, ale aj všeobecne.

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Dendrometric evaluation of stand structure and stem forms on Norway spruce (*Picea abies* [L.] Karst.) sample plots Doubravčice 1, 2, 3

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ABSTRACT: Stand structure can be described by aggregation indices (Clark-Evans, Pielou-Mountford, Hopkins-Skellam, David-Moore ones), and the values of indices for spruce sample plots are presented for concrete premature stand structures. The sample plot structure is described by graphs of a paired correlation function. The stem forms were studied by the method of Procrustes superimposition. Shape variability is also analysed by the principal components analysis and testing of the equality of mean form vectors is discussed.

Keywords: Norway spruce (*Picea abies* [L.] Karst.); stand structure; aggregation indices; paired correlation function; stem form; stem form variability; Procrustes superimposition

The importance of spatial stand structure has increased at present. This study is of practical importance for forest inventory (estimates of tree numbers, standing volume), for obtaining parameters to simulate the spatial distribution of trees within sample plots, for the description of close-to-nature well-structured stands, for optimisation of logging technologies, etc. The analysis of spatial distribution was dealt with by many researchers in different disciplines (DIGGLE 1983).

The examination of stem form has a long tradition in dendrometry and is of great importance for the construction of volume tables, assortment tables, tables of uniform height curves as well as growth models.

In the past 20 years so called geometric methods of shape description have been developed in connection with computer tomography and computer image processing (DRYDEN, MARDIA 1998). Their advantage consists in a clear definition of concepts and a possibility to compare shapes using multidimensional statistical methods. This article outlines several possibilities of applying these methods to the description of a spruce stem, which are related to the method of Procrustes superimposition.

MEASUREMENT METHODS AND CHARACTERISTICS OF SAMPLE PLOTS

Sample plots Doubravčice 1, 2, and 3 were established in the area of the School Forest Enterprise at Kostelec

nad Černými lesy in 1965. The original purpose of the plots was to study current volume increment in a non-mixed spruce stand. At present the measured data were digitised and used for the study of stand structure and shape forms.

The sample plots, sized 0.5 ha each, are adjacent to each other. After their establishment in 1965, the co-ordinates of single trees were measured on all plots and trees were also classified by Konšel's method. In 1966, 1971, and 1976 (the last vegetation years 1965, 1970, and 1975) the plots were cut sequentially. The length, crown length, height increments after 5, 10, 15, and 20 years were measured in the cut trees. Furthermore, an abbreviated stem analysis was performed. The diameters were examined in a 2-m section and at d.b.h. Current diameters were measured over bark and under bark and other diameters 5, 10, and 15 years ago. The lengths were measured with a band to the nearest 10 cm and the diameters with a calliper to the nearest 0.5 mm.

The sample sites were located namely within the forest type 2K3 – an acid beech-oak type, a smaller part of plot No. 3 was located within the forest type 2H8 – a loamy beech-oak type. A transition between the forest types 2K3 and 2H8 was reflected in the values of top heights. In 1965 the top heights were 26.1 m, 25.7 m and 27.2 m on plots 1, 2, 3 respectively. On plot 1, the volume of wood (wood to the top of 7 cm o.b. /'Derbholz'/) was 227.058 m³, stand density was 1.0 and site index by men-

Table 1. Doubravčice 1: selected mensurational characteristics

Calendar year	Age (yr.)	No. of trees	h_{100} (m)	h_g (m)	d_g (cm)	h_w (m)	d_w (cm)	h_v (m)	d_v (cm)
1955	60		22.2						
1960	65		24.5						
1965	70	514	26.3	23.3	21.6	24.1	23.0	24.4	23.7

Table 2. Doubravčice 2: selected mensurational characteristics

Calendar year	Age (yr.)	No. of trees	h_{100} (m)	h_g (m)	d_g (cm)	h_w (m)	d_w (cm)	h_v (m)	d_v (cm)
1955	60		21.2						
1960	65		23.7						
1965	70	425	25.7						
1970	75	393	27.3	24.4	24.0	25.0	25.3	23.6	23.4

Table 3. Doubravčice 3: selected mensurational characteristics

Calendar year	Age (yr.)	No. of trees	h_{100} (m)	h_g (m)	d_g (cm)	h_w (m)	d_w (cm)	h_v (m)	d_v (cm)
1960	65		25.4						
1965	70	473	27.2						
1970	75		28.5						
1975	80	346	29.3	26.4	26.7	27.0	28.2	26.4	26.7

surational tables was 26. On the second plot these values were 217.015 m³, 0.89, and 28, and on the third plot 252.992 m³, 0.90, and 28 respectively. Further taxation values are presented in Tables 1–3. In these tables h_{100} represents Weise's top height, h_g, d_g is medium stand height and stand basal area diameter, h_w, d_w is Weise's mean stand height and diameter, h_v, d_v is mean stand height and mean volume stem diameter.

Eight full stem analyses were performed on plot Doubravčice 3. Out of them, sample trees No. 317, 313 represent subdominant trees, sample trees No. 285, 171, 299, and 301 represent co-dominant trees, and sample trees No. 44 and 177 are dominant trees. The heights were fitted by Korf growth function and these height curves are shown in Fig. 1.

EVALUATION OF STAND STRUCTURE

The stand structure can be described by many methods. So-called *aggregation indices* belong to traditional methods.

First, the symbols will be introduced. Let us assume the examined sample plot to be of size S and to contain n trees, then the population density is $\lambda = n/S$. The distance of the i-th tree to its nearest neighbour is r_i. Also n pure random points can be located within the plot (e.g. with a random number generator). Let the distance of the i-th point to the nearest tree be denoted r_i'. Further on, we use the symbols ω_i and ω_i' for the second squares of r_i and r_i' respectively. The whole plot can be divided into N equally sized parts and we can examine how many trees

are located on these partial plots. Let the number of trees on the i-th partial plot be denoted x_i.

Some of the frequently used indices are presented:

Clark-Evans aggregation index (CLARK, EVANS 1954). It is defined as a ratio of average distance between

the nearest neighbours $\bar{r} = \sum_{i=1}^{n} r_i$ to expected distance r_E

in the case of so called Poisson forest, i.e. the forest with randomly distributed trees. This distance equals

$$r_E = \frac{1}{2\sqrt{\lambda}} . \qquad \text{Then} \qquad R = \frac{\bar{r}}{r_E} = 2\bar{r}\sqrt{\lambda}$$

Pielou-Mountford aggregation index (PIELOU 1959 and MOUNTFORD 1961). It is defined by the equation

$$a = \frac{1}{n}\pi\lambda \sum_{i=1}^{n} \omega_i'$$

Hopkins-Skellam aggregation index (HOPKINS, SKELLAM 1954). It is defined by the equation

$$A = \frac{\sum_{i=1}^{n} \omega_i'}{\sum_{i=1}^{n} \omega_i' + \sum_{i=1}^{n} \omega_i}$$

David-Moore aggregation index (DAVID, MOORE 1954). It is defined by the equation
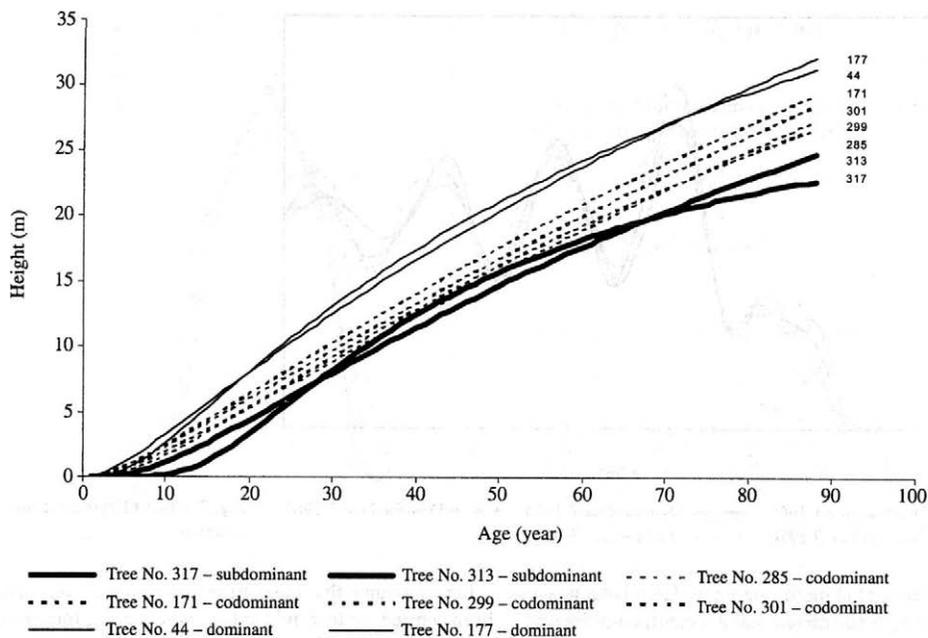
$$I = \frac{s_X^2}{\bar{X}} - 1$$

Fig. 1. Fitted height growth of sample trees from full stem analyses

where: $\overline{X}$ and s_x^2 represent arithmetic mean and variance of tree frequency on single partial plots x_i, respectively.

Table 4 shows the following characteristics for the indices: mean index value for a purely random tree distribution, ranges of values indicating aggregated and regular arrangements respectively.

A modern approach using a *paired correlation function* $g(r)$ was applied. The function is defined by the equation:

$$P(r) = \lambda^2 g(r)\, dx_1 dx_2$$

(PENTINEN et al. 1992) where dx_1 and dx_2 stand for the sizes of two infinitesimally small patches distant r from each other, $P(r)$ is the probability that there is one tree within each of the patches. The paired correlation function is equal to 1 in the case of Poisson forest and the above-presented definition. In some r the probability of

tree occurrence is smaller or higher than in the idealised forest, the relationship will be $g(r) < 1$ and $g(r) > 1$, respectively.

All four indexes together show the regular structure of the stands. Though the stand density of single stands differs, the differences in their spatial structure are not evident. No significant changes are apparent during evolution in time. Moreover, the periodical behaviour of the paired correlation function shows the stands were established at a regular spacing.

EVALUATION OF STEM FORMS

So-called *landmarks* were identified on the morphological stem curve. These landmarks originate either at the top edge of a stump or at 1/20 of the stem height (the stump height ranged between 10 and 35 cm) and continue by tenths of the stem length symmetrically at its left

Table 4. Overview of the aggregation indices

Index	Mean value	Aggregation	Regularity
Clark-Evans	$R = 1$	$R < 1$	$R > 1$
Pielou-Mountford	$a = 1$	$a > 1$	$a < 1$
Hopkins-Skellam	$A = 0.5$	$A > 0.5$	$A < 0.5$
David-Moore	$I = 0$	$I > 0$	$I < 0$
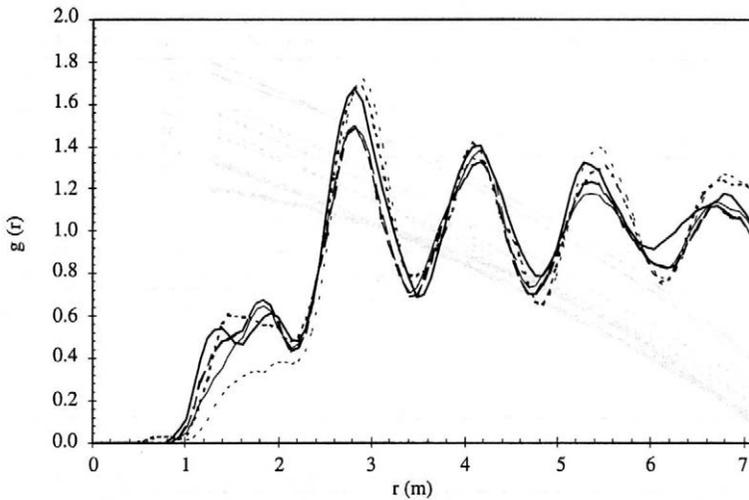
Doubravčice 1 1965 ——— Doubravčice 2 1965 ▪ ▪ ▪ Doubravčice 3 1965
——— Doubravčice 2 1970 • • • Doubravčice 3 1975

Fig. 2. Chart of pair correlation function

and right part including the stem top. Each landmark is localised using x (diameter) and y (height) co-ordinates. Then those co-ordinates form a matrix $k \times n$, where k is the number of landmarks and n is the number of dimensions. In our case $k = 21$ and $n = 2$. The matrix is called an *original configuration matrix* and it represents a basis for further statistical processing. This procedure is shown in Fig. 3. The shape form is defined as geometrical information on the configuration matrix after orthogonal shift, rotation, and re-scaling (MARDIA, DRYDEN 1998).

Procrustes superimposition was used to estimate the mean shape. KENT (1994 in MARDIA, DRYDEN 1998) defines the *full Procrustes mean shape* $\hat{\mu}$ as the eigenvector corresponding to the largest eigenvalue of the complex sum of squares and products matrix.

Let us assume that the configurations $w_1, ..., w_n$ have been centred, so that $w_i^* 1 = 0$, where w^* is transpose of the complex conjugate of w, 1 is vector of ones.

$$S = \sum_{i=1}^{n} w_i w_i^* / (w_i^* w_i) = \sum_{i=1}^{n} z_i z_i^*$$

where: $z_i = w_i / \|w_i\|$, $i = 1, ..., n$, are the pre-shapes.

The full Procrustes fits or *full Procrustes co-ordinates* of $w_1, ..., w_n$ are

$$w_i^P = w_i^* \hat{\mu} w_i / (w_i^* w_i), \qquad i = 1, ..., n$$

where: each w_i^P is the full Procrustes fit of w_i onto $\hat{\mu}$.

Calculation of the full Procrustes mean shape can also be obtained by taking the arithmetic mean of the full Procrustes co-ordinates, i.e. $\frac{1}{n} \sum_{i=1}^{n} w_i^P$ has the same shape as the Procrustes mean shape $\hat{\mu}$.

Procrustes co-ordinates were calculated with the software „tpsRegr" v. 1.20 by ROHLF (1998).

Fig. 4 shows full Procrustes mean shapes for each Konšel's tree class on plot Doubravčice 1. Tree class 1 is composed of dominants (108 individuals), tree class 2a of co-dominant major trees (228 individuals), tree class 2b of co-dominant minor trees (58 individuals), tree class 3 of intermediate trees (63 individuals), tree class 4 then of shadegrown vital trees (27 individuals). Dying and dead trees were considered as a separate group; as there was not enough material to evaluate them (only 4 individuals) they were added to class 4. The figure shows the averages of single classes form an ordered group. In the direction from the vertical stem axis the sequencing starts with class 4, then classes 3, 2b, 2a follow, and finally
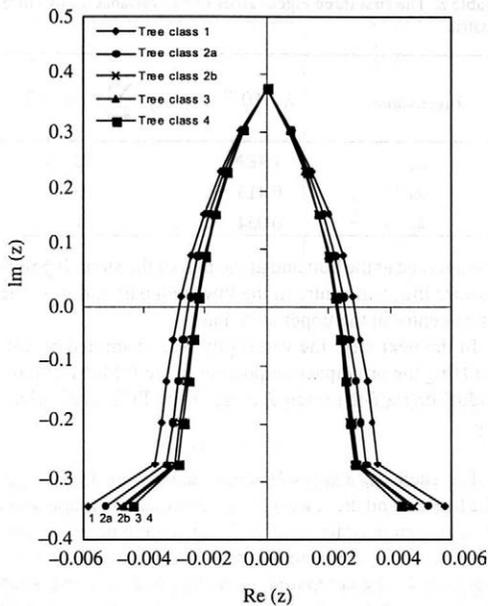

Fig. 3. Scheme of shape evaluation (by GOODALL, MARDIA 1992 in DRYDEN, MARDIA 1998), adapted

Fig. 4. Courses of full Procrustes mean shapes for single Konšel's tree classes. Stem butt has the height and diameter of the stump

$$D^2 = (\hat{\mu}_1 - \hat{\mu}_2)^T S_u^- (\hat{\mu}_1 - \hat{\mu}_2)$$

S_u^- is the Moore-Penrose generalised inversion of S_u (joined variance-covariance matrix),

$$S_u = (n_1 S_1 + n_2 S_2)/(n_1 + n_2 - 2),$$

$$S_1 = \frac{1}{n} \sum_{i=1}^{n} (w_i^P - \hat{\mu}_1)(w_i^P - \hat{\mu}_1)^T$$

where: S_1 – a variance-covariance matrix of the first selection,

S_2 – that of the second selection.

The null hypothesis is rejected if $F_{strat} \geq F_{M, n_1 + n_2 - M - 1} (\alpha)$. Table 6 shows the overviews of squared Mahalanobis distances, the values of test statistics and the critical values of Fisher distribution F for $\alpha = 0.05$.

There are statistically significant differences between the Procrustes mean shapes of tree class 1 and all the others excluding tree class 4 because of the smallest number of individuals in tree class 4. The Procrustes mean shapes of tree class 2a differ from the average of tree class 3. There are no significant differences between the averages of tree classes 2b, 3, and 4.

Similarly, the Procrustes mean shapes of whole plots Doubravčice 1, 2, and 3 were tested. Fig. B illustrates the courses of these shape averages at the cutting age of the plots (70, 75, and 80 years). The mean shape averages of all stems on the sample plots are located in the order Doubravčice 1, Doubravčice 2, Doubravčice 3 from the vertical stem axis. The reason of such location will be discussed in the following chapter dealing with variability. Also the mean form vectors were tested; the results are presented in Table 7.

Table 7 shows that there is a difference between mean shape vectors of plots No. 1 and 3.

class 1. The figure also suggests possible determination of 3 Konšel's tree groups by the shape. The first group is formed by tree class 1, the second by tree class 2a, and the third by classes 2b, 3, and 4.

Two independent sample *Hotellings T²* tests were applied to test the differences in Procrustes mean shapes.

The hypothesis $H_0 : \hat{\mu}_1 = \hat{\mu}_2$ is tested against the hypothesis $H_1 : \hat{\mu}_1 \neq \hat{\mu}_2$. The test statistics is:

$$F_{stat} = \frac{n_1 n_2 (n_1 + n_2 - M - 1)}{(n_1 + n_2)(n_1 + n_2 - 2)M} D^2$$

where: n_1, n_2 – numbers of individuals in the first and second sets,

M – the dimension of shape space,

D^2 – the squared *Mahalanobis distance* between

$\hat{\mu}_1$ and $\hat{\mu}_2$,

VARIABILITY

The *principal components analysis* was used to analyse the shape variability. The dominant trees on plot Doubravčice 1 were used as an example. The sample variance-covariance matrix was calculated for the tree set:

Table 5. Calculated values of aggregation indices

Plot	Calendar year	Density (ha)	Clark-Evans	Pielou-Mountford	Hopkins-Skellam	David-Moore
Doubravčice 1	1965	1,013	1.375	0.732	0.314	−0.536
Doubravčice 2	1965	879	1.356	0.788	0.338	−0.485
	1970	805	1.361	0.702	0.311	−0.450
Doubravčice 3	1965	937	1.410	0.859	0.338	−0.482
	1975	692	1.428	0.885	0.343	−0.586

Table 6. Mahalanobis distances and test results for single tree classes, Doubravčice 1

		Class 1	2a	2b	3
Class 1		X			
	D^2	1.55			
Class 2a	F_{stat}	2.66	X		
	F	1.46			
	D^2	2.53	1.09		
Class 2b	F_{stat}	1.95	1.14	X	
	F	1.50	1.46		
	D^2	2.77	1.65	0.33	
Class 3	F_{stat}	2.27	1.84	0.18	X
	F	1.50	1.46	1.55	
	D^2	3.55	2.31	0.94	0.37
Class 4	F_{stat}	1.46	1.24	0.25	0.11
	F	1.53	1.46	1.66	1.64

Table 7. Mahalanobis distances and results of tests between individual plots

		Plot No. 1	Plot No. 2	Plot No. 3
Plot No. 1		X		
	D^2	0.18		
Plot No. 2	F_{stat}	1.00	X	
	F	1.42		
	D^2	0.82	0.0001	
Plot No. 3	F_{stat}	4.21	0.0005	X
	F	1.50	1.42	

$$S = \frac{1}{n}(w_i^P - \hat{\mu})(w_i^P - \hat{\mu})^T$$

The orthogonal eigenvectors of S, denoted by χ_j are the principal components of S with corresponding eigenvalues

$$\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_j \geq 0$$

where: $j = \min(n - 1, M)$.

The eigenvalues of the variance-covariance matrix derived from a set of shapes of dominant trees are presented in Table 8.

As can be seen in Table 8, the first three principal components (PC) include 99% of all variability. Out of it the first two cover 96% of the variability. This fact indicates strong relationships between boundary points in the configuration matrix.

The structure in the j-th PC can be viewed through plots of an icon for mean shape $\hat{\mu}$ with displacement vectors

$$v(c, j) = \hat{\mu} + c\lambda_j^{1/2}\chi_j$$

for the shapes corresponding to $c \in \langle -3;3 \rangle$.

The first PC is symmetric, it points across the vertical stem axis. The second PC is asymmetric. It has an opposite direction at the butt and at the rest of the stem. The third PC covers just a little variability. It corresponds with

Table 8. The first three eigenvalues of the variance-covariance matrix

Eigenvalue	$\lambda_j \cdot 10^{-6}$	$\lambda_j / \sum_{j=1}^{P} \lambda_j \cdot 1$ (%)
λ_1	1.482	75
λ_2	0.413	21
λ_3	0.054	3

the average at the butt and at the half of the stem. It points toward the stem centre in the low stem part and from the stem centre in the upper stem part.

In the next step, the variability was examined by calculating the principal components score for the i-th individual on the j-th principal component. PC score is given by

$$s_{ij} = \chi_j^T(w_i^P - \hat{\mu})$$

For each PC always 10 individuals were found with the highest and the lowest PC score values. This approach was chosen in order to identify the source of variability. Dendrometric characteristics of such two groups were compared. The compared characteristics included: stem height, basal diameter, butt diameter, length, width, and volume of the crown, stem volume, volume increment in the past 5 years.

The trees with the lowest first PC score belong among trees with the highest basal diameter and butt diameter, they have wide and perfect crowns. On the other hand, the trees with the highest PC score have markedly narrower and sometimes one-sided crowns, smaller diame-
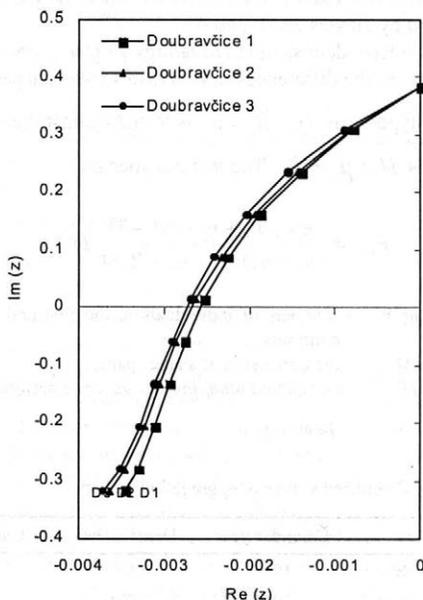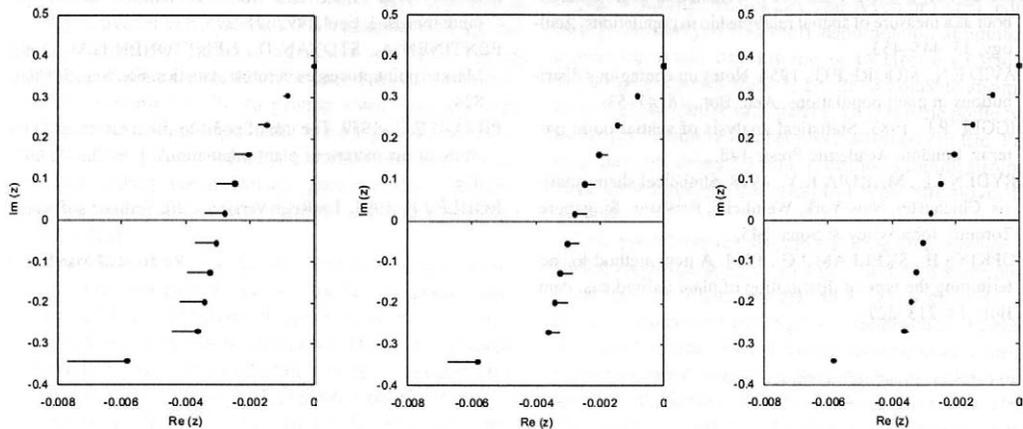

Fig. 5. Courses of full Procrustes mean shapes for whole sample plots Doubravčice 1, 2, and 3. Stem butt at the 1/20 of the height

Figs. 6, 7, and 8 show the first three PC with configurations evaluated at $c = -3; +3; +3$ standard deviations along each PC from the full Procrustes mean. The shape diameter with $c = 0$ is the Procrustes mean shape

ters and lower volume increment. The difference does not consist in the tree heights and crown lengths. These dendrometric characteristics support the hypothesis of the variability explained by the first PC is produced by a competition pressure upon individual trees. The competition pressure can roughly be estimated from the social position of the tree (in this case by Konšel's classification). As the first PC explains 75% of the variability and this variability does not seem to change considerably within individual tree classes, then the different courses of the full Procrustes means in Fig. 4 are explained by a different competition pressure on the individual tree classes. This hypothesis could be justified only after a long observation of the sample plot, calculation of competition indices of individual trees and following comparison of tree shapes. Similarly, the courses of the full Procrustes means for individual plots shown in Fig. 5 can be explained by the first PC by a lower competition among the trees on plot 3 than on plot 1 that is caused by fewer trees on plot 3. Another cause of statistically significant difference between plots 1 and 3 could consist in the shape change evoked by an age shift.

The trees with the highest second PC score are distinguished from the trees with the lowest second PC score by a profound difference in the basal diameter and breast-height diameter, hence the second PC is caused by the hypertrophy of the stem base. This hypertrophy might be caused by rot or buttress; unfortunately, the rot was not closely observed, therefore no explanation can be submitted.

Trees with the highest and the lowest third PC score differ from each other significantly in the crown width and volume. The crown lengths are almost the same in both groups. The factor able to explain this part of variability has not been found.

CONCLUSION AND DISCUSSION

For completeness a further analysis of the above-mentioned results would be necessary. In a traditional approach probability distribution can be derived for individual indices and so their significance tests can be formulated. This approach however requires many simplifying assumptions that cannot often be fulfilled in practice. There are also other statistical analysis methods of both aggregation indices and paired correlation functions, analysis of this issue is however beyond the scope of this article.

Application of full Procrustes co-ordinates is just one of the shape description methods. The others include methods like Procrustes tangent co-ordinates, Bookstein co-ordinates (BOOKSTEIN 1991) and others. The used stem diameters are the arithmetic means of two perpendicular measurements. The stems are therefore considered symmetric along their vertical axis. It would be more correct to consider the stems asymmetric with uniform orientation to cardinal points. Another problem consisted in not separating a possible shape change caused by age and competition pressure in Fig. 5. This issue will be treated in our next work. The height co-ordinates in the configuration matrix gain on by 1/10 of the tree height, which is a classical method used e.g. in true shape sequences. Obviously, this selection configuration is not the only possible one. The boundary points could be supplied or substituted e.g. by inflection points on the stem morphological curve.

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Dendrometrické zhodnocení porostní struktury a tvarů kmenů na smrkových zkusných plochách Doubravčice 1, 2, 3

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ABSTRAKT: Článek informuje o možnostech popisu struktury porostů pomocí indexů agregace (Clarkův-Evansův, Pielou-Mountfordův, Hopkinsův-Skellamův, Davidův-Mooreův) a na konkrétních porostních strukturách zachycuje hodnoty těchto indexů pro smrkové zkusné plochy předmýtního věku. Dále je struktura zkusných ploch zachycena průběhem grafů párové korelační funkce. Pro zkoumání tvarů kmenů bylo použito metody Procrustovy superimpozice. Součástí článku je také rozbor tvarové variability pomocí analýzy hlavních komponent a možnost testování shody středních tvarových vektorů.

Klíčová slova: smrk ztepilý (*Picea abies* [L.] Karst.); struktura porostu; indexy agregace; párová korelační funkce; tvar kmene; variabilita tvaru kmene; Procrustova superimpozice

Článek se zabývá některými v lesnictví zatím méně obvyklými metodami studia struktury porostů a tvarů kmenů. Popsané metody studia struktury porostů mohou mít praktický význam při inventarizaci lesa (odhady počtu stromů, zásob), získávání parametrů pro simulaci rozmístění stromů na zkusných plochách v růstových modelech, pro popis přírodě blízkých bohatě strukturovaných porostů, pro optimalizaci těžebních technologií atd.

Zkoumání tvaru kmene má v dendrometrii dlouhou tradici a také velký význam zejména pro konstrukci objemových tabulek, sortimentačních tabulek, tabulek jednotných výškových křivek i růstových modelů. V článku jsou použity tzv. geometrické metody popisu tvarů. Jejich předností je jednoznačná definice pojmu tvar a možnost vzájemného porovnávání tvarů na základě vícerozměrných statistických metod.

Článek obsahuje praktickou demonstraci všech teoreticky popsaných postupů na datech získaných ze zkusných ploch katedry hospodářské úpravy lesů LF ČZU Doubravčice 1, 2, 3. Jsou zde vypočteny také tradiční dendrometrické charakteristiky všech tří ploch.

Porostní struktura je zhodnocena na základě indexů agregace (Clarkův-Evansův, Pielou-Mountfordův, Hopkinsův-Skellamův, Davidův-Mooreův). Moderní trend ve studiu struktury porostů pak vyjadřuje párová korelační funkce.

Všechny čtyři indexy shodně ukazují na regulární strukturu porostů. Přestože je denzita jednotlivých porostů odlišná, rozdíly v jejich prostorové struktuře nejsou zřejmé. Výrazné změny nejsou patrné ani během vývoje v čase. Z periodického chování párové korelační funkce je navíc patrné, že porosty byly založeny v pravidelném sponu.

Pro úplnost by bylo potřebné udělat ještě statistickou analýzu uvedených výsledků. Při tradičním přístupu lze pro jednotlivé indexy agregace odvodit jejich pravděpodobnostní rozdělení a tedy i formulovat testy jejich významnosti. Tento přístup však vyžaduje řadu zjednodušujících předpokladů, které v praktických situacích nebývají často splněny. Existují i jiné metody statistické analýzy, jak indexů agregace, tak párových korelačních funkcí, rozbor této problematiky však překračuje rozsah článku.
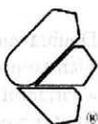
Tvary kmenů jsou zkoumány pomocí metody Procrustovy superimpozice. Práce se dále zabývá porovnáním tvarů kmenů roztříděných podle Konšelových stromových tříd a podle jednotlivých ploch. K testování shody Procrusterových středních tvarů byl použit Hottelingův T^2 test. V rámci Konšelovy stromové třídy 1 (předrůstavé stromy) byl na ploše Doubravčice 1 proveden rozbor variability za pomoci analýzy hlavních komponent a byl učiněn pokus o vysvětlení příčin jednotlivých složek variability.

Obr. 4 ukazuje, že vektory tvarových průměrů jednotlivých stromových tříd tvoří uspořádanou skupinu. Ve směru od svislé osy kmene je to stromová třída 4, následuje stromová třída 3, 2b, 2a, a konečně stromová třída 1. Z obrázku je také patrné, že je možné podle tvaru vymezit tři skupiny Konšelových stromových tříd. První skupinu tvoří stromová třída 1, druhou skupinu stromová třída 2a a konečně třetí skupinu tvoří stromové třídy 2b, 3, 4.

Tvar předrůstavých stromů na ploše Doubravčice 1 je možné zjednodušit do tří složek – hlavních komponent. První hlavní komponenta zahrnuje 75 % variability. Jedná se v lesnické terminologii o „plnodřevnost a neplnodřevnost" kmene. Druhá hlavní komponenta zahrnuje 21 % variability. Jedná se o zbytnění bazální části kmene oproti zbytku kmene. Třetí hlavní komponenta vysvětluje 3 % variability. Jedná se o stromy s náhradním vrcholem či vrcholem jinak poškozeným, další možnou příčinou je chyba v měření délek stromu.

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