Journal of
FOREST SCIENCE

Towards the bionomy of gall wasps *Andricus quercuscalicis* and *A. hungaricus* (*Hymenoptera, Cynipidae*)

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ABSTRACT: The paper deals with the biology of gall wasps *Andricus quercuscalicis* (Burgsd.) and *A. hungaricus* (Htg.) which got overpopulated in oak stands and seed orchards of southern Moravia in 1995. The main investigation was made in a 10-year old orchard of *Quercus robur* f. *slavonica* in the Valtice Forest District (Forest Enterprise Židlochovice). Galls of both cynipids were collected from the orchard on 23 October 1995 and placed into outdoor photoeclectors. The evaluation of 5-year rearings and gall analyses by sectioning provided information about development and size of galls. Some adults of *A. quercuscalicis* were leaving the galls after the 1st wintering (in April), other after the 2nd, 3rd or 4th wintering (in March). The first wintering included grown-up larvae, the second wintering included 33% of adults and 67% of larvae, the third wintering included 80% of adults and 20% of larvae, and the fourth wintering included only adults. Average fecundity was 1,126 (max. 1,555) eggs and was increasing with the increasing diapause duration from 925 eggs (in females after the 1st wintering) up to 1,297 eggs (in females after the fourth wintering). Outer galls were on average 20.8 mm wide and 16.2 mm high. Inner galls were on average 4.9 mm long, 3.9 mm wide and 3.2 mm high. 19.3% of larvae and pupae died without any obvious reason, 4.3% of larvae were killed by the chalcid *Ormyrus nitidulus* (F.), 9.2% of adults died in the inner galls and 6.3% in enclosed outer galls. Some 80% of adults left the galls via natural emergence holes in the outer galls and 20% of them bit out through the thinned walls of gall bases. The adults of *A. hungaricus* were leaving the galls after the 2nd and the 3rd wintering (exceptionally after the 1st and the 4th wintering), usually in the 2nd half of February and at the beginning of March. Average fecundity was 1,447 (max. 1,870) eggs and was increasing with the increasing diapause duration. The size of outer galls ranged between 20 and 43 (av. 32) mm. Inner galls were on average 5.4 mm long, 4.6 mm wide and 4.2 mm high. 16.2% of larvae and pupae died without any obvious reason, 8.5% of larvae were killed by the chalcid *Aulogymnus trilineatus* (Mayr), 9.8% imagoes died inside the inner galls and 2.1% died in the outer galls.

Keywords: *Andricus quercuscalicis*; *A. hungaricus*; diapause; hatching; natality; mortality; gall dimensions

Cynipids (*Cynipidae*) constitute a group of slim-waisted hymenoptera (*Apocrita*) from the superfamily of gall wasps (*Cynipoidea*) most abundant in species. Apart from several parasitic species and species living in galls as inquilines the family includes mainly numerous gall-forming species of which some may occasionally show as commercially important pests. There are some 140 gall-forming species in Europe (about 90 in the Czech Republic) (GAUSS 1982; MIKULA 1989). Most of them develop on oaks and only smaller numbers on maples, roses and on other plants (never on conifers). Of 16 cecidogenous genera of cynipids occurring in the Czech Republic the genus *Andricus* Hartig, 1,840 exhibits the highest number of species with a total of 38 species (MIKULA 1989). Representative of the genus most frequently occurring in the great part of the Czech territory are the gall wasp *Andricus quercuscalicis* /Burgsdorf, 1783/ and the gall wasp *A. hungaricus* /Hartig, 1843/ in southern Moravia.

Numbers of many cynipid species increased in the Czech Republic in 1994 and 1995 due to exceedingly warm and dry weather. A particularly heavy mass outbreak was observed in oak stands and seed orchards of southern Moravia in 1995. The unusually mass occurrence of conspicuous new neoplasms induced by gall-forming cynipids on oaks was first noticed by employees of the Židlochovice Forest Enterprise and by research workers of the Research Institute of Forestry and Game Management Jíloviště-Strnady at the Research Station in Staré Město near Uherské Hradiště. The increased concern of forest practice and breeders from the Research Institute was urged mainly by the fact that the above mentioned (and some other) gall wasp species enormously infested the seed orchards of Slavonic pedunculate oak (*Quercus robur* L. f. *slavonica* Gáyer) which is highly valued by forest practice, in years with outstanding crop of acorns.

The outbreaks of some cynipid species are in general rather frequent in many regions of central, southern and eastern Europe. Yet the biology of many species remained under a veil of many confusions for a long time (RATZE-BURG 1844). The complicated development of numerous gall-forming species, consisting in alternation of monosexual (i.e. parthenogenetic, agamic) and bisexual (i.e. amphigonous) generations, was first disclosed by WALSH (1864). The way of reproduction ('heterogony') was later corroborated by research results of ADLER (1877, 1881), BEIJERINCK (1880, 1882, 1896), MAYR (1881), KIEFFER (1914) etc. According to BEIJERINCK (1880, 1882), the imagoes of *A. quercuscalicis* change their host species with one generation developing on pedunculate oak (*Quercus robur* L.) and the other one on Turkey oak (*Q. cerris* L.). The gall wasp occurs, therefore, only in places with both tree species.

The alternation of two generations connected with the change of hosts and the infestation of different plant organs (roots, bark, shoots, buds, leaves, flowers and fruits) occurs – according to the present knowledge – in many cecidogenous cynipids. Gall wasps of the two alternating generations differ from each other in terms of size and partly also morphologically and the galls created by them are entirely different, too. These are reasons why the parthenogenetic and bisexual generations of the same species were described as different species and in many cases even as different genera before the genetic context between the respective generations of heterogonic gall wasps was known. For example, the species identity of *Cynips calycis* Burgsd. and *Andricus cerri* Beijer. and their dependence on more hosts were experimentally proven by Beijerinck as late as 1896. These systematic complications did not occur in agamic and bisexual cynipid species which create galls on one or several host species of the same genus, usually on a single plant organ (stem bark, shoots, buds, leaves, flowers and fruits).

The uniform body formation and vague coloration of adult cynipids make their determination very difficult even for experts. The determination can often be made thanks to only negligible differences and some species still remain undistinguishable from one another in morphological terms. Yet, their galls are as a rule so much characteristic that the species can be determined by them with no greater problem.

There are various theories about the proper causes of the gall formation. BEIJERINCK (1880), MAGNUS (1914) and other arrived at a conclusion that for example the galls of *A. quercuscalicis* develop only on the growing parts of plants their formation being attributable mainly to younger living larvae and not to injuries or secretions of accessory glands injected into the plant during oviposition. Also, according to the today's concept the young dividing tissues of plants are instigated to gall formation mainly by the gall-forming substance secreted mostly by young cynipid larvae. Since there are no special secretion organs revealed in the larvae so far, the origin of gall proliferation must be apparently sought in the secretions

of usual secretion organs (mainly salivary glands). According to KIEFFER (1914), the secretion of cynipid larvae salivary glands has a capacity to provoke the plant to the pathological formation of gall tissue. Galls are an ideal dwelling place for the larvae, offering good nutrition and considerable (although not absolute) protection from unfavourable abiotic and biotic impacts. However, there is still a lot of unclear about the way of action and structure of these species-specific gall-forming secretions (GAUSS 1976/1977, 1982).

There is a rather extensive entomological and forest-protection literature about the morphology, systematics, development and commercial importance of cynipids. The greatest attention of research workers was paid to commercially important gall-forming species whose galls are often very striking not only by their size but also by their shapes. One of the species is the gall wasp *A. quercuscalicis*. Galls ('oak-galls') on *Q. robur*, undoubtedly related to *A. quercuscalicis*, are mentioned already by RATZEBURG (1844). Thanks to the high content of tannic acids the oak-galls represented in the past (up to about the 20s of the 20th century) a valuable trading commodity intensively commercially used in tanneries, dyeing shops, for the production of high-quality black ink, therapeutic and other purposes (HARTWICH 1883, 1905). Bavaria imported the oak-galls mainly from Hungary and this is why for example SCHRANK (in RATZEBURG 1844) considered a possibility of intentional spreading of the gall wasp in some forest districts of southern Germany. However, this was taken for impossible by BURGSDORF (in RATZEBURG 1844) who assumed that the larvae and pupae wintering in the galls would not survive local frosts and die.

The gall wasp *A. quercuscalicis* is not only dealt with in collected works of different scopes (e.g. MAYR 1871; DARBOUX, HOUARD 1901; HOUARD, DARBOUX 1908–1909; DALLA TORRE, KIEFFER 1910; KIEFFER 1914; NÜSSLIN, RHUMBLER 1922; BURKERT 1927; ROSS, HEDICKE 1927; HEDICKE 1929, 1930; SMOLÁK 1941; ESCHERICH 1942; ZHIVOJINOVICH 1948; GUSEV, RIMSKIJ-KORSAKOV 1953; PFEFFER et al. 1954; GÄBLER 1955; IONESCU 1957; WEIDNER 1960; BUHR 1965; GAUSS 1982, etc.), but also in numerous special papers. The occurrence and development of the gall wasp in Germany were studied by WIMMER (1922), PFÜTZENREITER (1953), PFÜTZENREITER and WEIDNER (1959), EBERLE (1954, 1956), GAUSS (1976/1977), etc. Genetic consequences of the gall wasp spread to the north and west of Europe from Italy and Balkan due to intentional introduction of *Q. cerris* are mentioned by CSÓKA et al. (1998). The development of galls and the life cycle of cynipids from the genus *Andricus* were studied by COOK et al. (1998). The incidence, host tree species and also the development and parasitoids of the gall wasp were recently dealt with by e.g. MAXIMOVICH et al. (1982) from Bulgaria, SCUTAREANU and ROQUES (1993) from Romania, CSÓKA (1992, 1994) from Hungary, URBAN (1995) from Moravia, KELBEL (1996) from Slovakia,

Fig. 1. Two galls of *Andricus quercuscalicis* on the acorn cup of *Q. robur* f. *slavonica*. Valtice, 9 September 1994

Fig. 2. Galls of *A. hungaricus* on buds of *Q. robur* f. *slavonica*. Valtice, 9 September 1994

Fig. 3. Galls of *A. caputmedusae* and *A. quercuscalicis* on the same acorn cup of *Q. robur* f. *slavonica*. Next is an undamaged fruit. Valtice, 9 September 1994

STORK (1995) from the Netherlands and Belgium, and by SCHÖNROGGE et al. (1966a) and other from the viewpoint of a wider European context.

In several last decades, the gall wasp *A. quercuscalicis* rose a great attention in western Europe and especially in Great Britain and Ireland where it was unintentionally introduced from the continental Europe about at the beginning of the 60s and first found by CLARIDGE (1962). It was exactly Great Britain where the gall wasp distribution, life cycle, population dynamics and importance were studied in details (DARLINGTON 1974; MCGAVIN 1981; JUKES 1984; HAILS, CRAWLEY 1991, 1992; HAILS 1994, etc.). The gall wasp spread and abundance in Ireland were studied by SCHÖNROGGE et al. (1994) and in England by CRAWLEY and LONG (1995). Parasitoids and inquilines in galls of *A. quercuscalicis* in Great Britain were in details described by COLLINS et al. (1983), HAILS et al. (1990), SCHÖNROGGE et al. (1994), STONE et al. (1995), SCHÖNROGGE and CRAWLEY (1995, 1996b). Genetic differences in imagoes of different populations from the original and newly engaged (invasion) area were investigated by STONE and SUNNUCKS (1993). It was again Great Britain where gall wasp predators were studied (NOTTON 1990). Nevertheless, although the papers are numerous, the hitherto knowledge of the occurrence, biology, population dynamics and gradology of *A. quercuscalicis* still seems incomplete.

Unlike *A. quercuscalicis*, the gall wasp *A. hungaricus* is less spread and commercially almost unimportant. It is usually mentioned only in collected entomological papers. The submitted paper deals with the biology of both cynipid species which exhibited mass outbreaks in seed orchards on pedunculate oak (*Q. robur* f. *slavonica*) in

Valtice (Forest Enterprise Židlochovice) in 1994 and 1995.

MATERIAL AND METHODS

The most severe mass outbreak of the gall wasps *A. quercuscalicis* and *A. hungaricus* occurred in the Valtice Forest District (Forest Enterprise Židlochovice) in 1995 – in Stands 451 B3 and 716 D. The two localities are situated in a flat terrain at an altitude of about 170 m. Soil is deep clay-loam. Annual mean air temperature is 8.4°C and total annual mean precipitation amounts to 508 mm.

The seed orchard in Stand 451 B3 was established in 1960. Scions from the near 60-year-old trees of *Q. robur* f. *slavonica* were grafted on rootstocks of *Q. robur*. The highest fertility of the oak trees was recorded between 10 and 20 years of age. This overmature plantation does not belong in the set of gene plantations. Its health condition is poor, a particular reason being dropped water table due to the construction of the Nové Mlýny water reservoirs. The crop of acorns is to about 75% devalued by enormous infestation with the gall wasp *A. quercuscalicis* and he weevil *Curculio glandium* Marsh. (*Curculionidae*).

The seed orchard in Stand 716 D was established in 1985. It consists of 86 clones of *Q. robur* f. *slavonica* and 3 clones of *Q. petraea* (Matt.) Liebl., which were planted to check crossing possibilities. In the seed year 1995, acorn cups of *Q. robur* f. *slavonica* were to more than 80% infested by *A. quercuscalicis* (Fig. 1) and a great part of buds was infested with *A. hungaricus*
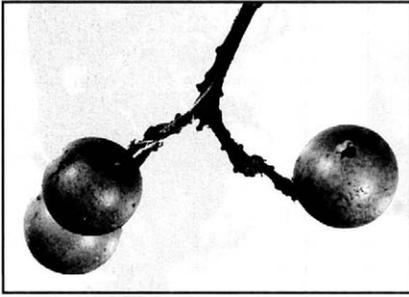
Fig. 4. A gall of *A. caputmedusae* on the acorn cup of *Q. petraea*. Valtice, 9 September 1996

Fig. 5. A gall of *A. foecundatrix* on the bud of *Q. robur* f. *slavonica*. Valtice, 23 October 1995
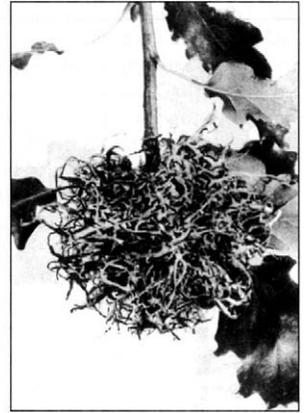
Fig. 6. Galls of *A. kollari* on the buds of *Q. robur* f. *slavonica*. Valtice, 23 October 1995
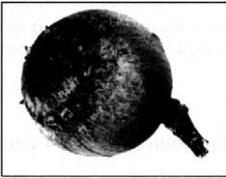
Fig. 7. A gall of *A. quercustozae* on the bud of *Q. robur* f. *slavonica*. Valtice, 23 October 1995

Fig. 9. Galls of *Cynips quercusfolii* on the leaves of *Q. robur* f. *slavonica*. Valtice, 23 October 1995

Fig. 8. Galls of *A. conglomeratus* on the twig of *Q. cerris*. Collections of the Department of Forest Protection and Game Management, Faculty of Forestry and Wood Technology, Mendel University of Agriculture and Forestry, Brno (MZLU Brno)

Fig. 10. Galls of *C. longiventris* on the leaf of *Q. robur* f. *slavonica*. Valtice, 23 October 1995

Fig. 11. Galls of *Janetia homocera* on the leaf of *Q. cerris*. Valtice, 23 October 1995
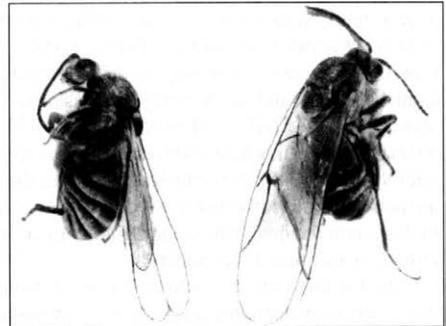
Fig. 12. Agamic females of *A. quercuscalicis*

(Fig. 2). Acorn cups of *Q. petraea* showed a high incidence of *A. caputmedusae* (Htg.) (Figs. 3 and 4). Buds of the two oak species often exhibited the development of *A. foecundatrix* (Htg.) (Fig. 5), *A. kollari* (Htg.) (Fig. 6) and rarely that of *A. quercustosae* (Bosc.) (Fig. 7). The seed orchard also showed an abundant occurrence of bark and bud cynipids *A. lignicola* (Htg.) and *A. conglomeratus* (Gir.) (Fig. 8). Numerous buds and leaves of oak trees were infested with *Cynips quercusfolii* L. (Fig. 9) and *C. longiventris* Htg. (Fig. 10).

There was *Q. cerris* occurring in the immediate and more distant surroundings of both seed orchards. Galls on male catkins of this oak species showed a development of very abundant individuals of *A. quercuscalicis* bisexual generation and acorns exhibited a very abundant occurrence of the agamic cynipid *Callirhytis glandium* (Gir.). Another more abundant cecidogenous cynipid species developing in shoots of *Q. cerris* was the bisexual gall wasp *A. multiplicatus* Gir. The abaxial (seldom adaxial) face of leaves often showed the enormous number of galls produced by the gall midge *Janetia homocera* (F. Loew.) (*Cecidomyiidae*) (Fig. 11).

The main investigation was made on the grown up galls of *A. quercuscalicis* and *A. hungaricus* collected on 23 October 1996 in Stand 716 D. The galls were taken to the Faculty of Forestry and Wood Technology Mendel University of Agriculture and Forestry in Brno, where they were separated by their originators and placed into two paperboard boxes (40 × 40 × 20 cm). The bottom and walls of the boxes were lined up with a plastic foil. In order to prevent the galls from drying out, the boxes were provided with small containers filled with wet absorbent cotton and the boxes themselves placed into black plastic bags. A hole of 3.5 cm in diameter was made in the upper part of the box side walls, into which bent glass test tubes each with a small amount of water were inserted. The boxes were then installed in the open (behind the window at the eastern face of the building). Moisture content of galls in these box photoeclectors was controlled three times a year at minimum and adjusted as required. The course of hatching of cynipids and their parasitoids, possibly inquilines was controlled in periods from February to September (incl.) for 4 subsequent years, usually in 1-week (or shorter as required) intervals.
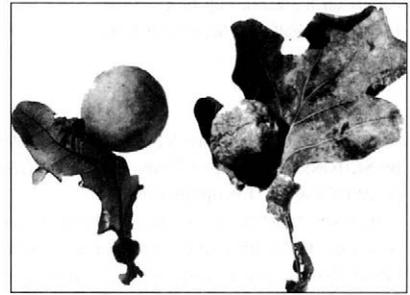
The hatched cynipids were either placed into 70% ethanol or used for the laboratory and field rearing to investigate their life length. Other insects hatched from the galls were placed into a conservation agent for later determination. Parasitoids from the superfamily *Chalcidoidea* were determined by Dr. Z. Bouček (England) for which he deserves cordial thanks from the author. The microscopic analysis of ovaries from the freshly hatched and naturally died gall wasp females was used to find out the number of ovarioles and natality (i.e. total number of eggs in ovaries). After the end of the rearings the galls were sectioned and analysed. The analysis and rearings helped to find out the general health condition of the cynipid population. In both cynipid species under study, the size of outer and inner galls was measured and evaluated (in *A. quercuscalicis* also in relation to the number of galls occurring on an acorn cup or to the acorn diameter).

The evaluation of nearly 5-year field and laboratory rearings (in the period from 23 October 1995 to 15 April 2000) and the subsequent analyses of galls by sectioning provided some new information mainly concerning the course of hatching, diapause, mortality, natality and size of outer and inner galls of the agamic generation of the gall wasps *A. quercuscalicis* and *A. hungaricus*.

RESULTS AND DISCUSSION

ANDRICUS QUERCUSCALICIS (BURGSD.) (SYN. *A. [CYNIPS] CERRI* BEIJER.)
OCCURRENCE

The gall wasp *A. quercuscalicis* shows the most abundant occurrence in south-eastern Europe and less frequent occurrences in central Europe. DALLA TORRE and KIEFFER (1910) mention its ample occurrence mainly in Austria, Hungary, Slavonia, Bosnia, Serbia, Greece and Asia Minor, and a rare occurrence in Germany, France and Italy. According to NÜSSLIN and RHUMBLER (1922), the cynipid does best in old light oak forests in the southeast of Europe (e.g. in Hungary, Croatia and Dalmatia). BUHR (1965) considers the centre of occurrence of the gall wasp to be south-eastern Europe with the adjacent territory of Asia Minor, and mentions its occasional incidence also in the Netherlands, Great Britain, France, Italy, and some individual (sometimes even abundant) occurrences in Germany. The natural range of the species including the apparently so far unfinished expansion of the gall wasp to the north and west of Europe is mentioned by GAUSS (1982) according to whom the species in question occurs not only in south-eastern Europe, but also in Germany, France, Italy, Spain, Belgium, the Netherlands and Great Britain. The gall wasp occurs also in the Czech Republic where it often shows mass outbreaks in some regions and becomes an important pest (KŘÍSTEK et al. 1992). The fact is documented by own observations of the author made in 1994 and 1995 in the Valtice Forest District (Forest Enterprise Židlochovice). Recently, the gall wasp is reported from many localities in Great Britain and Ireland (MCGAVIN 1981; COLLINS et al. 1983; JUKES 1984; HAILS et al. 1990; STONE, SUNNUCKS 1993; SCHÖNROGGE et al. 1994, 1995, 1996a,b; STONE et al. 1995; COOK et al. 1998, etc.).

DEVELOPMENT

The development of *A. quercuscalicis* exhibits a regular alternation of bisexual and agamic generations throughout the year. The bisexual generation develops in male catkins of *Q. cerris*, the agamic generation develops on acorn cups of *Q. robur* and more rarely on those of *Q. petraea*, *Q. pyrenaica* Wild. (according to some authors also on *Q. pubescens* Wild.). In Hungary for example, CSÓKA

(1994) found a highly dominant occurrence (97%) of agamic generation of the gall wasp on *Q. robur* and a rare (1.5%) occurrence on *Q. petraea* and *Q. pedunculiflora* K. Koch.

The bisexual generation of the gall wasp is established by agamic females which hatch from galls on the acorn cups fallen onto ground in the autumn. According to author's own findings, the gall wasps first winter in the galls mostly as grown-up larvae smaller part of which pupates, hatches and leaves the galls as early as the next spring. Greater part of the gall wasp population diapauses and leaves the galls after the 2nd up to the 4th wintering. Adults hatch from the galls usually after 1–3 weeks of the pupal stage. Freshly hatched adults dwell at the place of their hatching for several days to weeks (several months in the case of the diapausing subpopulation). Then they make a round oval emergence hole in the wall of inner galls and get into the open through a naturally developed oval aperture at the top of the outer gall. Then they spout liquid excrements from their digestive tract, which accumulated there during the larval development. The adults probably take in no solid food, they just suck water. Biting mouth organs serve them only for biting out the emergence hole in the inner gall (more rarely also in the outer gall provided that this hole is missing). In the case that the naturally developed emergence hole on the top of the outer gall is sealed, the imagoes are not capable to bite out through the lignified walls of outer galls and die inside the outer galls or bite out through the thinned basal walls of the galls.

According to DALLA TORRE and KIEFFER (1910), imagoes of the agamic generation (Fig. 12) hatch in February and March of the next year; according to KIEFFER (1914) it is in the spring of the 2nd to the 4th year. A conspicuously long (up to 3 years) larval quiescence is mentioned for example by ESCHERICH (1942). According to KŘÍSTEK et al. (1992), the larvae in the galls diapause from 1 to 3 years and hatch in March. The hatching of agamic females in February and March after the 1st up to the 3rd wintering is mentioned e.g. by BUHR (1965). A different opinion is advocated by SPEIGHT (1984) ac-

Table 1. Numbers and percentages of the adult gall wasps *A. quercuscalicis* and *A. hungaricus* hatched from galls in 1996–1999. The galls were collected in Valtice (Forest Enterprise Židlochovice) on 23 October 1995

Year	Andricus quercuscalicis		Andricus hungaricus	
	(number)	(%)	(number)	(%)
1996	86	23.5	4	1.9
1997	94	25.7	134	63.2
1998	154	42.1	70	33.0
1999	32	8.7	4	1.9
Total	366	100.0	212	100.0

cording to whom the adults hatch after the 1st and 2nd wintering in April or May.

However, some studies show that it is not only the larvae but also the adults which can diapause in the galls in relation to the course of meteorological factors (especially temperature). According to GAUSS (1976/1977), the agamic females hatch usually in February and March. In his rearings, there were only 2 (0.1%) agamic females hatching from 1,841 galls in the 1st year after wintering (up to the beginning of April). Fully developed imagoes were recorded in nearly 3% of the galls by 7 May and live larvae occurred in 80% of the galls. Nevertheless, as early as on 10 October the total of 200 galls analysed by sectioning revealed 159 galls (79.5%) with adults, 9 galls (4.5%) with larvae, and 32 galls (16%) with dead larvae or with larvae probably pecked up by birds. MCGAVIN (1981) even found out that less than a half of galls fallen onto ground towards the end of October contained grown-up larvae and more than a half of galls contained adults.

In the author's own rearings, there were 23.5, 25.7, 42.1 and 8.7% adults hatched from the total number of adults in the 1st, 2nd, 3rd and 4th years, respectively (Table 1, Fig. 13). In the 1st year after wintering, the adults were leaving galls in the course of April. After the 2nd wintering (i.e. in the 3rd year after maturation and galls fallen onto ground), the adults were leaving galls from the end of Feb-
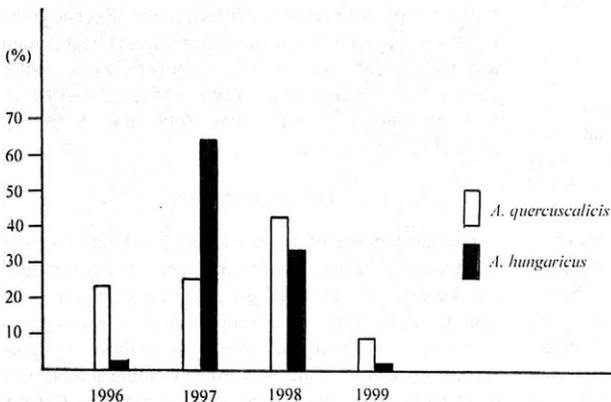

Fig. 13. The course of hatching of adult *A. quercuscalicis* and *A. hungaricus* (%) from galls made on *Q. robur* f. *slavonica* in 1995. MZLU Brno

Table 2. The course of leaving the galls by the adult gall wasps *A. quercuscalicis* and adult gall wasps *A. hungaricus* including mean daily temperatures at the time of gall leaving in 1996–1999. The galls were collected in Valtice (Forest Enterprise Židlochovice) on 23 October 1995

Year	Andricus quercuscalicis				Andricus hungaricus			
	Gall-leaving (from–to)	Mean	Gall-leaving (days)	Mean daily temperature (°C)	Gall-leaving (from–to)	Mean	Gall-leaving (days)	Mean daily temperature (°C)
1996	3. 4.–25. 4.	12 April	22	7.2	?	?	?	?
1997	26. 2.–4. 4.	7 March	37	5.4	14. 2.–13. 3.	27 February	27	5.5
1998	14. 2.–31. 3.	28 February	45	7.6	12. 2.–28. 2.	19 February	16	8.3
1999	2. 3.–26. 3.	11 March	24	6.9	27 February	27 February	1	4.4
Mean	14. 2.–25. 4.	13 March	35.7	6.6	12. 2.–13. 3.	24 February	22.4	6.4

ruary to the beginning of April. After the 3rd and 4th wintering, the adults were leaving galls from mid-February to the end of March and in March, respectively. They appeared in the open only at daily temperatures above 10°C and at average daily temperatures ranging between 5.4 and 7.6°C (Table 2). First time it was grown-up larvae wintering in the galls, second time there were 33% wintering adults and 67% larvae, third time 80% adults and 20% larvae, and fourth time only the adults. It follows that under conditions of Southern Moravia, only smaller part of *A. quercuscalicis* adults emerges in the open in the 1st year after wintering and the emergence occurs as late as in April. The late occurrence of these adults is preceded by the pupal stage which usually occurs in the 2nd half of March and at the beginning of April. However, the majority of adult gall wasps leave the galls in the 2nd, 3rd and 4th years after wintering – usually as

early as in March. These adults hatch during the preceding growing season and winter in the galls. The observations may lead to a conclusion that many individuals have to survive the winter period in true imaginal diapause or in pseudodiapause (quiescence), just waiting for the necessary increase of spring temperatures.

Imagoes of the agamic generation have wings that reach considerably over the abdomen end. Their body is 4–5 mm long, black-brownish and very finely hairy. In danger (e.g. on touch or shake given to the plant on which they sit), they take on a defensive position at which their legs and antennae are pulled in close to the ventral part of the body. At this death-imitating position they persist motionless until the danger is over. Soon after having left the galls, they invade on *Q. cerris* in order to deposit eggs into tiny foundations of male flowers. The imagoes of the agamic generation live a relatively long time. In

Table 3. Results from the analysis of ovaries in 132 parthenogenetic females of the gall wasp *A. quercuscalicis* and 92 parthenogenetic females of the gall wasp *A. hungaricus* hatched in 1996–1999. The galls were collected in Valtice (Forest Enterprise Židlochovice) on 23 October 1995

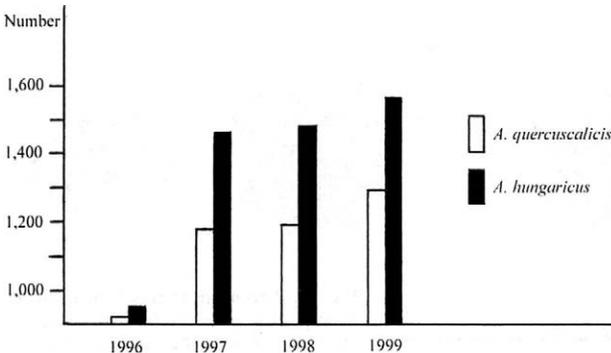| Year	Andricus quercuscalicis			Andricus hungaricus		
	Mean ovarioles	Mean eggs in ovarioles	Mean eggs	Mean ovarioles	Mean eggs in ovarioles	Mean eggs
1996	117.1	7.9	925	110.7	8.6	952
1997	118.8	9.9	1,176	137.5	10.6	1,458
1998	119.5	9.9	1,183	140.4	10.5	1,474
1999	120.1	10.8	1,297	120.0	13.0	1,560
Mean	118.5	9.5	1,126	136.5	10.6	1,447

Fig. 14. Average numbers of eggs in ovaries of *A. quercuscalicis* and *A. hungaricus* females which hatched from galls made on *Q. robur* f. *slavonica* in 1995. MZLU Brno

Table 4. Mean number of eggs including the number of analysed parthenogenetic females of the gall wasp *A. quercuscalicis* hatched in 1996–1999 (by the number of ovarioles and total). The galls were collected in Valtice (Forest Enterprise Židlochovice) on 23 October 1995

Year	Number of ovarioles (from–to)			
	95–110	111–130	131–149	Σ
1996	848/13	856/19	1,389/5	925/37
1997	1,000/13	1,202/10	1,380/10	1,176/33
1998	1,044/11	1,196/25	1,387/6	1,183/42
1999	1,177/10	1,413/8	1,430/2	1,297/20
Total	1,006/47	1,121/62	1,388/23	1,126/132

Table 5. Intensity of the infestation of pedunculate oak (*Q. robur* f. *slavonica*) acorn cups by galls of the gall wasp *A. quercuscalicis*. Valtice (Forest Enterprise Židlochovice), 23 October 1995

Galls on 1 acorn cup	Infested cups (%)		Number of galls	(%)
1	92	45.3	92	21.4
2	56	27.6	112	26.0
3	23	11.3	69	16.1
4	16	7.9	64	14.9
5	7	3.4	35	8.1
6	5	2.5	30	7.0
7	4	2.0	28	6.5
Total	203	100.0	430	100.0
Mean	–	–	2.1	–

the author's own rearings in the open they survived as long as from 16 to 36 (average 25) days while in the laboratory the length of their life was only 3–8 (average 4) days.

The eggs of *A. quercuscalicis* are milky white with fine and sheeny chorion. Their shape is oval to spindly, average length and width amount to about 0.15 and 0.086 mm, respectively. The physiological fertility (fecundity) of the agamic females is high. It was found out by analysing the ovaries of females hatched in the 1st to the 4th year after wintering that the average number of ovarioles and eggs in the ovarioles, and thus the average fecundity, increase with the increasing diapause (Tables 3 and 4, Fig. 14).

It follows that the total average fecundity of females is about 1,126 eggs with the fecundity of females hatched in the 1st year after wintering being lowest (some 925 eggs) and the fecundity of females hatched in the 4th year after wintering being highest (some 1,297 eggs). The absolutely lowest and highest physiological fertility of the examined females was 590 and 1,555 eggs, respectively. There were 95–149 (average 118.5) ovarioles in the ovaries, and 6–12 (average 9.5) eggs in one ovariole.

The diapause of *A. quercuscalicis* with duration varying from 1 to 4 years is a very remarkable phenomenon which apparently developed as a phylogenetic adaptation to eco-

logical (and particularly trophic) conditions. The great differentiation at the time of development of the agamic generation together with the enormous fecundity of females represent an efficient ecological strategy which makes it possible for the gall wasps to survive in unfavourable conditions and to rapidly increase the population density in optimal ecological conditions.

The eggs deposited by the agamic females into the male flowers of *Q. cerris* give rise to male and female larvae which induce the development of galls of the bisexual generation. The male catkins then often exhibit a development of sometimes even several tiny bottle- or cone-shaped galls of 1.0–1.5 (2) mm in length and some 1 mm width. These very thin-walled, dull and unhairy galls are greenish at the beginning, later yellowish to brownish. The total time period of the development of eggs, larvae and pupae of the bisexual generation is very short. Male and female adults hatch in the grown-up galls as early as in mid-May and emerge in the open at the same time (BUHR 1965). According to GAUSS (1982), the adults fly in May, according to SCHÖNROGGE et al. (1996a) it is as late as towards the end of May and at the beginning of June. Wasps of this generation are at all times much smaller than the agamic females. Their body is 1.5 mm long and most-
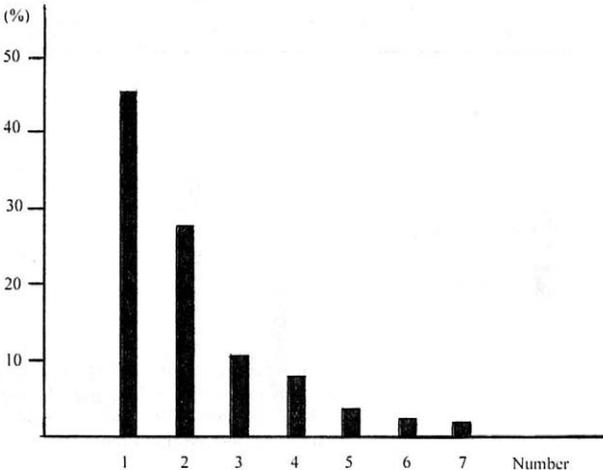

Fig. 15. Percentage of acorns with various numbers of *A. quercuscalicis* galls on the cups of *Q. robur* f. *slavonica*. Valtice, 23 October 1995

Fig. 16. Two galls of *A. quercuscalicis* on an acorn cup of *Q. robur* f. *slavonica*. Valtice, 23 October 1995
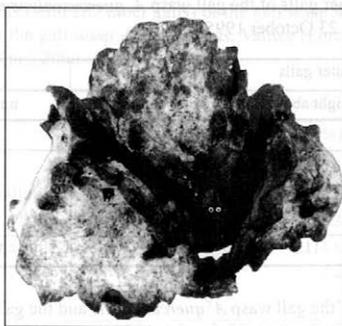
Fig. 17. Three galls of *A. quercuscalicis* on an acorn cup of *Q. robur* f. *slavonica*. Valtice, 23 October 1995

Fig. 18. Four galls of *A. quercuscalicis* on an acorn cup of *Q. robur* f. *slavonica*. Valtice, 23 October 1995

ly black with the sheeny abdomen and mostly amber yellow antennae and legs.

The imagoes of the bisexual generation live only a few days. Fertilized females deposit eggs into young cups of acorns their specific placement being near the acorn connection with the cup. There is usually one egg (exceptionally two eggs) laid at one place. However, there may be even several separate punctures made by the imago into a cup, each with one deposited egg. Larvae hatch from the eggs in several days, which induce the development of very species-characteristic galls. According to the number of laid eggs there is a maximum of 7 galls which can develop on a cup (Table 5, Fig. 15); according to MC-GAVIN (1981) it is as many as 6–7 galls and according to GAUSS (1982) and other up to 10 galls. The galls rapidly grow towards the end of spring and at the beginning of summer and mature towards the end of August and in September. Damaged fruits with the galls fall onto ground in the autumn and the gall wasps survive the unfavourable winter conditions in the galls.

DESCRIPTION OF GALLS

The agamic generation of *A. quercuscalicis* develops in the natural conditions of southern Moravia usually on the acorn cups of *Q. robur* from eggs deposited by the females of bisexual generation usually in May. Initially, the galls are green, spongy and strongly sticky on the surface; later, they are brown, lignified and non-sticky. They are connected with the inner face of the cup close at the circumference of its bottom by means of a basal tongue-shaped protuberance whose length is 4–7 mm. By means of this protuberance the intensively growing galls withdraw high amounts of nutrients which are then insufficient for the growth of fruits. The expanding galls envelop the dwarfing acorns and their cups to a greater part (or entirely) and suppress them on sides (and often even from above and from below) (Figs. 16–18).

In Czech, the galls are traditionally called 'oak-galls' (in German 'Knoppern', in English 'knopper galls'). Their shape is roughly conical of 18–25 mm in diameter and 15–20 mm in height (DALLA TORRE, KIEFFER 1910). From outside they are usually provided with 4–8 strongly protruding, pointless and often interrupted longitudinal ribs. Many galls have on their surface irregularly winged or rugged protuberances. There is an aperture developing at the top of the maturing outer galls, which conically widens into the spacious inner cavity. The cavity is initially split into two parts by means of a thin transversal division wall. The oval inner gall (exceptionally 2 galls) is located within a small space at the bottom (Figs. 19 and 20).

Fig. 19. Galls of *A. quercuscalicis*: a view from above (left) and a longitudinal section (right). The section through the outer gall clearly shows a dwarfed fruit (acorn with a cup) and an inner gall. Valtice, 15 April 1997

Fig. 20. Inner galls of *A. quercuscalicis*

Table 6. Mean size (mm) of outer and inner galls of the gall wasp *A. quercuscalicis* at different numbers of galls on an acorn cup. Valtice (Forest Enterprise Židlochovice), 23 October 1995

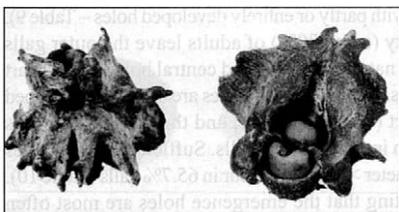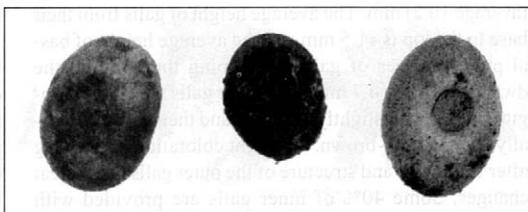| Galls on 1 cup	Outer galls				Inner galls			
	number	width	height above cup	total height	number	length	width	height
1	41	22.3	13.0	17.4	42	5.1	4.0	3.4
2	56	20.7	11.6	16.3	56	4.9	3.9	3.3
3–4	68	20.4	11.4	16.1	68	4.8	3.9	3.2
5–7	41	20.0	10.3	15.3	41	4.7	3.8	3.1
Total	206	20.8	11.5	16.2	207	4.9	3.9	3.2

Table 7. Mean size (mm) of inner galls of the gall wasp *A. quercuscalicis* and the gall wasp *A. hungaricus* at the varying width of outer galls. Valtice (Forest Enterprise Židlochovice), 23 October 1995

Andricus quercuscalicis					*Andricus hungaricus*				
Width of outer galls	number	length	width	height	width of outer galls	number	length	width	height
8–20	105	4.7	3.7	3.1	20–25	12	5.2	4.2	4.0
21–25	90	5.0	4.0	3.3	26–30	60	5.4	4.5	4.2
26–32	15	5.1	4.1	3.5	31–43	70	5.5	4.7	4.3
Total	210	4.9	3.9	3.2	–	142	5.4	4.6	4.2

Table 8. Dimensions (mm) of galls of the gall wasp *A. quercuscalicis*. Valtice (Forest Enterprise Židlochovice), 23 October 1995

Acorn diameter	Number of galls	Mean gall width	Mean gall height above cup	Mean gall height below cup	Total gall height
< 5.0	69	20.4	11.2	4.1	15.3
5.1–10.0	96	20.6	11.4	4.9	16.3
> 10.1	39	21.9	12.2	5.1	17.3
Total	204	20.8	11.5	4.7	16.2

According to BUHR (1965), the inner galls are oval, 3–5 mm long and connected to the outer galls at one place. Inside the galls, there is a chamber in which the gall wasp develops. The walls of inner galls are thin, consisting of trophic and protective (hard) layers. The trophic layer is formed by several layers of thin-walled cells rich in proteins, starch and vegetable oils. The trophic layer links up with the protective layer formed by thick-walled lignifying cells which provide strength to the inner galls and most probably considerably hamper the penetration of insect parasitoids and predators.

The author's own findings about the dimensions of outer and inner galls of *A. quercuscalicis* considerably differ from the literary data. The outer galls reach the width from 8 to 32 (average 20.8) mm and height from 10 to 23 (average 16.2) mm. The average height of galls from their base to the top is 11.5 mm and the average height of basal protuberances of galls enveloping the cup and the dwarfed acorn is 4.7 mm. The inner galls are shortly longitudinally oval, slightly flattened and their colour is usually grey to light-brown. The light coloration keeps long after the colour and structure of the outer galls mark great changes. Some 40% of inner galls are provided with a conspicuous central outgrowth on their upper side. The way of their fixation to the bottom of the outer galls is at all times horizontal. The inner galls are 3.6–6.1 (average 4.9) mm long, 3.1–4.5 (average 3.9) mm wide and 2.0–4.1 (average 3.2) mm high. The size of outer and inner galls gradually decreases with the increasing number of galls on 1 cup (Table 6). Nevertheless, the size of inner galls increases with the increasing width of outer galls (Table 7). The average size of acorns decreases with the increasing number of galls on one cup. This is why the galls with below-average acorns are on average smaller than those with above-average acorns (Table 8).

The adults leave the inner galls through the circular or oval emergence holes whose diameter ranges from 1.7 to 2.4 (average 2.0) mm (Fig. 21). The holes are localized on the 'head' end of the gall and their edges are smooth. The hard walls of inner galls represent a big obstacle for the adults, which is best documented by the fact that some 9.2% adults die inside them (of these some 4.4% adults die in galls with partly or entirely developed holes – Table 9). The majority (some 80%) of adults leave the outer galls through the naturally developed central holes in the heart of inner galls. However, these holes are not at all developed in small part (13.8%) of galls, and their diameter is less than 1.5 mm in other 20.5% galls. Sufficiently large holes (with a diameter > 1.5 mm) occur in 65.7% galls (Table 10). It is interesting that the emergence holes are most often missing or reaching improper sizes on the dwarfed galls. The adults are often capable of leaving the outer galls with no sufficiently large emergence holes available. Some 20% of adults get to the open through apertures bitten out in

Table 9. Results from the analysis of 206 galls (with 207 inner galls) of the gall wasp *A. quercuscalicis*, developed on 100 acorn cups, and 140 galls (with 142 inner galls) of the gall wasp *A. hungaricus*. Valtice (Forest Enterprise Židlochovice), collection of galls 23 October 1995, analysis of galls 15 April 2000

Galls	Andricus quercuscalicis		Andricus hungaricus	
	(number)	(%)	(number)	(%)
– left by adult gall wasps	126	60.9	90	63.4
– with dead gall wasp larvae and pupae in inner galls	40	19.3	23	16.2
– with dead adult gall wasps in outer galls	13	6.3	3	2.1
– with dead adult gall wasps in inner galls (with no outlet holes)	10	4.8	8	5.6
– ditto (with outlet holes)	9	4.4	6	4.2
– with parasitized gall wasp larvae	9	4.3	12	8.5
Total number of gall wasp inner galls	207	100.0	142	100.0
Number of outer galls left by the inquiline gall wasp *Synergus* sp.	4	–	–	–

Table 10. Diameter of the terminal hole in galls of the gall wasp *A. quercuscalicis*. Valtice (Forest Enterprise Židlochovice), 23 October 1995

Hole diameter	Number of galls	(%)
0	33	13.8
0.1–0.5	12	5.0
0.6–1.0	14	5.9
1.1–1.5	23	9.6
1.6–2.0	97	40.6
2.1–2.5	30	12.6
2.6–3.0	16	6.7
3.1–3.5	7	2.9
3.6–4.0	4	1.7
4.1–4.5	2	0.8
4.6–5.0	1	0.4
Total	239	100.0

the thinnest (0.2–0.7 mm) basal parts of the galls the very rare cases being recorded even with the existing sufficiently large naturally developed emergence hole. Nevertheless, the imagoes bite out through the thinned bases of the outer galls only with great difficulties and many of them (about 1/3) die. The lignified side walls of outer galls, which are 1–5 (10) mm thick represent an entirely insurmountable barrier for the wasps.

NATURAL ENEMIES

Galls of the agamic generation of *A. quercuscalicis* provide the gall wasps with food and fairly efficient protection against unfavourable weather conditions. The thick gall walls and the high content of tannic acids in them or the sticky surface provide a good (although not entirely perfect) protection of the gall wasps against their natural biotic enemies. Galls on acorn cups are pecked out by birds (mainly titmouse and nuthatch) and eaten out by small rodents whose species appurtenance has not been found out yet (GAUSS 1976/1977). According to this author, the damage by rodents amounts to as much as about 20% of the wintering gall wasp generation. The animals usually pick up the galls from the cups at first and then eat out the gall wasps from the bottom (i.e. thinnest) side with inquilines in the gall tissue being eaten only when occasionally present. The thin-walled galls of bisexual generation are often very intensively pecked out by birds (according to HAILS, CRAWLEY 1992 from 33 to 41%).

The role of insect parasitoids in controlling the numbers of agamic gall wasp generation is generally rather unimportant. The gall wasp in the inner galls is killed by *Megastigmus stigmatizans* (F.) and *Torymus regius* (Nees.) (*Torymidae*) (PFÜTZENREITER, WEIDNER 1959). According to SCHÖNROGGE et al. (1996b), solitary ecoparasitoids of the gall wasp are *M. stigmatizans* (F.) (*Torymidae*),

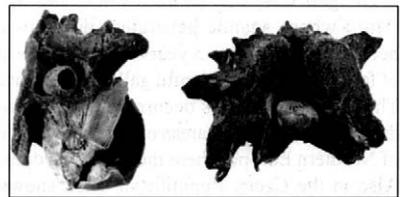Fig. 21. Inner galls of *A. quercuscalicis* with emergence holes for adults

Fig. 22. Left: A longitudinal section through the outer gall of *A. quercuscalicis* with a damaged acorn and inner gall left by adult gall wasp. Right: A longitudinal section through the outer gall with inner gall left by the chalcid *Ormyrus nitidulus* (F.). Valtice, 15 April 1997

Ormyrus nitidulus (F.) (*Ormyridae*), and *Aulogymnus trilineatus* (Mayr) (*Eulophidae*), the solitary endoparasitoid being *Sycophila biguttata* (Swederus) (*Eurytomidae*). *Mesopolobus jucundus* (Walk.) and *M. amaenus* (Walk.) (*Pteromalyidae*) develop as a gall wasp ectoparasitoid and an inquiline living in the walls of outer galls, and *Gelis formicarius* (L.) (*Ichneumonidae*) was raised from inner galls (SCHÖNROGGE et al. 1996a). The percentage of the gall wasp parasitization was very low (seldom exceeding 3%). With the exception of the ichneumon *G. formicarius*, all other parasitoid species were raised from galls collected in continental Europe.

There was the chalcid *Ormyrus nitidulus* (F.) (Fig. 22) developing in the inner galls of *A. quercuscalicis* in the studied seed orchard in Valtice, which killed 4.3% of the gall wasp larvae in 1995. The majority of adult chalcids (70%) were leaving the galls in mid-April of the next year. After the 2nd wintering the galls were left by about 20% (and after the 3rd wintering by about 10%) of adult chalcids, at all times towards the end of February. The difference of more than a month and a half in the time of leaving the galls is a signal that the chalcid apparently first winters as a larva, and second and third time as an adult. There is no doubt that the chalcid's diapause or the quiescence of imagoes play an important role at synchronizing its occurrence with the host gall wasp. As an inquiline rather frequently developing in the walls of outer galls was a gall wasp of the genus *Synergus* sp., whose adults were leaving the galls in mid-April after the 1st wintering, and towards the end of February after the 2nd and the 3rd wintering. It appears that the gall wasp also winters first in the stage of larva, and second and third time as an adult.

The very tiny, bare and thin-walled flower galls of the bisexual generation of the gall wasp *A. quercuscalicis* provide hardly any protection for their originators from parasitoids. For example in Great Britain, the gall wasp generation is parasitized at about 30% (HAILS, CRAWLEY 1991) and in Europe at more than 80% (STONE et al. 1995). Parasitoids most abundant in Great Britain are *Mesopolobus fuscipes* (Walk.), *M. xanthocerus* Thoms. and *M. tibialis* (Westw.) (COLLINS et al. 1983; HAILS et al. 1990, etc.)

COMMERCIAL IMPORTANCE

The gall wasps *A. quercuscalicis* and *A. testaceipes* (Htg.) whose agamic generation develops on the root necks of young (up to 5 years old) oak trees, are in terms of forestry the most harmful gall-forming species on oak. The abundant to mass occurrences of *A. quercuscalicis* are known from many areas of Europe (with the exception of Northern Europe where the gall wasp does not occur). Also in the Czech Republic, it often shows mass outbreaks and then becomes a serious pest (KŘÍSTEK et al. 1992). Severe losses are recorded in seed orchards (MAXI-MOVICH et al. 1982; SCUTAREANU, ROQUES 1993, etc.), which are always established of the highest quality oak

grafts from which early and frequent harvest of acorns of superb genetic quality is expected first. In the examined seed orchards of *Q. robur* f. *slavonica* in the Valtice Forest District (Forest Enterprise Židlochovice), the gall wasp nearly totally destroyed the copious crop of acorns in 1995.

Reasons of gall wasp gradations are not well known so far. An important role at the regulation of the gall wasp numbers is played by climatic and meteorological factors. The relationship between the increase in population density and mild winters is pointed out for example in detailed studies of its incidence made in Great Britain and Ireland from 1970. Yet, the sequence of gradations occurrences is very irregular. For example in south-western Germany, the gall wasp exhibited a mass outbreak in 1890, 1927, 1952, 1958 and 1974, i.e. after 37, 25, 6 and 16 years, respectively (GAUSS 1976/1977, 1982). PFÜTZENREITER (1953) and GAUSS (1976/1977) assume these irregularities in the pest occurrence to be related among other also to the nutrition of acorns, which is often affected by late frosts. Interesting is the fact that the most frequent and most intensive (up to nearly 100%) infestations by the gall wasp are recorded on oak trees which have been severely physiologically weakened by drought.

Thanks to their high (about 30%) content of tannic acids the galls were once massively used in industry. As a very valuable trading commodity they were collected particularly in Hungary, Serbia, Bosnia, Greece and Asia Minor (KIEFFER 1914). Some exporting countries such as Hungary, Croatia and Serbia intentionally supported the gall wasp's development (and thus production of galls) by economic measures. In order to maintain high population density of the gall wasp, small (and less marketable) galls were left behind in the oak stands. However, these dwarfed galls of different malformed shapes contributed to the planned goal only partly since it was exactly these galls in which a considerable portion of hatched adults died due to the frequent absence of naturally developed emergence holes in the galls. Also, the increased introduction of *Q. cerris* into local oak stands in countries of western and central Europe was to contribute in the past to reduce the imports of 'oak-galls'. More recently (about since the year 1920), the tannic acid and dyeing agents are produced chemically which made the lively trade with the 'oak-galls' cease nearly completely.

The galls of the gall wasp *A. quercuscalicis* deprive the acorns of assimilates and severely suppress the acorn mechanically. This is why the whole fruits (both cups and acorns) then exhibit various stages of dwarfing (from 50 to 95%). Because the acorns represent in the seed years an important component of winter food for mammals living in the open, the gall wasp can significantly restrict the feeding opportunities for these animals by a considerable reduction of the nutritive value of acorns (CORBET 1974). An analogy can be found in the past rearing of domestic pigs which were often partly depend-

ing on acorn nutrition. Regarding the minimum germinative capacity of damaged acorns, there is no doubt that the gall wasp can unfavourably influence also the general condition of natural regeneration in oak forests.

ANDRICUS (SYN. ADLERIA, CYNIPS) HUNGARICUS (HTG.) OCCURRENCE AND DEVELOPMENT

According to BUHR (1965), the gall wasp A. hungaricus (Fig. 23) occurs in great numbers on Q. robur and Q. pubescens in south-eastern Europe and seldom in Austria and in the former Czechoslovakia. CSÓKA (1994) found it in Hungary in 51 (47%) examined localities on Q. robur and exceptionally on Q. petraea.

The gall wasp's development is only very little known. According to the author's own findings, the gall wasp first winters at the stage of grown-up larvae in galls fallen onto ground in the autumn. In the natural conditions of southern Moravia, the majority (some 63%) of imagoes leave the galls in the 2nd year after wintering and great part of them (some 33%) in the 3rd year after wintering. Only a minimal number of wasps (some 2%) leave the galls as early as in the 1st (and the same number in the 4th) year after wintering (Table 1, Fig. 13). The imagoes emerge in open nature usually in the 2nd half of February, possibly at the beginning of March, i.e. about 1–2 weeks earlier than those of A. quercuscalicis (Table 2). According to BUHR (1965), the wasps occur in February and March.

Adult gall wasps leave the outer galls through round oval holes the diameter of which is about 2.5 mm. Greater part (some 55%) of the emergence holes is localized in the central third of the galls. Some 32% and 13% of emergence holes are usually situated in the basal and upper thirds of the galls, respectively. In this gall wasp we know only the parthenogenetic females (bisexual generation is evidently entirely missing). The females are very alike the agamic females of A. quercuscalicis but markedly larger. The length of their body (without wings reaching far over abdomen end) is from 4.5 to 5.5 (average 5) mm.

After having left the galls the females invade oak tree crowns from air or ground, and lay eggs into their lateral (rarely also terminal) buds. There is always one (exceptionally two) egg laid into a bud. In the case of danger, they can perfectly imitate death (akinesis). The eggs are lengthwise oval, narrowing on both ends, and somewhat larger than those of A. quercuscalicis (on average 0.17 mm long and 0.094 mm wide). Also the average number of ovarioles (136.5), average number of eggs per ovariole (10.6) and average physiological fertility of females (some 1,447 eggs) are higher than those of A. quercuscalicis. Similarly as in A. quercuscalicis, the average fertility of females is increasing with the increasing diapause (Tables 3 and 11, Fig. 14). The imagoes live from 4 to 10 (average 7) days in the laboratory and from 20 to 41 (average 28) days in the open.

Table 11. Mean number of eggs including the number of analysed parthenogenetic females of the gall wasp A. hungaricus hatched in 1996–1999 (by the number of ovarioles and total). The galls were collected in Valtice (Forest Enterprise Židlochovice) on 23 October 1995

Year	Number of ovarioles (from–to)			
	105–130	131–150	151–166	Total
1996	952/4	–	–	952/4
1997	1,192/14	1,550/20	1,645/10	1,458/44
1998	1,370/8	1,444/22	1,625/10	1,474/40
1999	1,560/4	–	–	1,560/4
Total	1,257/30	1,494/42	1,635/20	1,447/92

There are larvae hatched from the eggs, which further develop within the species-characteristic galls. The galls rapidly grow in the spring and in the first half of summer, mature towards the end of summer and beginning of autumn, and fall onto ground during the autumn. Galls collected from the seed orchard in Valtice contained developing chalcid Aulogymnus trilineatus (Mayr) (Eulophyidae) which killed 8.5% of the cynipid larvae there in 1995. Adult chalcids were leaving the outer and inner galls through emergence holes of 1.5 mm in diameter. The chalcids (similarly as the gall wasps) diapaused in the galls as long as up to 4 years. The greatest majority of them (62%) emerged in the open after the 3rd wintering. After the 1st wintering, the chalcids were leaving the galls as late as in the 2nd half of April, after other 3 years then in the 2nd half of March or at the beginning of April. The conspicuous divergence in the time of gall leaving obviously relates to the different time of pupation and hatching of the parasitoids and thus to the different wintering stages. As an inquiline with scanty development found in the walls of outer galls was the gall wasp Synergus sp., whose adults were leaving the galls as early as after the 1st wintering (about 20 May).

DESCRIPTION OF GALLS

The galls of A. hungaricus are of roughly spherical shape, slightly elongated at the base (Fig. 24). Their size is 20–43 (average 32) mm, according to DARBOUX and HOUARD (1901) 13–35 mm, according to DALLA TORRE and KIEFFER (1910) 20–25 (seldom 13–20) mm, according to ESCHERICH (1942) up to 25 mm, and according to ZHIVOJINOVICH (1948) up to 45 mm. The galls are yellow-brownish to brown, dull and with the exception of the base irregularly bulged. The bulges are max. 4 mm high, pointless or pointed, often irregularly interconnected with a network pattern of slightly elevated edges. Gall walls are spongy, somewhat rigid after maturation. By their size and general appearance the galls resemble the spherical bud galls of A. quercustozae (Bosc.) (Fig. 7) which are, however, sheeny and provided in the upper third with concentric rows of tiny bulges in circular arrangement.

Fig. 23. Parthenogenetic females of
A. hungaricus (from above and below)
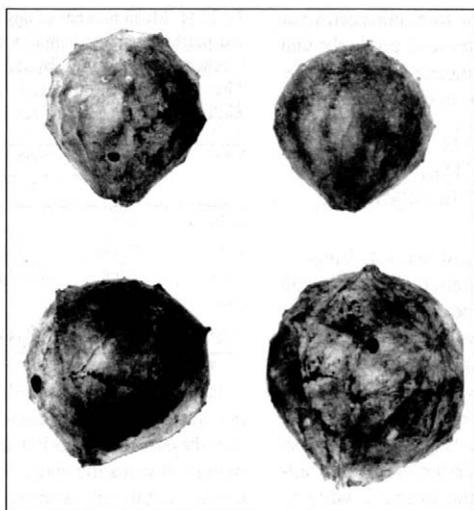
Fig. 24. Galls of A. hungaricus with emergence holes for
adults. Valtice, 15 April 1997

Fig. 25. A section through the
outer galls of A. hungaricus.
Above: An inner gall without the
emergence hole. Below: An inner
gall with the emergence hole of
the chalcid Aulogymnus trilinea-
tus (Mayr)

There is a large irregular cavity inside the mature outer gall, on the bottom of which an oval inner gall can usually be found (Fig. 25) placed horizontally. As many as about 1.3% of outer galls have two inner galls. The inner galls are light brown to brown, larger than those of A. quercuscalicis, and only slightly flattened dorso-ventrally (Fig. 26). Their length is 4.4–6.6 (average 5.4) mm, width 3.8–5.3 (average 4.6) mm and height 3.7–4.7 (average 4.2) mm. The size of the inner galls is increasing with the increasing width of the outer galls (Table 7). The inner galls are provided on their lower and upper sides with more or less apparent central protuberances. The lower protuberance serves to fix the inner galls to the outer galls.

Adult gall wasps leave the thin-walled inner galls through the round oval holes of about 2.4 mm in diameter, situated on one gall end (Fig. 27). It is not easy for the wasps to bite out the hole in the walls of hard inner galls, which is documented by numerous cases of their death inside the inner galls. In the author's own rearings the adults died in a total of 9.8% inner galls (of these the emergence hole was to a greater part or entirely completed in 4.2% galls) (Table 9). The very thick (but spongy) walls of outer galls do not represent a more serious obstacle for the great majority of adult gall wasps.

COMMERCIAL IMPORTANCE

The gall wasp A. hungaricus is one of the most abundant cynipid species in south-eastern Europe, developing in the bud galls of Q. robur. Its very conspicuous galls occur every year in great numbers also in the oak forests of southern Moravia. In 1995, the gall wasps A. hungaricus and A. quercuscalicis exhibited an enormous mass outbreak in Q. robur f. slavonica seed orchards in Valtice (Forest Enterprise Židlochovice) phy-
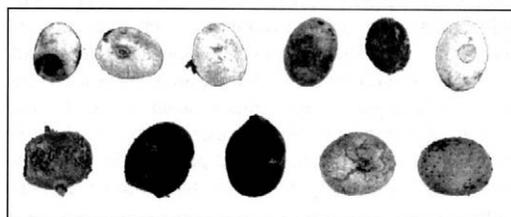
Fig. 26. Comparison of the size of inner galls of A. quercuscali-
cis (above) and A. hungaricus (below)

Fig. 27. Inner galls of A. hungaricus with emergence holes
for adults

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siologically weakened by drought. The very ample occurrence of the two gall wasp species adversely affected the health condition of local oak grafted plants and resulted in their dwarfing growth and drying out of crowns, sometimes even in the decline of whole trees. The example illustrates that the gall wasp *A. hungaricus* can show significant mass outbreaks even in the conditions of southern Moravia and thus contribute to the worsening health condition of seed orchards of *Q. robur.*
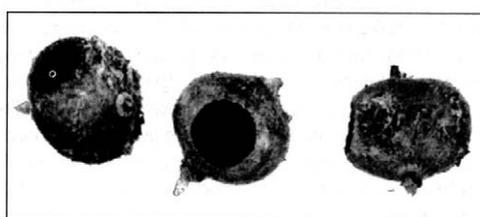
SUMMARY

Enormous mass outbreaks of the heterogonic gall wasp *Andricus quercuscalicis* (Burgsd.) and the parthenogenetic gall wasp *A. hungaricus* (Htg.) were recorded in oak stands and seed orchards of southern Moravia in the exceptionally dry and warm year 1995. The bionomy of the two gall wasps was studied in a 10-year old seed orchard of the valuable *Q. robur* f. *slavonica* in the Valtice Forest District (Forest Enterprise Židlochovice). Galls of both gall wasp species were collected from the orchard on 23 October 1995 and placed into field photoeclectors the same day. The evaluation of 5-year rearings and analyses of galls by sectioning brought the following new findings:

Andricus quercuscalicis

1. Females of the agamic generation of *A. quercuscalicis* were leaving galls after the 1st to 4th wintering. There were 23.5, 25.7, 42.1 and 8.7% adults which were leaving the galls after the 1st, 2nd, 3rd and 4th wintering, respectively. The first wintering included the grown-up larvae and the adults emerged in the open in April. The second wintering included 33% adults and 67% larvae, the third wintering included 80% adults and 20% larvae, and the fourth wintering included only adult insects. After the 2nd to the 4th wintering, the adults were leaving the galls mainly in March.

2. The agamic females deposit unfertilized eggs into the male flowers of *Q. cerris*. Individuals of a bisexual generation develop from the eggs in conical (up to 2 mm long) galls. The eggs are milky white, smooth, lengthwise oval, long about 0.15 mm and wide about 0.086 mm. Physiological fertility of the females is about 1,126 eggs. The lowest fertility is 590 (highest 1,555) eggs. With the increasing diapause the average fecundity of females increases from 925 eggs (in females after the 1st wintering) up to 1,297 eggs (in females after the 4th wintering). There are 95–149 (average 118.5) ovarioles in the ovaries, and 6–12 (average 9.5) eggs in one ovariole. In the open, the females of the agamic generation live 16–36 (average 25) days.

3. Male and female adults of the bisexual generation hatch usually in May. They deposit fertilized eggs into young acorn cups of *Q. robur* f. *slavonica*, usually one (exceptionally two) egg into one place. However, they can lay as many as 7 eggs into a cup. Larvae will hatch from these eggs, which induce a rapid creation of the

species-characteristic galls towards the end of spring and at the beginning of summer. The galls mature towards the end of August and at the beginning of September, and fall on ground in the autumn.

4. Galls of the agamic generation are originally green, spongy and sticky on the surface, later brown, lignified and unsticky. Their shape is roughly conical with a width of 8–32 (average 20.8) mm and height 10–23 (average 16.2) mm. From the outside they are provided with 4–8 longitudinal (often disrupted) ribs or with the winged or buldged protuberances. There is usually a hole at the top of outer galls, which conically opens into the spacious inner cavity on the bottom of which there is one (seldom two) inner gall. The inner galls are oval, slightly flattened dorso-ventrally and usually grey coloured. They are on average 4.9 mm long, 3.9 mm wide and 3.2 mm high. The average dimensions of outer and inner galls decrease with the increasing number of galls on an acorn cup. The inner galls are the place of development for the gall wasp larvae, pupae and adults. The adult gall wasps leave the galls through the emergence holes of about 2 mm in diameter.

5. As many as 19.3% of gall wasp larvae and pupae died without any obvious external reason. Other 4.3% larvae were killed by the chalcid *Ormyrus nitidulus* (F.). The majority of chalcids (70%) left the galls in mid-April next year and lesser part of them at the end of February after the 2nd or 3rd wintering. Some 9.2% of adults did not succeed in biting out through the hard inner galls and died; 6.3% adults died in the sealed outer galls. Some 80% adults left the outer galls through the naturally developed holes and 20% adults bit out of the sealed galls to the open through their thinned basal walls. Sufficiently large holes (with diameters over 1.5 mm) occurred in 65.7% galls, 20.5% galls had the holes smaller than 1.5 mm and the holes were entirely missing in a total of 13.8% galls.

6. The gall wasp *A. quercuscalicis* does the greatest damage to oak trees physiologically weakened by drought. The galls deprive the fruits (cups and acorns) of assimilates and suppress them mechanically due to which the acorns exhibit dwarfing at 50–95% and usually loose germination capacity. In 1995, the gall wasp destroyed nearly totally the ample crop of *Q. robur* f. *slavonica* acorns in the seed orchard.

Andricus hungaricus

1. Greater part (65%) of adult gall wasps *A. hungaricus* left the galls after the 2nd wintering and the considerable part of them (33%) after the 3rd wintering, exceptionally after the 1st or 4th wintering. They emerged in the open usually in the 2nd half of February or at the beginning of March, i.e. by about 1–2 weeks earlier than those of *A. quercuscalicis*. Their emergence holes are round oval with the diameter of about 2.5 mm.

2. There is only the agamic generation known in this gall wasp. Its females lay eggs mainly into the lateral buds of *Q. robur* with one (exceptionally two) egg being de-

posited into a bud. The eggs are lengthwise oval, on average 0.17 mm long and 0.094 mm wide. Physiological fertility of females is on average 1,447 (max. 1,870) eggs. The average fecundity of females increases with increasing diapause. There are 113–163 (average 136.5) ovarioles in the ovaries and 7–13 (average 10.6) eggs in one ovariole. The females live 20–41 (average 28) days.

3. The galls rapidly grow during the spring and in the first half of summer and mature towards the end of summer and at the beginning of autumn. Grown-up galls are of about spherical shape of diameter ranging from 20–43 (average 32) mm. Their colour is yellow-brownish to brown and their surface is irregularly bulged. There is a spacious cavity inside the spongy outer gall with the light-brown to brown oval inner gall on its bottom. Its length is about 5.4 mm, width 4.6 mm and height 4.2 mm. The size of inner galls increases with the increasing size of outer galls. The galls fall onto ground in the autumn.

4. As many as 16.2% larvae and pupae of *A. hungaricus* died in the galls without any obvious external reason. Other 8.5% larvae were killed by the chalcid *Aulogymnus trilineatus* (Mayr), 9.8% adults died inside the inner galls and 2.1% of them died in the outer galls. The chalcids (similarly as the gall wasps) diapaused in the galls as long as 4 years. They were leaving the galls in the 2nd half of April after the 1st wintering and as early as in the 2nd half of March or at the beginning of April in the following years.

5. The gall wasp *A. hungaricus* is one of very abundant cecidogenous species on *Q. robur* in southern Moravia. Its joint mass outbreak with *A. quercuscalicis* in the Valtice seed orchards in 1995 reflected in the generally worsened health condition of *Q. robur* f. *slavonica* grafted plants weakened by drought.

In the studied seed orchard, there were galls of *Andricus quercustozae* (Bosc.) sporadically found on *Quercus robur* f. *slavonica* and *Q. petraea*. Prior to this finding, the gall wasp was not reported from the territory of the Czech Republic.

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K biologii žlabatek *Andricus quercuscalicis* a *A. hungaricus* (*Hymenoptera*, *Cynipidae*)

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ABSTRAKT: Práce pojednává o biologii žlabatek *Andricus quercuscalicis* (Burgsd.) a *A. hungaricus* (Htg.), které se v roce 1995 přemnožily v dubových porostech a semenných sadech na jižní Moravě. Hlavní šetření bylo vykonáno v desetiletém sadu *Quercus robur* f. *slavonica* na polesí Valtice (LZ Židlochovice). 23. října 1995 byly ze sadu odebrány hálky obou druhů žlabatek a umístěny do venkovních fotoeklektorů. Vyhodnocením pětiletých chovů a analýzami hálek řezem byly získány poznatky o jejich vývoji a velikosti hálek. Někteří dospělci *A. quercuscalicis* opouštěli hálky po 1. přezimování (v dubnu), jiní po 2. až 4. přezimování (v březnu). Poprvé zimovaly dorostlé larvy, podruhé 33 % dospělců a 67 % larev, potřetí 80 % dospělců a 20 % larev a počtvrté pouze dospělci. Průměrná fekundita byla 1 126 (maximální 1 555) vajíček. Se vzcházející dobou diapauzy průměrná fekundita vzrůstala od 925 vajíček (u samiček po 1. přezimování) do 1 297 vajíček (u samiček po 4. přezimování). Vnější hálky byly průměrně 20,8 mm široké a 16,2 mm vysoké. Vnitřní hálky byly průměrně 4,9 mm dlouhé, 3,9 mm široké a 3,2 mm vysoké. Bez zřejmých příčin uhynulo 19,3 % larev a kukel, 4,3 % larev zahubila chalcidka *Ormyrus nitidulus* (F.), 9,2 % dospělců uhynulo ve vnitřních hálkách a 6,3 % v uzavřených vnějších hálkách. Kolem 80 % dospělců opustilo hálky přirozenými výletovými otvory ve vnějších hálkách a 20 % se navenek prokousalo přes ztenčené stěny bází hálek. Dospělci *A. hungaricus* opouštěli hálky po 2. a 3. přezimování (výjimečně po 1. a 4. přezimování), a to obvykle ve druhé polovině února a začátkem března. Průměrná fekundita byla 1 447 (maximální 1 870) vajíček. Se vzrůstající dobou diapauzy průměrná fekundita vzrůstala. Vnější hálky byly 20–43 (průměrně 32) mm velké. Vnitřní hálky byly průměrně 5,4 mm dlouhé, 4,6 mm široké a 4,2 mm vysoké. Bez zřejmých příčin uhynulo 16,2 % larev a kukel, 8,5 % larev zahubila chalcidka *Aulogymnus trilineatus* (Mayr), 9,8 % dospělců uhynulo ve vnitřních hálkách a 2,1 % ve vnějších hálkách.

Klíčová slova: *Andricus quercuscalicis*; *A. hungaricus*; diapauza; líhnutí; natalita; mortalita; rozměry hálek

V mimořádně suchém a teplém roce 1995 došlo v dubových porostech a semenných sadech na jižní Moravě k enormnímu přemnožení heterogonické žlabatky kalichové – *Andricus quercuscalicis* (Burgsd.) a partenogenetické žlabatky jižní – *A. hungaricus* (Htg.). Jejich biologie byla studována v desetiletém semenném sadu lesnicky cenného *Q. robur* f. *slavonica* na polesí Valtice (LZ Židlochovice). 23. října 1995 byly ze sadu odebrány hálky obou druhů žlabatek a umístěny do venkovních fotoeklektorů. Vyhodnocením pětiletých chovů a analýzami hálek řezem byly získány tyto hlavní poznatky:

Andricus quercuscalicis

1. Samičky agamní generace *A. quercuscalicis* opouštěly hálky po 1. až 4. přezimování. Po 1. přezimování hálky opustilo 23,5 % dospělců, po 2. přezimování 25,7 % dospělců, po 3. přezimování 42,1 % dospělců a po 4. přezimování 8,7 % dospělců. Poprvé zimovaly dorostlé larvy, přičemž dospělci se poprvé na volnosti objevovali v dubnu. Podruhé zimovalo 33 % dospělců a 67 % larev, potřetí 80 % dospělců a 20 % larev a počtvrté pouze dospělci. Po 2. až 4. zimování dospělci opouštěli hálky většinou v březnu.

2. Agamní samičky kladou neoplodněná vajíčka do samčích květů *Q. cerris* a z vajíček se v kuželovitých (až 2 mm dlouhých) hálkách vyvíjejí jedinci bisexuální generace. Vajíčka jsou mléčně bílá, hladká, podélně oválná, dlouhá kolem 0,15 mm a široká kolem 0,086 mm. Fyziologická plodnost samiček je kolem 1 126 vajíček. Nejnižší plodnost je 590 (nejvyšší 1 555) vajíček. Se vzrůstající dobou diapauzy průměrná fekundita samiček vzrůstá od 925 vajíček (u samiček po 1. přezimování) do 1 297 vajíček (u samiček po 4. přezimování). V ovariích je 95–149 (průměrně 118,5) ovariol a v jedné ovariole je 6–12 (průměrně 9,5) vajíček. Samičky agamní generace žijí ve venkovních podmínkách 16–36 (průměrně 25) dnů.

3. Samčí a samičí dospělci bisexuální generace se líhnou obvykle v květnu. Kladou oplozená vajíčka do mladých číšek žaludů. Na jedno místo vykladou obvykle jedno (výjimečně dvě) vajíčka. Do jedné číšky však mohou vyklást až sedm vajíček. Z nich se líhnou larvy, které koncem jara a začátkem léta indukují rychlou tvorbu druhově charakteristických hálek. Hálky koncem srpna a začátkem září dozrávají a na podzim opadávají na zem.

4. Hálky agamní generace jsou zpočátku zelené, houbovité a na povrchu lepivé, později hnědé, dřevnaté a nelepivé. Mají zhruba kuželovitý tvar o šířce 8–32 (průměrně 20,8) mm a výšce 10–23 (průměrně 16,2) mm. Zvnějšku jsou opatřeny 4–8 podélnými (mnohdy přerušovanými) kýly, případně křídlatými nebo hrbolatými výběžky. Při vrcholu vnějších hálek je obvykle otvor, který se kónicky rozšiřuje do prostorné vnitřní dutiny, na jejímž dně je jedna vnitřní hálka (zřídka dvě). Vnitřní hálky jsou oválné, mírně dorzoventrálně zploštělé a většinou šedě zbarvené. Jsou průměrně 4,9 mm dlouhé, 3,9 mm široké a 3,2 mm vysoké. Se vzrůstajícím počtem hálek na jedné číšce žaludu se průměrné dimenze vnějších i vnitřních hálek zmenšují. Ve vnitřních hálkách se vyvíjejí larvy, kukly a dospělci žlabatky. Dospělci hálky opouštějí výletovými otvory o průměru kolem 2 mm.

5. Bez zřejmých vnějších příčin uhynulo ve vnitřních hálkách 19,3 % larev a kukel žlabatky. Dalších 4,3 % larev zahubila chalcidka Ormyrus nitidulus (F.). Většina (70 %) chalcidek opustila hálky v polovině dubna příštího roku a menší část koncem února po 2. či 3. přezimování. Z tvrdých vnitřních hálek se nedokázalo navenek prokousat a následně uhynulo 9,2 % dospělců a v uzavřených vnějších hálkách uhynulo 6,3 % dospělců žlabatky. Kolem 80 % dospělců opustilo vnější hálky přirozeně vzniklými otvory a 20 % dospělců se z uzavřených vnějších hálek navenek prokousalo přes jejich ztenčené bazální stěny. Dostatečně velké otvory (o průměru nad 1,5 mm) se vyskytovaly u 65,7 % hálek, u 20,5 % hálek byly otvory menší než 1,5 mm a u 13,8 % hálek otvory zcela scházely.

6. Žlabatkou A. quercuscalicis jsou nejvíce poškozovány suchem fyziologicky oslabené duby. Hálky plodům (číškám i žaludům) odnímají asimiláty a mechanicky je utlačují. V důsledku toho žaludy z 50–95 % zakrňují a většinou ztrácejí klíčivost. Ve vyšetřovaném sadu byla v roce 1995 žlabatkou téměř zcela zničena bohatá úroda žaludů Q. robur f. slavonica.

Andricus hungaricus

1. Dospělci žlabatky A. hungaricus opouštěli hálky většinou (v 65 %) po 2. přezimování a značná část (33 %) po 3. přezimování, výjimečně po 1. nebo 4. přezimování. Na volnosti se objevovali většinou ve 2. polovině února, případně začátkem března, tj. zhruba o 1–2 týdny dříve než A. quercuscalicis. Jejich výletové otvory jsou kruhovitě oválné o průměru kolem 2,5 mm.

2. U této žlabatky je zatím známa pouze agamní generace. Její samičky kladou vajíčka hlavně do bočních pupenů Q. robur. Do jednoho pupenu vykladou jedno vajíčko (výjimečně dvě). Vajíčka jsou podélně oválná, průměrně 0,17 mm dlouhá a 0,094 mm široká. Fyziologická plodnost samiček je průměrně 1 447 (maximálně 1 870) vajíček. Se vzrůstající dobou diapauzy průměrná fekundita samiček vzrůstá. V ovariích je 113–163 (průměrně 136,5) ovariol a v jedné ovariole 7–13 (průměrně 10,6) vajíček. Samičky žijí 20–41 (průměrně 28) dnů.

3. Hálky během jara a první poloviny léta rychle rostou a koncem léta a začátkem podzimu dozrávají. Dorostlé hálky jsou přibližně kulovité o průměru 20–43 (průměrně 32) mm. Zbarveny jsou žlutohnědě až hnědě a jejich povrch je (kromě báze) nepravidelně hrbolkovaný. Uvnitř houbovité vnější hálky je prostorná dutina, na jejímž dně je světle hnědá až hnědá, oválná vnitřní hálka. Její délka je kolem 5,4 mm, šířka 4,6 mm a výška 4,2 mm. Se vzrůstající velikostí vnějších hálek velikost vnitřních hálek vzrůstá. Na podzim hálky opadávají na zem.

4. Bez zřejmých vnějších příčin v hálkách A. hungaricus uhynulo 16,2 % larev a kukel. Dalších 8,5 % larev zahubila chalcidka Aulogymnus trilineatus (Mayr), 9,8 % dospělců uhynulo ve vnitřních a 2,1 % ve vnějších hálkách. Chalcidky (stejně jako žlabatky) v hálkách diapauzovaly až čtyři roky. Po 1. přezimování hálky opouštěly až ve druhé polovině dubna, v dalších letech již ve druhé polovině března, případně začátkem dubna.

5. Žlabatka A. hungaricus patří na jižní Moravě k velmi hojným cecidogenním druhům na Q. robur. V semenných sadech ve Valticích se její společné přemnožení s A. quercuscalicis v roce 1995 odrazilo ve zhoršení celkového zdravotního stavu suchem oslabených roubovanců Q. robur f. slavonica.

Ve studovaném semenném sadu byly na Q. robur f. slavonica a Q. petraea zřídka nalézány hálky A. quercustosae (Bosc.). Tato žlabatka nebyla dosud na území ČR zjištěna.

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Ecological monitoring of Scots pine (*Pinus sylvestris* L.) growing in forest ecosystems at roadsides

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ABSTRACT: The results of monitoring of Scots pine (*Pinus sylvestris* L.) conducted in 1998–2000 according to international forest monitoring methodology (UN/ECE 1994) are presented. The indicatorial parameters (crown defoliation, foliage discolouration, state of tree tops, amount of dry branches etc.) of 684 sample trees at the distances of 10–20, 50–100,150–200, 250–300, 350–400 and 450–500 m from a highway were evaluated and discussed. The results have indicated that pines at the farthest distance (450–500 m) from the roadbed have the best health condition (mean defoliation 23.6 ± 2.2%) in comparison with trees growing close to the highway (43.3 ± 1.5%). Amount of dry branches depends on a distance from the highway as follows: at the permanent observation plots closest to the highway – 30.2 ± 1.2%, furthest – 12.8 ± 1.8%. State of pine tops is good – at all permanent observation plots more than 70% of the healthy tree tops were estimated.

Keywords: monitoring; Scots pine; roadsides; indicatorial parameters

Under increasing environmental pollution and its impact on nature, biological tests for the assessment of environmental state are applied at a larger scale. Trees are considered to be sensitive indicators of climatic changes and anthropogenic activity, resembling environmental variations in their growth and state. Crowns of trees have a contact area with the atmosphere several times bigger than other plants. The crown's filter transfers pollutants five or six times more effectively than other vegetation (KAIRIUKŠTIS et al. 1992). Conifers, especially Scots pine (*Pinus sylvestris* L.), are very sensitive to the environment pollution and can serve as biological tests for the assessment of pollution impact (SPOREK 1981; STRAVINSKIENE 1997, etc.).

Transport is the largest source of pollution in Lithuania. More than 70% of car traffic falls to the main highways and suburban roads. Traffic emissions are gradually increasing. Burning fuels emits into the environment carbon monoxide (80%), hydrocarbons (15%), nitrogen oxides (5%), small amounts of lead, benzapyrene and other harmful substances. The largest share of traffic emissions in Lithuania include the following pollutants: carbon monoxide – 258 thousand tons, hydrocarbons – 60 thousand tons, nitrogen oxides – 36 thousand tons and sulphur dioxide – 5.5 thousand tons (BALTRENAS et al. 1996).

In winter, seeking to avoid ice formation on the road surface, sodium and calcium chlorides are spread on Lithuanian highways. The amount of spread salts depends on meteorological conditions in winter. Approximately 30–40 thousand kg of chlorides fall per one km

of highways each winter. It was found (ARMOLAITIS, BARTKEVIČIUS 1996) that the residues of these substances (small amount of chlorides) may accumulate even at 50–100 m from the highway. Aerosol droplets of the substances damage trees, growing up to 10–15 m from the roadbed. Therefore, in spring the needles on lower branches of pine trees become brownish.

Studies have shown (ARMOLAITIS, BARTKEVIČIUS 1996) that in forests nearly the main highway in Lithuania "Vilnius-Klaipeda" the most polluted by nitrogen oxides, benzapyrenes and heavy metals (Pb, Cr, Ni, Ti, V, Fe, etc.) is up to 50–60 m wide roadside belt, whereas in open areas even 100–200 m wide roadside belt is contaminated. Especially effective against pollutants is a dense forest with undergrowth and underbrush.

Forest plantations at roadsides accumulate pollutants near the roadbed and prevent their further distribution. Trees that grow as forest shelterbelts absorb carbon monoxide, sulphur dioxide and other harmful substances. They also accumulate heavy metals that are found in traffic emissions. Even 3–5 m of protective road plantings collect and accumulate about 40–60% of lead and heavy metals from traffic emissions. Trees reduce the contamination near the roadbed and at the same time indicate the influence of pollution on trees. Forest ecosystems serve as a cleaning equipment and are gathering pollutants, which are disseminated in open fields in the environs.

The landscape and height of roadbed influence the distribution of pollutants at the roadside. When the height of the roadbed is 0.5–1.2 m, the largest portion of pollutants fall out at the distance of 10–25 m from roadsides,

when the height of the roadbed is 1.2–1.5 m the largest flow of emissions falls out at the distance of 20–30 m. Therefore, the concentration of pollutants at the distance of 10–20 m from the roadbed is also high. If the road surface is close to the level of surroundings, then, farther from the roadside the concentration of traffic pollutants evenly diminishes (MAGONE 1989).

The monitoring of forest ecosystems at the roadsides has not been conducted and the state of trees at the roadsides has not been widely studied until now; therefore the morphological indicatorial parameters of Scots pines (*Pinus sylvestris* L.) growing at the roadsides were chosen as the object of present study.

MATERIAL AND METHODS

The aim of the investigation was to conduct an ecological monitoring and to estimate the health condition of Scots pine trees at different distances from the highway "Vilnius-Klaipeda" according to the main indicatorial parameters (crown defoliation, foliage discolouration, the state of tree tops, the amount of dead branches, etc.) of forest monitoring.

The following studies were carried out: choice of the study object; gathering of experimental information; estimation of the health condition of pines according to their crown defoliation and foliage discolouration (dechromation), state of the tree tops and amount of dead branches; estimation of pine needle retention at different distances from the highway.

Monitoring of Scots pine was performed and the experimental material was collected in the summer seasons 1998, 1999 and 2000 according to international forest monitoring methodology (UN/ECE 1994). The end of July and the beginning of August present the most suitable time for forest monitoring (HANISH, KILZ 1990).

The sample trees were selected at permanent observation plots (POP). At different distances from the roadbed (10–20; 50–100; 150–200; 250–300; 350–400 and 450–500 m) 36 sample trees were selected for the assessment in each POP and distributed within 6 assessment subplots (AS) with 6 sample trees in each, located at the distance of 25 m to the north, east, south and west of the POP centre. Distribution of sample trees into 6 assessment subplots (6 sample trees in each) differs from the international forest monitoring methodology (UN/ECE 1994). The sample trees from the upper layer belonging to 1–3 Kraft class were chosen. The total number of AS is 114, the total number of examined trees – 684.

Crown defoliation and foliage discolouration are the most important biological diagnostic tests for tree health condition assessment.

Crown defoliation is not only the loss of existing foliage, but also that part of the foliage which is able to form in normal conditions, but did not form in the existing ones. The natural fall of leaves during autumn is not considered. In other words, defoliation means the loss compared to the reference tree whose crown defoliation does not exceed 10% (OZOLINČIUS 1996). The reference tree is usually a tree of the same growth, social class as the sample tree, belongs to the same type of branching, grows in the vicinity of the sample tree. The photo of the reference tree corresponding to a sample tree according to special atlases can be used. We used special atlases with the photos of reference trees (MULLER, STIERLIN 1990).

Defoliation degree of the whole crown and of the upper third of the crown was estimated in 5% gradation.

According to crown defoliation degree the sample trees were divided into 5 defoliation classes: 0 – conditionally healthy trees (crown defoliation up to 10%); 1 – slightly defoliated trees (11–25%); 2 – moderately defoliated trees (26–60%); 3 – severely defoliated trees (61–99%); 4 – dead trees (crown defoliation equals 100%).

Foliage discolouration (dechromation) – one of the main forest monitoring parameters – shows the part of needles or leaves (%) which have changed their colour due to the negative impact of external environmental factors. Sample trees were divided into 4 discolouration classes: 0 – without foliage changes in colour (discolouration up to 10%); 1 – slight discolouration (11–25% of foliage has a changed colour); 2 – moderate discolouration (26–60%); 3 – severe discolouration, when over 60% of the foliage does not have the natural colour.

Changes of tree foliage colour due to the lack or excess of some elements (nitrogen, potassium, magnesium, etc.), impact of heavy atmospheric pollution or effects of fungal diseases (TAYLOR et al. 1991), droughts (INNES, BOSWELL 1989) and other reasons are widely known and spread in some countries of Western Europe. The foliage discolouration of Scots pine is not a common phenomenon in Lithuanian forest ecosystems (Monitoring… 1999).

Severe crown defoliation and foliage discolouration show the negative influence of environmental impact on a tree and indicate its damage (UN/ECE 1994).

The tree top state and the amount of dead branches in the tree crown was estimated as follows. The scale of the state of tree tops: 0 – top is healthy; 1 – completely broken; 2 – dead; 3 – damaged. The scale for the amount of dead branches in the crown: 0 – up to 15% of dead branches, 1 – 16–30% of dead branches, 2 – 31–50% of dead branches, 3 – over 50% of dead branches. Dead branches under a live crown are not included.

Average needle retention of pine is indicated visually within 0.1 year accuracy. For the evaluation of needle retention, 3–4 model branches in the upper third of the crown were selected. Age of terminal shoots containing all needles and the share of the length of the last (oldest) shoot with remaining needles are evaluated with the help of binoculars.

When the crown defoliation exceeds 10%, defoliation type is defined for each sample tree. The following crown defoliation types were defined: 1 – top defoliation; 2 – defoliation under the top; 3 – base; 4 – peripheral 5 – inner; 6 – uniform and 7 – window.

Top (1) defoliation type is defined for the cases when defoliation of the upper part of the crown exceeds defoliation in the rest of the crown by not less than 20%. Under-top (2) defoliation type should be applied when defoliation of the under-top part of the crown is at least by 20% higher than that of the other crown part. Base (3) defoliation type is applicable in the case when defoliation at the bottom part of the crown is by 20% higher than in the other parts. The peripheral (4) type of defoliation is used for the cases when over 25% of all tree branches have dead terminal shoots due to late or early frosts and insect damage. The inner (5) defoliation type is common for trees, the older needles of which are damaged by fungi and diseases and the crown is more sparse in the interior. The uniform (6) crown defoliation type is applicable when defoliation in various crown parts does not differ by more than 20%. This defoliation type can be caused by changes in environmental conditions and is characteristic of tree responses to air pollution. Window (7) crown defoliation type is used when defoliation in the window (the most sparse part of the crown) is at least 20% higher than in the other parts of the crown (Monitoring… 1999).

RESULTS AND DISCUSSION

The results of investigation have indicated that the crowns of Scots pine (*Pinus sylvestris* L.) trees growing at the closest distance to the highway are mostly defoliated. Even 48% of sample trees growing at the closest distance from the highway are severely damaged (class 3 of defoliation), 45% of sample trees were included in class 2 of defoliation. Only 7% of dead trees (defoliation 100%) have been identified here. No healthy trees showing the good environmental state were found here. The status of pines growing at the distance of 50–100 m from the highway is slightly better than that of the pines growing 10–20 m away. At such a distance the greatest part (52%) of the examined pines are moderately defoliated (crown defoliation is 26–60%), severely defoliated trees whose crown defoliation reaches 61–99% account for 44% and only 4% of the examined pines are mostly defoliated (4 classes of defoliation). No conditionally healthy and slightly defoliated trees were found at this distance.

Health condition of trees at the distances of 150–200 and 250–300 m from the highway is gradually improving. At the latter distance conditionally healthy tree represent 3% and 8%; slightly defoliated ones – 14% and 19% of sample trees; even 61% and 56% are moderately defoliated and included in 2 defoliation class; 22% and 17% of the sample trees show severe defoliation, respectively. At the distance of 350–400 m, only 7% of sample pine trees are severely, 33% – moderately, 45% – slightly defoliated and 15% are conditionally healthy. Health condition of sample pine trees at the furthest distance (450–500 m) from the highway is the best according to crown defoliation parameters (Fig. 1).

At the closest distance of 10–20 m from the highway, mean defoliation of pine trees amounts to 43.3 ± 1.5%. With the increasing distance from the roadside, defoliation of Scots pine trees is decreasing as follows: at the distance of 50–100 m the mean defoliation of sample pine trees is 41.5 ± 2.3%, at 150–200 m – 38.7 ± 1.7%, at 250–300 m – 35.3 ± 2.2%, at 350–400 m – 28.4 ± 2.4% and at 450–500 m – only 23.6 ± 1.3% (Table 1). Crown defoliation of pine trees growing at the closest distances from the roadbed exceeds by 15–20% mean defoliation of pines in Lithuanian forests. This difference indicates the traffic pollution impact on pine forest plantations at the roadsides.

Fig. 2 illustrates the mean pine crown defoliation dynamics in 1998–2000. Assessing changes in the state of pine trees growing near the highway according to crown defoliation parameters in 1998–2000, a statistically reliable ($P = 0.95$) improvement was observed in 1999–2000, as compared to 1998, expressed by a decreased defoliation of sample trees growing up to 300 m from the roadbed. At the further distance from the roadbed changes in the state of pine trees are insignificant, statistically unreliable – in separate years crown defoliation of the trees differs insignificantly from mean pine defoliation indices in Lithuanian forests.

Crown defoliation type of the examined Scots pines has also been investigated. The base (3) and uniform (6) crown defoliation types are dominating at all permanent observation plots (Table 1). The greatest part of examined pines growing at the distance up to 300 m from the roadbed has the base (3) crown defoliation type. The uni-

Table 1. Mean crown defoliation (%); distribution of sample Scots pine trees (%) according to crown defoliation type and classes of foliage discolouration

Distance from highway (m)	Number of sample trees	Mean crown defoliation (%)	Crown defoliation type							Foliage discolouration class			
			1*	2	3	4	5	6	7	0	1	2	3
10–20	162	43.3 ± 1.5	0	9	40	12	5	34	0	45	55	0	0
50–100	66	41.5 ± 2.3	0	3	42	24	5	26	0	57	43	0	0
150–200	162	38.7 ± 1.7	2	8	48	3	2	32	5	66	34	0	0
250–300	66	35.3 ± 2.2	0	2	46	8	2	28	14	83	17	0	0
350–400	66	28.4 ± 2.4	0	0	40	9	3	38	10	73	27	0	0
450–500	162	23.6 ± 1.3	0	2	34	11	6	45	0	82	18	0	0

Note: crown defoliation types: 1* – top defoliation; 2 – defoliation under the top; 3 – base; 4 – peripheral; 5 – inner; 6 – uniform; 7 – window

a) class 0 – 0%, class 1 – 0%, class 2 – 45%,
   class 3 – 48%, class 4 – 7%
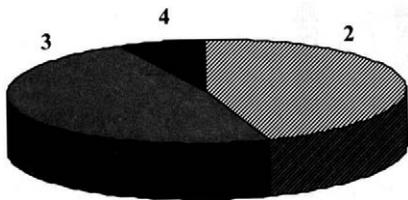
b) class 0 – 0%, class 1 – 0%, class 2 – 52%,
   class 3 – 44%, class 4 – 4%
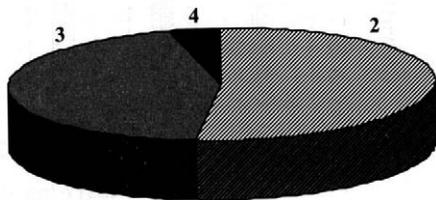
c) class 0 – 3%, class 1 – 14%, class 2 – 61%,
   class 3 – 22%, class 4 – 0%
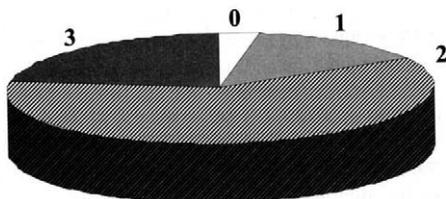
d) class 0 – 8%, class 1 – 19%, class 2 – 56%,
   class 3 – 17%, class 4 – 0%
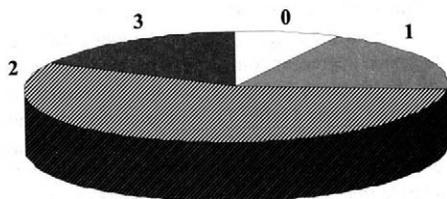
e) class 0 – 15%, class 1 – 45%, class 2 – 33%,
   class 3 – 7%, class 4 – 0%
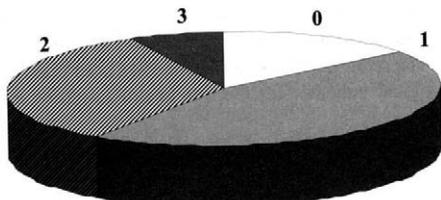
f) class 0 – 21%, class 1 – 57%, class 2 – 22%,
   class 3 – 0%, class 4 – 0%
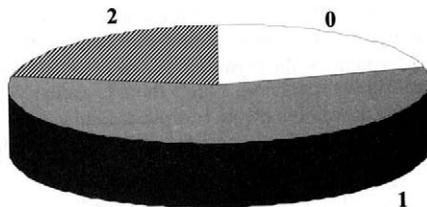
Fig. 1. Distribution of sample pine trees (%) growing at different distances – a) 10–20 m; b) 50–100 m; c) 150–200 m; d) 250–300 m; e) 350–400 m; f) 450–500 m – from the highway according to classes of crown defoliation
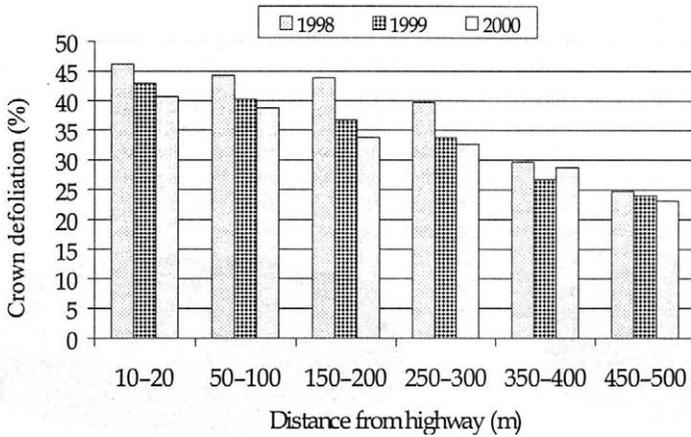
Fig. 2. Dynamics of the mean crown defoliation of Scots pines growing at different distances from the highway in 1998–2000

form (6) crown defoliation type prevails among pines growing at farther distances. This defoliation type can be caused by changes in environmental conditions and is characteristic of tree responses to air pollution impact (Monitoring… 1999). Other types of tree crown defoliation are not frequent and common at the roadsides of highways in Lithuania.

Our study has indicated that pines at the closest distance from the highway have the highest foliage discolouration degree, as compared to pines at further distance. As the distance increases, foliage discolouration class becomes lower (Table 1). At the closest distance from the highway, pines of discolouration class 1 (foliage discolouration 11–25%) predominate – even 55% of the sample trees belong to this class. Without colour changes of the foliage (discolouration up to 10% – class 0) have been estimated 45% of examined trees. At the furthest distance – 450–500 m from the roadbed – the greatest part (even 82%) of examined pines is without foliage changes in colour; slight foliage dechromation has been estimated for 18% of sample trees. The changes of pine tree foliage colour in forest ecosystems near the roadbed are influenced by impacts of aerosol substances of chlorides.

The highest amount of dead branches has been estimated for Scots pines that grow closest (10–20 m and 50–100 m) to the highway. The trees at the farthest distance from the highway have the lowest amount of dead branches. Table 2 illustrates the mean amount of dead branches, the distribution of examined pine trees (%) according to the amount of dead branches in their crowns. It is shown that with increasing distance from the roadbed the amount of dead branches decreases.

Fig. 3 shows the mean amount of dead branches (%) in pine tree crowns at different distances from the highway in 1998–2000. The average amount of dead branches depending on the distance is changing as follows: 10–20 m – 32.2 ± 1.2% of dead branches, 50–100 m – 27.5 ± 1.9%, 150–200 m – 24.6 ± 1.5%, 250–300 m – 21.6 ± 2.0%, 350–400 m – 16.3 ± 2.1%, 450–500 m – 12.8 ± 1.8% (Table 2). As illustrated by the presented data, at the closest distance (10–20 m) the highest amount of dead branches and at the furthest distance (450–500 m) from the highway the lowest amount of dead branches is found. The amount of dead branches in the crowns of studied pine trees in 1999 and 2000, as compared to 1998, has decreased only in a 100 m wide roadside belt. At the further distance the differences in separate years are small and statistically unreliable. The amount of dead branches of examined pine trees, growing up to 300 m distance from the roadbed exceeds by 8–15% the average amount of pine dead branches in Lithuanian forests.

The retention of coniferous needles is an important biological indicator for the tree health condition and can
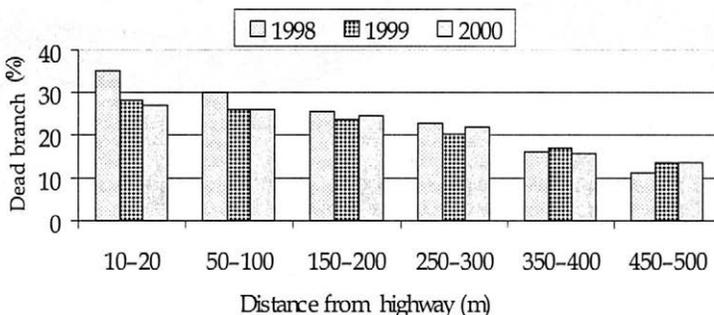

Fig. 3. Average amount of dead branches (%) in the crowns of Scots pine trees at different distances from the highway in 1998–2000

Table 2. Mean amount of dead branches and distribution of sample trees (%) according to the amount of dead branches in the crowns of pine trees

Distance from the highway (m)	Number of sample trees	Mean amount of dead branches (%)	Scale of dead branches (%)			
			up to 15	16–30	31–50	over 50
10–20	162	30.2 ± 1.2	6	43	51	0
50–100	66	27.5 ± 1.9	8	36	56	0
150–200	162	24.6 ± 1.5	11	46	38	0
250–300	66	21.6 ± 2.0	31	43	26	0
350–400	66	16.3 ± 2.1	36	53	11	0
450–500	162	12.8 ± 1.8	46	32	22	0

serve for environmental status assessment. Damaged trees usually lose their old needles sooner than healthy ones. Trees growing in optimal environmental conditions have longer retention of needles. The standard retention of Scots pine needles that indicates optimal tree growth conditions in Lithuanian forests is 4 years. It serves as a control. Short age of needles indicates unfavourable growth conditions.

It was established that needle retention depends on the meteorological conditions and geographic latitude (JUKOLA-SULONEN et al. 1990). The decrease of average needle retention of Scots pine during the last 30-year period is caused by growing atmospheric pollution (JAL-KANEN et al. 1995).

According to the results of our study mean retention of Scots pine needles at the closest distance (10–20 m) from the highway is the shortest (1.9 ± 0.04 years). At farther distances from the highway it has increased: at 50–100 m – 2.0 ± 0.07 years, at 150–200 m – 2.3 ± 0.04, at 250–300 m – 2.5 ± 0.07, at 350–400 m – 3.0 ± 0.05, at 450–500 m – 3.1 ± 0.03 years (Table 3). In comparison with control age (4 years) this diagnostic test shows the negative impact of traffic pollution on pine growth, state of environment at the closest distance and the negative influence of basic ecoclimatic factors at the farther distance from the highway.

It was determined that health condition of Scots pine trees depends on their social class: the examined pines of higher social Kraft class 1 have lower defoliation degree and lower amount of dead branches as compared with the sample trees of Kraft classes 2 and 3 (Table 4).

Table 3. Mean needle retention of sample Scots pine trees

Distance from the highway (m)	Mean needle retention (years)
10–20	1.9 ± 0.04
50–100	2.0 ± 0.07
150–200	2.3 ± 0.04
250–300	2.5 ± 0.07
350–400	3.0 ± 0.05
450–500	3.1 ± 0.03

Table 4. Mean crown defoliation and amount of dead branches of sample Scots pine trees (%) depending on Kraft classes and distance from the highway (according to average data of 1998–2000 year measurements)

Kraft class	Number of sample trees	Mean crown defoliation (%)	Mean amount of dead branches (%)
10–20 m from the highway			
1	27	37.3 ± 2.7	22.7 ± 2.2
2	84	41.0 ± 2.2	30.4 ± 2.2
3	51	51.2 ± 2.2	36.8 ± 1.4
50–100 m from the highway			
1	15	35.1 ± 3.9	21.5 ± 3.6
2	35	40.9 ± 2.0	27.4 ± 2.2
3	16	46.3 ± 1.3	35.0 ± 1.7
150–200 m from the highway			
1	33	33.9 ± 4.5	18.5 ± 5.7
2	87	37.4 ± 2.7	24.9 ± 3.3
3	42	43.0 ± 1.4	29.5 ± 2.1
250–300 m from the highway			
1	13	26.5 ± 2.5	16.5 ± 3.1
2	35	35.3 ± 1.8	21.5 ± 1.8
3	22	40.8 ± 1.6	26.7 ± 1.8
350–400 m from the highway			
1	18	22.5 ± 4.5	11.6 ± 3.2
2	29	29.9 ± 2.6	16.0 ± 2.7
3	19	35.2 ± 2.1	21.6 ± 2.5
450–500 m from the highway			
1	42	17.6 ± 3.6	8.2 ± 1.7
2	87	23.4 ± 1.6	11.6 ± 2.8
3	33	30.8 ± 1.5	20.6 ± 2.7

The mean crown defoliation of examined pines of Kraft class 1 growing at the distance of 10–20 m from the highway amounts to 37.3 ± 2.7%. Defoliation of pines of Kraft classes 2 and 3 is 41.0 ± 2.2% and 51.2 ± 2.2% respectively. At the farthest distances from the highway crown defoliation decreases: in pines of Kraft class 1 at the distance of 50–100 m it amounts to 35.1 ± 3.9%, of Kraft classes 2 and 3 – to 40.9 ± 2.0% and 46.3 ± 1.3% respectively. The pines of Kraft class 1 growing at the distance of 450–500 m have the lowest crown defoliation parameters, compared to close distances and sample trees of Kraft classes 2 and 3. The amount of dead branches depends on social classes in a very similar way (see Table 4).

Having checked variation reliability of pine crown morphological indices by the help of F criterion, it was found that in 1999–2000 the state of examined pines at the closest distance to the roadbed (up to 300 m) was reliably improving as compared to the state in 1998.

Visual assessment of tree crown parameters is comparatively fast and simple, but not completely objective. On the other hand it is noticed that a large part of deviations

in the assessment data of these parameters is not systematic and depends on the number of sample trees: due to a higher number of sample trees the evaluation differences of monitoring parameters are decreasing (GERTNER, KÖHL 1995; DOBBERTIN et al. 1997). The monitoring parameters (crown defoliation, foliage discoloration, amount of dead branches in the crowns, needle retention, etc.) of Scots pine (*Pinus sylvestris* L.) serve as the natural monitors and indicators to objectively evaluate the influence of all changes taking place in forest ecosystems at roadsides, especially the impact of traffic pollution. Special studies on the impact of chlorides on the state of pine trees, carried out in 1994–1996 (ARMOLAITIS, BARTKEVIČIUS 1996), failed to prove that chlorides have a certain impact on the state of pine trees. Changes in the heath condition of roadside trees are related to the impact of transport pollutants, first of all, nitrogen oxides and benzapyrene.

CONCLUSIONS

According to the results of monitoring of Scots pine (*Pinus sylvestris* L.) growing in forest ecosystems at roadsides, performed in 1998–2000, the following conclusions were drawn. At the different distances from the roadbed the morphological parameters of pine tree crowns are different. The highest crown defoliation (43.3 ± 1.5%) is characteristic of trees growing near the highway. With increasing distance crown defoliation decreases: at the distance of 50–100 m defoliation amounts to 41.5 ± 2.3%, at 150–200 m – 38.7 ± 1.7%, at 250–300 m – 35.3 ± 2.2%, at 350–400 m – 28.4 ± 2.4%. The lowest (23.6 ± 1.3%) crown defoliation and the best health condition of pines were estimated at the farthest distance from the highway.

Discoloration of pine trees at the roadsides of highways of Lithuania is not a very widespread phenomenon in Lithuania. At the closest distance class 1 of discoloration (discoloration 11–25%) is dominating (55% of sample trees); class 0 (discoloration up to 10%) has been estimated for 35%. At the farthest distance even 82% of examined pines are without any symptoms of foliage dechromation, slight foliage discoloration has been estimated for 18% of sample trees.

It was found that the state of tree tops of pines at roadsides is generally good – more than 70% of healthy tree tops was observed on each permanent observation plot.

The amount of dead branches at a certain distance from the highway is changing as follows: 10–20 m – 30.2 ± 1.2% of dead branches, 50–100 m – 27.5 ± 1.9%, 150–200 m – 24.6 ± 1.5%, 250–300 m – 21.6 ± 2.0%, 350–400 m – 16.3 ± 2.1%, 450–500 m – 12.8 ± 1.8%. The lowest amount of dead branches has been estimated at the farthest distance from the highway, the highest – at the closest one. It has indicated the largest influence of traffic emissions on the pine state near the highway.

The shortest needle retention (1.9 ± 0.04 years) has been estimated at the closest roadsides. At larger distances from the highway it has increased: at 50–100 m – 2.0 ± 0.07 years, at 150–200 m – 2.3 ± 0.04, at 250–300 m – 2.5 ± 0.07, at 350–400 m – 3.0 ± 0.05, at 450–500 m – 3.1 ± 0.03 years. This diagnostic test indicates the unfavourable growth conditions caused by the negative impact of traffic pollution on pine growth at the closest distances.

The results of forest monitoring at roadsides have indicated that differences in morphological parameters of Scots pine (*Pinus sylvestris* L.) at different distances from the highway are statistically reliable ($P = 0.95$) and can reflect the environmental conditions at roadsides depending on the amount of traffic emissions and their distribution.

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Ekologický monitoring borovice lesní (*Pinus sylvestris* L.) v lesních ekosystémech podél silnic

ABSTRAKT: V práci jsou předloženy výsledky sledování borovice lesní (*Pinus sylvestris* L.), které se uskutečnilo v letech 1998–2000 podle mezinárodní metodiky lesnického monitoringu (UN/ECE 1994). Byly zhodnoceny a diskutovány indikativní parametry (defoliace koruny, ztráta barvy jehličí, stav vrcholků stromů, množství uschlých větví atd.) u 684 vzorníků rostoucích ve vzdálenosti 10–20, 50–100, 150–200, 250–300, 350–400 a 450–500 m od hlavní silnice. Výsledky naznačily, že borovice nacházející se v největší vzdálenosti (450–500 m) od vozovky vykazují nejlepší zdravotní stav (střední defoliace 23,6 ± 2,2 %) ve srovnání se stromy rostoucími v blízkosti vozovky (43,3 ± 1,5 %). Množství uschlých větví závisí na vzdálenosti od hlavní silnice takto: na trvalých pozorovacích plochách nejblíže k silnici – 30,2 ± 1,2 %, nejdále od silnice – 12,8 ± 1,8 %. Stav vrcholků borovic je dobrý; na všech trvalých pozorovacích plochách bylo zjištěno více než 70 % zdravých vrcholků.

Klíčová slova: monitoring; borovice lesní; okolí silnic; indikativní parametry

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Spectral reflectance models for spruce (*Picea abies* L.) damage estimation employing aerial digital data

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ABSTRACT: The paper deals with spruce damage estimation employing spectral reflectance models. These were derived on the basis of large scale aerial digital data. Not only original digital data sets were used for model construction but also some other data employing components of IHS transformation, PCA analysis and image algebra. On some color composites it is possible to distinguish spruce damage in great detail at the level of single crowns and also within them. The differences in crown morphology and color differences were considered as the principal characters in the damage detection for purposes of spectral signature collection. The crown surface spectral profiles and methods of discriminant analysis were used for selection of the best digital data sets for spruce defoliation detection. Reflectance models derived enable to estimate spruce defoliation with different accuracy (SE% = ± 11–50%), coefficients of determination vary in the range of 0.25–0.96. In spite of the fact that the accuracy of reflectance models is not very favorable, they are a good basis for collection of information for two-phased sampling procedures. Damage dot estimations by reflectance models are useful also for analysis and interpolation of damage with respect to spatially correlated data employing geostatistics methods. An example of both approaches is presented in this paper.

Keywords: defoliation; spectral reflectance models; two-phased sampling; geostatistics

A lot of applications have been developed for the forest damage assessment and monitoring employing aerial and satellite data. Methods of remote sensing render more and new information about the forest damage, forest health condition, and offer new possibilities for data acquisition, mainly in digital form for computer processing.

Most applications employing aerial photographs for the forest damage and other forest variables assessment were based on the visual interpretation of color and color-infrared photographs (MURTHA 1983; HILDEBRANDT 1988; ŽÍHLAVNÍK 1999), recent approaches were based on damage spectral signatures investigation of aerial digital data (KENNEWEG 1989; BEISCH 1996).

Digital form of aerial data enables to derive and use spectral reflectance models for the forest damage assessment. BUNNIK (1984) published an extensive review of physical reflectance models (numerical and analytical) which simulate the reflectance for varying plant canopies and crop characteristics (mainly agricultural crops). These models employ the geometric and optical properties with respect to viewing directions, arrangement of leaves and crop layers. Physical models are difficult to invert and too complicated for practical applications, mainly in the field of forestry where different physical variables in the tree canopies are very difficult or even impossible to measure. Therefore, in the near future it is possible to expect forestry applications of only semi-empirical or rather empirical spectral reflectance models, where forest characteristics are estimated by means of stochastic models, i.e. dependent forest variable is a function of its spectral signature.

This paper describes spruce (*Picea abies* L.) damage estimation employing empirical spectral reflectance models derived on the basis of large scale aerial digital data. In spite of the fact that the accuracy of reflectance models is different and not very favorable, they are a good means for collection of first phase information of two-phase sampling procedures. In the large area applications damage dot estimations by the above-mentioned models are a good basis also for analysis and interpolation of damage with respect to its spatial variability and correlation employing geostatistics principles. An example of both approaches is presented in this paper.

MATERIAL AND METHODS

THE STUDY AREA AND IMAGE DATA

The pure spruce forest area (5,549 hectares) in the Northern part of Slovakia suffering a high degree of damage due to air pollution has been chosen as a study area. ŠMELKO et al. (1996) describe biometrics data measurement and ocular damage estimation for all the trees of

permanent monitoring plots (PMP) established on the study area in a network 1×1 km. A part of PMP (22) was chosen for large-scale (1:1,000) aerial photography on CIR Kodak 2443 film material. The entire study area was photographed on the same film material at the scale 1:20,000. Technical details of aerial photography and transformation of PMP false color aerial photographs to digital aerial data – Red (R), Green (G), Blue (B) file were described in the previous paper (SCHEER 1993).

IMAGE DATA PROCESSING

Processing of image data was carried out in Erdas Imagine Ver. 8.2. system for image analysis. Image enhancement techniques with the goal to improve the visual interpretability of spruce damage on aerial digital data were a very important part of data processing. Such approaches as multi-image manipulation of R, G, B files (rationing, differencing), PCA analysis and IHS color transformations were used for digital data enhancement. Distinctive details of spruce damage at the level of single crowns and also within them were possible to distinguish on some final color composites. The differences in crown morphology and color differences were considered the principal characters in the damage detection for purposes of spectral signatures collection. Spectral profiles (spatial and surface crown spectral profiles) were used for selection of the "optimal digital data sets" for a distinguishing of spruce defoliation. These optimal data sets for signature collection were employed with respect to prior knowledge of spruce defoliation from ground survey and single trees identification on aerial photographs.

RESULTS

RESULTS OF IMAGE ENHANCEMENT AND SPECTRAL SIGNATURES MEASUREMENT

The question is, what type of digital aerial data (original or enhanced via multi-image manipulation) is more suitable for spruce damage detection. To answer this question, the following digital data sets were investigated:
– three original bands R, G, B (these bands from CIR aerial film were created employing three color filters in the process of film digitalization on Chromoscan 4) – Bands 1, 2, 3,
– three components of PCA analysis (PC1, PC2, PC3) – Bands 4, 5, 6,
– three components of IHS color transformation (Intensity, Hue, Saturation) – Bands 7, 8, 9,
– simple image differentiation of original bands R–G, this differentiation was carried out with respect to spectral sensitivity of CIR film material and prior knowledge of damage detection in this digital data type (BUITEN, CLEVERS 1993; SCHEER 1993) – Band 10.

Hence, ten aerial digital data sets were investigated with respect to their convenience for spruce defoliation interpretability according to the pan-European monitoring system (defoliation and discoloration) UN/ECE and EC, 1998:

Defoliation class	Needle loss	Degree of defoliation
0	up to 10%	none
1	> 10–25%	slight (warning stage)
2	> 25–60%	moderate
3	> 60–< 100%	severe
4	100%	dead

For the interpretation of 5%-steps defoliation in the above mentioned defoliation classes on digital aerial data many of color composites were investigated. The best resolution of defoliation was provided by color composite (R, G, B coding) from bands 1, 5, 6 and composite 8, 5, 6. This fact is evident also from spruce defoliation spectral profiles which are shown in Fig. 1. The profiles express a dotted record of defoliation measurement in single tree crowns. However, relatively large variation of pixel values ($DN \equiv x$) within the crowns exists due to the presence of different damage (defoliation) symptoms. Bands 2, 3, 5, 8 provide the best resolution of defoliation from the single bands. Spectral crown surface profiles from these bands enable the variation of DN values to be judged in single tree crowns with respect to defoliation class. An example of these profiles is shown in Fig. 1 where the spectral variation of all classes in band 3 is documented. Major conclusions of crown surface profiles analysis can be summarized as follows:
– the biggest spectral variation in all investigated bands exists in crowns with slight and moderate defoliation (classes 1, 2), crowns with or without severe defoliation and dead are more homogeneous (classes 0, 3, 4),
– with respect to different spectral responses and DN variation due to the presence of different damage symptoms in single crowns, crown illumination conditions (shaded areas), it is very important to collect the spectral signatures not on the basis of whole tree crown measurement but only on those parts.

Completely, 199 spectral signatures were measured employing screen digitizing in the different spruce crowns defoliation classes. Table 1 gives an overview of the statistical characteristics for spectral signatures measurement. Very similar conclusions with respect to suitability of aerial digital data for spruce damage detection in comparison with spectral profiles analysis can be drawn also from the statistical analysis. The most suitable bands for defoliation detection are bands 2, 3, 5, 8 where DN mean values of defoliation classes are distant enough. The variation in mentioned bands in defoliation classes is quite homogeneous except band 5 in class 0 and band 8 in classes 3 and 4. However, a certain overlap in the spectral range still exists in each spectral band. Box and Whisker plots in Fig. 2 indicate these overlaps between the classes for band 2. DN mean values in this band are quite distinct (except classes 3 and 4) but intervals $\bar{x} \pm t_{0.05} \cdot s_x$ where individual values of x_i ($\equiv$ DN) vary with 68 and 95% probability respectively are overlap-
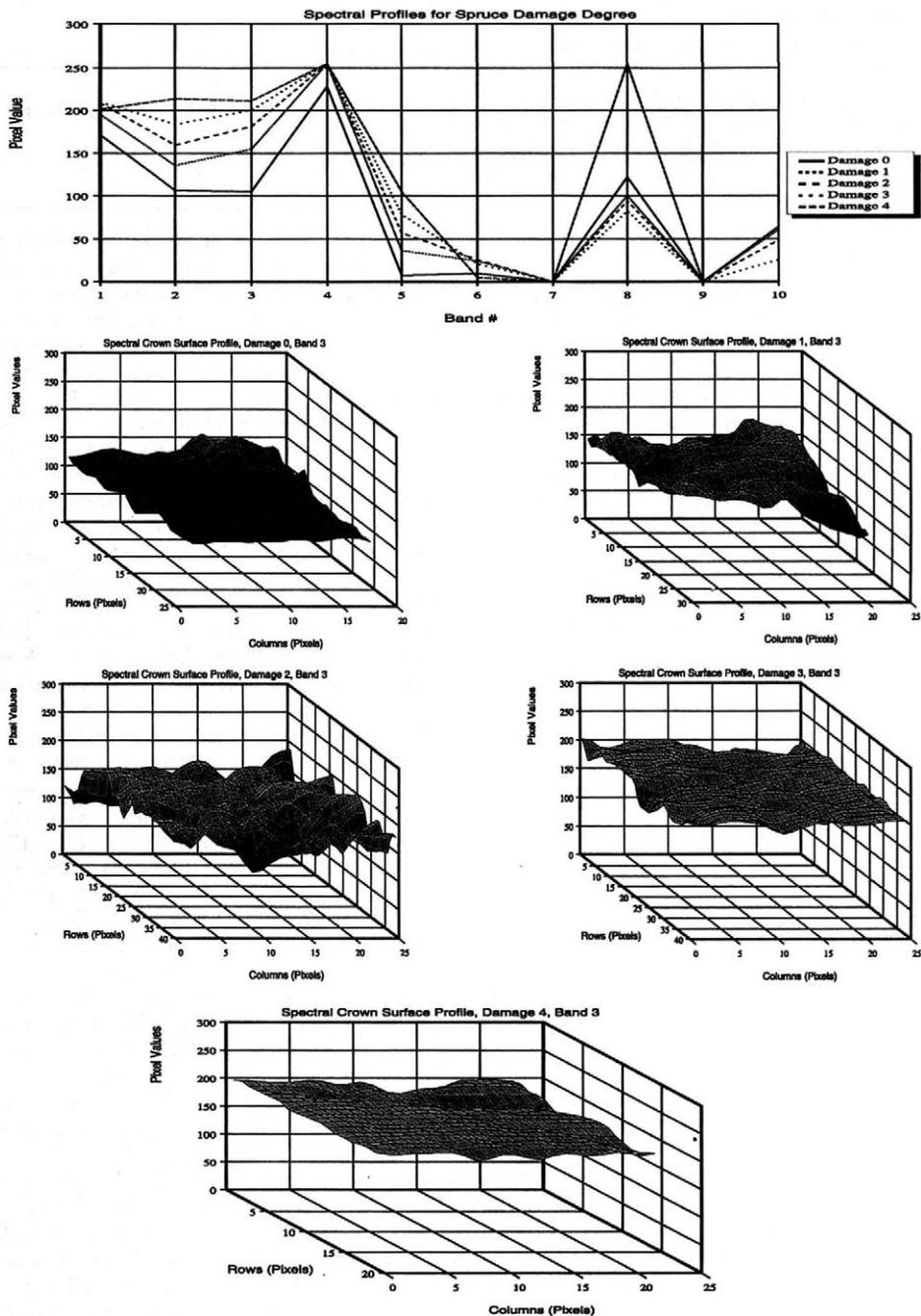
Fig. 1. Spectral profiles and surfaces of spruce defoliation

Table 1. Statistical characteristics of spectral signatures (DN values $\equiv \bar{x}$) measurement for defoliation classes in single bands

Band	Statistics	Defoliation class				
		0	1	2	3	4
1	n	13	30	76	65	15
	$\bar{x}$	179	190	197	192	181
	s_x %	6.5	4.7	3.6	13.3	12.6
2	n	13	30	76	65	15
	$\bar{x}$	109	132	152	188	185
	s_x %	10.9	8.2	9.6	9.8	11.8
3	n	13	30	76	65	15
	$\bar{x}$	133	155	174	194	191
	s_x %	9.2	6.1	6.3	7.6	8.7
4	n	13	30	76	65	15
	$\bar{x}$	239	251	253	252	249
	s_x %	4.9	1.8	0.9	2.9	4.2
5	n	13	30	76	65	15
	$\bar{x}$	7	31	53	83	101
	s_x %	36.1	24.8	16.9	10.6	15.5
6	n	13	30	76	65	15
	$\bar{x}$	28	35	39	18	26
	s_x %	7.8	34.3	41.0	57.2	62.7
7	n	13	30	76	65	15
	$\bar{x}$	0.8	0.9	1.0	0.9	1.0
	s_x %	22.5	6.1	3.0	8.8	5.0
8	n	13	30	76	65	15
	$\bar{x}$	98	100	90	153	171
	s_x %	2.3	4.5	3.5	49.6	51.9
9	n	13	30	76	65	15
	$\bar{x}$	0	0	0	0	0
	s_x %	0	0	0	0	0
10	n	13	30	76	65	15
	$\bar{x}$	70	57	44	11	5
	s_x %	13.2	15.3	21.5	81.5	85.0

ping mainly between the contiguous classes. A similar situation is found in other bands.

Results of stepwise discriminant function analysis for spectral bands are given in Table 2. Tree defoliation in 5% defoliation steps was used as a grouping variable (21 groups). The order of entered variables (E) as well as partial lambda values indicate the contribution of the respective variable (spectral band) to the discriminatory power of the model. Wilks' lambda as a measure of overall model discrimination can assume values in the range from 0 (perfect discrimination) to 1 (no discrimination). The main result of discriminant analysis is that all four above mentioned spectral bands as well as band 10 have a significant contribution (with $P > 0.99$) to defoliation detection, p-level < 0.01 (p-level is associated with the respective F value associated with the respective Wilks' lambda).

RESULTS OF REGRESSION ANALYSIS AND SPECTRAL REFLECTANCE MODELS

The different regression models were used for investigation of relationships between tree defoliation and spectral signatures. Tree defoliation ground data (dependent variable) and corresponding spectral signatures (independent variables) were used in order to derive the spectral reflectance models for estimation of tree damage (defoliation) from aerial digital data. Linear spectral reflectance models and corresponding characteristics are listed in Table 3. These models, where spectral bands with a significant contribution to defoliation detection were employed (except band 8), provide expressively better results than if other spectral bands are used. The correlation coefficients are significant with $P > 0.99$, they vary in the range 0.76–0.97. R-square (variance explained), this coefficient of determination measures a reduction in the total variation of defoliation due to the spectral bands.
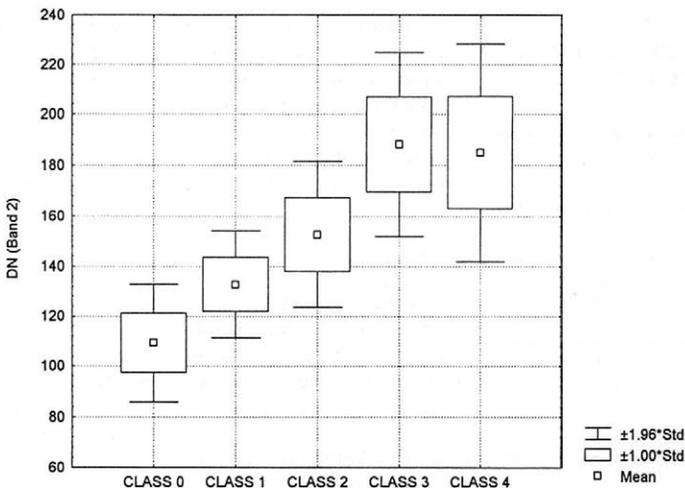

Fig. 2. Box and Whisker plot for Band 2

±1.96*Std.
±1.00*Std.
□ Mean

Table 2. Results of defoliation discriminant analysis for respective spectral bands

Statistical discriminant analysis	Discriminant function analysis summary N of wars in model: 5; Grouping: defoliation (21 grps) Wilks' lambda: 0.00527 $F(100.853) = 16.477, P < 0.0000$			
$N = 199$	Wilks' lambda	Partial lambda	F-remove 20.1744	p-level
Band (5) (E)	0.023526	0.224142	30.11466	0.000000
Band (8) (E)	0.008896	0.592745	5.97747	0.000000
Band (10) (E)	0.006521	0.808690	2.05814	0.007049
Band (3) (E)	0.007229	0.729432	3.22709	0.000016
Band (2) (E)	0.006913	0.762824	2.70499	0.000264

The most favorable variance explained gives band 5 (94.1%) in model No. 3 which also corresponds with the results of discriminant analysis. This spectral reflectance model also gives a high precision value (SE% = ± 13.1%).

The summary of stepwise regression is given in Table 4. The multiple spectral reflectance model represents this summary with several independent variables, however, significant with $P > 0.95$ are only variables – spectral bands 5, 4 and 8 (p-level < 0.05). Also very interesting is analysis of multiple R or R-square change with respect to the influence of individual independent variables. It is documented in Table 4 that a contribution of nonsignificant independent variables (spectral bands 2, 1, 7) to these changes is too small.

For the computation of the relationship between a set of spectral bands and defoliation nonlinear estimations were also used. Such a relationship is shown in Fig. 3. Exponential model $y = -126.118 + \exp(4.814567 + (0.0060552) \cdot x)$ was employed for estimation of the relationship between spectral band 5 and defoliation. This type of model is commonly used in order to study the growth of the population but also in other applications it brings good results. Statistics of this model are as follows: $R = 0.98$, variance explained (R^2) is 96%, SE% = ±10.7%. Also other types of nonlinear models were investigated in this phase of data processing, however their statistics were less favorable.

EXAMPLES OF SPECTRAL REFLECTANCE MODELS UTILIZATION

Parameters of all above mentioned models are different, their accuracy is not very favorable for direct esti-

Table 3. Linear spectral reflectance models for estimation of tree defoliation

Model No.	Regression model	R	Variance explained (%)	SE (%)
1	DEF = –76.06 + 0.80652 . Band 2	0.81	65.6	± 31.3
2	DEF = –1,244.70 + 1.0089 . Band 3	0.76	57.8	± 34.9
3	DEF = –10.41 + 1.0646 . Band 5	0.97	94.1	± 13.1
4	DEF = 92.16 – 1.124 . Band 10	–0.92	84.6	± 21.2

DEF – defoliation, R – correlation coefficient, SE (%) – standard error in percentage

mation of defoliation. However, these models could be a good basis for collection of the first phase information of the two-phased sampling procedure as well as for damage dot estimation of damage regionalization employing kriging and interpolation geostatistics procedures.

TWO-PHASED DAMAGE ASSESSMENT

The use of this sampling procedure (two-phased sampling with regression) will be documented on the model example of spruce damage assessment throughout the entire study area employing CIR digital aerial data 1:20,000.

For this model example the following data validity is assumed:

– the CIR aerial photographs 1:20,000 are converted to digital form and processed in the same manner as CIR aerial photographs from permanent monitoring plots,
– then the same or very similar suitability of single bands for estimation of defoliation is expected as well as accuracy of spectral reflectance models.

Based on the previous experience from aerial digital data processing and sampling applications the following steps are possible to be taken in two-phased sampling assessment of spruce damage at the study area:

1. phase (aerial)

– an aerial sample plot is used as a sample unit, the area of this unit is one hectare on the ground (0.5 × 0.5 cm square in the scale of aerial data), $n_1 = 200$,
– systematic sampling is possible to recommend for sample unit selection,
– aerial sample plot spectral signatures (mean DN values) are collected by full area sample plot measurement.

2. phase (ground)

– a ground sample plot of one hectare is used as a sample unit, a part of identical aerial sample plots is chosen for the ground phase, $n_2 = 30$,
– mean plot damage (percentage of defoliation) from ocular damage assessment of single trees is calculated according to the pan-European monitoring system at systematically distributed sites.

For the improvement of the method accuracy and efficiency, calculation of some defoliation characteristics

Table 4. Multiple spectral reflectance model for estimation of tree defoliation (summary of stepwise regression)

Statistical multiple regression	Regression summary for dependent variable: Defoliation $R = 0.98079527$, $R^2 = 0.96195936$, adjusted $R^2 = 0.96066059$, $F(6.192) = 809.21$, $P < 0.0000$, standard error of estimate: 5.7409, intercept = 130.9729, $P < 0.000$					
$N = 199$	Beta	Standard error of Beta	t (192)	p-level	Multiple R	R-square change
Band 5	0.902531	0.038712	23.31427	0.000000	0.975699	0.951988
Band 4	−0.194284	0.048714	−3.98825	0.000095	0.978152	0.004794
Band 2	0.084889	0.049493	1.71516	0.087929	0.979944	0.003509
Band 8	0.066121	0.027242	2.42715	0.016141	0.980294	0.000689
Band 1	0.072340	0.042635	1.69674	0.091367	0.980555	0.000510
Band 7	0.059774	0.038786	1.54112	0.124935	0.980795	0.000471

Beta – regression coefficient

calculated from defoliation of permanent monitoring plots such as the 2nd phase characteristics was used:

$\bar{x}_D = 53.7\%$ – mean PMP defoliation,

$s_D = \pm 28.9\%$ – standard deviation of defoliation,

$r_{1,2} = 0.98$ – correlation coefficient of the relationship between defoliation and spectral band 5 (exponential model of the relationship is considered),

$$k = \frac{c_2}{c_1} = 8$$

where: c_1, c_2 – the costs per sample unit in phase 1 and 2,

i.e. we consider that ground phase sample costs per sample unit are 8 times higher in comparison with aerial sample costs. Usually, k is expected in the range of 5–15 if aerial photographs are applied in two-phased sampling (SCHEER et al. 1997; AKÇA et al. 1993).

According to commonly used formulas (ŠMELKO 1990) the standard error of the method employing the

above mentioned procedure and characteristics is $s_{\bar{D}} = \pm 2.3\%$. This error introduces the precision $\Delta_D\% = \pm 8.6\%$ with 95% probability. If we wanted to achieve e.g. precision $\Delta_D\% = \pm 10\%$ ($s_{\bar{D}} = \pm 2.7\%$), then the optimal size of samples for this precision, $k = 8$ and second phase data variance are $n_1 = 173$, $n_2 = 11$. When the aerial sample is 8 times cheaper, this sample size makes two-phased sampling profitable because for the same precision of damage assessment on the study area but by one-phased sampling (only ground measurement) we need $n = 116$ sample units. It means that costs of the proposed two-phased sampling procedure are about 3.5 times lower in comparison with the costs we need for one-phased ground sampling (for two-phased sampling we need 261 cost units, for the ground assessment 928).

This sampling design represents the classical approach of two-phased sampling with regression. Its advantage is a possibility to estimate the target variable (defoliation) for all first phase units on the basis of auxiliary variable(s) (DN of spectral bands) or to correct the target variable if

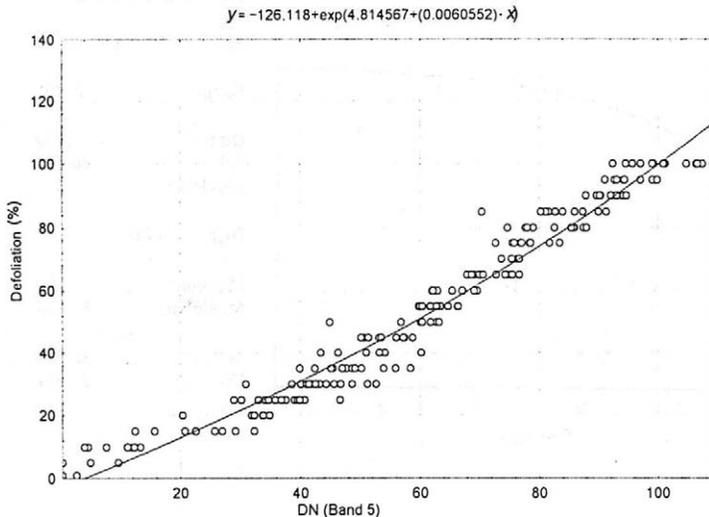$y = -126.118 + \exp(4.814567 + (0.0060552) \cdot x)$

Fig. 3. Exponential spectral reflectance model

the first phase data are its estimates. In this context also with respect to recent knowledge of aerial data damage interpretation a very interesting question appears: what on the basis of what to correct? To correct the aerial damage estimations on the basis of ground damage estimations (measurements) or vice versa. This second approach seems to be presently more actual mainly with respect to a possibility to collect better and new information (extravisual damage detection) from color infrared photographs. However, some problems of this correction approach must still be investigated e.g. design, sample size and size of area to be inventoried with respect to sampling efficiency.

GEOSTATISTICS REGIONALIZATION OF FOREST DAMAGE

Geostatistics is a methodology for the analysis of spatially correlated data. The characteristic feature is use of variograms as a tool for structural analysis of regionalized variables. Forest damage, because it is distributed in space, is also a regionalized variable. The theory of geostatistics as well as its practical applications are described in numerous books and articles e.g. WACKERNAGEL (1998).

Forest damage variogram analysis was based on an estimation of defoliation employing exponential spectral reflectance model and aerial digital data of the study area in the scale 1:20,000. Dot information about forest damage represents these estimations away from each to other 500 meters (a network 500 × 500 m on the study area). Distribution of these estimations ($n = 188$) signalizes that most defoliation is concentrated in the South-West and North-West part of the study area.

The experimental variogram (omnidirectional) of defoliation is shown in Fig. 4. The angular tolerance of 90 degrees on either side of any specified direction line allows all pairs to be included regardless of direction. This maximizes the number of pairs in each distance class, which usually gives the best or smoothest variogram. From this omnidirectional variogram we can usually get the best estimate of the intercept (nugget) and maximum value (sill) parameter for the variogram model, as well as the best idea of what type of model should be fitted. The following information is relevant to our omnidirectional experimental variogram (semi-variogram):

– Totally 12,265 pairs of data values were used for variogram computation. The choice of distance class interval (lag) was suitable because the first four experimental points up to $h = 2.7$ km were estimated with at least 1,500 pairs each. The variogram is not generally valid beyond one half of the maximum distance between samples (in our experiment the distance was 11 km), however toward the limit of reliability, where the variogram has not a typical course with the elements of auto-correlation ($h = L/2 \cong 5.5$ km), the number of pairs for estimation of experimental points 7 and 8 was even higher than 1,000. Thus, the reliability of this omnidirectional semi-variogram can be considered as sufficient.

– An exponential model with a nugget effect was fitted to the experimental semi-variogram $\gamma(h) = 1 - \exp(-h/a)$, with $C_0 = 5\%$ for the nugget constant, with a sill $C_1 = 68\%$ and a range $a_1 = 2.3$ km.

– The tangent to the curve at the origin was approximated by the average linear behavior of the first three experimental points. Thus average linear behavior gives the value $C_0 = 5\%$ when extrapolated to $h = 0$. The

Variogram for DEKS

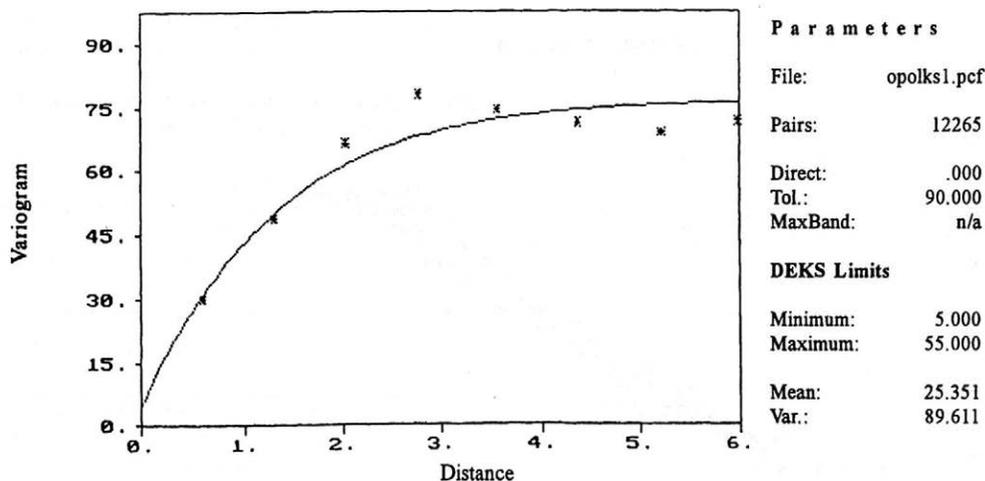| Parameters	
File:	opolks1.pcf
Pairs:	12265
Direct:	.000
Tol.:	90.000
MaxBand:	n/a
DEKS Limits	
Minimum:	5.000
Maximum:	55.000
Mean:	25.351
Var.:	89.611

Fig. 4. Semi-variogram of defoliation

total sill value, $C_0 + C_1 = 73\%$ was estimated as a value around which the variogram becomes stable. The value of range (where the function reaches approximately 95% of the maximum) $a_1 = 2.3$ km was estimated as a value of h at which the preceding tangent intersects the sill.

For the interpolation of forest damage in the territory outside of its assessment the method of block kriging was used. The cross validation technique for testing the validity of a variogram was employed, the Z score value calculated on the basis of variability differences between observed and estimated defoliation demonstrates that model defoliation derived from the block kriging is not biased (Z score = 0.75 < $z_{0.05}$ = 1.98). The kriged results have been entered to the defoliation contours map where the forest damage is expressed as a continuous variable, contours splice areas with the same degree of defoliation. Unfortunately, due to the lower quality of figure outputs from GEO-EAS software running under DOS where the geostatistical analysis was performed, this map was not possible to present in this paper.

CONCLUSIONS

The semi-empirical spectral reflectance models derived from different spectral aerial digital data are a suitable means for collection of forest damage data. It is possible to expect very good results employing some spectral data of PCA analysis and IHS color transformation. When modeling the relationship of reflectance and forest damage, a number of disturbing factors can influence it. Therefore, accuracy, time and spatial validity of reflectance models are limited.

In spite of the mentioned deficiencies reflectance models are a very important source of information for practical procedures of damage assessment. An example of two-phased damage assessment brings about sufficient accuracy and what is important also very high efficiency.

A large use of reflectance models in geostatistical analysis of forest condition is to be expected. Dot information of forest damage (but also other regionalized forest variables) is interpolated employing variogram analysis and kriging. By such procedures we are able to assess the forest condition on very large areas with sufficient accuracy and efficiency.

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Modely spektrálnej odraznosti pre odhad poškodenia smreka (*Picea abies* L.) pomocou digitálnych údajov leteckých snímok

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ABSTRAKT: Práca sa zaoberá odhadom poškodenia smrekových porastov pomocou spektrálnych modelov odraznosti, ktoré boli odvodené z digitálnych údajov leteckých snímok veľkých mierok. Okrem pôvodných digitálnych údajov boli pri konštrukcii modelov použité aj odvodené údaje v rámci IHS transformácie, PCA analýzy a obrazovej algebry. Pre výber optimálnych súborov digitálnych údajov boli použité spektrálne profily korún a metódy diskriminačnej analýzy. Odvodené spektrálne modely umožňujú odhad defoliácie s rôznou presnosťou (SE% = ± 11–50 %), koeficienty determinácie nadobúdajú hodnoty v rozmedzí 0,25–0,96. Napriek tomu, že presnosť modelov nie je veľmi priaznivá, sú dobrým základom pre zber informácií v rámci dvojfázových výberových postupov. Bodové odhady poškodenia pomocou spektrálnych modelov sú tiež vhodné pre analýzu a interpoláciu poškodenia s ohľadom na priestorovú koreláciu údajov pomocou geoštatistických údajov. Príklady obidvoch postupov sú v práci prezentované.

Kľúčové slová: defoliácia; spektrálne modely odraznosti; dvojfázový výber; geoštatistika

Digitálna forma leteckých snímok umožňuje využívať pri odhade poškodenia lesa nové prístupy, založené na modeloch spektrálnej odraznosti. Napriek tomu, že modely neposkytujú najpriaznivejšie rámce presnosti, môžu byť dobrým základom pre dvojfázové zisťovanie poškodenia. Pri veľkoplošných aplikáciách sú bodové odhady poškodenia pomocou týchto modelov východiskom pre jeho regionalizáciu na princípoch geoštatistiky pri zohľadnení priestorovej variability a autokorelácie v poškodení lesa.

Uvádzané prístupy boli použité i v rámci nášho experimentu na modelovom území smrekových porastov (5 549 ha) v severnej časti Slovenska, ktoré sú silne poškodené hlavne vplyvom imisií. Ako experimentálny materiál boli použité farebné infračervené letecké snímky CIR Kodak 2443 v mierke 1 : 1 000 zhotovené na 22 trvalých monitorovacích plochách (TMP) a z celého územia objektu v mierke 1 : 20 000. Spracovanie digitálnych súborov údajov sa uskutočnilo v systéme pre obrazovú analýzu Erdas Imagine Ver. 8.2.

Hlavný dôraz bol kladený na metódy vylepšovania obrazu a multiobrazovej manipulácie (rôzne druhy indexov, PCA-analýza, farebné transformácie) s cieľom odvodiť nové digitálne údaje, ktoré by poskytovali zlepšenú interpretovateľnosť stupňov poškodenia (defoliácie). Z jednotlivých kanálov najlepšie rozlíšenie poskytujú kanály 2, 3, 5, 8, čo je zrejmé z obr. 1, ktorý znázorňuje spektrálne profily kanálov podľa stupňov poškodenia a spektrálne profily povrchu korún. Podobný uzáver vyplýva aj z výsledkov diskriminačnej analýzy v tab. 2, z ktorých je zrejmé, že spomínané kanály spolu s kanálom 10 majú signifikantný príspevok na rozlíšenie stupňov poškodenia.

Výsledky regresnej analýzy poskytujú tab. 3 a 4. Odvodené modely sú signifikantné s $P > 99$ %, miery tesnosti kolíšu v rámci 0,76–0,97, stredná chyba odhadu defoliácie pomocou spektrálnych signatúr dosahuje úroveň 10–30 % v závislosti od typu použitých údajov.

Ďalšia časť práce uvádza príklady praktickej aplikácie modelov spektrálnej odraznosti k odhadu poškodenia na modelovom území pomocou dvojfázového regresného výberu a regionalizácii poškodenia na princípe geoštatistiky.

Pri dvojfázovom regresnom výbere odhadu poškodenia bola dosiahnutá presnosť Δ_D% = ± 8,6 % pri 95% spoľahlivosti, čo je však nezanedbateľné, celý postup kombinácie snímkového odhadu a terestrického zisťovania je vysoko efektívny. V závislosti od pomeru nákladov $k = \frac{c_2}{c_1}$ (kde c_2, c_1 sú potrebné náklady na výberovú jednotku v 2., resp. 1. fáze zisťovania) celkové náklady dvojfázového zisťovania v porovnaní s jednofázovým (len terestrickým) odhadom poškodenia môžu byť 1,5 až 4-násobne nižšie.

Základom geoštatistickej regionalizácie poškodenia z jeho bodových odhadov je skúmanie priestorovej variability a autokorelácie poškodenia v závislosti od vzdialenosti skusných plôch („bodov"), na ktorých sa zisťuje. V našom experimente bolo poškodenie odhadnuté na leteckých snímkach 1 : 20 000 v sieti 500 × 500 m ($n = 188$). K vyrovnaniu experimentálneho variogramu bol použitý exponenciálny model γ (h) = 1 – exp ($-h/a$) s hodnotou pre nugget $C_0 = 5$ % a sill $C_1 = 68$ % (obr. 4). Parametre použitého modelu ako aj výsledky blokového krigingu (Z score = 0,75 < $z_{0,05}$ = 1,98) dokumentujú nevychýlenosť odhadu poškodenia (regionalizáciu) mimo miest jeho zisťovania.

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Concentrations of nutrient elements and microelements in the needles of *Abies alba* Mill. as an environmental indicator in the Carpathian Mts.

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ABSTRACT: Concentrations of Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, F, Fe, Hg, K, Li, Mg, Mn, N, Na, Ni, Pb, Rb, S, Se, Sr, V and Zn were measured in the previous-year growth (2-year old) needles of white fir (*Abies alba* Mill.) from the Carpathian Mountains. Evaluation of metal concentrations in needles was discussed in relation to pollution of forest environment with heavy metals and limit (critical) values of the studied metals for plants. The highest values of the studied elements were found in the Slovak part of the Carpathian Mountains in the vicinity of industrial sources. The highest values of Al, Ba, Cd, Cr, F, K, Mg were found near the Thermal Power Plant ENO Zemianske Kostoľany and the Aluminium Plant in Žiar nad Hronom. The highest concentrations of Cu, Fe, Hg, Zn were determined in the localities influenced by a non-ferrous metallurgic plant in Krompachy and a mercury processing plant in Rudňany. High concentrations of As, Fe, Mn, S, and V occurred in the vicinity of ferrous metallurgic plants in Podbrezová and Košice. Elevated above normal concentrations of Be, Cr, Na, Ni and Pb in fir reflect regional pollution of the environment with these elements. Elevated concentrations of Co, Se and Li, in the absence of Slovak sources of these elements, indicate the effect of a long-range transport from the heavily polluted areas in Poland and the Czech Republic. Liming of the pollution-weakened forest stands was a probable reason for increased concentrations of Ca in fir needles. This study proves that fir needles can be used as bioindicators of environmental contamination with heavy metals.

Keywords: element concentrations (Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, F, Fe, Hg, K, Li, Mg, Mn, N, Na, Ni, Pb, Rb, S, Se, Sr, V, Zn); air pollution; *Abies alba;* forests; Carpathian Mts.

Air pollutants like SO_2, NO_2 and heavy metals are considered one of the main causes of forest decline in Central Europe (AGREN 1997, 1998; BYTNEROWICZ 1997; RÜHLING, STEINNES 1998). The region on the border of Slovak Republic, Poland and Czech Republic was declared the second black triangle in Europe with substantially higher concentrations of heavy metals than in the first black triangle on the border of Czech Republic, Poland and Germany (MARKERT et al. 1996). Information about the air pollution status of the Carpathian forests is essential for a better understanding of environmental stresses. The Carpathian forests represent unique reservoirs of many endemic, rare, and unusual plant and animal species in Central Europe. White fir (*Abies alba* Mill.) is well distributed in the Carpathian Mountains. This species has attracted significant attention of scientists because of its decline and reduced genetic diversity caused by air pollution (KORMUŤÁK 1996; LONGAUER 1993).

Water is the main constituent of foliage of forest tree species as its content is on average 90%. Dried bodies of foliage are dominated by carbon (44.5%), oxygen (42.5%), hydrogen (6.5%), nitrogen (2.5%), phosphorus (0.2%), sulphur (0.3%), alkali metals and alkaline earth metals. Foliage is composed mostly of nonmetals. Thanks to their increased contents in vegetation, nine elements are referred to as macro elements. Elements whose concentrations in plants are lower but still are crucial for their life are called microelements. These comprise chlorine (2,000 mg/kg), silicon (1,000 mg/kg), manganese (200 mg/kg), sodium (150 mg/kg), iron (150 mg/kg), zinc (50 mg/kg), boron (40 mg/kg), copper (10 mg/kg), chromium (1.5 mg/kg), molybdenum (0.5 mg/kg), and cobalt (0.2 mg/kg). Both macroelements and microelements are indispensable to growth and normal life of forest tree species, and can be replaced by no other element. Therefore they are referred to as essential (MAŇKOVSKÁ 1996). Elements designated as structural ones (carbon, hydrogen, nitrogen, oxygen, phosphorus, sulphur, silicon, calcium) form ether proteins, carbohydrates and nuclear acids or directly structural tissues (calcium). Electrolytic elements include potassium, sodium, calcium, chlorine, and magnesium, while enzymatic ones are vanadium, chromium, molybdenum, manganese, iron, cobalt, nickel, copper, zinc, boron, tin, selenium, fluorine, iodine and magnesium. Nitrogen and sulphur are biochemically bound in carbon chains and create organic matter following reduction of their previously high oxi-

dation state (nitrates or sulphates). In contrast, phosphorus and boron and silicon are found in the highest valence. They are not reduced and largely create ester groups with OH in most molecules and partly in saccharides. On the other hand, the electrolytic elements are needed to create specific physiologic potential and play an important role in maintaining defined osmotic conditions in cellular metabolism.

Foliar analyses of toxic elements and nutrients in foliage of forest trees (such as for *Picea abies* Karst., *Pinus sylvestris* L., *Fagus sylvatica* L. or *Quercus* sp.) have been used for evaluation of air pollutant impacts on forest ecosystems (MAŇKOVSKÁ 1996; RAITIO 1995; STEFAN et al. 1997). Foliage of forest trees is capable of accumulating high amounts of metal elements deposited on their surface or in the wax layer (so called exogenous metal content) (MAŇKOVSKÁ 1996).

Deposition of nutritionally important elements to foliage can improve vitality of trees. However, surface deposition may also have unfavourable effects when the biological limits for a given element are exceeded. Similarly, unfavourable chemical conditions in the root zone can lead to the disturbance of the supplies of nutrients and elemental imbalance of trees. The interpretation of the results of foliar analyses is made by means of limit (critical) values of elements (MAŇKOVSKÁ 1996). Many factors may influence abilities of trees to accumulate individual elements in their foliage (RAITIO 1995).

Information about the air pollution status of the Carpathian forests is essential for a better understanding of environmental stress.

The aim of this paper is to present the actual data about concentrations of Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, F, Fe, Hg, K, Li, Mg, Mn, N, Na, Ni, Pb, S, Se, Sr, Rb, V, Zn in 2 years old needles of *Abies alba* Mill. based on the results for the Carpathian part of mountain forests of Slovakia. We are also interested in the difference between element concentrations of 2 years old fir needles from the Carpathian mountain forests of Romania, Poland, Ukraine and Czech Republic.

MATERIALS AND METHODS

Research sites (Fig. 1) were established in Slovakia (Table 1), the Czech Republic, Poland, Ukraine and Romania (Table 2) in December 1995. Altogether 483 trees of predominant or dominant class in the second age category (21–40 years old) were sampled. Samples of needles were analysed unwashed. Concentrations of elements were determined by atomic absorption spectroscopy: Al, Ba, Ca, Cu, Fe, Mn, Mg, Na, Sr, Rb, Zn (Perkin-Elmer model 3030B); Co, Cd, Cr, Be, Ni, Pb, V (Perkin-Elmer model 3100, HGA-600); As, Se (AAS 3030B, MHS-20 Perkin-Elmer); Hg (trace mercury analyser TMA-254, Tesla Holešovice). Concentrations of F were determined colorimetrically with SPECOL 11 Carl Zeiss Jena, of S with a LECO SC 132 analyser and of N with a LECO SC 228 analyser.

Fig. 1. List of localities

Observations of fir needle surfaces were performed with a scanning electron microscope JEOL 840 A and by using an EDX analyser LINK 10000. The wax surface SEM was done at the Forest Research Institute in Zvolen. The wax quality was determined by evaluation of two hundred stomata per needle. 20 needles were evaluated per each tree. Quantification changes in the epistomatal wax structure of five distinct classes were defined by two criteria: different crystal wax morphology and the varying share of changed wax structures in the stomatal area (MAŇKOVSKÁ 1996 – Table 3). We used C_o – coefficient of occlusion (arithmetical mean of wax quality of 200 stomata per needle). The stomata samples were evaluated by Kolmogorov-Smirnov statistical nonparametric test for qualitative attribute. Particles deposited on surface and in stomata were assessed according to their morphology and EDX spectra (Table 4). Particles deposited on fir needles were assigned into 4 basic categories (biological, mineral, coal-oil ash, and industrial particles). The accuracy of data was verified by the analysis of standard plant samples and by comparison with the results obtained in 109 laboratories within the IUFRO quality assurance working group (HUNTER 1994). The samples were evaluated by common statistical methods (Student test, PCA).

RESULTS AND DISCUSSION

Foliar analyses of *A. alba* show that the greatest load by air pollutants is in the Slovak part of Carpathian Mountains (Table 5), namely in the surroundings of industrial plants where also the highest values of studied elements were found.

Aluminium is a metallic element and is not essential for fir needles. The mean concentration of aluminium in the white fir needles in Slovakia ranged between 146 and 688 mg/kg. Concentrations of Al in the Ukraine were

Locality	Parent rock	Specific rated emissions (t/km²)			Main sources of emissions	Pollution deposition type	Number of PMP
		SO₂	NOx	solid slope			
Beskydy [1]	Paleocene-Eocene: sandstones, flysch with reef limestone block	2–5	< 1	2–5	Heavily polluted by the industry in the neighbouring Czech Republic and Poland	A_3, A_4	5
Branisko [2]	Upper Eocene-Oligocene: sandstones, clay-stones, marlstones	< 2	< 1	< 2	Ferrous metallurgy plants	A_1, A_3	5
Čergov [3]	Eocene: sandstones, graywacke/arkosic sand-stones, microconglomerates	< 2	< 1	< 1	Heavily polluted by the industry in neighbouring Poland	A_3, A_4	7
Javorník [4]	Eocene: sandstones, graywacke/arkosic sand-stones, microconglomerates	5–10	2–10	5–10	Regional pollution – Nonpoint source	A_1	5
Kremnické vrchy [5]	Amphibolites, amphibole gneisses basic meta-volcanics	2–5	1–2	< 2	Regional pollution – Aluminium plant – 50 km	A_1, A_3	5
Low Tatras – northern part [6]	Gneisses, metamorphoses volcanites, schist, granites	2–5	1–2	< 2	Regional pollution – Nonpoint source	A_1, A_3	5
Low Tatras – southern part [7]	Amphibolites, granites, variegated limestones	2–5	1–2	< 2	Ferrous metallurgy plants	A_1, A_3	7
Ondavská vrchovina [8]	Lias-Dogger: shales, sandstones, breccia lime-stones and breccias	< 2	< 1	< 2	Polluted by the industry in neighbouring Poland	A_1	5
Oravská Magura [9]	Senonian: marls, sandstones, limestones, con-glomerates	2–5	2–5	< 2	Heavily polluted by the industry in the neighbouring Czech Republic and Poland	A_1, A_3	5
Šarišská vrchovina [10]	Eocene: sandstones, graywacke/arkosic sand-stones, microconglomerates	< 2	< 1	< 2	Polluted by the industry in neighbouring Poland and regional pollution	A_1, A_3	5
Spiš [11]	Middle-Upper Triasic mainly dolomites, locally limestones and shales	> 10	< 1	2–5	Non-ferrous metallurgy plants + Mercury plant + Barium plant	A_3, A_1	123
Spišská Magura [12]	Eocene: sandstones, calcareous claystones-flysch	< 2	< 1	< 2	Non-ferrous metallurgy plants + Mercury plant	A_1	5
Štiavnické vrchy [13]	Amphibolites, amphibole gneisses basic meta-volcanics	2–5	1–2	< 2	Regional pollution – Aluminium plant – 50 km	A_1, A_2	17
Strážovské vrchy [14]	Granodiorites, tonalites, granites, leucocrate granites	5–10	2–10	2–5	Regional pollution	A_1, A_4	5
Veporské vrchy [15]	Silurian-Devonian: metamorphosed volcanites, metasands, phyllite, Cherts, rare carbonates	5–10	1–2	< 2	Regional pollution – Non ferrous metallurgy plants + Barium plant	A_1, A_3	10
Vtáčnik [16]	Middle-Upper Triasic, variegated limestones, partially dolomites, shales and sandstones	> 10	> 10	< 2	Regional pollution – Thermal power plant – 20 km – Aluminium plant – 50 km	A_1, A_2	5
HighTatras [17] – National Park	Eocene-sandstones, calcareous claystones-flysch	< 1	< 1	< 1	Polluted by the industry in neighbouring Poland and regional pollution	A_1, A_3	83

Note: A_1 = Acid pollution deposition type with fly ash
A_2 = Acid pollution deposition type with fly ash, fluorine and chloride
A_3 = Acid pollution deposition type with smelter dust
A_4 = Acid pollution deposition type with organic matter
PMP = Permanent monitoring plot

Table 2. List of localities, parent rock and number of samples

Country	Locality		Parent rock	Altitude (m)	Number of samples
Romania					**124**
	South Carpathians	Muntele Aninae, Semenic, Valiug	Schists	700–750	15
A, B,		Muntele Mare, Valea Ierii	Schists	900–1,050	4
C, D,	Central Carpathians	Facegi, Busteni	Limestones	1,000	20
E, F,		Pojana Brasov	Limestones	1,100–1,250	8
G, H		Pojana Ruska	Limestones	1,100	20
		Cristian	Schists	600–700	11
	East Carpathians	Muntele Bystrica, Tazlau	Sandstones	500–650	24
		Muntele Bystrica, Vorotec	Flysch	640–760	22
Poland					**28**
	Biesczady	Losie	Schists	600–700	10
I		Tarnawa Niżna	Schists	600–700	18
Ukraine					**10**
K, L	Carpathian Russia	Rachov, Marmoros ridge, Menčul	Schists	700–1,200	10
Czech Republic					**24**
	North Moravia	Králický Sněžník, Malá Morava	Sandstones	700	1
M, N, O	Nízký Jeseník Mts.	Město Albrechtice	Sandstones	700	4
		Česká Ves	Sandstones	700	14
	Hrubý Jeseník Mts.	Karlovice	Schists	750	5

similar to the values found in Slovakia (208–660 mg/kg). For the entire Carpathian range the highest concentrations were determined in Romania (348–688 mg/kg); Poland (244–402 mg/kg); the Czech Republic (194–452 mg/kg). According to MAŇKOVSKÁ (1996), the allowable limit value for aluminium in the foliage of forest tree species is 180 mg/kg. Aluminium was present in 97.2% of the stomata of fir needles.

The concentration of arsenic in the white fir needles (in mg/kg) in Slovakia ranged within 1.03 ± 2.44, in Ukraine within 0.09 ± 0.07, in Romania within 0.05 ± ± 0.03, in Poland within 0.08 ± 0.03 and in Czech Republic within 0.20 ± 0.14. MARKERT (1993) gives as al-

Table 3. Classification of changes of the epistomatal wax of *A. alba*

Class 1:	A maximum of 10% of the total stomatal area shows the beginnings of fusion of single wax tubules
Class 2:	Several of the apically aggregated wax tubules fuse to small wax tufts at different parts of the epistomatal area. The latter cover 10% to 25% of the total stomatal area
Class 3:	In addition to the wax tufts plate-like wax parts can be found that, in total, cover more than 25% and up to 50% of the total stomatal area
Class 4:	More than 50% and up to 75% of the total stomatal area show small parts of wax tufts as well as large platelet wax forms
Class 5:	More than 75% of the total stomatal area is characterized by considerably changed wax microstructures. The stomatal antechamber is almost or completely occluded with an amorphous wax plug

lowable limit values for arsenic in the foliage of forest tree species the concentration 0.214 mg/kg. The highest concentrations of total arsenic were found in the surroundings of large industrial plants (in southern part of the Low Tatras, in Spiš and the locality Vtáčnik). It is obviously connected with combustion of low grade Slovak coal with high content of arsenic. The content of arsenic in the needles of *A. abies* in Slovakia is statistically significantly increased when compared with Ukraine, Poland, Romania and Czech Republic. Arsenic was present only in 0.8% of the stomata of fir needles.

The concentration of barium in the white fir needles (in mg/kg) in Slovakia ranged within 36.9 ± 24.5, in Ukraine within 46.8 ± 13.7, in Romania within 43.2 ± ± 11.9, in Poland within 25.3 ± 2.2 and in Czech Republic within 28.4 ± 7.5. MAŇKOVSKÁ (1996) gives as allowable limit values for barium in the foliage of forest tree species the concentration within 60 mg/kg. The highest contents were found in the locality Vtáčnik. Barium was present only in 0.5% of the stomata of white fir needles.

The concentration of beryllium in the white fir needles (in mg/kg) in Slovakia ranged within 0.012 ± 0.012, in Ukraine within 0.009 ± 0.005, in Romania within 0.011 ± 0.01, in Poland within 0.001 ± 0.001 and in Czech Republic within 0.005 ± 0.004. MAŇKOVSKÁ (1996) gives as allowable limit values for beryllium in the foliage of forest tree species the content 0.02 mg/kg. The highest concentrations of beryllium were found in the

Table 4. Criteria for classifying into categories of solid particles

Category	Morphology	Major EDX spectrum
A-vegetal	characteristic of spores or pollen (a)	low peak to background ratio for variable amounts of Si, S, Ca, K, P
B-mineral	nonspherical, irregular form, large particles, origin from soil, calcite (CaCO₃), dolomite (Ca, Mg (CO₃)₂), SiO₂, CaSO₄ and more complex mixture of alkaline origin	high peak to background ratio for Si or Ca and variable of Al, K, Ti, Fe, Na
C-oil-fly ash	smooth sphere rich in Al, Si, S; cenosphere with Al-Si, V, and Ni; sulphate rich in Cr, Fe, Ni with metal-black shine	Al, Si, V, Ni, Cr
D-coal-ash E-coal-oil- -fly ash	smooth glasslike sphere with Al-Si smooth porous particles with carbon content together with category C and D	same as mineral Al-Si Al-Si
F-industrial	various particles which correspond to factory technology:	
	aluminium factory	I Al
	cement factory	II Ca
	magnesite factory	III Mg
	ferrous factory	IV Fe
	nonferrous metal factory	V Mn, Ni, Zn, Br, Rb, Sr
	different	VI

High Tatras National Park. Beryllium was not present in the stomata of fir needles.

The variability of calcium in fir needles depends on soil. The content of calcium in principle correlates with the level of magnesium and the mean concentration (in mg/kg) in Slovakia is within $12,755 \pm 6,344$, in Ukraine within $12,474 \pm 5,186$, in Romania within $16,949 \pm 3,017$, in Poland within $14,981 \pm 1,317$ and in Czech Republic within $15,127 \pm 4,176$. Limit value of calcium for optimal nutrition represents for coniferous species 6,000 mg per kg (STEFAN et al. 1997). Mean content of calcium in 2 years old needles of fir on the whole territory of Slovakia reached the value 12,774 mg/kg (MAŇKOVSKÁ 1996). The content of calcium can be classified as increased mainly in Beskydy Mts., in Strážovské hills, Javorník, Kremnické hills, Vtáčnik and Oravská Magura. The increased level can be connected with the liming of stands. Next it will be necessary with the assessment of calcium to consider its occurrence in the stomata of foliage. Calcium is present in the particles arising in the combustion of fossil fuels. It was present in 93.4% of the stomata of foliage.

The concentration of cadmium in the white fir needles (in mg/kg) in Slovakia amounts 0.26 ± 0.17, in Ukraine 0.16 ± 0.02, in Romania 0.13 ± 0.06, in Poland 0.27 ± 0.10 and in Czech Republic 0.25 ± 0.07. Limit value for cadmium in the foliage of forest tree species was set 0.5 mg/kg (MAŇKOVSKÁ 1996). Cadmium was not present in the stomata of fir needles.

The values of cobalt in the white fir needles (in mg/kg) amount to: 0.23 ± 0.19 in Slovakia, 0.13 ± 0.12 in Ukraine, 0.11 ± 0.05 in Romania, 0.14 ± 0.01 in Poland and 0.16 ± 0.08 in Czech Republic. Limit value for cobalt in the foliage of forest tree species was set 0.2 mg/kg (MAŇKOVSKÁ 1996). The highest values of cobalt were found in Javorník and Šarišská vrchovina. Cobalt was not present in the stomata of fir needles.

The values of chromium in the white fir needles (in mg/kg) amount to: 0.59 ± 0.72 in Slovakia, 2.20 ± 5.90 in Ukraine, 0.45 ± 0.16 in Romania, 0.26 ± 0.02 in Poland and 0.43 ± 0.15 in Czech Republic. Limit value for chromium in the foliage of forest tree species was set 0.8 mg/kg (MAŇKOVSKÁ 1996). Chromium was present in 1.6% of the stomata of fir needles.

The values of copper in the white fir needles (in mg per kg) amount to: 7.9 ± 6.9 in Slovakia, 4.6 ± 1.1 in Ukraine, 4.4 ± 0.5 in Romania, 3.6 ± 0.7 in Poland and 4.3 ± 0.4 in Czech Republic. KAUPENJOHAN et al. (1989) give for spruce the value 2.5–3 mg/kg; JOCHHEIM (1993) considers the content Cu < 5 mg/kg as a limit content and the values above 100 mg/kg as an extreme load by air pollutants. Exogenous copper was present in 0.4% of the stomata of analysed foliage of forest tree species. The contents of total copper higher than 5 mg/kg are present on about 2/3 of the territory of Slovakia. The highest values of Cu were found in the region of Spiš. Copper was present only in 0.4% of the stomata of fir needles.

The values of fluorine in the white fir needles (in mg per kg) amount to: 8.1 ± 4.9 in Slovakia, 3.8 ± 0.7 in Ukraine, 5.7 ± 2.4 in Romania, 6.2 ± 1.6 in Poland and 8.7 ± 2.2 in Czech Republic. MAŇKOVSKÁ (1996) gives for fir needles the limit value 8.7 mg/kg. Higher content of total fluorine 5 mg/kg is on 2/3 of the territory of Slovakia and it is present in the surroundings of industrial plants. Concentrations of total fluorine higher than 10 mg/kg were found in the white fir needles in Kremnické hills and Vtáčnik. Fluorine was not present in the stomata of fir needles.

The values of iron in the white fir needles (in mg/kg) amount to: 232 ± 983 in Slovakia, 177 ± 56 in Ukraine, 123 ± 19 in Romania, 92 ± 20 in Poland and 116 ± 33 in Czech Republic. STEFAN et al. (1997) give as optimum for iron the value 200 mg/kg for foliage of forest tree species. High values were recorded also on the northern border of Slovakia. The highest concentrations of iron were found in Spiš and Javorník. It is connected with Ostrava-Karviná and Katowice region, and on the eastern border with Poland. Iron was present in 94.4% of the stomata of fir needles.

The values of mercury in the white fir needles (in mg per kg) amount to: 0.125 ± 0.098 in Slovakia, $0.036 \pm$

Table 5. Concentration of elements in 2 years old needles of *A. alba* in Slovakia (arithmetical mean in mg/kg)

Localities	Al	As	Ba	Be	Ca	Cd	Co	Cr	Cu	F	Fe	Hg	K
Beskydy	324	0.151	47.1	0.007	22,938	0.25	0.19	0.36	4.0	9.3	105	0.047	4,095
Branisko	244	0.239	34.5	0.006	13,120	0.14	0.12	0.31	4.2	8.3	96	0.124	5,358
Čergov	334	0.231	51.9	0.008	13,127	0.32	0.21	0.69	5.6	6.3	136	0.115	6,283
Javorník	463	0.459	46.1	0.014	18,895	0.21	0.28	0.80	4.1	5.9	245	0.098	5,062
Kremnické vrchy	362	0.285	41.1	0.012	17,711	0.35	0.19	0.47	4.3	10.9	174	0.049	4,957
Low Tatras Nat. Park – S	266	4.013	33.8	0.010	9,567	0.15	0.10	0.32	2.6	5.4	65	0.040	4,372
Low Tatras Nat. Park – N	146	0.240	43.9	0.008	11,021	0.10	0.06	0.45	3.8	5.3	79	0.076	4,218
Ondavská vrchovina	367	0.255	49.9	0.010	12,911	0.36	0.31	0.63	5.4	8.5	206	0.056	5,638
Oravská Magura	242	0.297	41.6	0.003	16,645	0.12	0.06	0.54	3.6	9.1	111	0.046	5,239
Šarišská vrchovina	457	0.346	25.4	0.012	11,940	0.24	0.27	0.62	5.6	9.2	164	0.137	5,153
Spiš	348	1.258	30.7	0.011	11,149	0.24	0.24	0.56	8.9	7.9	273	0.150	5,428
Spišská Magura	283	0.040	35.4	0.003	7,836	0.28	0.08	0.35	6.4	5.2	72	0.125	6,615
Štiavnické vrchy	553	0.239	43.1	0.020	14,406	0.36	0.16	0.32	7.1	8.8	173	0.045	6,001
Strážovské vrchy	435	0.401	43.7	0.013	20,630	0.35	0.08	0.74	4.8	6.3	185	0.092	3,926
Veporské vrchy	315	0.205	43.6	0.005	12,326	0.16	0.14	0.49	6.4	6.6	145	0.084	6,097
Vtáčnik	688	0.829	80.1	0.009	17,928	0.36	0.06	0.79	5.5	13.1	222	0.049	7,009
High Tatras Nat. Park	333	0.189	35.4	0.099	13,560	0.14	0.04	0.28	3.9	7.6	89	0.074	3,917

Table 5 continuation

Localities	Li	Mg	Mn	N	Na	Ni	Pb	Rb	S	Se	Sr	V	Zn
Beskydy	0.03	581	3,034	10,400	22.2	5.8	0.67	0.33	1,240	0.041	19.9	0.33	54.0
Branisko	0.09	1,666	6,466	20,600	29.6	1.1	0.80	3.39	3,134	0.029	18.3	1.69	42.2
Čergov	0.12	955	785	17,514	41.8	2.6	1.73	2.23	1,730	0.049	12.3	0.22	50.4
Javorník	0.27	796	1,905	16,417	52.8	12.6	4.91	1.62	2,180	0.119	16.0	0.54	44.3
Kremnické vrchy	0.13	998	1,937	12,325	25.4	2.4	2.15	22.38	1,698	0.045	35.1	0.32	36.1
Low Tatras Nat. Park – S	0.10	597	628	12,763	16.4	2.7	0.87	3.04	1,489	0.024	19.5	0.16	27.1
Low Tatras Nat. Park – N	0.11	1,086	1,023	12,800	19.9	1.5	1.21	4.77	1,455	0.026	16.9	0.46	48.0
Ondavská vrchovina	0.13	899	1,245	16,120	32.6	4.9	2.96	2.67	1,642	0.086	15.8	0.29	39.5
Oravská Magura	0.88	892	472	10,733	25.1	3.3	1.73	1.46	1,097	0.043	22.7	0.51	45.6
Šarišská vrchovina	0.16	905	2,836	15,367	52.6	6.5	1.22	3.12	1,983	0.047	14.8	0.42	41.0
Spiš	0.16	1,036	2,091	18,156	42.9	3.5	2.68	6.05	2,241	0.077	17.8	1.13	59.0
Spišská Magura	0.08	738	323	20,800	46.9	6.2	1.60	2.28	1,157	0.030	7.6	0.13	34.3
Štiavnické vrchy	0.13	1,381	1,192	14,235	32.9	2.7	2.33	12.15	1,679	0.031	53.5	0.25	49.3
Strážovské vrchy	0.13	1,218	2,265	15,147	55.1	3.4	2.40	4.00	1,350	0.029	10.9	0.38	58.1
Veporské vrchy	0.25	928	1,076	10,400	37.3	3.2	1.98	7.87	1,300	0.031	17.4	0.29	38.9
Vtáčnik	0.10	1,773	708	20,550	40.3	1.8	2.01	16.21	1,635	0.065	41.1	0.46	37.8
High Tatras Nat. Park	0.03	1,074	1,909	10,400	18.8	5.6	1.18	1.65	1,275	0.003	22.1	0.14	41.0

0.008 in Ukraine, 0.045 ± 0.009 in Romania, 0.045 ± 0.004 in Poland and 0.047 ± 0.014 in Czech Republic. Limit value for mercury in the foliage of forest tree species was set 0.1 mg/kg (MAŇKOVSKÁ 1996). The content of mercury in the foliage of forest tree species in Slovakia can be assessed as increased, with extreme values almost 70-times exceeding limit value in the region of Spiš. Mercury was not present in the stomata of fir needles.

The values of potassium in the white fir needles (in mg/kg) amount to: 5,683 ± 1,507 in Slovakia, 5,262 ± ± 871 in Ukraine, 5,079 ± 375 in Romania, 4,692 ± 264 in Poland and 4,364 ± 358 in Czech Republic. The variability of potassium in the foliage of forest tree species depends on the soil. Exogenous potassium was present

in 78.5% of the fir stomata of analysed foliage of forest tree species. STEFAN et al. (1997) give for Europe the values within 1,400–1,1250 mg/kg. Potassium was present in the 14% stomata of white fir needles.

The values of lithium in the white fir needles (in mg per kg) amount to: 0.17 ± 0.24 in Slovakia, 0.17 ± 0.06 in Ukraine, 0.04 ± 0.02 in Romania, 0.03 ± 0.001 in Poland and 0.08 ± 0.07 in Czech Republic. MAŇKOVSKÁ (1996) gives for foliage of tree species the values within 0.5–3.4 mg/kg. The content of total lithium was higher than 0.2 mg/kg in Slovakia and was exceeded in Oravská Magura, Javorník and Veporské hills. Lithium was not present in the stomata of fir needles.

The values of magnesium in the white fir needles (in mg/kg) amount to: 1,120 ± 476 in Slovakia, 1,092 ± 346

in Ukraine, 1,506 ± 334 in Romania, 1,110 ± 165 in Poland and 959 ± 232 in Czech Republic. The variability of magnesium in the foliage of forest tree species depends on the soil. The values for magnesium in spruce needles in Europe range from 570 to 3,750 mg/kg (STEFAN et al. 1997). Low values of Mg correlate with yellowing of needles. Exogenous magnesium was present in 48.9% of the surface of analysed foliage of forest tree species. The highest values of magnesium were found in the locality Vtáčnik and Branisko.

The values of manganese in the white fir needles (in mg/kg) amount to: 1,836 ± 1,579 in Slovakia, 534 ± 287 in Ukraine, 897 ± 339 in Romania, 1,028 ± 688 in Poland and 1,969 ± 966 in Czech Republic. Of the parameters studied only the content of manganese in spruce needles correlates with the loss of needles. Therefore manganese is being assessed as damage indicator for tree species. Already the stage of manganese mobility shows a labile status in the regime of mineral elements of forest trees. RAITIO et al. (1995) found in healthy spruce needles the value 320 mg/kg and in declining needles 1,300 mg/kg. Mobility of manganese indicates the disturbance of physiological balance which leads to the imbalance with iron (the ratio should be 1:2, value 0.5). In Slovakia this ratio is 0.13, in Ukraine 0.33, in Romania 0.14, in Poland 0.09 and in Czech Republic 0.06. The highest concentration of manganese was found in Slovakia in Branisko. Manganese was present in 20% of the stomata of fir needles.

The values of nitrogen in the white fir needles (in mg per kg) amount to: 17,413 ± 5,306 in Slovakia, 17,223 ± ± 3,119 in Ukraine, 12,306 ± 1,010 in Romania, 11,050 ± 636 in Poland and 11,030 ± 1,149 in Czech Republic. STEFAN et al. (1997) give as optimum for nitrogen in spruce needles the value 17,000 mg/kg. The results of the first assessment of nitrogen content in the foliage of forest tree species in Europe (4,200–23,800 mg/kg) showed that on relatively many permanent monitoring plots in Germany, Slovakia and Great Britain there were found high values (STEFAN et al. 1997). Higher content of total nitrogen than 20,000 mg/kg is obvious in Spišská Magura, Branisko and Vtáčnik. Nitrogen was not present in the stomata of fir needles.

The values of sodium in the white fir needles (in mg per kg) amount to: 41 ± 45 in Slovakia, 33 ± 31 in Ukraine, 15 ± 4.2 in Romania, 18 ± 3 in Poland and 27.2 ± 10.4 in Czech Republic. MAŇKOVSKÁ (1996) found for *A. alba* in Slovakia the concentrations within 43.4 ± 48.3 mg/kg. The content of sodium higher than 50 mg/kg was found in Strážovské hills, Javorník and Šarišská vrchovina. Sodium was present in 15% of the stomata of fir needles.

The values of nickel in the white fir needles (in mg/kg) amounts to: 3.6 ± 2.3 in Slovakia, 6.7 ± 2.8 in Ukraine, 7.3 ± 3.2 in Romania, 6 ± 0.1 in Poland and 4.0 ± 1.2 in Czech Republic. The content of nickel higher than the limit concentration 2 mg/kg (MAŇKOVSKÁ 1996) is in Central and Eastern Slovakia. It is connected with indus-

trial regions. The highest values were found in fir needles in Javorník. Sodium was present in 6.8% of the stomata of fir needles.

The values of lead in the white fir needles (in mg/kg) amount to: 2.5 ± 2.9 in Slovakia, 4.7 ± 1.6 in Ukraine, 0.5 ± 0.4 in Romania, 0.6 ± 0.1 in Poland and 1.0 ± 0.8 in Czech Republic. The content of lead higher than the limit concentration 5 mg/kg (MAŇKOVSKÁ 1996) was found in Central and Eastern Slovakia and it is connected with industrial regions. Lead does not represent any significant load for the Carpathian Mountains. Only 1% of the studied localities are influenced by more than twofold concentration in excess of the limit value. Lead was not present in the stomata of fir needles.

The values of rubidium in the white fir needles (in mg per kg) amount to: 6.6 ± 7.9 in Slovakia, 6.0 ± 7.1 in Ukraine, 10.4 ± 17.4 in Romania, 4.8 ± 4.9 in Poland and 8.5 ± 10.7 in Czech Republic. The rubidium content was higher than the limit concentration 6 mg/kg (MAŇKOVSKÁ 1996). TOBLER et al. (1994) and MARKERT (1993) found for *P. sylvestris* 8.1 mg/kg. Rubidium content higher than 20 mg/kg was found in Vtáčnik in Central Slovakia. Rubidium was not present in the stomata of fir needles.

The values of sulphur in the white fir needles (in mg per kg) amount to: 2,117 ± 909 in Slovakia, 1,675 ± 271 in Ukraine, 1,426 ± 146 in Romania, 1,285 ± 177 in Poland and 1,430 ± 220 in Czech Republic. The results of the first assessment of sulphur content in the foliage of forest tree species in Europe (400–2,300 mg/kg) showed that on relatively many permanent monitoring plots in Germany, Slovakia and Great Britain there were found high values (STEFAN et al. 1997). The value 1,000 mg/kg can be considered as the limit value for sulphur. The data recorded on total foliar sulphur are surprisingly high also in comparison with our data from 1975 (MAŇKOVSKÁ 1983). They confirm great effects of sulphur oxides on the whole territory of Slovakia. Higher content of total sulphur than 1,000 mg/kg is present on more than 4/5 of the territory of Slovakia. The highest concentrations of sulphur were found in Branisko, Romania. Sulphur was present only in 0.4% of the stomata of fir needles.

The values of selenium in the white fir needles (in mg per kg) amount to: 0.068 ± 0.065 in Slovakia, 0.052 ± ± 0.022 in Ukraine, 0.009 ± 0.009 in Romania, 0.014 ± ± 0.009 in Poland and 0.038 ± 0.010 in Czech Republic. MARKERT (1992) gives for plants the value within 0.01– 0.05 mg/kg. Selenium occurs in nature together with sulphur. The value of selenium 0.03 should be considered as the limit value. Values higher than 0.05 mg/kg occur on about one half of the territory of Slovakia. Values higher than the given concentration of total selenium in fir needles occur in Ondavská vrchovina, in Spiš and Vtáčnik. Selenium was not present in the stomata of fir needles.

The values of strontium in the white fir needles (in mg per kg) amount to: 22.0 ± 35.4 in Slovakia, 16.9 ± 4.03 in

Table 6. Concentration of elements in 2 years old needles of *A. alba* (mg/kg) in four European countries

Country	Ukraine		Romania		Poland		Czech Republic		Slovakia	
Element	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Al	430 (137)	208–660	517 (115)	348–688	323 (111)	244–402	333 (90)	194–452	371 (189)	15–1,668
As	0.09 (0.07)	0.02–0.28	0.05 (0.026)	0.009–0.082	0.084 (0.025)	0.066–0.101	0.20 (0.14)	0.01–0.36	1.03 (2.44)	0.023–18.2
Ba	46.8 (13.7)	27.0–75	43.2 (11.9)	26.7–64.3	25.3 (2.2)	23.7–26.8	28.4 (7.5)	17.9–39.6	36.9 (24.5)	4.2–202
Be	0.009 (0.005)	0.002–0.016	0.011 (0.01)	0.005–0.031	0.001 (0.001)	0.0001–0.001	0.005 (0.004)	0.0002–0.011	0.012 (0.012)	0.0001–0.099
Ca	12,474 (5,186)	7,473–25,552	16,949 (3,017)	11,895–20,193	14,981 (1,317)	14,050–15,912	15,127 (4,176)	7,651–19,610	12,755 (6,344)	1,974–69,331
Cd	0.16 (0.02)	0.13–0.21	0.132 (0.056)	0.056–0.227	0.27 (0.10)	0.20–0.34	0.25 (0.07)	0.12–0.30	0.26 (0.17)	0.010–0.97
Co	0.13 (0.12)	0.01–0.38	0.105 (0.049)	0.052–0.197	0.14 (0.01)	0.14–0.15	0.16 (0.08)	0.06–0.26	0.23 (0.19)	0.001–1.20
Cr	2.2 (5.9)	0.38–21.9	0.45 (0.16)	0.28–0.80	0.26 (0.02)	0.25–0.27	0.43 (0.15)	0.25–0.63	0.59 (0.72)	0.010–8.03
Cu	4.6 (1.1)	3.2–6.9	4.4 (0.5)	2.1–5.4	3.6 (0.7)	3.2–4.1	4.3 (0.4)	3.8–4.8	7.9 (6.9)	2.3–69
F	3.8 (0.7)	2.5–4.8	5.7 (2.4)	3.7–11.1	6.2 (1.6)	5.0–7.3	8.7 (2.2)	4.5–10.8	8.1 (4.9)	1.0–65
Fe	177 (56)	115–312	123 (19)	93–154	92 (20)	78–106	116 (33)	83(157)	232 (983)	12–14,004
Hg	0.036 (0.008)	0.027–0.05	0.045 (0.009)	0.036–0.065	0.045 (0.004)	0.042–0.047	0.047 (0.014)	0.036–0.065	0.125 (0.098)	0.020–0.705
K	5,262 (871)	4,007–7,106	5,079 (375)	4,538–5,486	4,692 (264)	4,506–4,879	4,364 (358)	3,865–4,782	5,683 (1,507)	2,288–12,131
Li	0.17 (0.06)	0.12–0.34	0.04 (0.02)	0.03–0.07	0.03 (0.001)	0.03–0.033	0.08 (0.07)	0.03–0.22	0.17 (0.24)	0.02–2.54
Mg	1,092 (346)	494–1,709	1,506 (334)	877–1,921	1,110 (165)	993–1,226	959 (232)	789–1,409	1,120 (476)	351–2,820
Mn	534 (287)	238–1,062	897 (339)	401–1,251	1,028 (688)	541–1,514	1,969 (966)	492–3,043	1,836 (1,579)	31–8,112
N	17,223 (3,229)	12,600–22,300	12,306 (1,010)	11,000–13,550	11,050 (636)	10,600–11,500	11,030 (1,149)	9,300–12,100	17,413 (5,305)	9,300–38,200
Na	33 (31)	16–132	15 (4.2)	11–24	18 (3)	16–20	27.2 (10.4)	16.1–42	41 (45)	0.9–613
Ni	6.7 (2.8)	2.7–11.6	7.3 (3.2)	2.4–13.5	6 (0.1)	5.6–5.8	4.0 (1.2)	1.9–5.1	3.6 (2.3)	0.23–15.3
Pb	4.7 (1.6)	2.5–7.2	0.5 (0.4)	0.01–1.0	0.6 (0.1)	0.5–0.6	1.0 (0.8)	0.3–2.3	2.5 (2.9)	0.01–26.9
Rb	6.0 (7.1)	1.6–26.1	10.4 (17.4)	1.0–53	4.8 (4.9)	1.3–8.2	8.5 (10.7)	3.4–30.1	6.6 (7.9)	0.32–56
S	1,675 (271)	1,220–2,140	1,426 (146)	1,310–1,760	1,285 (177)	1,160–1,410	1,430 (220)	1,080–1,640	2,117 (909)	690–5,930
Se	0.052 (0.022)	0.003–0.088	0.009 (0.009)	0.001–0.026	0.014 (0.009)	0.007–0.020	0.038 (0.010)	0.028–0.052	0.068 (0.065)	0.001–0.50
Sr	16.9 (4.03)	10.6–22.1	19.3 (5.7)	12.9–27.5	16.1 (6.9)	11.2–21	26.6 (10.9)	11.8–36.7	22.0 (35.4)	2.2–360
V	0.28 (0.11)	0.15–0.49	0.15 (0.13)	0.01–0.41	0.18 (0.09)	0.11–0.24	0.07 (0.10)	0.001–0.25	0.92 (1.97)	0.001–15.5
Zn	34.2 (9.4)	22.5–57.9	39.8 (7.7)	31.5–55.7	68 (17.3)	55.9–80	50.8 (14.3)	39.2–79	55.5 (35.4)	16.9–403
n	10		124		28		24		297	
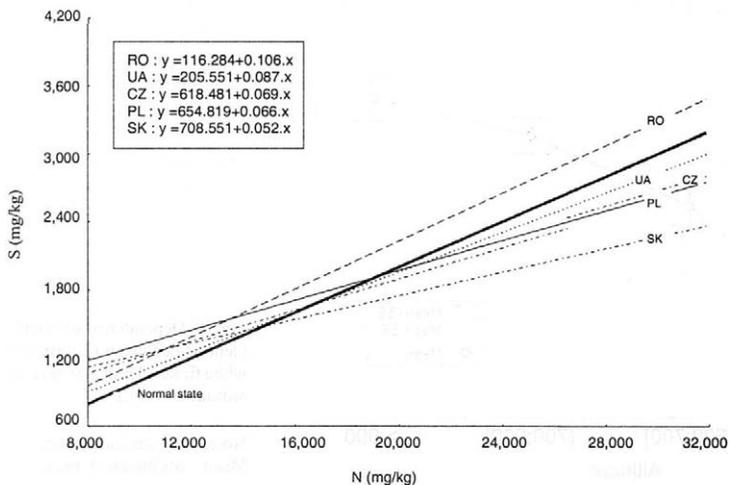
Fig. 2. Concentration dependence of sulphur on nitrogen in 2 years old white fir needles in Slovakia

The chart legend:
RO : y =116.284+0.106.x
UA : y =205.551+0.087.x
CZ : y =618.481+0.069.x
PL : y =654.819+0.066.x
SK : y =708.551+0.052.x

Axes: S (mg/kg) vs N (mg/kg). Labels: RO, UA, CZ, PL, SK, Normal state

Ukraine, 19.3 ± 5.7 in Romania, 16.1 ± 6.9 in Poland and 26.6 ± 10.9 in Czech Republic. MARKERT (1992, 1993) gives for *P. sylvestris* 0.95 mg/kg. Increased content of strontium appeared in several localities of South and Central Slovakia. The content of total strontium higher than 50 mg/kg was found in Štiavnické hills. Strontium was not present in the stomata of fir needles.

The values of vanadium in the white fir needles (in mg/kg) amount to: 0.92 ± 1.97 in Slovakia, 0.28 ± 0.11 in Ukraine, 0.15 ± 0.13 in Romania, 0.18 ± 0.09 in Poland and 0.07 ± 0.10 in Czech Republic. Limit value for vanadium in the foliage of forest tree species was set 1.0 mg/kg (MAŇKOVSKÁ 1996). The highest values of vanadium were found in Branisko and Spiš. Vanadium represents a significant load only in 4.5% of the localities studied. Vanadium was present in 16.1% of the stomata of fir needles.

The values of zinc in the white fir needles (in mg/kg) amount to: 55.5 ± 35.4 in Slovakia, 34.2 ± 9.4 in Ukraine, 39.8 ± 7.7 in Romania, 68 ± 17.3 in Poland and 50.8 ± 14.3 in Czech Republic. STEFAN et al. (1997) give as optimum for zinc the value 50 mg/kg for the spruce needles. Higher concentration than 55 mg/kg was found in Spiš and Strážovské hills. Zinc was present only in 2.6% of the stomata of fir needles.

The equilibrium of individual elements in plants is a precondition of their normal growth. Similar chemical properties due to roughly equal ion radicals and charges probably cause interactions between individual elements in plant organisms. Synergic and antagonistic relationships between individual elements are disturbed by polluted atmosphere. Well-known are the correlations between P, N, K, Ca and Mg in 54 higher and lower plant

$$y = -64.91 + 0.068 \cdot x$$
$$r_{yx} = 0.66, \ p < 0.05$$

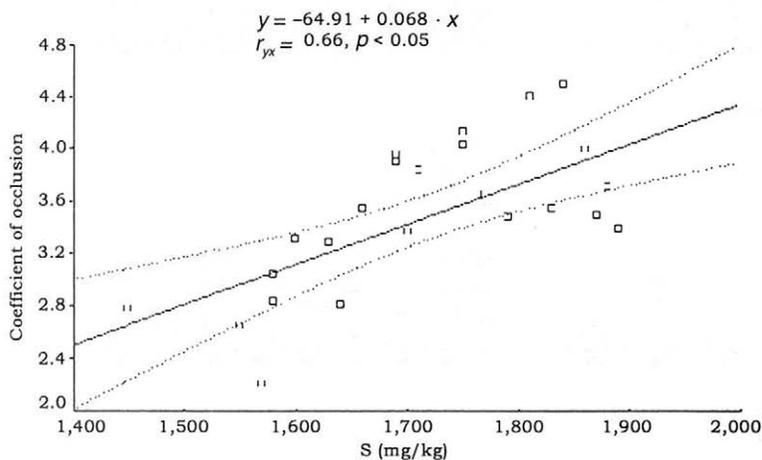Axes: Coefficient of occlusion vs S (mg/kg)

Fig. 3. Dependence of coefficient of conclusion on total sulphur concentration in 2 years old white fir needles in Slovakia

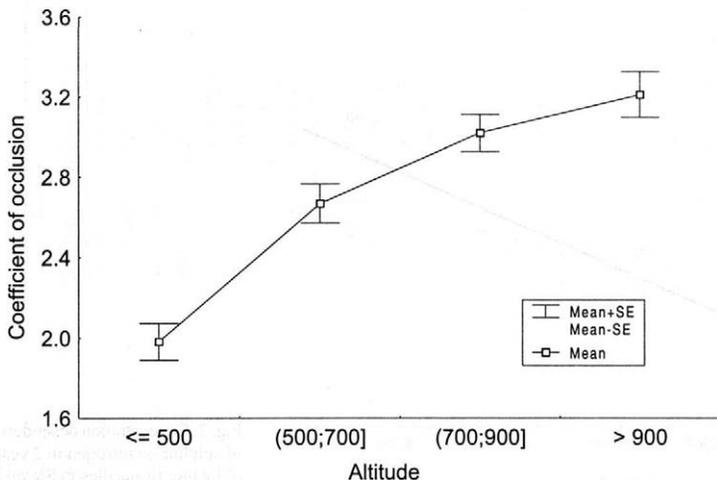Fig. 4. Dependence of coefficient of occlusion (2 years old white fir needles in Slovakia) on altitude intervals

Note: SE – standard error, Mean – arithmetical mean

species. P and N play a role in protein biosynthesis, while Ca and Mg are common enzymatic activators in metabolic physiological processes. Surprisingly, in contrast to data presented by MARKERT (1993), only highly positive correlation pairs ($r > 0.9$) of locally emitted elements were found in Aluminium plant for Cr/Pb, Magnesite plant Mg/S, metallurgy complex As/Cr, Al/Pb, and in military area for Cu/Na. In the Low Tatras National Park only positive correlation between Cr and Fe, in the High Tatras National Park between As and Cu was found. Between the pairs of elements Be/Co and Be/Na we found positive correlation $r > 0.9$ and negative correlation was found for the pair of elements Be/N only in the Czech Republic. External concentrations and higher standard deviations in industrial areas confirm the effect of polluted air.

Statistically significant differences in the concentrations of Al, Be, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Li, Mg,
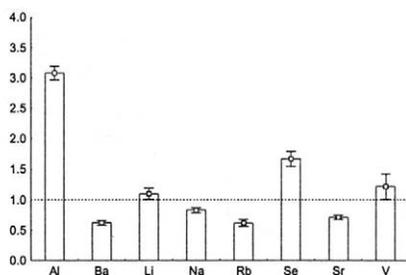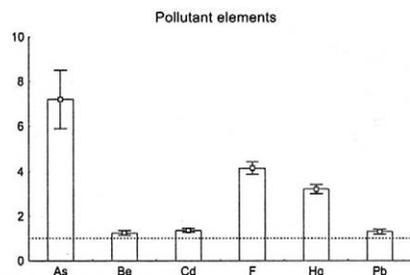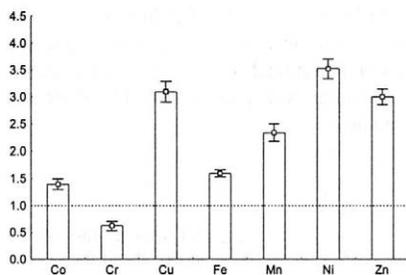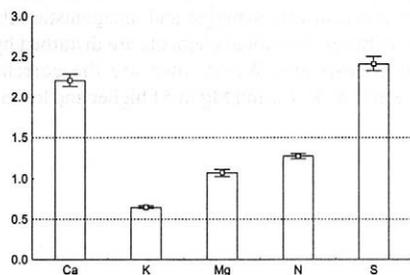
Fig. 5. Slovak white fir loading by coefficient of charge (K_z)

Mn, N, Na, Ni, Pb, S, V and Zn in the white fir needles were found between all studied countries (Table 6). Metal concentrations in needles were evaluated based on pollution of the forest environment with heavy metals and limit concentrations of the studied metals for plants. The highest values of the studied elements were found in the Slovak part of the Carpathian Mountains in the vicinity of industrial sources. The highest values of Al, Ba, Cd, Cr, F, K, Mg were found near the Thermal Power Plant ENO Zemianske Kostoľany and the Aluminium Plant in Žiar nad Hronom. The highest concentrations of Cu, Fe, Hg, Zn were determined in the localities influenced by the Non-ferrous Metallurgic Plant in Krompachy and the Mercury Processing Plant in Rudňany. High concentrations of As, Fe, Mn, S and V occurred in the vicinity of the Ferrous Metallurgic Plants in Podbrezová and Košice. Elevated above normal concentrations of Be, Cr, Na, Ni and Pb in fir needles reflect regional pollution of the environment with these elements (Fig. 5). To calculate total pollution impact, we applied pollution impact coefficient K_z which expresses to what extent the limits of evaluated elements in foliage of white fir needles were exceeded (MAŇKOVSKÁ 1996). Elevated concentrations of Co, Se and Li, in the absence of Slovak sources of these elements indicate the effect of a long-range transfer from the heavily polluted areas in Poland and the Czech Republic. Liming of the pollution-weakened forest stands was a probable reason for increased concentrations of Ca in fir needles. Concentration dependence of sulphur on nitrogen in 2 years old white fir needles for all studied countries is in Fig. 2.

Dependence of the coefficient of occlusion on total sulphur concentration in 2 years old white fir needles in Slovakia is in Fig. 3 and dependence of the coefficient of occlusion on altitude intervals in Slovakia is in Fig. 4. Stomata of observed needles of *A. abies* in the vicinity of non-ferrous plants contained aluminium as a part of minerals, ashes (Al–Si) and particles Al_2O_3; iron as a part of particles of minerals, ashes and Fe_2O_3 (vicinity of a metallurgic complex and thermal power plant); potassium as a part of mineral and biological particles and Mn, Na, V, Ni, Zn, Cr, As, Ba and Cu. This fact is especially important for the assessment of elements with significant nutritive value.

CONCLUSION

1. Based on foliar analyses of *A. alba* the greatest load by air pollutants is in the Slovak part of Carpathian Mountains, namely in the surroundings of industrial plants where also the highest values of studied elements were found. In the concentrations of Al, Be, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Li, Mg, Mn, N, Na, Ni, Pb, S, V and Zn in the white fir needles we found statistically significant differences between Slovakia and Romania, Ukraine, Poland and Czech Republic except for Sr and Rb.

2. The highest values of Al, Ba, Cd, Cr, F, K, Mg in the needles of *A. alba* were found in mountain forests in the vicinity of Thermal Power Plant ENO Zemianske Kostoľany and Aluminium Plant in Žiar nad Hronom. The highest concentrations of Cu, Fe, Hg, Zn in the white fir needles were found in the localities influenced by Non-ferrous Metallurgy Plant Krompachy and Mercury Plant Rudňany. Vicinity of Ferrous Metallurgy Plants Podbrezová and Košice was reflected in above-limit contents of As, Fe, Mn, S, V. The highest concentrations of Be, Cr, Na, Ni and Pb in fir needles result from regional pollution. Maximal values of Co, Se and Li regarding the absence of Slovak sources of air pollutants stem from remote transfer of air pollutants from Poland and Czech Republic and increased concentration of Ca obviously from the liming of stands endangered by air pollution.

3. SEM-investigation of white fir needle waxes from the Slovak part of Carpathian Mountain forest showed that there is a statistically significant difference in mean wax quality between coefficient of occlusion and altitude. Epistomatal waxes were damaged, that means the beginning – of formation of pure and amorphous waxes.

4. Stomata of observed white fir needles contained aluminium as a part of minerals, ashes (Al–Si) and particles Al_2O_3 (vicinity of aluminium plant); iron as a part of particles of minerals, ashes and Fe_2O_3 (vicinity of metallurgy complex and thermal power plant); potassium as a part of mineral and biological particles and Mn, Na, V, Ni, Zn, Cr, As, Ba and Cu were found in the vicinity of non-ferrous plants. This fact is especially important for the assessment of elements with significant nutritive value.

5. This study proves that white fir needles can be used as bioindicators of contamination of Carpathian Mountains forests by pollutants.

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Koncentrace nutričních a stopových prvků v jehličí *Abies alba* Mill. jako environmentální indikátor v Karpatech

ABSTRAKT: Koncentrace Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, F, Fe, Hg, K, Li, Mg, Mn, N, Na, Ni, Pb, Rb, S, Se, Sr, V a Zn byly zjištěny ve dvouletém jehličí jedle (*Abies alba* Mill.) v Karpatech. Hodnocení obsahu kovů v jehličí je diskutováno ve vztahu ke znečištění lesního prostředí těžkými kovy a limitními monitanmi těchto studovaných prvků v rostlinách. Na základě listových analýz *A. alba* je nejvíc imisemi zatížena slovenská část karpatských lesů, a to v okolí průmyslových zdrojů, kde jsme zjistili i nejvyšší hodnoty sledovaných prvků. Nejvyšší hodnoty Al, Ba, Cd, Cr, F, K, Mg v jehličí *A. alba* byly nalezeny v lesích v blízkosti teplárny ENO Zemianske Kostoľany a hliníkárny ZSNP v Žiaru nad Hronom. Nejvyšší koncentrace Cu, Fe, Hg, Zn v jehličí *A. alba* jsme našli na lokalitách, které jsou ovlivněny kovohutěmi Krompachy a Rudňany. Blízkost železáren v Podbrezovej a Košicích se projevila zase na nadlimitních obsazích As, Fe, Mn, S, V. Nejvyšší koncentrace Be, Cr, Na, Ni a Pb v jedlovém jehličí pochází z regionálního znečištění. Maximální hodnoty Co, Se a Li s ohledem na nepřítomnost slovenských zdrojů imisí pochází z dálkového přenosu imisí z Polska a České republiky. Zvýšené koncentrace Ca pochází zřejmě z vápnění imisemi ohrožených porostů. Práce poukazuje na možnost využití jehličí jedle jako bioindikátor kontaminace prostředí těžkými kovy.

Klíčová slova: koncentrace prvků (Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, F, Fe, Hg, K, Li, Mg, Mn, N, Na, Ni, Pb, Rb, S, Se, Sr, V, Zn); znečištění; *Abies alba;* lesy; Karpaty

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