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STANDS FOR ECOLOGICAL MONITORING OF FORESTS IN POLLUTED AREAS IN THE LICHEN BIOINDICATION AND MORPHOPHYSIOLOGICAL CHARACTERIZATION OF TREE MIDDLE URALS (RUSSIA, SVERDLOVSK REGION)

The study area covered an area of approximately 25 x 30 km around the city of Revda with a population of approximately 400000. The main source of industrial air pollution in the whole area is SUMZ, a large copper-smelting plant founded more than 50 years ago The pollution by polymetallic dust combined with sulphur dioxide caused an increase in soil acidity and metal concentrations in the upper soil layer. Extremely high metal concentrations and remarkable exceedances near SUMZ as compared to background conditions were found - for Cu - up to 90-115-fold. Lichen diversity gradually decreased with increasing soil contamination and applicable for purposes of ecological monitoring over the whole study area. The generalised state index of morphological and physiological parameters from artificial tree stands was correlated with the index of atmospheric purity. R^2 was higher within a distance of 13 km from SUMZ (31.8%) than outside this distance (10.7%) but was still statistically significant. In conclusion both epiphytic lichens and tree stands of the complex ecosystem boreal forest were injured at pollution levels lower or equal to the official Russian human health standard values (HHS) recommended for air pollution levels. Further, to the inherent interest of a forest monitoring per se, lichen bioindication and the morphophysiological tree stand characterization as elaborated in this project turned out promising and cost efficient approaches to monitor the environmental pollution in extended industrial areas.

A joint research programme was financially supported by INTAS, the International Association for the promotion of cooperation with scientists from the independent states of the former Soviet Union. Three research teams from the Urals State Forestry Engineering Academy, the Institute of Plant and Animal Ecology and the Institute of Forest, both from the Russian Academy of Sciences, co-operated in this project between September 1994 and 1997. More than 20 scientists from Ekaterinburg were involved in this multidisciplinary project.

The aim of the project was to develop a method for ecological monitoring in and around heavily polluted areas in the Middle Urals, using forest trees and epiphytic (tree colonising) lichens as bioindicators.The project was divided into the following different modules:

1. A detailed description of the tree stands based on morphological and physiological characterisations of naturally occurring trees of certain age.

2. Quantitative floristical analyses of epiphytic lichens which are sensitive tested to atmospheric pollutants such as sulphur dioxide. Available models to cal- culate a widely used "index of atmospheric purity" (IAP) had to be and a standardized method for a bioindication and biomonitoring with epi- phytic (tree colonising) lichens had to be proposed for the Middle Urals.

3. Pulse-amplitude modulated chlorophyll fluorescence had to be tested to measure early impairment of pollution-related tree and lichen vitality.

The different data sets had to be analysed by a geographic information system and spatial analysis of pollution data, tree stand characterization and lichen-bioindication had to be presented. This paper summarizes a few results; detailed information concerning the project can be obtained from the final report submitted to INTAS (Scheidegger, 1998).

Material and Methods

A detailed description of the methods is given in (Scheidegger, 1998). 10 trees of Betula pubescens/pendula were analysed per plot. 198 plots have been studied. To standardize floristical data vertical trees with an estimated age > 60 years were selected. The following parameters were registered for each tree trunk: total list of species; species frequency (from 1 to 10) at two levels (at the base of trunk and 100-150 cm above ground).

From these data we calculated an “Index of atmospheric purity” (IAP) by using the following formula:

$$IAP = \frac{1}{10}\sum\nolimits_{n}^{i} QF$$

where n is the number of species per site, F is the frequency of each species at each site; Q is the ecological index of a species, which was calculated as an average number of epiphytes occurring with a species at all sites investigated (LeBlanc & De Sloover, 1970). In fact Q expresses a numerical "resistance" or "toxicotolerance" of species: resistant species have higher values of Q. Three versions of IAP were calculated: one for the base of the trunks, (IAP 1) one for the height 1,0-1,5 m (IAP 2) and a third considering the total lichen cover between the base and 1.5 m above ground (IAP avg).

We determined the concentrations of heavy metals (Cu, Pb, Zn, Cd) in the upper soil layer (0-5 cm) at each plot (3 mixed samples, each from the 5 individual subsamples). Measurements of mobile forms of metals were performed using a Karl Zeiss atomic-absorption spectrometer AAS-3. S and heavy metals contamination in lichen thallies was measured by ICPAES method.

For the morphophysiological assessment of artificial pine stands, 140 plots with 20–40 year old trees were selected. On each plot the dominant tree species and their densities were determined. The diameters of 200 trees were measured. From these trees the forty individuals with diameters closest to the mean diameter value were selected for further investigation. The diameter increments over the past 5 and 10 years were determined for all these forty trees. The heights and vertical increments for the last 5 and 10 years were measured for 3 trees with median values of diameter. From these 140 study plots 129 were selected for the analysis of the generalized state index (GSI), and of these 109 were selected for physiological research. Physiological investigation of the photosynthetic apparatus of pine needles included the measurement of chlorophyll *a* and *b* and carotenoid content of 2-year-old pine needles. The shoots for this purpose were taken from the south-west facing middle parts of crowns of trees selected. For this investigation, 15 pine trees per each plot were chosen. In addition, the measurement of the photochemical quantum efficiency of PSII Fv/Fm $(Fm-F_0)/Fm$ parameter which characterizes the non-cyclic electron transport effectiveness in pine needles was carried out. For adaptation purposes, before measurement the shoots were exposed for 30 minutes to a temperature of 22°–25 °C at a constant photon flux density (PFD = 50 micro mol quanta $m^{-2} s^{-1}$). For fluorescence laboratory measurements needles still attached to their shoots were used.

The fast fluorescence characteristics of chlorophyll in pine needles were measured by means of the fluorimeter PAM-2000 (Walz, Germany) and the Leaf-Clip Holder 2030-B (Walz, Germany). These characteristics included Ft (measuring light-induced fluorescence value), Fm^1 (saturated light-induced peak fluorescence value), the Photochemical quantum efficiency of PSII and q_N parameters.

All physiological characteristics (pigment and proline content, chlorophyll fluorescence value, stem impedance value) were compared with those of the controls during August and September once or twice during a period of two weeks. This experimental approach allowed a reduction of the effects of seasonal changes (Krivosheeva, Shavnin et al., 1991; Shavnin, Fomin, 1993) on the parameters' value.

The generalized state indices for tree stands were calculated by applying the method of geometric means to state indices which had been computed separately for each particular characteristic. Taking into consideration the morphological, physiological and total parameter set revealed the morphological, physiological and total generalized state index (GSImorph, GSIphys, GSI total) respectively. These state indices were taken to be equal to their desirability values which had been calculated using the Harrington's formula (Adler et al., 1976):

$$d_i = 100 \exp. [-\exp. (-y_i')],$$

where d_i is the desirability value of i-th parameter; y_i'- encoded value of i-th parameter.

These linear equations were used to encode those characteristics measured on particular objects as given above for the earlier model (Kalinin et al., 1991). However, since the weight assigned to a particular parameter used in calculating a particular generalized state index depended on the normalized deviation value t, the earlier model was modified to make more unbiased choice of t. That is, the procedure of choosing reference values which were used to define the function $d_i = f(y_i')$ was changed. The first reference value was then specified as following: $d_{1i} = 63$, $y_i' = 0.75$, while the second reference value defined the poorest state is $d_{2i} = 5$, $y_i' = -1.1$. The first point corresponds to the point of inflection of the curve $d_i = f(y_i^1)$ while the choice of the second one is based on preceding experimental work on the model. The introduction of these two values allowed the calculation of the coefficients A_0 and A_1 of the equation coding:

$$y_i^1 = A_0 + A_1 y_{im}$$

where y_{im} is the measured value of y for particular i parameter for a particular experimental plot.

The measured value of a particular parameter for the control plot was taken as corresponding to the first reference value. Then the measured values of the same diagnostic parameter for all sample plots were analysed to find the lower-range parameter value. This value was assumed to correspond to the second reference value. Since the obtained y'-scale is linear, specifying the two reference values allows to encode diagnostic parameters measured for the rest of the sample plots. The increase in d_i means upgrading the object's characteristic on the i-th parameter.

The digital topographical maps were scanned from maps of the scale of 1:200000 (ETH-library, Switzerland) and a 3-D model of the study area was calculated by means of the Geographic Information System (GIS) ARC/INFO at WSL (Birmensdorf, Switzerland). The ARC EDIT component of GIS was used in digitizing the topographic maps. The TIN, GRID (kriging and idw methods) modules were used to calculate borderlines of pollution zones, and ARCPLOT was applied for printing the results.

The study area covered a rectangle of approximately 25 x 30 km around the city of Revda with a population of approximately 400000. The main source of industrial air pollution in the whole area is SUMZ, a large copper-smelting plant founded more than 50 years ago and located north-west of the city, when the vicinity to the Degtyarsk copper mine favoured the selection of this industrial site. However, at present the Degtyarsk copper mine is exhausted, and some other mines (e.g. from Kazakhsthan) supply SUMZ with ore. The emission level of SO_2 and other pollutants had been approximately 100000 - 150000 tons per year until the late 1980's. When the SUMZ production was reduced in the early 1990's the emission levels consequently dropped.

Results and discussion

48 species of epiphytic lichens were determined on birch trunks in Revda-Pervouralsk industrial area. Lichen communities composed by 18-22 species were common for the weakly polluted zone. Sensitive lichen species were also common in this region. A decrease in diversity of lichen species and their frequencies (IAP) up to their total disappearance was the general tendency of transformation of the epiphytic lichen communities under the emission of SUMZ. Fig. 1 shows that the index of atmospheric purity IAP reached high values under unpolluted conditions at a long distance from SUMZ but rapidly decreased closer than 13 km from SUMZ. This was a result of an unequal sensitivity of lichen species to the various components of the environmental pollution. Further, the frequency of more tolerant species such as *Hypogymnia physodes* was also decreasing as one moved closer to the plant. An extended "lichen desert" is formed in the area 0 - 2.5 km from the emission source (Map 1).

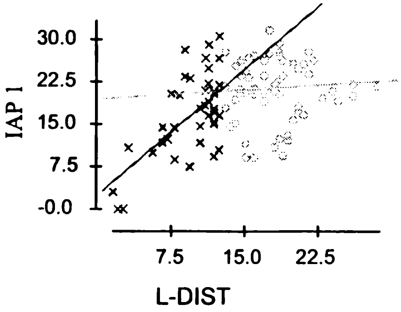

Fig. 1. Scatterplot of IAP 1 versus distance from SUMZ; x: <13 km from SUMZ, o: >13 km from SUMZ

The pollution by polymetallic dust combined with sulphur dioxide gaused an increase in soil acidity and metal concentrations in the upper soil layer. We found extremely high metal concentrations (Fig. 2) and remarkable exceedances near SUMZ as compared to background conditions: Cu - up to 90-115-fold, Pb up to 15-21-fold, Zn - up to 10-19-fold, Cd - up to 10-16- fold. The soil contamination index K which displays by how many times the various pollutants measured exceeded the background level, reached

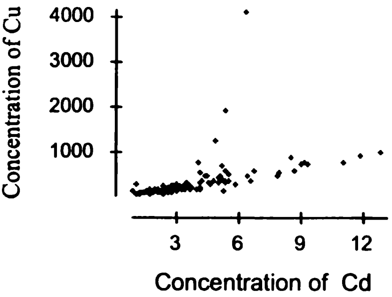

Fig. 2. Scatterplot of Cu and Cd soil concentration (ppm); the group of data points with very high Cu content but average Cd content are very close to SUMZ

values as high as 128 at these sites and was further processed by GIS to a map which distinguished between 4 different contamination levels (Map 2).
Parallel to the soil contamination, highly increased metal concentrations were found in lichen thalli near the emission source (Fig. 3) as compared to background conditions: The same trend was found for sulphur (Fig. 4) ,however, this element was only measured in lichens. Exceedances were up to 8-10 for Cu, up to 6-8 for Pb, up to 2,5-3 for Zn and up to 8-9- fold for Cd. However, the method has its limitations at a short distance from the pollution source, because lichens are usually not found in the quantities needed for the elemental analysis.

The analysis of the measured parameters did not show any significant correlation to the soil contamination parameter K (Fig. 5). Only after a Harrington transformation was carried out in order to obtain state indices, significant correlation was found between morphological tree data and environmental parameters such as soil contamination and IAP. Fig. 6 shows that the state index of tree height increment decreased with increasing environmental pollution as indicated by the IAP. When taking into consideration the GSI total set of morphological and physiological parameters, 31% of its variance was explained by IAP 1 at distances less than 13 km from SUMZ (Fig 7).

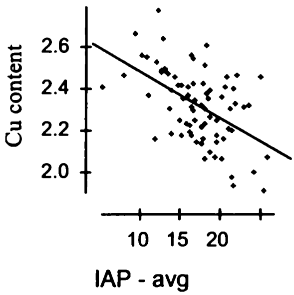

Fig. 3. Cu content (log) of Hypogymnia physodes versus IAP-average (R^2=25.3%)

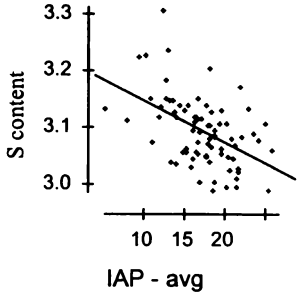

Fig. 4. S content (log) of Hypogymnia physodes versus IAP-average (R^2=22.4%)

R^2 dropped to about 10% when the whole study area was considered (Fig. 8)

The spatial analysis of the generalized state index GSI which takes into consideration both morphological and physiological parameters (Map 2) shows a similar pattern as the lichen diversity data (Map 1). A cross-correlation analysis obtained after the GIS analysis of all indices investigated is given in Table 1. The main results are summarized below:

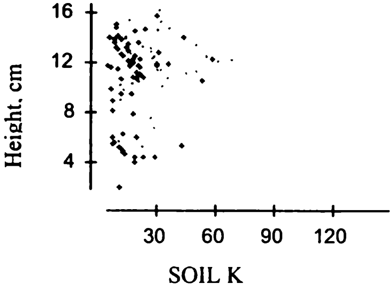

Fig. 5. Tree height calculated for 15 year- old trees against soil contamination parameter K

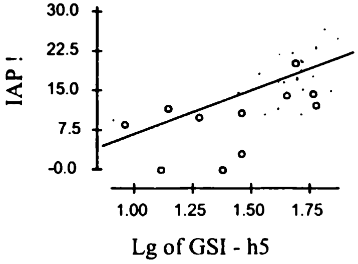

Fig. 6. IAP 1 versus lg GSIh5 (state index of tree-height increment); only plots with a distance < 13 km from SUMZ (R^2=27.3%)

1. There is a positive correlation ($R^2 \approx$ 0.5) between lichen bioindication assessment of tree stands and the GSI - parameters which characterize the vitality of tree stands.

2. There is a negative correlation (K = – 0.45) between the heavy metal contents of soils and the GSI calculated by morphometric characteristics; no correlation was found between heavy metals content and GSI calculated by physiological characteristics. The different variants of the index of

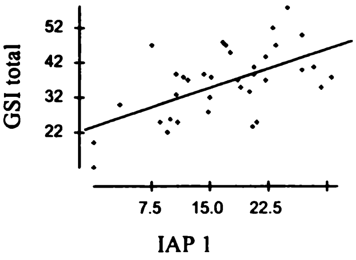

Fig. 7. GSI (total.) versus IAP 1; only plots with a distance < 13 km from SUMZ (R^2=31.8%)

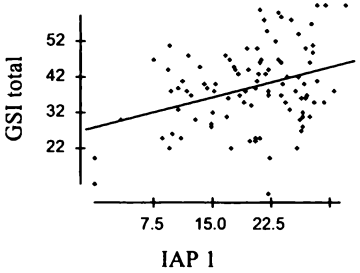

Fig. 8. GSI (total.) versus IAP 1 (R^2=10.7%)

atmospheric purity (IAP) revealed a higher correlation with the heavy metal contamination of the soil than with the GSI of the tree stands.

3. The heavy metal contents of *Hypogymnia physodes* showed a higher correlation with IAP parameters than with the GSI of the tree stands.

Low correlation between generalised state index values calculated by morphometric characteristics, and those calculated by physiological characteristics might indicate the complementary nature of the respective GSI parameters.

Anthropogenic air and soil pollution exert a detrimental effect on almost all forest sites located in the study area. Although a close dependence between the tree stand parameters, the epiphytic lichen community and the soil contamination was found close to the pollution centre, considerable differences were encountered at a longer distance from SUMZ. One possible explanation relates to the fact that it was often impossible to observe both lichen diversity and tree stand characterization in close vicinity. This might have reduced R^2 in the various regression analyses but was overcome in the cross correlation analysis of the spatially interpolated data. The second explanation is that at decreasing contamination levels both lichen diversity and tree stand characterization increasingly depend on the ecological heterogeneity of the study area. Because spatial ecological data such as precipitation, temperature or insolation were not available in a reasonablespatial resolution the influence from these factors could not be resolved during the project.

Table 1

Cross Correlation Coefficients for Different Characteristics of Tree Stands, Lichen Communities and Soils in the Area of Research

characteristics		GSI	GSI	GSI	GSI	lichen indices				metal content of soil					metal cont. of lich.		
		morph.	phys.	total	imp.	fl	iap1	iap2	iapavg.	Cu	Cd	Zn	Pb	sum.	Cu	Zn	Pb
GSI	morp.	1.00	0.12	0.84	0.35	0.50	0.52	0.52	0.53	-0.47	-0.36	-0.27	-0.31	-0.45	-0.51	-0.45	-0.32
GSI	phys.	0.12	1.00	0.59	0.13	0.09	0.23	0.24	0.24	-0.14	0.11	-0.14	-0.10	-0.07	-0.04	-0.02	-0.05
GSI	total	-	-	1.00	0.36	0.45	0.54	0.57	0.56	-0.43	-0.24	-0.14	-0.32	-0.39	-0.44	-0.35	-0.29
GSI	imp.	-	-	-	1.00	0.39	0.37	0.34	0.36	-	-	-	-	-	-	-	-
	fl	-	-	-	-	1.00	0.80	0.74	0.79	-0.72	-0.61	-0.53	-0.60	-0.74	-0.72	-0.76	-0.50
lich.	iap1	-	-	-	-	-	1.00	0.90	0.98	-0.72	-0.59	-0.45	0.59	0.72	-0.73	-0.66	-0.47
ind.	iap2	-	-	-	-	-	-	1.00	0.97	-0.64	-0.60	-0.45	-0.54	-0.66	-0.77	-0.65	-0.47
	iapav.	-	-	-	-	-	-	-	1.00	-0.70	-0.58	-0.46	-0.58	-0.71	-0.76	-0.67	-0.48
met.	Cu	-	-	-	-	-	-	-	-	1.00	0.62	0.52	0.80	0.95	0.62	0.66	0.44
cont.	Cd	-	-	-	-	-	-	-	-	-	1.00	0.95	0.72	-	0.77	0.74	0.53
in	Zn	-	-	-	-	-	-	-	-	-	-	1.00	0.68	-	0.66	0.63	0.48
soil	Pb	-	-	-	-	-	-	-	-	-	-	-	1.00	-	0.56	0.57	0.44
	Sum.	-	-	-	-	-	-	-	-	-	-	-	-	1.00	0.71	0.73	0.51
met.	Cu	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	0.92	0.68
cont.	Zn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	
in	Pb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00
lich.		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note. GSI - generalized state index; morph. - GSI calculated from morphometric characteristics of tree stands; phys. - GSI calculated from physiological characteristics; total - GSI calculated from morphometric and physiological parameters; imp. - GSI calculated from electric impedance of tree stems; fl - amount of lichen species, iap 1 - index of atmospheric purity determined at the base of tree stems; iap 2 - determined at the height 1,3 m; iap avg. - average value calculated from iap 1 and iap 2; sum. - index of summarized metal content.

The calculated levels of heavy metal pollution values compared with the standardized assessments of the diversity of epiphytic lichens in mature forests, and of the generalized state index GSI of artificial pine tree plantations revealed that both components of the complex ecosystem boreal forest are depressed at pollution levels lower than or equal to the official HHS values recommended for air pollution levels. Further, to the inherent interest of a forest monitoring per se, lichen bioindication and the morphophysiological tree stand characterisation as elaborated in this project may be promising and cost efficient approaches to monitor the environmental pollution in extended industrial areas.

LITERATURE

Adler U. N., Markova E. M., Granovskii U. V. Experiment Design in Seeking Optimum Conditions. Moscow. 1976. 278 P. (In Russian).

Kalinin V. A., Kriouk V. I., Luganskii N. A., Shavnin S.A. Model for assessing status of damaged tree stands // The Soviet Journal of Ecology. 1991.Vol. 3. P. 21 – 28.

Krivosheeva A.A., Shavnin S.A., Kalinin V.A., Venediktov P.S. Effect of industrial pollutants on seasonal changes of chlorophyll content in Scotch pine needles // Soviet Plant Physiology. 1991. Vol. 38. P. 126 – 130.

Shavnin S.A., Fomin A.S. Seasonal changes in the chlorophyll fluorescence of Scotch pine needles // Soviet Plant Physiol. 1993. Vol. 40. P. 176 – 180.

LeBlanc F., De Sloover J. (1970) Relation between industrialization and the distribution and growth of epiphytic lichens and mosses in Montreal // Canad. Jour. Bot. 1970. Vol. 48. P. 1485-1496.

Scheidegger. C. (1998). Lichen Bioindication and Morphophysiological Characterisation of Tree Stands for an Ecological Monitoring of Forests in Polluted Areas in the Middle Urals (Russia, Sverdlovsk Region). 1998. INTAS. Brussels.