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REVIEW

Air pollution in Slovakia (Central Europe): a story told by lichens (1960–2020)

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Abstract

Researches and applied lichenological studies carried out in Slovakia were reviewed, with reference to the period 1960–2020. Field studies and reviews devoted to the causal relation between environmental pollution and lichens are presented, encompassing the use of biodiversity and bioaccumulation techniques as well as ecophysiological parameters in native and transplanted lichens. The review includes pioneering up to recent monitoring studies of air pollution effects in urban and industrial areas, monitoring changes in species distribution between the nineteenth and twentieth centuries due to atmospheric pollution and habitat alteration, the retreat of sensitive species (with a focus on *Lobaria pulmonaria* (L.) Hoffm.), as well as recent regional and large-scale biomonitoring in forests. Beside urban pollution, the topics cover copper and mining activities, mercury pollution, magnesite and aluminium production, steel and cement industry. Finally, also indoor biomonitoring has been considered.

Keywords Bioaccumulation · Biomonitoring · Biodiversity · Heavy metals · Sulfur dioxide · Western Carpathians

Introduction

In the second half of the twentieth century the territory of Central Europe including Slovakia has been exposed to increased amounts of emissions, mainly SO_2, NO_x, heavy metals (e.g. copper, lead, cadmium), or fluorine compounds (Maňkovská et al. 2008, 2017; Lisowska 2011) respect to the first half of the twentieth century and it was known as the "Black Triangle II" (Maňkovská et al. 2008; Kolář et al. 2015). The emissions and subsequent air pollution resulted in negative impacts on human health and the environment, both at local and large scale. The concentrations of PM_{10} and $PM_{2.5}$ have been often exceeding the EU limit values also in recent periods (Anonymus 2020) and air pollution by PM_{10}, $PM_{2.5}$, as well as NO_2 has been the main problem of several urban areas in Slovakia (https://www.eea.europa.eu/themes/air/country-fact-sheets/2020-country-fact-sheets/slovakia).

However, emission trends in Slovakia have significantly changed since 1990s. Socio-political changes after 1989 resulted in a general decrease of emissions (Mladý 2019). Progressive air protection was introduced in 1991 by the Act No. 309/1991 Coll. on the environment, as amended and implemented. New environmental friendlier industrial technologies have been introduced and in agriculture sector livestock numbers decreased, more than 50% in cattle, swine and sheep (Mladý 2019). Decreasing trends of total emissions of SO_2, NO_X, NH_3 or $PM_{2.5}$ have been recorded, especially in 2000s (Anonymus 2020).

Monitoring air quality with lichens as well as monitoring lichens have been widely used across a broad scale of terrestrial habitats since William Nylander's time (Nylander 1866; Nimis et al. 2002; Abas 2021). Due to their anatomical, morphological as well as physiological traits, lichens respond to the atmospheric environment, including air quality, as they lack structures hampering the uptake of eventual contaminants.

This work provides an up to date overview on the studies connected with the use of lichens as indicators of air pollution effects in Slovakia and the recent history and problems of air pollution in Central Europe, with reference to the period 1960–2020. We selected field studies and reviews devoted to the effects of air pollution and habitat alteration on lichens,

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as well as the use of lichens for biomonitoring, which is the key concept of "monitoring lichens – monitoring with lichens" (Nimis et al. 2002), encompassing the topics of lichen biodiversity, bioaccumulation of heavy metals and ecophysiology.

Materials and methods

Overall, 50 papers have been deeply examined (Table 1). The results of the same study presented in several contexts (e.g., abstracts and short contributions of conference lectures or presentations) and research articles based on laboratory experiments were not included. The same stands for bioaccumulation studies that do not report the original values of measured concentrations of pollutants in the samples. Floristic studies and noteworthy records of species were included only when specifically referred to air pollution. The selected articles have been classified as follows (some of them have been assigned to more than one group).

Investigated topics – 5 categories:

I. 26 articles referred to industrial pollution sources, such as a magnesite factory (Blanár et al. 2019; Pišút and Pišút 2006; Pišút 1974, 1978), mining areas (Demková et al. 2019b), fertilizing plants (Jelínková 1973), metallurgic/steel works (Dzubaj et al. 2008; Bačkor et al. 2003; Lackovičová and Kontrišová 1998; Kontrišová and Lackovičová 1989), copper and mercury smelters (Banásová et al. 2010; Banásová and Lackovičová 2008; Banásová and Lackovičová 2004; Hadjúk and Lisická 1999; Lackovičová, 1995; Lackovičová et al. 1994; Lackovičová and Pišút 1992; Pišút 1984; Pišút 1962), superphosphate (Kaleta 1973) and aluminium works (Pišút and Lisická-Jelínková 1974; Pišút and Lányi 1972) and a cement factory (Paoli et al. 2014, 2015, 2016, 2017);

II. 12 articles included atmospheric pollution in urbanized areas (Paoli et al. 2019b; Demková et al. 2019a; Lackovičová et al. 2013; Guttová et al. 2011, 2013; Fačkovcová 2011; Dzubaj et al. 2008; Lackovičová et al. 2008; Bačkor et al. 2003; Holub and Lackovičová 1991; Lisická 1976; Hajdúk et al. 1975);

III. 6 studies focused on monitoring selected lichen species at local scale (Paoli et al. 2020; Hadjúk and Lisická 1999; Pišút 1986; Pišút and Lisická 1985; Pišút and Lisická 1985; Lackovičová 1981);

IV. 6 studies focused on selected lichen species at national/regional level (Pišút 1999; Pišút 1997; Liška and Pišút 1989; Pišút 1985; Pišút 1981; Pišút 1970);

V. 3 studies focused on monitoring epiphytic lichen diversity in forest sites over large areas (Guttová et al. 2017; Svoboda et al. 2010, 2011).

Type of study area (see Table 1 for references):

- 41 biomonitoring studies were carried out around local air pollution sources or areas;
- 9 studies focused on national/regional level or in any case, large areas.

From methodological point of view (methods used):

- 36 articles included a biodiversity assessment – diversity, distribution (see Table 1 for references);
- 17 articles reported a bioaccumulation study, carried out with native (Demková et al. 2019a; Paoli et al. 2014; Dzubaj et al. 2008; Pišút and Pišút 2006; Bačkor et al. 2003; Lackovičová et al. 1994; Kontrišová and Lackovičová 1989; Pišút 1978; Pišút 1974), or transplanted lichens (Paoli et al. 2020; Paoli et al. 2015, 2017, 2019b; Demková et al. 2019b; Guttová et al. 2011; Holub and Lackovičová 1991; Kaleta 1973);
- 11 articles included an assessment of thallus vitality, e.g., ecophysiological responses and/or anatomical/morphological and/or ultrastructural parameters by means of transplants (Paoli et al. 2020; Blanár et al. 2019; Paoli et al. 2015, 2016, 2019b; Lackovičová et al. 2013; Bačkor et al. 2003; Lackovičová 1981; Kaleta 1973), or native samples (Dzubaj et al. 2008; Lackovičová 1995).

The methodology for the assessment of air quality (and its effects) by lichens has been evolving. In the first studies, epiphytic lichen diversity as a proxy for air quality has been used for the calculation of the so-called Index of Atmospheric Purity (IAP) according Le Blanc and De Sloover (1970). The method was implemented and adapted in Slovakia by Pišút and Lisická-Jelínková (1974) and Lackovičová (1981) and was used to model air quality of the study areas. The following parameters were assigned to each of the recorded species: ecological factor Q (average number of accompanying species in the sampling plot), combined degree of abundance and vitality "f" (value 1 – scattered occurrence of several dying thalli or 1–2 normally developed thalli; value 3 – abundant occurrence of damaged thalli, or scattered occurrence of well-developed, healthy thalli; value 5 – abundant healthy thalli). This approach was applied in Pišút and Lisická-Jelínková (1974), Pišút (1974, 1978), Lackovičová (1981), Lackovičová and Kontrišová (1998), Pišút and Pišút (2006) and more recently in Guttová et al. (2013) and Paoli et al. (2014).

In recent studies (Guttová et al. 2017; Svoboda et al. 2010, 2011), the so-called Lichen Diversity Values (LDVs) were used following standard protocols (Asta et al. 2002). LDVs are calculated as the sum of frequencies of epiphytic lichens in a sampling grid consisting of four 50 × 10 cm^2 ladders, each divided into five 10 × 10 cm^2 units. The grid is placed

Table 1 The list of examined papers with details on the topic, type of the study and its goals, methods, time period and a summary of main findings. The number of topic category (I – V) refers to that given in Materials and Methods

References	Topic	Type of study and goals	Methods	Period	Main findings
Paoli et al. 2020	III: Monitoring lichen species	Local: selected sites in the Malé Karpaty Mts and Nízke Tatry Mts; investigating whether air pollution potentially limits the success of translocation where the species is actually extinct	Element concentrations (Al, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, S, Zn), ultrastructure and chlorophyll fluorescence emission in transplants of *Lobaria pulmonaria*.	12 months: between May – June 2016 and May – June 2017	The success of lichen translocation can be limited by current air pollution. This would suggest limitations in recolonization of beech forests by sensitive species, such as *L. pulmonaria*
Blanár et al. 2019	I: Industrial pollution: magnesite	Local: Slovenské rudohorie Mts; investigating how dust fallout from magnesite factories affects biodiversity and species composition of oak-hornbeam forests	Monitoring biodiversity (flowering plants, ferns, cyanobacteria, macromycetes, slime molds, briophytes and lichens) and environmental parameters (C, Ca, Mg, S, N, P, K in the soil, bark pH, light) along four degradation stages	2011–2016	Concerning lichens, the occurrence of nitrophilous epiphytic species differentiates unaffected oak-hornbeam woodlands from the plots close to the sources of alkaline dust
Paoli et al. 2019b	II:	Indoor/outdoor pollution in urban and rural areas	Local: Bratislava and Madunice; investigating the contribution of outdoor pollution by heavy metals to indoor air quality	Element concentrations (Al, As, Ca, Cd, Cr, Cu, Fe, Pb, S, Sb, V, Zn) by ICP-MS and chlorophyll *a* fluorescence emission in lichen transplants (*Evernia prunastri*)	2 months: between October and December 2017
Higher outdoor concentrations in the urban area, indoor concentrations were overall similar. An indoor uptake occurred for traffic related elements (Cd, Cu and Pb)					
Demková et al. 2019a	II: Urban environment	Local: Prešov; investigating dust depositions in nine streets with various traffic, comparing the accumulation capacity of different lichens	Element concentrations (Al, As, Ba, Cd, Cr, Cu, Fe, Li, Mn, Ni, Pb, Zn) by ICP-OES in native *Phaeophyscia orbicularis, Physcia adscendens, Xanthoria parietina*	2 campaigns: June and September 2017	Significant uptake of Cr, Fe, Ni, Pb and Zn due to traffic emissions. Higher element concentrations were reported in *P. orbicularis*
Demková et al. 2019b	I: Industrial pollution: mining area	Local: former mining area of Dubník (Eastern Slovakia); investigating the complex impact of open mining pits and heaps of waste material	Element concentrations (As, Cd, Cu, Fe, Mn, Ni, Sb, Pb, Zn) by ICP-OES in moss and lichen bags (*Hypogymnia physodes*) and in topsoil (together with soil enzymes)	6 weeks: transplants started in summer 2018	The investigated sites were considered as moderately up to extremely polluted, especially in correspondence of the heaps of waste material
				2004–2006	

Table 1 (continued)

References	Topic	Type of study and goals	Methods	Period	Main findings
Guttová et al. 2017	V: Large scale monitoring	National: 29 sites in oak forests; investigating the influence of air pollution and forest management on lichen communities	Biodiversity: Lichen Diversity Values (LDVs), functional and morphological traits		Higher share of fruticose lichens in semi-natural/ natural stands and of pioneer and tolerant species in managed stands
Paoli et al. 2017	I: Industrial pollution: cement mill	Local: Rohožník; assessing magnetic properties in relation to depositions around a cement mill, quarries, in rural and urban sites; assessing temporal changes of depositions	Element concentrations (by ICP-MS or ICP-OES) and magnetic properties in lichen transplants (*E. prunastri*). Comparison with native samples (*X. parietina*)	6 months: July 2011 – January 2012	Rock mineralogy influenced deposition and magnetic properties of lichens. Airborne pollutants progressively increased. Investigating magnetic parameters contributed to source apportionment.
Paoli et al. 2016	I: Industrial pollution: cement mill	Local: Rohožník; assessing ultrastructural damages and the vitality of lichens exposed to dust depositions	Ecophysiological parameters (chlorophyll *a* fluorescence, TBARS, water soluble proteins, dehydrogenase) and ultrastructure (TEM) in transplants of the cyanolichen *Peltigera praetextata*. Comparison with green algal lichens *E. prunastri* and *X. parietina*	6 months: July 2011 – January 2012	*P. praetextata* underwent remarkable changes due to microclimatic conditions, *E. prunastri* was very sensitive to dust and *X. parietina* was the most tolerant
Paoli et al. 2015	I: Industrial pollution: cement mill	Local: Rohožník; assessing the effects of dust pollution on the ecophysiology and ultrastructure of lichens; investigating overall depositions in transplants	Bioaccumulation (Al, As, Ca, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, S, Ti, V, Zn) by ICP-MS or ICP-OES in *E. prunastri*; ultrastructural (TEM) and physiological parameters (chlorophyll *a* fluorescence emission, dehydrogenase activity) in *E. prunastri* and *X. parietina*	6 months: July 2011 – January 2012	Dust deposition led to ultrastructural alterations, including lipid droplets increase, swelling of cellular components, thylakoids degeneration, plasmolysis. The cells showed an aged appearance, especially in *E. prunastri.* A calculated Pollution Load Index (PLI) was higher around the quarries
Paoli et al. 2014	I: Industrial pollution: cement mill	Local: Rohožník; assessing the impact of dust pollution on lichen diversity and element deposition during cement production	Lichen Diversity (modified IAP) and bioaccumulation (Al, As, Ca, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, S, Ti, V, Zn by ICP-MS or ICP-OES) in native *X. parietina*	2011	Lichen communities shifted from acidophilous-oligotrophic (natural condition) toward basi-nitrophilous approaching the sources of dust. Native lichens were enriched in Ca, Ti, Fe, V, Al and Ni around the cement plant and the quarries
Guttová et al. 2013	II: Urban environment	Local: Spišská Nová Ves; assessment of environmental quality based on epiphytic lichen diversity as a proxy	Biodiverstiy by Index of Atmospheric Purity (IAP); zonation of study area based on environmental quality (Regularized Spline with Tension approach)	2008–2009	Epiphytic lichen diversity in the town is low, with dominating nitrophytic species and generalists. The study area was divided in three zones: low (IAP 6.1–9), moderate (IAP 3.1–6) and high air pollution (IAP 0.2–3) corresponding to the major socio-economic settings as well as natural features.

Table 1 (continued)

References	Topic	Type of study and goals	Methods	Period	Main findings
Lackovičová et al. 2013	II: Urban environment	Local: Bratislava; investigating whether air quality still limits the distribution of sensitive lichen species	Ecophysiological parameters: chlorophylls content and degradation, cortical and medullar metabolites and soluble proteins in transplanted (wooden frame) *E. prunastri.* Comparison with air quality reflected by total epiphytic lichen diversity	6 months: December 2008 – May 2009	*E. prunastri* is recolonizing sites with lower eutrophication in Bratislava, as also depicted by lichen diversity. Transplants were not affected after 6 months, except in eutrophicated (NO_x) sites
Fačkovcová 2011	II: Urban environment	Local: Piešťany town; investigating changes of epiphytic flora	Biodiversity: occurrence, abundance and vitality of epiphytic lichens; comparison with previous survey (1936)	2010	Impoverishment of sensitive species recorded from the past (*Ramalina fraxinea, Anaptychia ciliaris*), recolonization mostly by nitrophilous species and only occasionally by oligotrophic ones (*Pleurosticta acetabulum*)
Guttová et al. 2011	II: Urban environment	Local: Bratislava; assessing bioaccumulation of trace elements under a decreased load of air pollution; comparing the accumulation capacity of different species	Bioaccumulation (Cu, Cd, Cr, Mn, Ni, Pb, Zn by AAS) in transplants (lichen bags) of *E. prunastri*, *H. physodes, Parmelia sulcata*	3 months: December 2006 –February 2007	Lichens reflected a significant decrease of air pollution with respect to previous studies and chemical data prior to 1989. Exposed to Control ratios indicated that *E. prunastri* was the most efficient accumulator
Svoboda et al. 2011	V: Large scale monitoring	Regional: 48 oak stands in Central Europe (Czech Republic, Slovakia and Hungary); see below	Deeper analysis of the relevés collected in Svoboda et al. 2010	Not specified	Characterization of the main lichen communities in oak forests and of the indicator species for natural old stands
Svoboda et al. 2010	V: Large scale monitoring	Regional: 48 oak stands in Central Europe (Czech Republic, Slovakia and Hungary); investigating the interaction between anthropogenic pressures and lichen diversity	Biodiversity by Lichen Diversity Values (LDV); four oaks in each locality were investigated	Not specified	Air pollution, forest fragmentation and age were identified as the main anthropogenic factors affecting epiphytic lichen diversity
Banásová et al. 2010	I: Industrial pollution: copper	Local: Krompachy; long-term monitoring of vascular plant, bryophytes and li-chens	review of biomonitoring studies with plants and lichens and new data presented	Reference period 1989–2009	Improvement in plant and lichen diversity during recent air pollution history, from culmination (1989–1992), decrease (1993–2003) up to 2009
Dzubaj et al. 2008	I/II: Urban environment; industrial pollution: steel	Local: Košice; investigating bioaccumulation of heavy metals and tolerance in the lichen *X. parietina*	Bioaccumulation (Al, Cd, Cu, Fe, Mn, Pb, Sb and Zn, by AAS) and ecophysiological parameters (content of photosynthetic pigments and parietin, chlorophyll *a* fluorescence emission, TBARS and CO_2 gas exchange) in native *X. parietina*	Autumn 2005	Metal accumulation highlighted the contribution from pollution sources in Košice (steel factory and traffic). The lack of correlations between metal content and physiological damages reflected a high degree of pollution tolerance in *X. parietina*
Banásová and Lackovičová 2008	I: Industrial pollution sources	Local: Krompachy and Rudňany; long term biomonitoring with plants and lichens	Review of previous surveys (1987, 1991, 2003) and new biodiversity survey in 2007	2007	Recent positive changes (2007) in the environment, consisting in increase of species diversity and cover for vascular plants and

Table 1 (continued)

References	Topic	Type of study and goals	Methods	Period	Main findings
					cryptogams and beginning of secondary succession
Lackovičová et al. 2008	II: Urban environment	Local: Bratislava; review of previous works and new data on air quality improvements from lichen monitoring	Counting of total diversity and occurrence of epiphytic lichens in standard trees in 89 monitoring stations	2006–2007	Lichens detected positive changes in environmental conditions in Bratislava
Pišút and Pišút 2006	I: Industrial pollution: magnesite	Local: Jelšava (SE Slovakia); assessing temporal changes in dust pollution after technological improvements in the period 1973–2004	Biodiversity: temporal changes in lichen communities (IAP method); bioaccumulation of Mg in (in situ) *X. parietina* and assessment of bark pH	2003–2004, comparison with data collected in 1973 (Pišút 1974, 1978)	Decrease of Mg deposition, lichen recolonization by nitrophilous species and occasionally by oligotrophic sensitive lichens
Banásová and Lackovičová 2004	I: Industrial pollution: copper	Local: Krompachy; monitoring the impact of the local copper plant on grasslands and epigeic lichens	Phytosociological relevés along a gradient of distance from the plant; analysis of As, Cu, Pb and Zn in soil	1987–1993 and 2003	Increase of species diversity and cover for some epigeic lichens, improvements of air quality, soil still contaminated
Bačkor et al. 2003	I/II: Urban environment; industrial pollution: steel	Local: Košice; biomonitoring of air pollution effects in the urban area and in relation to the presence of a steel factory	Bioaccumulation (EDX-microanalysis) in various native lichens; eco-physiological parameters (chlorophyll content and degradation) in transplanted *H. physodes;* biodiversity assessment	16 weeks: October 2000 – February 2001	Lichen diverstity increased with the distance from the city centre; accumulation of Ca, Fe, S and a diffused chlorophyll degradation were measured especially close to steel factory and city centre
Pišút 1999	IV: Monitoring lichen species	National; mapping the distribution of common and rare species between 1970 and 1981	Field research for the presence of lichens over 372 quadrants of approximately 135 km^2 and a literature review from 1970	1970–1981	Distributional maps of about 180 epiphytic lichens over the whole territory of Slovakia
Hadjúk and Lisická 1999	I/III: Industrial pollution: copper; monitoring selected species	Local: Krompachy; monitoring epigeic species around the local copper smelter	Assessing the distribution of the fruticose lichen *Cladonia rei* in habitats affected by airborne heavy metals and SO_2	August 1998	*C. rei* was found to grow (together with the moss *Ceratodon purpureum*) in highly contaminated soils and evaluated as a very tolerant species
Lackovičová and Kontrišová 1998	I: Industrial pollution: metallurgy	Local: Orava region; assessment of air pollution effects around metallurgic factories	Biodiversity: IAP methods	1985–1986	Zonation of areas: from highly impacted close to the factories (high metals accumulation, average no. of lichens per station=1.7) up to relatively not impacted (average no. of lichens > 4)
Pišút 1997	IV: Monitoring lichen species	National; mapping the distribution of common and rare species	Revision of herbarium specimens, summary of published records and field research	Until 1997	The article refers the retreat of numerous epiphytic lichens (from 423 known species to about 200 in 1997), expansion of few acidophilous tolerant species enhanced by the acidity of the barks caused by SO_2 pollution
Lackovičová 1995	I: Industrial pollution: copper	Local: Krompachy region; mapping epiphytic lichen diversity in relation to airborne pollutants	Occurrence, abundance and vitality of epiphytic lichens	Between 1980 and 1990	Absence of fruticose and foliose epiphytic species within a radius of about 2 km from the smelter. Only three toxitolerant crustose species occasionally occurring within such area

Table 1 (continued)

References	Topic	Type of study and goals	Methods	Period	Main findings
Lackovičová et al. 1994	I: Industrial pollution sources	Local: Spišská Nová Ves and smelters in Rudňany (Hg) and Krompachy (Cu) area	Bioccumulation of As, Cd, Cu, Hg, Pb, Zn (by AAS) in the lichen *H. physodes*(native) and spruce needles.	July 1991	Very high environmental contamination by As and Hg, as shown by the plant and lichen material analysed (especially in Rudňany)
Lackovičová and Pišút 1992	I: Industrial pollution sources	Local: Spišská Nová Ves, Rudňany and Krompachy; assessing the level of acidification and changes in lichen biota in polluted area	Biodiversity: frequency of epiphytic lichens on 400 trees (study area of 720 km^2). Measuring pH in *H. physodes*, barks and needles of conifers. Detection of F in barks of beech and spruce	Not specified	Poor lichen diversity with predominance of acidophilous species. The substrates were overall acidified. Fluoride levels were higher in Rudňany than in Krompachy
Holub and Lackovičová 1991	II: Urban environment	Local: Bratislava; testing biological methods to detect urban and industrial pollution	Bioaccumulation (Cd, F, Pb, S) in transplanted (bags) lichens (*H. physodes*) and mosses (*Sphagnum capillifolium*), leaves of spontaneous ruderal species (*Artemisia vulgaris*); growth of pot plants (*Fagopyrum esculentum*)	Transplants: 3–6 months during 1989	The study outlined the influence of multiple sources of pollution on element depositions (traffic, waste incinerator, glasswork, chemical and fossil fuel plants, petrochemical refinery, rubber production)
Liška and Pišút 1989	IV: Monitoring lichen species	Regional: Czech Republic, Slovakia; overview on lichen mapping over large spatio-temporal scales	Mapping the distribution of common and rare species and focus on threatened epiphytic lichens e.g., *L. pulmonaria*	Up tp 1989	The article highlights the importance of large scale monitoring of both rare and common species to assess the effects of environmental changes
Kontrišová and Lackovičová 1989	I: Industrial pollution: metallurgy	Local: Orava region; assessment of air pollution level around metallurgic factories	Bioaccumulation in native lichens (*H. physodes*), plants and mosses. Biodiversity: occurrence and abundance of epiphytic lichens	1985–1986	High heavy metals content in target organisms especially around two main metallurgic factories, zonation of the area according to the impact
Pišút 1986	III: Monitoring lichen species	Local: surroundings of Bratislava; investigating changes of lichen flora	Biodiversity: repeated survey of saxicolous and epiphytic species on the same naturalistic paths	1960, 1984	Disappearance of sensitive lichens and their substitution by more acidophilous ones
Pišút and Lisická 1985	III: Monitoring lichen species	Local: surroundings of Bratislava; investigating changes of epiphytic flora	Biodiversity: repeated survey on the same tree trunk (*Quercus robur*) by means of a sampling net consisting of 312 quadrats (each ca. 175 cm^2)	1973, 1975, 1981, 1983	Negative variations of epiphytic lichens over time: *Lecanora chlarotera* disappeared, foliose and fruticose species were reduced (*Parmelina tiliacea, Parmelia glabratula, E. prunastri*). Lichens were partially substituted by green algae and mosses
Pišút and Liška 1985	III: Monitoring lichen species	Local: Slanské vrchy Mts (East Slovakia); lichen diversity assessment and evaluation of temporal changes in different substrates.	Monitoring of species presence over 37 localities across the mountain range	1977–1982	Comparison with former literature data. Significant decrease of epiphytic species
Pišút 1985	IV: Monitoring lichen species	National; description of the distribution of selected species until 1970 and the situation between 1970 and 1981	Biodiversity: part of the field research for the presence of lichens over 372 quadrants over the whole territory of Slovakia	until 1981	Distributional maps of *H. physodes, Lecanora conizaeoides, Lobaria amplissima, L. pulmonaria, Menegazzia terebrata, Parmelia contorta,*

Table 1 (continued)

References	Topic	Type of study and goals	Methods	Period	Main findings
					Porricondyla quercina, Ramalina farinacea, R. fraxinea and Scoliciosporum chlorococcum
Pišút 1984	I: Industrial pollution sources	Local: Rudňany; assessing the effects of air pollution (SO_2 and Hg) by means of epiphytic lichens	Biodiversity: Braun-Blanquet method with epiphytic lichens, 185 trees investigated along three main transects. Repetition of the study carried out in 1960	1982	Higher extension of the heavily polluted area respect to 1960. Spreading of acidophilous tolerant lichens, retreat (or loss) of fruticose and foliose SO_2 sensitive species
Lackovičová 1981	III: Urban environment, forest habitats	Local: Bratislava and Malé Karpaty mountains; biomonitoring of air pollution effects	Biodiversity (IAP method) and anatomical features in transplants of *H. physodes* (alteration of the surface of the thallus)	Transplants in 1973 (3 months)	Scarse presence of epiphytic lichens in the area of Bratislava and its immediate surroundings in the 1980's, due to air pollution. Biodiversity increases in Malé Karpaty Mts, in parallel with the distance from the polluted area. In transplants exposed in Bratislava, 95% of the surfaces were altered
Pišút 1981	IV: Monitoring lichen species	Regional: Czechoslovakia; brief review concerning the reasons for lichen decline	Literature review and an overview (opinion paper) by Ivan Pišút concerning lichen decline in Czechoslovakia	Up to 1981	The study outlined the multiple sources of alteration for lichens in certain areas of Czechoslovakia
Pišút 1978	I: Industrial pollution: magnesite	Local: Teplá Voda, Jelšava (SE Slovakia); assessing the spatial impact of Mg emissions from a magnesite factory	Biodiversity: IAP method; Bioaccumulation of Mg in (in situ) *X. parietina*; monitoring of bark pH	1973–1974	Zonation of IAP values: lichen-desert in sites exposed to the highest Mg deposition from magnesite works, increase of alkalinity
Lisická 1976	II: Urban and Industrial pollution	Local: Stupava; assessing the effects of air pollution on lichen diversity and comparison with parks in Bratislava	Biodiversity: review of studies on the effects of air pollutants on vegetation; occurrence of epiphytic species in Stupava park	Not specified	Negative impact of several pollutants on vegetation; from 40 up to 90% more lichens found in Stupava park respect to urban parks in Bratislava
Hajdúk et al. 1975	II: Urban and industrial pollution	Local: Bratislava and its surrounding (Rusovce); assessing the effects of emissions on lichen diversity	Biodiversity: occurrence of epiphytic species in town parks	Not specified	Scarse presence of epiphytic lichens in Bratislava town parks with dominance of acidophilous crustose and absence of fruticose species. In Rusovce park, higher abundance of foliose species with occasional occurrence of fruticose
Pišút 1974	I: Industrial pollution: magnesite	Local: Lubeník, Jelšava (SE Slovakia); assessing the spatial impact of Mg emissions from a magnesite factory	Biodiversity: IAP method; Bioaccumulation of Mg in (in situ) *X. parietina*; monitoring of bark pH	1973	Zonation of IAP values: lichen-desert in sites exposed to the highest Mg depositions from magnesite works and increase of alkalinity
Pišút and Lisická-Jelínková 1974	I: Industrial pollution: aluminium	Local: Žiar nad Hronom; assessing the impact of an aluminium factory on lichens	Biodiversity: IAP method	1973	Impoverishment of epiphytic lichen biota and injuries depended on the reliefs and prevailing winds. Three zones of impact were detected: „lichen desert",

Table 1 (continued)

References	Topic	Type of study and goals	Methods	Period	Main findings
					transient zone and less impacted zone
Kaleta 1973	I: Industrial pollution	Local: Bratislava; assessing the effect of air pollution around a superphosphate factory with lichens	Visual assessment of damage and detection of F accumulated in 150 transplants of *H. physodes* and bark on eight localities in Bratislava	Transplants from 27.10.1971 to 13.1.1972	The transplants showed a fast degradation (visible signs of damage) and higher accumulation of F (levels up to 4.8 mg/g) in the most impacted sites Higher F values in lichen than in bark
Jelínková 1973	I: Industrial pollution: fertilizing plant	Local: Duslo Šaľa (Central-Western Slovakia); assessing the effects of emissions on lichen diversity	Biodiversity: presence and abundance of epiphytic species	1968–1970	Three zones of impact of could be identified, the impact extending over several kilometers, before a normal lichen vegetation could develop
Pišút and Lányi 1972	I: Industrial pollution: aluminium	Local: Kremnica, about 16 km from the factory in Žiar nad Hronom	Biodiversity: floristic survey	1964–1970	Local lichen communities at that time were rather rich. Negligible impact of air pollution
Pišút 1970	IV: Monitoring lichen species	National; Investigating the retreat of endangered species (e.g., *L. pulmonaria*) due to anthropization	Biodiversity: revision of herbarium specimens, published records and field research	Reference period 1791–1970	Progressive decrease of colonized localities, shift to remote and higher mountain regions. Intensive forest logging, agriculture and heavy industrial pollution threatened the species
Pišút 1962	I: Industrial pollution sources	Local: Rudňany; assessing the effects of air pollution (SO_2 and Hg) on the lichen biota	Biodiversity: occurrence of lichens (epilithic, epigeic, epiphytic) based on Braun-Blanquet method along transects (with intervals 20–50 m) and target sites	1960–1961	Lichen diversity decreases approaching the local smelter. Zonation of the area (three zones) according to the impact of air pollution

systematically on the N, E, S and W cardinal sides of the bole of each tree, 1 m above the ground. The LDV of each tree corresponds to the sum of frequencies of epiphytic lichens in the grid and the LDV of each monitoring site was the arithmetic mean of the LDV measured for each sampled tree (Asta et al. 2002; CEN 2014).

Results and discussion

Urban pollution

A first observation about the retreat of sensitive lichens caused by urban pollution in Slovakia dates back to 1905, when Zahlbruckner reported the disappearance of *Lobaria pulmonaria* (L.) Hoffm. and *Ramalina fraxinea* (L.) Ach. from the outskirts of Bratislava (Zahlbruckner 1905). Slovakia is located at the south eastern margin of one of the most polluted areas in Central Europe and till the 1980s, air pollution from sulfur dioxide and heavy metals dramatically affected air quality in all Central European urban areas. In Bratislava, up to 62 400 tons of airborne pollutants were emitted in 1985 (43 745 of which consisting of SO_2) by numerous pollution sources, including a waste incinerator, glass-works, chemical and fossil fuel plants, a petrochemical refinery, rubber production, car traffic, heating systems, which on the whole released a mixture of toxic heavy metals in the atmosphere (Závodský 2007). According to Babušík et al. (1988) the worst situation concerning atmospheric SO_2 in Bratislava was observed in 1975 (67 $\mu g/m^3$ yearly average). For a comparison, in 2019, after a decreasing trend over recent years, SO_2 concentrations in ambient air of Bratislava corresponded to a yearly average of 5.3 $\mu g/m^3$ (Krajčovičová et al. 2020). During the period 1987–1991 the mean daily concentrations of SO_2 in Bratislava exceeded the upper recommended limit according to the air quality guidelines for Slovakia in 14% of cases (Bachárová et al. 1996). In the 1980s, the first restrictions to the release of airborne pollutants in Bratislava were introduced and utilization of coal for heating was replaced by gas. Vehicular traffic became the principal problem linked to air quality (Závodský 2007). An increase of pH (measured in precipitation) from 4.19 (1980) to 4.51 (1989) was registered (Lackovičová and Kontrišová 1996 , with the highest acidity corresponding to elevated sites or close to the main sources of pollution.

The use of plants and lichens as bioaccumulators (Holub and Lackovičová 1991) and of the diversity of epiphytic lichens as indicator (Lackovičová 1981) witnessed the impact of the main pollution sources. In the 1970s and the 1980s a large lichen desert (complete absence of lichens) was present in the urban/industrial area of Bratislava (Lackovičová 1981; Pišút 2000). The situation was similar in the municipal outskirts: Lackovičová (1981) reported an impoverishment of the lichen flora in chestnut trees at the edge of the Western Carpathians by 90% in about 80 years. A scarce presence of epiphytic lichens in Bratislava and its immediate surroundings was related to the poor air quality: biodiversity increased only in some parts of the Malé Karpaty Mts (the borders of the Western Carpathians), positively correlated with the distance from the polluted industrialized zone (Lackovičová 1981). In 1973, Lackovičová (1981) carried out a transplant experiment and found out that up to 95% of the surface of the lichen *Hypogymnia physodes* (L.) Nyl. taken from a clean control area was damaged after three months of exposure in Bratislava.

The diversity of epiphytic lichens was studied in urban parks in Bratislava and its surroundings (Rusovce and Stupava) by Hajdúk et al. (1975) and Lisická (1976). The latter study was also connected to dust emissions from a local cement factory in Stupava (closed later in 1980s; Závodský 2007). Parks in the outskirts of the town were much more colonized by epiphytic lichens (foliose and fruticose species) than urban parks in the centre of Bratislava, where fruticose lichens were completely missing and bark of local trees was colonized predominantly by crustose lichens, under the evident influence of sulfur emissions. Noteworthy is that, Lisická (1976) reported an increase of species from 40 up to 90% in the surroundings (namely, the park in Stupava) respect to urban parks in Bratislava (Hajdúk et al. 1975) and the absence of toxitolerant acidophilous species, such as *Lecanora conizaeoides* Nyl. ex Crombie, typically abundantly present in sulphur-rich environments, such the centre of Bratislava at that time.

In 1989, political, socio-economic and legislative changes led to a radical decrease of emissions, particularly visible in the urban area of Bratislava. After retreat during the peak of SO_2 pollution in Central Europe (1950–1990), in the 1990s epiphytic lichens started to recolonize lichen-desert areas of the town (Pišút 2000). Lackovičová et al. (2008) reported the presence of 61 lichen taxa on 215 monitored trees, with a lower diversity close to an oil refinery, an incinerator and the city centre (0–4 species per tree), while higher diversity (> 7 species per tree) was observed in the outskirts of the town. Recolonization was dominated by nowadays common nitrophilous lichens, such as *Physcia adscendens* (Fr.) H. Olivier, *Xanthoria parietina* (L.) Th. Fr., *Phaeophyscia nigricans* (Flörke) Moberg, while oligotrophic sensitive species were still scanty or in some cases considered as locally extinct. More sensitive species, such as the fruticose lichen *Evernia prunastri* (L.) Ach. re-appeared in sites with lower eutrophication, keeping a vital physiological status also when transplanted for six months in the urban area (Lackovičová et al. 2013). In 2007, a study with transplants of the lichens *E. prunastri*, *H. physodes* and *Parmelia sulcata* Taylor confirmed a significant decline of heavy metal pollution (Cu, Cd, Cr, Mn, Ni, Pb and Zn) with respect to the period prior to 1990 (Guttová et al. 2011).

Lichen community changes over years were also reported from urban environments of smaller towns which are not in the vicinity of large emission sources. For example, Pišút (1981) pointed out an impoverishment of the epiphytic lichen flora in parks of spa town Piešťany, from 27 epiphytic species in 1936 (Suza 1936 , 1948) up to 15 species in 1976. Sensitive species, such as *Anaptychia ciliaris* (L.) Flot., *Melanelixia glabra* (Schaer.) O. Blanco, A. Crespo, Divakar, Essl., D. Hawksw. & Lumbsch or *R. fraxinea*, were lost. Despite a recent survey in 2010 revealed the presence of 32 species, the recolonization of the most sensitive ones did not occur (Fačkovcová 2011).

Biomonitoring of air pollution with lichens in other towns of Slovakia has started more recently. Bačkor et al. (2003) investigated air pollution effects in Košice (the second largest town in Slovakia, about 236,000 inhabitants): the diversity of epiphytic lichens, the accumulation of selected elements in native lichens and bark samples (by EDX-microanalysis), and the level of chlorophyll degradation (as reflected by OD_{435}/OD_{415} ratio) in transplants of the lichen *H. physodes* were used as indicators in order to characterize the impact and the chemical nature of emissions, also in relation to the presence of important steel works in the area. The results highlighted the absence of a lichen desert, but a limited biodiversity, which increased with the distance from the city centre and the steel works (on the whole 17 epiphytic species were found). The majority of recorded lichens were common (Pišút 1999), however, noteworthy was the presence of species considered pollution sensitive and "vulnerable" in Slovakia, e.g., *E. prunastri*, *Flavoparmelia caperata* (L.) Hale, *Parmelina tiliacea* (Hoffm.) Hale and *Vulpicida pinastri* (Scop.) J.-E. Mattsson & M. J. Lai (Pišút et al. 1998; Guttová et al. 2013). Coherently with biodiversity, ecophysiological parameters in the transplants indicated a diffused reduction of chlorophyll *a* content paralleled by chlorophyll degradation, especially close to the steel factory and the city centre. A higher uptake of several elements, including Ca, Fe and S was measured in native lichens harvested close to the steel factory (Bačkor et al. 2003).

In the town of Prešov (the third largest city in Slovakia), Demková et al. (2019a) investigated dust depositions in native lichen thalli along nine streets characterized by different traffic intensity and reported a relevant contamination by heavy metals (Cr, Fe, Ni, Pb and Zn). Prešov, with more than 94 000 inhabitants, has experienced a significant increase of traffic in recent years, furthermore, the lack of a traffic bypass increased traffic problems in the centre and lead to a worsening of air quality. In fact, element concentrations in *Phaeophyscia orbicularis* (Neck.) Moberg and *P. adscendens* revealed very high peaks, in particular concerning As, Ba, Cr, Fe, Mn, Pb and Zn.

Industrial pollution

Between 1960 and 1961 a lichen monitoring was carried out around the mercury smelter in Rudňany (North-East Slovakia) to assess the effects of airborne pollutants (especially SO_2 and Hg) in the environment (Pišút 1962). This research can be considered as the first biomonitoring study specifically devoted to the assessment of air pollution effects using lichens in Slovakia (epilithic, epigeic and epiphytic, based on Braun-Blanquet method). An increasing diversity of lichen species was observed with the distance from the local source of pollution and a zonation of the area into three zones of impact was reported. Negative effects of pollution were clearly detected in the distribution of selected foliose epiphytic species approaching the smelter (e.g., *Xanthoparmelia conspersa* (Ehrh. ex Ach.) Hale, *P. sulcata*, *H. physodes*, *X. parietina*). About 20 years later, Pišút (1984) carried out another monitoring study in the same area, focusing on epiphytic lichens. On the whole, 185 trees were investigated along three sampling transects. Thirty-two lichen species were recorded, many of them were scarcely distributed and the thalli appeared damaged. In comparison with the previous period, when a heavy disturbance was identified already within 4 km from the smelter in Rudňany, 20 years later the heavily impacted zone enlarged especially in northeast direction (at least up to 9 km), where it was connected with the polluted areas from nearby factories from Spišská Nová Ves and Krompachy. In fact, increasing emissions from newly built factories with higher productivity and also a new 200 m high smokestack in Krompachy, spread pollutants over a larger area. The strong effect of increasing amounts of SO_2 and acidification of the substrata was evident also in changes of the lichen biota. Numerous species (mainly foliose and fruticose lichens, such as *Usnea* sp., *Parmelina tiliacea*, *Platismatia glauca* (L.) W. L. Culb. & C. F. Culb.), which were present in the past, were not recorded again in 1982. The boundaries of the most impacted area, where only few foliose species appeared (*H. physodes* and *P. sulcata*), were further shifted from the smelter and were accompanied by the spreading of SO_2 tolerant acidophilous lichens, such as *L. conizaeoides* (which was rare in 1960, but one of the most abundant in 1982), *Scoliciosporum chlorococcum* (Stenh.) Vězda, *Lepraria incana* (L.) Ach., *Hypocenomyce scalaris* (Ach. ex Lilj.) M. Choisy (Pišút 1984).

In 1991, Lackovičová and Pišút carried out a field sampling of native *H. physodes* and spruce needles to investigate atmospheric pollution by heavy metals in the Spiš region, between Spišská Nová Ves and the smelters in Rudňany and Krompachy (Lackovičová et al. 1994), an area still widely contaminated by SO_2 and heavy metals. It was the first study reporting Hg concentrations in lichens in Slovakia: extremely high values (6.19 ppm) were measured about 5.5 km SE from the pollution source in Rudňany (with high concentrations, 0.5 ppm, also in control sites) and extremes of As (2.35 ppm) were measured at about 6 km SW from the source. Noteworthy, normally developed thalli of *H. physodes* could not grow closer than 4.2 km from Rudňany. Those (high) concentrations of Hg reported in lichens (and also in spruce needles) allowed hypothesizing that Hg emissions in Rudňany at the time were much more extended than depicted by values officially declared. Other works in spruce forests southward from Rudňany and Krompachy by Maňkovská (1984) and Maňkovská et al. (1989) highlighted the extension of heavy metal pollution affecting the area and a comparison with those few data available at the time from smelters in the Orava region (North Slovakia; Kontrišová and Lackovičová 1989) revealed that the Spiš region was much more polluted, especially by Cu and Zn. Long-range transportation of pollutants from the areas of Krompachy and Košice were even considered as a possible cause for the impoverishment of the lichen flora in remote areas such as Slanské vrchy Mts (about 40 km away), as suggested by Pišút and Lisická (1985), based on the observation of the diffusion of acidophilous toxitolerant species (such as *L. conizaeoides*) and decrease of air pollution sensitive ones.

Concerning the diversity of lichens, Lackovičová and Pišút (1992) mapped the distribution of epiphytic lichens over 400 trees (the phorophytes were mainly conifers) in the area. A total of 39 lichen taxa were identified. Compared to the past, the condition of the epiphytic lichen flora was clearly poor (Lackovičová and Pišút 1992). However, more than ten years later Banásová and Lackovičová et al. (2008) reported an improvement of environmental conditions and positive effects on plant and lichen communities around the smelters in Rudňany and Krompachy.

Between 1971 and 1972, Kaleta (1973) carried out 150 transplants of *H. physodes* and relative bark samples (*Pinus sylvestris*) in eight localities in the eastern part of Bratislava, including a superphosphate factory. Such type of factories usually released to the environment high amounts of SO_2 and fluoride (F). A visual assessment of the damage endured by the transplants and the analysis of F accumulated in lichen and bark samples after 3 months revealed the impact of industrial pollution in Bratislava. In particular, the transplants showed a fast degradation (visible signs of damage) and higher accumulation of F (levels up to 4.8 mg/g) in the most impacted sites. The amount of F was generally higher in the lichen respect to the bark (Kaleta 1973).

Jelínková (1973) investigated the effects of emissions from the chemical fertilizing plant operating since 1958 in Duslo Šaľa (Central-Western Slovakia) and reported a zonation of epiphytic lichen vegetation, which appeared clearly susceptible to the airborne emissions from the factory. Three main zones were identified according to the distance from the factory: the first, characterized by visibly damaged thalli grown in the vicinity of the facility; the second by the appearance of foliose (*Parmelia*) species, which were missing in the first zone. The impact of the chemical plant extended over several kilometers, before a normal lichen vegetation could develop in the third zone. The species *Physcia biziana* (A. Massal.) Zahlbr. var. *aipolioides* Nádv. and *X. parietina* seemed to be the most tolerant to air pollution in the area.

In 1973, Pišút and Lisická-Jelínková investigated the impact of pollutants released from an aluminium smelter in Žiar nad Hronom (Central Slovakia) using lichens as indicators. During the smelting of aluminum, the initial raw materials (aluminium oxides) are dissolved into liquid sodium hexafluoroaluminate, then electrolyzed: as a result of this process, F gaseous compounds and inorganic fluorides are released. Therefore, the impact of aluminium smelters to the environment is largely determined by F and SO_2 pollution. Based on the application of the IAP method (De Sloover and Le Blanc 1968), Pišút and Lisická-Jelínková (1974) demonstrated the impact of the aluminium smelter in the surrounding environment and found out an impoverishment of the epiphytic lichen biota. They detected three main zones according to the intensity of the impact: "lichen desert", transient zone with damaged thalli and a less impacted zone, depending on the reliefs and direction of prevailing winds.

However, a floristic study carried out in 1964 and 1970 in the nearby area of Kremnica, about 16 km from the smelter (but in a separated valley), revealed no impact on local lichen communities, which were rather rich and characterized also by the presence of rare species (Pišút and Lányi 1972), suggesting that at that time, the emissions from the smelter impacted only the local lichen biota. However, the authors also pointed out that in the long-term, air pollution from the smelter could likely affect also the area of Kremnica.

The Orava region (North Slovakia) is another area extensively concerned by the presence of phytotoxic gases and dust pollution in the atmosphere (mostly Cd, Cr, Cu, Mn, Ni, Pb, Zn and SO_2) especially from the metallurgical industry. Between 1985 and 1986 the levels of air pollution in vascular plants, native mosses and lichens (*H. physodes*), as well as the effects on lichen diversity in spruce and pine trees were studied over an area of 450 km^2. The study encompassed 33 monitoring stations and the results indicated high values of heavy metals deposition, especially around two main metallurgic factories in the localities Istebné and Široká (Kontrišová and Lackovičová 1989). In particular, referring to the lichen, relevant peaks were detected, e.g., for As (up to 9.2 μg/g), Cu (29.5 μg/g), Cr (75 μg/g), Mn (630 μg/g). The results of the epiphytic lichen diversity assessment in terms of occurrence, abundance and vitality of the species were published later in details (Lackovičová and Kontrišová 1998). On the whole, both articles pointed out a zonation of the area based on the quality of the environment: from highly impacted sites close to the factories (with high heavy metal depositions, average no. of lichens per station = 1.7) up to those relatively not impacted (average no. of lichens > 4). With the distance from the factories, higher IAP values were calculated and an increasing number of macrolichens was observed (Lackovičová and Kontrišová 1998).

Copper and mining activity

The area of Krompachy is known for the presence of a large copper smelter, operating with several interruptions since 1843. A first modernization of the plant was carried out in 1935 and a second after the second world war, in 1951. The main pollutants released to the environment were SO_2 (more than 13,000 tons in 1989), SO_3, and heavy loads of particulate dust containing especially As (69 tons in 1989), then Cu and Zn, but also Fe, Pb, S, Sb, Sn. The polluting source is located at the bottom of a valley, with frequent temperature inversions and a limited wind flow, which generally hampered the dispersion of the pollutants. In order to reduce the contamination of the environment at local level, a tall chimney (200 m) was built in the 1970s, spreading pollutants into a wider area. In parallel with the increase of Cu production, SO_2 emissions rapidly increased from 1980, reaching a peak between 1985 and 1990. Air pollution induced large degradation processes, including vegetation destruction and forest decline. Since 1992, due to technological improvements and a lower production, air quality started to improve, with values after 2001 within legal limits (data from the Ministry of Environment of the Slovak Republic, www.env.gov.sk). Hence, based on biomonitoring studies carried out with plants and lichens around the Cu smelter, Banasová et al. (2010) highlighted three main periods of recent air pollution history in Krompachy: 1) culmination (1989–1992); 2) decrease (1993–2003); 3) present time (after 2007).

In the 1980s, the occurrence of epiphytic lichens, their abundance and vitality were investigated according to the distance from the copper plant (see in Lackovičová 1985, 1995). A lichen desert for fruticose and foliose species was observed within 2 km from the source, with occasional presence of three toxitolerant crustose species (*L. conizaeoides*, *S. chlorococcum* and *L. incana*). Noteworthy, the thalli of *L. conizaeoides*(known as S-tolerant) were highly sorediate and lacked fruiting bodies (apothecia) for sexual reproduction, in particular in the area permanently influenced by heavy metals and S emissions. Hadjúk and Lisická (1999) carried out observations on epigeic lichens and reported the presence of the fruticose species *Cladonia rei* Schaer. (referred as not very common in Slovakia) in the vicinity of the Cu smelter. In particular, the lichen was abundant in highly contaminated soils from heavy metals and SO_2 (together with the moss *Ceratodon purpureus* (Hedw.) Brid.). Hence, the species was evaluated as toxitolerant, able to colonize habitats where most of the vascular plants and other cryptogams disappeared. Banásová and Lackovičová (2004) investigated the impact of the Cu plant in Krompachy on grasslands and epigeic lichens by means of phytosociological relevés along a distance (and altitudinal) gradient on the NE facing slope respect to the plant. The content of toxic elements (As, Cu, Pb, Zn) was investigated in soil samples. They reported the results from two monitoring surveys: the first in the period 1987–1993 and the second in 2003. The first one highlighted the degradation of plant communities and soil quality at the end of the eighties. The highest degradation corresponded to the area of maximum deposition from the smokestack. After limitation of SO_2 emissions in the nineties, air pollution significantly decreased, but soil still remained contaminated by heavy metals (especially As, Cu and Zn) and was characterized by low pH. Nevertheless, in 2003 survey, some lichens (*C. rei*, *C. fimbriata* (L.) Fr., *Diploschistes muscorum* (Scop.) R. Sant., *Placynthiella icmalea* (Ach.) Coppins & P. James and the moss *C. purpureus*) clearly extended their cover also to highly disturbed sites. A survey carried out in 2007 has shown positive changes in the environment, consisting in increase of species diversity and cover also for vascular plants and several cryptogams, as well as successful secondary succession (Banásová and Lackovičová 2008). The number of lichen species doubled respect to the survey of 2003 and data from the following survey carried out in 2009 revealed an ongoing recolonization by epiphytic lichens and retreat of acidophilous species, such as *L. conizaeoides*, which was much more common in the past (Banásová et al. 2010). Furthermore, the lichen desert disappeared.

Demková et al. (2019b) investigated the complex impact of open mining pits and heaps of waste material in the former mining area of Dubník (Eastern Slovakia), that represented the largest opal deposit in Europe (from the Roman times up to the nineteenth century) and an important part of the Slovak mining history. The long and intensive exploitation of the area and the presence of numerous mining bodies resulted in a severe water, soil and air pollution. About 30 years after the closure of the mining activities, element concentrations in soil and the activity of soil enzymes were investigated. Moss (of the genus *Dicranum, Hypnum* and *Polytrichum*) and lichen bags (*H. physodes*) were used as biomonitors of air pollution. The investigated sites were considered as moderately up to extremely polluted, especially in correspondence of the heaps of waste material. Soils were especially contaminated by Cd, Fe, As and Sb of geochemical origin, which negatively influenced also the activity of soil enzymes. Relative accumulation factors in the transplants varied according to the species, pointing out an accumulation for most of the investigated elements (Cd, Fe, Mn, Ni, Pb), which was particularly evident for As and Sb in moss bags (Demková et al. 2019b). Also the samples prior to the exposure were significantly enriched in some elements (e.g., As, Cd and Mn in the lichen, Fe, Mn and Pb in the moss), reflecting the particular geochemistry of the area (Čergov Mts). Other relevant studies carried out by the same authors around tailing ponds did not report original values.

Steel

The town of Košice is an active centre for metallurgy, being the principal basis for the US Steel industry. The steel factory is one of the largest private employers in Slovakia, with about 12 000 workers and represents one of the most important producers of steel in Europe. Similarly to other large steel factories, it was considered as one of the main producers of SO_2 and heavy metal emissions in Slovakia, especially in the past. Bačkor et al. (2003) investigated the chemical nature of pollution in lichens from Košice also in relation to the presence of the steel factory. Various species were sampled (study sites in Table 5, see Bačkor et al. 2003) and in particular, tolerant crustose (*Lecanora chlarotera* Nyl.) and foliose (*Physcia tenella* (Scop.) DC.) lichens, as both grow close to the sources of air pollution. Afterwards (in 2005), since the foliose species *X. parietina* was one of the few foliose lichens growing also in the vicinity of the steel factory, it was employed to test its tolerance regarding the two previously identified polluting sources, i.e., the steel factory and traffic in the centre of Košice (Dzubaj et al. 2008). Heavy metals (Al, Cd, Cu, Fe, Mn, Pb, Sb and Zn) and selected ecophysiological parameters (content of photosynthetic pigments and parietin, chlorophyll *a* fluorescence emission, thiobarbituric acid reactive substances – TBARS and CO_2 gas exchange) were compared. As a result, higher amounts of the investigated elements were recorded in relation to the distance from the two polluting sources and in particular, all tested metals (except of Cu) had higher concentrations in the proximity of the steel factory. However, except for TBARS production and to some extent CO_2 gas exchange, none of the tested physiological parameters showed a clear correlation between metal accumulation and physiological alterations, likely reflecting the high degree of pollution tolerance in this lichen and explaining its abundance in Košice (Dzubaj et al. 2008). The concentrations of Sb in *X. parietina* appear very high (34–101 μg/g dw, mean 50.5), also in the control site (43.8 μg/g dw). As examples of comparison in *X. parietina*, levels of 0.48 ± 0.03 (μg/g dw) were found in rural areas of Central Italy (Paoli et al. 2013); concentrations of 0.11–42 (mean 7.2 μg/g dw) were reported in the urban polluted area of Granada (Spain), 0.10–0.37 μg/g dw in nearby remote sites (Parviainen et al. 2020).

Magnesite

In the 1950s and 1960s, the production of magnesium oxide in Slovakia rapidly grew, with a consequent dispersion into the environment of high loads of polluting dust and gases (particularly SO_2). In 1973–1974 large lichen deserts (total absence of epiphytic and epilithic species) were observed in the vicinity of two neighbouring Mg factories, in Lubeník and Teplá Voda (Pišút 1974, 1978). Levels of Mg up to 4000 μg/g were reported in autochthonous samples of the lichen *X. parietina*. The alkalinity of depositions negatively influenced plant and lichen communities for kilometers, according to orographic factors and prevailing winds around the factories. High values of bark pH (generally > 8) were measured in the vicinity of the factories and in spoil heaps where loads of basic dust were released and corresponded to the lowest number of lichen species. Generally, alkaline dust depositions cause a rise in bark pH, hence a hypertrophication and replacement of acidophilous with xero-nitrophilous lichens (e.g., Paoli et al. 2014). A study carried out 30 years later (Pišút and Pišút 2006), showed that a decreased load of emissions (since 1985, when new filters were installed) allowed the recolonization of formerly desert areas by mosses and lichens, especially by nitrophilous species. Furthermore, the shy occurrence of few oligotrophic species, such as *H. physodes, Usnea* sp., *E. prunastri* and *Ramalina fastigiata* (Pers.) Ach., suggested a possible future recolonization of formerly unsuitable sites. Between 2011 and 2016 a study was carried out along four degradation stages in the same area (Blanár et al. 2019). High concentrations of Mg, Ca, Fe, S, C/N in soil samples corresponded to an increase of alkaline dust close to the emission sources and a general decrease of biodiversity. This phenomenon was evident from oak-hornbeam woodlands, up to halophilous procoenoses (with *Agrostis stolonifera* L. and *Puccinellia distans* (Jacq.) Parl.) on degraded soils with eroded magnesite crust and biocrusts (formed by cyanobacteria; tolerant bryophytes and pioneer terrestrial lichens, such as *Thelidium zwackhii*(Hepp) A. Massal.) and finally, in habitats with no vegetation. Degradation stages were characterized by a small amount of symbiotic macromycetes and by a high proportion of saprotrophic macromycetes. The study pointed out that the occurrence of nitrophilous epiphytic lichens differentiated unaffected oak-hornbeam woodlands from the plots close to the emission source (Blanár et al. 2019).

Cement pollution

The biological and chemical effects of airborne pollutants released during cement production were recently investigated around a cement mill near Bratislava (Rohožník), with an emphasis on dust pollution. Lichen diversity, element depositions, magnetic properties, physiological parameters and ultrastructural alterations in native and transplanted lichens were studied (Paoli et al. 2014, 2015, 2016, 2017). The research outlined how dust depositions modify epiphytic lichen communities, which shifted from acidophilous-oligotrophic toward basi-nitrophilous approaching the sources of alkaline dust; in addition, in proximity of the sources, lichens showed an asymmetrical distribution on the tree boles of *Fagus*, being basiphilous tolerant species positively influenced by dust depositions (Paoli et al. 2014). However, lichens disappeared under the influence of the highest depositions, i.e. close to kiln operations and along dirt roads. The elemental content of native thalli (*X. parietina*) was significantly enriched in Ca, Ti, Fe, V, Al and Ni around the cement plant and the quarries with respect to the surrounding environment (Paoli et al. 2014). Transplants of *E. prunastri* exposed up to six months, rapidly accumulated (within 30 days) dust-related elements (namely Ca, Fe, Ti), while airborne pollutants from combustion processes (e.g. S) progressively increased (Paoli et al. 2015). Lichen transplants (*X. parietina*, *E. prunastri* and *Peltigera praetextata* (Flörke ex Sommerf.) Zopf) exposed to dust pollution showed peroxidation of membrane lipids, altered photosynthetic performances (especially in oligotrophic species, namely *E. prunastri* and *P. praetextata*), ultrastructural alterations consisting in lipid droplets increase, swelling of cellular components, thylakoids degeneration and occasional plasmolysis, which on the whole gave the cells an aged appearance (Paoli et al. 2015, 2016). The magnetic properties of native (*X. parietina*) and transplanted (*E. prunastri*) thalli were influenced by rock mineralogy and the processes of cement production, with stronger signals detected in native thalli (Paoli et al. 2017).

Monitoring lichen species between the nineteenth and twentieth centuries

Mapping the distribution of common and rare species is important for tracing the effects of environmental changes. Several reports referred to this topic in relation to air pollution in Slovakia (Pišút 1970, 1986, 1997, 1999; Pišút and Lisická 1985; Liška and Pišút 1989). In a review of the possible reasons for lichen decline, Ivan Pišút (1981) outlined the multiple sources of alteration for lichens in former Czechoslovakia and reported several lichens as extinct due to a combination of factors: industry/urbanization and related pollution, forest management (changes in forest composition, shortening of logging periods), agricultural practices (intensive use and spreading of pesticides and fertilizers), increasing tourism and related urbanization, collections for medical/commercial purposes (e.g., for *Cetraria islandica*).

From the point of view of chemical ecology, until the 1980s the acidification of the environment was the cause of the impoverishment of the lichen flora in several contexts. As an example, Pišút and Lisická (1985) carried out an interesting study by monitoring biodiversity over the same tree (312 sampling quadrats on *Quercus robur*) in the vicinity of Bratislava, between 1973 and 1983. They reported a progressive decline of epiphytic lichens, partially substituted by the green alga *Pleurococcus vulgaris* Meneghini and the moss *Hypnum cupressiforme* Hedw. Similarly, studying lichens over the same naturalistic paths in 1960 and 1984, Pišút (1986) reported the disappearance of sensitive lichens and their substitution by more acidophilous ones (such as *L. conizaeoides*).

Moving to broader scale, between 1975 and 1981 a comprehensive monitoring of epiphytic lichens according to the example of Great Britain (1964), the Netherlands (1972) and Western Germany (1973), was performed in order to map the distribution of lichens within the territory of Slovakia (summarized in Pišút 1999). Later on (1978), the investigation started also in Bohemia and Moravia and in the following years also in other European countries. Data from a field research over 372 quadrants of approximately 135 km^2 and a literature review from 1970 were considered (Pišút 1999): the outputs of such impressive monitoring in Slovakia were partially published in numerous works (Liška and Pišút 1989; Pišút 1978, 1981, 1985, 1990) and finally summarized in the form of distributional maps for epiphytic species (Pišút 1999), which still serve as an important source of information for lichenological research.

Liška and Pišút (1989) highlighted the importance of large scale monitoring of common and rare indicator species over space and time to demonstrate the influence of various factors, especially the acidification of the environment due to air pollution by SO_2. Based on the results of the species monitoring, no more than 200 epiphytic lichens were supposed to be present in the territory of Slovakia in the eighties, respect to the previously known presence of more than 400 species (Pišút 1997, 1999). Until the 1980s oligotrophic sensitive lichens as well as some common nitrophilous species reduced their distribution. *P. sulcata*, a fairly toxitolerant lichen able to grow in areas with average winter concentrations of SO_2 up to 70 $\mu g/m^3$(Hawksworth and Rose 1970), and *H. physodes*, similarly tolerant to high amounts of SO_2, were among the most common epiphytic species. This latter one, being a nitrophobic species, was missing from southwest lowlands characterized by high eutrophication from intensive agriculture. Out of nitrophilous species, *X. parietina*, *P. adscendens*, *P. orbicularis* were distributed mostly in N-rich environments. Some acidophilous lichens (e.g., *L. conizaeoides* and *S. chlorococcum*) could significantly spread due to their tolerance to SO_2 (Pišút 1985, 1999). For example, *L. conizaeoides*, previously known only from 4 localities, was abundantly recorded in 143 quadrants of the monitoring network, especially in western and central Slovakia, along the main sources of air pollution and related valleys. The spreading continued even after 1981, not only horizontally but also vertically: before 1981 the highest localities were situated below 1000 m a.s.l., meanwhile, in the eighties and nineties, they reached elevations up 1350 m (Pišút 1985, 1999).

Similar distributional changes were observed for inconspicuous acidophilous species such as *S. chlorococcum*, which was almost unknown from the past. In the 1940s, only 2 localities were reported in Slovakia (Szatala 1942), however, in the 1970s its presence was reported in 124 quadrants along the whole country and later data suggested further spread. Likewise, a spreading was observed in the case of *H. scalaris* and *H. caradocensis* (Leight. ex Nyl.) P.James & Gotth.Schneid. which colonized phorophytes especially in highly acidic environments (e.g. Bralce in Štiavnické vrchy Mts). Another toxitolerant species known to tolerate high concentrations of SO_2 (even about 125 $\mu g\ m^{-3}$– Hawksworth and Rose 1970) as well as eutrophicated environments is *Amandinea punctata* (Hoffm.) Coppins & Scheid. Its increasing frequency in the 1970s was highly significant. In some impacted areas, such as around the chemical plant in Šaľa or in Žiarska valley, it was the most abundant lichen (Jelínková, 1970; Pišút and Lisická-Jelínková 1974).

An interesting spreading was revealed also in the case of *P. biziana* (A. Massal.) Zahlbr. var. *aipolioides* Nádv., a toxitolerant, photo-nitrophilous species growing especially on isolated trees. Nádvorník (1947) reported only one locality from Slovakia, but the large scale monitoring (Pišút 1999) revealed its presence over 70 quadrants, mostly in the southwestern part of Slovakia, in particular in the vicinity of pollution sources, such as urban environments and even oil refineries. The monitoring carried out in 2001–2007 confirmed the presence of the species in south-western part of the country in 100 quadrants (Lisická et al. 2007).

Pišút (1997) affirmed that "the future of many epiphytic lichens seemed to be hopeless until the end of the 1980s", because the load of air pollution, huge emissions of fertilizers in rural areas and drastic effects of intensive forest management were too extensive. However, the change of political and economical situation after 1989 in central and eastern European countries – including Slovakia, had brought a certain improvement of air quality and a more favourable outlook for the future, in the way that "…the retreat of sensitive species and even the spread of invading acidophilous lichens will probably slow down". He also pointed out at the spreading of nitrophilous species under increasing levels of nitrogen compounds (Pišút 1997), which in fact occurred and still is ongoing.

The retreat of air pollution sensitive lichens and the case of *L. pulmonaria*

Several epiphytes linked to the natural/semi-natural forests of higher altitudes and requiring higher air humidity, exhibited a dramatic reduction of their distribution, which was evident especially in the 1970s. Combined effects of air pollution, changes in forest management, intensive agricultural practices were among the most relevant factors explaining the decline of epiphytic lichens and the extinction of rare species from previously colonized areas (Pišút 1981; Liška and Pišút 1989). As examples, *Alectoria sarmentosa* (Ach.) Ach., *Belonia herculina*(Rehm) Hazsl., *Bryoria bicolor* (Ehrh.) Brodo & D. Hawksw., *Evernia divaricata* (L.) Ach., *Fuscidea cyathoides* (Ach.) V. Wirth & Vězda, *Leptogium saturninum* (Dicks.) Nyl., *Lobaria amplissima* (Scop.) Forss., *Menegazzia terebrata* (Hoffm.) A. Massal., *Nephroma parile* (Ach.) Ach., *Parmelia submontana* Nádv. ex Hale, *Ramalina obtusata*(Arnold) Bitter. and many others, were found only in few (≤ 7) monitoring quadrants. A significant decrease was also documented for sensitive species, such as *L. pulmonaria* (see below) and *R. fraxinea*. All above mentioned species were later included in the Red List of Lichens of Slovakia (Pišút et al. 2001) as critically endangered (CR). Some of them are currently under legal protection (e.g., *Alectoria sarmentosa*, *B. bicolor*, *L. pulmonaria*; Decree no 170, Ministry of the Environment of the Slovak Republic of 19 April 2021 implementing Act No. 543/2002 Coll. on nature and landscape protection).

There are also many taxa, e.g., *Usnocetraria oakesiana* (Tuck.) M. J. Lai et J. C. Wei, *Stictis urceolatum* (Ach.) Gilenstam, *Lobarina scrobiculata* (Scop.) Nyl. ex Cromb., *Megalaria grossa* (Pers. ex Nyl.) Hafellner, *Hypotrachyna sinuosa* (Sm.) Hale, *Sticta fuliginosa* (Hoffm.) Ach., *S. sylvatica* (Huds.) Ach., which were reported from Slovakia in the past, but considered as extinct since the second half of the twentieth century (Pišút 1999; Pišút et al. 2001). Pišút and Liška (1985) investigated lichen diversity in 1977 and 1982 over 37 localities in remote areas of Slanské vrchy Mts (East Slovakia). In comparison with former literature data, a significant decrease of epiphytic species was reported. Numerous species associated to indigenous forests at lower altitude resulted as extinct, such as *L. pulmonaria*, *Nephroma resupinatum* (L.) Ach. and members of the taxon Caliciales, which were even abundant in the past. Lichens at lower altitude were likely impacted by forest management and intensive agricultural practices, while at higher altitude, the influence of long-range transportation of pollutants was hypothesized as a likely cause of alteration for the local lichen flora. Saxicolous and epigeic lichens were less affected. Noteworthy, they found out the presence of interesting saxicolous and epigeic species associated to heavy metal rich substrates (e.g., *Lecanora epanora* (Ach.) Ach., *Lecanora subaurea* Zahlbr., *L. handelii* J. Steiner, *Stereocaulon nanodes* Tuck., *Rhizocarpon oederi*(Weber) Körb.).

A noteworthy example of threatened species, which is considered as extinct from most of the previously colonized areas in Slovakia, is the forest macrolichen *L. pulmonaria* (Liška and Pišút 1989). The thallus is foliose, often exceeding 20–30 cm in diameter, with green algae (as main photobiont) and nitrogen-fixing cyanobacteria within its internal cephalodia. It is considered as an "umbrella species" and represents a suitable indicator of forests hosting other rare lichen species, such as many cyanolichens worthy of conservation (Nascimbene et al. 2013). The species has suffered a general decline throughout Europe as a consequence of air pollution and intensive forest management and currently it is red-listed in several European countries, especially in Central Europe (Paoli et al. 2019a). Interesting details on the history of its retreat in Slovakia have been reported by Pišút (1970) and the main drivers causing the retreat were discussed by Pišút (1971), who linked it with industrialization and intensification of forest management.

The first record of this sensitive lichen in Slovakia dates back to 1791. There were no reasons to presume that it could become threatened, as it was regularly reported (herbarium specimens and literature data) for the next 100 years from numerous areas of the country. However, in 1894, Zahlbruckner referred for the first time about the retreat of *L. pulmonaria* from the surroundings of Bratislava (Zahlbruckner 1894), in parallel with the industrialization of the area. This could be the first observation on the sensitivity of lichens to air pollution in Slovakia. Later, Jindřich Suza (in 1948; see also Lackovičová 1979) reported that the species was about to disappear and its occurrence was limited in the Malé Karpaty Mts to the mossy bases of tree boles in more humid sites. In fact, Suza's prognosis became reality and his findings from the 1930s were the last vouchers documenting the presence of the species in the region (Lackovičová 1979). A continuous decrease of colonized localities was reported, as in most of Central Europe. As an example, in the inner Western Carpathians (Štiavnické vrchy Mts), there were 12 records of known localities in 1856, only four in the period 1900–1937 and none later on. As already mentioned, in the surroundings of Bratislava *L. pulmonaria* vanished during the 1930s: the retreat was also accompanied by a significant reduction of colonized habitats and a shift of the distributional range (in Slovakia between 150 and 1400 m) to more remote and higher mountain regions (lower altitude about 600 m, with only few exceptions). A similar trend was described also for other species (e.g., *Lobaria amplissima*, *Collema nigrescens*). A breaking point occurred in 1940, due to the relevant changes in political conditions, as reported by Pišút (1970): war, exploitation of the forests, intensification of agricultural activities and a heavy industrial pollution worsened the status of the environment. Later on, those areas (and lichens) concerned by increased urbanization and industrial development were directly affected by high heavy metals and SO_2 pollution; rural and remote areas were affected by agricultural exploitation and intensive forest management practices leading to habitat fragmentation, shortening of the logging period, replacement of beech by spruce forests. Noteworthy, *L. pulmonaria* is enhanced in habitats characterized by stable ecological conditions, very vulnerable in discontinuos, uniform (and light) forest patches. Additionally, beech is the main phorophyte for *L. pulmonaria* in Slovakia. Before 1970 *L. pulmonaria* was reported from 50 mapping units of the regional forest monitoring network, decreasing to 14 in the following 30 years, which means 27 localities in 9 orographical units (Pišút 1985, 2005). Actually *L. pulmonaria* is extint from several of the previously colonized areas and, on the whole, the remaining populations are depleted and vulnerable.

To investigate whether air pollution potentially limits the recolonization in sites where *L. pulmonaria* disappeared during the last century, a translocation experiment (about 125 thalli) was carried out in 2016 in beech forests at the foot of the Malé Karpaty Mts (municipality of Bratislava) and the Nízke Tatry Mts (Paoli et al. 2020). The localities were carefully selected with regard to prevent the contact with eventual local populations of *L. pulmonaria* and hence, a potential erosion of local genetic diversity. The effectiveness of lichen translocation was assessed in terms of permanence and health of the transplants and presence of newly formed individuals. Heavy metals, thallus ultrastructure and photosynthetic performances were used as proxies of the effects of air pollution. After one year, those thalli transplanted in the Nízke Tatry Mts (site with negligible pollution) survived, attached by themselves and developed new propagules. On the other hand, the translocation was not considered successful in the Malé Karpaty Mts (municipality of Bratislava), where the thalli did not attach by themselves, showed visible symptoms of damage, a partial alteration of the photosynthetic performance and an accumulation of trace metals (mostly As, Mn, Ni, Pb, S, Sb, Zn, occasionally Cd, Cr and Cu). The results highligthed the link between the unsuccess of the translocation and air pollution and suggested that current air quality still limits the possibility of recolonization in the Western Carpathians (Paoli et al. 2020). On the other hand, the interaction with climatic parameters under current conditions should be better explored.

Regional biomonitoring in forests

A regional study carried out in 48 selected oak stands of Central Europe (including Czech Republic, Slovakia and Hungary) identified air pollution, forest fragmentation and forest age as the main anthropogenic factors affecting epiphytic lichen diversity (Svoboda et al. 2010). The effects of air pollution were prevalent in the intensively human-exploited areas of Bohemia and Moravia (Czech Republic), heavily affected by air pollution especially in the past, and where the lowest lichen diversity was generally reported. Forest fragmentation and forest age were the main drivers shaping lichen communities respectively in agricultural stands and forested areas (Svoboda et al. 2010). A deeper analysis of the species composition of the relevés and their relationship with environmental parameters, natural factors and human impacts, suggested that forest degradation and air pollution during the last century were the main causes for the scarsity or even the complete absence of sensitive indicator species typical of high-quality environments (Svoboda et al. 2011).

A large dataset (period 2004–2006) of lichen diversity indices based on morphological and functional traits of the species was used to investigate the response of lichen communities to air quality and forest management in 29 oak dominated stands distributed in the Western Carpathians (Guttová et al. 2017). The level of air quality was summarized as a function of NO_x, SO_2 and particulate matter atmospheric concentrations in areas with high environmental quality up to heavily disturbed environments. The stands were also classified according to management practices, in managed (areas subjected to periodic logging) and semi-natural (which currently have the status of National Nature Reserve and where long-term management practices were implemented). The results showed that higher environmental levels of pollution were associated to the reduced presence of fruticose species (high surface/volume ratio and hence higher sensitivity to pollution), while low environmental levels of pollution were associated to the diffusion of common resistant lichens as well as to a higher share of fruticose and in general pollution sensitive species. Concerning management practices, a higher share of fruticose lichens was associated to semi-natural and natural stands, whereas a higher share of foliose (pioneer and tolerant) species was associated to the managed stands (Guttová et al. 2017). The study outlined that the investigated forest ecosystems are mainly oligotrophic environments, with a limited degree of eutrophication. In fact, the Western Carpathians can be overall regarded as a N-limited and acidophilous environment, where the past and wide presence of acidic pollution influenced also lichen communities, dominated here by acidophilous and oligotrophic species.

Indoor pollution

Recently also to the topic of lichen monitoring in relation to indoor air quality attracted the attention of researchers (Demková et al. 2018, 2019c; Paoli et al. 2019b). Demková et al. (2018, 2019c) carried out original experiments in an underground parking and university indoor environments in the town of Prešov using moss and lichen bags. It is indeed a pity that only relative accumulation factors (instead of the original concentrations) were published, since the information on control values is missing.

Paoli et al. (2019b) carried out a "citizens science" experiment that involved teachers and students in monitoring indoor air quality in public and private environments. During autumn 2017, the lichen *E. prunastri* taken from a control area was exposed for two months indoors and outdoors in schools and dwellings in a rural area (Madunice) and in the urban area of Bratislava. The study allowed testing the contribution of outdoor pollution by heavy metals to indoor concentrations and assessing whether the vitality of indoor exposed samples was comparable to those exposed outdoors. In lichens exposed outdoors an increase of most of the investigated elements (Al, As, Cd, Cr, Cu, Fe, Pb, S, Sb, V, Zn) was reported in the urban area and only a few (As, Cd, Cu, Pb and Sb) in the rural area. Indoor concentrations were overall similar, both in rural and urban buildings, independently of the outdoor conditions. An indoor uptake occurred for a few traffic related elements (Cd, Cu and Pb), but on the whole, indoor air quality in the schools was not affected. The lichens maintained their vitality during the indoor exposure (as reflected by chlorophyll *a* fluorescence emission), further supporting the use of lichen biomonitoring as a suitable method for assessing indoor air quality (Paoli et al. 2019b).

Conclusion

Lichen biomonitoring of air pollution in Slovakia during the period 1960–2020 reflected key events of the political and socio-economic situation in Central and Eastern Europe:

- During the period of heavy industrialization, air pollution from sulfur dioxide and heavy metals dramatically influenced air quality in all Central European urban areas and around industrial sources until the end of the eighties. The negative effects of emissions could be clearly detected as impacts on biodiversity and heavy metal depositions. Lichen deserts were diffused. Oligotrophic species exhibited a dramatic reduction of their distribution, which was evident especially in the 1970s. Later on, some of them were considered as extinct. Toxitolerant (generally acidophilous) lichens could diffuse in sulphur-rich environments.
- The changing of political and socio-economic situation after 1989 in Central and Eastern Europe led to a radical decrease of emissions (by sulphur dioxide and heavy metals) and an improvement of air quality, slowing the retreat of sensitive species and the spread of acidophilous. Epiphytic lichens started to recolonize lichen desert areas.
- With the improvement of air quality in the 2000s, lower environmental levels of pollution were generally associated to the diffusion of common resistant lichens and the recolonization was chiefly dominated by nitrophilous lichens (under increasing levels of nitrogen) instead of the original acidophilous communities. Also some oligotrophic species shily reappeared.
- Air pollution (especially in the past) and habitat fragmentation (nowadays) are considered as the main anthropogenic factors influencing epiphytic lichen diversity in forests. Current air quality still limits the possibility of recolonization by sensitive threatened species typical of clean environments, such as the forest macrolichen *L. pulmonaria*, actually extinct from most localities in Slovakia.

As concluding remark, biomonitoring of air pollution using lichens has been evolving: current research has brought a progress in methods as well as researched aspects and identified gaps and opportunities for future monitoring studies (Abas 2021; Brunialti et al. 2019; Ellis 2019). Pending anthropogenic disturbances, e.g., atmospheric pollution, climate change or forest management modify lichen biology, chemistry and diversity, and such changes can be explored or monitored also at the level of phylogenetic or functional traits (Giordani 2019). In particular, new aspects of lichen vitality, chemical-functional traits, physiology of particular lichen bionts may represent useful tools for early warnings about harmful environmental effects of air pollution, which could be suitable also for a follow up of several lichenological researches in Slovakia.

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Declarations

Ethical approval The authors are aware of ethical responsibilities included in submission guidelines for the authors (https://www.springer.com/journal/11756/submission-guidelines?IFA#Instructions%20for%20Authors).

Conflict of interest The authors declare that they have no conflict of interest.

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