Acta Bot. Neerl. 46(4), December 1997, p. 403–412

Air pollution monitoring by lichens in a small medieval town of central Italy

F. MONACI*, R. BARGAGLI* and D. GASPARO†

**Dipartimento di Biologia Ambientale, Università di Siena, Via delle Cerchia 3, 53100 Siena; and †Ecothema Srl, Via Stuparich 16, 34125 Trieste, Italy*

SUMMARY

Air quality and the deposition pattern of trace elements were assessed in Siena (Central Italy) using epiphytic lichens. Air quality was assessed in terms of the Index of Atmospheric Purity (IAP) based on frequency counts of lichen species in 25 stations in the urban area. Forty-six species of epiphytic lichens were found. There were no lichen desert areas and some widespread species of lichens which could facilitate future surveillance monitoring programmes were identified. Trace element deposition was estimated by analysing the thalli of *Parmelia caperata,* collected in 28 urban sites. Among the elements considered (Al, B, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, P, Pb, S, Zn) Pb was the most widespread, indicating that despite the progressive introduction of unleaded fuel this metal is still emitted copiously (and/or resuspended) by traffic. The results of the two biomonitoring approaches used in the study area were compared.

Key-words: air pollution, biomonitoring, lichens, *Parmelia caperata.*

INTRODUCTION

People living in cities are exposed to a large spectrum of atmospheric pollutants, which are a threat to human health. Because most of these substances occur in very low concentrations, that vary considerably in space and time, they are problematic to measure. Atmospheric pollution control policies are therefore normally based on analytical determinations of the principal atmospheric pollutants with automatic recording equipment. Although quality assurance programmes have been established for air pollution monitoring, it is debatable whether they provide a sufficient guarantee for human health. It is assumed that control of the principal pollutants automatically protects people against the risks associated with continuous exposure to complex mixtures of contaminants. Moreover, the high cost of automatic recording apparatus and its maintenance limits the number of sampling points, even in relatively small urban areas.

In this context, biological monitors have much to offer, enabling a high spatial and temporal density of sampling points and providing a pertinent 'time integral' of possible biological effects of airborne pollutants (Nimis 1990). They also make it possible to detect relative concentrations of persistent atmospheric pollutants such as PCBs, PAHs, trace elements and radionuclides which cannot be measured by automatic recording devices.

Lichens are probably one of the most valuable atmospheric pollutant biomonitors and many authors have discussed the use of these organisms in environmental monitoring (Ammann *et al.* 1987; Bargagli 1989). Although a large number of different techniques using epiphytic lichens as biomonitors exists, two are more widely used than the others.

The first is based on the well-known sensitivity of lichens to several phytotoxic gases (sensitive biomonitoring). By measuring the responses of lichens at the population or community level it is possible to estimate the biological effect of air pollution. The Index of Atmospheric Purity (De Sloover 1964) is a biotic index widely used to quantify such responses. It has a high predictive power for ambient levels of mixtures of phytotoxic pollutants (Liebendörfer *et al.* 1988).

The second method is based on some resistant foliose lichen species which can be used as bioaccumulators of persistent pollutants (accumulative biomonitoring). Their ability to reflect aerial concentrations of pollutants has also been proven on a quantitative basis, especially for metals (Sloof 1995).

These two approaches were used in the urban environment of Siena, a small Tuscan town without automatic monitoring stations. Very sparse data on SO_2, NO_X, CO and Pb was available from a mobile detection station. The main cause of concern was presumably not the absolute levels of emissions, because traffic is light and forbidden in much of the town centre, but rather the functional inadequacy of the streets for even limited traffic, because of the topographical complexity of their medieval structure. Trace element concentrations in lichens were monitored because some metals may have synergistic toxicity and hazard may exist even under low-dose exposure conditions. Symptoms of chronic exposure to metals can be non-specific and the sensitivity of current clinical tests may be inadequate for early diagnosis of subtle biochemical or 'no-effect' distress syndromes (Nriagu 1989; Cislaghi & Nimis 1997). Some trace elements can also be used as 'tracers' for other pollutants and enable emission sources to be apportioned (Sloof 1993).

The aim of this research was to monitor air quality and trace element deposition in order to assist decision makers on the subject of traffic control and urban development in Siena.

MATERIAL AND METHODS

Study area

The study area (approx. 6·8 km^2) included urban and suburban Siena (Tuscany, Italy). Although some new suburbs were built in the 1970s, the town centre maintains its ancient structure with narrow, twisting streets that limit traffic flow. Because of the prevalently touristic vocation of the town and little industry, traffic is presumably the main source of atmospheric pollution. The roads with the highest traffic density are in the northern part of the town, where most of the population is concentrated.

The climate of Siena can be described as Tyrrhenian. The average annual temperature is 13·5°C (January 4·6°C; July 23·5°C). The average annual rainfall is 700 mm, concentrated in autumn and winter. Snow and fog are very rare. The average wind speed is 2·2 m/s (data from 1995), prevalently from NNW.

Index of Atmospheric Purity (IAP)

Sampling was carried out in summer 1995 and was preceded by identification of the main tree species in the study area. Lime (*Tilia cordata*) was selected as the species with

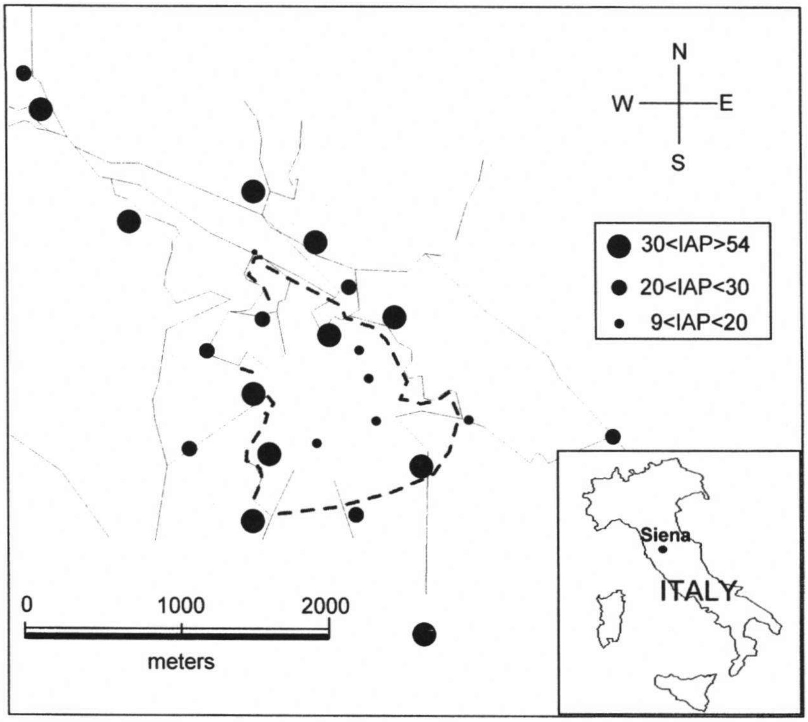

Fig. 1. Location of the sampling stations (●) and respective IAP values indicated by size of circles. The heavy broken line indicates the ancient city walls.

the most homogeneous distribution. The Calibrated Lichen Index of Atmospheric Purity of Liebendörfer *et al.* (1988), modified by Nimis *et al.* (1991), was determined at 25 sampling stations (Fig. 1). By testing 20 different IAP formulas against real pollution data, the sum of the frequencies of all lichen species within a sampling grid of 10 subunits proved to have the highest statistical correlation with the combined concentrations of different pollutants. This simple index has a great advantage over other IAP indices, since toxitolerance values do not have to be assigned to each species:

$$IAP = \Sigma_1^n F$$

where n is the number of species in each sampling plot and F is the average frequency of each species. On the whole, 80 relevées were performed in the study area. Species known to be pollution resistant, namely *Lepraria incana*, *Leprocaulon microscopicum* and *Lecanora conizaeoides,* were not included in the statistical analysis.

Chemical analysis

P. caperata was chosen as trace element biomonitor as it was one of the most widespread species in the study area and it is regarded as a valuable bioaccumulator of persistent atmospheric pollutants (Bargagli *et al.* 1987). Thalli of this species were collected at 28 sites in the town (Fig. 1) and 29 unpolluted sites on the Montagnola Senese 10 km NW of Siena, after a dry period of 20 days. At each sampling station, at least six thalli were cut from lime bark (*Tilia cordata*) in Siena and holm oak (*Quercus ilex*) on the

Montagnola Senese and pooled into a mixed sample. In the laboratory, peripheral parts of the thallus, easily identified by the colour of the lower surface and corresponding to 1 year of growth (Nimis *et al.* 1993), were separated using a stainless steel scalpel. The selected material was then dried at 40°C for 24 h and homogenized by grinding in a mill with Teflon balls. About 150 mg of dry homogenized material was digested in a Teflon bomb with 2 ml concentrated HNO_3 at 120°C for 9 h. Element analysis was performed by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) and Electrothermal Atomic Absorption Spectrometry with Zeeman background correction (ZETAAS). Total concentrations of major (Ca, K, Mg, P, S) and trace (Al, B, Ba, Cd, Cr, Cu, Fe, Mn, Na, Pb, Zn) elements were determined on the basis of three replicates to check sample homogeneity and mineralization. During each series of analysis, accuracy was checked by simultaneous analysis of standard reference material 'Tomato Leaves' no. 1573a from NIST (Gaithersburg) and lichen material (TP 24; TP 25) from the European Community Bureau of Reference (BCR) and it was generally found to be within 10%. More details on sample collection, preparation and analysis procedures are available in previous papers (Bargagli 1995).

Statistical analysis

As the data had a normal distribution, parametric statistics were used. Summary statistics were used to calculate means and standard deviations, analysis of variance (ANOVA) for differences between groups and coefficient r for correlations between variables. All statistical analyses were performed using the software program Statistica® (StatSoft Inc.).

RESULTS AND DISCUSSION

Epiphytic lichen communities and IAP values

Forty-six lichen species were identified in the study area. This is a large number for an urban environment, and is higher than the number reported for another urban environment of central Italy with similar environmental and climatic conditions (Gasparo *et al.* 1989). It is similar to or higher than the number reported in less urbanized environments (Nimis *et al.* 1991; Recchia *et al.* 1993).

The 43 species considered in this study are listed according to their frequency (Table 1). The most common four lichens in Siena were, in descending order, *Physcia adscendens, Physconia grisea, Lecidella elaeochroma* and *Hyperphyscia adglutinata.* These species determined, to a large extent, the IAP values for the study area and the IAP value computed using their frequencies (IAP_4) was positively correlated with that calculated by using overall species (IAP_{tot}; $r=0{\cdot}80$, $P<0{\cdot}01$, $IAP_{tot}=1{\cdot}66*IAP_4+7{\cdot}37$). A better approximation of the total IAP value in each station was obtained using seven lichen species which were distributed in more than two-thirds of the sampling stations ($r=0{\cdot}89$, $P<0{\cdot}01$, $IAP_{tot}=1{\cdot}17*IAP_7+7{\cdot}60$). The possibility of a quick and reliable estimate of air quality in Siena based on a limited number of lichen species has important practical implications, as further surveillance biomonitoring programmes will be carried out by technical personnel with no specific expertise in lichens.

The IAP values (Fig. 1) show that Siena does not have serious atmospheric pollution and a 'lichen desert' (IAP ranging from 0 to 5), which is common in many urban areas, was not found in this town. Most of the study area had a 'very low' level of pollution

Table 1. Number of records (# rec), frequency (f) and number of stations (# stat) with lichen species in each sampling station of the study area. Maximum number of records is 800 (10 × 80 relevées)

	Species	# rec	f	# stat		Species	# rec	f	# stat
1	*Physcia adscendens*	409	0·51	19	23	*Pertusaria albescens*	8	0·01	3
2	*Physconia grisea*	283	0·35	16	24	*Physcia aipolia*	8	0·01	3
3	*Lecidella elaeochroma*	217	0·27	18	25	*Candelariella reflexa*	7	<0·01	1
4	*Hyperphyscia adglutinata*	190	0·24	17	26	*Parmotrema chinense*	7	<0·01	6
5	*Parmelia subrudecta*	167	0·21	16	27	*Physcia pusilloides*	7	<0·01	2
6	*Xanthoria parietina*	165	0·21	16	28	*Ramalina fastigiata*	7	<0·01	4
7	*Candelaria concolor*	145	0·18	12	29	*Parmelia acetabulum*	4	<0·01	3
8	*Parmelia caperata*	145	0·18	17	30	*Caloplaca pyracea*	3	<0·01	1
9	*Physcia orbicularis*	124	0·16	8	31	*Candelariella vitellina*	3	<0·01	2
10	*Parmelia tiliacea*	90	0·11	12	32	*Physcia semipinnata*	3	<0·01	1
11	*Candelariella xanthostigma*	73	0·09	15	33	*Anaptychia ciliaris*	2	<0·01	2
12	*Parmelia sulcata*	70	0·09	12	34	*Arthonia punctiformis*	2	<0·01	1
13	*Parmelia subaurifera*	69	0·09	7	35	*Hypogymnia physodes*	2	<0·01	1
14	*Lecanora chlarotera*	68	0·09	13	36	*Parmelia elegantula*	2	<0·01	1
15	*Physcia tenella*	45	0·06	3	37	*Physconia perisidiosa*	2	<0·01	2
16	*Evernia prunastri*	44	0·06	5	38	*Diploicia canescens*	1	<0·01	1
17	*Arthonia radiata*	26	0·03	3	39	*Parmelia exasperata*	1	<0·01	1
18	*Physcia biziana*	23	0·03	9	40	*Parmelia exasperatula*	1	<0·01	1
19	*Parmelia glabratula*	18	0·02	2	41	*Parmelia glabra*	1	<0·01	1
20	*Buellia punctata*	15	0·02	3	42	*Pertusaria pertusa*	1	<0·01	1
21	*Lecanora argentata*	12	0·02	3	43	*Physconia distorta*	1	<0·01	1
22	*Lecanora carpinea*	9	0·01	3					

(IAP ranging from 30 to 50) as defined by Nimis *et al.* (1991). Car exhaust was probably the main source of pollution, as the stations with lowest IAP had the heaviest traffic (for example, along the roads immediately to the WNW of the centre and certain roads to the east which connect the highways leading N and SW).

Most of the northern part of the town showed low levels of pollution, considering its population and traffic density. Environmental and climatic conditions may therefore play an important role in determining the residence time of air pollutants in these areas. Exposure to the prevailing winds and the modern topography of the streets in this part of the town probably facilitate dispersal of phytotoxic gases. The 'canyon' configuration of the streets in the town centre may be responsible for the rather low IAP values found there. The heterogeneous altimetry of the town did not seem to explain the air quality pattern found in Siena, as IAP values and the altitude of the sampling stations were not significantly correlated (P>0·05).

Bioaccumulation of trace elements

Average trace element concentrations in homogeneous mixtures of six thalli of *P. caperata* from the urban and control areas are shown in Table 2. These values were compared with published 'background levels' for *P. caperata* in other Italian towns (Table 3). The reference values of this study were generally the lowest, except for Cr and Mn. This is probably due to the tufaceous geological composition of the study area.

The concentrations of Al, Ba, Cr, Cu, Fe, Pb and S in lichens from the Siena urban area were significantly higher (P<0·01) than those in lichens from the control

Table 2. Average (±SD) macro- and microelement concentrations (μg/g or percentage of dry weight) in thalli of *P. caperata*, collected in the study area (n=28) and in an unpolluted area (n=29). Significant differences (P<0·01) between the two areas are marked[a]

Elements	Unit	Urban area	Control area	Urban/control ratio
Al	ppm	1087 ± 562	396 ± 148	2·7[a]
B	ppm	11·0 ± 7·0	9·8 ± 3·0	1·1
Ba	ppm	13·1 ± 6·2	9·0 ± 1·9	1·5[a]
Cd	ppm	0·29 ± 0·11	0·26 ± 0·08	1·1
Cr	ppm	3·7 ± 2·3	2·3 ± 0·8	1·6[a]
Cu	ppm	12·6 ± 5·0	7·82 ± 2·35	1·6[a]
Fe	ppm	850 ± 417	306 ± 83	2·8[a]
Mn	ppm	29·6 ± 8·2	29·9 ± 10·9	1·0
Na	ppm	87·2 ± 26·5	93·3 ± 18·7	0·9
Pb	ppm	41·8 ± 32·8	5·61 ± 2·72	7·5[a]
Zn	ppm	40·3 ± 10·2	36·9 ± 6·3	1·1
Ca	%	2·04 ± 0·07	2·06 ± 1·02	1·0
K	%	0·48 ± 0·11	0·49 ± 0·13	1·0
Mg	%	0·09 ± 0·02	0·09 ± 0·08	1·0
P	%	0·21 ± 0·04	0·19 ± 0·03	1·1
S	%	0·27 ± 0·05	0·15 ± 0·04	1·8[a]

Table 3. Comparison of mean values of metal concentrations (μg/g dry weight) in *P. caperata* from the control area near Siena and background values from other parts of Italy

	Al	Cd	Cr	Cu	Fe	Mn	Pb	Zn	References
Siena	396	0·26	2·29	7·8	306	29·9	5·61	36·9	Present study
La Spezia	351	0·80	0·87	12·4	210	22·8	24·4	45·0	Nimis *et al.* 1993
Savona	427	0·62	0·52	5·7	280	18·1	12·2	49·2	Castello *et al.* 1994
Trieste	290	0·33	0·82	7·7	386	19·3	10·0	42·0	Bargagli *et al.* 1991
Vicenza	286	0·45	0·92	6·9	308	19·6	8·9	29·6	Nimis *et al.* 1989

stations. Urban levels were much higher for Pb (7·5 times), Fe (2·8) and Al (2·7). Enrichment of Pb in the Siena environment is attributable to automobile emissions while that of Fe and Al is presumably due to soil contamination of lichens (Lee *et al.* 1994). Some essential major elements (Ca, K, Mg, P, S) are also reported in Table 2 as they are useful to identify metabolic changes in lichens due to environmental stresses that affect element uptake. It has been demonstrated, for example, that Ca affects Cd uptake by the lichen *Peltigera membranacea* (Brown & Avalos 1993). However, macronutrient levels of major essential elements did not indicate any physiological stress in lichens as they were almost the same in the urban and control data sets.

Mn, Na and Zn showed no significant differences between urban and control levels. These elements are frequently associated with the industrial emissions, tyre abrasion (Zn), resuspended soil (Mn) and sea aerosol (Na; Lee *et al.* 1994). The small difference between Cd levels in urban and control areas and the low concentrations of this metal with respect to previous lichen biomonitoring data (Bargagli *et al.* 1991; Nimis *et al.* 1993) suggest that there are no significant man-made sources in the study area. Cd is

Table 4. List of significant correlations ($P<0.01$) between elements in lichens from the urban area ($n=28$) and the control area ($n=29$)

	r	
Significant correlations	Urban area	Control area
Al/Ba	0·69	0·60
Al/Cr		0·63
Al/Cu	0·55	
Al/Fe	0·85	0·78
Al/Pb	0·75	
Al/Zn		0·75
Ba/Cu	0·61	
Ba/Fe	0·77	
Ba/Mn	0·76	
Ba/Pb	0·68	
Ba/Zn		0·51
Ca/Cd	0·50	
Ca/Pb	0·43	
Cd/Zn		0·46
Cr/Fe	0·61	0·52
Cr/Mn	0·50	
Cr/Zn		0·47
Cu/Fe	0·61	
Cu/Mn	0·59	
Cu/Pb	0·53	
Fe/Mn	0·71	
Fe/Pb	0·72	
Fe/Zn		0·62

principally produced by industrial activities such as smelting, paint and plastics manufacturing (Lee *et al.* 1994) which do not take place in Siena.

Of all the elements considered, only Cu showed a significant inverse correlation with IAP values ($r=-0{\cdot}67$; $P=0{\cdot}008$). The lack of significant relationships between trace element concentrations in *P. caperata* thalli and IAP values, previously found for instance by Herzig *et al.* (1989) in two Swiss localities, is probably due to the narrow range of IAP values in Siena (9–54; coefficient of variation (CV) 19·5%, compared to 35·9 and 83·1% in the two Swiss towns) and the limited number of observations for the correlation analysis ($n=15$). This result may be explained by the fact that IAP values reflect environmental levels of phytotoxic gaseous pollutants such as SO_2 and NO_X rather than those of trace elements, which are less phytotoxic and are mainly associated with airborne particulates. In addition, the predictive power of lichen total S for atmospheric SO_2 is doubtful, as little research has been done on uptake and distribution of S, especially under controlled environmental condition (Brown 1995).

Table 4 shows the significant ($P<0{\cdot}01$) correlations between elements of the urban and the control area dataset. The results were interpreted by taking Al and Pb as 'tracers' of soil contamination and traffic pollution, respectively. Despite the introduction of unleaded fuel, Pb is still the most abundant heavy metal in urban environments (Lyons *et al.* 1993; Monaci & Bargagli 1995). Few significant ($P<0{\cdot}01$) correlations were found between trace element concentrations in lichens from the control area and almost all were attributable to soil contamination of samples (Al/Ba, Al/Cr, Al/Fe, Al/Zn, Cr/Fe, Fe/Zn). Soil particles may be trapped in the loose hyphal weft of the medulla (Olmez *et al.* 1985). Other correlations could be due to input of elements by long-range transport (Cd/Zn, Cu/Zn). Evidence exists that several airborne elements may be deposited very far from their emission sources (Zechmeister 1995). Correlations between Cd, Cu and Zn are often found in biotic and abiotic matrices, as these elements have quite similar biogeochemical behaviour and interactions in certain biochemical processes (Kabata-Pendias & Pendias 1984).

Compared with lichens from rural areas, those from the Siena urban environment were characterized by more significant relationships between lithophilic elements (Al/Fe, Cr/Fe) and between lithophilic and Pb (Al/Pb, Fe/Pb). These relationships are due presumably to the resuspension of exhaust particles, deposited on the roadside and aggregated with soil (Al-Chalabi & Hawker 1996). Wind, the shearing stress of tyres and vehicle induced turbulence cause resuspension of these particles (Nicholson 1988). The 'street canyons' of Siena may enhance resuspension processes, thus increasing the significance of the correlations between traffic related and crustal elements in lichens. However, element uptake mechanisms in lichen thalli, especially those of airborne particles, may also play a role in determining the accumulation pattern and the relationships between elements.

Pb concentrations in thalli of *P. caperata* collected in Siena were highly variable, extending over a range (5·5–138 μg/g d.w.) of 2·5 orders of magnitude. In contrast with IAP results, the highest Pb emission points were in a sampling station near an intersection that connects a highway and a ring-road. Although no traffic data exist for this peripheral part of the town, the highest levels of traffic in Siena probably occur there. The sampling stations ranking second and third for Pb levels in lichens near the ancient city walls where traffic intensity and complex topographic conditions play an important role in determining metal concentrations. The canyon configuration of these streets and low traffic speed limit contaminant dispersal. Slow-moving traffic releases relatively large Pb particles (with diameters greater than 5 μm) that deposit very close to the roadside (Hughes *et al.* 1980). The pattern of Al in the study area was very similar to that of Pb, reflecting resuspension of soil by traffic.

CONCLUSIONS

Two different lichen biomonitoring methods were used in this study. The air quality pattern in Siena was determined on the basis of the frequencies of different species of epiphytic lichens (i.e. using their species-specific sensitivity to the complex mixture of phytotoxic pollutants in the urban environment). The distribution of trace elements was evaluated quantitatively by analysing thalli of a tolerant species, known to be a reliable bioaccumulator of persistent atmospheric pollutants.

Traffic was found to be the main source of atmospheric pollution in Siena; however, air quality and trace element deposition pattern did not always coincide. Essentially, IAP values reflected the emission of gaseous phytotoxic pollutants in the urban environment (i.e. zones with higher traffic density and/or slow-moving traffic), whereas the significantly higher concentrations of Al, Ba, Cr, Cu, Fe, Pb and S and in urban lichens showed a distribution mainly determined by the street topography and particulate resuspension processes.

In conclusion, the present results show that lichens may be used as indicators of air quality and as biomonitors of trace element pollution in complex urban environments, enabling pin-pointing of high risk areas.

ACKNOWLEDGEMENTS

This work was funded by the Regione Toscana, Dipartimento della Sanità e delle Politiche per la Salute (Grant 231/A) and Siena Parcheggi SpA.

REFERENCES

Al-Chalabi, A.S. & Hawker, D. (1996): Retention and exchange behaviour of vehicular lead in street dust from major roads. *Sci. Total Environ.* **187:** 105–119.

Ammann, K., Herzig, L., Liebendörfer, L. & Urech, M. (1987): Multivariate correlation of deposition data of eight different air pollutants to lichen data in a small town in Switzerland. *Adv. Aerobiol.* **51:** 401–406.

Bargagli, R. (1989): Determination of metal deposition patterns by epiphytic lichens. *Toxicol. Environ. Chem.* **18:** 249–256.

Bargagli, R. (1995): The elemental composition of vegetation and the possible incidence of soil contamination of samples. *Sci. Total Environ.* **176:** 121–128.

Bargagli, R., Iosco, F.P. & D'Amato, M.L. (1987): Zonation of trace metal accumulation in three species of epiphytic lichens belonging to the genus *Parmelia. Cryptogamie, Briol. Lichénol.* **8:** 331–337.

Bargagli, R., Gasparo, D., Lazzarin, A.G., Olivieri, O. & Tretiach, M. (1991): Lichens as indicators and monitors of atmospheric pollutants in NE Italy: preliminary data on the integrated testing system. *Botanika Chronika* **10:** 977–982.

Brown, H.D. (1995): Physiological and biochemical assessment of environmental stress in bryophytes and lichens. In: Munawar, M. *et al.* (eds.): *Bioindicators of Environmental Health*, pp. 29–44. SPB Academic Publishing, Amsterdam.

Brown, H.D. & Avalos, A. (1993): The role of calcium in intracellular cadmium uptake by the lichen *Peltigera membranacea. Ann. Bot.* **71:** 429–438.

Castello, M., Nimis, P.L., Alleteo, D. & Bellio, M.G. (1994): Biomonitoring of SO_2 and metal pollution with lichens and barks in Savona (N Italy). *Boll. Soc. Adr. Sci.* **75:** 61–83.

Cislaghi, C. & Nimis, P.L. (1997): Lichens, air pollution and lung cancer. *Nature* **387:** 463–464.

De Sloover, J. (1964): Vegetaux epiphytes et pollution de l'air. *Rev. Quest. Scient.* **25:** 531–561.

Gasparo, D., Castello, M. & Bargagli, R. (1989): Biomonitoraggio dell'inquinamento atmosferico tramite licheni. Studio presso un inceneritore (Macerata). *Studia Geobot.* **9:** 153–250.

Herzig, R., Liebendörfer, L., Urech, M., Ammann, K., Cuecheva, M. & Landolt, W. (1989): Passive biomonitoring with lichens as part of an integrated biological measuring system for monitoring air pollution in Switzerland. *Intern. J. Environ. Anal. Chem.* **35:** 43–57.

Hughes, M.K., Lepp, N.W. & Phipps, D.A. (1980): Aerial heavy metal pollution and terrestrial ecosystems. *Adv. Ecol. Res.* **11:** 218–327.

Kabata-Pendias, A. & Pendias, H. (1984): *Trace Elements in Soils and Plants*. CRC Press, Boca Raton.

Lee, D.S., Garland, J.A. & Fox, A.A. (1994): Atmospheric concentrations of trace elements in urban areas of the United Kingdom. *Atmos. Environ.* **28:** 2691–2713.

Liebendörfer, L., Herzig, R., Urech, M. & Ammann, K. (1988): Evaluation und kalibrierung der Schweizer flechten-indikationsmethode mit wichtigen luftschadstoffen. *Staub Reinhalt. Luft.* **48:** 233–238.

Lyons, J.M., Chandra, V., Hafner Main, H. & Friedlander, S.K. (1993): Size distribution of trace metals in the Los Angeles atmosphere. *Atmos. Environ.* **27:** 237–249.

Monaci, F. & Bargagli, R. (1995): Biomonitors as a tool to evaluate trace element deposition in complex urban environments. *Proceedings of the 10th World Clean Air Congress, Helsinki*, 28 May–2 June **2:** 238–241.

Nicholson, K.W. (1988): A review of particle resuspension. *Atmos. Environ.* **22:** 2639–2651.

Nimis, P.L. (1990): Air quality indicators and indices: the use of plants as bioindicators for monitoring air pollution. In: Colombo, A.G. & Premazzi, G. (eds.): *Proceedings of the Workshop on Indicators and Indices for Environmental Impact Assessment and Risk Analysis*, pp. 93–126. JRC, Ispra, May 1990. EUR 13060 EN.

Nimis, P.L., Lazzarin, G., Bargagli, R., Benedet, A., Castello, M., Gasparo, D., Lausi, D., Olivieri, S. & Tretiach, M. (1989): I licheni come bioindicatori di inquinamento atmosferico nell'area di Schio-Thiene-Breganze (VI). *Boll. Mus. Civ. St. Nat. Verona* **16:** 1–154.

Nimis, P.L., Lazzarin, A. & Gasparo, D. (1991): Lichens as bioindicators of air pollution in the Veneto (NE Italy). *Studia Geobot.* **11:** 3–77.

Nimis, P.L., Castello, M. & Perotti, M. (1993): Lichens as bioindicators of heavy metal pollution. A case study at La Spezia (N Italy). In: Markert, B. (ed.): *Plants as Biomonitors. Indicators for heavy metals in the terrestrial environment*, pp. 265–284. VCH, Weinheim.

Nriagu, J.O. (1989): A silent epidemic of environmental metal poisoning. *Environ. Pollut.* **50:** 139–161.

Olmez, I., Cetin Gulovali, M. & Gordon, G.E. (1985): Trace element concentrations in lichens near a coal-fired power plant. *Atmos. Environ.* **19:** 1663–1669.

Recchia, F., Castello, M. & Gasparo, D. (1993): Biomonitoraggio dell'inquinamento atmosferico tramite licheni nella provincia di Pescara. *Studia Geobot.* **13:** 313–348.

Sloof, J.E. (1993): *Environmental lichenology: biomonitoring trace-element air pollution.* Thesis, Delft University of Technology, Delft.

Sloof, J.E. (1995): Lichens as quantitative biomonitors for atmospheric trace-element deposition, using transplants. *Atmos. Environ.* **29:** 11–20.

Zechmeister, H.G. (1995): Correlation between altitude and heavy metal deposition in the Alps. *Environ. Pollut.* **89:** 73–80.