Environ Monit Assess (2011) 182:375–383
DOI 10.1007/s10661-011-1882-4

Air quality monitoring system using lichens as bioindicators in Central Argentina

Cecilia Estrabou · Edith Filippini · Juan Pablo Soria · Gabriel Schelotto · Juan Manuel Rodriguez

Received: 7 August 2010 / Accepted: 25 January 2011 / Published online: 19 February 2011

Abstract Air quality studies with bioindicators have not been well developed in South America. In the city of Córdoba, there are not permanent air pollutant measurements by equipment. In order to develop an air quality biomonitoring system using lichens, we applied a systematic sampling in the city of Córdoba, Argentina. A total of 341 plots were sampled in the area of the city which is a square of 24 × 24 km. In each sample plot we selected three phorophytes and estimated the frequency and cover of lichen species growing at 1.5 m on trunks. We also calculated the Index of Atmospheric Purity (IAP) using lichen frequencies. Maps with number of lichen species, cover values, and IAP were performed. The lichen community was described with nine species where *Physcia undulata* and *Physcia endochryscea* were the most frequent. Moreover, these two species were dominant in the community with the highest cover index. The central area of the city is considered a lichen desert with poor air quality. The southeast and northwest areas of the city showed the highest IAP values and number of species. In general, the city shows fair air quality and few areas with good and very good air quality.

Keywords Urban · GIS · Air pollution · Lichen community · IAP

C. Estrabou (✉) · E. Filippini · J. P. Soria · G. Schelotto · J. M. Rodriguez
Centro de Ecología y Recursos Naturales Dr. R. Luti, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, Av. Vélez Sarsfield 299, Córdoba, Argentina
e-mail: cecilia.estrabou@gmail.com

J. M. Rodriguez
CONICET, Consejo Nacional de Investigaciones Científicas y Técnicas, Córdoba, Argentina

Introduction

Hundreds of works have been published in the last decades using lichens as air quality bioindicators and showing pollution data by gaseous pollutants, like that which is summarized by Conti and Cecchetti (2001) and Hawksworth et al. (2005). Nevertheless, in South America, this early stage of air quality analysis with bioindicators studies has not been well developed. Relatively few works have been carried out in urban areas and concerned communities (Anze et al. 2007; Calvelo et al. 2009; Estrabou 1998; Martins et al. 2008).

Hi-tech gaseous pollutant measurement systems are expensive. In addition, they are frequently destroyed by vandalic actions. Thus, it is difficult to obtain data in a permanent way if obtainable at all. This is the case of the city of Córdoba, where data come from previous years and no updated one are recorded. An alternative system for measuring air quality is imperative.

Developed in 1968, the Index of Atmospheric Purity (IAP) quantifies environmental conditions using lichens as bioindicators. It also relates the number of species of a sampling site to its sensitivity to stressing environmental factors, mainly air pollution (De Sloover and LeBlanc 1968). Then diverse modifications arose from the original formula of the IAP, for example the Index of Poleotolerance was developed in Estonia (Trass 1973)—a comparable model to the IAP but with a value of poleotolerance.

In order to eliminate the influence of different substrates on the IAP, Moore (1974) introduced the Index of Lichen Abundance. Thus, several modifications of IAP's original formula have been suggested in numerous studies in the world. Asta et al. (2002) presented the first attempt to develop a directive that incorporates several different methodologic approaches in IAP18, with a vision of wide application at European level.

In this paper, we develop an air quality monitoring system based on the use of lichens, for the whole city of Córdoba, Argentina, using the IAP approach and geographic information system methodology. Moreover, we discuss the response of lichen species to different environments in the city.

Methods and materials

Study area

Córdoba city is located in the center of Argentine and it has an irregular topography with a surface of 576 km^2 and 440 m height above sea level. The climate is subhumid and there is 790 mm annual average precipitation concentrated in summer. Annual average temperature is 17.4°C and winds come predominantly from the north and south (National Meteorological Service). Currently, the city has a population of 1,300,000 inhabitants according to 2008 census.

Nowadays, 532,896 vehicles circulate around the city 213,000 more than in 1999 according to Transit Control Center Córdoba Townhall. The great amount of automotive traffic is the main cause of air pollution (Bravo 1977). Industrial pollution ranks in second place. Moreover, Córdoba's topography favors polluting agents accumulation due to the fact of being in the Suquia River's valley, which is surrounded by mountains, diminishes the action of winds giving place to an important concentration of polluting agents in the city (Kopta 1999).

As in any large city, a general environmental quality impairment is present which is mirrored in the loss of water and air quality along with the disappearance of green spaces.

Methodology

A systematic sampling was conducted based on 576 sample stations. They were disposed regularly on 1-km side cells grid. Within each cell, a radius of 200 m around the central point of each plot was determined and three phorophytes were selected (Fig. 1).

Average values of coverage and frequency of lichen species were obtained in 359 sampled plots—representing 1,077 phorophytes registered—the remaining 217 were not sampled because of different restrictions like the difficult access or lack of substrate.

The coverage and distribution of the lichen species are partly influenced by size and species of phorophyte (McCarthy 2004). Consequently, the selected phorophytes, alive or dead, had to fulfill the following requirements: rough and appropriate crust to carry lichens (LeBlanc and De Sloover 1970), diameter of the trunk greater to 10 cm, not injured.

In order to find each tree, the methodology suggested by Asta et al. (2002) was followed. To measure the total coverage and every lichen species coverage, digital photography was used (McCarthy and Zaniewski 2001; Purvis et al. 2002; Wetmore 1981). These ones were taken on a grid of 20 × 20 cm placed on the southwestern side of the trunk at 1.5 m from the ground (Estrabou 1998). Coverage values were determined on photographs as a percentage.

Data analysis

Even though working with the same phorophytes throughout the city is advisable, this is not

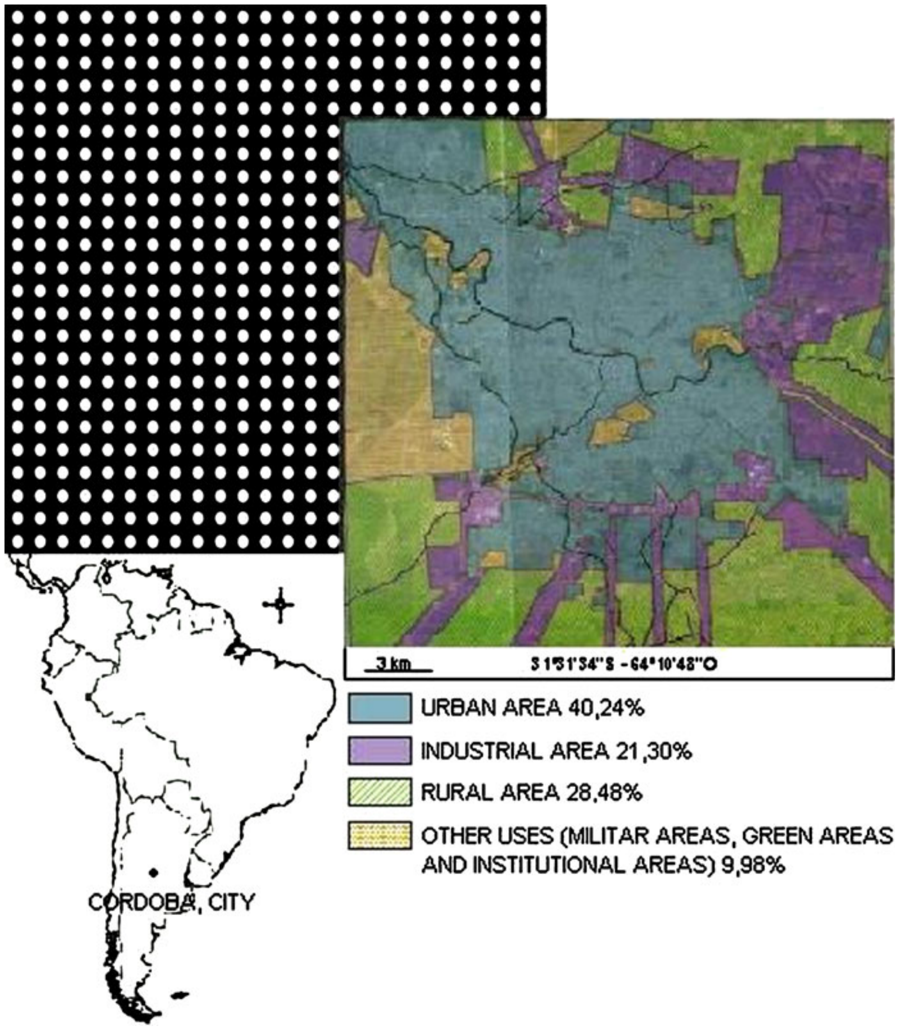

Fig. 1 Córdoba county with a land-use map (modified from Cordoba Urban Zoning Direction 2007) and the sampling grid used with 576 sample stations (*circle cells*). Each cell is 200 m radius around a central point

possible in Córdoba city due to a predominance of different species of trees in each area. Thus, only those species of phorophytes with no significant differences (Kruskal–Wallis test, Infostat v. 2009) in lichen coverage in similar environmental conditions were considered. As a consequence, the selected phorophytes for this study were *Melia azedarach*, *Fraxinus americanus*, *Acer negundo*, *Tabebouia* spp., *Tipuana tipu*, *Robinia pseudoacacia*, *Acacias* spp., *Prosopis* spp., *Ulmus* sp., *Ligustrum* sp., *Celtis tala*, *Aspidosperma quebracho-blanco*, and *Populus* spp. The phorophytes *Pinus* spp., *Jacaranda mimosifolia*, *Morus alba*, *Salix* spp., and *Quercus humboldtii* were not considered for the sampling and they were found in 18 sample plots.

An Index of Atmospheric Purity was calculated in each of the 341 sampled plots. It was based on the sum of frequencies of epiphytic lichen species on three phorophytes trail, according with the following formula (Herzig and Urech 1991):

$$\text{IAP}: \sum_{1}^{n} F$$

Coverage, number of species, and IAP data were assembled in maps using Geographic Information System IDRISI Andes program, version 15.00.

Table 1 List of recorded families and species of lichens, their growth forms and responses to atmospheric pollution

Species	Growth forms	Response to atmospheric pollution
Family Physiaceae		
Physcia undulata Moberg	Foliose	Resistant
Physcia endochryscea Kremp.	Foliose	Resistant
Family Candelariaceae		
Candelaria concolor (Dicks.) Stein.	Crustose	Resistant
Family Parmeliaceae		
Parmotrema pilosum (Stizenb.) Elix & Hale	Foliose	Tolerant
Punctelia microsticta (Müll. Arg.) Krog	Foliose	Tolerant
Parmotrema reticulatum (Taylor) Hale & A. Fletcher	Foliose	Tolerant
Family Ramalinaceae		
Ramalina celastri (Spreng) Krog & Swinscow	Fruticulose	Sensitive
Family Teloschistaceae		
Teloschistes cymbalifer (Meyen) Müll.	Fruticulose	Sensitive
Family Collemataceae		
Leptogium cyanescens (Ach.) Körb	Foliose	Sensitive

Results

Nine epiphytic lichen species with different growth habits and different response to pollution were found around the county of Córdoba city (Table 1).

Furthermore, a map with the number of species sampled for the 341 plots is presented in Fig. 2.

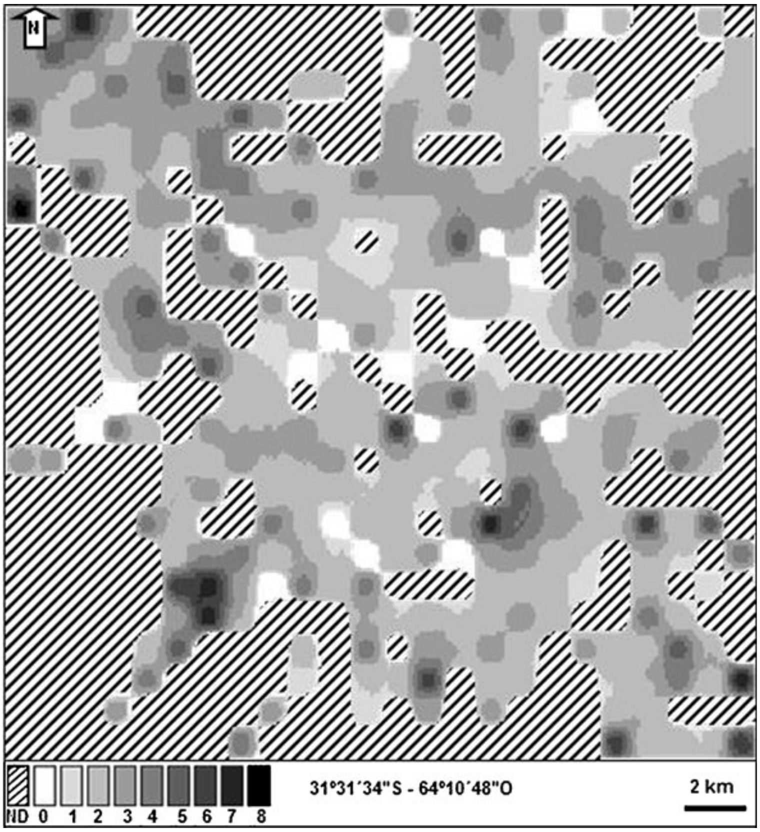

Fig. 2 Map of Córdoba county with the number of species in each sample plot. *Lines* correspond to plots not sampled

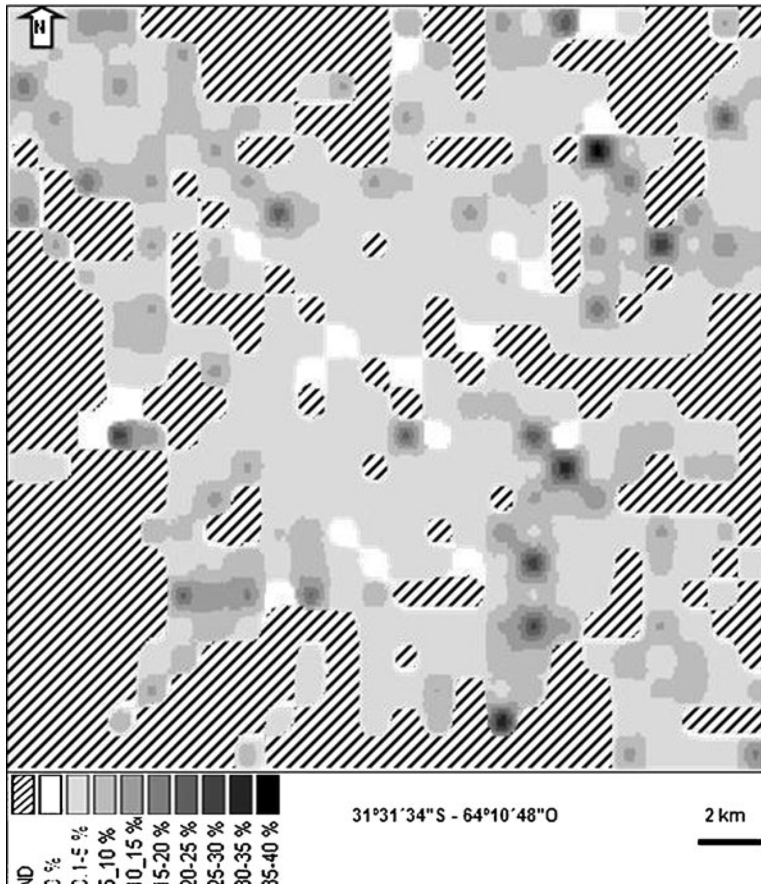

Fig. 3 Map of Córdoba county with the average lichen coverage in each sample plot. *Lines* correspond to plots not sampled

Lichens were absent in 18 of the 341 sampled plots whereas a single species was found in 102 plots and six, seven, or eight species were found only in 14 sampled plots.

In order to estimate the total lichen coverage, 341 plots were sampled where 146 plots showed coverage values ranging between 0% and 2%; 141 plots between 2% and 10%; 40 plots between 10% and 20%; and 14 plots above 20% (Fig. 3).

A map with the Index of Atmospheric Purity—pollution isolines—was obtained from frequency values of lichen species recorded in each sample plot (Fig. 4).

Out of 341 sampled plots, 302 plots showed less than three IAP values (fair and poor air quality). Only 39 plots had equal to or greater than three IAP values (good and very good air quality; Table 2).

Discussion

A lichen desert—where phorophytes trunks are devoid of lichens—located in the central area of the county is clearly demarcated. Intermediate and outer zones are intermingled forming a puzzle that is not coincident with the delimitation of the three areas proposed by Sernander (1926) and Hawksworth and Rose (1970) or the demarcation of lichen zones reported by Kauppi and Halonen (1992).

We suggest a continuous critical area corresponding to the 59 sampling plots with IAP values between 0 and 1. According to the IAP scale developed in the present work, air quality in most of the area of Córdoba city could be estimated as fair because 302 out of 341 total sampled plots registered less than three IAP values and only 38

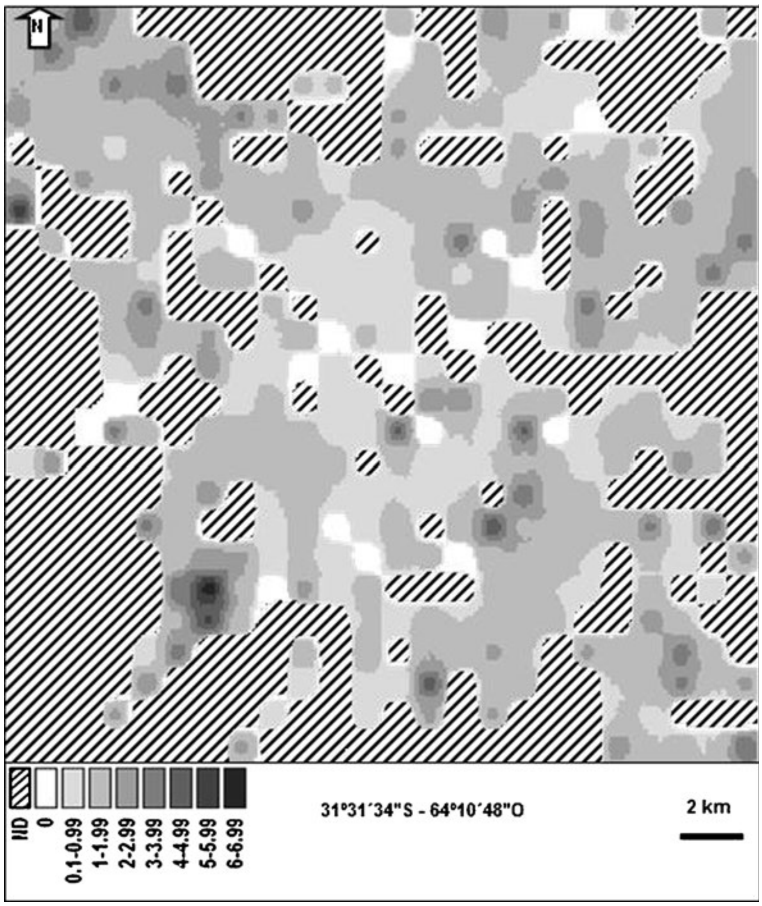

Fig. 4 Map of Córdoba county with the Index of Atmospheric Purity obtained from frequency of lichen species recorded in each sample plot. *Lines* correspond to plots not sampled

plots showed equal to or greater than three IAP values.

Air quality is assessed by means of the diversity and frequency of the community of lichen species named as "poor-fair-good-very good", quantitatively by an index—the IAP. In a city with scarcity of lichens (a total of nine species), the presence of each one is considered as very important, so, the IAP is ranked taken into account changes in each species. Comparison is only possible if certain preconditions are met: either the survey areas to be compared are situated in regions for which the same assessment matrix applies or the sampled trees belong to species, whose barks have similar properties (VDI 3957 2004).

Therefore the results are difficult to compare. For example, Gombert et al. (2003) recorded 83 epiphytic lichen species in Grenoble, southeast France, and the IAP values varying from 5.9 to 71.7, with the same formula of IAP applied for us. Stamenkovic et al. (2010) recorded 19 species of lichens in the city of Dimitrovgrad (Serbia) and the IAP values varied from 1 to 3.

It was observed that sampling sites with high IAP values were in correspondence with those

Table 2 Number of sampled plots, air quality, and its correspondence with the different IAP-range

Sampled plots	IAP range	Air quality
65	$0 \leq$ IAP <1	Poor
237	$1 \leq$ IAP <3	Fair
34	$3 \leq$ IAP <5	Good
5	$5 \leq$ IAP <7	Very good

particular sites with more than six epiphytic lichen species. These plots are located in the northwest of the city—the area with highest density of vegetation (Fig. 1)—and the southeast—neighborhoods with lots of trees on the sidewalks and large squares. Low and very low IAP values can be found in the lichen desert—downtown—and in the northeast of the city. We suggest that the use of pesticides and chemical fertilizers in crops that are frequent there can be an admissible explanation to these low IAP values based on the increase in cover values at these stations with low IAP (Fig. 3).

The northeast and southeast of the city were the areas that exhibited the highest total coverage values. These values are important to reinforce IAP data. However, they are not reliable in the assessment of air quality. Many sampling plots showed high coverage values (Fig. 3) for the nitrophilous lichens *Physcia undulata* and *Physcia endochryscea*, however, these sample plots showed low IAP values (Fig. 4). Therefore the presence of these species indicates bad air quality due to the presence of nitrogen oxides (Estrabou 1998). Likewise, studies have shown the relationship between the presence of fertilizers source and the rise of nitrophilous species (Davies et al. 2007; Frati et al. 2007; Loppi and De Dominicis 1996).

Both the number of lichen species map and IAP map are very similar. Thus, it can be suggested that plots with a high species richness of epiphytic lichens are related to sites with high air quality.

Physcia undulata, the species with higher coverage values, is mostly present in each sample plot. *P. endochryscea* is the second most abundant species. Both are resistant and highly frequent in areas surrounding downtown together with *Candelaria concolor*. This species is also resistant. However, it is heliophilous and it is absent in shady areas. Remarkable others species of Physciaceae and *C. concolor* have been reported with a similar behavior in Europe (Nimis 1987; Nimis and Tretiach 1995; VDI 3957 2004), Bolivia (Canseco et al. 2006), and Costa Rica (Monje-Nájera et al. 2002; Saenz et al. 2007).

Parmotrema pilosum, *Punctelia microsticta*, *Parmotrema reticulatum*, and *Leptogium cyanescens* are tolerant species that begin to appear in peripheral zones.

Ramalina celastri and *Teloschistes cymbalifer* were observed having a similar pattern; disappearing in the most polluted areas and becoming more abundant in those areas further from pollutant emission sources (traffic, industries, etc.). The presence of these species indicate very good air quality, confirming their behavior as sensitive species. Morphological (Estrabou et al. 2004) and physiological (Gonzalez et al. 1996) damage have been demonstrated on *R. celastri* exposed to polluted areas.

Estrabou et al. (2005) found similar patterns in the composition and coverage of the lichen communities between the city of Córdoba and the Salinas Grandes which is a depression with poor vegetation and salty environment, with high temperatures and lack of suitable substrates. Both hostile environments present a similar lichen communities composition.

In the last 10 years, we have observed an important decrease in the number of lichen species which accounts for a 50% since 1998 (Estrabou 1998). We consider that this drastic reduction is a consequence of a huge increase in road traffic. According to Córdoba Townhall, the number of cars in 2009 was 532.896 in a city with 1.3 million inhabitants. As Stein and Toselli (1996) argue, the main cause of air pollution in big cities is the large amount of road traffic, specifically, the use of private, individual cars.

This air quality monitoring system was incorporated to the Córdoba Townhall agenda and will be apply once a year to obtain air quality indicators for the county. In general, the actual situation reflects poor air quality for the whole city.

References

Anze, R., Franken, M., Zaballa, M., Pinto, M. R., Zeballos, G., Cuadros, M. A., et al. (2007). Bioindicadores en la detección de la contaminación atmosférica en Bolivia (online). *Redesma, 1*(1), 53–74.

Asta, J., Erhardt, W., Ferretti, M., Fornasier, F., Kirschbaum, U., Nimis, P. L., et al. (2002). Mapping lichen diversity as an indicator of environmental quality. In P. L. Nimis, C. Scheidegger, & P. Woseley

(Eds.), *Monitoring with lichens—monitoring lichens, NATO science series IV, earth and environmental sciences* (pp. 273–279). Dordrecht: Kluwer Academic Publishers.

Bravo, V. (1977). *El impacto de la contaminación del aire provocada por los automóviles*. C.I.F.C.A. Fundación Bariloche.

Calvelo, S., Baccalá, N., & Liberatore, S. (2009). Lichens as bioindicators of air quality in distant areas in Patagonia (Argentina). *Environmental Bioindicators, 4*, 123–135.

Canseco, A., Anze, R., & Franken, M. (2006). Comunidades de líquenes: Indicadores de la calidad del aire en la ciudad de La Paz, Bolivia. *Acta Nova, 3*(2), 286–306.

Conti, M. E., & Cecchetti, G. (2001). Biological monitoring: Lichens as bioindicators of air pollution assessment—A review. *Environmental Pollution, 114*, 471–492.

Cordoba Urban Zoning Direction (2007). *Urban zoning plan 2007*. Córdoba Townhall.

Davies, L., Bates, J. W., Bell, J. N. B., James, P. W., & Purvis, W. O. (2007). Diversity and sensitivity of epiphytes to oxides of nitrogen in London. *Environmental Pollution, 146*(2), 299–310.

De Sloover, J., & LeBlanc, F. (1968). Mapping of atmospheric pollution on the basis of lichen sensitivity. In R. Misra, & B. Gopal (Eds.), *Proceeding of the symposium on recent advances in tropical ecology, international society for tropical ecology* (pp. 42–56). Varanasi: Banaras Hindu University.

Estrabou, C. (1998). Lichen species identification and distribution according tolerance to airborne pollution in the city of Córdoba, Argentina. In M. P. Marcelli, & M. R. D. Seaward (Eds.), *Lichenology in latin america: History, current knowledge and applications* (pp. 165–169). São Paulo: CETESB.

Estrabou, C., Stiefkens, L., Hadid, M., Rodríguez, J. M., & Pérez, A. (2004). Effects of air pollutants on morphology and reproduction in four lichen species. *Ecología en Bolivia, 39*(2), 33–45.

Estrabou, C., Stiefkens, L., Hadid, M., Rodríguez, J. M., & Pérez, A. (2005). Estudio comparativo de la comunidad liquénica en cuatro ecosistemas de la Provincia de Córdoba. *Boletín de la Sociedad Argentina Botanica, 40*(1–2), 1–10.

Frati, L., Santoni, S., Nicolardi, V., Gaggi, C., Brunialti, G., Guttová, A., et al. (2007). Lichen biomonitoring of ammonia emission and nitrogen deposition around a pig farm. *Environmental Pollution, 146*(2), 311–316.

Gombert, S., Asta, J., & Seaward, M. R. D. (2003). Assessment of lichen diversity by index of atmospheric purity (IAP), index of human impact (IHI) and other environmental factors in an urban area (Grenoble, southeast France). *Science of the Total Environment, 324*(1–3), 183–199.

Gonzalez, C. M., Casanovas, S. S., & Pignata, M. L. (1996). Biomonitoring of air pollutants form traffic and industries employing *Ramalina ecklonii* (Spreg.) Mey. And Flot. in Córdoba, Argentina. *Environmental Pollution, 91*(3), 269–277.

Hawksworth, D. L., & Rose, F. (1970). Qualitative scale for estimating sulphur dioxide air pollution in England and Wales using epiphytic lichens. *Nature, 227*, 145–227.

Hawksworth, D. L., Iturriaga, T., & Crespo, A. (2005). Líquenes como bioindicadores inmediatos de contaminación y cambios medio-ambientales en los trópicos. *Revista Iberoamericana Micologia, 22*, 71–82.

Herzig, R., & Urech, M. (1991). Flechten ald Bioindikatoren. *Bibliotheca Lichenologica, 43*, 1–283, *30*, 1–297.

Kauppi, M., & Halonen, P. (1992). Lichens as indicators of air pollution on Oulu, northern Finalnd. *Annales Botanica Fennici, 29*, 1–9.

Kopta, R. F. (1999). *Problemática Ambiental con Especial Referencia a la Provincia de Córdoba*. Córdoba: Fundación Ambiente Cultura y Desarrollo ACUDE.

LeBlanc, F., & De Sloover, J. (1970). Relation between industrialization and the distribution and growth of epiphtyic lichens and mosses in Montreal. *Canadian Journal of Botany, 48*(8), 1485–1496.

Loppi, S., & De Dominicis, V. (1996). Effects of agriculture on epiphytic lichen vegetation in central Italy. *Israel Journal of Plant Science, 44*, 297–307.

Martins, S., Käffer, I., & Lemos, L. (2008). Liquens como bioindicadores da qualidade do ar numa área de termoelétrica, Rio Grande do Sul, Brasil. *Hoehnea, 35*(3), 425–433.

McCarthy, D. (2004). *The Hamilton Lichen Survey 2004*. St. Catharines: Brock University, Departments of Earth Sciences and Biology.

McCarthy, D. P., & Zaniewski, K. (2001). Digital analysis of lichen cover: A technique for use in lichenometry and liquenology. *Arctic, Antarctic and Alpine Research, 33*(1), 107–113.

Monje-Nájera, J., González, M. I., Rivas Rossi, M., & Méndez-Estrada, V. H. (2002). Twenty years of lichen cover change in a tropical habitat (Costa Rica) and its relation with air pollution. *Revista de Biología Tropical, 50*(1), 309–319.

Moore, C. C. (1974). A modification of the “Index of Atmoshperic Purity” method for substrate differences. *The Lichenologist, 6*, 156–157.

Nimis, P. L. (1987). I macrolicheni d’Italia chiavi analitiche per la determinazione. *Gortania, Atti del Museo Friulano di Storia Naturale, 8*, 101–220.

Nimis, P. L., & Tretiach, M. (1995). The lichens of Italy—A phytoclimatical outline. *Cryptogamic Botany, 5*(2), 199–208.

Purvis, O. W., Erotokritou, L., Wolseley, P. A., Williamson, B., & Read, H. (2002). A photographic quadrat recording method employing image análisis of lichens as an indicador of enviromental change. In P. L. Nimis, C. Scheidegger, & P. Woseley (Eds.), *Monitoring with lichens—monitoring lichens, NATO science series IV, earth and environmental sciences* (pp. 337–341). Dordrevht: Kluwer Academic Publishers.

Saenz, A. E., Flores, F., Madrigal, L., & Di Stefano, J. F. (2007). Estimación del grado de contaminación del aire por medio de la cobertura de líquenes sobre troncos de árboles en la ciudad de San José, Costa Rica. *Brenesia, 68*, 29–35.

Sernander, R. (1926). *Stockholms natur*. Upsala: Almquist and Wiksells.

Stamenkovic, S., Cvijan, M., & Arandjelovic, M. (2010). Lichens as bioindicator of air quality in Dimitrovgrad (South-eastern Serbia). *Archives of Biological Sciences Belgrade, 62*(3), 643–648.

Stein, A. F., & Toselli, B. M. (1996). Street level air pollution in Córdoba city, Argentina. *Atmospheric Environmental, 30*, 3941–3945.

Trass, H. (1973). Lichen sensivity to air pollution and index of poleotolerance (I.P.). *Folia Cryptogamica Estonica, 3*, 19–22.

VDI 3957 (2004). *Biological measurement procedures for determining and evaluating the effects of ambient air pollutants on lichens (bio-indication). Mapping the diversity of epiphytic lichens as indicators of air quality*. Part 13. Beuth Verlag GmbH, Alemania.

Wetmore, C. M. (1981). Lichens and air quality in Big Bend National Park, Texas. *Bryologist, 84*(3), 426–433.