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Abstract: Uso del Sistema de Información Geográfica y líquenes para mapear la contaminación del aire en una ciudad tropical: San José, Costa Rica. There are no studies of air pollution bio-indicators based on Geographic Information Systems (GIS) for Costa Rica. In this study we present the results of a project that analyzed tree trunk lichens as bioindicators of air pollution in 40 urban parks located along the passage of wind through the city of San Jose in 2008 and 2009. The data were processed with GIS and are presented in an easy to understand color coded isoline map. Our results are consistent with the generally accepted view that lichens respond to the movement of air masses, decreasing their cover in the polluted areas. Furthermore, lichen cover matched the concentration of atmospheric nitrogen oxides from a previous study of the same area. Our maps should be incorporated to urban regulatory plans for the city of San José to zone the location of schools, hospitals and other facilities in need of clean air and to inexpensively assess the risk for breast cancer and respiratory diseases in several neighborhoods throughout the city. Rev. Biol. Trop. 61 (2): 557-563. Epub 2013 June 01.

Key words: air quality color code, environmental monitoring, dispersion mapping, lichenology.

Even though most lichen bioindicator studies have been done in temperate regions, lichens have also been used as bioindicators in tropical cities, albeit infrequently. For example, a recent review of lichen biomonitoring studies conducted in one of the largest tropical countries, India, found that despite the obvious advantages of this technique, it has seldom been used in that country (Shukla & Upreti 2012). The same applies to other tropical ecosystems and therefore, studies with lichens as bioindicators from tropical regions have special value (Monge-Nájera *et al*. 2002b, Anze *et al.* 2007).

Old methods like the Index of Air Purity (IAP) require more work and time than new methods such as the Random Points Method (Monge-Nájera *et al*. 2002a,b), but even so they old methods are still used (e.g. Fernández-Salegui *et al*. 2003, McCarthy *et al*. 2009, Käffer *et al*. 2011, Estrabou *et al*. 2011). In Europe, the IAP has been replaced by the European standard methodology (Llop *et al*. 2011). A lichen standard cannot be produced for the tropics for lack of updated taxonomic studies (Hawksworth *et al*. 2005), but fortunately bioindication does not need identification to the species level and the method of Monge-Nájera *et al*. (2002a,b) is adapted to the ecological and financial conditions of tropical countries.

Lichen bioindication has shown that air pollutants follow air currents in large and small scales. For example, the topographic conditions make the Columbia River Gorge an 'exhaust pipe' for air pollutants, which is reflected in deposition and lichen thallus nitrogen (Fenn *et al*. 2007). Some lichens have evolved resistance to particular contaminants and therefore their presence is not evidence of clean air (Fenn *et al*. 2007).

To our knowledge, the oldest use of a Geographic Information System (GIS) to analyze

and predict traffic pollution was by Mor-agues & Alcaide (1996), who quantified the human population, wildlife and historic sites affected by different pollution levels, albeit without using lichens. In the field of applied lichenology, GIS have more recently been used to follow the lichen re-colonization of the once highly polluted Ruhr Basin in Germany (Kricke & Beige 2004), and to map lichen species distribution in Germany and Italy (Loppi 2004), but despite its potential (Wei *et al*. 2012) the technique is surprisingly rare in studies of how pollution changes with the evolution of cities (Monge-Nájera *et al*. 2002a,b, Shochat *et al*. 2006).

Specifically in Costa Rica, where this study was conducted, the law states that the use of natural resources must be sustainable, including greenhouse gases and gases that affect the ozone layer (Costa Rica 1993). The use of lichens as bioindicators in Costa Rican ecosystems started in the 1970s with the work of Luis Fournier and collaborators, who used transplants, cell counts and natural communities to assess the air pollution across eleven stations in San José, the capital city (Méndez & Fournier 1980). A decade later, colonies of the European standard lichen, *Hypogymnia physodes*, were transplanted from Germany to San José, Costa Rica where they survived for months and acquired the appearance of the surrounding local lichens. Thus, from the point of view of biomonitoring, the local species reacted to air pollution like the European standard lichen (Grüninger & Monge-Nájera 1988). Subsequently, it was shown that primary and secondary school students could learn to properly assess air pollution in their tropical communities by simply measuring lichen cover on urban tree trunks, as inspired by the data previously collected in European high schools (Méndez-Estrada *et al*. 1999).

Another study conducted in Costa Rica but designed for world-wide use, compared three methods to measure lichen cover on tree trunks: (1) the 100 uniform squares template traditionally used in North America, (2) the European 200 uniform points template and (3) computer-generated random points templates (10cm X 20cm), utilizing a 100-point or a 50-point version. The 50 random points template was the best because it reduced time and costs by nearly 50% while maintaining acceptable reliability values (Monge-Nájera *et al*. 2002b).

The only study in Costa Rica that analyzed the species composition of urban lichen communities found that low cover sites had species resistant to vehicle gases (Sáenz *et al*. 2007); these were predominantly foliose species with narrow lobes (*Physcia* and *Dirinaria*) and the crustose *Lecanora* (a lichen with relatively lower contact air surface). In the beginning of the 21st century, the average lichen cover in the Eastern part of San José was 36%, a relatively high value that probably reflected a reduction of lead in gasoline and an increase in green areas (Monge-Nájera *et al*. 2002a, Sáenz *et al*. 2007).

The most recent study in Costa Rica analyzed 40 parks located along the passage of wind through San José (Neurohr *et al*. 2011). The study corroborated the hypothesis that air pollution was lower in areas where the wind entered the city and viceversa. It also found that dry season cover was lower, a pattern that contrasts with temperate habitats, which are more influenced by temperature than by rain (Neurohr *et al*. 2011).

The aim of this article is to complement the previous study (Neurohr *et al*. 2011) with a detailed GIS map of air pollution and to compare published atmospheric nitrogen oxides (NO_x) levels with our lichen cover data. Our hypotheses are that pollution is heterogeneous along the city and that nitrogen oxide levels match pollution reflected in lichen cover.

MATERIALS AND METHODS

The city of San José, Costa Rica (9°56'16'' N - 84°06'55'' W) is located at a mean altitude of 1 200m on what was originally a tropical forest. The rainy season is from May through November (around 2 000mm) and temperatures usually range from 20°C to 28°C. The central

region, represented in our study, had 350 000 inhabitants in 2010 (Municipalidad de San José 2010, Tribunal Supremo de Elecciones 2011), and has nearly 200 small parks, many of them with lichens on the tree trunks.

We studied the lichen cover on tree trunks in a computer-generated random sample of 40 parks located in the central part of the city. Instead of considering the taxonomic constitution of the community, which is not reliable because the taxonomy of these tropical species has not been updated, we decided to include only the overall cover of foliose lichens, which is a reliable method (Monge-Nájera *et al.* 2002b).

To measure the lichen cover we used a 10x20cm template with random points, applying it 1.5m above ground to the side with greater lichen coverage; see Monge-Nájera *et al.* (2002b) for a detailed description and validation of this method, and Neurohr *et al*. (2011) for a statistical analysis of lichen cover in relation to the wind path.

Lichen cover values were processed with ArcGIS (V 9.3) software to produce a GIS map of pollution isolines with a color code that can be understood by the general public. The most familiar of these codes is the traffic light, associating red with danger, yellow with intermediate conditions, and green with safety. The isoline algorithm used is based on the uniform distribution of the value differences between two adjacent points.

For comparison, we produced a map of nitrogen oxides based on data from the University of Costa Rica Foundation for Research (FUNDEVI) (2007). The FUNDEVI study used a United States Environmental Protection Agency dispersion model to map nitrogen pollution in the San José urban zone (FUNDEVI 2007). We applied a Binomial test (quantitativeskills.com) to the hypothesis that the nitrogen and lichen maps matched; for this, we divided each map into 180 square cells and selected 90 cells with a random number generator (the chosen cells were the same of both

maps to make matching possible). We then recorded if the pollution level in each cell was low, intermediate or high. If the level was the same in both maps, we noted it as a match, and viceversa. The results in quantitativeskills.com indicated that the minimal sample size for the test was 17 cells, thus our sample of 90 cells was high above the minimum sample size.

RESULTS

The areas of San José, Costa Rica with low lichen cover -reflecting higher levels of air pollution- are located in three main sections. A smaller section in the West of the city around the Mata Redonda neighborhood; a larger section surrounding the hospital and market areas of Carmen, Catedral, Hospital and Merced (extending North to San Francisco and Calle Blancos), and another small section in Southeast area that includes San Pedro and Curridabat (Fig. 1).

The area with higher lichen cover -and less pollution- is located in the Northeast, where the dominating winds enter the city, and matches the densely populated neighborhoods of Anselmo Llorente, Guadalupe, San Rafael, Sabanilla and Mata de Plátano (Fig. 1). This is a positive finding considering that large numbers of middle and low class people live in this part of the city.

A statistical comparison of the lichen and nitrogen map (Fig. 2) indicates that lichen cover matches the air concentration of nitrogen oxides: 72 of the 90 cells in which we divided the maps, have the same level of air pollution (Binomial test p<0.0001).

The areas of Calle Blancos, Mata Redonda, downtown San José, San Pedro, Curridabat, San Sebastián and San Francisco de Dos Ríos have the lowest means of lichen cover, and consequently the highest levels of pollution. The lowest levels of nitrogen oxides were recorded in Guadalupe and Sabanilla, which correspondingly resulted in increased levels of lichen cover (Figs. 1 and 2).
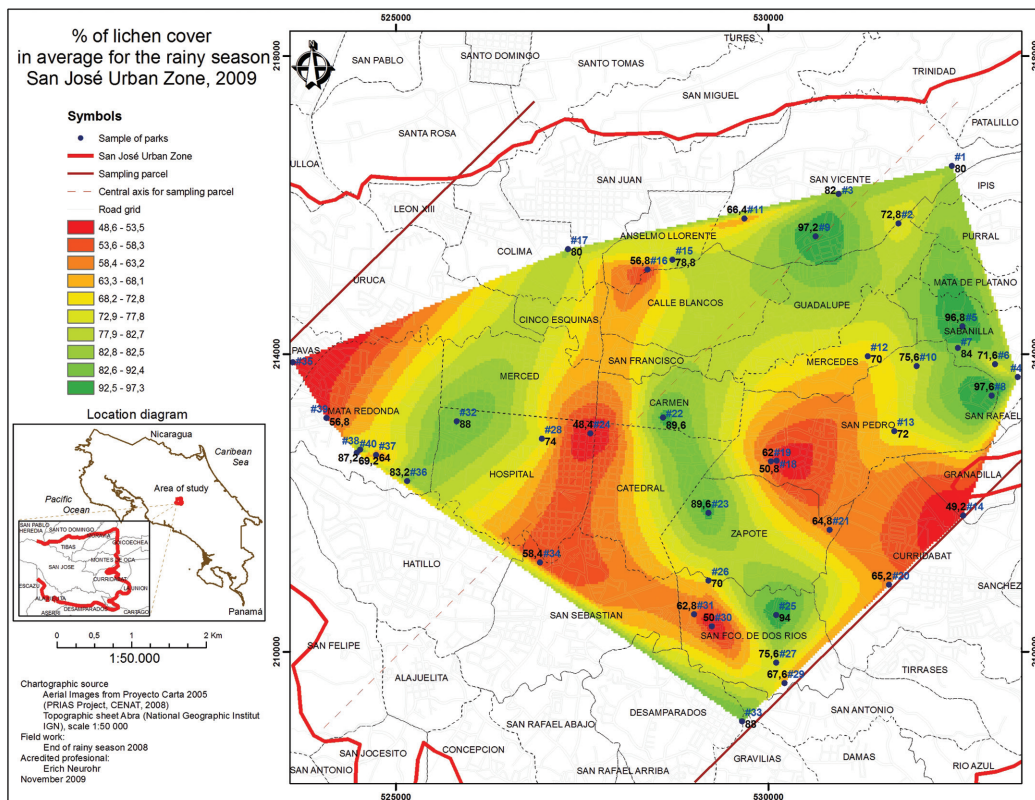
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Fig. 1. Lichen cover isoline map for San José, Costa Rica, during the rainy season. Red areas on the map indicate higher levels of air pollution where lichen cover is low. Yellow areas indicate intermediate levels of pollution and lichen cover. Green areas indicate low levels of air pollution (high lichen cover). Blue numbers near dots indicate sampling site number in our database and black numbers mark the mean lichen cover at the sampling site.

DISCUSSION

The lichen cover that we found in San José has a clear relation with the nitrogen oxide levels of pollution from automotive traffic origin. Automobiles are the primary source of urban air pollutants in cities such as San José, with low levels of industrial development (Pujol 2002). Our results differ from research conducted in heavily industrialized cities, in which the lower lichen cover values are strongly associated with the location of factories and other industrial facilities (Chiras 2006, Wannaza *et al.* 2012). These associations are in agreement with our results since San José is used for commerce and services, rather than for factories and industrial activities. In the case of San José, it is advantageous that some densely populated areas of the city have low levels of air pollution.

Our study not only adds to the recent but growing list of projects that use GIS to study air pollution through lichens in urban areas (Conti & Cecchetti 2001, Shochat *et al.* 2006), but for Costa Rica and Latin America it is innovative by presenting isolines that were mathematically produced by GIS rather than by a more subjective interpretation from sampling points as done in earlier research (Méndez & Fournier 1980, Monge-Nájera *et al.* 2002a, Kricke & Beige 2004, Ferreira *et al.* 2012).

In conclusion, our hypotheses that pollution is heterogeneous along the city and that vehicular pollutants match lichen cover are in

Fig. 2. Air concentration of nitrogen oxides (NO$_x$) in San José, Costa Rica (based on data from the public source Fundevi 2007); hatching on the map indicates areas of greater overlap between NO$_x$ and lichen data.

agreement with the data we obtained. Furthermore, we encourage the use of isoline maps to present better distribution results for large area studies regarding lichen biomonitoring, as done by other recent researchers such as Ferreira *et al.* (2012) for pollution from cement factories. We believe the laypersons would benefit from the "traffic light" color code maps: these can help them identify areas with higher levels of pollutants to persuade the authorities to take measures for improving air quality. Our color code GIS maps of air pollution should be incorporated when developing urban regulatory plans for the city of San José: the location of schools, hospitals and other facilities in need of clean air can be zoned appropriately, and traffic routes can be changed to mitigate the harmful effects of the atmospheric pollution on the urban inhabitants (Fuga *et al.* 2008).

Nitrogen oxides are particularly important because they are indicators for traffic-related air pollution and because there is a connection between post-menopausal breast cancer and exposure to nitrogen dioxide (Crouse *et al.* 2010). The way in which lichen cover corresponds with air concentration of nitrogen oxides in San José, as found in the present study, can be utilized to inexpensively and rapidly assess the risk for breast cancer in several neighborhoods throughout the city.

Real-time pollution maps in cellular telephones allow drivers to avoid undesirable routes (Ehrlich 2009). If the cost of real time systems were reduced to levels affordable for tropical countries, this might be the first real alternative to lichen biomonitoring. Until then, lichens are the most realistic option for Latin America, Africa and other predominantly

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tropical regions. A third option is a web portal where users can add their own biomonitoring lichen data to demographic and socio-economic indicators (Centre for Development Finance 2010).

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RESUMEN

En Costa Rica no hay estudios de la contaminación del aire basados en los Sistemas de Información Geográfica (SIG). En este artículo se muestran los resultados de un estudio que analizó los líquenes en troncos de árboles de 40 parques urbanos situados a lo largo del paso del viento por la ciudad de San José, durante los años 2008 y 2009. Los datos fueron procesados mediante SIG y se presentan de manera simple en un mapa de isolíneas con códigos de color. Los resultados concuerdan con la opinión generalmente aceptada de que los líquenes reaccionan ante la circulación de masas de aire al decrecer su cobertura en las zonas más contaminadas. Además, la cobertura de líquenes coincidió con la concentración de óxidos de nitrógeno en la atmósfera, tomada de un estudio previo en la misma zona. Nuestros mapas deben incorporarse en los planes reguladores de la ciudad de San José para zonificar la ubicación de escuelas, hospitales y otros edificios que demanden aire puro, así como para identificar de manera económica el riesgo de cáncer de pecho y enfermedades respiratorias en los diferentes barrios de la ciudad.

Palabras clave: calidad del aire, código de color, bioindicadores, monitoreo ambiental, mapa de dispersión, ciudad tropical, liquenología.

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