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Epiphytic macrolichens in Seoul: 35 years after the first lichen study in Korea

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Abstract

Many lichens have been used as bioindicators for air pollutants such as SO_2. The first ecological study on lichens in Korea was conducted in 1975 by Kim and Lee, disclosing that areas adjacent to the center of Seoul were lichen deserts. Air quality in Seoul has improved significantly since the 1980s. However, the distribution of lichen species has not been reevaluated since then. We examined the spatial and temporal pattern of lichen distribution by selecting six (inner city green [ICG] and four (outer city green [OCG]) sites, based on the distance from the city center of Seoul and the land use pattern. The change in lichen distribution was related to yearly mean concentrations of SO_2, NO_2, and O_3 for the years 1980-2009. Four and 13 lichen species were found in ICGs and OCGs, respectively. Although mean sample numbers per species were much higher in the former, species richness tended to increase with distance from the city center. Since 1980, SO_2 has declined drastically to < 0.01 ppm in both ICGs and OCGs, indicating that SO_2 is no longer a limiting factor for lichen establishment and growth. In contrast, NO_2 has increased steadily for 20 years (1989-2009) and a considerable proportion of lichen species in both ICGs and OCGs are known as nitrophilic or pollution-tolerant species. Appearance of nitrophiles in both ICGs and OCGs and the dominance of a few lichen species in ICGs may reflect the effects of the increase in NO_2. In contrast to SO_2 and NO_2, O_3 was higher in OCGs, but it was difficult to identify a causal relationship between O_3 and lichen distribution.

Key words: air pollutants, bioindicator, lichens, Seoul, temporal and spatial variation

INTRODUCTION

Air pollutants clog urban cities; thus, it is difficult to judge the quality of the atmosphere with just a few components. In this case, we can judge air quality by analyzing the response of species to several air pollutants in consideration. In particular, epiphytic macrolichens on tree bark are excellent air pollution bioindicators. For example, they receive nutrition and moisture through the thallus surface, and they have long lives. They also are able to concentrate pollutants, because they do not have cuticles and deciduous parts (Nash 2008). Therefore, epiphytic macrolichens have been used as air pollution bioindicators since lichen extinction was first observed in Paris (Nylander 1866, cited in Hawksworth and Rose 1970).

Until the mid-late 20th century, many studies revealed that a high concentration of SO_2 disturbs the growth of lichens (Hawksworth and Rose 1970, Sugiyama et al. 1976, Eversman 1978, McCune 1988, Nimis et al. 1990). Results of these studies also indicated that lichen loss was con-

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spicuous near the city center or pollution sources. For example, 129 lichen species within 16 km of London became extinct between 1800 and 1970 (Laundon 1970). Conversely, the number of lichen species tended to increase with distance from the city center. In a study in London, Rose and Hawksworth (1981) showed that areas in the atmosphere with SO_2 > 0.04 ppm (120-130 μg/m^3) were lichen deserts where lichen existence was impossible. Interestingly, lichens are recolonizing areas that used to be lichen deserts (Henderson-Sellers and Seaward 1979, Rose and Hawksworth 1981, Hawksworth and McManus 1989, Bates et al. 1990, Seaward 1997).

Although SO_2 has decreased recently, nitrogen oxides (NOx) such as NO and NO_2, and O_3 have been increasing. The change in air pollutants has been accompanied by a decrease in *Lecanora conizaeoides* in North America and Europe, which is an SO_2-tolerant species (Bates et al. 2001, Hauck et al. 2001), as well as an increase in pollution-tolerant species such as *Phaeophyscia orbicularis*, *Physcia adescendens,* and *Xanthoria parietina* (Seaward 1997) and nitrophilic species such as *Candelaria concolor* and *Phaeophyscia rubropulchra* (Sigal and Nash 1983, de Bakker 1989, Jovan and McCune 2005). Furthermore, global warming acts as a new threat to symbiotic lichens (Geiser and Neitlich 2007). Reports of changes in lichen distribution and air quality are occurring simultaneously in urban and natural environments, suggesting that multi-disciplinary approaches to lichens are necessary.

According to the first ecological study on Korean lichens by Kim and Lee (1975), areas within 5 km of Gwanghwamun (city center hereafter) were lichen deserts. By 1991, this area expanded to 15 km from the city center and coincided with areas that had an SO_2 concentration > 0.01 ppm (Kim 1991). Considering the phytotoxic effects of SO_2 on lichens, their results revealed that air quality in Seoul was quite poor from 1970-1980. However, the Clean Air Act was enacted in 1990, leading to a decrease in SO_2 concentration in Seoul. Specifically, the concentration has decreased after 1991 to < 0.04 ppm and has been maintained < 0.01 ppm since 1998 (Ministry of Environment 2010). Assuming 0.04 ppm SO_2 as a tolerance limit, it would take approximately 5 years for an epiphytic lichen on rocks such as *Lecanora muralis* to establish in an environment (Henderson-Sellers and Seaward 1979). If so, the lichens that became extinct due to their SO_2 sensitivity could have become reestablished by now in Seoul.

In Korea, lichen studies have been conducted on the distribution in relation to pollution centers (Lee et al. 1993, 1994, Yu et al. 1995, Chu and Kim 1998, Kim and Kang 2001), selection of bioindicator species in response to air pollution sources (Hur and Kim 2000), and taxonomic diversity (Park 1990, Ka et al. 1997, Moon 1998). However, the extent of lichen studies is very limited. Thus, analyses have not been conducted on whether lichens have established themselves in inner city greens (ICGs), and, if they have, what species have done so, what lichens exist outside the city, and what the species composition and richness are in comparison to Kim and Lee (1975). The spatial and temporal patterns of lichen distribution are critical data to set standards for Seoul's atmosphere policy and for an overall evaluation of nature conservation policy.

In this study, we attempted to solve the following questions: 1) In Seoul, do species composition and richness differ between inner and outer city greens (OCGs)?; 2) Are there any changes in species composition and richness since the initial study conducted 35 years ago?; 3) Are the particular lichens' temporal and spatial distributions related to the level of SO_2, NO_2, or O_3?

MATERIALS AND METHODS

Study sites and sampling

Seoul is located in the center of the Korean Peninsula (126°59" E, 37°34" N) and is 30.30 km long and 36.78 km across with a total area of 605.52 km^2. The Han River flows through the center of the city, crossing in a west to east direction. Namsan stands close to the center of the city. Twenty-six mountains border the edge of the city (Seoul Metropolitan Government 2010). According to climate data (30 year average from 1971-2000), Seoul's mean temperature is 12.2°C, relative humidity is 66.8%, yearly rainfall is 1,344 mm, and yearly mean wind speed is 2.4 m/s (Korea Meteorological Administration 2001).

Lichen investigations were conducted in areas that matched the following three criteria: 1) green areas located 5, 10, 15, and 20 km from the city center; 2) areas that were formed long enough ago for lichens to have become established; 3) areas where studies have been conducted previously, so that temporal comparisons would be possible. Consequently, we selected the following ten sites, six within and four outside a 10 km radius from the city center (Fig. 1). Six ICGs (Boramae Park, Chandeokgung, Dosan Park, Namsan Park, Samnung Park, and Sangdo Park) were selected from parks and palaces with long histories of greens located in areas with a relatively high level of air pollution (Oh and Chung 2007). Four OCGs (Bukhansan, Cheonggyesan, Gwanaksan, and Suraksan)

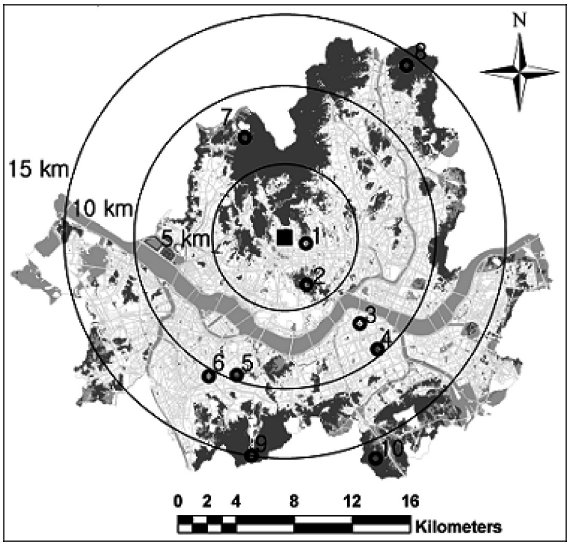

Fig. 1. Location of the city center (■) and ten study sites in Seoul, Korea. Numbers represent sites: 1, Chandeokgung; 2, Namsan; 3, Dosan Park; 4, Samnung Park; 5, Boramae Park; 6, Sango Park; 7, Bukhansan; 8, Suraksan; 9, Gwanaksan; 10, Cheonggyesan.

were chosen from outer Seoul. Bukhansan is located within 10 km from the city center but is treated as an OCG because of its ecological value as a national park.

We collected epiphytic macrolichens on tree bark in May-June 2010. We searched entire trails for ICGs and investigated trees on some of the hiking paths for the OCGs. We spent almost similar time sampling at each site. Sampling was conducted < 2 m from the ground, largely in the southern part of trees ranging from the southeast to southwest sides. ICG samples were taken from an average of 6.4 tree species per site, e.g., *Zelcova serrata, Ginkgo biloba*, and *Acer palmatum*, whereas OCGs were from an average of 4.0 tree species per site, e.g., *Pinus densiflora*, *P. rigida,* and *Z. serrata*. Finally, we collected 133 samples: 84 from ICGs and 49 from OCGs. The lichens we obtained were stored at -20°C until they were prepared as specimens. We rinsed the samples with distilled water and removed extraneous material to prepare the specimens. Then, we dried the samples with dry towels and compressed lightly in old newspaper. The specimens were finally prepared by repeating the drying/compressing procedure. Specimens were stored in Sungshin Women's University Plant Herbarium. Although some previous studies (e.g., Kim and Kang 2001) included lichens on various substrates, we decided to focus on epiphytic macrolichens on tree bark. The species of lichens were confirmed using monographs (Hale 1969, Yoshimura 1994, Brodo et al. 2001). We used new names for cases in which the lichen species name had been changed. For example, *Cladonia bacillaris* was changed to *C. macilenta*.

Lichen identification

Specimens were identified based on exterior characteristics and a chemical composition analysis. We examined the thallus and reproductive structures and conducted chemical analyses following the color test (Nylander 1866), microcrystal tests (Asahina 1937), and thin layer chromatography (Culberson 1972).

Data analysis

Following LeBlanc and De Sloover (1970), we calculated the ecological index, *Q*, to reflect the number of species coexisting with a particular lichen species at each site:

$$Q = \frac{\sum Sn_i}{Sn}$$

where *Sn* indicates the number of sites in which a certain species appeared, and Sn_i indicates the number of species coexisting with that species at a particular site. The spatial pattern of lichen distribution was examined by comparing lichen species collected at ICGs and OCGs in 2010. The relationship between lichen abundance and types of greens (ICGs and OCGs) was tested using the X^2 test for the four abundant species with samples ≥ 8 (*Candelaria concolor, Cladonia macilenta, Phaeophyscia hispidula*, and *Physciella melanchra*). We used the Pearson's correlation analysis to understand the lichen distribution patterns with respect to the distance from the city center. We compared these results with lichens examined in previous studies to examine the lichen temporal distribution pattern (e.g., Kim and Lee 1975) to the 2010 data.

We obtained data on air pollutants (SO_2, NO_2, and O_3) during the past 20 years (1989-2009; 1980-2009 for SO_2) (Ministry of Environment 2010). Air quality monitoring in Seoul began at ten stations in 1989 but has been conducted at 27 stations since 1998. We used the data from the station closest to each site, and when there were two stations close to the same site (e.g., Changdeokgung and Namsan), we used the mean values. To determine whether significant changes occurred in air quality since 1989, we conducted paired *t*-test analyses to compare the air pollutant levels between the initial three years (1989-1991) versus the recent three years (2007-2009) using overall means derived from all stations in Seoul. Most ICGs were close to roads and a number of people passed by the areas, leading to little difference between values recorded from stations nearby. Thus, in the case of the ICGs, we obtained both the initial and recent 3-year mean data for SO_2, NO_2, and O_3 from nearby stations. Indeed, four ICGs had 20 years of data. In contrast, even the closest station recorded significantly different values from values recorded within forests in the case of OCGs (Yoo 2008). Only two (Bukhansan since 1999, Gwanaksan since 2009) of the four OCGs had stations within forests, and we used the 3-year mean data derived from stations within the forests. We conducted the Wilcoxon two-sample test to identify the relationship between Seoul's ICG and OCG air quality and species richness; the significance of the t and Z statistics was examined with a one-tailed test.

RESULTS

Lichen spatial distribution pattern

The 133 epiphytic macrolichens collected from ten sites were composed of four families, seven genera, and 13 species (Table 1). The 84 samples collected from six ICGs were composed of four species from two families with a mean of 2.5 species per site (range, 2 to 3 species) and a mean of 21 samples per species. With the exception of *Candellaria concolor* (Candelariaceae), the other three species belonged to Physciaceae and mostly coexisted in ICGs. Although *C. concolor* only appeared in Bukhansan, the other three species were found together in at least two OCGs. Therefore, although the ICG species richness was quite low, little difference in species composition was observed with the exception of *Phaeophscia rubropulchra*.

In the OCGs, there were 49 samples (13 species in four families) with means of 12 samples and 5.5 species per site (range, 2 to 8 species) and a mean of 3.8 samples per species. In addition to the two families observed in the ICGs, two additional families (Cladoniaceae and Parmeliaceae; three and six species each) were observed as well. Of these nine species, *Cladonia macilenta* and *Myelochroa aurulenta* were found in almost all OCGs, whereas the other species were found only at particular sites. Overall, Bukhansan (eight species), Suraksan (seven species), and Cheonggyesan (five species) all had species richness twice as high as that of the ICGs, whereas Gwa-

Table 1. Lichen species and the number of lichen samples collected at each site in Seoul

	Inner city green						Outer city green				
	Boramae Park (9.8)	Changdeok -gung (1.5)	Dosan Park (7.7)	Namsan Park (2.9)	Samnung Park (9.8)	Sangdo Park (10.4)	Bukhan -san (7.2)	Cheong -gyesan (16)	Gwanak -san (14.8)	Surak -san (18)	*Q*
Candelariaceae											
Candelaria concolor	2	2	1	1	1		1				3.67
Cladoniaceae											
Cladonia chlorophaea									3		2
Cladonia macilenta							3	3	8	5	5.5
Cladonia ochrochlora										1	7
Parmeliaceae											
Myelochroa aurulenta							1	2		1	6.67
Myelochroa entotheiochroa										1	7
Myelochroa hayachinensis							1				8
Myelochroa irrugans										1	7
Parmotrema clavuliferum							1				8
Punctelia rudecta							1				8
Physciaceae											
Phaeophyscia hispidula	1	3			7	1		3		1	3.83
Phaeophyscia rubropulchra				1			1	3			5.33
Physciella melanchra	13	13	15	9	10	5	1	2		4	4
Species richness	3	3	2	3	3	2	8	5	2	7	

Ecological index *Q* is provided for each species. Distance (km) from the city center of Seoul is indicated within parentheses.

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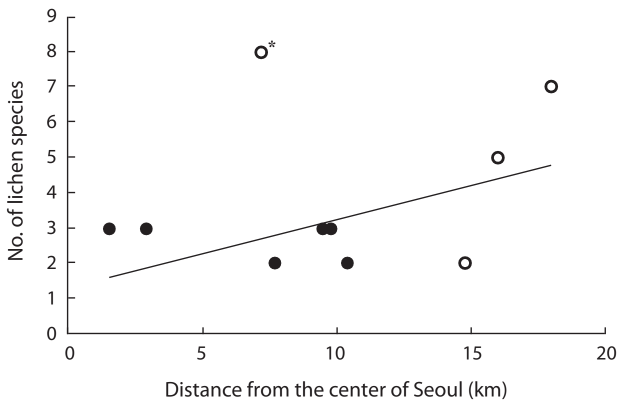

Fig. 2. Relationship between the number of lichen species found at each site and its distance from the center of Seoul (r = 0.34, P = 0.3402). A regression line was drawn to indicate the linear trend upon deleting a single outlier site with an asterisk (Bukhansan). ●, inner city green; ○, outer city green.

naksan only had two congeneric species (*C. chlorophaea* and *C. macilenta*).

The abundance per site of the four most abundant species (*Candelaria concolor, Cladonia macilenta*, *Phaeophyscia hispidula, and Physciella melanchra*) was not much different between the ICGs and OCGs (mean number of samples = 14.2 vs. 12.0). However, there was a tendency that a particular species occurred at a certain site (X^2 = 63.23, P < 0.0001, N = 115). *C. macilenta* was not found in ICGs, but was found four times more than the expected value of the OCGs. *P. melanchra* was found in both ICGs and OCGs, comprising 54.1% of the samples. However, it occurred slightly more frequently than the expected value in ICGs, and much less than that of OCGs. Species (except for *C. macilenta*) found only in OCGs were usually only spotted once per site. The ecological index, *Q,* was as low as 2 (*C. chlorophaea*) to 8 (*M. hayachinensis, P. clavuliferum*, and *P. rudecta*) (Table 1). With the exception of *C. chlorophaea*, which was only found in Gwanaksan, species that appeared in OCGs had a higher *Q* (range, 5.5 to 8) than those found in both OCGs and ICGs (range, 3.67 to 5.33).

The distance from the city center was not significantly correlated with species richness (r = 0.34, P = 0.3402). However, excluding Bukhansan, the tendency for increasing species richness with distance from the city center was marginally significant (Y = 0.191X + 1.310, r = 0.63, P = 0.0719) (Fig. 2).

Lichen temporal distribution pattern

Some of the ten sites examined in this study had also been studied in previous studies (Table 2). Three lichen species each were found in ICGs such as Chandeokgung and Namsan, which were previously lichen deserts. *C. concolor* and *P. melanchra* were found at both sites, whereas *Parmotrema clavuliferum* and *Phaeophyscia rubropulchra* were present at only one site (Table 1). Just two OCG species (*Cladonia macilenta* and *C. chlorophaea*) were observed in Gwanaksan, eight in Bukhansan, and seven in Suraksan, which was more (one species reported in Suraksan [Lee et al. 1994]) or less (17 species reported in Bukhansan [Moon 1998]) than previous studies (Table 3). Thus, five of the eight species in Bukhansan were common in this study and that of Moon (1998). In contrast, only a single species of the seven species in Suraksan was also found in Lee et al. (1994) (Table 3).

Change in SO_2, NO_2, and O_3 atmospheric concentrations

Fig. 3 shows that the mean concentrations of air pollutants in Seoul have changed greatly with time. SO_2 was 0.094 ppm in 1980 but decreased drastically to 0.006 ppm after 2000, just 6% of 1980, and has been maintained at a similar level since that time. NO_2 was 0.027 ppm in 1989 but increased 1.3 times by 2009 to 0.035 ppm. During the same period, O_3 increased 2.6 times, from 0.008 ppm to

Table 2. Record of sites examined in lichen studies in Seoul since 1975

	Inner city green						Outer city green			
	Boramae Park	Chang -deokgung	Dosan Park	Namsan Park	Samnung Park	Sangdo Park	Bukhan -san	Cheonggye -san	Gwanak -san	Surak -san
Kim and Lee 1975		+		+			+		+	
Lee et al. 1993				+					+	
Lee et al. 1994										+
Moon 1998							+			

+ indicates sites that were also examined in this study.

Table 3. Comparison of lichen species among studies conducted since 1975 at three sites in Seoul

	Bukhansan					Gwanaksan					Suraksan				
	Kim and Lee 1975	Lee et al. 1993	Lee et al. 1994	Moon 1998	2010	Kim and Lee 1975	Lee et al. 1993	Lee et al. 1994	Moon 1998	2010	Kim and Lee 1975	Lee et al. 1993	Lee et al. 1994	Moon 1998	2010
Anzia japonica	+		+	-	-	+	-			-					
Candelaria concolor	-			+	+										
Cetrelia nuda	+			-	-										
Cladonia caespiricia	-			+	-										
Cladonia chlorophaea	-		-	+	-	-	-			+			+		-
Cladonia humilis	-			+	-										
Cladonia macilenta	-		-	+	+	-	+			+			+		+
Cladonia ochrochlora	-			+	-								-		+
Cladonia pleurota	-			+	-										
Cladonia ramulosa	-			+	-										
Cladonia subconistea	-			+	-										
Cladonia sp. 22													+		-
Menegazzia terebrata	+		+	-	-	+	-			-					
Myelochroa aurulenta	-			-	+								-		+
Myelochroa entotheiochroa													-		+
Myelochroa hayachinensis	-			+	+										
Myelochroa irrugans	-			+	-								-		+
Myelochroa leucotyliza	-			+	-										
Parmotrema clavuliferum	-			-	+										
Parmotrema tinctorum	+		+	-	-	+	-			-					
Phaeophyscia hirtuosa	-			+	-										
Phaeophyscia hispidula	-			+	-								-		+
Phaeophyscia rubropulchra	-			+	+										
Physciella melanchra	-			+	+								-		+
Punctelia rudecta	-			-	+										
Pyxine limbulata	-			+	-										
Stereocaulon sp.1													+		-
Xanthoparmelia piedmontensis													+		-

Among the sites examined in previous studies, only three sites possess information on lichen species that could be compared with those in this study (under the 2010 column). + and - represent presence and absence of each lichen species.

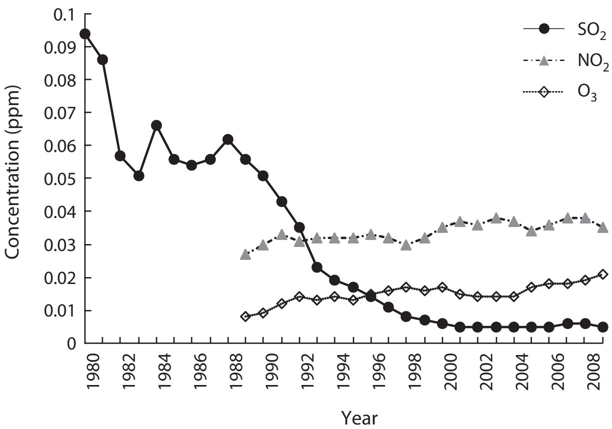

Fig. 3. Mean concentration (ppm) of air pollutants in Seoul from 1989 to 2009 (1980 to 2009 for SO_2).

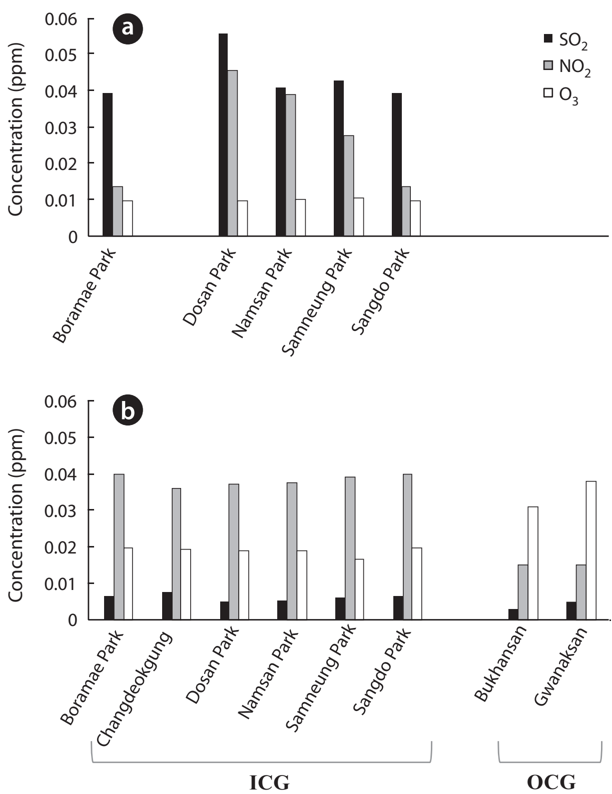

Fig. 4. Mean concentration (ppm) of air pollutants (a) during the initial 3 years (1989-1991) at the four inner city greens (ICGs) and (b) during the recent 3 years (2007-2009) at the six ICGs and two outer city greens (OCGs).

0.021 ppm. Comparing data from the initial 3 years to the recent 3 years, SO_2 was the only pollutant that decreased (paired t-test: $t = 9.45$, $P < 0.0001$). NO_2 increased marginally ($t = -2.11$, $P = 0.0543$) and O_3 increased significantly ($t = -15.20$, $P < 0.0001$). Considering only four ICGs with 20 year records of air pollutants, the temporal pattern of air pollutants was similar to that based on the overall means in Seoul (SO_2 $t = 7.16$, $P = 0.0056$; O_3 $t = -11.74$, $P = 0.0013$) (Fig. 4a). Yet the marginal significance of the NO_2 increase disappeared most likely due to small sample size ($t = -0.63$, $P = 0.5755$).

The recent 3-year mean concentrations of air pollutants differed slightly or considerably between the ICGs and OCGs (Fig. 4b). Regardless of green type, SO_2 concentration decreased greatly compared to that in the 1980s. However, it was still slightly higher in ICGs than in OCGs (Wilcoxon two-sample test $Z = -1.51$, $P = 0.0656$; 0.006 ± 0.0010 ppm vs. 0.004 ± 0.0012 ppm). NO_2 concentration was 2.5 times higher in ICGs than that in OCGs ($Z = -1.84$, $P = 0.0326$; 0.038 ± 0.0017 ppm vs. 0.015 ± 0.0002 ppm). In comparison, O_3 concentrations were 1.8 times higher in OCGs than in ICGs ($Z = 1.86$, $P = 0.0318$; 0.019 ± 0.0011 ppm vs. 0.034 ± 0.0052 ppm).

DISCUSSION

This study examined the spatial and temporal changes in lichen distribution by reevaluating the first ecological research on Korean lichens (Kim and Lee 1975). Our results showed that lichens have re-established themselves in ICGs of Seoul, which had been a lichen desert until 1991. However, despite the reestablishment of lichens in ICGs, these are more monotonous in terms of species composition and are lower in species richness than OCGs. For example, four species (2-3 species per site) were found in ICGs, whereas 13 species (5-8 species per site) were observed in OCGs, except for Gwanaksan. Consequently, OCGs such as Bukhansan, Cheonggyesan, and Suraksan possess twice higher species richness than that of the ICGs. An increase in species richness as distance from pollution sources increases has also been observed in other cities in Korea, e.g., Ulsan (Chu and Kim 1998), Yeochun Industrial Estate (Yu et al. 1995), Chongju (Kim and Kang 2001), and Samchonpo Thermoelectric Power Plant (Kim et al. 2004). However, it should be noted that there were significant differences in species composition in the OCGs compared with those in previous studies (Table 3). Such differences either may reflect that air quality is improving (Chu and Kim 1998) or that there is a difference in sampling intensity or species identification among studies. Unfortunately, the specimens from previous studies were not stored; thus, it is impossible to discuss these possibilities.

The distance from Seoul city center does not account completely for lichen species richness. Although

Bukhansan is very close to the city center, it exhibited a relatively higher level of species richness. If lichens are more abundant in old-growth forest than in young forests, and in continuous rather than in fragmented forests (Marmor et al. 2011), we believe that Bukhansan, which is a national park, may provide sufficient habitat for a number of lichens. In contrast, lichen species richness in Gwanaksan was quite low in this study, which agreed with previous studies (Kim and Lee 1975, Lee et al. 1993). As all lichen samples in Gwanaksan were obtained from red pines, low species richness may reflect that red pines with strongly acid bark do not support diverse lichens.

Most lichens are very sensitive to air pollutants, particularly SO_2 (Hawksworth and Rose 1970, Sigal and Nash 1983, van Dobben and ter Braak 1998, Bates et al. 2001). However, as SO_2 concentration decreases, lichen species re-establish themselves, whereas species that have a high requirement for sulfur such as *Lecanora conizaeoides* tend to decrease in abundance (Henderson-Sellers and Seaward 1979, Bates et al. 2001, Hauck et al. 2001). For example, six lichen species in London that were considered extinct for 200 years were found again between 1953 and 1967 (Rose and Hawksworth 1981). Based on the growth rate of lichens, they concluded that the lichens re-established themselves as SO_2 decreased to 50% of their pre-1960 levels or to approximately 0.04 ppm. According to another study, it takes approximately 5 years for epiphytic lichen on rocks, such as *Lecanora muralis*, to re-establish at the same concentration (Henderson-Sellers and Seaward 1979). Kim (1991) suggested that the concentration limit for lichens is 0.01 ppm. SO_2 concentration in Seoul has decreased drastically from 0.094 ppm in the 1980s to 0.04 ppm post-1992 and has been maintained at a level < 0.01 ppm since 1998. However, SO_2 concentration in both ICGs and OCGs is far lower than 0.04 ppm (Rose and Hawksworth 1981), 0.02 ppm (Sugiyama et al. 1976), or 0.01 ppm (Kim 1991). Therefore, the SO_2 concentration in Seoul may not function as a main factor limiting lichen existence, because sufficient time has passed for lichens sensitive to SO_2 to distribute and re-establish. Because current major cities in Korea exhibit similarly low levels of SO_2, we assumed that it does not act as a pollutant restricting lichen distribution in other cities as well.

The increase in NOx, including NO_2, influences many lichens. For example, since approximately 20 years ago, acidophilic lichens have been decreasing in the Netherlands, most likely due to an increase in NOx or NH_3 (van Dobben and ter Braak 1998, 1999, van Herk et al. 2003). When NO_2 concentration is > 0.019 ppm only tolerant species survive, and lichen species richness will decrease further (Davies et al. 2007). In Seoul, yearly mean concentrations of NO_2 have increased by 1.3 times from 1989 to 2009, reaching 0.035 ppm. This is higher than the 0.019 ppm suggested by Davies et al. (2007) or the 0.03 ppm air quality standard in Korea. NO_2 in ICGs contribute greatly to such a high NO_2 concentration (3-year mean for ICGs and OCGs was 0.038 ppm vs. 0.015 ppm). Additionally, the speed at which NO_2 increased was much greater in ICGs than in OCGs.

Tolerant species and/or nitrophilic species that belong to Candelariaceae, Physciaceae, and Teloschistaceae have been found in London (Davies et al. 2007). Four species belonging to Candelariaceae and Physciaceae were also found in Seoul in 2010. Of these four species, *Candelaria concolor* (Perlmutter 2010) and *Phaeophyscia rubropulchra* are nitrophilic species (Geiser and Neitlich 2007, Lawrey 2010). In particular, *C. concolor*, which appeared mostly in ICGs and therefore had low *Q* values, is a tolerant species that occupies lichen desert edges (Conti and Cecchetti 2001). The other two species (*Phaeophyscia hispidula* and *Physciella melanchra*) found in ICGs are also likely to be nitrophilic species and must be studied further. However, the more surprising result is that *M. aurulenta*, *P. rudecta*, and *P. rubropulchra*, which coexist with other species in presumably relatively clean OCGs, are nitrophilic species (Lawrey 2010). Finding nitrogen bioindicators throughout Seoul may indicate that NOx concentration is quite high in all areas from the city center to outer Seoul.

Lichen species diversity decreases linearly with an increase in NOx (Davies et al. 2007). Increases in bark acidity (van Herk et al. 2003) or nutrient accumulation in bark (Davies et al. 2007) may contribute to a reduction in species diversity. In this study, four species abundant in ICGs comprised 101 of the 133 samples. If we assume that sampling efforts did not differ greatly at each site, such observations show that a few nitrophilic species are dominant in Seoul's high NO_2 environment. If acidophilic species are under stress of NH_3 (Jovan and McCune 2005) or NOx (Larsen et al. 2007) deposition, acidophilic species in Gwanaksan such as *C. chlorophaea* and *C. macilenta* (Gombert et al. 2004) may decline further. According to Geiser and Neitlich (2007), it may be difficult to identify the direct effects of NO_2, because SO_2 and NO_2 are often positively correlated with each other. However, this appears not to be the case in Seoul, considering the drastic decrease in SO_2 and considerable increase in NO_2.

O_3 is a secondary pollutant that is generated from a photochemical reaction between NOx and volatile organic compounds (VOC) (Haagen-Smit 1952). The amount of

O_3 in Seoul has steadily increased from 0.008 ppm in 1989 to 0.021 ppm in 2009 but is still below the air quality standard. Although Korea restricts O_3 to a mean of 0.1 ppm/h or a mean of 0.06 ppm/8 h, other countries have additional restrictions limiting the number of days the two aforementioned means rise above these levels (Seoul Metropolitan Government 2010). Considering the destructive effects of O_3 on health and ecology, similar rules may have to be implemented in Korea. In this study, we only considered the yearly means of SO_2, NO_2, and O_3 when analyzing the spatial and temporal patterns of lichen distribution. This is considered a limitation, because it is difficult to fully understand all the effects air pollutants cause with their yearly means, when their effects change seasonally and even daily. It is also notable that an increase in O_3 was much greater in OCGs than in ICGs, which are exposed to a greater amount of automobile exhaust and other combustion activities (recent 3-year means, 0.019 ppm vs. 0.034 ppm). If the amount of biogenic VOCs (BVOCs) released by forests is 10 times greater (Middleton 1995) than anthropogenic petrochemical production and use, and BVOCs are more reactive than anthropogenic VOCs (Stockwell and Kuhn 1998), it is possible that OCGs in Seoul have a greater concentration of O_3 than that of the ICGs. However, despite the importance of BVOCs to oxidizing power of the atmosphere and greenhouse gases and differences in BVOC emission among plant species (e.g., Lim et al. 2011), studies on BVOC in Korea are still in the initial stages. Although it is known that O_3 level does not exert a great influence on lichen diversity (McCune 1988, Nali et al. 2007), several lichen species are sensitive to SOx, NOx, and O_3 (Sigal and Nash 1983, Conti and Cecchetti 2001, Lovett et al. 2009). For example, 0.1 ppm O_3 causes a 50% reduction in photosynthesis of *Flavoparmelina caperata* (Rose and Nash 1983). Considering that O_3 is steadily increasing, it is important to assess the influence of both BVOCs and O_3 on lichens.

The distribution of lichens in Seoul has changed greatly in the past 35 years. In this study, we have been able to deduce the following three results. First, in 2010, the lichen composition and species richness were different between ICGs and OCGs in Seoul. Second, although the species composition was different, this study and previous studies agree in terms of the linear trend between species richness and the distance from the city center. Third, SO_2 is no longer a limiting factor for lichen existence in ICGs and OCGs. Instead, NO_2, whose concentration has steadily increased in the past decades, appears to affect species composition and richness. Unlike SO_2 or NO_2, O_3 level was much higher in OCGs. However, we could not directly relate O_3 to lichen distribution. Diverse approaches using fumigation experiments, factorial designs incorporating multiple pollutants at once, and long-term monitoring are necessary to identify the importance of lichens to an air quality rating system and to evaluate the health of urban, and suburban areas, as well as forests.

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