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Research Paper

Bryophytes as bioindicators of the atmospheric environment in urban-forest landscapes

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ABSTRACT

Bryophytes have been used as indicators to evaluate atmospheric conditions in urban areas. However, further research is needed for their effective application. In this study, we focused on four metrics related to atmospheric problems in urban areas (nitrogen concentration [% N], isotope ratio of nitrogen [δ^{15}N], index of atmospheric purity [IAP], and richness of hygrophilic life-forms [RHL]). Then, using linear and generalized linear models, we examined the influence of land use on these four metrics in urban atmospheric environments, and evaluated the usefulness and limitation of them. The % N and δ^{15}N models were well explained by the influence of nitrogen sources and/or sinks. The RHL models were significantly affected by urban and forest areas, reflecting urban heat islands. Surprisingly, IAP was higher in urban areas, but comparisons of IAP are not informative in areas with narrow pollution gradients. Land use strongly affected % N and δ^{15}N models in smaller areas because of a point-source influence of nitrogen pollution, whereas RHL was strongly influenced by land use at larger scales owing to drought stress in urban settings. Correlations among the metrics revealed that severe drought stress tended to occur in areas with high nitrogen pollution. The nitrogen pollution sources were diverse, with no significant correlation of δ^{15}N values with % N.

1. Introduction

In urban areas, changes in atmospheric environments have caused serious problems for both human health and the ecosystem as a whole (Breitner et al., 2009; Gurjar et al., 2010; Kopáček & Posch, 2011; Organization for Economic Cooperation and Development, 2012; Shibata et al., 2015; The World Meteorological Organization and the International Global Atmospheric Chemistry, 2012). Generally, urban development itself is accompanied by the loss of or decrease in green areas, which often causes forest fragmentation. At the edges of these fragmented forests, pronounced drought stress occurs because light intensity and wind exposure increase (Murcia, 1995). These environmental changes (edge effects) have a negative effect on biodiversity, as drought-sensitive species disappear (Aragón, Abuja, Belinchón, & Martínez, 2015; Gignac & Dale, 2005; Laurance et al., 2006, 2007; Zartman, 2003) and alien species increase (Honnay, Verheyen, & Hermy, 2002; Pauchard & Alaback, 2006). Bettez and Groffman (2013) investigated the effects of urbanization on nitrogen (N) deposition, and revealed that the increase in N deposition was a result of increased amounts of dry deposition associated with stationary sources (e.g., power plants) and mobile sources (e.g., highway vehicles). This increase in N input affects both species composition through changes in competitive biological interactions (Bobbink et al., 2010) and ecological processes (Groffman & Pouyat, 2009; Thomas, Canham, Weathers, & Goodale, 2010).

While environmental evaluation using physicochemical techniques is more accurate and stable than evaluation methods using bioindicators, the use of physical equipment is often costlier and time consuming (Holt & Miller, 2010). In addition, bioindicators also have the following advantages: first, they can convey the cumulative effects of both chemical pollutants and habitat alteration during the life span or residence time of a given organism; second, they can reflect the indirect biotic effects of pollutants; and finally, biotic indices are a more effective means of ecosystem monitoring, as they reflect changes at the ecosystem level (Holt & Miller, 2010).

Bryophytes are one of the most popular taxonomic groups used as bioindicators of atmospheric environments. They are nonvascular plants that can grow on the surfaces of tree trunks or rocks, and generally absorb water and nutrients directly through leaf surfaces from the immediate environment (Dymytrova, 2009; Harmens et al., 2011; Onianwa, 2001; Pearson et al., 2000; Schröder et al., 2010; Zechmeister, Dirnböck, Hülber, & Mirtl, 2007; Zechmeister et al.,

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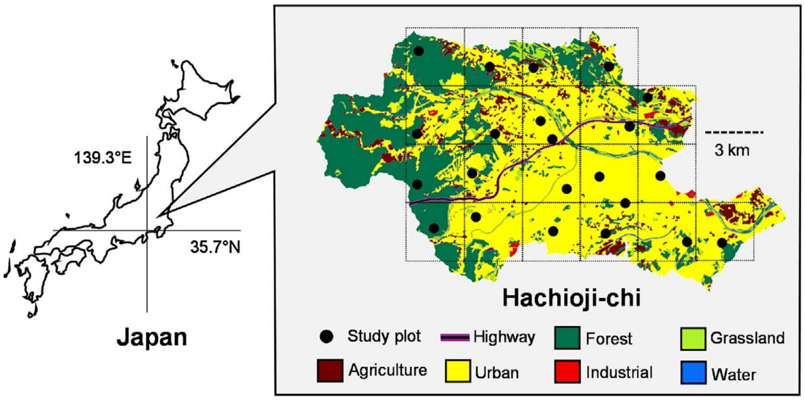

Fig. 1. The study site is located in Hachioji-shi, Tokyo, Japan, and sampling plots were established in each 3 × 3 km grid cell.

2008). Owing to these properties, bryophytes have been used to evaluate atmospheric pollution in many parts of the world (e.g., Agnan, Séjalon-Delmas, Claustres, & Probst, 2015; Boquete, Fernández, Aboal, Real, & Carballeira, 2009; Fernández, Aboal, Real, & Carballeira, 2007; Oishi, 2013; Schröder et al., 2010; Vuković et al., 2015).

Among various types of atmospheric pollution, N pollution has received a lot of attention in recent years because of its increasing threat to environments at a global scale (e.g., Kopáček & Posch, 2011; Shibata et al., 2015). The evaluation of N pollution by bryophyte indicators is based on the strong correlation of N content (% N) in bryophytes with atmospheric N concentration (Harmens et al., 2011; Schröder et al., 2010). Furthermore, the stable isotope ratio of N in bryophytes ($\delta^{15}N$) has been used to diagnose sources of nitrogen, as the signature of N in nitrogen oxides (NO_x) is higher than that of reduced nitrogen (NH_y) (Liu, Xiao, Liu, & Xiao, 2008; Pearson et al., 2000; Zechmeister et al., 2008). The response of $\delta^{15}N$ to nitrogen sources is more complicated than that of % N; while this value was lower near NHy sources (e.g., farms; Liu et al., 2008), higher values were observed near NO_x sources (e.g., motor way; Pearson et al., 2000).

Not only the chemical properties of bryophytes but also the diversity (species richness, cover, and life-forms) has been used to evaluate atmospheric environments. The index of atmospheric purity (IAP) is one of the most popular indicators of bryophyte diversity. This indicator was first proposed in the 1970s and is calculated from the species richness and cover of epiphytic bryophytes and lichens (LeBlanc & De Sloover, 1970). Previous studies reported that lower IAP values were recorded in urban areas because epiphytes are generally vulnerable to atmospheric pollution (e.g., Krommer, Zechmeister, Roder, Scharf, & Hanus-Illnar, 2007; Taoda, 1972). Recently, bryophyte life-forms have also been utilized as indicators for the evaluation of environments (Oishi, 2009; Oishi & Morimoto, 2016; Pardow, Gehrig-Downie, Gradstein, & Lakatos, 2012; Vieira, Séneca, Sérgio, & Ferreira, 2012). The use of bryophyte life-forms as indicators is based on the close relationships between life-forms and the surrounding environments. For example, in fragmented forests with severe drought stress, the richness of hygrophilous life-forms (RHL) could reflect overall humidity, providing an estimate for total species richness (Oishi & Morimoto, 2016).

As shown above, bryophytes have been reported to be useful indicators for the evaluation of atmospheric environments in urban areas. However, further study is required to fully understand their utility as indicators. Researchers do not yet know how effective the combinational use of bryophyte features is for understanding atmospheric environments in urban areas, or what limitations these features have in practical applications. Until now, few studies have adopted a combinational use of bryophyte features for the evaluation of urban environments (e.g., Giordano et al., 2004; Krommer et al., 2007). These studies have examined urban environments from diverse viewpoints; thus, the effectiveness of such combinational use warrants further study. When examining the usefulness of such parameters, however, we have to keep in mind that the sensitivity of bryophyte features to targeted environments is expected to decrease with increasing distance from sampling points. This limitation has been implied by several studies (e.g., Bignal, Ashmore, & Headley, 2008; Pitcairn et al., 2003; Skinner et al., 2006). Therefore, an examination of the influenced area (zone of influence) is essential to correctly interpret the environment evaluated by bioindicators.

In this study, focusing on the possible strong correlation of bryophyte features with land use types (e.g., urban, agricultural, and industrial areas), we first evaluated the atmospheric environments using bryophyte features, and then analyzed the influence of land use on them. Based on these results, we examined the usefulness of their combinational application and determined the zone of influence in urban-forest landscapes.

2. Materials and methods

2.1. Study site and plots

The study site was located in Hachioji City in the northwestern part of Tokyo, Japan (Fig. 1). This city is part of the Tokyo capital region and has a population of nearly 0.6 million people. The altitude ranges from 63.0 to 862.7 m. The climate is characterized by large differences in temperature between summer and winter owing to its inland basin location. The annual mean temperature is ca. 14.4 °C, with the highest temperature in August (26.1 °C) and the lowest in January (3.2 °C) (averages from 1981 to 2010) (Japan Meteorological Agency, 2016). Hachioji is roughly divided into two parts. The eastern part has been developed as a city matrix, while the western part is a mountainous areas. A highway crosses the middle of the city from east to west. This city is ideal for examination of the practical use of bryophyte metrics, as it contains variable land-use types from urbanized to mountainous areas.

We established a 3 × 3 km grid across the city and sampled one or two sites in each grid cell, except in inaccessible areas. Previous studies proposed that grid sampling (sampling sites are established at the vertices of the grid) and random sampling (sampling points are established randomly in a particular size of grid) are the most effective