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Epiphytic macrolichen indication of air quality and climate in interior forested mountains of the Pacific Northwest, USA

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ABSTRACT

Biomonitoring can provide cost-effective and practical information about the distribution of nitrogen (N) deposition, particularly in regions with complex topography and sparse instrumented monitoring sites. Because of their unique biology, lichens are very sensitive bioindicators of air quality. Lichens lack a cuticle to control absorption or leaching of nutrients and they dynamically concentrate nutrients roughly in proportion to the abundance in the atmosphere. As N deposition increases, nitrogen-loving eutrophic lichens become dominant over oligotrophic lichens that thrive in nutrient-poor habitats. We capitalize on these characteristics to develop two lichen-based indicators of air-borne and depositional N for interior forested mountain ecosystems of the Pacific Northwest and calibrate them with N concentration measured in $PM_{2.5}$ at 12 IMPROVE air quality monitoring sites in the study area. The two lichen indices and peak frequencies of individual species exhibited continuous relationships with inorganic N pollution throughout the range of N in ambient $PM_{2.5}$, suggesting that the designation of a critical level or critical load is somewhat arbitrary because at any level above background, some species are likely to experience adverse impacts. The concentration of N in $PM_{2.5}$ near the city of Spokane, Washington was the lowest measured at an instrumented monitoring site near known N pollution sources. This level, $0.37\,\mu g/m^3$/year, served as a critical level, corresponding to a concentration of 1.02% N in the lichen *Letharia vulpina*, which is similar to the upper end of background lichen N concentrations measured elsewhere in the western United States. Based on this level, we estimate critical loads to be 1.54 and 2.51 kg/ha/year of through-fall dissolved inorganic N deposition for lichen communities and lichen N concentration, respectively. We map estimated fine-particulate ($PM_{2.5}$) N in ambient air based on lichen community and lichen N concentration indices to identify hotspots in the region. We also develop and map an independent lichen community-based bioclimatic index, which is strongly related to gradients in moisture availability and temperature variability. Lichen communities in the driest climates were more eutrophic than those in wetter climates at the same levels of N air pollution.

1. Introduction

Anthropogenic biologically active nitrogen (N) emissions have increased 10-fold since 1860 and represent a major disruption to the global N cycle (Galloway et al., 2004). This excess N is concentrated in Europe, Asia, and North America where food production and combustion of coal and fossil fuels contribute ammonia (NH_3) and nitric oxide emissions (NO, NO_2; Galloway et al., 2004). N deposition has profound effects on human and ecosystem health including decreased water and air quality, eutrophication of freshwater ecosystems, changes in plant community composition, increased soil emissions of nitrogenous greenhouse gases (Fenn et al., 1998), and complex interactions with fire regimes (Fenn et al., 2003a).

N emissions grew with population in the western United States during the past century (Fenn et al., 2003b) and population is projected to continue growing faster in the west than in the rest of the United States (USCB, 2005). However, enforcement of the Clean Air Act has resulted in reductions in nitrate and ammonia deposition in the western United States since the 1990s (CASTNET, 2012). Currently, the forested western mountains remain less impacted by N

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deposition than much of the rest of the country and sources of N emissions in the region are localized around urban, agricultural and industrial areas (Fenn et al., 2003a; Pardo et al., 2011). The effects of localized sources can be difficult to detect at the coarse spatial scale of deposition monitors in the region, especially because many instrumented sites are established at baseline sites far from known pollution sources.

Recent efforts have aimed to increase N deposition monitoring in western states; however, instrumented sites are expensive and their number is limited (Greaver et al., 2012). For example, our study area (Fig. 1) represents 57 million acres, 3% of the total acreage of the contiguous United States, and is served by only 12 active interagency monitoring of protected visual environments (IMPROVE) sites that monitor N in $PM_{2.5}$ near wilderness areas and three National Atmospheric Deposition Program (NADP) sites that monitor precipitation chemistry. Pre-industrial deposition of total N deposition in coniferous forests of the temperate northern hemisphere are estimated to be 0.16–2.13 kg N/ha/year (Holland et al., 1999) and estimates in our study area for 2012 were 1 to 7.2 kg N/ha/year (Schwede and Lear, 2014). To identify changes in N deposition and emerging hotspots in a region with complex topography, a biomonitoring approach has the potential to provide cost-effective and practical information about the distribution of N deposition. Furthermore, biomonitoring provides direct evidence of air pollution effects on sensitive biota and, to the extent that ecological roles of sensitive biota are understood, biomonitoring can help identify broader ecological ramifications of changing air quality.

Lichen community composition and concentration of elemental N in lichen thalli are proven approaches to biomonitoring N deposition patterns in many regions (van Herk et al., 2003; Geiser and Neitlich, 2007; Geiser et al., 2010; Johansson et al., 2012; Jovan et al., 2012; Root et al., 2013). Lichens have a unique biology formed through a symbiosis between a fungus and algae or cyanobacteria. Biomonitoring with lichens is effective because as N deposition increases, nitrogen-loving eutrophic lichens become dominant over oligotrophic lichens that thrive in nutrient-poor habitats. Furthermore, because lichens lack a cuticle to control absorption or leaching of nutrients, they dynamically concentrate nutrients roughly in proportion to the abundance in the atmosphere (Herzig et al., 1989); recent work suggests that lichen N concentration is highly correlated with throughfall dissolved inorganic N deposition (Root et al., 2013).

Lichen communities are also valuable bioclimatic indicators (van Herk et al., 2002; Ellis et al., 2007; Geiser and Neitlich, 2007; Giordani and Incerti, 2008). Because tree-dwelling lichens lack roots to access stored water, their physiology is dependent on humidity and rainfall events occurring at times when temperatures favor photosynthesis (Palmqvist et al., 2008). We expect these organisms to respond more quickly to climate changes than organisms that have structures buffering climatic impacts on their physiology (*e.g.*, roots or cuticles). Some lichens have the potential to become established on newly available substrates within a single year whereas others are more dispersal limited (Sillett et al., 2000). New lichen species can join a community on the time-scale of a decade following forest manipulations that affect micro-climate (Root et al., 2010). Because individual lichen species have different climatic optima, lichen community composition could be used to detect changing climate regimes.

Ecosystems in our region are subject to the one of the steepest precipitation gradients in the contiguous United States. The crest of the Cascades receives greater than 330 cm of precipitation per year while the woodlands 70 km to the east receive only 24 cm per year (PRISM; June 2012; http://www.prismclimate.org). This gradient in moisture availability is coupled with a change in temperature variability; wetter sites have more uniform temperatures throughout days and months whereas drier sites have hot summers and cold winters as well as hot days and cold nights (PRISM). These strong climatic gradients across a relatively contiguous forested ecosystem make the forested western mountains an ideal study area in which to examine climate effects on lichen communities.

We use lichen indicators to address four objectives: (1) develop indices for deposition and ambient air concentrations of N-containing air pollutants based on lichen community composition and lichen N concentration; (2) calibrate lichen N pollution indices with instrumented air quality monitoring sites in the region; (3) develop a bioclimatic indicator based on lichen communities that is independent of air pollution impacts; (4) map N pollution and climate bioindicators to allow us to interpret patterns in the region. These indices are developed with a long-term goal of using lichen bioindication to monitor status and trends of air quality and climate in the interior forested mountains of the Pacific Northwest, USA as well as contribute to a broader understanding of the utility of lichens as bioindicators.

2. Methods

2.1. Study area

The study area was in the northwestern United States, in the rain shadow of the Cascade Mountains. We defined the boundaries using the Northwest Forested Mountain Level III ecoregion (EPA, 2012) and county boundaries along the crest of the Cascade Mountains (Fig. 1). Forest composition ranged from montane *Tsuga mertensiana* and *Abies lasiocarpa* forests to mixed conifers including *Pinus ponderosa* and *Pseudotsuga menziesii* at mid-elevations to sparse semi-arid *Juniperus occidentalis* or *Celtis reticulata* woodlands in the driest sites.

2.2. Lichen data

Lichen communities were sampled during 1437 visits to 1006 unique locations (Table A.1). Most plots ($n = 628$) were sampled on a 5.4 km systematic grid by the USDA Forest Service Air Program (Geiser, 2004). We also included 406 plots on a 23 km grid by Forest Inventory and Analysis (Will-Wolf, 2010). Both programs included re-visits for quality control ($n = 139$). Off-frame plots ($n = 264$) established by the USDA Forest Service Air Program targeted polluted areas or atmospheric sampling sites to contribute to model-building.

Lichen abundances were recorded and vouchers were collected on 0.38-ha plots following the Forest Inventory and Analysis (FIA) lichen protocol (Will-Wolf, 2010). Lichen taxonomy was consistent with Esslinger (2011) with a few exceptions. We distinguish the yellow form of *Bryoria fremontii* (historically referred to as *Bryoria tortuosa*, Velmala et al., 2009), because the characteristics distinguishing this growth form may be linked to climatic variables of interest. We followed Miadlikowska et al.'s (2011) designation of *Hypogymnia lophyrea* and *Hypogymnia hultenii.*

At 879 visits, lichen thalli were collected for elemental N measurements. Technicians collected 20 g of one or more species of lichen for total N analysis (Geiser, 2004); typically these data were not available for FIA plots. Because no single lichen species could be found at all plots, a suite of target species included: *Alectoria sarmentosa*, *B. fremontii*, *Bryoria* spp., *Evernia prunastri*, *Hypogymnia imshaugii*, *Hypogymnia inactiva*, *Letharia columbiana*, *Letharia vulpina*, and *Platismatia glauca*. The most frequently-available species was *L. vulpina* (532 visits).

Lichen samples were analyzed with several standard reference materials including digestates of one of two in-house lichen standards of *A. sarmentosa* analyzed every 10th sample. We corrected