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A simple tool for estimating throughfall nitrogen deposition in forests of western North America using lichens

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ABSTRACT

Anthropogenic nitrogen (N) deposition has had substantial impacts on forests of North America. Managers seek to monitor deposition to identify areas of concern and establish critical loads, which define the amount of deposition that can be tolerated by ecosystems without causing substantial harm. We present a new monitoring approach that estimates throughfall inorganic N deposition from N concentration in lichens collected on site. Across 84 study sites in western North America with measured throughfall, a single regression model effectively estimated N deposition from lichen N concentration with an R^2 of 0.58 and could be improved with the addition of climate covariates including precipitation seasonality and temperature in the wettest quarter to an R^2 of 0.74. By restricting the model to the more intensively sampled region including Oregon, Washington, and California, the R^2 increased to 0.77. Because lichens are readily available, analysis is cost-effective, and accuracy is unaffected by mountainous terrain, this method allows development of deposition estimates at sites across broad spatial and topographic scales. Our approach can allow land managers to identify areas at risk of N critical load exceedance, which can be used for planning and management of air pollution impacts.

1. Introduction

Anthropogenic nitrogen (N) deposition has impacted ecosystems of western North America by changing ecosystem functioning and community composition of some organisms (Fenn et al., 2003a). Excess N deposition has been linked to increased invasion by exotic plants (Fenn et al., 2011; Weiss, 1999) and changes in community composition of lichens (Geiser and Neitlich 2007), ectomycorrhizal fungi (Lilleskov et al., 2008), alpine plants (Bowman et al., 2006), and diatoms (Baron, 2006). N deposition has also impacted ecosystem attributes such as foliar chemistry (Rueth and Baron, 2002), soil chemistry (Baron et al., 2000; Breiner et al., 2007), fine root biomass and NO_3-leaching (Baron et al., 2011; Fenn et al., 2008) and freshwater acidity (Baron et al., 2011; Sullivan et al., 2005). To prevent the decline of forested ecosystems from N deposition impacts, managers and policy makers are increasingly interested in determining N critical loads (Fenn et al., 2010; Pardo et al., 2011), levels of N deposition that can be sustained without adverse effects on communities and ecosystem functioning based on current knowledge (Porter et al., 2005).

Critical loads of N are preferably based on measurements of total N deposition, but are more commonly based on deposition of dissolved inorganic N (DIN) because dissolved organic N is not routinely measured, especially across deposition networks. In practice, critical loads are often based on DIN deposition in throughfall (e.g., Fenn et al., 2008), such as in this study. Throughfall DIN consists of NO_3-N and NH_4-N, both of which are forms of N that are readily biologically available. The establishment and application of critical loads requires accurate measurements of N deposition to calibrate empirical models of critical loads and, subsequently, to monitor status, trends and exceedances. However, cost-effective techniques that measure the major components of N deposition are still in development (Table 1). Individual stations in the western United

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Table 1
Types of N deposition measures available.

Type	Examples	Advantages	Disadvantages
Passive biological monitors	Epiphytic lichens (Herzig et al., 1989) bryophytes (Pitcairn et al., 2003)	Accurate at sites where measured Integrates N deposition and effects Minimal costs	Potential for organisms to accumulate N differently under different conditions
Passive chemical monitors	Passive gas samplers (Bytnerowicz et al., 2002)	Allows for more extensive monitoring than non-passive methods	Data only available for the duration of study Gas samplers provide only time-averaged concentrations
	IER[a] throughfall and bulk deposition collectors (Fenn and Poth, 2004)	Accurate at sites where measured.	IER samplers do not provide ionic concentrations in or pH of precipitation or throughfall solutions
National instrumented networks for dry deposition	CASTNET[b] (Baumgardner et al., 2002) IMPROVE (1995)[c]	Many years of data available	Few sites in western United States Most monitor only some components Fluxes calculated have high uncertainty.
National instrumented networks for wet deposition	NADP-NTN (2012)[d]	Many years of data available Accurate at sites where measured	Dry deposition is not measured
National and regional spatial models	NADP (2012)[e] CMAQ[f] (Appel et al., 2011)	NADP provides multi-year estimates across large areas CMAQ includes all major N pollutants and provides estimates of total N deposition	Interpolations are not as accurate as measured methods May not be available at spatial scale of interest
	ClimCalc (Ollinger et al., 1993)	Large-scale mapping of deposition possible	Simulated deposition is uncertain because of uncertainty in emissions data and simulation model deficiencies

[a] Ion Exchange Resin (IER).
[b] Clean Air Status and Trends Network (CASTNET).
[c] Interagency Monitoring of Protected Visual Environments (IMPROVE).
[d] National Atmospheric Deposition Program – National Trends Network (NADP-NTN).
[e] National Atmospheric Deposition Program (NADP).
[f] Community Multiscale Air Quality (CMAQ).

States monitor wet deposition of inorganic N in precipitation (NADP, 2012) and particulates in aerosols (IMPROVE, 1995) but are limited in their ability to integrate these sources with meteorological patterns and vegetation interactions to provide regional-scale estimates of total deposition affecting forest processes. CASTNET sites (Baumgardner et al., 2002) provide dry deposition estimates for select ions at monitoring sites that are co-located with NADP wet deposition samplers, but there are only 29 CASTNET sites in western North America. Individual researchers have established sites monitoring concentrations of gaseous nitric acid, ammonia, and nitrogen dioxide (Bytnerowicz et al., 2002) and estimates of throughfall N deposition (Fenn et al., 2008). Air quality simulation models such as the Community Multiscale Air Quality model (CMAQ; Appel et al., 2011) provide estimates of total inorganic deposition and various N species across the modeling domain (Fenn et al., 2003b, 2010) but these simulated deposition estimates may not be as accurate as site-specific measurements and are more effective at defining broader spatial scale deposition.

Cost-effective monitors that integrate wet and dry deposition N sources are needed for understanding the distribution and effects of N deposition on forests. Measures of wet or dry deposition alone are typically well-correlated with ecosystem responses (Geiser and Neitlich, 2007; Jovan et al., 2012; Williams et al., 1996; Williams and Tonnessen, 2000) but may underperform compared to more complete measures of deposition. For example, N measured in throughfall explained >30% more variability in lichen community composition than partial measures, most of which were significantly correlated to lichens as well as each other (Jovan et al., 2012).

Throughfall N deposition provides an integrative lower-bound estimate of total inorganic N deposition to forested ecosystems (Lovett and Lindberg, 1993). A passive throughfall monitoring approach relies on ion exchange resins (IER) that absorb inorganic ions from wet deposition as well as dry and cloudwater deposition that washes from canopy surfaces above the monitors (Fenn et al., 2009; Fenn and Poth, 2004). Small-scale studies have found that throughfall N measured with IERs is well-correlated with changes in epiphytic communities and ecosystem attributes (Breiner et al., 2007; Fenn et al., 2007, 2008; Jovan et al., 2012; McMurray et al., 2013).

N concentrations in epiphytic lichens are potentially an alternative approach to passively monitor N deposition in forests. Lacking a cuticle, lichens accumulate N and other water soluble nutrients roughly in proportion to their abundance in the atmosphere (Herzig et al., 1989). Implementation is simple because lichens are readily available throughout forests in the region and require no set-up. Past work shows lichen N concentrations are strongly correlated with the lichen community composition shifts associated with increasing N deposition (Fenn et al., 2008; Geiser and Neitlich, 2007; Geiser et al., 2010), thus linking deposition with biological effects. However, lichen N values have not formerly been calibrated against N deposition measurements across a large region. Our objective was to model the relationship between N concentration in lichen thalli against throughfall N deposition measured across the western United States. If sufficiently accurate, researchers and managers could use the model to estimate throughfall deposition in kilograms per hectare per year for new sites based on N concentrations (% of dry weight) in lichen thalli.

2. Methods

Throughfall IER monitors were established between 2000 and 2011 at 84 sites in western North America (Fig. 1) as part of several separate studies (Table 2). Each site included 9-12 IER funnel collectors attached to IER columns installed under the forest canopy