Environmental Pollution 234 (2018) 902–914

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Feasibility of coupled empirical and dynamic modeling to assess climate change and air pollution impacts on temperate forest vegetation of the eastern United States☆

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ARTICLE INFO

Article history:
Received 28 March 2017
Received in revised form
20 October 2017
Accepted 2 December 2017

Keywords:
Forest understory
Biodiversity
Nitrogen
Climate change
Acidification

ABSTRACT

Changes in climate and atmospheric nitrogen (N) deposition caused pronounced changes in soil conditions and habitat suitability for many plant species over the latter half of the previous century. Such changes are expected to continue in the future with anticipated further changing air temperature and precipitation that will likely influence the effects of N deposition. To investigate the potential long-term impacts of atmospheric N deposition on hardwood forest ecosystems in the eastern United States in the context of climate change, application of the coupled biogeochemical and vegetation community model VSD+PROPS was explored at three sites in New Hampshire, Virginia, and Tennessee. This represents the first application of VSD+PROPS to forest ecosystems in the United States. Climate change and elevated (above mid-19th century) N deposition were simulated to be important factors for determining habitat suitability. Although simulation results suggested that the suitability of these forests to support the continued presence of their characteristic understory plant species might decline by the year 2100, low data availability for building vegetation response models with PROPS resulted in uncertain results at the extremes of simulated N deposition. Future PROPS model development in the United States should focus on inclusion of additional foundational data or alternate candidate predictor variables to reduce these uncertainties.

1. Introduction

The cycling of nitrogen (N) and carbon (C) has been significantly altered since preindustrial times, primarily through activities associated with the growth of the human population, production and application of N-based fertilizers, the prevalence of concentrated livestock operations with associated emissions of ammonia, and fossil fuel combustion (Schlesinger, 1997; Vitousek et al., 1997; Galloway et al., 2008). Emissions of N-containing compounds such as NO_x, NH_3, and N_2O and atmospheric deposition of N to terrestrial ecosystems have altered competitive relationships among plant species and decreased the cover of some N-efficient species by creating an environment that favors nitrophilous (prefer high N) species (Bobbink et al., 2010). Emissions of C and N, as components of greenhouse gases, have also contributed to changes in temperature and precipitation, which will likely continue in the future (Intergovernmental Panel on Climate Change [IPCC] 2013).

The bioavailability of N and patterns in air temperature and precipitation affect plant understory communities in multiple ways (Parmesan, 2006; Bobbink et al., 2010; Porter et al., 2013). Increased N supply and climate change are recognized as two of the most important stressors to terrestrial plant biodiversity in the United States (Sala et al., 2000; Millennium Ecosystem Assessment [MEA] 2005). Changes in plant community structure caused by N and/or

☆ This paper has been recommended for acceptance by Dr. Jorg Rinklebe.

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https://doi.org/10.1016/j.envpol.2017.12.002
0269-7491/

climate change contribute to declining species richness and biodiversity in many regions (Bobbink et al., 2010). Increased temperature and changes in precipitation affect habitat suitability and can cause additional loss of species (Parmesan, 2006; Lenoir et al., 2008). Warmer climate may also increase soil mineral weathering and litter decomposition and thus enhance recovery of soils and vegetation negatively affected by past soil acidification caused by sulfur (S) and N deposition (Reinds et al., 2009; Aherne et al., 2012; Gaudio et al., 2015).

Effects of changes in N supply and climate on sensitive plant species have become important management issues for national parks and wilderness areas (Porter et al., 2005, 2012, 2013). Adverse effects of atmospheric N deposition on plant communities can be compounded by climate change (Davidson et al., 2011; Porter et al., 2013), which will affect virtually all aspects of N cycling (Suddick et al., 2013), and will have impacts on both terrestrial and aquatic ecosystems. Spatial and temporal patterns in temperature and precipitation are expected to change substantially over the next century (IPCC, 2013; Melillo et al., 2014). Even as N deposition levels continue to decrease in the eastern United States, the potential for forest ecosystem recovery from high cumulative historical N deposition is uncertain, especially in the context of a changing climate (Phelan et al., 2016).

Despite reductions in N emissions throughout much of the eastern United States during recent decades, air concentrations and deposition of reactive N are several-fold higher than under preindustrial conditions in this region (Volpe Horii et al., 2005; Galloway et al., 2008; Sullivan, 2017). Mitigation strategies for N emissions have not been as successful as those for S emissions (Aguillaume et al., 2016; Ochoa-Hueso et al., 2017; Sullivan, 2017). Excess N supply increases growth of some plant species at the expense of others (Suding et al., 2005). Addition of N can affect terrestrial plant communities that are commonly limited or co-limited by N availability, including temperate hardwood forests (Elser et al., 2007).

Dynamic biogeochemical-ecological coupled models have been developed to make long-term projections of ecosystem response to multiple stressors at the species level (deVries et al., 2010). Two prominent examples of coupled models to examine the impacts from climate change and N deposition are ForSAFE-Veg (Belyazid et al., 2011a, 2011b) and the more recently developed VSD+PROPS[1] (Reinds et al., 2014; Bonten et al., 2016). ForSAFE-Veg predates VSD+PROPS, and the latter offers potential for addressing some challenges associated with ForSAFE-Veg in two key areas. First, the biogeochemical components differ in that ForSAFE is more process oriented, and as such has many more data requirements that currently restrict its applicability across large areas compared with the simpler VSD+. Second, the vegetation components differ in that species in the Veg component of ForSAFE-Veg are defined by mathematical equations based on expert opinion to represent unobservable fundamental niches, whereas species in the PROPS component of VSD+PROPS are defined using statistical relationships based on empirical data and thus more closely approximate realized niches influenced by competition among species. ForSAFE-Veg has been more heavily used than VSD+PROPS in Europe (Belyazid et al., 2011a, 2011b; Rizzetto et al., 2016) and exclusively used in the United States (McDonnell et al., 2014; Phelan et al., 2016) to model the interactive effects from climate change and N deposition on plant communities. The extent to which modeling with VSD+PROPS would contribute to an improved understanding of vegetation community responses in the United States, where only ForSAFE-Veg has been applied thus far, is unknown.

The goal of this research was to assess the feasibility of VSD+PROPS for evaluating the effects of simultaneous changes in N deposition and climate on the habitat suitability of characteristic plant species in the eastern United States. Specific objectives included: (1) parametrization and calibration of the VSD+ model at target sites distributed across the eastern United States, (2) development of statistical models to estimate the probability of occurrence for plant species (PROPS) that can be found in the United States, (3) identification of data gaps that limit model application and development, and (4) linkage of VSD+ with PROPS to examine the interactive influences of climate and N deposition on plant communities through time. The N deposition loads at which plant species losses occur have not previously been determined except for a few correlational and site specific studies (Pardo et al., 2011; Simkin et al., 2016). However, such knowledge is critical to maintenance of biodiversity and biodiversity-related ecosystem services that affect human well-being (U.S. EPA, 2009).

2. Methods

We developed PROPS models for 327 species and applied the VSD+PROPS model chain to three hardwood forest ecosystems located in different portions of this large region (in New Hampshire, Virginia, and Tennessee). The PROPS models were developed to represent statistical relations between species occurrence and five abiotic drivers of plant occurrence (Fig. 1). Three of these drivers (air temperature, precipitation, and N deposition) are provided as direct input to PROPS. The other two drivers (soil solution pH and C:N) require output from a dynamic biogeochemical model to simulate change in species occurrence through time. The VSD+ model was used to generate time-series of soil solution pH and soil C:N to use as input for the PROPS model applications.

2.1. Site descriptions

Three sites were selected for VSD+PROPS modeling across a broad geographical region on different forest types, based partly on availability of input data for the models derived from field measurements, laboratory analyses, and other model results (e.g., MAGIC, PROFILE). Landscape protection status was used to evaluate candidates to include sites managed to maintain a primarily natural state. The selected sites are a northern hardwood site (Hubbard Brook) located in the White Mountains National Forest (NF) at the Hubbard Brook Experimental Forest Long Term Ecological Research Station in New Hampshire; a mixed oak site (Piney River) in Shenandoah National Park (NP), Virginia; and a sugar maple-mixed oak site (Cosby Creek) in Great Smoky Mountains NP, Tennessee. Location and general site attributes are summarized in the Supplementary Material, SM1.

2.2. US PROPS model development

The vegetation model (PROPS) of the VSD+PROPS model chain consists of species-specific statistical response functions that define niche requirements related to aspects of climate, N deposition, and soil chemistry. A database of PROPS functions has previously been developed for a set of plant species in Europe (Wamelink et al., 2011; Reinds et al., 2014). We developed an analogous set of functions for plant species found in the United States to facilitate PROPS model application at our sites in the eastern United States

[1] VSD+ is an extension of the Very Simple Dynamic (VSD; Posch and Reinds, 2009) biogeochemical model that incorporates an enhanced description of changes in C and N pools. PROPS (PRobability of Occurrence for Plant Species) is the vegetation response model.