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Spatial variation of atmospheric nitrogen deposition and critical loads for aquatic ecosystems in the Greater Yellowstone Area☆

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ABSTRACT

Current and historic atmospheric nitrogen (N) deposition has impacted aquatic ecosystems in the Greater Yellowstone Area (GYA). Understanding the spatial variation in total atmospheric deposition (wet + dry) of N is needed to estimate air pollution deposition critical loads for sensitive aquatic ecosystems. This is particularly important for areas that have an increasing contribution of ammonia dry deposition to total N (TN), such as the GYA. High resolution geostatistical models and maps of TN deposition (wet + dry) were developed using a variety of techniques including ordinary kriging in a geographic information system, to evaluate spatial variability and identify areas of elevated loading of pollutants for the GYA. TN deposition estimates in the GYA range from <1.4 to 7.5 kg N ha^{-1} yr^{-1} and show greater variability than wet inorganic N deposition. Critical loads of TN deposition (CL_{TNdep}) for nutrient enrichment in aquatic ecosystems range from less than 1.5 ± 1.0 kg N ha^{-1} yr^{-1} to over 4.0 ± 1.0 kg N ha^{-1} yr^{-1} and variability is controlled by differences in basin characteristics. The lowest CL_{TNdep} estimates occurred in high elevation basins within GYA Wilderness boundaries. TN deposition maps were used to identify critical load exceedances for aquatic ecosystems. Estimated CL_{TNdep} exceedances for the GYA range from 17% to 48% depending on the surface water nitrate (NO_3^-) threshold. Based on a NO_3^- threshold of 1.0 μmol L^{-1}, TN deposition exceeds CL_{TNdep} in approximately 30% of the GYA. These predictive models and maps can be used to help identify and protect sensitive ecosystems that may be impacted by excess atmospheric N deposition.

1. Introduction

1.1. Atmospheric deposition of nitrogen

Globally, a rising number of ecosystems are being affected by deposition from increases in anthropogenic nitrogen (N) emissions (Aber, 1992; Bobbink et al., 2010; Fenn et al., 1998; Matson et al., 2002). One sensitive ecosystem to N deposition is the high elevation, aquatic and terrestrial, alpine zone in the Greater Yellowstone Area (GYA) (Fig. 1). Over the last decade, measurements of bulk deposition in the northern Rocky Mountains within the United States (U.S.) have been estimated between 0.5 and 6.0 kg N ha^{-1} yr^{-1} and vary based on location and elevation (Burns, 2003; Grenon et al., 2010; McMurray et al., 2013, 2014; Blett et al., 2011). Background levels of N deposition averaged across the western U.S. are estimated to be < 1.0 kg N ha^{-1} yr^{-1}, with measured levels at some sites <0.5 kg N ha^{-1} yr^{-1} (Holland et al., 1999; Sverdrup et al., 2012). It is likely that current levels of atmospheric N deposition from anthropogenic sources are and will continue to impact sensitive ecosystems in the Rocky Mountains (Baron, 2006; Baron et al., 2011; Beem et al., 2010; Saros et al., 2011). Sources of N emissions in the region that contribute to N deposition include motor vehicles, agriculture, urban areas, and oil and gas industries east and south of the GYA (Spaulding et al., 2015). In addition, high ammonia (NH_3) emissions from agriculture in the Snake River Valley of Idaho and Northern Utah (both west of the GYA) are believed to

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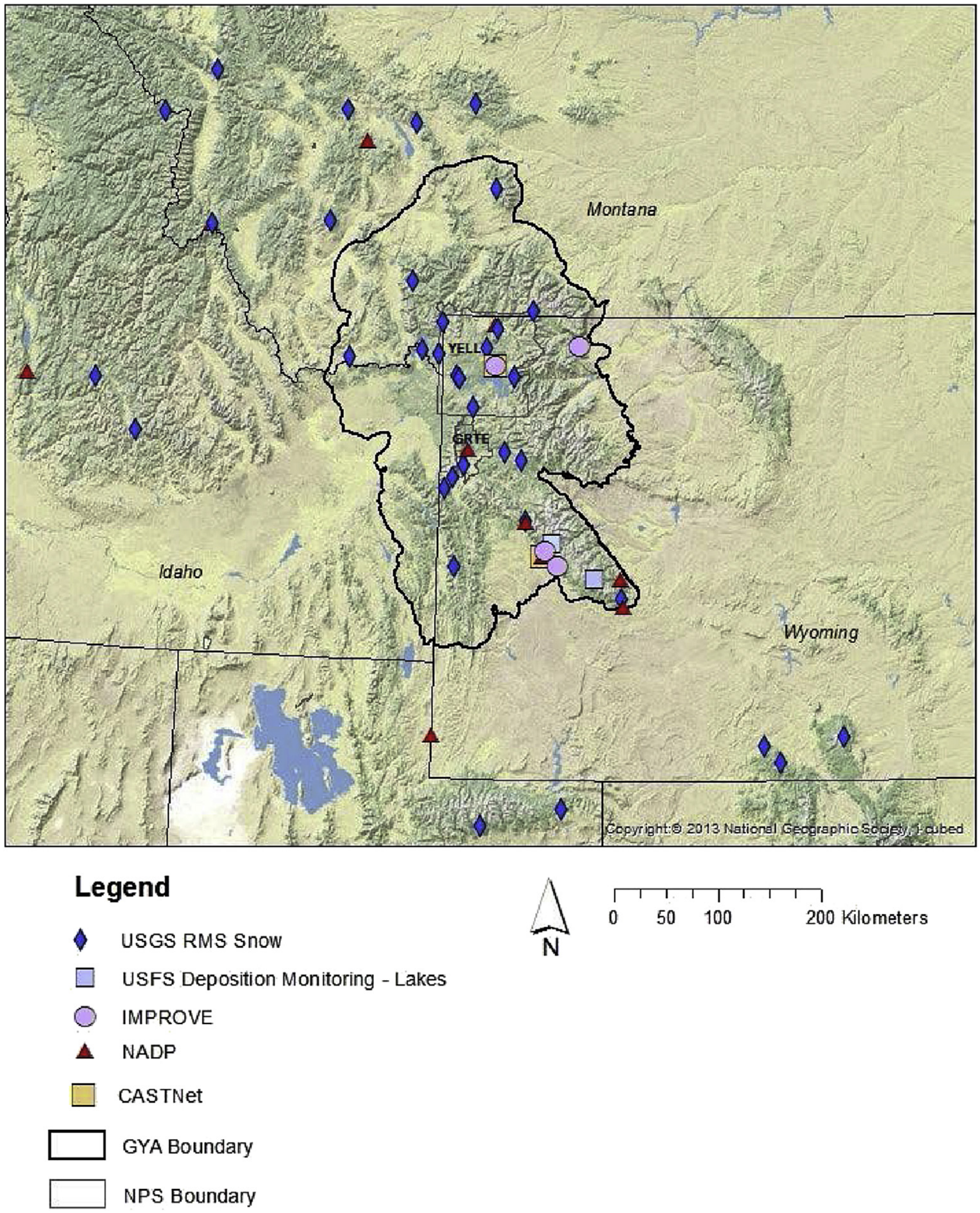

Fig. 1. Location of wet and dry deposition monitoring sites (n = 59) for the Greater Yellowstone Area (GYA) in the northern Rocky Mountains.

contribute to increased NH_3 dry deposition (Benedict et al., 2013; Clarisse et al., 2009; Spaulding et al., 2015) and are becoming a major component of total N (TN) (wet + dry) deposition in parts of the GYA.

Estimating TN deposition is an evolving science due to recent improvements in measurement techniques and environmental monitoring, combined with advances in modeling at finer spatial and temporal resolution. Previously modeled N deposition estimates that cover large spatial scales such as the U.S. and western Europe (Holland et al., 2005), lack fine spatial resolution in areas like the U.S. Rocky Mountains and the GYA that have topographically complex terrain and thus limited monitoring at high-elevations. Recent advances in N deposition modeling include improved estimates of N deposition at a continental scale using a nested modeling approach with the GEOS-Chem global chemical transport model to estimate N deposition and terrestrial critical loads in U.S. National Parks (Ellis et al., 2013) and the more recent TN deposition hybrid modeling approach by Schwede and Lear (2014). Resource managers use estimates of N deposition to determine how they should best protect sensitive ecosystems and it is important to continue to develop estimates of wet and dry N deposition at even finer spatial resolution.

While wet and dry N deposition measurements are available for some locations within the GYA, modeling is needed to estimate N deposition at locations where measurements are not possible due to lack of access or other related issues. Average annual atmospheric deposition estimates indicate areas of high wet inorganic N deposition (>3.0 kg N ha^{-1} yr^{-1}) in the Rocky Mountain region including the GYA (Nanus et al., 2003, 2012). However, dry deposition though difficult to measure and quantify in topographically complex terrain, is an important contributor to atmospheric TN. Recent work in the GYA has demonstrated the importance of including dry deposition in the estimate of TN deposition in high elevation areas (Benedict et al., 2013; Prenni et al., 2014).