National Park Service
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Natural Resource Stewardship and Science

Thresholds for Protecting Pacific Northwest Ecosystems from Atmospheric Deposition of Nitrogen

State of Knowledge Report

Natural Resource Report NPS/PWRO/NRR—2014/823

ON THE COVER
View from Hurricane Ridge, Olympic National Park
Photograph by: Tonnie Cummings

Thresholds for Protecting Pacific Northwest Ecosystems from Atmospheric Deposition of Nitrogen

State of Knowledge Report

Natural Resource Report NPS/PWRO/NRR—2014/823

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Abstract

The National Park Service and U.S. Forest Service manage areas in the states of Idaho, Oregon, and Washington – collectively referred to in this report as the Pacific Northwest - that contain significant natural resources and provide many recreational opportunities. The agencies are mandated to protect the air quality and air pollution-sensitive resources on these federal lands. Human activity has greatly increased the amount of nitrogen emitted to the atmosphere, resulting in elevated amounts of nitrogen being deposited in park and forest ecosystems. There is limited information in the Pacific Northwest about the levels of nitrogen that negatively affect natural systems, i.e., the critical loads. The National Park Service and U.S. Forest Service, with scientific input from the U.S. Geological Survey, have developed an approach for accumulating additional nitrogen critical loads information in the Pacific Northwest and using the data in planning and regulatory arenas. As a first step in that process, this report summarizes the current state of knowledge about nitrogen deposition, effects, and critical loads in the region. It also describes ongoing research efforts and identifies and prioritizes additional data needs.

Acknowledgments

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Acronyms

AQRV	air quality related value
CASTNET	Clean Air Status and Trends Network
CEC	Commission for Environmental Cooperation
CL	critical load
CLAD	Critical Loads of Atmospheric Deposition Science Committee
CMAQ	Community Multi-Scale Air Quality atmospheric model
CO_2	carbon dioxide
DIN:TP	Dissolved Inorganic Nitrogen to Total Phosphorus ratio
FIA	Forest Inventory and Analysis
FLAG	Federal Land Managers Air Quality Related Values Work Group
FLM	Federal Land Manager
FOCUS	Focal Center Utility Study
$kg\ ha^{-1}\ yr^{-1}$	kilograms per hectare per year
IMPROVE	Interagency Monitoring of Protected Visual Environments
N	nitrogen
NADP	National Atmospheric Deposition Program
NEPA	National Environmental Policy Act
NP	National Park
NPS	National Park Service
PNW	Pacific Northwest
PRISM	Parameter-elevation Regressions on Independent Slopes Model
TDEP	Total Deposition Science Committee
TL	target load
USGS	U.S. Geological Survey
USFS	U.S. Forest Service

Introduction

The National Park Service (NPS) and U.S. Forest Service (USFS) manage several areas in the states of Idaho, Oregon, and Washington - collectively referred to in this report as the Pacific Northwest (PNW; Figures 1 and 2). These areas include a diversity of habitats that host spectacular views, many recreational opportunities, abundant fish and wildlife, numerous lakes, and headwaters of large river systems that provide a significant portion of the region's water supply. Because clean air is critical for the healthy functioning and enjoyment of these ecosystems, the NPS and USFS need to protect air quality and air pollution sensitive resources on lands they manage. Air pollution sensitive resources, also called air quality related values (AQRVs), include lakes, streams, vegetation, soils, wildlife, and visibility.

Human activity has led to a substantial increase in nitrogen (N) emissions over the past hundred years, raising questions about the effect of excess N on natural habitats. In 2011, Pardo et al. published a comprehensive report summarizing available information about levels of added N that negatively affect natural ecosystems in the United States. The authors concluded PNW-specific data were limited. Because there are several sources of N in the region (Figure 3), NPS and USFS air quality staff became concerned that lack of N effects information would inhibit their ability to adequately protect PNW park and forest resources. Therefore, the agencies - with scientific input from the U.S. Geological Survey (USGS) - developed a coordinated approach for accumulating additional N effects information and using the data in planning and regulatory arenas (Appendix A). This report, intended for PNW forest and park managers, as well as for federal and state regulators, summarizes the current state of knowledge about levels of N that affect natural resources in the region. It provides a PNW-focused summary of the Pardo et al. (2011) report. This report also describes: sources and effects of N deposition, legal mandates for NPS and USFS air quality protection efforts, the concept and use of critical loads and target loads to protect resources, and potential interactions of N and climate change. Most importantly, it summarizes current N effects studies in the PNW and prioritizes data needed to improve understanding of how N affects regional forest and park AQRVs.

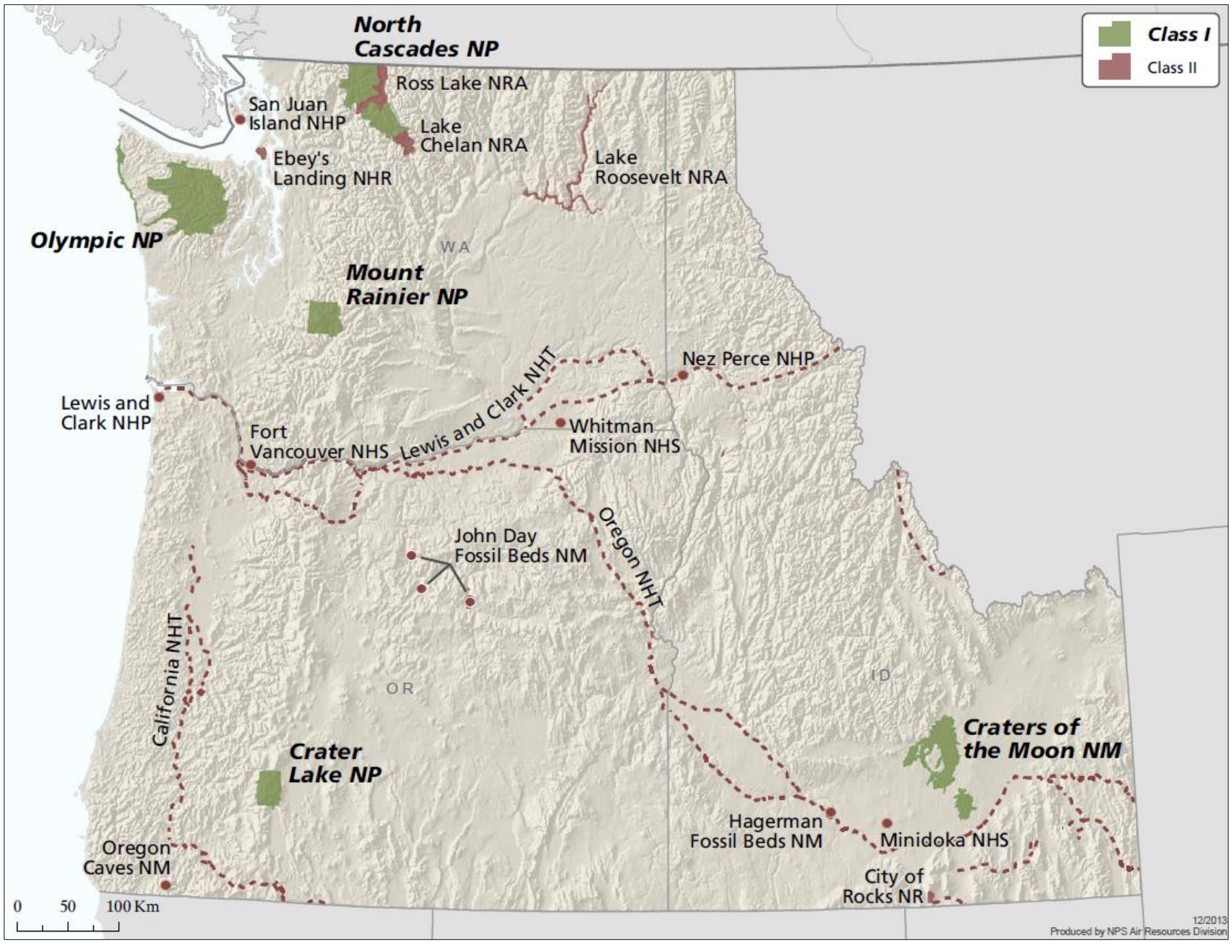

Figure 1. NPS areas in the PNW (produced by NPS, 2013).

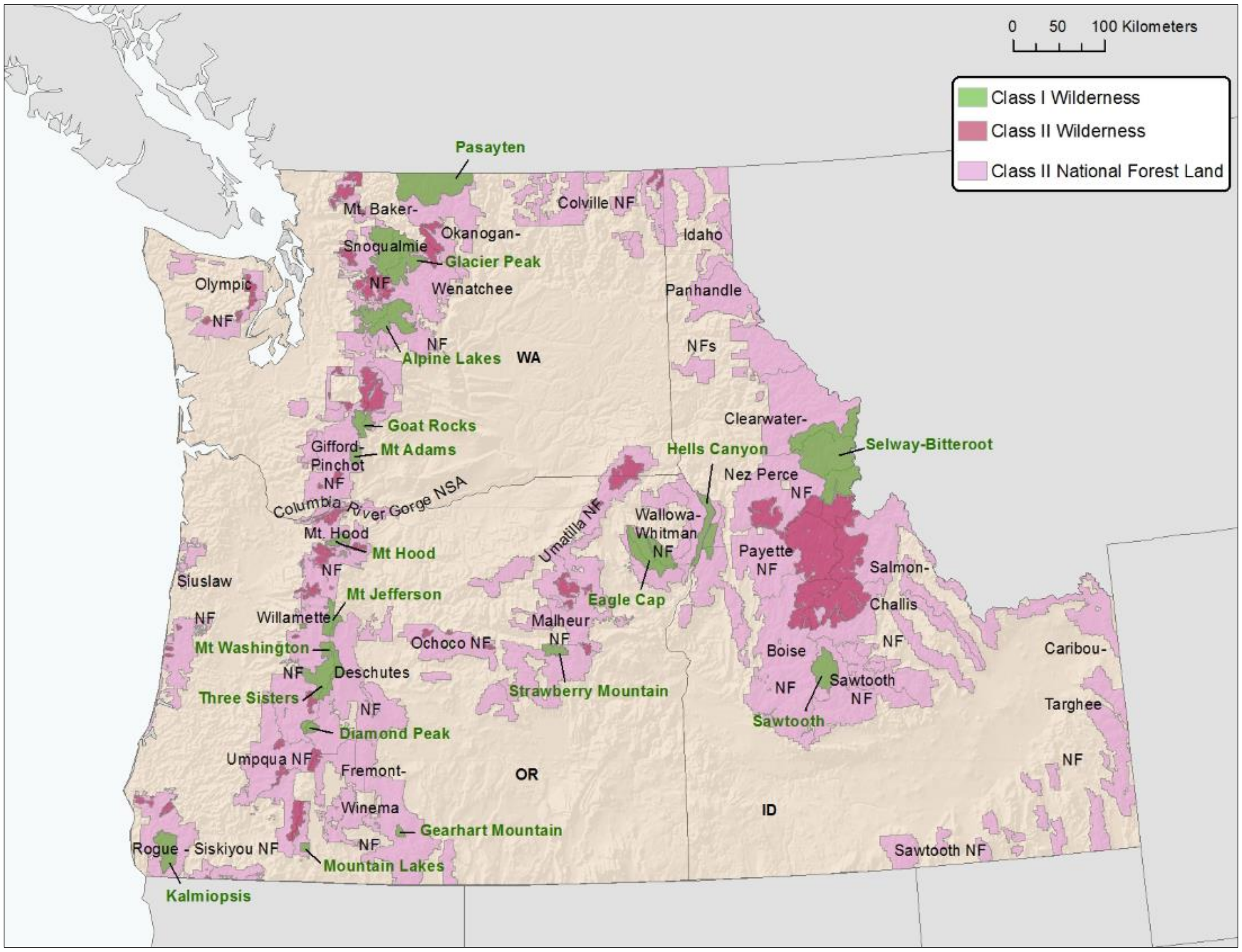

Figure 2. USFS areas in the PNW (produced by USFS, 2013).

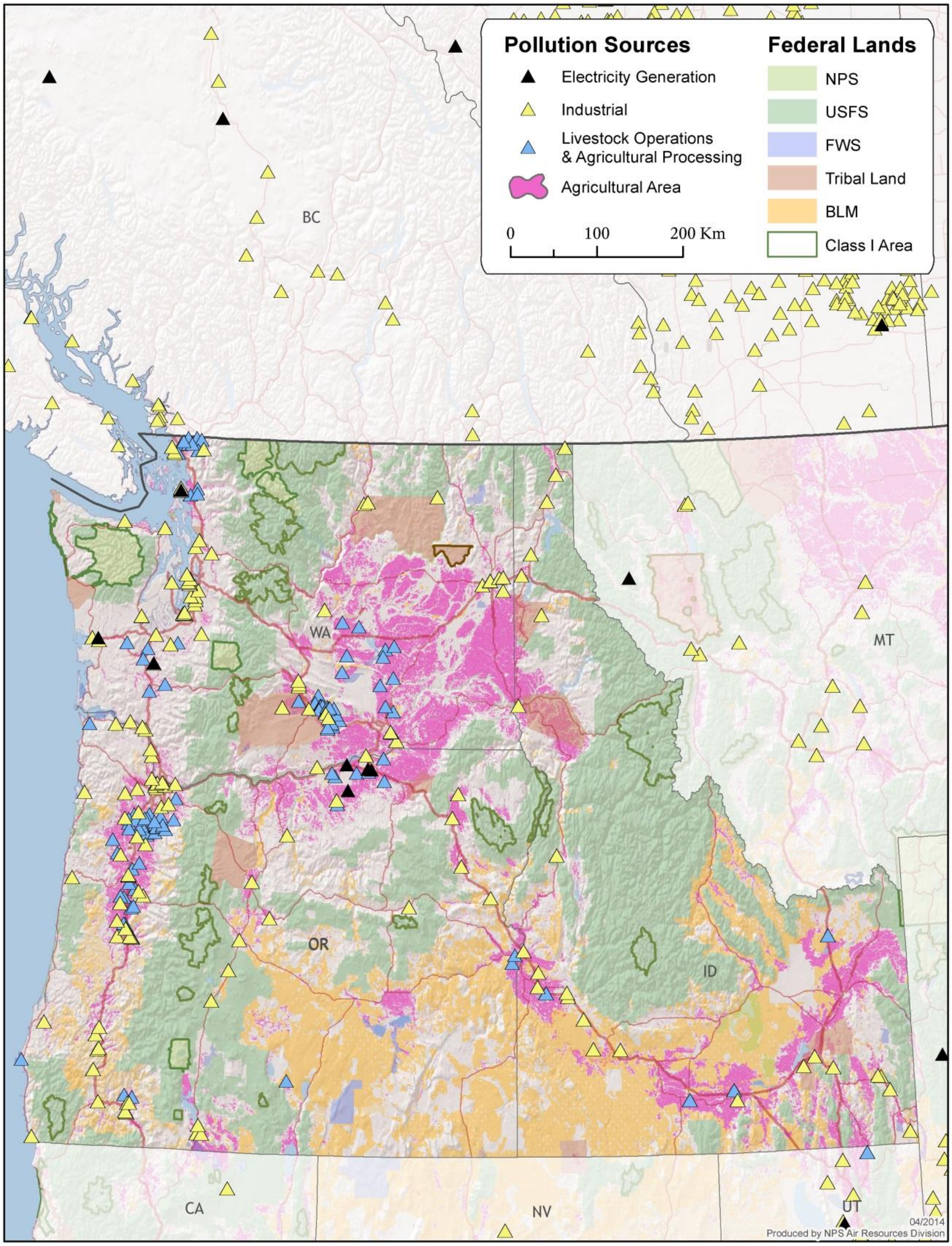

Figure 3. Public lands and air pollution sources in the PNW (produced by NPS, 2014). Triangles designate point sources that emit greater than 100 tons per year of nitrogen oxides.

Sources and Effects of Nitrogen Deposition

Nitrogen is an essential nutrient for all living organisms. Plants and animals rely on bacteria to convert inert atmospheric N gas (which represents 78 percent of the atmosphere) into useable forms. Useable N is tightly recycled within ecosystems until it is eventually lost in leaching or gaseous forms. This process is known as the N cycle (Figure 4). Many ecosystems are N-limited and thus the addition of N from the atmosphere or direct application can alter ecosystem functions that are adapted to naturally low levels of nitrogen.

Nitrogen in the atmosphere is deposited onto ecosystems in a variety of chemical forms. Inorganic forms of N deposition have been studied via several coordinated monitoring networks nationally, and are therefore the best understood. Inorganic N deposition occurs in both chemically reduced forms (e.g., ammonia and ammonium, mostly from livestock and agriculture although vehicle emissions are the main source in urban areas [Bishop et al., 2010]) and oxidized forms (i.e., nitrogen oxides, mostly from fossil fuel combustion). Nitrogen may also be deposited in organic forms that span a range of reduced and oxidized compounds (e.g., urea, amines, proteins, and nucleic acids). While organic N may contribute significantly to total deposition, it is rarely measured and will not be considered here further. All forms of N are deposited through either wet deposition (i.e., rain, snow, clouds, and fog) or dry deposition (i.e., particles and gases) onto lakes, streams, soils, and vegetation. In seasonally Mediterranean-like climates such as the PNW, wet N deposition typically dominates in winter months and dry N deposition dominates in summer months.

Over time, excess N deposition alters biodiversity and plant and soil chemistry, with cascading effects through the ecosystems. Excess N deposition also leads to increased nitrate leaching to water bodies, where it can cause eutrophication, acidification or dead zones. Nitrogen deposition can affect visitor use and enjoyment of public lands and can reduce ecosystem services, i.e., ecological resources and processes that benefit humankind. Potential effects of N deposition on natural ecosystems are discussed in detail in several reports and journal articles, e.g., Fenn et al. (2003), Grulke et al. (2009), Compton et al. (2011), Pardo et al. (2011), Davidson et al. (2012), Greaver et al. (2012), and Suddick et al. (2012) and summarized in Table 1.

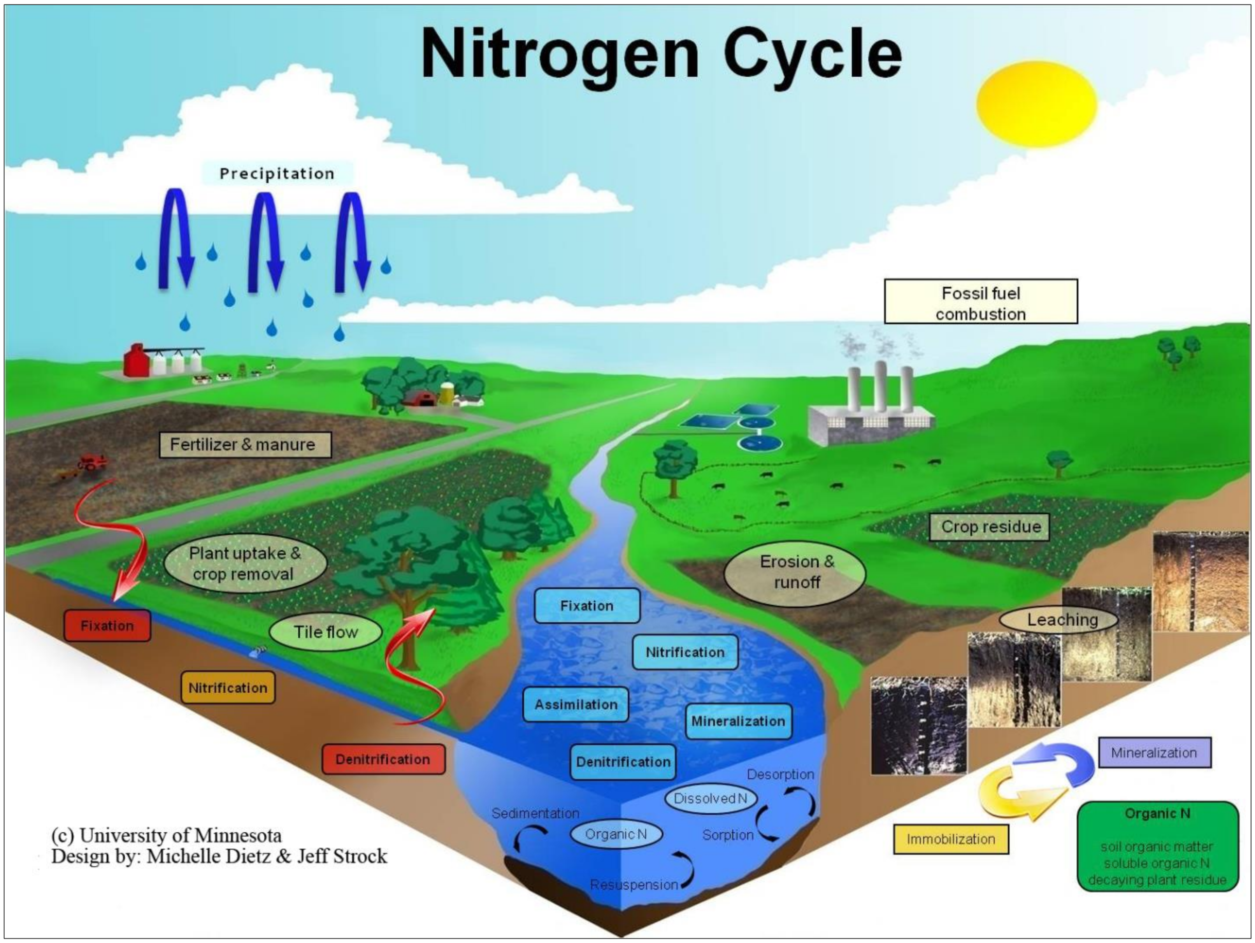

Figure 4. The nitrogen cycle (produced by University of Minnesota, 2014).

Table 1. Indicators and impacts of N deposition on natural ecosystems

		Terrestrial	**Aquatic**
Ecological Indicators	Changes in soil chemistry	a,e	
	Tree and plant chemistry, growth, and mortality; forest health metrics	a,e	
	Changes in mycorrhizae, lichen, and native species richness, abundance and/or diversity	a,e	
	Changes in diatom (phytoplankton) communities		a,e
	Changes in water chemistry (e.g., acid neutralizing capacity, nitrate)		a,e
	Increased algal productivity; shift from oligotrophic to eutrophic species; changes in water clarity	e	e
Ecological Impacts	Increase in invasive species	a,e	a,e
	Loss of biodiversity; habitat decline	a,e	a,e
	Decreased water quality		a,e
	Decline in fish health		a,e
	Increased risk of harmful algal blooms		e
	Increased risk of wildfire from excess exotic grasses	e	
	Exacerbated impact due to climate change	a,e	a,e
Negative Impacts to Ecosystem Services	Hunting and fishing	a,e	a,e
	Recreational experiences (ecotourism)	a,e	a,e
	Forest products (timber, berries, etc.)	a,e	
	Purification of water and air	a,e	a,e
	Global warming potential (i.e., carbon storage and other greenhouse gases)	a,e	a,e

a = possible effects from N acidification

e = possible effects from N eutrophication

Legal Mandates for Air Quality Protection

The Clean Air Act provides the foundation for protection of air quality on federal lands. The 1977 Clean Air Act Amendments direct Federal Land Managers (FLMs), including the NPS and the USFS, to "preserve, protect, and enhance the air quality" in 158 mandatory Class I national parks and wilderness areas (42 U.S.C. 7470 et seq.). Aside from Class I areas, all lands managed by the FLMs are designated Class II. The 1977 Amendments give FLMs an "affirmative responsibility" to protect the AQRVs in Class I areas. Congress further stated that "the Federal land manager should assume an aggressive role in protecting the air quality values… [and in] the case of doubt the land manager should err on the side of protecting the air quality-related values for future generations" (Senate Report No. 95-127, 95th Congress, 1st Session, 1977). Other bases for air quality protection in NPS and USFS areas include: 1) the Wilderness Act directive that wilderness areas be managed to preserve their natural conditions (16 U.S.C. 1131-1136); 2) National Environmental Policy Act (NEPA) requirements that all federal agencies examine the environmental consequences of major proposed actions and conduct a decision-making process that incorporates public input (42 U.S.C. 4321-4346); and 3) 1976 National Forest Management Act requirements that the USFS develop and implement management plans for each forest or grassland following the premise that "National Forests are ecosystems and their management… requires an awareness and consideration of the interrelationships among plants, animals, soil, water, air, and other environmental factors within such ecosystems" (16 U.S.C. 1600-1614). Forest Management Plans and park planning documents must go through the public review process outlined in NEPA.

For air quality protection in Class II areas, the NPS relies on the 1916 Organic Act which directs the agency to conserve the resources and values of parks in a manner that will leave them "unimpaired for the enjoyment of future generations" (16 U.S.C. 1) and the 2006 Management Policies that provide guidance for protection of air quality and AQRVs in all NPS areas.

The USFS has different and sometimes multiple management objectives on the land it manages. For example, Class I wilderness areas are managed in accordance with the Clean Air Act and Wilderness Act. Non-Class I wilderness areas are managed consistent with the Wilderness Act but do not receive the same level of air quality protection as provided in Class I areas. Non-wilderness lands are managed according to multiple use objectives (e.g., habitat protection, recreation, forest products, etc.) in accordance with Forest Management Plans.

In practice, the NPS and USFS monitor air quality and/or AQRVs to understand spatial and temporal pollution trends and resource conditions. The FLMs do not regulate the sources of air pollution that may adversely affect their resources. Rather, the NPS and USFS work with federal, state, and local regulatory agencies to remedy existing and prevent future impacts on sensitive resources. The FLMs review and comment on applications for proposed new and/or modified air pollution sources, provide input on air quality rules and regulations, and participate in air quality-related workgroups and committees. The FLMs rely on rigorous science to accurately assess existing conditions and attribute cause, and they relay this information to the regulatory agencies that have the ability to effect change. Hence, monitoring and assessment are key tasks of FLMs in fulfilling their responsibility to preserve, protect, and enhance air quality and AQRVs.

The Concept and Use of Critical Loads and Target Loads

The term critical load (CL) is used to describe the science-based threshold for ecosystem sensitivity to air pollution. A CL is technically defined as "the quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment are not expected to occur according to present knowledge " (Nilsson and Grennfelt, 1988). Critical loads are typically expressed in terms of kilograms per hectare per year (kg ha^{-1} yr^{-1}) of wet or total (wet + dry) deposition. Critical loads can be developed for a variety of ecosystem responses, including shifts in diatoms, increases in invasive grass species, changes in soil chemistry, and lake and stream acidification. For example, Baron (2006) and Saros et al. (2011) recommended a CL of 1.5 kg wet N ha^{-1} yr^{-1} to prevent unwanted changes in diatom communities of subalpine lakes in the Rocky Mountains. To develop a CL, it is necessary to estimate the amount of N that is being deposited, identify an ecological response, and determine the threshold for the response.

Target loads (TL) are based on CLs and represent a policy or management decision about the amount of deposition that could be allowed without jeopardizing resource protection (Porter et al., 2005). Target loads are typically set at a level that minimizes adverse, human-caused changes in ecosystem structure or function. In areas where the CL has not been exceeded, the FLM typically incorporates a margin of safety by selecting a TL that is lower than the CL. Federal Land Managers may select more or less stringent TLs depending on differing agency directives, land designations or land management objectives.

In areas where the CL is exceeded, the FLM usually selects a TL intended to restore natural ecosystem function. For example, based on 20 years of research documenting N deposition effects on soils, vegetation, and lakes at Rocky Mountain National Park (NP) in Colorado, the NPS determined CLs for aquatic resources had been exceeded (Porter and Johnson, 2007). In response, the Colorado Air Quality Control Commission formed a subcommittee that developed a plan to reverse increasing trends in N deposition at the park and remedy N deposition effects. To achieve that goal, the subcommittee established a glidepath for decreasing N deposition with identified TLs (Interim Milestones) along the timeline (Figure 5). The endpoint for the glidepath, based on the CL (which is the resource management goal established for the park), is 1.5 kg wet N ha^{-1} yr^{-1} by the year 2032 (Morris et al., 2014).

While CLs and TLs have been used for several years in Europe and Canada to set emission targets, their use in the U.S. has been limited (Porter and Johnson, 2007). In 2006, the Critical Loads of Atmospheric Deposition (CLAD) Science Committee was formed under the National Atmospheric Deposition Program (NADP) to facilitate collaboration on CL topics. Soon after, CLAD initiated the Focal Center Utility Study (FOCUS) to develop a consistent process for calculating and mapping CLs in the U.S. (Blett et al., 2014). The U.S. CL database developed and maintained through the FOCUS project is available on the CLAD website (http://nadp.sws.uiuc.edu/committees/clad/) and will likely result in increased use of CLs and TLs to protect NPS and USFS resources in the future.

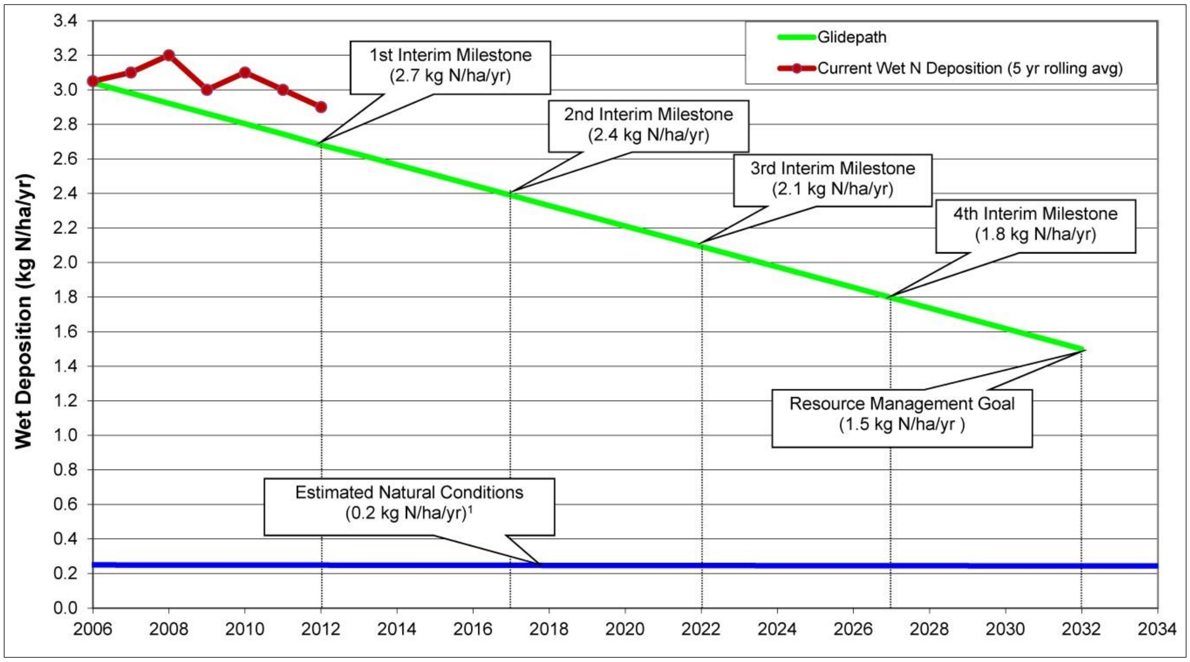

Figure 5. Glidepath and current wet N deposition at Rocky Mountain NP (from Morris et al., 2014).

Estimating Inorganic N Deposition

The amount of N deposited to an ecosystem is the total sum of all chemical species in all wet and dry forms. The NADP is a network that measures precipitation amount and chemistry to estimate pollutant deposition in rain and snowfall. There are currently 12 NADP sites operating in the PNW (see map at http://nadp.sws.uiuc.edu/sites/ntnmap.asp). While NADP does a good job measuring wet deposition at low elevation sites, there are relatively few NADP monitors at high elevations (that often receive much greater precipitation and which comprise a substantial proportion of NPS and USFS lands in the PNW). Also, NADP does not measure wet deposition in fog and cloudwater. The Clean Air Status and Trends Network (CASTNET) measures particle and gas concentrations in the air and then calculates dry deposition. While CASTNET data were collected at four sites in the PNW in the past, there are no sites operating at this time (see map of inactive sites at http://java.epa.gov/castnet/epa_jsp/sites.jsp#inactive). Because CASTNET does not measure several N pollutants - including ammonia, nitric oxide, and nitrogen dioxide - CASTNET underestimates dry N deposition at some sites (Sparks et al., 2008; Fenn et al., 2009). To obtain information about atmospheric ammonia gas concentrations, NADP installed Ammonia Network monitoring sites at Craters of the Moon National Monument in Idaho in 2010 and at Mount Rainier NP in Washington in 2011 (http://nadp.sws.uiuc.edu/amon/).

As with NADP, there are no high-elevation CASTNET sites in the PNW; however, high-elevation deposition data have been collected at a few sites in the region using other techniques. Staff at Mount Rainier NP have been monitoring bulk, i.e., wet plus some dry, deposition at Paradise (at 1,654 m) since 1989. Results show nitrate concentrations in deposition are significantly higher at Paradise than at the park's Tahoma Woods (at 421 m) NADP and CASTNET sites (Agren et al., 2013). Fenn et al. (2013) conducted throughfall sampling at Mount Rainier, North Cascades, and Olympic National Parks in Washington from 2005 to 2007. Throughfall is a bulk deposition measurement that incorporates wet deposition with the wash-off of dry particles and gases from the leaf surface. Throughfall monitoring has been used widely across Europe (e.g., Bleeker et al., 2003), in California (Fenn et al., 2010), and in other parts of the U.S. and Canada (Pardo et al., 2011) to establish critical loads. While high canopy uptake of deposited nitrate limits the usefulness of the throughfall method for monitoring total N deposition, Fenn et al. (2013) used the sulfur:nitrogen ratios in wet deposition and throughfall sulfur deposition to estimate a range of total N deposition in forest stands in the three PNW parks.

Deposition estimates frequently include both monitoring data and atmospheric modeling results. For example, the NADP's Total Deposition (TDEP) Science Committee is combining data from NADP, CASTNET, and other monitoring programs with output from the Community Multiscale Air Quality (CMAQ) modeling system to develop national maps of total N deposition (http://nadp.sws.uiuc.edu/committees/tdep/). CMAQ is a regional air quality model that simulates atmospheric physics and chemistry to predict pollutant transport, transformation, and deposition (http://cmascenter.org/cmaq/). Given the coarse grid size used in CMAQ modeling, as well as some assumptions that go into the model, CMAQ tends to over- or under-predict total deposition in complex terrain. The TDEP committee is evaluating methods to improve the accuracy of total deposition estimates that rely on CMAQ results.

In addition to ambient monitoring and atmospheric modeling, researchers are investigating the use of biomonitors to predict N deposition. For example, Root et al. (2013) recently showed lichen N concentration can be used to estimate N deposition in forested ecosystems in the western U.S. The deposition estimates can then be used to identify areas that potentially exceed CLs. Similar to throughfall monitoring, measuring N concentrations in lichens does not account for N uptake by the forest canopy.

All of the monitoring and modeling methods described above focus on inorganic N deposition; additional studies are needed to determine the contribution of organic N to total deposition.

Determining Ecosystem Response

Several methods are used to determine ecosystem response to N deposition (NADP, 2013). Empirical approaches are based on observation of ecosystem responses to specific deposition levels. These relationships are developed using dose-response experiments or by measuring ecosystem responses along gradients of deposition over space or time. Mass balance approaches are used to model chemical changes in soils and surface waters that result from atmospheric deposition, which can then be related to ecological changes of interest. Mass balance approaches can use both intensive dynamic models that assess ecosystem response to increases or decreases in atmospheric deposition and steady-state models that require less data and are used to estimate the deposition level that will allow ecosystem sustainability over the long term.

Nitrogen Critical Loads in the PNW

For consistency with the Pardo et al. (2011) assessment of N deposition effects and CLs across the U.S., this report uses the ecosystem classification system developed through the Commission for Environmental Cooperation (CEC) for North America (CEC, 1997). This classification system has four hierarchical levels; Level 1 divides North America into 15 broad ecoregions. An ecoregion is a geographically defined area that contains distinct physical features and biological communities. The PNW includes portions of three Level 1 ecoregions (Figure 6): North American Deserts (i.e., Great Basin grasslands and rangelands), Marine West Coast Forests (i.e., Westside forests) and Northwestern Forested Mountains (i.e., Eastside and Klamath-Siskiyou forests). For the most part, the ecoregion descriptions in this section are taken from Pardo et al. (2011).

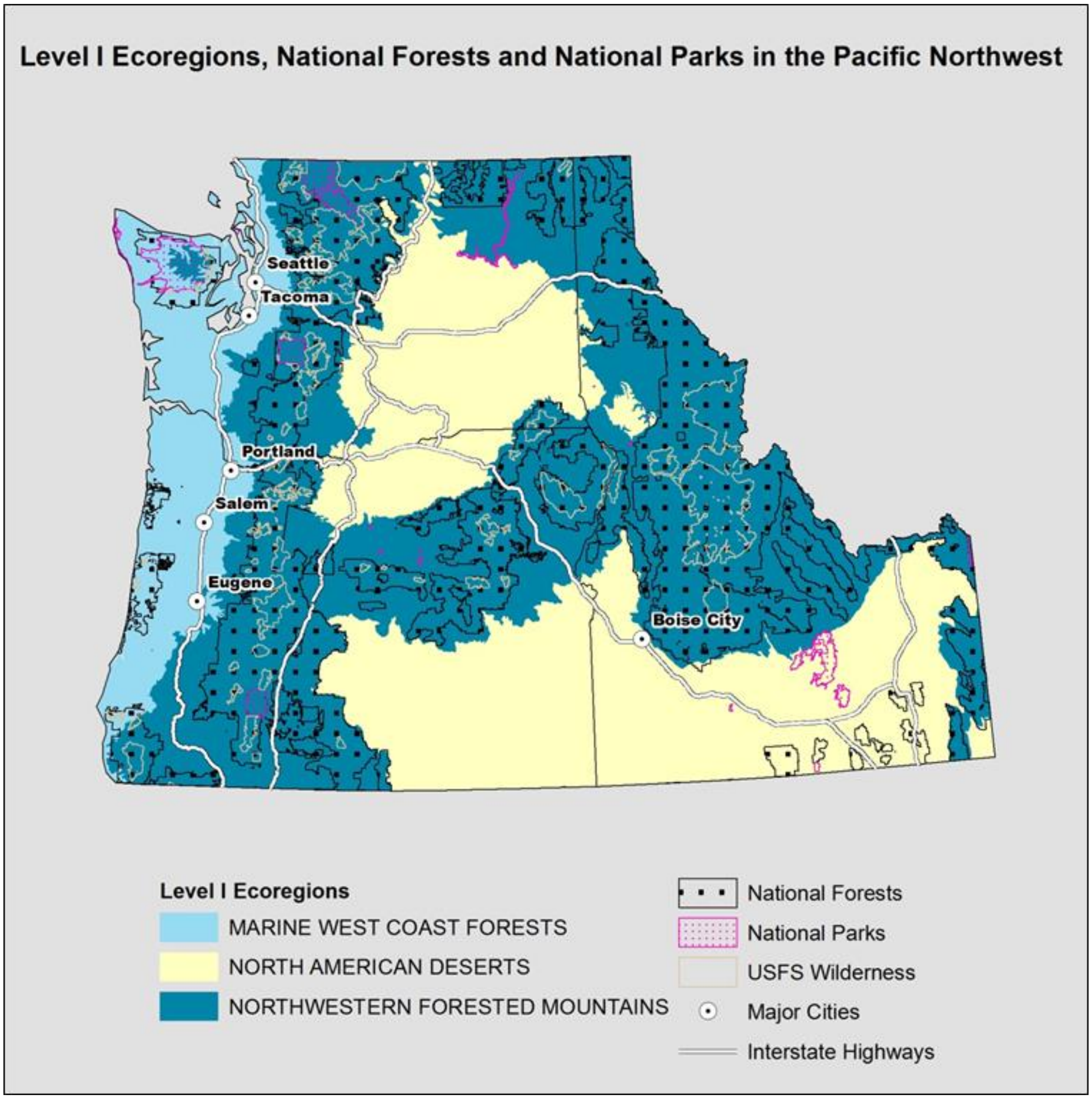

Figure 6. Level 1 ecoregions, national forests, and national parks in the PNW (produced by USFS, 2014). Olympic NP is encompassed by more than one ecoregion - part of the park is in the Marine West Coast Forests and part of it is in the Northwestern Forested Mountains.

North American Deserts Ecoregion

North American deserts and semi-deserts extend from British Columbia to Mexico (CEC, 1997).

They are characterized by aridity (130 to 380 mm annual precipitation); shrub and succulent vegetation with trees in riparian areas and higher elevation woodlands; and dry, low organic matter soils that are high in calcium carbonate in some regions. The ecoregion can be subdivided into cold northern deserts and semi-deserts (Columbia Plateau, Snake River Basin, Great Basin, and greater Colorado Plateau) and warm southern deserts (Mojave, Sonoran, and Chihuahuan). Average annual temperatures in the northern deserts are about 9°C. The cold deserts and semi-deserts are arid to semi-arid with marked seasonal temperature extremes, a winter moisture regime, and some snow. They lie in the rain shadow of the Cascade and Sierra Nevada Mountains to the west and are blocked from moist Gulf Coast air masses by the Rocky Mountains to the east.

Sagebrush (*Artemisia* spp.) dominates these deserts, with saltbush (*Atriplex* spp.) and greasewood (*Sarcobatus* spp.) on more alkaline soils. The Great Basin is characterized by sagebrush and rabbitbrush (*Chrysothamnus* spp.). Typical plants of the Mojave Desert are the creosote bush (*Larrea tridentata*) and Joshua tree (*Yucca brevifolia*). The Sonoran Desert’s structurally diverse vegetation includes the paloverde tree (*Parkinsonia* spp.), saguaro cactus (*Cereus gigantea*), cholla (*Cylindropuntia* spp.), and agave (*Agave* spp.). American tarbush (*Flourensia cernua*), creosote bush, soaptree yucca (*Yucca elata*), grama grasses (*Bouteloua* spp.), and tobosagrass (*Pleuraphis mutica*) distinguish the Chihuahuan Desert. Pinon-juniper woodlands occur at the higher elevations above both cold and warm deserts.

Marine West Coast Forests Ecoregion

The Marine West Coast Forests ecoregion encompasses the Pacific Coast from central Alaska and the Aleutian Islands south through northern California (CEC, 1997). Topography is mountainous bordered by coastal plains, resulting in widely contrasting ecological zones. Soils range from very nutrient rich to nutrient poor; N is the nutrient most commonly limiting to plant productivity, although some areas are naturally very rich in N. The maritime influence of the Pacific Ocean results in high annual precipitation (600 to 5,000 mm), a long growing season, and moderate mean annual temperatures of 5 to 9°C. Fog is common and is a potentially significant source of N deposition (Bormann et al., 1989). Within North America, all of the wettest climates, many of the most productive forests, and all temperate rain forests occur in this ecoregion. These forests provide timber and old growth habitat and contain substantial stocks of carbon. Boreal forests occur in the northern latitudes, with cool subalpine forests and alpine conditions at higher elevations. Many lowland aquatic ecosystems in this region sustain a diversity of anadromous salmonids that can be a significant source of marine-derived N to rivers and lakes, whereas upland aquatic ecosystems are often nutrient poor.

Tree species composition of the Marine West Coast Forests varies by latitude, and from north to south, and includes white spruce (*Picea glauca*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), Alaska yellow cedar (*Callitropsis nootkatensis*), red alder (*Alnus rubra*), western red cedar (*Thuja plicata*), Douglas-fir (*Pseudotsuga menziesii*), and California redwood (*Sequoia sempervirens*). Many of these trees can reach large size and live to great age. In the drier rain shadow areas, Oregon white oak (Garry oak; *Quercus garryana*) and Pacific madrone (*Arbutus menziesii*) occur with Douglas-fir. Mountain hemlock (*Tsuga mertensiana*) and Pacific silver fir (*Abies amabilis*) dominate subalpine forests; alpine tundra is dominated by shrubs, herbs, bryophytes, and lichens.

Northwestern Forested Mountains Ecoregion

The Northwestern Forested Mountains are ecologically diverse and geographically widespread, encompassing the mountain ecosystems of central and northwestern North America (CEC, 1997). Geographically, they extend from the Rocky Mountains and the Sierra Nevada north through the Siskiyous, the east side of the Cascade Range, and then east of the Coast Ranges to interior Alaska. Climatically, the region is characterized by a transition from a moist, maritime climate in the northwest to a continental and drier climate in the Rockies. Annual precipitation varies with elevation and latitude, from 2,600 mm in the northern mountains, to 400 mm in other mountainous areas, to between 250 to 500 mm in the valleys. Orographically-generated rainfall creates both rain shadows and wet belts, often in close proximity. Mean annual temperatures range between –6°C in the north to 7 to 10°C in the south. Similar to the Marine West Coast Forests ecoregion, fog is a potentially significant source of N.

The vegetation of the Northwestern Forested Mountains ecoregion is extremely diverse, with distinct community zonation occurring along elevation gradients. Alpine communities at the highest elevations contain various forb, lichen and bryophyte, and shrub associations. Subalpine communities include lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), Pacific silver fir, grand fir (*Abies grandis*), Engelmann spruce (*Picea engelmannii*), limber pine (*Pinus flexilis*), and whitebark pine (*Pinus albicaulis*). Mid-elevation forests are characterized by ponderosa pine (*Pinus ponderosa),* Douglas-fir, lodgepole pine, quaking aspen (*Populus tremuloides*), willow (*Salix* spp.), and juniper (*Juniperus* spp.) in the east, and by western hemlock, western red cedar, Douglas-fir, and western white pine (*Pinus monticola*) in the west and southwest. White spruce and black spruce (*Picea mariana*) dominate the Alaskan portion of the ecoregion. Vegetation of the interior valleys in the southern portion of the region includes big sagebrush (*Artemisia tridentata*), rabbitbrush, and antelope bitterbrush (*Purshia tridentata*).

Regionwide N CLs

Until recently, very few N CL studies had been conducted in the PNW. This was because the relatively lower historic N deposition in the region compared to other more chronically polluted areas of the U.S. made collection of CL data a lower national priority. Thanks to a partnership between the USFS Forest Inventory and Analysis (FIA) Program and the USFS Pacific Northwest Region Air Program, extensive lichen monitoring has taken place in the PNW. Therefore, the largest dataset for CLs in the PNW is based on lichen chemistry and community composition (Pardo et al., 2011). This monitoring has mostly focused on epiphytic lichens, those species growing on trees and shrubs, as indicators of air quality (Fenn et al., 2007; Geiser et al., 2008; Geiser et al., 2010). The ecological impact is quantified by doing a regression on N deposition against the proportion of lichen species that are oligotrophic (sensitive to N), mesotrophic (neutral to N), and eutrophic (insensitive to N).

Modeled studies of large-scale lichen community response provide CL estimates that range from 2.5 to 7.1 kg total N ha^{-1} yr^{-1} in PNW Northwestern Forested Mountains (Geiser et al., 2010); 2.7 to 9.2 kg total N ha^{-1} yr^{-1} in PNW Marine West Coast Forests (Geiser et al., 2010); and approximately 3 kg total N ha^{-1} yr^{-1} for PNW North American Deserts (Geiser et al., 2008; Table 2). This range of values reflects the variation in both regional climate and forest vegetation.

Based on CMAQ modeling, estimates of higher CL values are most applicable for wetter areas and/or naturally N-rich hardwood forests growing on valley floors; however, given the previously-discussed discrepancies with CMAQ, the high end of this range is expected to decrease. Fenn et al. (2007) and McMurray et al. (2013) measured N deposition with on-site throughfall collectors and monitored the response of individual lichen species. They found enhanced thallus N concentrations and noticeable damage to lichens at around 4 kg total N ha^{-1} yr^{-1}. Therefore, this amount of deposition may be considered a reliable CL for pollution-sensitive lichen species such as *Letharia vulpina*. Ellis et al. (2013) used the GEOS-Chem global chemical transport model to estimate total N deposition at 45 NPS areas including Mount Rainier, North Cascades, and Olympic National Parks. They compared modeled deposition at the PNW parks to lichen CLs and concluded critical loads may be exceeded at the three parks. Ellis et al.'s modeled N deposition estimates were much higher than Fenn et al.'s (2013) estimates derived from throughfall data. This difference highlights the need for better measurements and modeling of deposition used to develop CLs.

Where PNW-specific data are not available, CLs derived from studies in other geographic areas, but with similar ecosystems, are provisionally used (Table 2). Following the approach of Pardo et al. (2011), assessments of the reliability of the CL estimates are as follows:

- High reliability when a number of published papers of various studies show comparable results,
- Medium reliability when the results of some studies are comparable,
- Low reliability when very few or no data are available in the PNW. In this case, CL estimates are based on expert judgment of the applicability of data collected in similar ecosystems outside the region.

In general, as N deposition increases, additional AQRVs are affected and ecological effects become more pronounced. One of the goals of the PNW N CL strategy is to identify CLs for a number of ecological receptors and develop a continuum of expected effects. Figure 7 illustrates cumulative potential adverse ecological effects in the PNW based on the CLs listed in Table 2.

Critical loads for the PNW, as well as for other areas of the country, are continually being updated and refined. The overview in Table 2 represents the most current CL data relevant to the PNW at the time of this report, but additional information will no doubt be available in the future. The CLAD website (http://nadp.sws.uiuc.edu/committees/clad/) should be the best place to obtain up-to-date CL information, both from the FOCUS database and from links to recent publications.

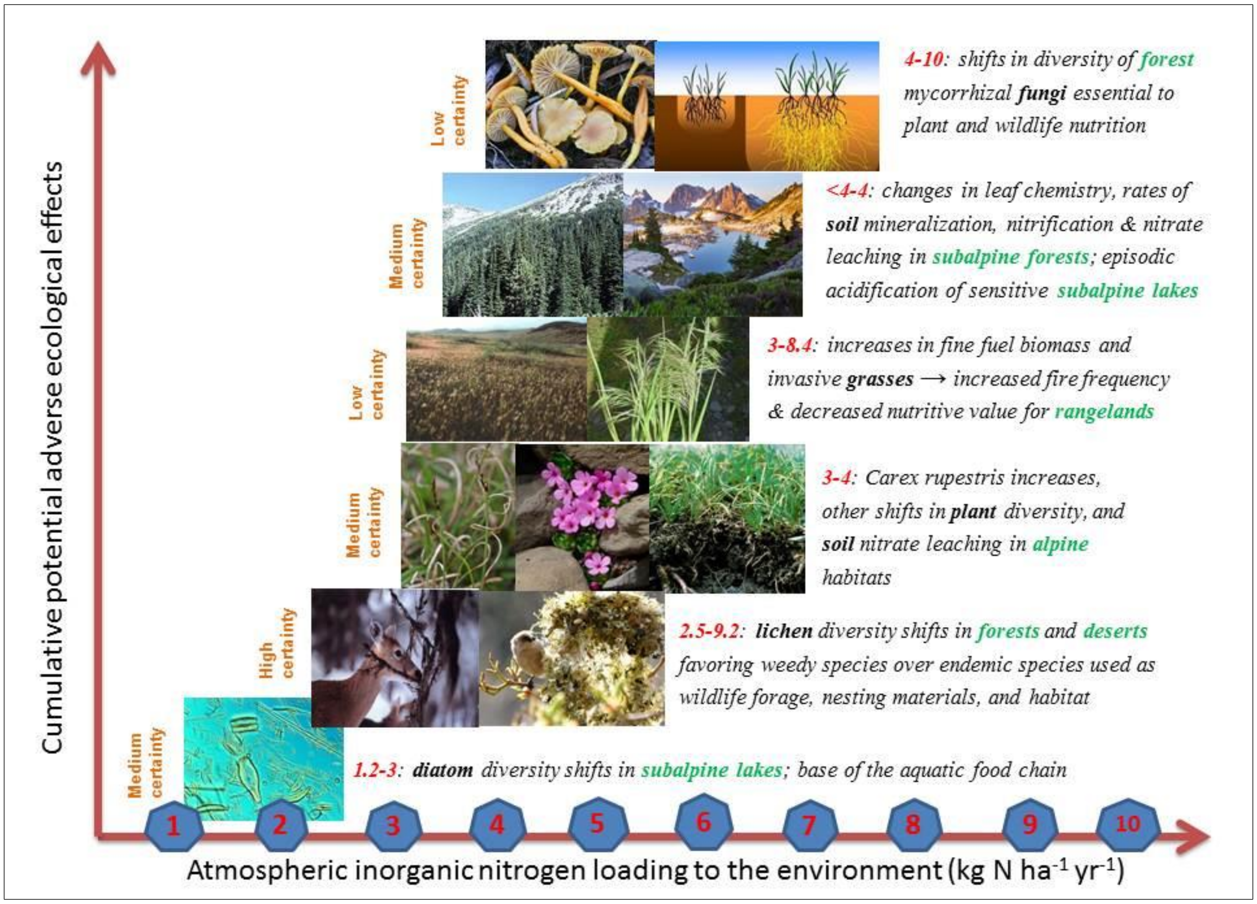

Figure 7. Cumulative potential adverse ecological effects associated with atmospheric N deposition in the PNW (produced by USFS, 2013). The reliability assessments are as follows: High Certainty when a number of published papers of various studies show comparable results, Medium Certainty when the results of some studies are comparable, and Low Certainty when very few or no data are available in the PNW so the applicability is based on expert judgment.

N CLs for PNW North American Deserts

As limited research has been conducted specific to CLs in PNW North American Deserts, estimates for these areas come from studies done elsewhere (generally warmer, more southerly areas) in the ecoregion. Data indicate a CL of 3 kg total N ha^{-1} yr^{-1} based on lichen chemistry and community changes (Geiser et al., 2008), and 3 to 8.4 kg total N ha^{-1} yr^{-1} for changes in vegetation communities that include changes in biomass, composition, and native/invasive components (Allen et al., 2009; Rao et al., 2010; Table 2). Of particular interest is evidence that invasive cheatgrass (*Bromus tectorum*) in the PNW is a superior competitor for added N than native sagebrush communities (Witwicki et al., 2013), and that its growth in warmer semi-arid regions is stimulated by added N at around 3 kg total N ha^{-1} yr^{-1} (Rao et al., 2010). These traits open the possibility that N deposition may increase cheatgrass and wildfire occurrence in semi-arid areas of the PNW. Supporting evidence comes from a recently-completed study that evaluated N deposition and vegetation cover at 10 sites along an N deposition gradient in the Snake River Plains in southern Idaho (Apel et al., 2014). Sites with higher N deposition supported higher overall plant cover, with greater percent cover of cheatgrass and lower percent cover of native forbs.

N CLs for PNW Marine West Coast Forests and Northwestern Forested Mountains

For PNW Marine West Coast Forests and Northwestern Forested Mountains, the greatest confidence is in the CLs for lichens. Using results from over 1,400 lichen plots in western Oregon and Washington, Geiser and Neitlich (2007) developed a model that combined an air pollution gradient with lichen community data to relate N deposition to species diversity. Modeled air quality scores were divided into six classes - Best, Good, Fair, Degraded, Poor, and Worst. The critical load was based on the air quality score separating the Fair class from the Degraded class. On average, N-sensitive lichen species comprised less than 33 to 43 percent of species richness at plots receiving this score. Using the same set of plots, Geiser et al. (2010) identified CLs across western Oregon and Washington. The authors determined lichen N CLs were only exceeded in and around major cities, in the Puget Sound Trough, on the valley floor of the Columbia River Gorge, and along the Interstate-5 corridor (Figure 8).

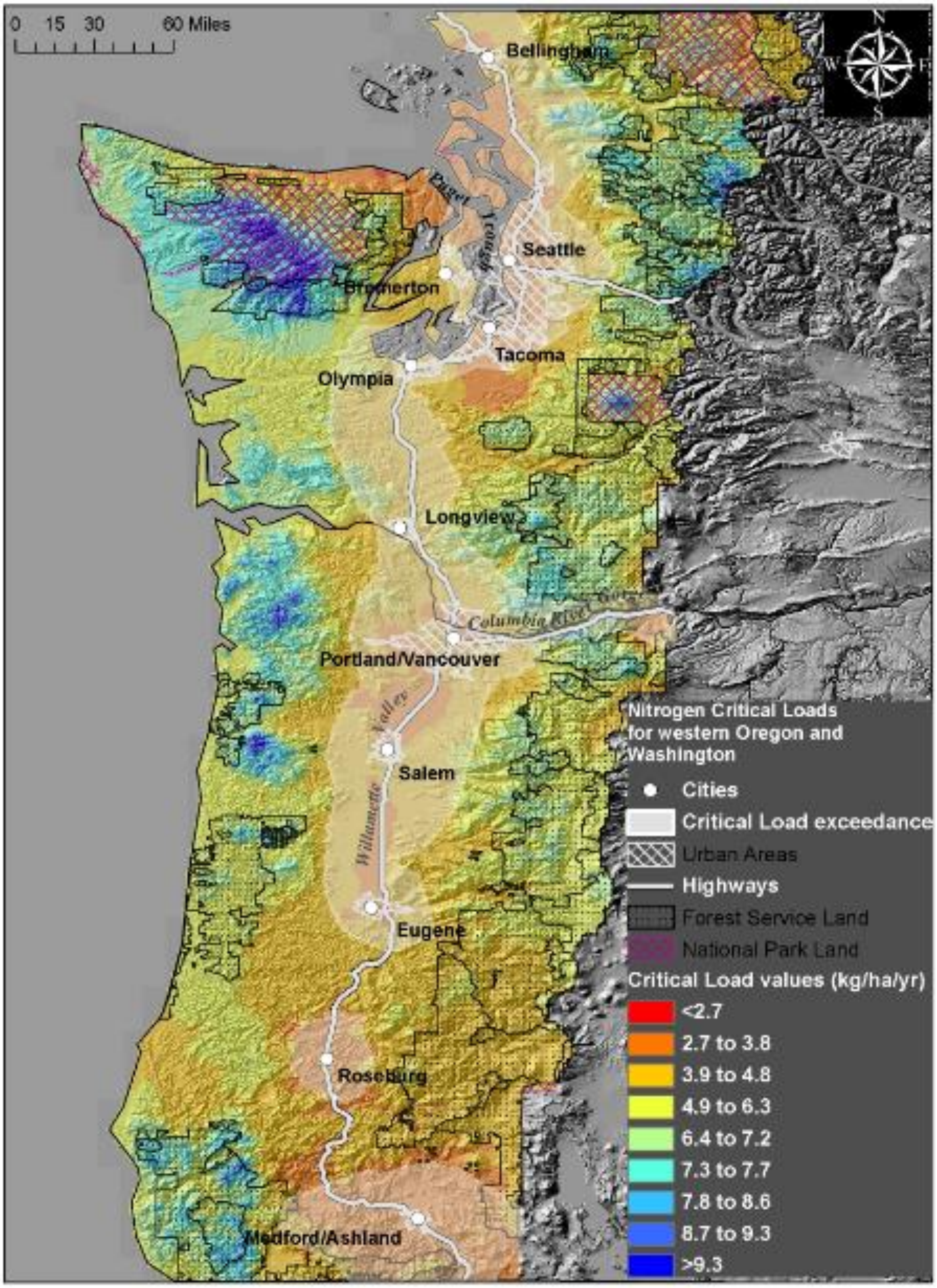

Figure 8. Lichen community-based critical loads for total N deposition in western Oregon and Washington (produced by USFS, 2012).

Critical loads for trees, understory vegetation, and soils in Douglas-fir dominated and mixed forests of low-to-mid elevations across the PNW, and in coastal Sitka spruce forests within the PNW Marine West Coast Forests, have not been determined, as studies have not yet been conducted in the region. However, studies in white spruce forests of southeast Alaska (of a single site near a fertilizer production facility) have developed CL ranges of 4 to 10 kg total N ha^{-1} yr^{-1} for plant, mycorrhizal, and soil responses (Whytemare et al., 1997; Lilleskov, 1999; Lilleskov et al., 2001; Table 2). These white spruce forests display CL values that overlap with regional lichen-based estimates. Applicability of these results to the PNW geographic area is unclear, however, because natural soil N fertility varies to much higher levels across the PNW, and may increase forest susceptibility to added N (Perakis and Sinkhorn, 2011; Perakis et al., 2013).

No CL studies have been completed for subalpine forests in the PNW. The most relevant data are from studies conducted in the Engelmann spruce-subalpine fir forests in the Rocky Mountains. These areas display CL values < 4 kg total N ha^{-1} yr^{-1} for a variety of plant and soil chemical responses (Rueth and Baron, 2002; Rueth et al., 2003; Table 2). However, applicability of these CL values to subalpine fir and hemlock forests that dominate the PNW is unknown. Likewise, alpine vegetation in the Rocky Mountains displays CL values of 3 to 4 kg total N ha^{-1} yr^{-1} for the response of individual plant species and soil chemical changes and 10 kg total N ha^{-1} yr^{-1} for plant community response changes (Bowman et al., 2006; Bowman et al., 2012; Table 2).

Data on aquatic ecosystems of the Rocky Mountains show high-elevation lakes are among the most sensitive resources, and can display changes in diatom (phytoplankton) assemblages at deposition as low as 1.5 kg wet N ha^{-1} yr^{-1} (Baron 2006; Baron et al., 2011; Saros et al., 2011; Table 2). Sheibley et al. (2014) identified a CL of 1.2 kg wet N ha^{-1} yr^{-1} for one PNW lake, Hoh Lake at Olympic NP. Data from low-nutrient high elevation lakes in Europe and the Rocky Mountains indicate a mass ratio of dissolved inorganic nitrogen to total phosphorus (DIN:TP) exceeding 3.4 signifies a threshold response for shifts from nitrogen limitation to phosphorus limitation (Bergstrom, 2010). The applicability of this DIN:TP ratio in the PNW is unknown. As with terrestrial ecosystems, use of aquatic CLs from other areas should be done with caution as there is wide background variation in N levels in lakes and streams across the PNW due to natural N fixation inputs from several woody riparian alder (*Alnus*) species.

Table 2. CLs for N deposition in the PNW (in kg N ha^{-1} yr^{-1})[1]. Shaded cells are selected as most representative of PNW CLs[2].

Critical Load	Deposition Measure	Ecological Receptor	Ecosystem Effect	Ecoregion/Area	Comments	Reliability for PNW[3]	Reference
0.2	Wet N	Natural background deposition	No effect	Marine West Coast Forests	Wet deposition average at remote sites in Alaska and Hawaii	High	http://nadp.sws.uiuc.edu/
1.2	Wet N (PRISM[4] corrected NADP)	high-elevation lake biota	Nutrient enrichment (diatoms)	Marine West Coast Forests/Washington	Hoh Lake in Olympic NP	High	Sheibley et al., 2014
1.5	Wet N (PRISM corrected NADP)	high-elevation lake biota	Nutrient enrichment (diatoms)	Northwestern Forested Mountains/Sierra Nevada	Average of 30 Sierra Nevada lakes	Medium	Baron et al., 2011
1.5	Wet N (NADP)	high-elevation lake biota	Nutrient enrichment (diatoms)	Northwestern Forested Mountains/Rocky Mountains	Rocky Mountain NP, Colorado & other sites in the Rocky Mountains	Medium	Baron 2006; Saros et al., 2011
2.0	Wet N (PRISM corrected NADP)	high-elevation lake biota	Nutrient enrichment (diatoms)	Northwestern Forested Mountains/Rocky Mountains	Average of 285 Rocky Mountain lakes	Medium	Baron et al., 2011
2.5-7.1	CMAQ[5] modeled total N	Coniferous forest lichens	Lichen community changes (40 percent composition of eutrophic species)	Northwestern Forested Mountains/Oregon and Washington	1,411 plots CL range shows precipitation-dependent response	High	Geiser et al., 2010
2.7-9.2	CMAQ modeled total N	Coniferous forest lichens	Lichen community changes (40 percent composition of eutrophic species)	Marine West Coast Forests/Oregon and Washington	1,411 plots CL range shows precipitation-dependent response	High	Geiser et al., 2010
3.0	Total N (PRISM corrected NADP)	high-elevation lake biota	Nutrient enrichment (diatoms)	Northwestern Forested Mountains/Rocky Mountains	Average of 285 Rocky Mountain lakes	Medium	Baron et al., 2011
3	Modeled N	Desert lichen	Lichen thallus N concentrations; cover of eutrophic lichens	North American Deserts/Columbia Plateau	Riparian Habitat, Hells Canyon National Recreation Area, Idaho and Oregon	Low	Geiser et al., 2008

Table 2. CLs for N deposition in the PNW (in kg N ha^{-1} yr^{-1})[1]. Shaded cells are selected as most representative of PNW CLs[2]. (continued)

Critical Load	Deposition Measure	Ecological Receptor	Ecosystem Effect	Ecoregion/Area	Comments	Reliability for PNW[3]	Reference
3-4	Ambient N + additions	Alpine vegetation	Alpine vegetation (change in *Carex rupestris* indicator species cover)	Northwestern Forested Mountains/Rocky Mountains	Rocky Mountain NP and Niwot Ridge, Colorado CL range shows site-dependent response	Medium	Bowman et al., 2006; Bowman et al., 2012
3-8	Modeled N	Desert grasses	Production of fine fuel (red brome and splitgrass) sufficient to support fire	North American Deserts/Sonoran and Mojave	Modeled using DayCent[6] CL range shows increasing fire risk probability	Low	Rao et al., 2010
3-8	Passive samplers and bulk deposition	Desert vegetation	Increase in cheatgrass and decrease in native forbs	North American Deserts/Upper Columbia Basin	Craters of the Moon National Monument, Idaho Density of native vegetation decreased	Medium	Apel et al., 2014
3.1-5.2	N as canopy throughfall	Coniferous forest lichens	Lichen community composition and sensitive species response	Northwestern Forested Mountains/ Oregon and Washington	Columbia River Gorge CL range shows sensitive species responses (from initial decline to 50 percent mortality)	Medium	Fenn et al., 2007
<4	Wet N	Subalpine forests	Foliar chemistry, mineralization, nitrification, nitrate leaching	Northwestern Forested Mountains/Rocky Mountains	Rocky Mountain NP Effects are cumulative over time	Medium	Rueth and Baron, 2002; Rueth et al., 2003
4.0	Total N (PRISM corrected NADP)	high-elevation lakes	Episodic acidification of surface waters	Northwestern Forested Mountains/Rocky Mountains	Average of 285 Rocky Mountain lakes	Medium	Baron et al., 2011
4	N as canopy throughfall	Coniferous forest lichens	Lichen sensitive species response	Northwestern Forested Mountains/Montana and Wyoming	Sensitive lichen species (*Usnea lapponica* and *Letharia vulpina*)	High	McMurray et al., 2013
4-10	Bulk deposition	Mycorrhizal fungi, plants, soils	Fungal community changes; declines in fungal diversity	Marine West Coast Forests/Alaska	N gradient study near Kenai	Low	Whytemare et al., 1997; Lilleskov 1999; Lilleskov et al., 2001
8.4	Throughfall and bulk collectors	Desert grasses	Increased biomass of invasive grasses	North American Deserts/Sonoran and Mojave	Pinon juniper and creosote scrub plant communities in Joshua Tree NP, California	Low	Allen et al., 2009

Table 2. CLs for N deposition in the PNW (in kg N ha^{-1} yr^{-1}) [1]. Shaded cells are selected as most representative of PNW CLs[2]. (continued)

Critical Load	Deposition Measure	Ecological Receptor	Ecosystem Effect	Ecoregion/Area	Comments	Reliability for PNW[3]	Reference
9	Ambient N + additions	Alpine soil chemistry	nitrate leaching below rooting zone in alpine	Northwestern Forested Mountains/Rocky Mountains	Rocky Mountain NP	Medium	Bowman et al., 2012
10	Ambient N + additions	Alpine vegetation community	Community changes in alpine vegetation species composition	Northwestern Forested Mountains/Rocky Mountains	Niwot Ridge	Medium	Bowman et al., 2006

[1] As summarized in Pardo et al. (2011), along with other, more recent (2011 and later) sources. All data must apply to one or more of the three PNW ecoregions to be included in this table.

[2] Based on proximity to PNW, reliability, and similarity to ecosystem types found in Idaho, Oregon, and Washington

[3] Reliability is “high”, “medium”, or “low” after Pardo et al. (2011). Reliability estimates from Pardo et al. are downgraded one level (i.e., high to medium) if based on data from outside the PNW.

[4] PRISM = Parameter-elevation Regressions on Independent Slopes Model

[5] CMAQ = Community Multi-Scale Air Quality atmospheric model. Note that CMAQ modeling overestimates deposition for many PNW high-elevation areas; therefore CLs derived using estimates from this model may change in the future.

[6] DayCent = DayCent is a daily time series biogeochemical model.

Potential Interactions of Climate Change and N Deposition

Nitrogen can negatively impact biodiversity in plant communities, with species that are better adapted to high N levels outcompeting species adapted to low N levels. Climate change can exacerbate this effect with increases in temperatures and changes in precipitation regimes that favor some species over others.

In the PNW, average regional temperature rose about 1ºC over the last century, with some areas experiencing increases over 2ºC (Karl et al., 2009). Temperatures are projected to increase another 2 to 6ºC during this century. Models project that winter precipitation will increase while summer precipitation may decrease in the region. With warming, earlier seasonal snowmelt will lead to reduced summer streamflows. Reduced flows combined with higher summer temperatures will increase drought stress in trees and vegetation and increase the risk of forest fires.

Temperature, atmospheric carbon dioxide (CO_2) concentrations, hydrologic processes, and N cycling all interact to affect forest growth, mortality, and regeneration (Ryan et al., 2014). In colder areas of the region, increases in N deposition and warming may increase forest growth and carbon storage; in warmer and/or drier areas, however, intensified summer drought may be more important than N deposition in shaping carbon storage. For example, high elevation forests on the west side of the Cascade Mountains are expected to see increased growth over the short term, but in the longer term forest growth will decrease (Dalton et al., 2013). Species' response to climate change will vary. Local populations of some species may be extirpated. Biological diversity may increase in some locations (e.g., at higher elevations) and decrease in others (e.g., in the lower elevation, eastern areas of the Cascade Range) (Dalton et al., 2013). The interaction of climate change and increased N deposition may make forests more susceptible to secondary stressors such as insects or disease (Bytnerowicz et al., 2013).

Although there have been few controlled studies on climate change and N interactions, field observations give an indication of potential effects on biodiversity. For example, in arid southern California, elevated N deposition and changing precipitation patterns have promoted the invasion of non-native annual grasses into native shrub communities (Allen et al., 2009; Fenn et al., 2010). This, in turn, has increased fire risk and frequency (Rao et al., 2010). Controlled experiments in a grassland found that elevated CO_2 and N each, and in combination, decreased plant diversity. Losses in diversity were greatest in combined treatments of increased temperature, precipitation, $CO_{2,}$ and N (Zavaleta et al., 2003). Ecosystem modeling of an alpine plant community in Colorado projected that N and climate change can interact to drive losses in biodiversity greater than those caused by either stressor alone (Sverdrup et al., 2012). However, some studies have found that increases in CO_2 can offset the negative effects of N on diversity (Reich, 2009).

Climate change may increase N availability in ecosystems. For example, retreating alpine glaciers are releasing stored N into streams and lakes, where increasing N has been linked to shifts in diatom communities (Saros et al., 2010). Glacial melting and associated sediment transport could be a significant source of N in some high-elevation PNW lakes. Warming increases N mineralization in soils, increasing N availability (Butler et al., 2011), although interactions between temperature and soil moisture are especially important for nitrogen availability in PNW soils (Powers, 1990).

The impacts of climate change and N interactions will be influenced by many biotic and abiotic factors and will vary by ecosystem and species, making it difficult to predict site-specific outcomes. In general, reducing N deposition is considered a good strategy for increasing ecosystem resilience to climate change (Porter et al., 2012).

Current Efforts and Data Gaps

In 2006, the NPS, USFS and USGS, in conjunction with Washington's Northwest Clean Air Agency, sponsored the Pacific Northwest Nitrogen Deposition and Critical Loads Workshop (Waddell and Greenwood, 2006). The workshop included a half-day devoted to exploring research gaps and developing an agenda for future research activity to support setting N CLs in the PNW, with a focus on northwest Washington. Following up on the recommendations from that workshop, the NPS and USFS have funded and/or endorsed several projects, including a number of current efforts discussed below. Some of the ongoing studies are limited in scope or spatial extent and should be considered pilot projects, results of which will inform the need to do additional work in the future.

Given the significant advances in development and use of N CLs since 2006, the NPS, USFS, and USGS decided to re-visit Waddell and Greenwood's (2006) recommendations. In addition, they expanded their evaluation of data gaps to include NPS and USFS areas in Idaho and Oregon. This report provides an updated, and prioritized, list of data needs relative to N CLs in the PNW based on the following considerations: the number of ecological receptors for which CLs have been identified, the reliability of those CLs, and anticipated ability to use the data to inform and influence the protection of NPS and USFS resources. The list is not exhaustive; the NPS and USFS welcome other suggestions and proposals to acquire N CL data in the PNW. Decisions about which projects to pursue will be influenced by a number of factors including available funding, opportunities for collaboration, projected changes in emission sources and/or source areas, improved estimates of N deposition, and better understanding of ecosystem response to N.

Ongoing Research

Several projects are investigating N effects on PNW ecosystems; in addition, a couple of national efforts will inform CL development in the region (Table 3).

Simpson, Zabowski, and Edmonds (University of Washington) began a three-year study in 2012 to assess the effects of N deposition on high elevation plant and soil communities in Mount Rainier, North Cascades, and Olympic National Parks. The researchers fertilized plots with three application rates of N (3, 5, and 10 kg N ha^{-1} yr^{-1}) and are monitoring changes in plant and soil N concentrations. An associated project is studying the effects of N enrichment on soil mycorrhizal fungi at Mount Rainier and North Cascades National Parks.

Poinsatte and Evans (Washington State University) are investigating how three subalpine vegetation communities at Mount Rainier NP respond to N deposition from snowmelt by measuring the ability to store or emit N. They fertilized plots using the same N application rates as Simpson, Zabowski, and Edmonds and are monitoring soil nitrous oxide emissions, soil N leaching, and plant uptake of N. The project should indicate if any of the studied communities are likely to be affected by increased N deposition.

Root (USFS) is completing a model to score lichen communities in northern Idaho, eastern Oregon, and eastern Washington along air pollution and climate gradients and is establishing CLs based on N concentrations in fine particulates measured by Interagency Monitoring of Protected Visual Environments (IMPROVE) monitors in the region. In a related project, Geiser, Jovan, and others (USFS) are using best available deposition data and national scale FIA lichen community data collected on public and private land to refine lichen CLs for major ecoregions of the U.S., including the three Level 1 ecoregions of the PNW.

A research group including Evans and Anderson (Washington State University), Williams (University of Wyoming), and Pardo, Geiser, and McMurray (USFS), is studying stable N isotope ratios to identify and map N deposition from different agricultural and industrial sources. This work is currently based on about 200 sites in Idaho, Montana, Oregon, Washington, and Wyoming and regional NADP monitors. The researchers are also evaluating additional samples from national forests and parks in New England which were co-located with deposition samplers.

There is a critical gap in the development of aquatic N CLs in the PNW. Although many high elevation PNW lakes have low acid neutralizing capacity, it is suspected these lakes respond to N enrichment at lower levels than would cause acidification. Previous work on N effects in PNW lakes has been confounded by the difficulty in determining the N-limitation of alpine lakes (Saros, 2009), the occurrence of N-fixing alders in many watersheds (Clow and Campbell, 2008), or uncertainty about the N sensitivity of diatom species found in PNW lakes (Sheibley et al., 2014). To help determine aquatic CLs, Williams and Beutel (Washington State University) began a two-year project in 2013 to study changes in diatom communities associated with N enrichment of lake water in Mount Rainier, North Cascades, and Olympic National Parks. The researchers are conducting two additional projects in North Cascades NP: one investigates the effect of glacier melting on mountain lake chemistry; the other will develop and test regression models that use landscape characteristics and N deposition to identify lakes that likely exceed CLs.

There is very limited information about CLs in vegetation communities and soils of the PNW, with the exception of past studies of lichen and ongoing studies of alpine communities. At the national level, the USGS Powell Center is sponsoring two projects that will inform critical loads in the PNW. One is led by Allen (University of California – Riverside) to better understand the biological and ecological responses of terrestrial vegetation to atmospheric N deposition in five focus areas of the U.S. One of the regional focus areas is forests of Oregon and Washington. Analysis for the PNW will use soil, understory vascular plant, tree, and lichen survey data collected across public and private forest lands through the FIA Program. A second project is led by Smithwick (Pennsylvania State University) to better understand how plant and soil chemical properties influence the response of forest trees to N deposition. This project is national in scope, and will include representation from the PNW.

Table 3. N CL projects currently being conducted in the PNW

Organization	Objective	Locations	Results Expected
University of Washington	Document effects of N fertilization on alpine/subalpine communities.	One site each at Mount Rainier, North Cascades, and Olympic National Parks	2015
University of Washington	Document N effects on mycorrhizal fungi in alpine/subalpine soil.	One site each at Mount Rainier and North Cascades National Parks	2014
Washington State University	Evaluate the response of three subalpine plant communities to N deposition.	One site at Mount Rainier NP	2015
USFS	Refine N CLs for changes in lichen communities using lichen N concentrations, IMPROVE data, and direct measurements of throughfall.	5,000 surveys in Idaho, Oregon, and Washington	northern Idaho, eastern Oregon and Washington 2014 western Oregon and Washington 2015
Washington State University, University of Wyoming, and USFS	Use N isotope ratios in lichens and NADP data to identify N emission sources and map deposition of N and ammonium vs. nitrate.	About 200 survey sites throughout the northwestern U.S. including Idaho, Oregon, and Washington	2016
Washington State University	Conduct nutrient enrichment studies in high elevation lakes to determine diatom N CLs.	Three sites each in Mount Rainier, North Cascades, and Olympic National Parks	2015
Washington State University	Use existing data to determine the influence of presence/absence of permanent snow or ice in the watershed on the water chemistry of high elevation lakes.	108 lakes at North Cascades NP	2014
Washington State University	Use existing data to develop and test models to predict lake sensitivity to N deposition.	108 lakes at North Cascades NP	2015

Table 3. N CL projects currently being conducted in the PNW (continued)

Organization	Objective	Locations	Results Expected
USGS Powell Center	Analyze FIA soils, understory vegetation, and tree data to better understand forest vegetation responses to N deposition.	About 500 surveys in Oregon and Washington	2016
USGS Powell Center	Analyze FIA soils, and tree and soil chemical data, to better understand forest biogeochemical response to N deposition.	All existing FIA and published available data for Oregon and Washington	2017

Additional Data Needs

Additional work is needed to improve estimates of N deposition (including organic N) and to improve understanding of ecological responses to N deposition in the PNW (Table 4).

Because N deposition in the region is relatively low and levels are often close to the lower end of the CL range identified for sensitive species, like lichens, it is critical to improve site-specific deposition estimates. Information is lacking regionwide about the potential interactions of N with existing climate gradients, in addition to projected changes in temperature, precipitation patterns, and CO_2. It is important to understand how natural background variation in ecosystem N status across the region - which is unusually high in the PNW relative to other regions worldwide - may influence ecosystem sensitivity to additional N. Aside from the extensive lichen dataset, information about CLs in the Marine West Coast Forests and Northwestern Forested Mountains ecoregions is limited. No CL studies have been conducted in the PNW's North American Deserts ecoregion.

Table 4. Data needs and priorities relative to N CLs in the PNW

Ecosystem	Information Needed	Rationale	Approach	Priority
Regionwide				
Aquatic/Terrestrial	Improved site-specific estimates of N deposition.	There are few deposition monitoring sites in the PNW and there are very few high elevation data. Current models, such as CMAQ, are not adequate to capture fine-scale gradients in deposition, particularly in the PNW where N deposition is relatively low and there are large ranges in precipitation and dry deposition over complex terrain.	Focusing on areas/resources with suspected high sensitivity, collect N deposition data (e.g., bulk, throughfall) that can be used to evaluate and augment modeled deposition estimates.	High
Aquatic/Terrestrial	Identify interactions of N deposition and climate change that affect surface waters, soils, and vegetation.	Excess N deposition may exacerbate climate change-induced stress on species and ecosystems in many ways, including impacts on the following: - N concentrations and cycling in soils and surface waters when there is a shift from snow-dominated to rain-dominated conditions. - Distribution and amount of grass, shrub, forest, and alpine habitats. - Forest growth, mortality, and regeneration. - Carbon storage. - Susceptibility to other stressors such as pests, disease, and wildfire.	Evaluate existing datasets and current research efforts for linkages between climate change and N deposition effects data. Conduct N fertilization experiments along climate (e.g., temperature, precipitation) gradients and/or use N deposition gradients to investigate ecosystem response.	High

Table 4. Data needs and priorities relative to N CLs in the PNW (continued)

Ecosystem	Information Needed	Rationale	Approach	Priority
Marine West Coast Forests and Northwestern Forested Mountains				
Aquatic/Terrestrial	Determine the influence of natural lake, stream, and soil N levels on CLs.	Some lakes, streams, and soils in the PNW naturally have very high N levels due to past and present influence of symbiotic N-fixing alders and geologic N sources. Other areas have naturally low N levels. This natural variation, which is higher in the PNW than in other regions, will influence ecosystem susceptibility to additional N from atmospheric deposition. Comparing sites that contain alder to those that don't would provide insight into longer-term effects of N enrichment and supplement data from shorter-term fertilization studies.	Use background soil N gradients, fertilization studies or air pollution gradients to identify CLs. Use measured N levels in mass balance models to predict CLs.	High
Aquatic	Refine sensitivity ranges for high elevation lakes to N deposition.	There is a great deal of uncertainty regarding the number of lakes in the PNW that are more responsive to added N than to addition of other nutrients.	Use existing data to determine the percentage of lakes that are N-limited relative to those that are limited by phosphorus or other nutrients, and evaluate whether these differences are influenced by rates of N deposition or other environmental factors.	High
Aquatic	Identify N and N plus sulfur CLs for episodic acidification of high elevation lakes.	While eutrophication may be more likely than acidification at current levels of N deposition in the PNW, additional N or N plus sulfur deposition could episodically acidify poorly-buffered lakes.	Use N and sulfur deposition gradients and/or enrichment experiments to evaluate changes in macroinvertebrate and plankton communities.	Low

Table 4. Data needs and priorities relative to N CLs in the PNW (continued)

Ecosystem	Information Needed	Rationale	Approach	Priority
Marine West Coast Forests and Northwestern Forested Mountains				
Terrestrial	Determine N sensitivity of high-elevation biological soil crusts.	Crusts are a critical component of the ecosystem because they stabilize soils, fix atmospheric N, and promote establishment of vascular plants.	Conduct fertilization experiments and/or use N deposition gradients to identify and monitor sensitive lichen and moss species in crusts.	Medium
Terrestrial	Identify CLs for trees and understory vegetation in low- to mid-elevation forests.	Though alpine/subalpine plants are thought to be more sensitive than those in lower elevations, given the social, cultural, economic, and recreational value of lower-elevation forests, it is important to identify CLs in those areas.	Analyze available FIA vegetation data along regional N deposition gradients. Use fertilization studies and/or N deposition gradients to determine response of plant species/communities to additional N.	Medium
Terrestrial	Determine sensitivity of forest soils to N deposition.	This information would provide insight on N cycling to complement and inform both vegetation studies and watershed transport of N to downstream aquatic ecosystems.	Approaches range from simple observational estimates (e.g., comparing soil carbon:nitrogen ratios to known response thresholds), to N fertilization experiments and/or gradient studies, to sophisticated biogeochemical modeling.	Medium
Terrestrial	Identify CLs for vegetation.	There is currently little information specific to the PNW.	Use fertilization studies and/or N deposition gradients to determine response of plant species/communities to N.	High

Table 4. Data needs and priorities relative to N CLs in the PNW (continued)

Ecosystem	Information Needed	Rationale	Approach	Priority
Marine West Coast Forests and Northwestern Forested Mountains				
Terrestrial	Determine relationship between N deposition and abundance of invasive grasses, including cheatgrass, North Africa grass (*Ventenata dubia*), and medusahead (*Taeniatherum caput-medusae*).	The proliferation of invasive grasses in desert ecosystems is a significant concern.	Use fertilization studies and/or N deposition gradients to determine response of plant species/communities to N.	Medium
Terrestrial	Determine N sensitivity of desert biological soil crusts.	Crusts are a critical component of the ecosystem because they stabilize soils, fix atmospheric N, and promote establishment of vascular plants.	Use fertilization experiments and/or N deposition gradients to identify and monitor sensitive lichen and moss species in crusts.	High

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Other Resources

CASTNET website, http://epa.gov/castnet/javaweb/index.html

NADP website, http://nadp.sws.uiuc.edu/

NPS Air Resources Division website, http://www.nature.nps.gov/air/

USFS Air Resource Management website, http://www.fs.fed.us/air/

USFS Lichen Air Quality Database website, http://gis.nacse.org/lichenair/index.php

Appendix A

Recommended Approach for Establishing and Implementing Nitrogen Critical Loads and Target Loads for National Forests and National Park Service Areas in the Pacific Northwest (Idaho, Oregon, and Washington)

July 2014

Introduction

The Clean Air Act, the Wilderness Act, and agency policies provide the basis for the National Park Service (NPS) and the U.S. Forest Service (USFS) to work with regulatory agencies and others to protect the air quality and air pollution-sensitive resources of National Forests and NPS areas. One way to do this, particularly as it pertains to pollutant deposition, is through the use of critical loads (CL) and target loads (TL). A CL is the amount of deposition below which harmful environmental effects are not expected to occur. Critical loads are determined through ecosystem studies and modeling. A TL identifies an acceptable amount of deposition based on policy, economic, temporal or other considerations. A TL may be lower or higher than its associated CL.

The objectives that follow recommend an approach for developing and implementing nitrogen (N) CLs and TLs for all National Forests and NPS areas in Idaho, Oregon, and Washington, i.e., the Pacific Northwest. The timeline for completing the objectives will depend on availability of NPS and USFS staff, financial resources, and data. We expect this to be an iterative process. As new information becomes available, we will revise CLs and TLs accordingly. We intend to revisit the objectives every five years, determine progress, and modify our approach, as needed.

OBJECTIVE #1: CREATE DOCUMENTS THAT SUMMARIZE THE CURRENT STATE OF KNOWLEDGE ABOUT N CLs IN THE PACIFIC NORTHWEST

Strategy 1: In consultation with other subject matter experts, write a report that describes potential effects of N deposition, explains the concept and use of CLs and TLs, summarizes available information about N CLs in the Pacific Northwest, and identifies and prioritizes data gaps.

Thresholds for Protecting Pacific Northwest Ecosystems from Atmospheric Deposition of Nitrogen: State of Knowledge Report will be published by July 2014.

Strategy 2: Prepare a 2 to 4 page fact sheet targeted for USFS and NPS managers, regulators, and the public that summarizes the State of Knowledge report.

OBJECTIVE #2: COLLECT ADDITIONAL DATA SPECIFIC TO N CLS IN THE PACIFIC NORTHWEST

Strategy: Encourage and support research that will further understanding of N CLs, including possible interactions with climate change, and urge researchers to publish their results. In particular, promote studies that were identified as a high priority in the State of Knowledge report described in Objective 1.

OBJECTIVE #3: DETERMINE N TLS FOR THE PACIFIC NORTHWEST

Strategy: Use identified CLs and agency policies and mandates to develop N TLs.

Given that USFS and NPS each have unique mandates that guide management of their areas, it is possible the agencies will develop different TLs. Nevertheless, the agencies will work together to develop a common rationale for setting those TLs.

OBJECTIVE #4: IDENTIFY WHICH NATIONAL FORESTS AND NPS AREAS EXCEED N CLS AND TLS

Strategy: Develop GIS maps of the region indicating areas that exceed identified N CLs and TLs.

Consult with other subject matter experts to determine the most appropriate data/tools to use for best estimates of N deposition. Develop GIS maps that indicate National Forest and NPS area boundaries, with layers for N deposition, CL exceedances, and TL exceedances.

Information sources for N deposition include, but are not limited to:
- National Atmospheric Deposition Program (NADP) Total Deposition Science Committee (national effort related to improving deposition estimates)
- Community Multi-scale Air Quality Model (CMAQ) estimates of total, wet, dry, oxidized, and reduced N deposition
- Interagency Monitoring of Protected Visual Environments (IMPROVE) particle data
- Throughfall monitoring data collected as part of several studies in the Pacific Northwest
- National CL tools being developed by USFS for their 2012 Forest Planning Rule.

OBJECTIVE #5: OBTAIN FEEDBACK FROM STAKEHOLDERS ON RECOMMENDED CLS, TLS, AND AREAS WITH EXCEEDANCES AND WRITE A REPORT SUMMARIZING THE RESULTS

***Strategy 1**:* Discuss and solicit input on Objectives 3 and 4 with internal and external stakeholders including National Forest and NPS staffs, state air quality agencies, and the U.S. Environmental Protection Agency.

***Strategy 2**:* Incorporate stakeholder comments into a report that describes the concept and use of CLs and TLs, summarizes the process used to develop N TLs for the Pacific Northwest, and provides maps of CL and TL exceedances. Distribute the report to stakeholders and post it on USFS and NPS websites.

OBJECTIVE #6: IMPLEMENT USE OF N CLS AND TLS IN NATIONAL FORESTS AND NPS AREAS

***Strategy*:** USFS and NPS will implement the CLs and TLs through each agency's planning and/or policy mechanisms, as appropriate. Both agencies will use the CLs and TLs in conjunction with Federal Land Managers Air Quality Related Values Work Group (FLAG) permit review guidance. The CLs and TLs will be linked to other environmental factors such as climate change and fire.

In addition, the USFS will:

- Incorporate CLs and TLs into Forest Plan Revisions under the 2012 Planning Rule. Emphasis will be on: 1) documenting desired conditions, 2) demonstrating the relationship between desired conditions and monitoring data, and 3) demonstrating that the connection is adequately supported by credible science. Additionally, USFS directives will be revised to guide Forest Planners in the need for CLs and TLs.
- Continue to provide input to USFS Watershed Condition Assessment and Terrestrial Condition Framework as a means of identifying watersheds in need of restoration.

In addition, the NPS will:

- Continue to work on park- and region-specific initiatives to develop and implement CLs and TLs.
- Develop guidance for incorporating CLs and TLs into park planning processes, using CLs and TLs to identify desired conditions, evaluate current conditions, and inform park management activities.

OBJECTIVE #7: IDENTIFY THE CONTRIBUTING SOURCES OF EMISSIONS TO AREAS EXCEEDING N CLS AND TLS

Strategy 1: Develop a tool or a suite of tools to characterize source apportionment in areas where CLs or TLs are exceeded.

Work with the NADP Total Deposition Science Committee and U.S. Environmental Protection Agency, state, NPS, and USFS atmospheric modelers to determine best methods to identify pollution sources. Tools may include regional air quality models (e.g., CMAQ, CAMx), source attribution models (e.g., Positive Matrix Factorization), trajectory analysis models (e.g., Hysplit), source apportionment based on lichen analysis or other methods. Since this could be an extensive exercise, areas of interest will be prioritized. A demonstration project may be helpful to determine the best process to use.

Strategy 2: Work with states, U.S. Environmental Protection Agency, and other potential stakeholders to determine how to use the source apportionment information to achieve emission reductions.

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