



Mapping of Nitrogen Critical Loads for Selected National Parks in the Western United States

Natural Resource Report NPS/NRSS/ARD/NRR—2016/1286



ON THE COVER

Photograph of Saguaro cacti, Rincon Mountain District, Saguaro National Park
Photograph courtesy of the National Park Service (Alice Wondrak Biel)

Mapping of Nitrogen Critical Loads for Selected National Parks in the Western United States

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Summary

Air pollution has long been recognized as a significant stressor to natural resources in national parks. Significant impacts to surface waters, soils, vegetation, wildlife, and visibility have been documented in a wide range of ecosystems across portions of the United States, including within the National Park system. Nitrogen (N) in human-caused air pollution has been found to affect natural plant communities, changing species composition, facilitating the spread of invasive species, altering fire cycles, and ultimately reducing native plant diversity. Nitrogen in air pollution results from emissions associated with energy, transportation, agriculture, and other sources. Airborne N is eventually deposited to the Earth's surface through rain, snow, and dryfall. In recent years, N sources have increased in some regions, with concomitant increased risks to sensitive ecosystems, particularly those that evolved under naturally low N conditions. In the western U.S., the combination of increased N sources, together with the presence of N-sensitive receptors, has been responsible for a variety of chemical and biological changes in aquatic and terrestrial ecosystems. As documentation of these changes increases, scientists have been able to identify the levels of N addition at which ecosystems begin to change, a deposition loading known as the "critical load" (CL). Pardo et al. (2011a) compiled empirical data on N CLs in ecoregions throughout the United States for a variety of N-sensitive resources, including lichens, mycorrhizal fungi, herbaceous plants and shrubs, and forests. These CLs are generally reported by Pardo et al. (2011a) as ranges for a given ecoregion. Because ecosystems vary, sometimes substantially, within an ecoregion, the CL range for a given receptor may not apply to all plant communities or all portions of the ecoregion. When selecting appropriate CLs for a specific national park, it is important to examine the scientific basis of the CL, that is, whether the CL estimate was based on a specific vegetation type, and whether that vegetation type occurs in the park. Here, we evaluate empirical CL estimates for ecoregions in the western United States and analyze available vegetation data to specify appropriate CL ranges for selected national parks. We also examine total (oxidized and reduced) N deposition estimates in and near the parks. We compare deposition estimates for 2011 to park N empirical CLs to evaluate the likelihood that CLs are exceeded in NPS areas. Our focus is on 15 national park units located in the southwestern United States and in the Northern Great Plains (NGPN) and the Rocky Mountain (ROMN) National Park Service (NPS) Inventory and Monitoring (I&M) networks. The parks selected for study include many of those that have been identified as having N-sensitive ecosystems. Some of the parks have experienced in recent years increasing levels of nearby energy, agricultural, mineral extraction, and/or transportation development, with associated increasing N emissions.

This report evaluates N CLs and their potential exceedances (extent to which ambient deposition exceeds the CL required for resource protection) at selected national parks throughout the intermountain western United States, in the context of potential new N emissions sources, including energy development and agriculture. The CL and exceedance estimates presented here were based on the lower limits of the ranges of CL, by ecoregion, reported by Pardo et al. (2011a). This was done to conform with the NPS mandate when considering CL to err on the side of resource protection.

Based on these lower limits of the CL ranges reported by Pardo et al. (2011a), terrestrial resources in some of the parks identified for study were either in exceedance of the N CL during 2011 or received

ambient total (wet plus dry) N deposition that was below, but within 1 or 2 kg N/ha/yr of the CL. Thus, nutrient sensitive terrestrial resources in some of these parks may be experiencing adverse impacts associated with CL exceedance. In other cases, appreciable increases in nitrogen oxides (NO_x), ammonia (NH₃), or other N-containing emissions and deposition may trigger exceedances in the future.

Of the parks that were evaluated in this study, estimated N CL exceedances were most pronounced in Hovenweep National Monument (HOVE), Mesa Verde (MEVE), and Saguaro (SAGU) national parks. A small portion of Grand Canyon National Park (GRCA) was in exceedance. In addition, large portions of Black Canyon of the Gunnison (BLCA), Carlsbad Caverns (CAVE), Rocky Mountain (ROMO), Badlands (BADL), and Theodore Roosevelt (THRO) national parks and Colorado (COLM) and Dinosaur (DINO) national monuments received N deposition in 2011 that was within 1 kg N/ha/yr or less below the estimated N CL. Much of Arches (ARCH), Canyonlands (CANY), Natural Bridges (NABR), and Wind Cave (WICA) national parks received N deposition in 2011 that was below, but within 2 kg N/ha/yr of, the N CL. These results provide estimates of relative risk of nutrient enrichment to sensitive plant communities among the parks selected for study.

The deposition data shown in this report are estimates for 2011 and may not fully capture current deposition levels, particularly in areas where NO_x and/or NH₃ emissions have recently changed. This uncertainty in model estimates of N deposition, and the spatial and temporal variability inherent in these estimates, influence our assessment of where and to what extent exceedances occur. Thus, it will be important to continue to track N deposition and to evaluate likely impacts on CL exceedance and associated effects on nutrient-sensitive vegetation in these and other national park units.

Acknowledgments

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Introduction

Site Selection

Atmospheric deposition of N is an important ecosystem stressor in many national park units in the conterminous United States. Existing point and nonpoint N emissions sources associated with energy, transportation, agricultural, and industrial activities are common in many areas. NO_x emissions from coal fired power plants and motor vehicles have been substantially reduced in the past decade under the requirements of the Regional Haze Rule or to meet the national ambient air quality standard for ozone and vehicle emission standards. Oil and gas (O&G) exploration and production are ongoing and have increased rapidly in many areas. High-interest/visitation parks, potentially affected by these relatively new or changing emissions sources, were identified by the NPS Air Resources Division (NPS-ARD) for detailed study here (Table 1, Map 1). Most of the study parks are located in the southwest. Three are located in the Northern Great Plains. One (ROMO) is located in the Rocky Mountains. Boundaries of desert regions, which are highly sensitive to nutrient enrichment, relative to NPS network boundaries are shown in Map 2.

Deposition

Deposition of N to the parks selected for study was derived from a variety of anthropogenic and natural sources, including motor vehicles, power plants, agriculture, industry, lightning, and biological N fixation. Deposition of NO_x and other pollutants derived from emissions related to O&G exploration and production are emerging as an important threat to air quality in various regions of the western United States. The recent increase in O&G development in the United States has been spurred by improved technological advancements, including horizontal drilling and hydraulic fracturing (fracking) combined with economic conditions that were favorable to these more expensive drilling techniques. These “unconventional” techniques have opened basins and geologic formations to development that previously were thought to be non-recoverable or non-economic resources. However, equipment associated with both conventional and unconventional oil and gas development emits air pollutants, including N. In large oil and gas fields, cumulative N emissions from oil and gas operations can be significant and rival large point sources.

Emissions of reduced N from confined animal feeding operations (CAFOs) and other agricultural developments are important sources of reduced N in some regions. Sensitive plant receptors respond to inputs of both oxidized and reduced N.

Critical Load Background

Deposition of N from human activities have the potential to affect soils, vegetation, and surface waters in national parks and monuments located generally downwind of emissions sources. In particular, increased N loading to natural ecosystems can cause changes in plant communities, sometimes favoring exotic and invasive species over native species (Fenn et al. 2003). Such changes in vegetation can affect fire regimes, including in JOTR (Rao et al. 2010).

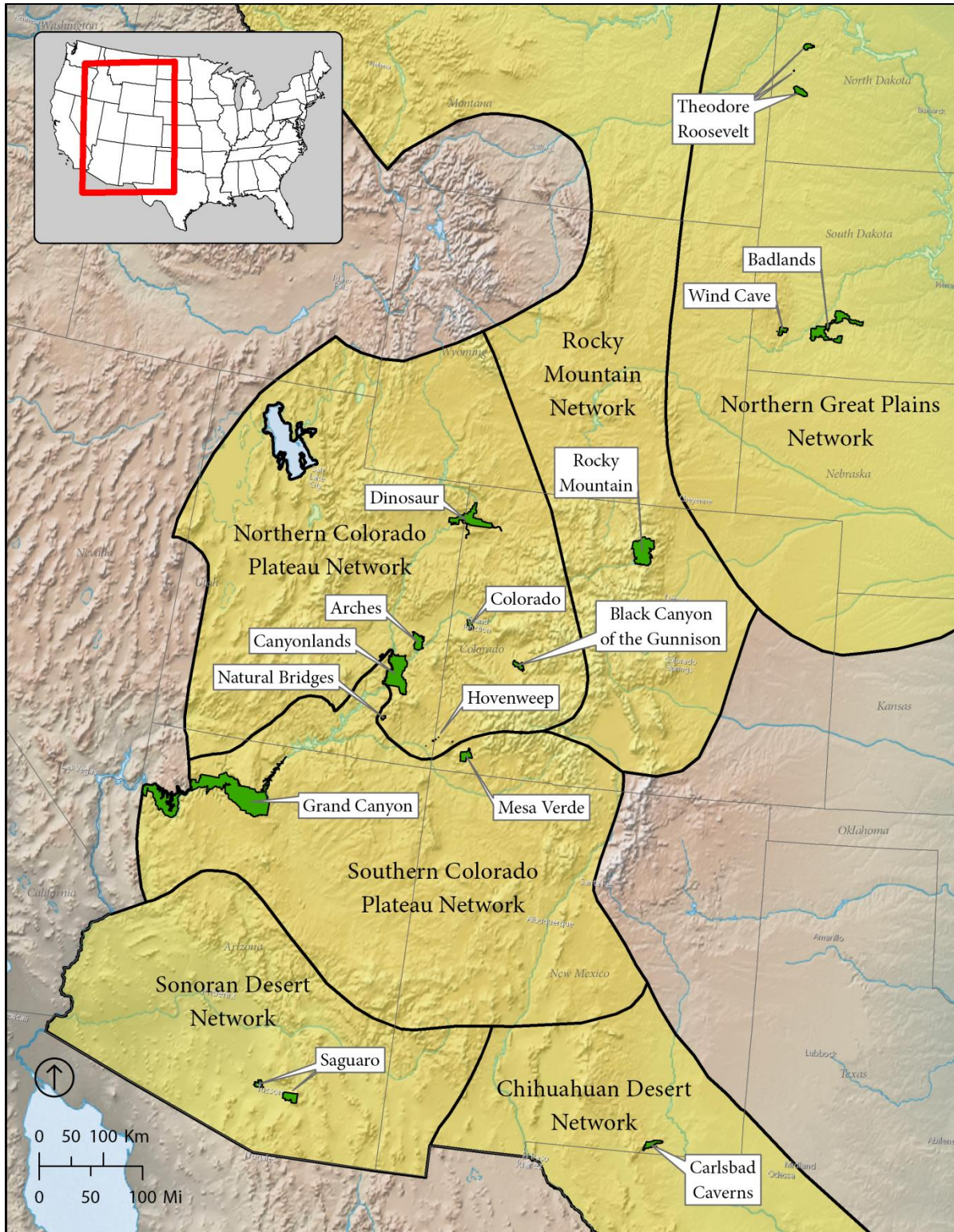
The CL is the pollutant loading rate below which adverse impacts are not expected to occur to sensitive ecosystem receptors. The CL is commonly calculated to protect against either N enrichment or acidification. Resources differ in their sensitivity to damage from air pollutant deposition of N.

Table 1. Parks in the intermountain West, Rocky Mountains, and Northern Great Plains regions identified for this analysis as high-interest for evaluation of critical loads of N deposition. NPS I&M Program network names and codes are provided.

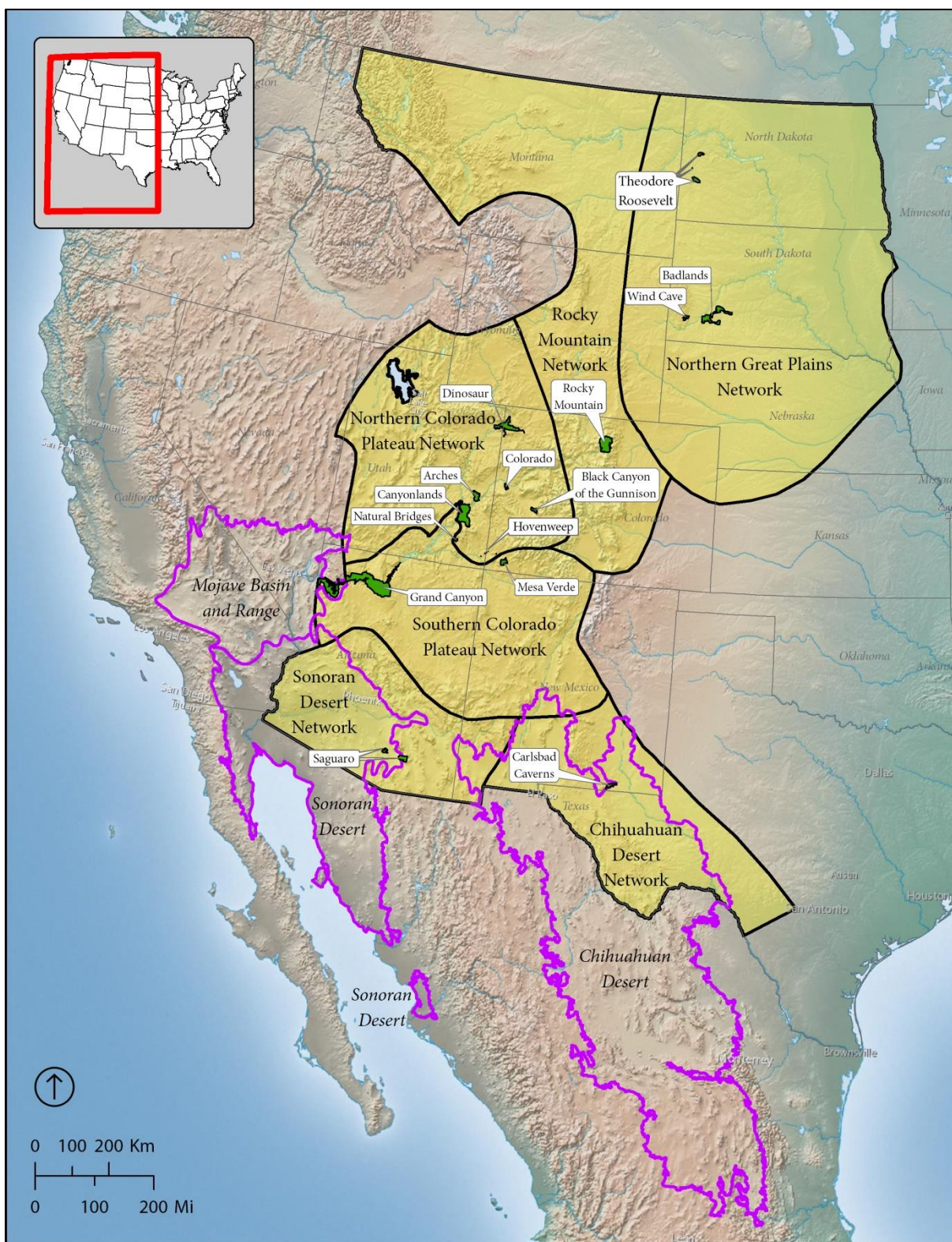
Park Code	Park Name	Network Code	NPS I&M Network Name	Level I Ecoregion
GRCA	Grand Canyon NP	SCPN	Southern Colorado Plateau	North American Deserts and Temperate Sierras ²
MEVE	Mesa Verde NP	SCPN	Southern Colorado Plateau	North American Deserts
CAVE	Carlsbad Caverns NP	CHDN	Chihuahuan Desert	North American Deserts and Temperate Sierras ¹
ARCH	Arches NP	NCPN	Northern Colorado Plateau	North American Deserts
BLCA	Black Canyon of the Gunnison NP	NCPN	Northern Colorado Plateau	North American Deserts
CANY	Canyonlands NP	NCPN	Northern Colorado Plateau	North American Deserts
COLM	Colorado NMN	NCPN	Northern Colorado Plateau	North American Deserts
DINO	Dinosaur NMN	NCPN	Northern Colorado Plateau	North American Deserts
HOVE	Hovenweep NMN	NCPN	Northern Colorado Plateau	North American Deserts
NABR	Natural Bridges NMN	NCPN	Northern Colorado Plateau	North American Deserts
SAGU	Saguaro NP	SODN	Sonoran Desert	North American Deserts and Southern Semiarid Highlands
ROMO	Rocky Mountain NP	ROMN	Rocky Mountain	Northwestern Forested Mountains
BADL	Badlands NP	NGPN	Northern Great Plains	Great Plains
THRO	Theodore Roosevelt NP	NGPN	Northern Great Plains	Great Plains
WICA	Wind Cave NP	NGPN	Northern Great Plains	Great Plains

¹ For the purposes of this analysis, CAVE and SAGU were treated as occurring entirely within the North American Deserts ecoregion to err on the side of resource protection for this analysis.

² Most of GRCA is located within the North American Deserts ecoregion. The small portion that occurs in the Temperate Sierras ecoregion is ignored for this analysis.



Map 1. High-interest area for evaluation of N CL issues in the intermountain West, northern Great Plains, Rocky Mountains, and southwestern desert regions, showing park lands selected for intensive study.



Map 2. Location of desert regions in the southwestern United States and northern Mexico relative to NPS network boundaries.

The CLs are variable by ecoregion and vegetation type. In terrestrial systems, the CLs are often especially low (high sensitivity to damage) for protection of lichens and mycorrhizal fungi.

There are multiple approaches that can be used to estimate the CL. These include deposition gradient studies, experimental N and/or S addition, and steady-state or dynamic modeling. Each approach entails strengths and weaknesses (Sullivan and Jenkins 2014). An individual national park will not have a single CL. Rather, it will have a matrix of CLs depending on the resources to be protected, the method used to estimate the CLs, and the desired level of protection. Available estimates of a CL for a particular ecosystem element are evolving as additional studies are conducted and new information becomes available. Therefore, the CL estimates presented in this report are subject to change, and likely will change, in the future.

In 2011, Pardo et al. (2011a) summarized empirical N CLs for various Level 1 ecoregions of the United States (CEC 1997). Individual chapters of the Pardo et al. (2011a) compilation address land areas evaluated in this report and provide a basis for estimating CL exceedances in the national parks. These chapters were written by Allen and Geiser (2011), Bowman et al. (2011), Clark (2011), Fenn and Geiser (2011), and Pardo et al. (2011b). These CLs define the amount of N deposition below which ecosystems or specific ecosystem receptors are unlikely to be harmed by nutrient enrichment processes. Thus, the empirical CLs compiled by Pardo et al. (2011a) identified tipping points for sensitive resource damage due to N enrichment under elevated N input levels. This report uses the CL data of Pardo et al. (2011a), together with N deposition model estimates for 2011, to provide an assessment of potential impacts of N deposition on sensitive ecosystem receptors for the high interest parks listed in Table 1. The focus is on plant communities identified by Pardo et al. (2011a) as being sensitive to N deposition.

Increased atmospheric loading of N, which is frequently limiting to plant growth, benefits some plant species at the expense of others. Under high N loading, plant species richness and biodiversity often decrease. Non-native invasive species are often among those that benefit the most from N addition. In arid and semi-arid plant communities, there can also be interactions with water availability and wildland fire.

Pardo et al. (2011a) reported nutrient CLs from numerous studies, aggregated to an ecoregion scale. Here, we build upon that effort by developing park-specific estimates of CLs and CL exceedances at a finer park scale. We narrowed the list of parks to consider based in part on perceived threats, including O&G development. These CL estimates are based on park vegetation data and more recent estimates of atmospheric N deposition for 2011. It is hoped that results of these analyses will improve understanding of CLs and exceedance at the park scale within the study areas addressed in this report. Refined information on CLs and air quality related values (AQRV) within specific national park units is needed to address ongoing and emerging threats to park resources from O&G development, agricultural activities, vehicular emissions, mineral extraction, and industrial development.

Report Focus

The focus of this assessment is on selected park lands in the intermountain west, Great Plains, and southwestern desert regions that are known to contain N-sensitive receptors and that have been exposed to increased N deposition in recent years due to local energy, agricultural, transportation, and/or mineral extraction development. Sources of atmospheric N emissions are increasingly emerging as potentially important in these regions. This study builds upon an earlier similar effort by Sullivan and McDonnell (2013) that was based on emissions and deposition estimates for 2008. This new analysis is updated to 2011 and also includes some new parks and an appendix depicting source apportionment analyses to identify the role of O&G emissions in contributing N deposition to the national parks under study here.

Approach

Vegetation Typing

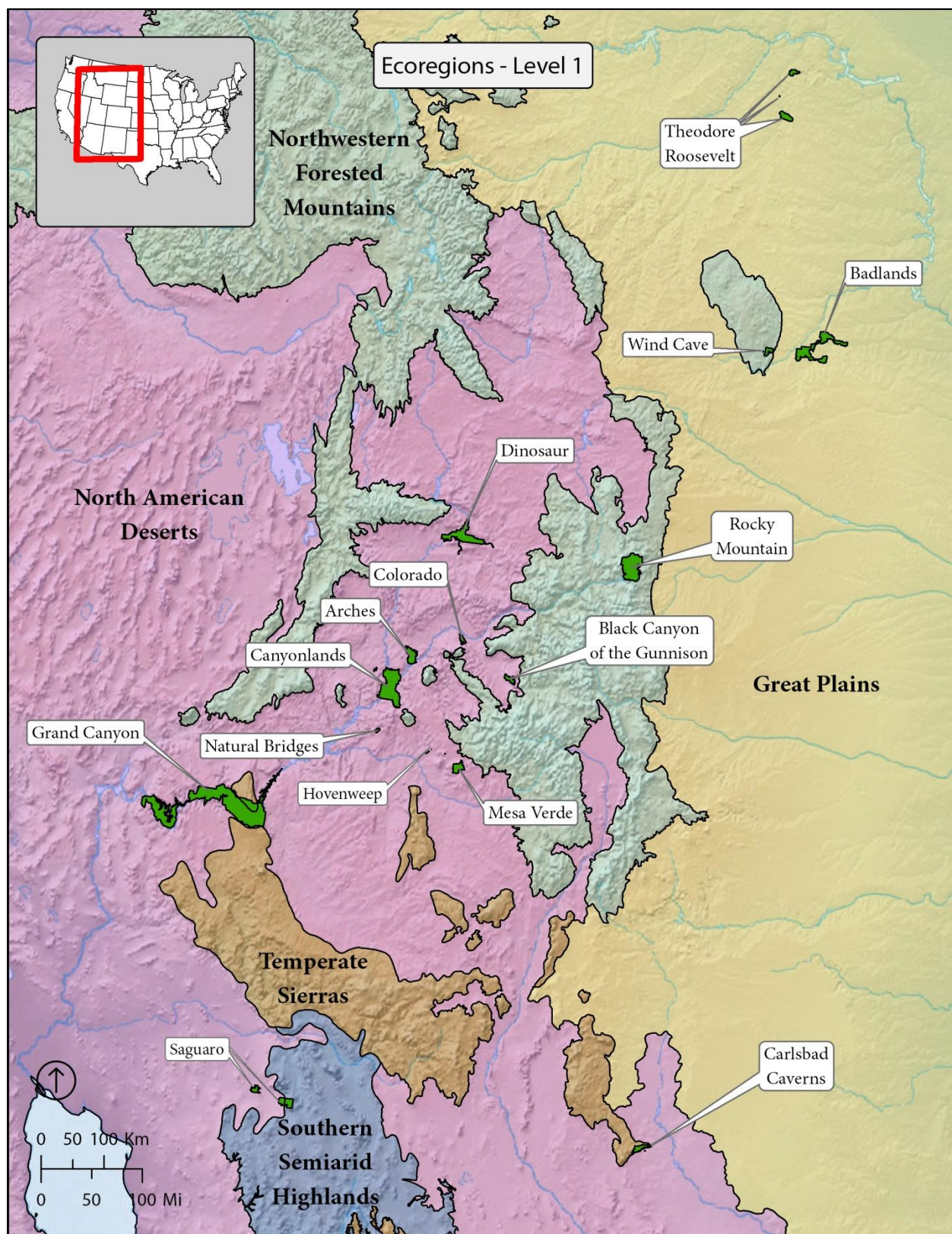
The U.S. Geological Survey (USGS) and NPS constructed vegetation maps for most of the national parks selected for inclusion in this study as part of the NPS I&M Program. The I&M Program and the USGS classified, described, and mapped vegetation in 250 national parks from photographic interpretation of 1:12,000-scale color infrared aerial photos taken in 1997. Vegetation map classes (0.5 ha minimum mapping unit) were determined through field reconnaissance, data collection, and analysis in accordance with the National Vegetation Classification System (FGDC 1996). These vegetation mapping unit data were used in this analysis to determine the spatial distribution of CL values within each of the high-interest parks.

Recent I&M vegetation maps were not available for one study park (SAGU) at the time of preparing this report. For that park, vegetation types and their spatial distribution were obtained from the LANDFIRE (2008) database. The LANDFIRE existing vegetation type (EVT) data were used as the basis for vegetation classification for that park. The EVT data were developed at 30 m resolution using statistical decision tree models based on Landsat imagery, elevation and biophysical landscape characteristics. The data were intended to represent the current vegetation species composition for a given site.

The vegetation community types associated with the map units for each vegetation dataset were grouped according to the sensitive ecosystem components listed in Pardo et al. (2011a) for each ecoregion. The original vegetation community name often listed the dominant species, for example chokecherry shrubland or ponderosa pine woodland. These vegetation map units were classified as “shrubland” and “woodland” ecosystem types, respectively, to match the Pardo et al. (2011a) ecosystem component designations. Vegetation coverages that have been updated by NPS since the earlier Sullivan and McDonnell (2013) report were used for this new analyses. This was the case for GRCA. Only vegetation types that received a CL designation by Pardo et al. (2011a) are mapped. Vegetation survey metadata, which provided additional information on the species present within a given map unit, were consulted to ensure proper classification into the Pardo et al. (2011a) ecosystem components.

Results of analyses conducted for this study are organized hierarchically in this report, by Level I ecoregion (North American Deserts, Northwestern Forested Mountains, and Great Plains; Map 3), by NPS I&M networks within ecoregions, and by national park units within networks. Within each subject network and national park unit, we report available data on empirically determined N CL values, total N (including both oxidized and reduced chemical species) deposition, and CL exceedances.

One park (CAVE) straddled two Level I ecoregions, Temperate Sierras and North American Desert. A small portion of GRCA is also within the Temperate Sierras Level I ecoregion. Pardo et al. (2011a) did not identify empirical CLs for the Temperate Sierras ecoregion intended to protect vascular plant species against terrestrial eutrophication, although they identified CLs to protect epiphytic lichens (4-7 kg N/ha/yr) and to protect against elevated NO_3^- in stream and spring waters (15 kg N/ha/yr) in this



Map 3. Level I ecoregions within the study area.

ecoregion. Pardo et al. (2011a) did identify relatively low CLs in the North American Desert ecoregion to protect desert grasslands, shrublands, and woodlands against nutrient N enrichment. SAGU is also split across two ecoregions: North American Deserts and Southern Semiarid Highlands. For the purposes of this analysis, CAVE and SAGU are treated as occurring entirely within the North American Desert ecoregion. This approach conforms with the NPS mandate to err on the side of resource protection in assessing CLs because CL values in desert ecosystems tend to be relatively low. The small portion of GRCA that occurs within the Temperate Sierra ecoregion is ignored for this analysis because CL values were not available.

Estimating Critical Loads

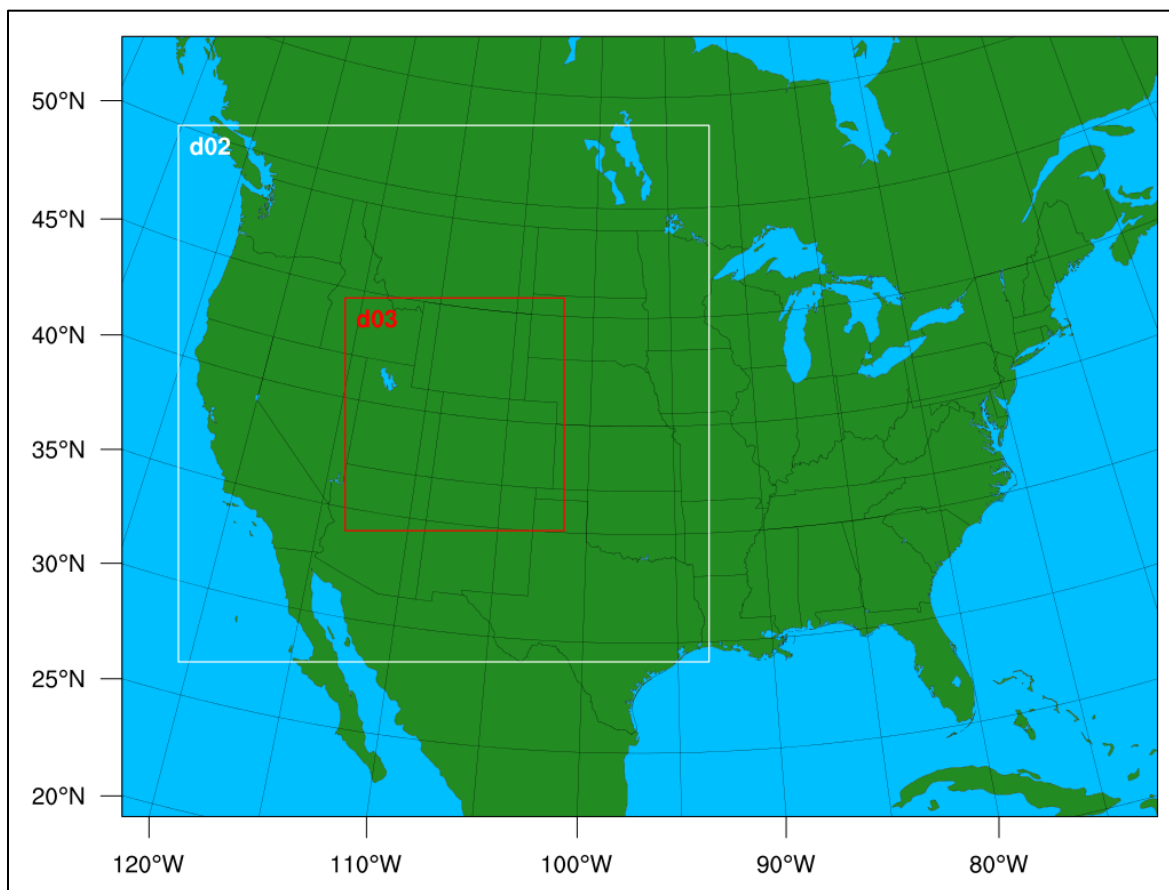
Critical load estimates assigned to various general vegetation types by Pardo et al. (2011a) were extracted from their report and matched with parks in which these vegetation types occurred. These CL estimates were specific to a variety of vegetation types, and included (depending on data availability) various tree, shrub, forb, and graminoid communities. National parks and national park networks considered in this analysis were classified according to the Level 1 ecoregions in which they occurred (Table 1). Critical load estimates compiled by Pardo et al. (2011a) for Level I ecoregions were matched to the high-interest parks in each ecoregion. Critical loads and CL exceedances were mapped for the identified high-interest parks at the scale of available vegetation and deposition data to reflect within-park differences in the sensitivity of park resources. For evaluating CLs, we rely upon Pardo et al.'s (2011a) lower end of reported empirical CL. This was done in order to comply with the NPS mandate to err on the side of resource protection in evaluating CLs and exceedances. Information on CL from sources other than Pardo et al. (2011a) was also used to describe the sensitivity of plant communities to N input. Such information was presented together with CL estimates compiled by Pardo et al. (2011a) to evaluate the state of scientific understanding regarding park resource sensitivity within the study area to N inputs.

We applied Pardo et al.'s (2011a) compilation of ecoregional CL estimates to produce CL maps of the selected national parks and monuments considered to be at risk from increases in N deposition from O&G, mineral extraction-related activities, agricultural, and other emissions sources. Using the available spatial vegetation type data described above, CL estimates compiled by Pardo et al. (2011a) were mapped across national parks for a variety of plant community endpoints and receptors. The CLs were analyzed with respect to vascular plant species in this report. The Pardo et al. (2011) report also includes CL for lichens, bryophytes and mycorrhizae for some ecoregions. However, these organisms are not represented in the vegetation datasets used in the analyses reported here.

Estimating Atmospheric Deposition

Nitrogen deposition was simulated with the Comprehensive Air Quality Model with Extensions (CAMx); version 6.1 was used for this study (ENVIRON 2014). CAMx is an Eulerian-grid chemical transport model that simulates the governing physical and chemical processes to predict the fate of atmospheric trace species. These processes include advective and turbulent transport, gaseous-, aqueous-, and particle-phase chemical transformation, emissions, and wet and dry deposition. The CAMx model domain consisted of a national-scale 36 km grid, with nested 12 km (western US) and 4 km (Intermountain West) grids, as shown in Map 4. Details of the model grids and configuration

options are shown in Table 2. These simulations are based on the Three-State Air Quality Study (3SAQS; University of North Carolina and ENVIRON 2014, Adelman and Baek 2015) “Base11a” modeling platform developed for the Intermountain West Data Warehouse (IWDW 2016).



Map 4. The CAMx nested grid modeling domain: 36 km (outer grid), 12 km (“d02”) and 4 km (“d03”).

The simulated atmospheric N deposition values provided here are estimates for a particular point in time using one modeling tool. Interannual variability can be pronounced, as can fine-scale spatial variability within individual national parks (Schwede and Lear 2014). Emissions inventories that provide part of the foundation for atmospheric modeling do not include all emissions sources. In particular, the smaller sources tend to be under-represented. Different deposition modeling tools often provide different estimates, especially of the dry component of deposition (Sullivan and McDonnell 2014). These uncertainties, and others, influence estimates of total N deposition at any given location and the use of these estimates in calculating CL exceedances.

Table 2. CAMx configuration options.

Science Options	Sub-options	CAMx Base 2011a Configuration
Model Codes	n/a	CAMx v6.10 – April 2014 Release
Horizontal Grid Mesh	n/a	36/12/4 km
	36 km grid	148 x 112 cells
	12 km grid	239 x 206 cells
	4 km grid	281 x 299 cells
Vertical Grid Mesh	n/a	25 vertical layers, defined by WRF
Grid Interaction	n/a	36/12/4 km two-way nesting
Initial Conditions	n/a	15 day spin-up on 36 km grid
Boundary Conditions	n/a	36 km from global chemistry model
Emissions	Baseline Emissions Processing	SMOKE, MOVES2014 and MEGAN
	Sub-grid-scale Plumes	No plume-in-grid
Chemistry	Gas Phase Chemistry	CB6r2
	Aerosols	CF2
Meteorological Processor	n/a	WRFCAMx
Horizontal Diffusion	n/a	Spatially varying
Vertical Diffusion	n/a	CMAQ-like in WRFCAMx
	Diffusivity Lower Limit	Kz_min = 0.1 to 1.0 m ² /s or 2.0 m ² /s
Deposition Schemes	Dry Deposition	Zhang dry deposition scheme
	Wet Deposition	CAMx-specific formulation
Numerics	Gas Phase Chemistry Solver	Euler Backward Iterative (EBI) -- Fast Solver
	Vertical Advection Scheme	Implicit scheme w/ vertical velocity update
	Horizontal Advection Scheme	Piecewise Parabolic Method (PPM) scheme
	Integration Time Step	Wind speed dependent

Estimating Exceedances

Areas where CLs were exceeded by ambient (2011) deposition were identified by comparisons between the 3SAQS CAMx model estimates of total N deposition and the Pardo et al. (2011a) CLs. Locations where N deposition was greater than the specified CL were considered to be in exceedance. We also mapped the difference between CL and ambient N deposition in 2011 to show how close ambient deposition was to the CL and to indicate where CLs were exceeded.

Despite the errors inherent in the emissions inventory and the deposition and source apportionment modeling, the resulting data and maps will assist NPS in responding more quickly and accurately to

proposed development near parks and in assessing natural resource conditions. This information will be helpful in quantifying how much deposition is likely to harm resources in the context of existing sensitive receptors, available dose/response data, and current and future estimates of emissions and deposition.

Results: Critical Loads Research Summary

North American Deserts Ecoregion

Woodland, shrubland, and grassland vegetation types in the North American Deserts Ecoregion are known to be highly sensitive to N inputs. Allen and Geiser (2011) estimated that the lower end of the range of nutrient N empirical CL for these plant communities in this ecoregion is about 3 kg N/ha/yr.

The North American Deserts Level I ecoregion includes the Chihuahuan, Mojave, and Sonoran deserts and national park lands within the Southern Colorado Plateau (SCPN), Northern Colorado Plateau (NCPN), Sonoran Desert (SODN), and Mojave Desert (MOJN) networks (Maps 1 and 2). Within these largely desert networks, there are 11 national park lands considered in this analysis: ARCH, BLCA, CANY, CAVE, COLM, DINO, GRCA, HOVE, MEVE, NABR, and SAGU. In addition, Joshua Tree National Park (JOTR), although not explicitly considered for this analysis, is located in proximity to the study region and has been relatively well-studied regarding ecological effects of atmospheric N deposition on desert vegetation.

Nitrogen deposition in North American deserts interacts with climate, presence of non-native plant species, and fire regimes. Ecological theory suggests that pulse dynamics of resource availability should confer advantages to invasive annual species that compete with native perennial species after wildfire in desert environments. Esque et al. (2010) quantified inorganic N dynamics following experimental fires in a Mojave Desert shrub community. Soil parameters and production of annual plants were measured beneath shrubs and in interspaces between shrubs during six months following fire. After late-season rains and where soil inorganic N pools were elevated after fire, productivity of the predominant invasive grasses (*Schismus* spp) increased and native annuals declined. Results suggested that increased N availability can favor invasive annuals over native plant species. Predicted changes in precipitation will likely interact with N cycling to alter invasive annual plant dominance following wildfire in the future.

Some level of N deposition is considered natural, although the exact amount cannot be determined and undoubtedly varies spatially. Human-caused N sources contribute additional (often the majority of) N deposition. Responses of desert vegetation communities to N addition have been shown to include change in plant species composition, increase in biomass of non-native invasive species, and decrease in relative abundance and richness of native herbaceous species (Allen and Geiser 2011). The abundance of invasive non-native plant species has increased during recent decades in North American desert ecosystems, likely due in part to N deposition (Brooks 2003, Allen et al. 2009). Exotic grasses, in particular, respond strongly to increased N supply in desert environments. Increased grass cover, in turn, can contribute to greater fire frequency (Brooks et al. 2004, Brooks and Matchett 2006).

Critical loads of N deposition have been estimated in a number of studies for vegetative communities in the North American Deserts ecoregion, mostly in the southern portion. These estimates may be applicable for protection of sensitive receptors in a number of national park desert networks, including the Southern Colorado Plateau, Northern Colorado Plateau, Sonoran Desert, and Chihuahuan Desert networks.

Biomass of native blue grama (*Bouteloua gracilis*) grass in desert grassland at the Sevilleta Long-Term Ecological Research (LTER) site in the Chihuahuan Desert in New Mexico increased in response to N addition at a rate of 20 kg N/ha/yr (Báez et al. 2007). In contrast, a change in ambient N deposition from 1.7 to 2.4 kg N/ha/yr at the control plot during the 16-year experiment did not cause a change in blue grama biomass. Based on this work, the CL to protect blue grama biomass may be somewhere between 2.4 and 20 kg N/ha/yr. This is a wide range.

Experimental N addition has been shown to reduce soil moisture in sagebrush steppe, perhaps due to increased shrub growth. This would be expected to decrease herbaceous plant productivity (Inouye 2006). Experimental fertilization with N at very high levels (72 kg N/ha/yr) at the Jornada LTER site in New Mexico caused increased growth of native annual forbs during winter, but decreased growth during summer (Gutierrez and Whitford 1987). This variable response may have been due, at least in part, to increased water limitation during summer. Barker et al. (2006) determined that water availability was the most important limiting factor for productivity of the desert shrub creosote bush (*Larrea tridentata*), a common evergreen shrub in warm North American deserts.

Allen et al. (2009) estimated the CL to be approximately 8.4 kg N/ha/yr (3.4 kg N/ha/yr deposited plus 5 kg N/ha/yr fertilized) during wet years at JOTR in the Mojave Desert, just outside the Southern Colorado Plateau Network, to protect against increased coverage of invasive non-native grasses. They found that the response of desert vegetation was determined by multiple factors in addition to the N deposition level, also including soil properties and moisture availability. These findings were further corroborated by DayCent modeling conducted by Rao et al. (2010). Modeling results suggested the CL levels shown in Table 3.

Table 3. CL levels suggested by modeling results.

Model Condition	CL Levels
Lower elevation desert dominated by the invasive and common Mediterranean grass (<i>Schismus barbatus</i>)	3.1-8.2 kg N/ha/yr
Higher elevation desert dominated by the invasive grass red brome (<i>Bromus rubens</i>)	3.0-5.7 kg N/ha/yr

There were important connections with fire risk. Modeled deposition above 8.2 kg N/ha/yr (low elevation) and 5.7 kg N/ha/yr (high elevation), thus above the respective CL at these two locations, caused fire risk to be controlled by precipitation rather than N input (Rao et al. 2010). The desert environment in and near JOTR appears to be experiencing increasing impacts associated with changes in the grass fire cycle (Brooks and Matchett 2006). These data help to inform dose-response and CL issues elsewhere in the North American Deserts ecoregion.

The studies by Allen et al. (2009) at JOTR suggested that the CL of N to protect desert vegetation in this park against increase in invasive grass biomass due to N enrichment may be as low as about 8 kg N/ha/yr during wet years (Allen and Geiser 2011). Pardo et al. (2011a) reported empirical CL values in the North American Deserts ecoregion for the protection of lichens and herbaceous plants. The

lower end of the reported range was 3 kg N/ha/yr for both of these sensitive receptors. Modeled ambient N deposition reported by Pardo et al. (2011a) was higher than the estimated CL at JOTR. This suggests that the CL for protection of terrestrial plant communities against adverse effects associated with nutrient N enrichment may have already been exceeded at this park. Ellis et al. (2013) estimated the empirical N CL for JOTR in the range of 3-8.4 kg N/ha/yr for protection of herbaceous plants.

From 1989 to 2004, Baez et al. (2007) observed a 43% increase in ambient N deposition at a study site in the Chihuahuan desert, from 1.7 to 2.5 kg N/ha/yr, resulting in an additional 5.9 kg N/ha deposition over that time period. This increase in N deposition may have caused changes in the plant community, as suggested by fertilization studies of blue grama and black grama (*Bouteloua eriopoda*) with addition of relatively large amounts of N over a short period of time. With additions of 20 kg N/ha in one season, blue grama was favored over black grama, the dominant species at the time of the study (Báez et al. 2007).

Enhanced N could play a role in the recently observed invasion of some exotic plant species within parts of the Mojave and Sonoran deserts. However, water is often more limiting than N in desert ecosystems. Brooks (2003) found that plant responses were influenced by specific rainfall events rather than by average annual rainfall, with the annual plants thriving in a year when high rainfall events triggered germination. In the Mojave desert, the shrub creosote bush showed no increased growth response to experimental N additions at 10 and 40 kg N/ha/yr as calcium nitrate ($\text{Ca}(\text{NO}_3)_2$), but did respond to increased water (Barker et al. 2006). Conversely, invasive annuals showed a greater response to elevated N than did native species. Though their invasion was correlated with greater N deposition, no causation has been established (Fenn et al. 2003).

In ecosystems of southern California, elevated N deposition and changing precipitation patterns have prompted the conversion of native shrub communities to plant communities dominated by non-native annual grasses. Both empirical and modeling studies suggest that N input and climate change can interact to drive losses in biodiversity greater than those caused by either stressor alone (Porter et al. 2013).

In the Chihuahuan desert, greater ecosystem N losses in shrublands (0.33 kg/ha/yr) versus grasslands (0.15 kg/ha/yr) corresponded with greater water runoff in shrublands. Even with runoff nutrient losses, both vegetation types showed a net accumulation of total N, just over 2 kg N/ha/yr, with atmospheric N deposition of about 2.5 kg/ha/yr (Schlesinger et al. 2000).

Fertilization experiments by Brooks (2003) in the Mojave desert showed that increased levels of N deposition could favor the expansion of non-native species where they are already prevalent. At very high N application rates of 32 kg N/ha/yr over two years, both density and biomass of non-native plants increased. Non-native biomass increased 54% while native species biomass declined by about 39%.

Allen et al. (2009) evaluated the effects of reactive N on native and non-native plant species in JOTR. This park receives moderate levels of air pollution, including N, from the Los Angeles Basin.

Extractable soil N was generally higher at study sites that received higher atmospheric N deposition. Nitrogen fertilizer was applied at levels of 5 and 30 kg N/ha/yr at four sites over a two-year period. Low-elevation sites were dominated by creosote bush scrub and higher-elevation sites by pinyon-juniper woodland. Non-native grass biomass increased significantly at three of four treatment sites that received 30 kg N/ha/yr, but not at the sites that received 5 kg N/ha/yr. Experimental studies by Allen et al. (2009) at JOTR suggested that the CL of N to protect desert vegetation in this park against increased invasive grass biomass due to N enrichment during wet years may be as low as about 8 kg N/ha/yr (Allen and Geiser 2011). Modeling results using the daily Century model (DayCent; Brooks and Matchett 2006, Allen and Geiser 2011) were similar.

Application of N fertilizer along an N depositional gradient in creosote bush scrub and pinyon-juniper woodland in JOTR suggested that the response of desert vegetation to added N varied by wetness condition. Fertilization rates ranged from 5 to 30 kg N/ha/yr, in addition to about 3 to 12 kg N/ha/yr of ambient atmospheric deposition (Tonnesen et al. 2007, Allen and Geiser 2011). During 2003, which was a dry year, vegetation biomass remained unchanged. During 2004, a moderate precipitation year, two of four experimental plots showed increased biomass of non-native invasive grasses at addition of 30 kg N/ha/yr, but not at 5 kg N/ha/yr. During the wettest year (2005), invasive grass biomass increased at both N treatment levels (Allen et al. 2009). Productivity of native forbs decreased in response to N addition at these sites, but increased at another treatment site that had only sparse invasive grass cover.

Creosote bush demonstrated a twofold to threefold increase in stem growth, a 2.5- to 4-fold increase in viable seed production, and a 17% to 35% increase in leaf N in response to large N additions at sites around Mono Lake, CA. The experimental N was applied in March and November as NH_4NO_3 , at a high cumulative addition rate of 233.6 g N per plant (Drenovsky and Richards 2005).

The DayCent model was applied to plant communities in the deserts of southern California by Rao et al. (2009, 2010). Invasive non-native grass production was simulated from 2003 to 2008 under varying levels of N input and precipitation, resulting in changing fire frequency. Simulated fire risk increased at levels of N deposition above about 3 kg N/ha/yr. The simulated risk leveled off at N deposition above 5.7 kg N/ha/yr in pinyon-juniper and above 8.2 kg N/ha/yr in creosote bush scrub (Rao et al. 2010). Earlier studies (Brooks 2003, Brooks and Matchett 2006) had suggested a link between fire risk and increased grass productivity caused by elevated atmospheric N deposition.

Allen and Geiser (2011) reported CLs for the North American Deserts ecoregion. Values of N CL were reported for lichens and for several vascular plant communities can be seen in Table 4.

Table 4. Values of N CL by lichen and vegetation community.

Community	CL N	Source
Lichens. Change in community composition; increased N concentration in thallus	3 kg N/ha/yr	Porter (2007), Geiser et al. (2008)
Vascular plants. Change in community composition of shrubland, woodland, and desert grassland	3-8.4 kg N/ha/yr	Allen et al. (2009), Inouye (2006), Rao et al. (2010)

Estimates of CL in portions of the ecoregion that include this network were considered to be fairly reliable for protecting vascular plants, but less reliable (mainly expert judgment) for protecting lichens (Allen and Geiser 2011).

The CL to protect lichens in the western Sierra Nevada has been estimated to lie in the range of 3.1 to 5.2 kg N/ha/yr (Fenn et al. 2008, Bowman et al. 2011). Fenn et al. (2008) concluded that community composition of epiphytic macrolichens begins shifting from oligotrophic to more mesotrophic species at around 3.1 kg N/ha/yr, and shifts further to domination by eutrophic lichen species above about 5.2 kg N/ha/yr. Oligotrophic lichens may be completely eliminated at N deposition near 10 kg N/ha/yr (Bowman et al. 2011)

Rao et al. (2011) evaluated native plant species richness and exotic plant cover across overlapping gradients in precipitation (18.6 to 7.9 cm/yr), wind, and N deposition (14.7 to 2.4 kg N/ha/yr) in the Colorado Desert of southern California. Part of the 85-km study transect was in JOTR, ending at Pinto Basin. Patterns of native plant diversity were assessed using non-metric multidimensional scaling. Diversity was split into two axes: one strongly correlated with precipitation and the other strongly correlated with disturbance factors, which in turn were positively associated with exotic grass and forb cover. Native annual plants are important, in part, because they constitute a large proportion of the total plant diversity of arid southwestern vegetation types. It appeared that the patterns of disturbance and the cover of exotic species negatively affected native annual plant species diversity.

Newingham et al. (2012) assessed the effects of enhanced summer monsoons, N deposition, and soil disturbance on the productivity, reproduction, and herbivory of creosote bush. Results suggested that increased precipitation and N input may result in only small increases in growth of this species, and that any biomass gains may be lost to herbivory.

Southern Colorado Plateau Network

SCPN contains two parks considered in this analysis: GRCA and MEVE. Critical loads of N deposition are analyzed for each of these parks in the sections that follow.

Dose-Response and Critical Loads

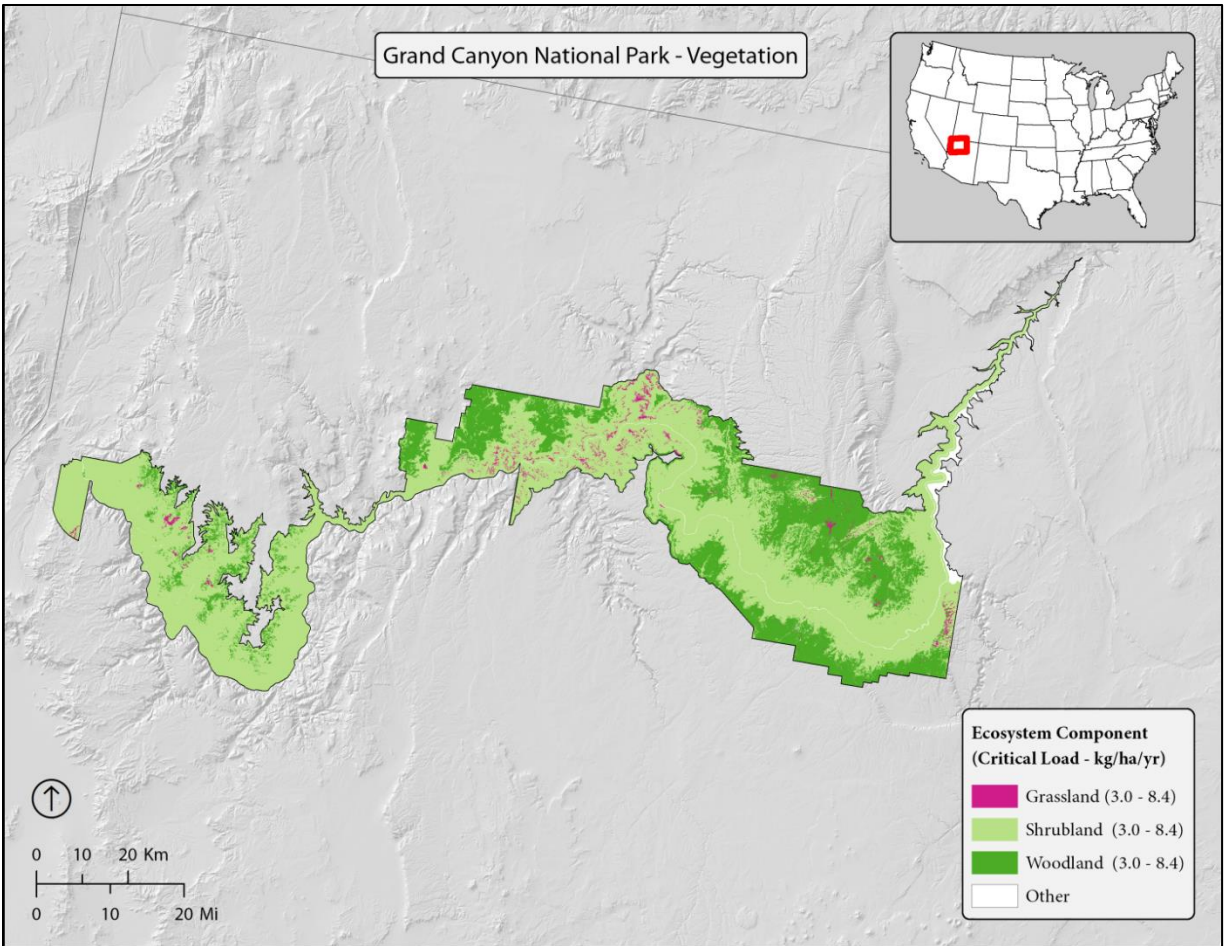
Grand Canyon National Park

Most of GRCA is located within the North American Deserts Level I ecoregion, with the western portion of the park within the Mojave Desert Level III ecoregion. Although a minor portion of the

park occurs within the Temperate Sierras Level I ecoregion, there is limited information available on CLs for the Temperate Sierras and what information is available pertains mostly to NO_3^- leaching in Mexico. Our analyses for GRCA presented here are therefore focused on the North American Deserts ecoregion which covers most of the park.

The Mojave is the driest and hottest of the North American deserts. Therefore, scarcity of water frequently limits plant growth. Creosote bush and Joshua tree (*Yucca brevifolia*) are characteristic plants of the Mojave Desert.

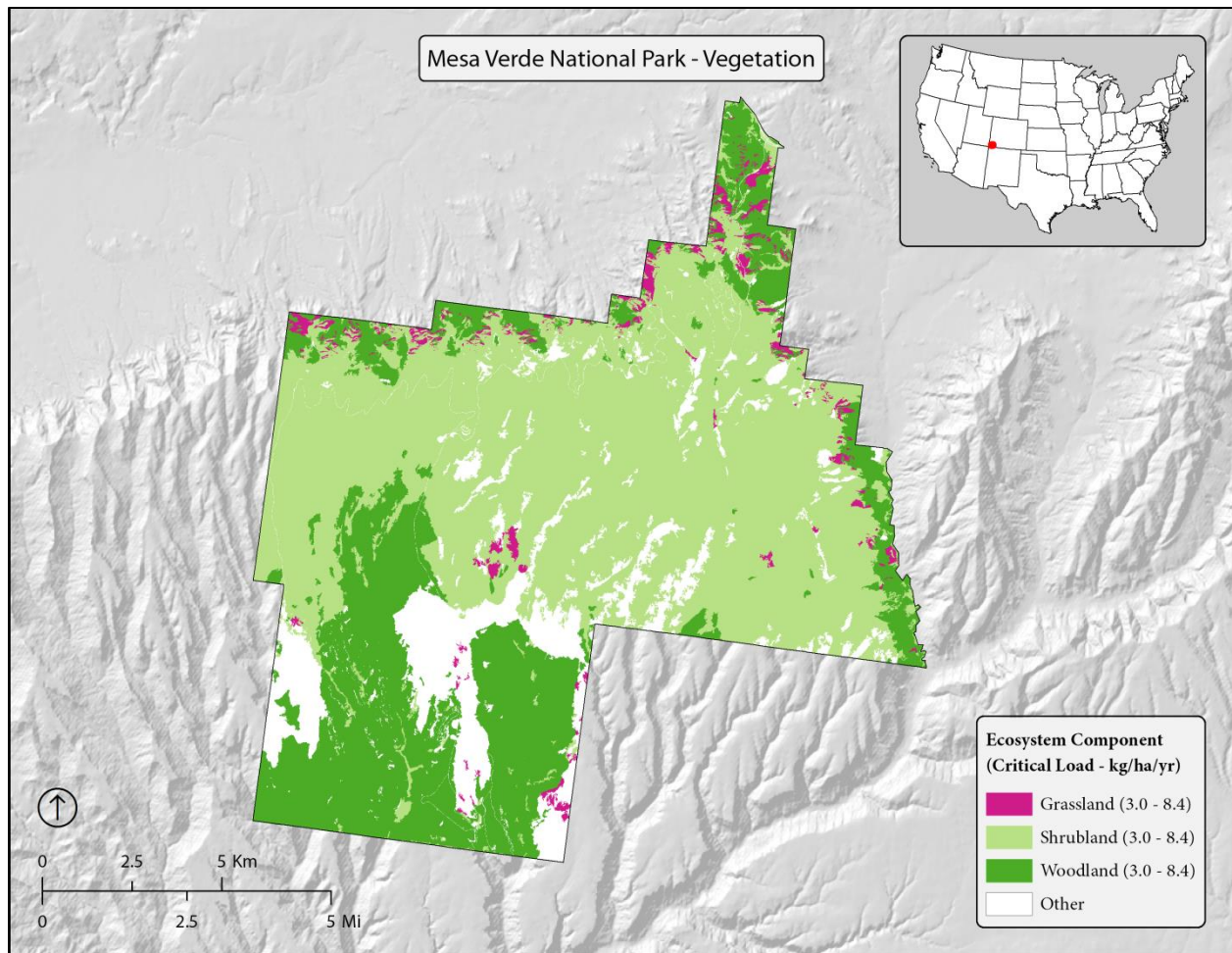
Portions of GRCA covered by woodland, shrubland, and grassland are shown in Map 5. The majority of the park is covered by shrubland. Each of these plant community types was estimated by Allen and Geiser (2011) to be sensitive to N deposition and to have CL in the range of 3 to 8.4 kg N/ha/yr. Locations in GRCA where these plant communities occur and where ambient deposition is higher than 3 kg N/ha/yr would be in exceedance of the CL for protecting these potentially N-sensitive plant communities against change in community composition. This same CL (3 kg N/ha/yr) was also judged by Allen and Geiser (2011) to be applicable to protection of lichen community composition in desert plant communities such as are found in GRCA.



Map 5. Locations in Grand Canyon National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).

Mesa Verde National Park

Portions of MEVE covered by woodland, shrubland, and grassland are shown in Map 6. Shrublands predominate. Each of these plant community types was estimated by Allen and Geiser (2011) to be sensitive to N deposition and to have CL in the range of 3 to 8.4 kg N/ha/yr. Locations in MEVE where these plant communities occur and where ambient deposition is higher than 3 kg N/ha/yr would be in exceedance of the CL for protecting these potentially N-sensitive plant communities against change in community composition. This same CL (3 kg N/ha/yr) was also judged by Allen and Geiser (2011) to be applicable to protection of lichen community composition in these desert plant communities such as are found in MEVE.

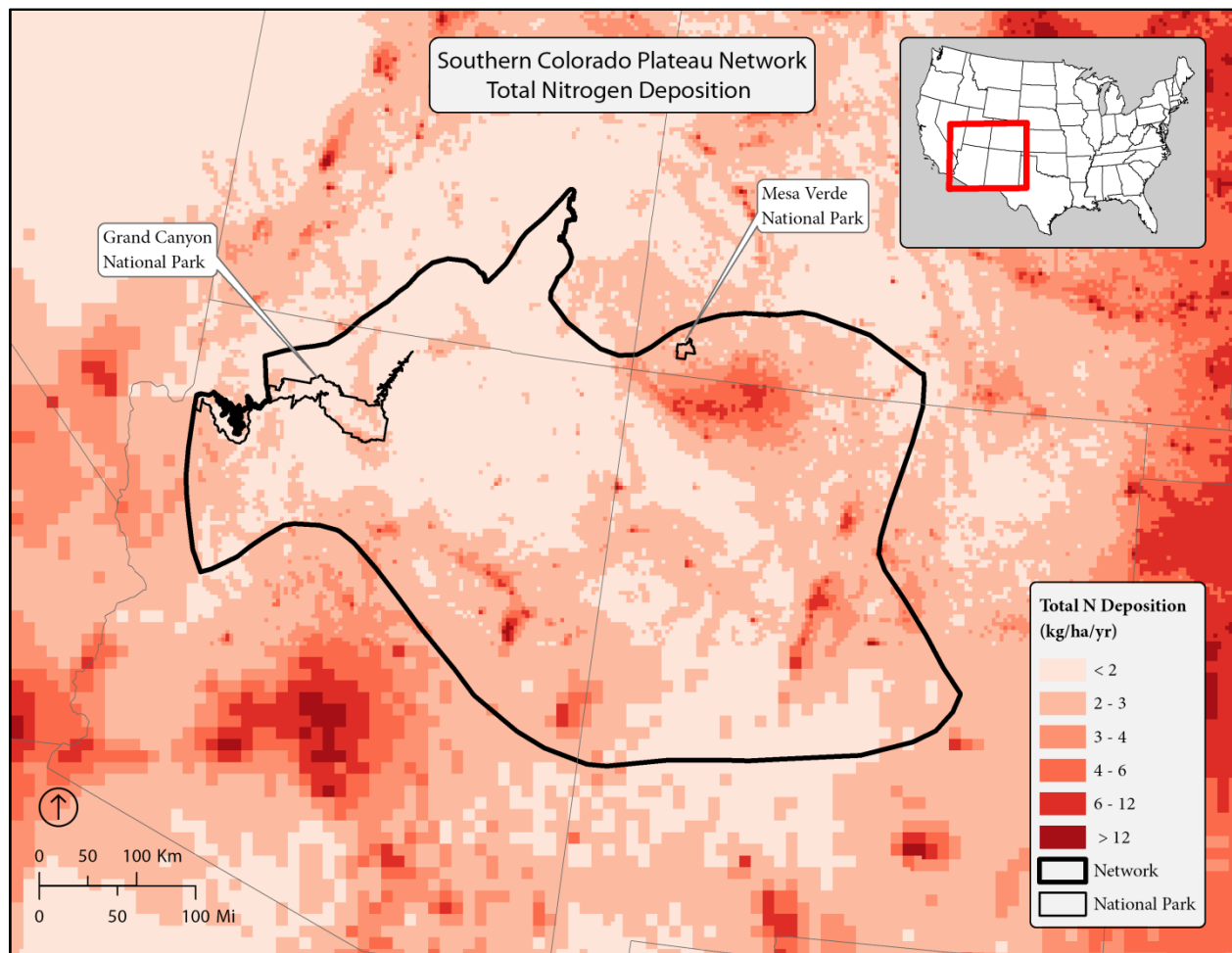


Map 6. Locations in Mesa Verde National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).

Atmospheric Deposition

The Navajo Generating Station near GRCA and the San Juan and the Four Corners Generating Stations in NW New Mexico near MEVE are among the largest electric utility sources of NO_x emissions in the United States. These NO_x emissions sources, and others, may contribute N deposition at these parks. By 2020, it is planned that Navajo, San Juan and Four Corners Generating Stations will shut down coal fired units and San Juan and Four Corners will install NO_x controls on remaining units. Thus, while oil and gas development may increase NO_x emissions, power plant emissions will likely decrease.

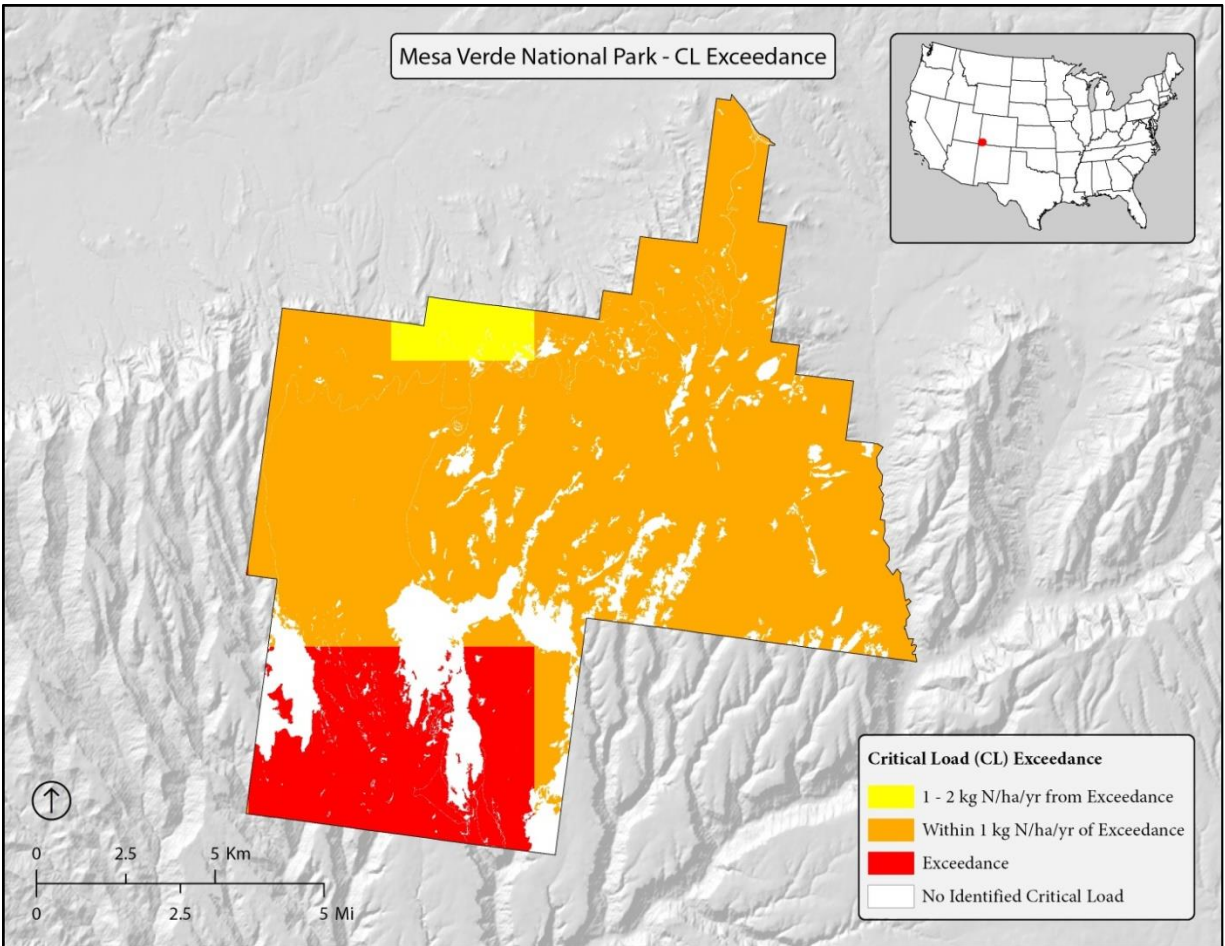
Estimates of total wet plus dry N deposition for SCPN, generated with the CAMx model, were highly variable. They were generally less than 3 kg N/ha/yr in and around GRCA and in the range of 2-4 kg N/ha/yr in and around MEVE (Map 7).



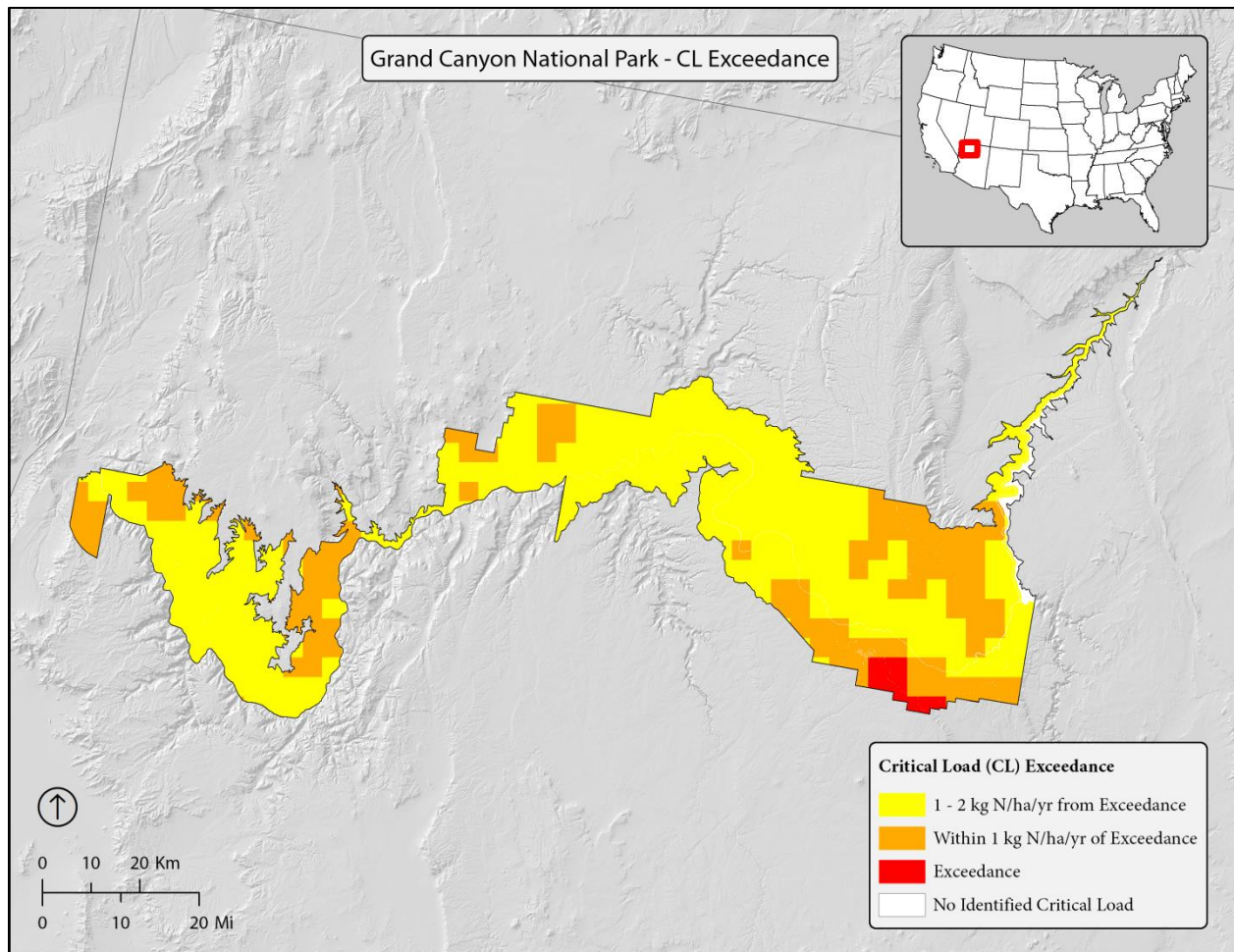
Map 7. CAMx model estimates of total wet plus dry N deposition (kg/ha/yr) for the year 2011 throughout the Southern Colorado Plateau Network.

Critical Load Exceedance

Exceedance reflects the extent to which N deposition exceeds the CL required for resource protection. Most of the southern portion of MEVE receives ambient N deposition that is in exceedance of the lower estimate of the N empirical CL reported by Allen and Geiser (2011); the remainder is largely below, but within 1 kg N/ha/yr of, exceedance (Map 8). Although only very small portions of GRCA are in exceedance of estimated CLs, scattered portions of the park are close (within 1 kg N/ha/yr) to exceedance (Map 9), and much of the rest of the park is within 2 kg N/ha/yr of exceedance. This means that estimated ambient N deposition is almost as high as the estimated CL. Thus, it is likely that nutrient effects caused by N deposition may occur under ambient N loading at MEVE, and significant portions of GRCA may be at risk if N emissions increase appreciably over 2011 levels.



Map 8. Locations of vegetation types in Mesa Verde National Park that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas in white do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.



Map 9. Locations of vegetation types in Grand Canyon National Park that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas in white do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.

Chihuahuan Desert Network

A portion of CAVE occurs within the North American Deserts Ecoregion, within the Chihuahuan Desert Network. The balance occurs in the Temperate Sierras ecoregion, for which Pardo et al. (2011a) did not specify CLs for vascular plants. For this analysis, CAVE is treated as being part of the North American Deserts ecoregion.

Dose-Response and Critical Loads

There are few published studies documenting nutrient enrichment tipping points or impacts on natural resources in the Chihuahuan Desert Network. Nevertheless, desert ecosystems are generally considered to be sensitive to N inputs (Fenn et al. 2003). The ecosystems in these parks may therefore be highly sensitive to nutrient N enrichment and may be threatened by eutrophication if atmospheric N loads increase dramatically in the future.

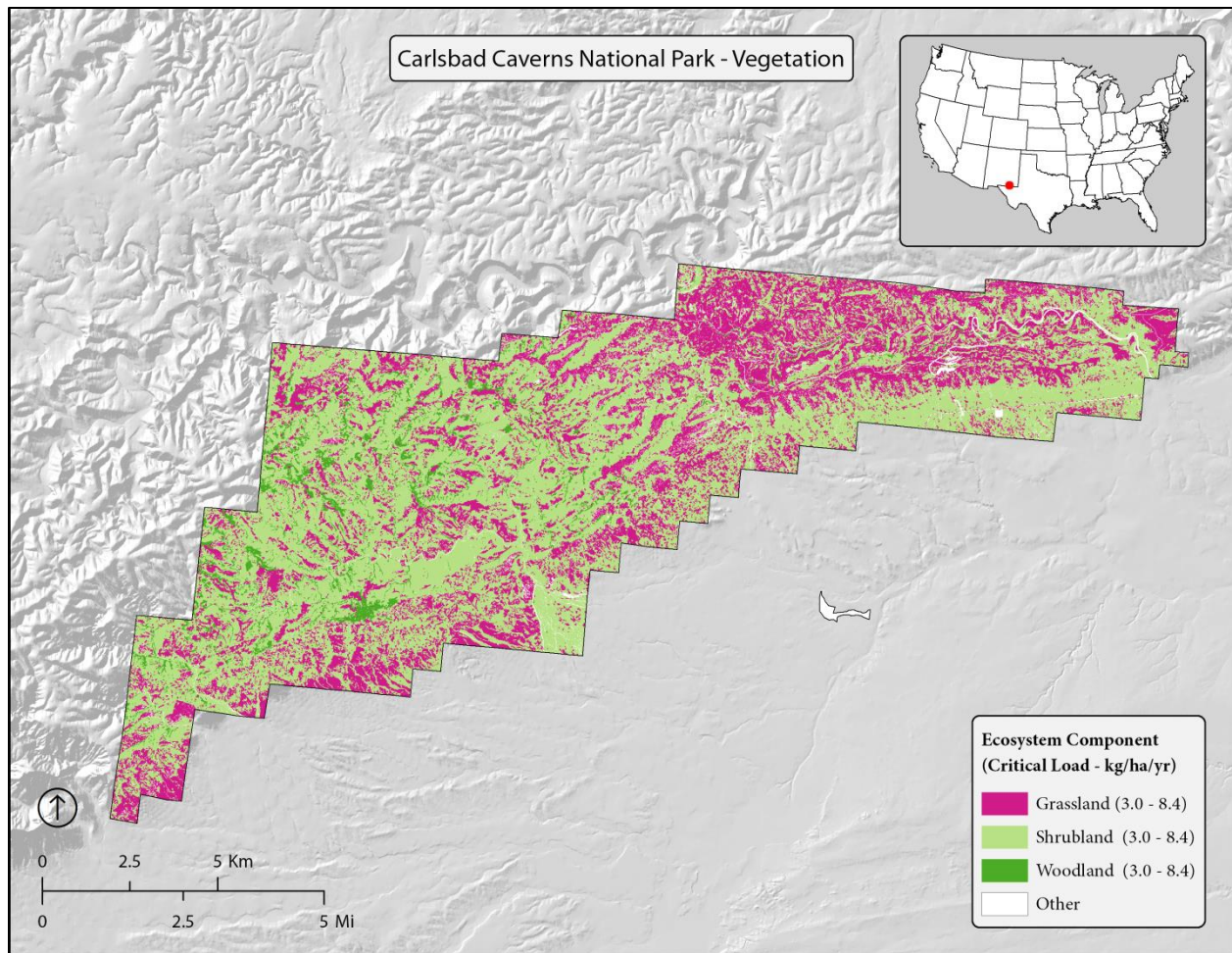
Water is typically the key limiting driver of ecosystem processes in the Chihuahuan Desert and other arid regions. Nevertheless, N can limit plant production where and when moisture is available, especially after rainstorms (Austin et al. 2004). Báez et al. (2007) quantified long-term trends in N deposition and its impacts on desert plant community structure. Based on two independent fertilization studies, Báez et al. (2007) concluded that continued inputs of N are likely to increase grass cover, decrease legume abundance, and may favor blue grama at the expense of the current dominant grass species, black grama (*B. eriopoda*). Even though N deposition levels are relatively low, increased N deposition in the future might cause changes in plant community structure (Báez et al. 2007).

Available data on empirical CLs of N in the Chihuahuan Desert Network compiled by Pardo et al. (2011a) suggested that the CL for resource protection was consistently greater than or equal to 3 kg N/ha/yr for the protection of lichens and herbaceous plants. Ellis et al. (2013) estimated the CL for N deposition to protect the most sensitive ecosystem receptors in 45 national parks. They estimated the N CL for CHDN parks in the range of 3 to 8.4 kg N/ha/yr for protection of herbaceous plants using data from Pardo et al. (2011a).

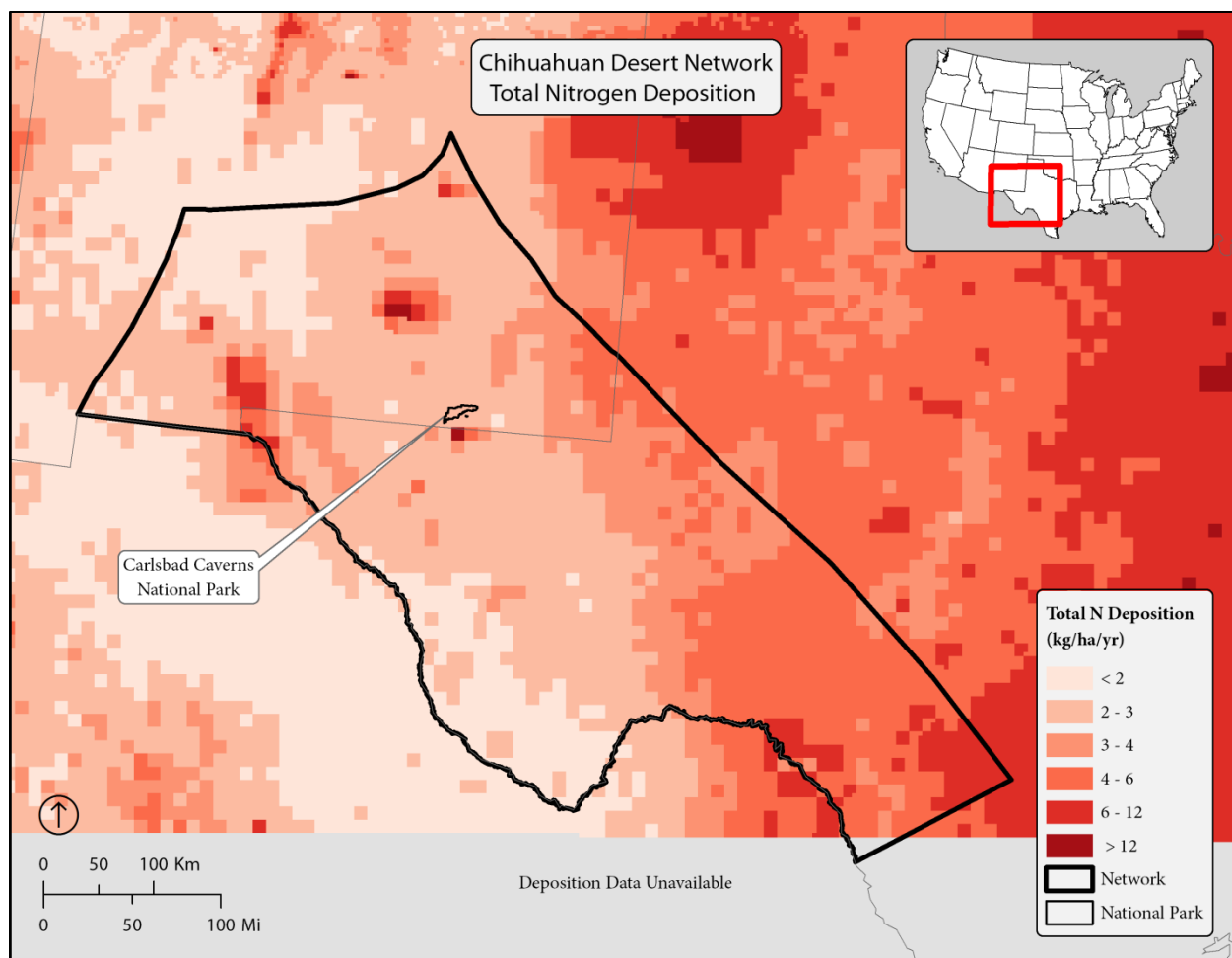
Portions of CAVE covered by woodland, shrubland, and grassland are shown in Map 10. Shrublands and grasslands predominate. Each of these plant communities had CLs identified by Allen and Geiser that were in the range of 3 to 8.4 kg N/ha/yr. Locations in CAVE where these plant communities occur and where ambient N deposition is higher than 3 kg N/ha/yr would be in exceedance of the CL for protecting these plant communities against changes in community composition.

Deposition and Exceedance

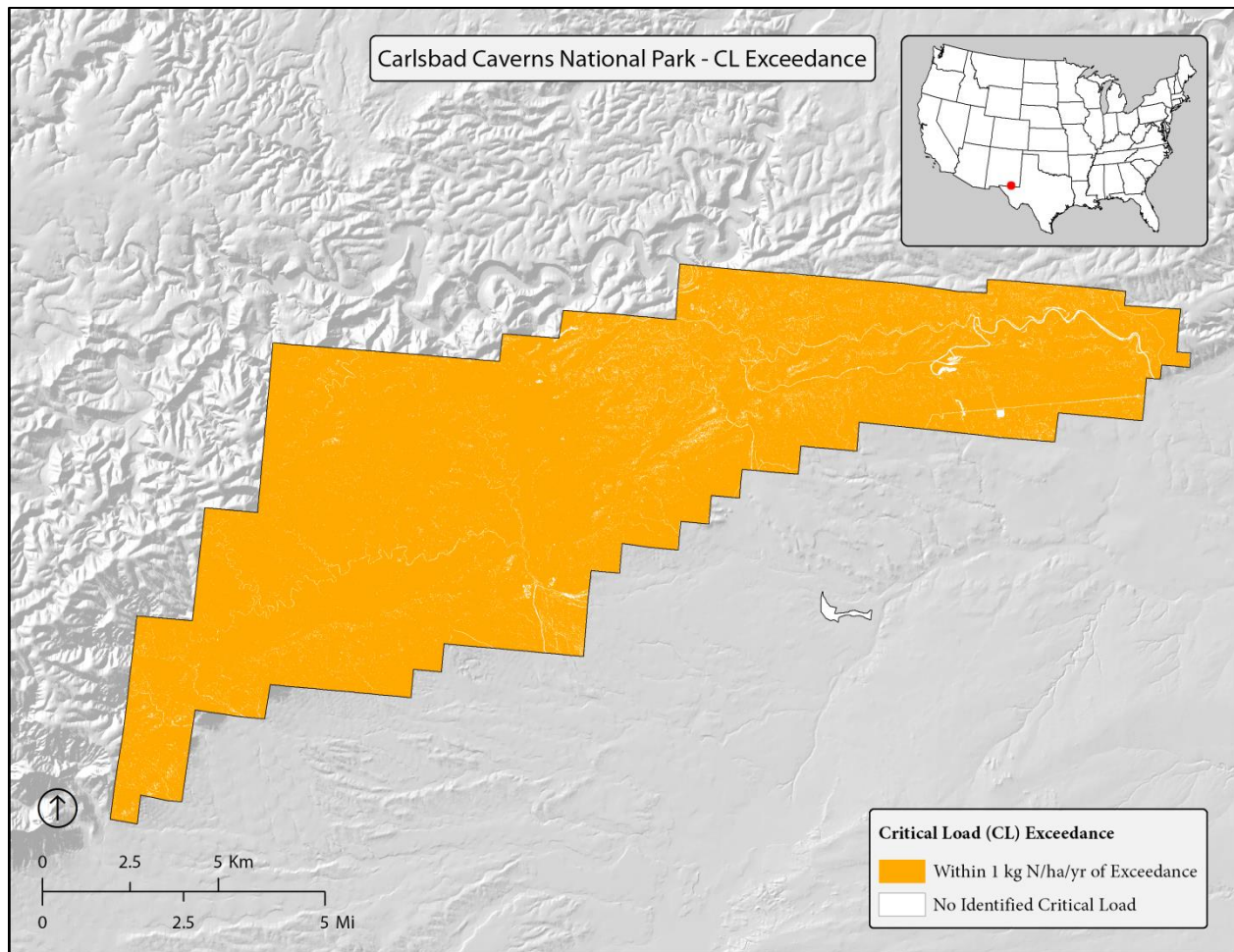
Estimates of total wet plus dry N deposition for CHDN during 2011, generated with the CAMx model, are given in Map 11. They ranged from less than 2 kg N/ha/yr to more than 6 kg N/ha/yr. Estimated deposition at the location of CAVE was in the range of 2-3 kg N/ha/yr. No portion of CAVE was found to be in exceedance of the nutrient N CL, although the entire park was with 1 kg N/ha/yr of exceedance (Map 12).



Map 10. Locations in Carlsbad Caverns National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).



Map 11. CAMx model estimates of total wet plus dry N deposition (kg/ha/yr) for the year 2011 throughout the Chihuahuan Desert Network.



Map 12. Locations of vegetation types in Carlsbad Caverns National Park that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas in white do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.

Northern Colorado Plateau Network

NCPN contains seven national park lands that are subjects of this analysis: ARCH, BLCA, CANY, COLM, DINO, HOVE, and NABR. Empirical CLs are summarized below for each.

Dose-Response and Critical Loads

Terrestrial resources in the parks in NCPN are expected to be highly sensitive to N enrichment from atmospheric N deposition, given the widespread distribution of arid and semi-arid plant communities. Because N deposition levels are variable in this network and may increase, impacts of excess N may occur now or in the future at some locations.

Only limited research has been conducted on the effects of atmospheric N deposition on nutrient dynamics of native plant communities in the NCPN. Some research has been conducted on lichens and microbotic soil crusts (Belnap 1991, Belnap et al. 2008, McCrackin et al. 2008). A fertilization

experiment in an arid grassland demonstrated a large difference in the response of native and non-native plants to added N. For two years, plots were treated with 0, 10, 20, or 40 kg N/ha/yr as a potassium NO₃⁻ (KNO₃) solution (Schwinning et al. 2005). Galleta (*Hilaria jamesii*) and Indian ricegrass (*Oryzopsis hymenoides*) showed no increase in leaf photosynthesis or tiller size, but ricegrass showed a 50% increase in tiller density in the second year at the 20 and 40 kg N/ha/yr application levels. For both species, the increased N application hastened the onset of water stress. Unexpectedly, non-native Russian thistle (*Salsola iberica*) showed rapid growth response to the highest fertilization rate in the first summer when rainfall was above average. Schwinning and colleagues (2005) suggested that the timing and amount of N deposition could facilitate noxious weed invasion and thus change community composition in arid grasslands. Nevertheless, interactions with water availability may also be important.

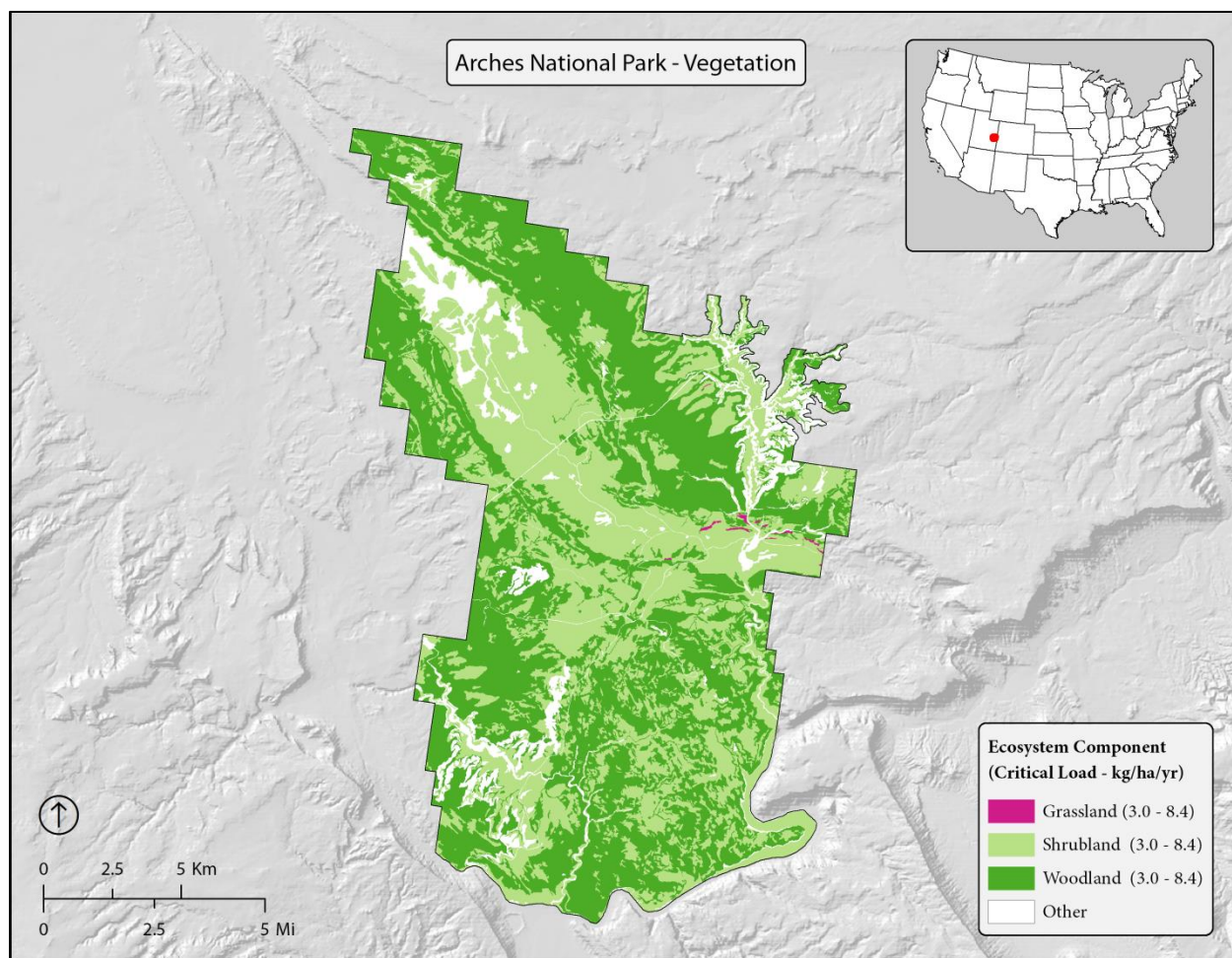
Portions of ARCH, BLCA, CANY, COLM, DINO, HOVE, and NABR that are covered by woodland, shrubland, and grassland are shown in Maps 13-19. The relative abundance of these plant community types varies by park. Each was estimated by Allen and Geiser (2011) to be sensitive to N deposition and to have CL in the range of 3 to 8.4 kg N/ha/yr. Locations in the park where these plant communities occur and where ambient N deposition is higher than 3 kg N/ha/yr are in exceedance of the CL for protecting these potentially N-sensitive plant communities against change in community composition. This same CL (3 kg N/ha/yr) was also judged by Allen and Geiser (2011) to be applicable to protection of lichen community composition in desert plant communities such as are found in these NCPN parks.

Deposition

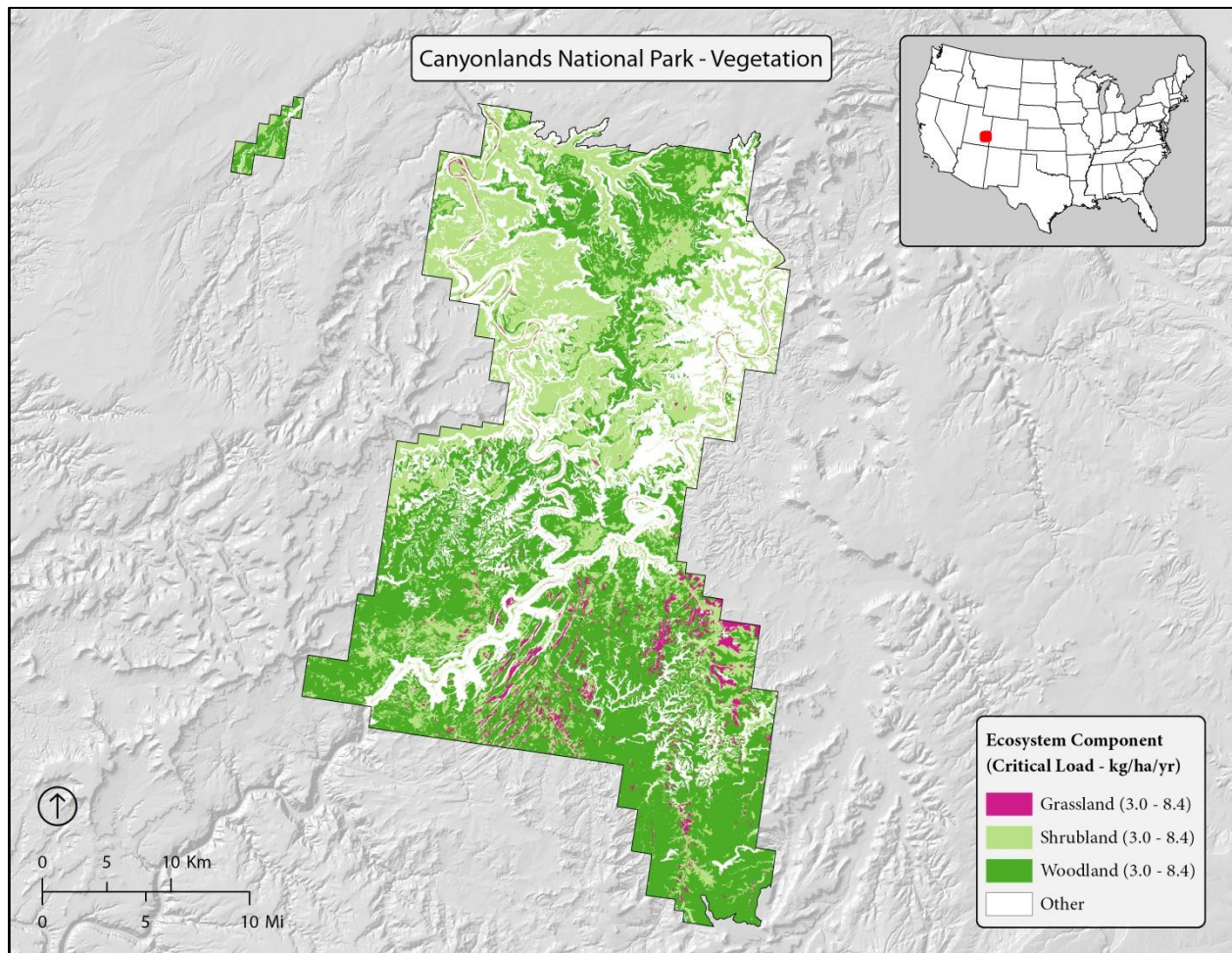
Map 20 shows CAMx model estimates of total wet plus dry N deposition for NCPN. Total N deposition within the network region was highly variable, ranging from less than 2 kg N/ha/yr around CANY and ARCH to more than 4 kg N/ha/yr in portions of northcentral Utah (Map 20).

Exceedance

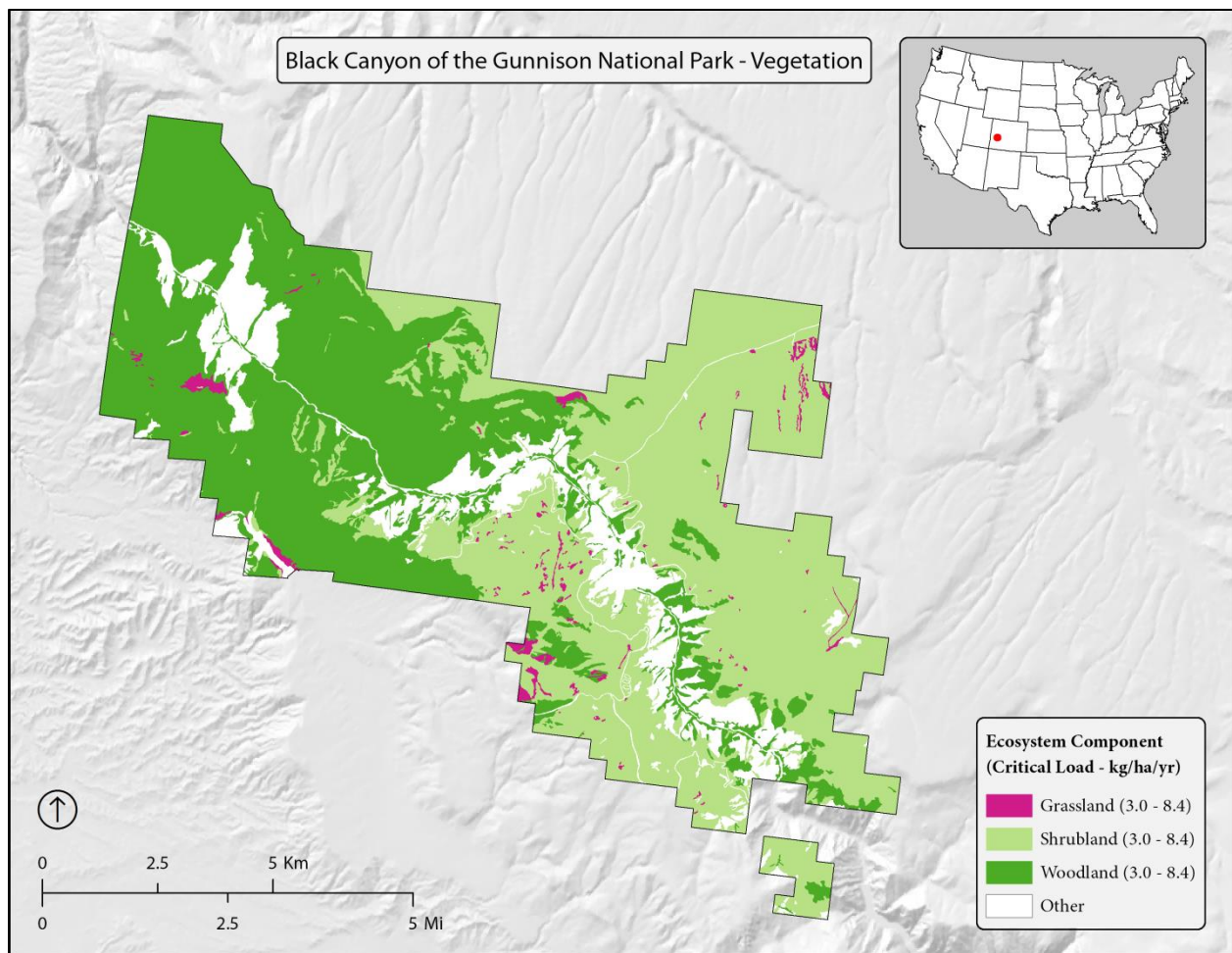
Exceedance maps for the seven national park units in NCPN that are subjects of study here are shown in Maps 21 through 27. There are no areas of N exceedance in ARCH, DINO, BLCA, CANY, or COLM. Essentially all of BLCA and roughly half of both COLM and DINO receive ambient N deposition that is below, but close (within 1 kg N/ha/yr) to, exceedance. Most of ARCH and CANY and also portions of COLM, DINO, and BLCA are within 2 kg N/ha/yr of exceedance. Thus, any appreciable increase in N emissions, from O&G exploration and production, agriculture, EGU, or other sources, may increase the risk of excess nutrient effects throughout most of the park lands within NCPN that are under study in this analysis.



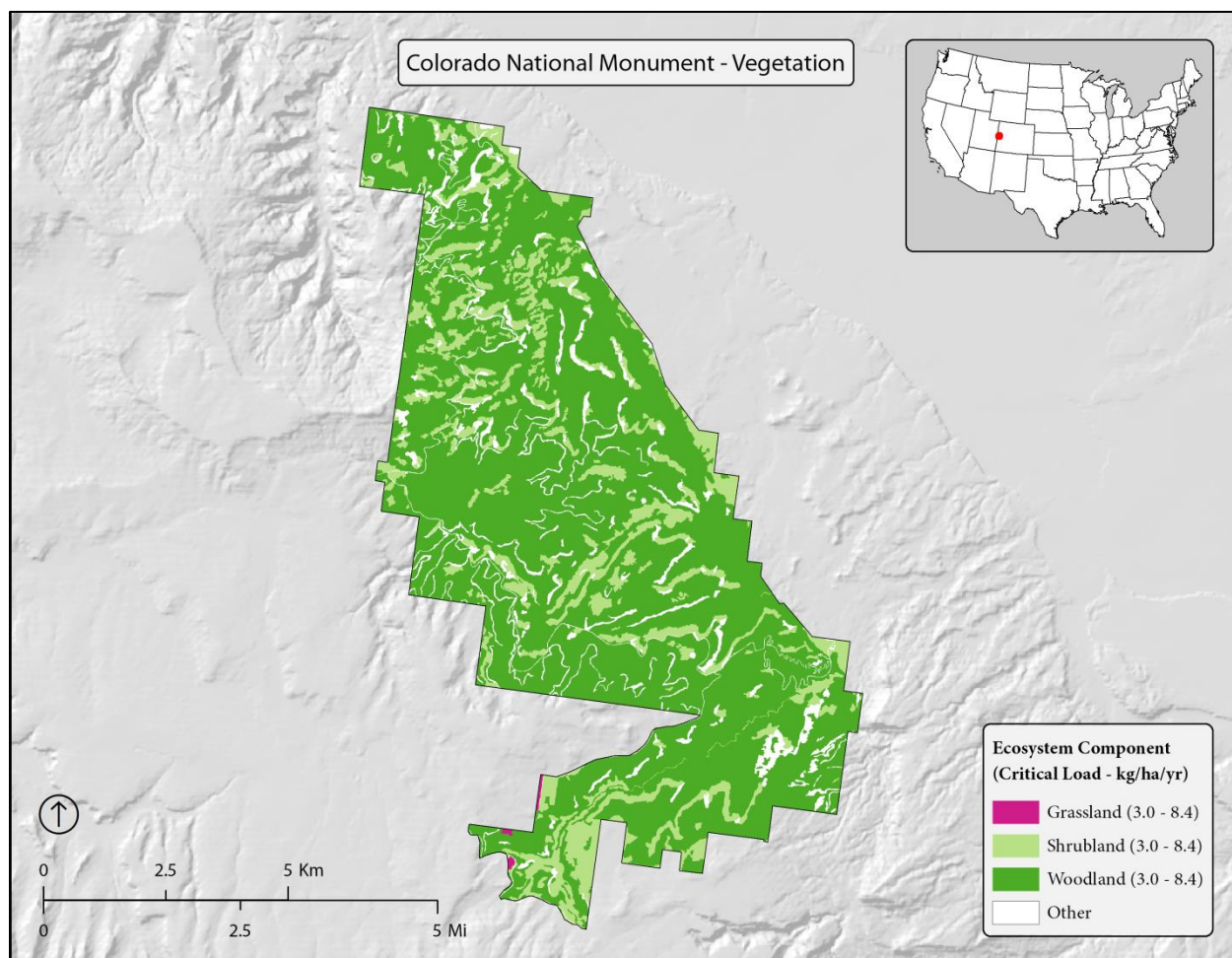
Map 13. Locations in Arches National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).



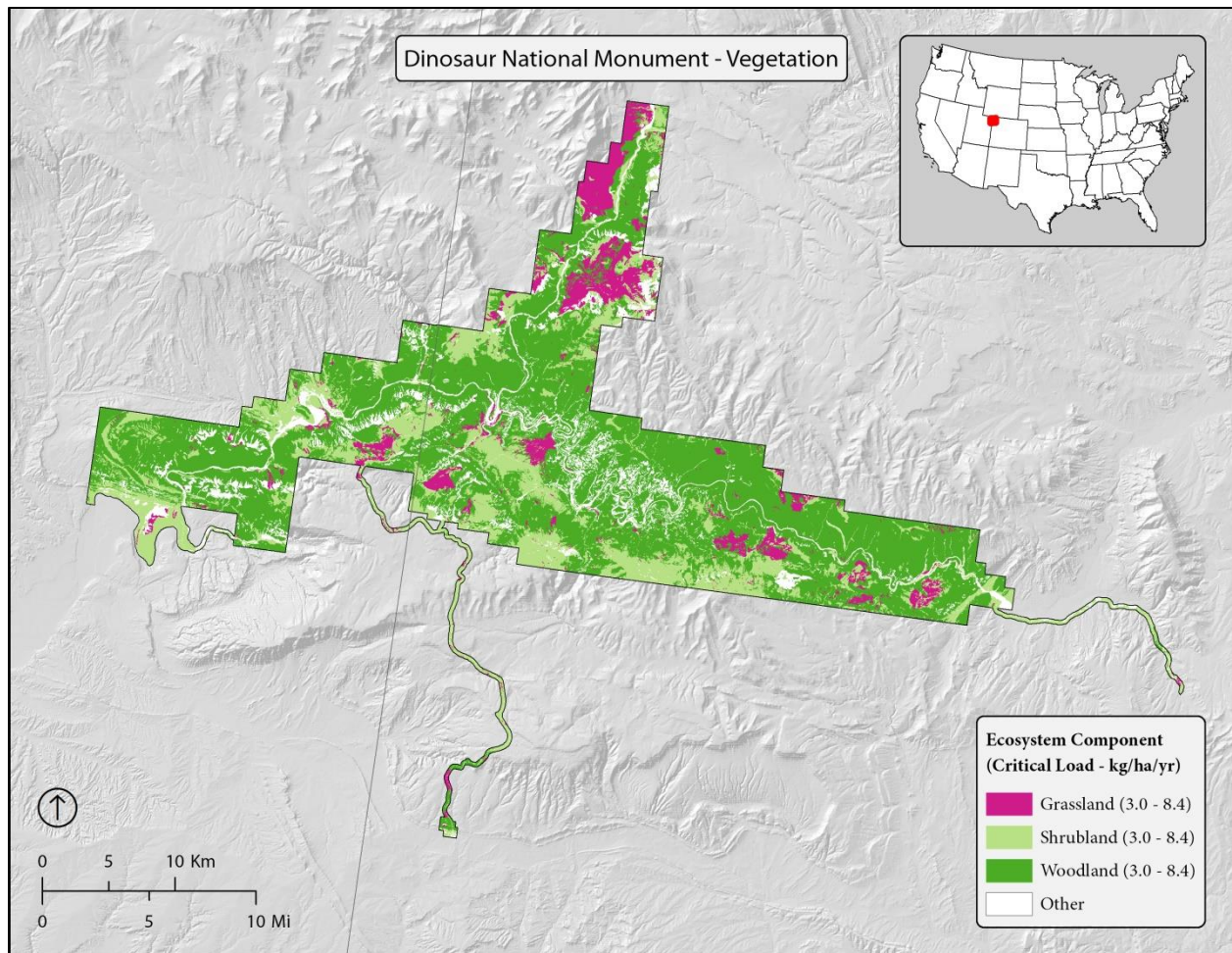
Map 14 Locations in Canyonlands National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).



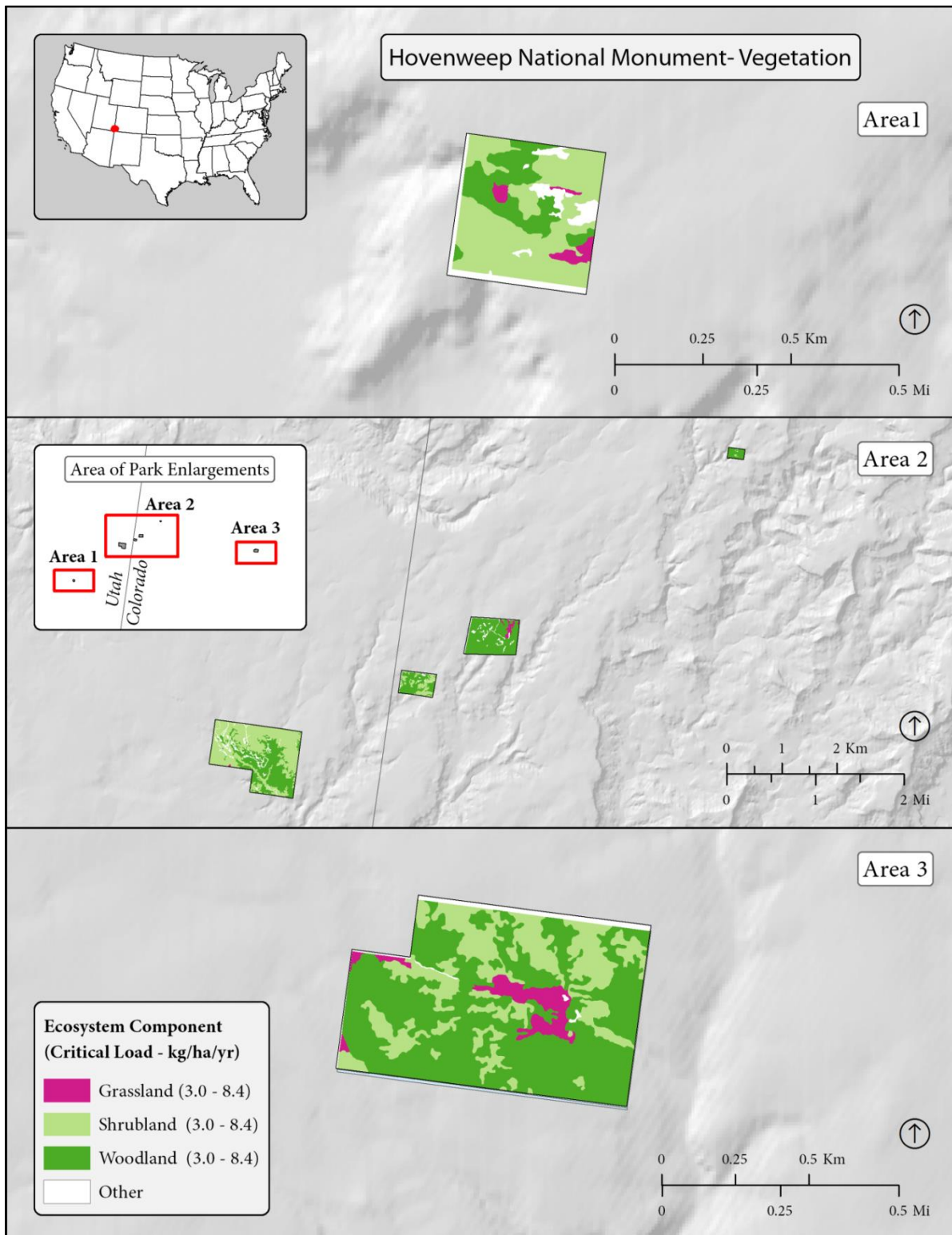
Map 15. Locations in Black Canyon of the Gunnison National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).



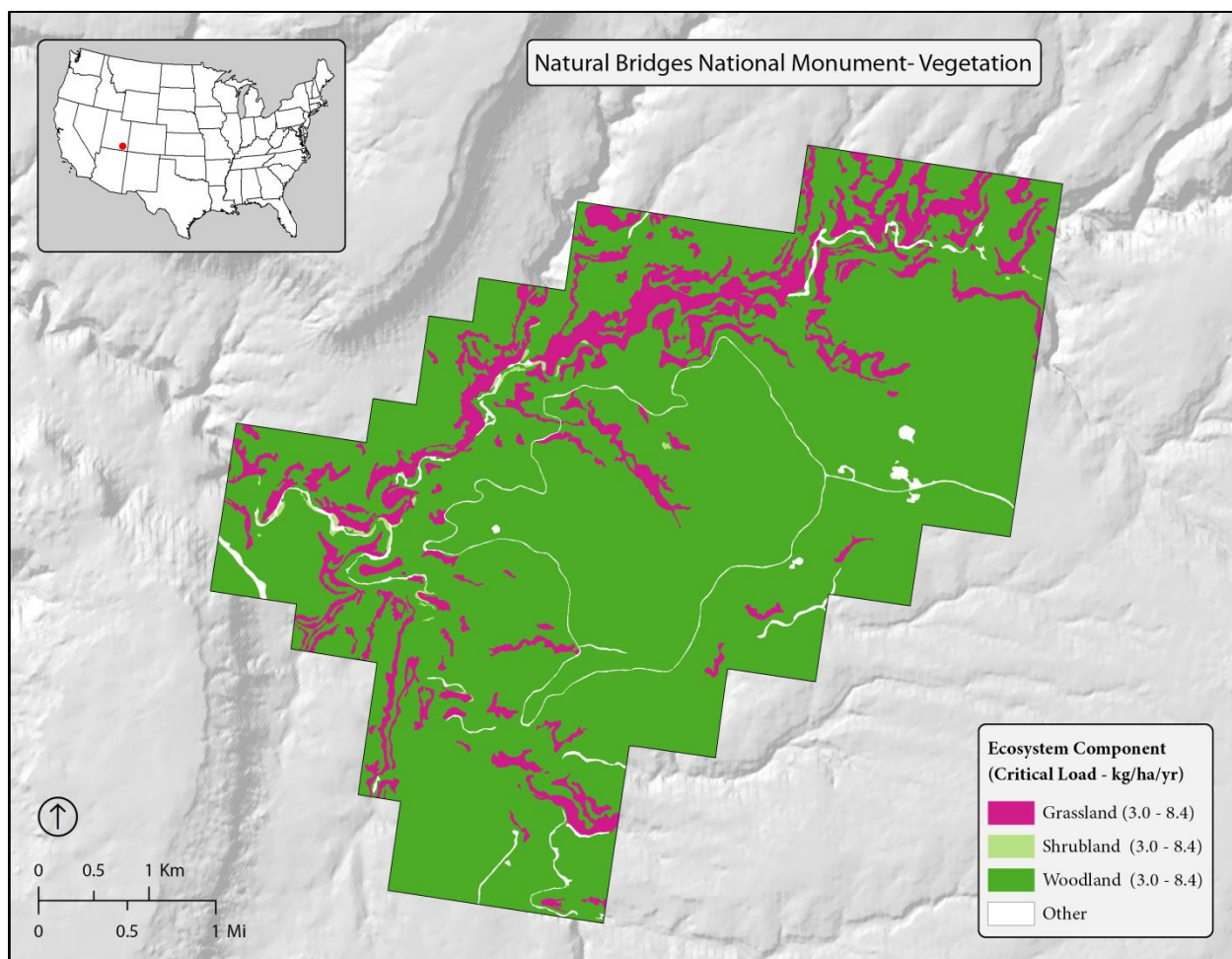
Map 16. Locations in Colorado National Monument having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).



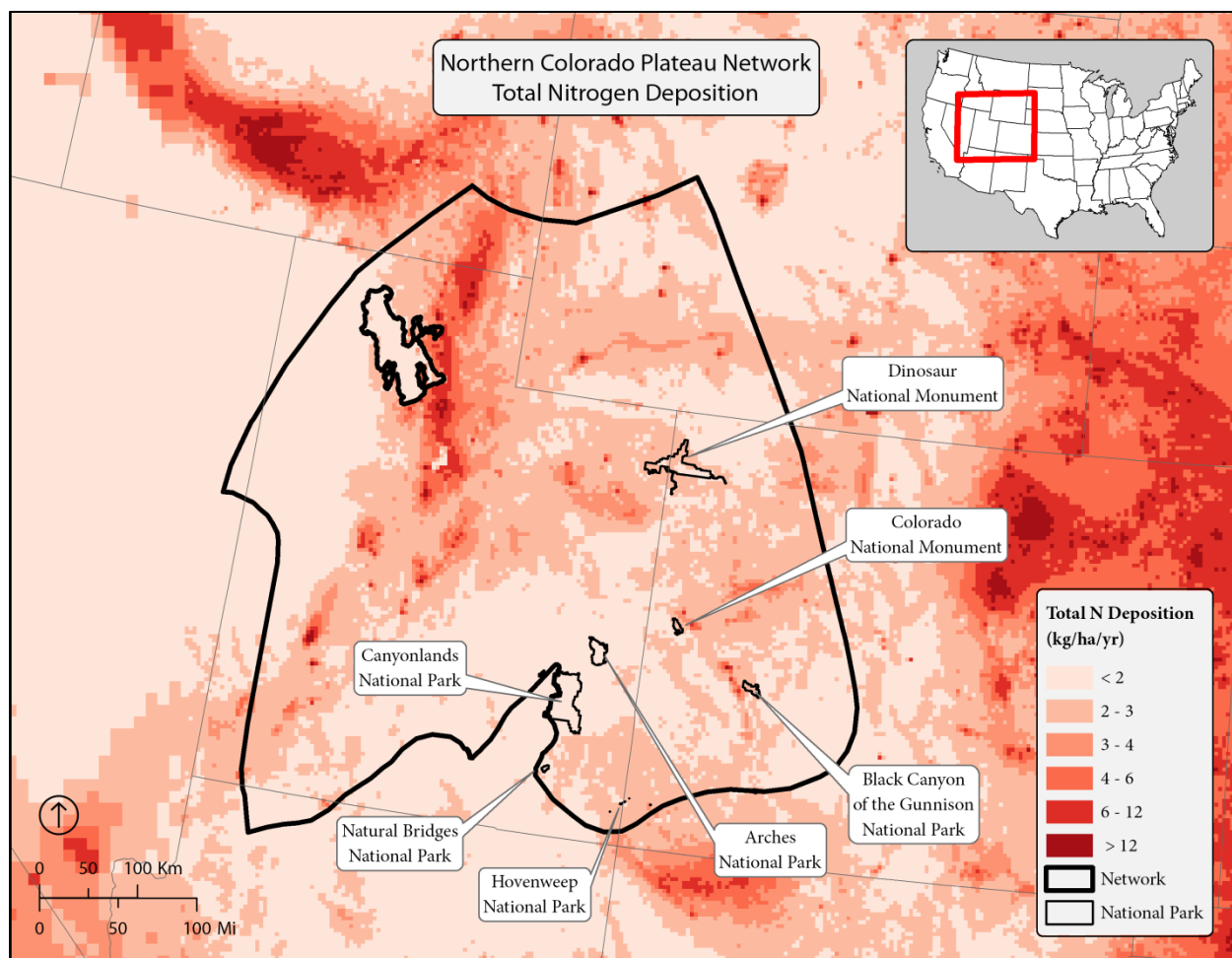
Map 17. Locations in Dinosaur National Monument having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).



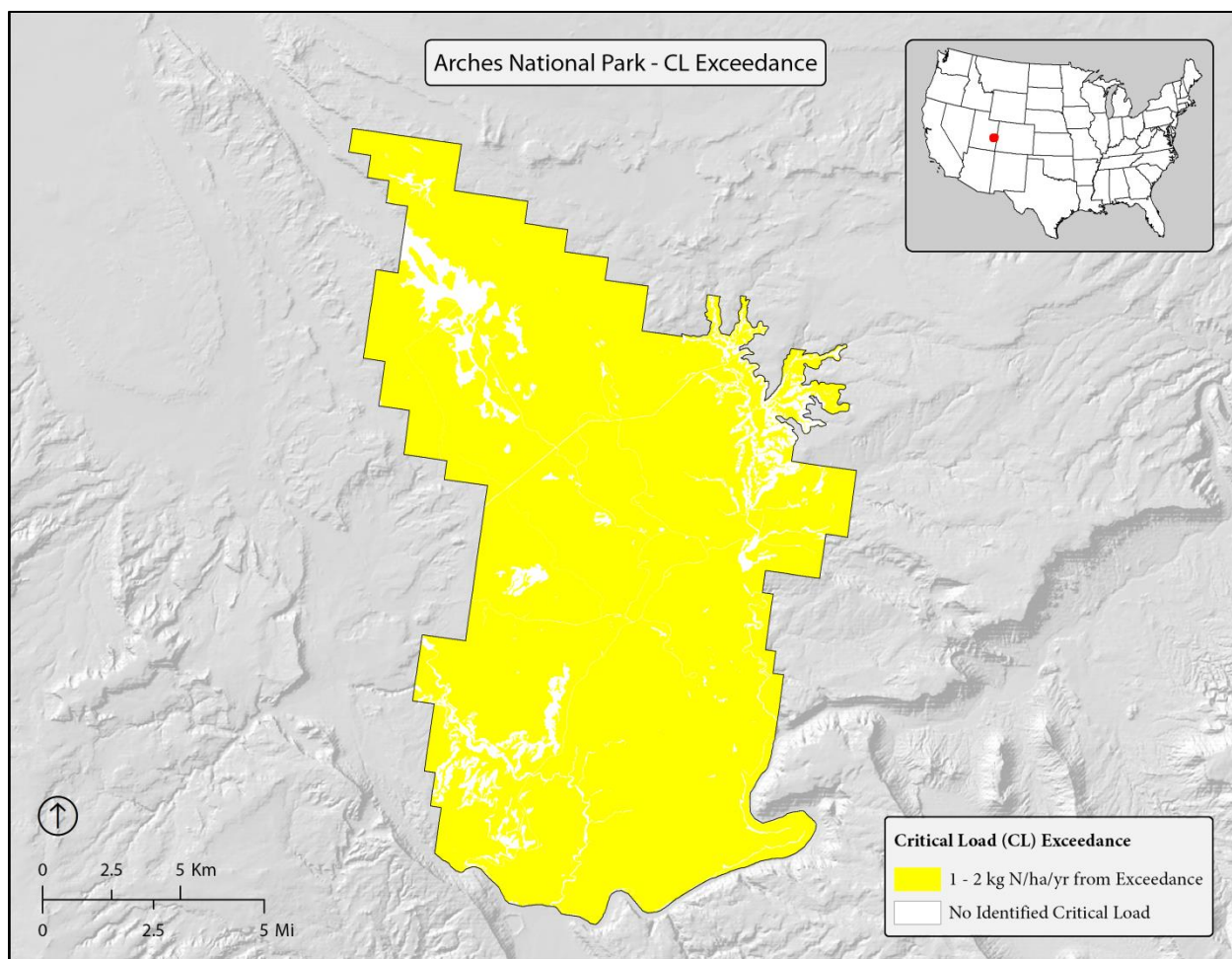
Map 18. Locations in Hovenweep National Monument having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).



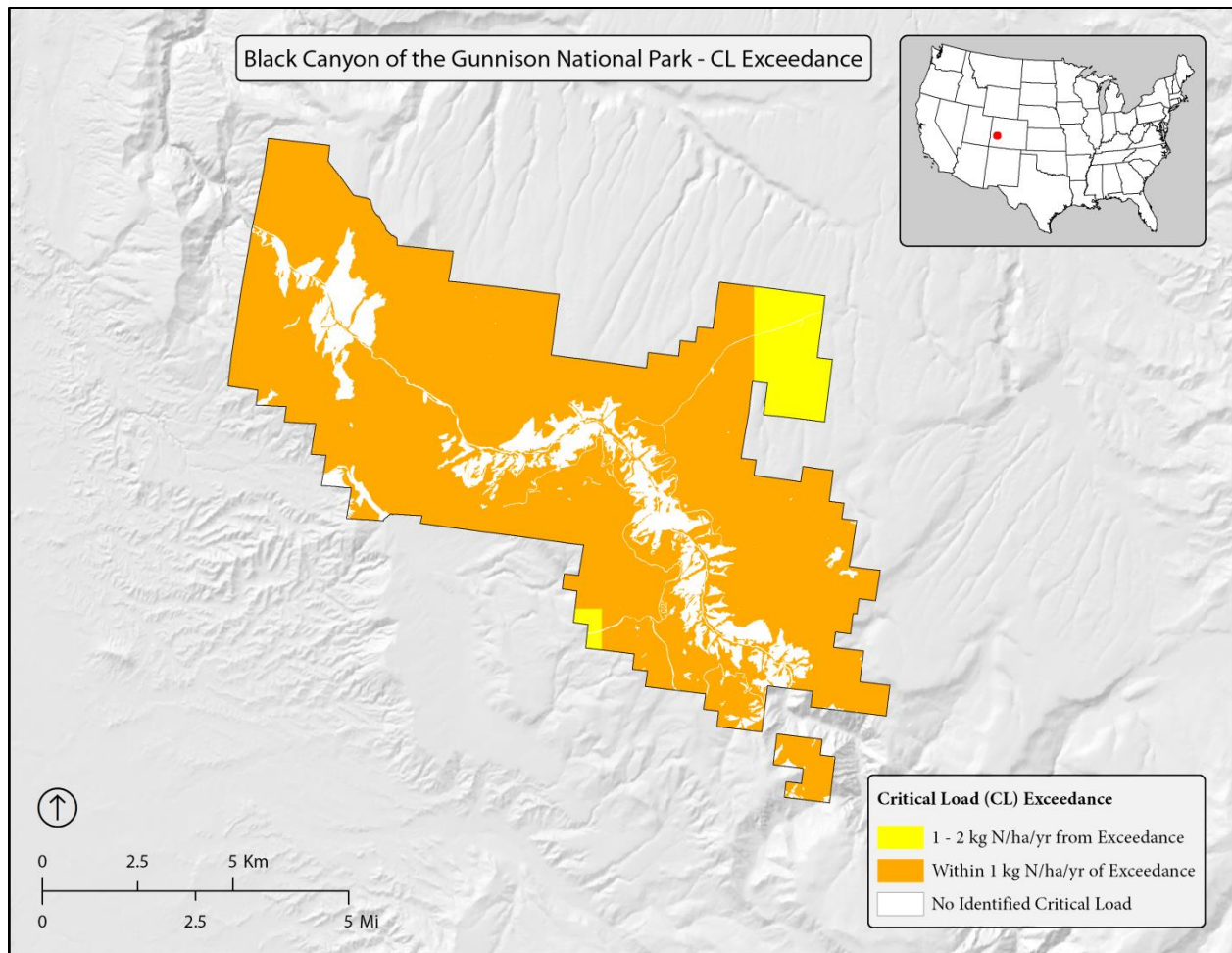
Map 19. Locations in Natural Bridges National Monument having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).



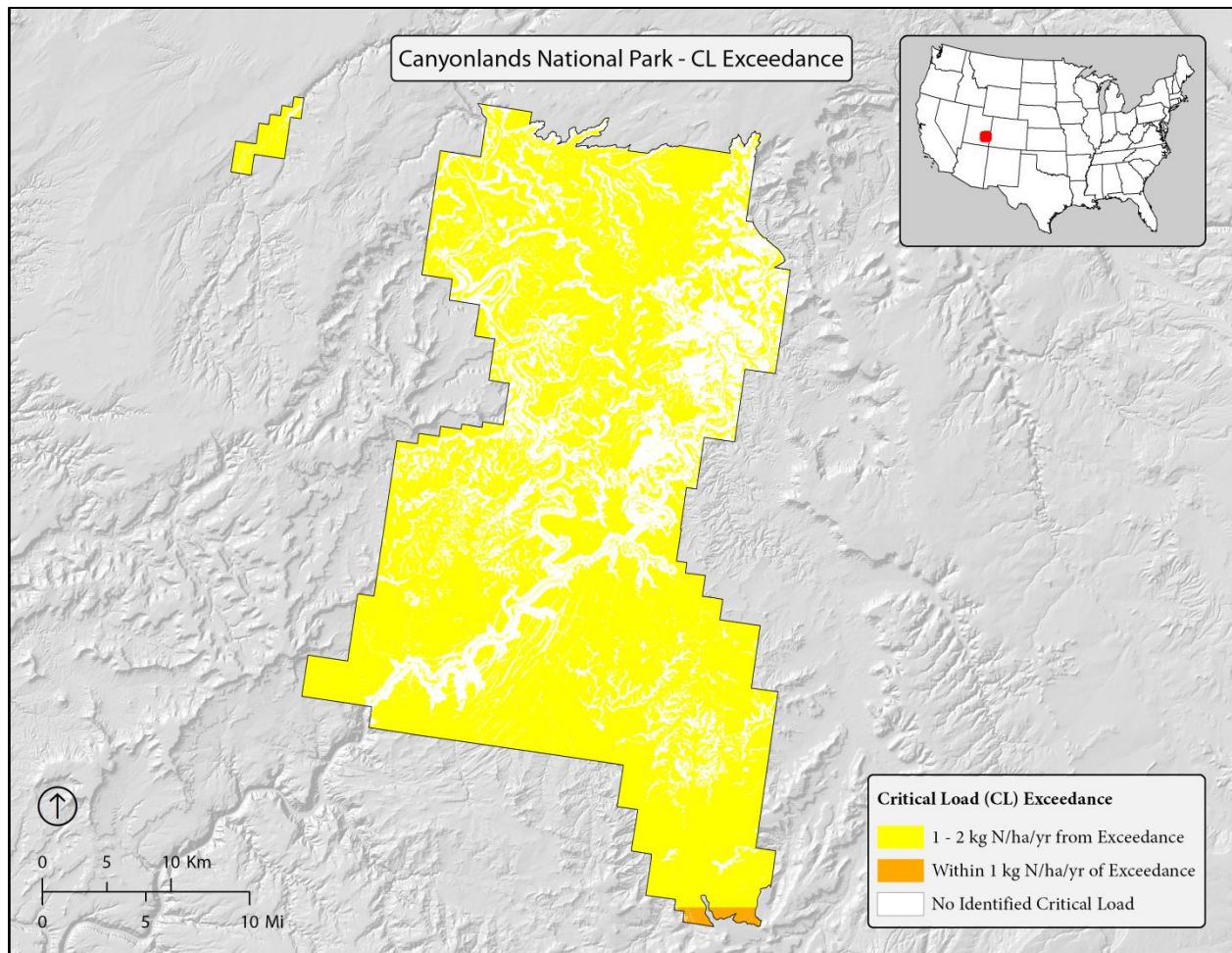
Map 20. CAMx model estimates of total wet plus dry N deposition (kg/ha/yr) for the year 2011 throughout the Northern Colorado Plateau Network.



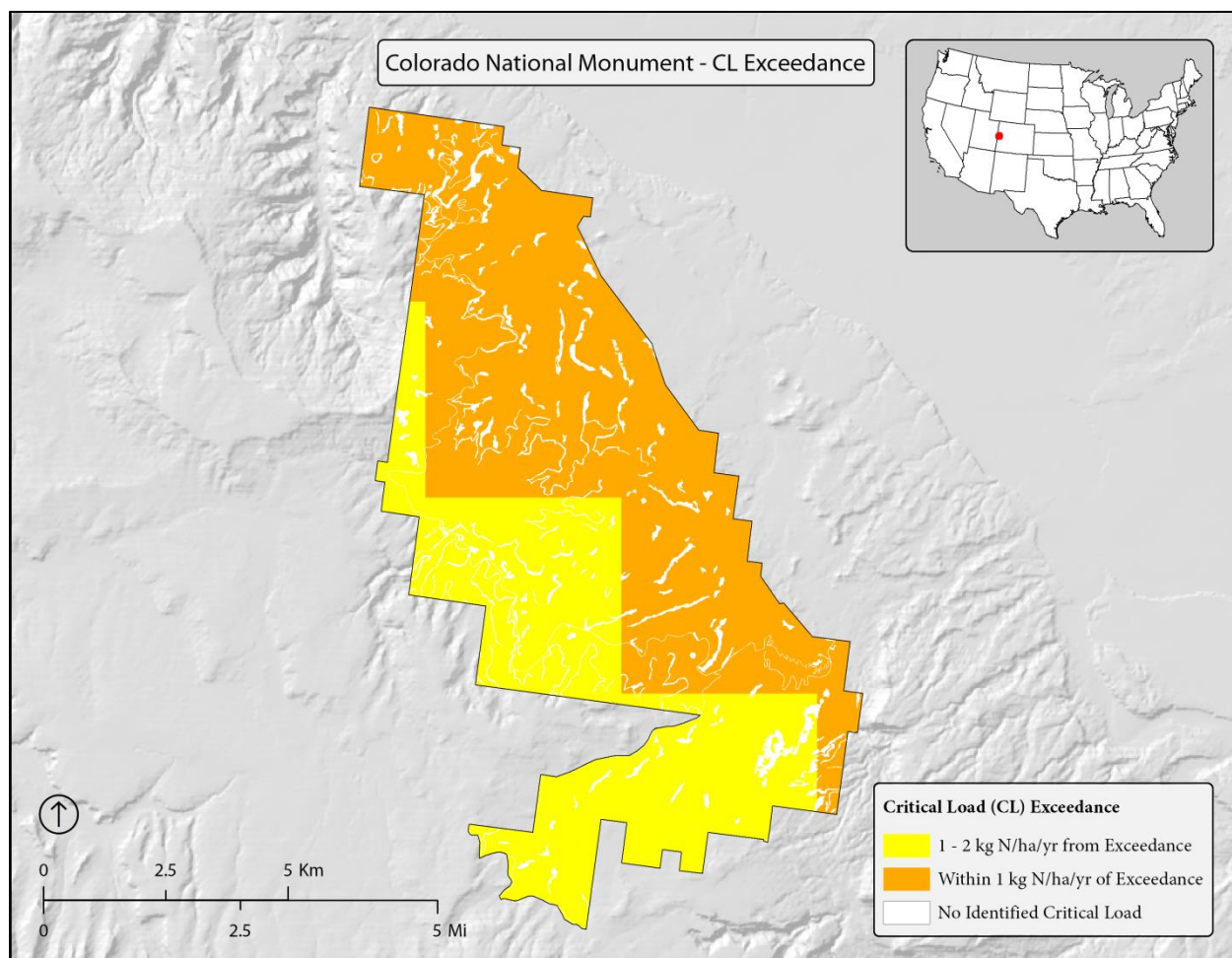
Map 21. Locations of vegetation types in Arches National Park that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas showing the background color do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.



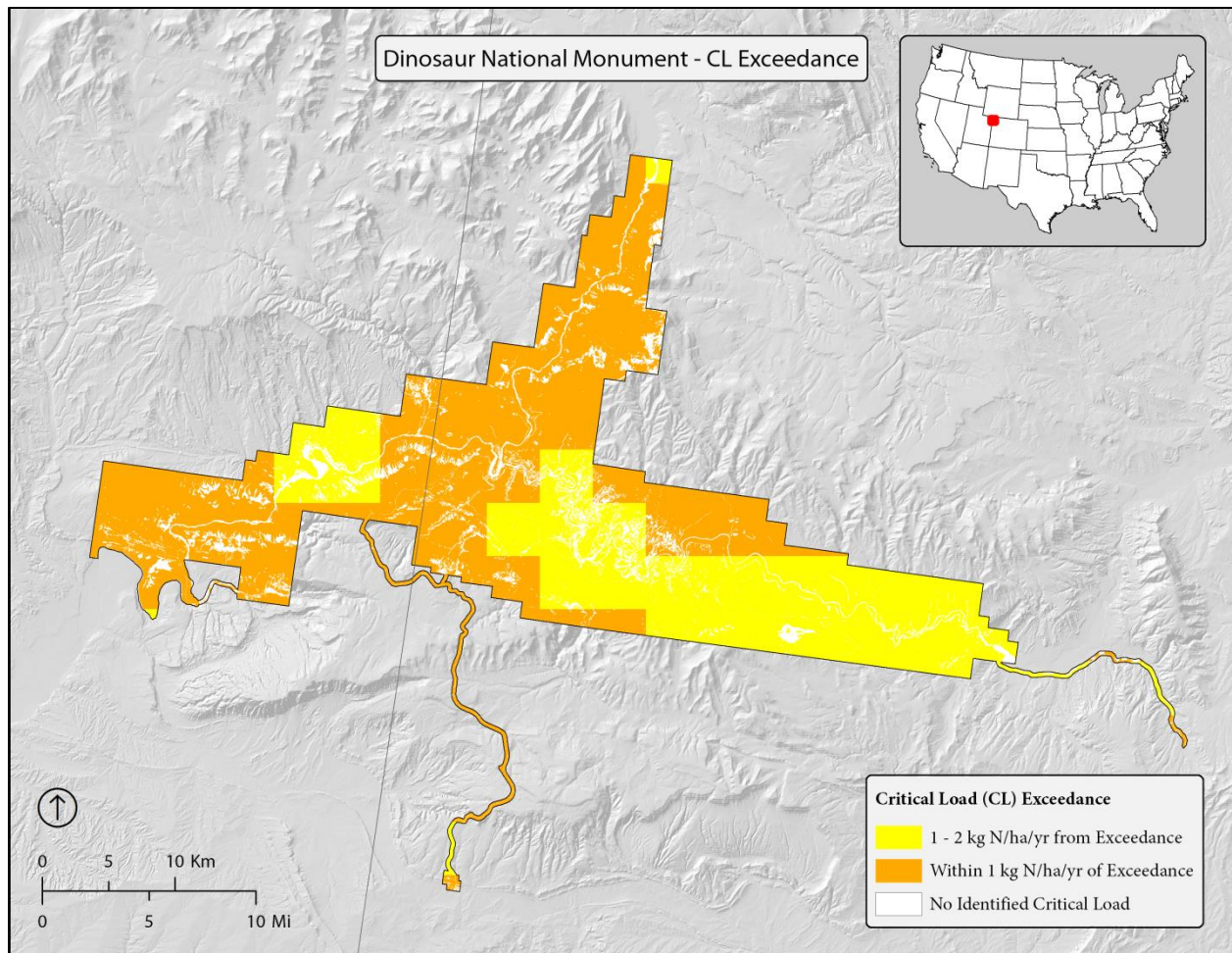
Map 22. Locations of vegetation types in Black Canyon of the Gunnison National Park that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas showing the background color do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.



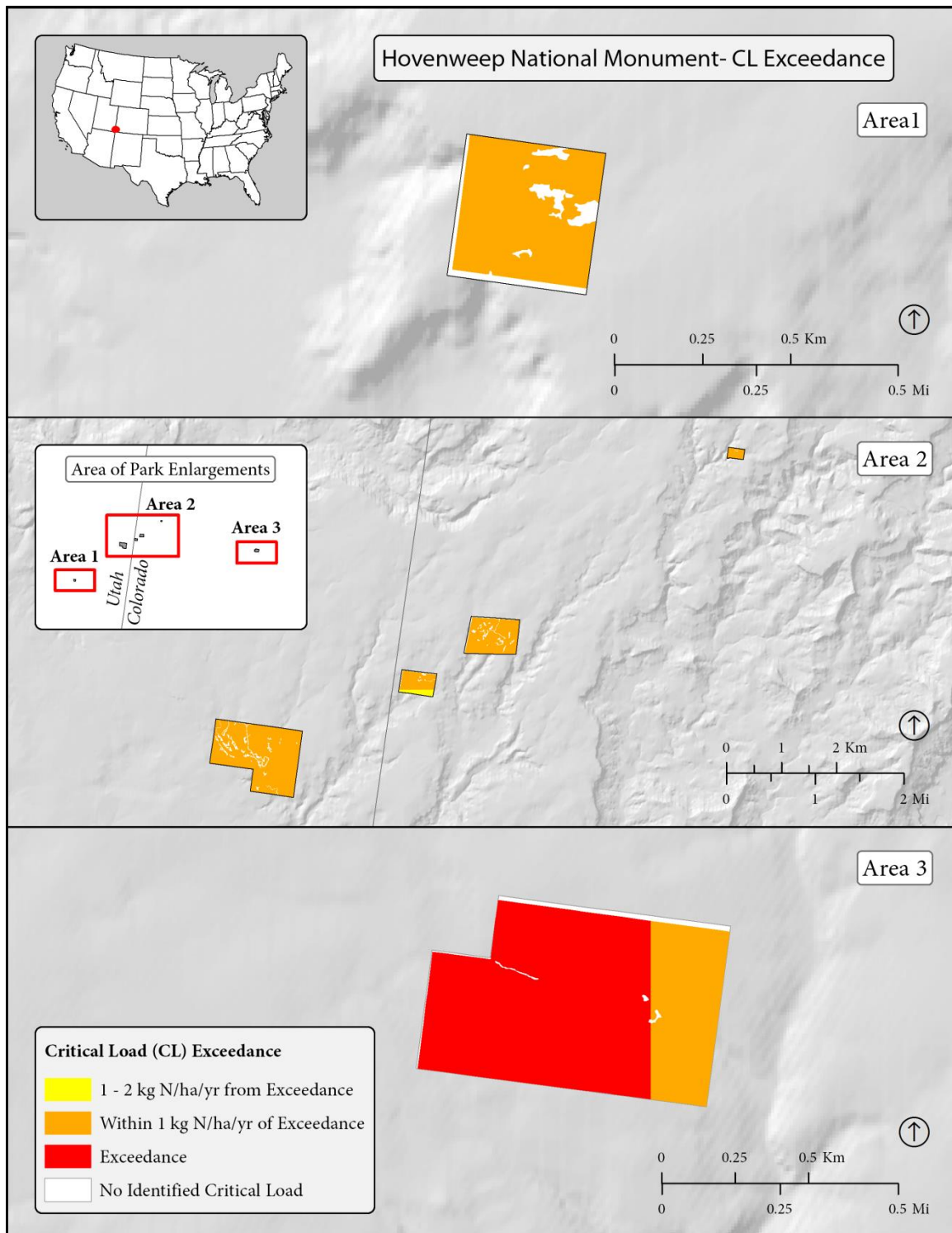
Map 23. Locations of vegetation types in Canyonlands National Park that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas showing the background color do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.



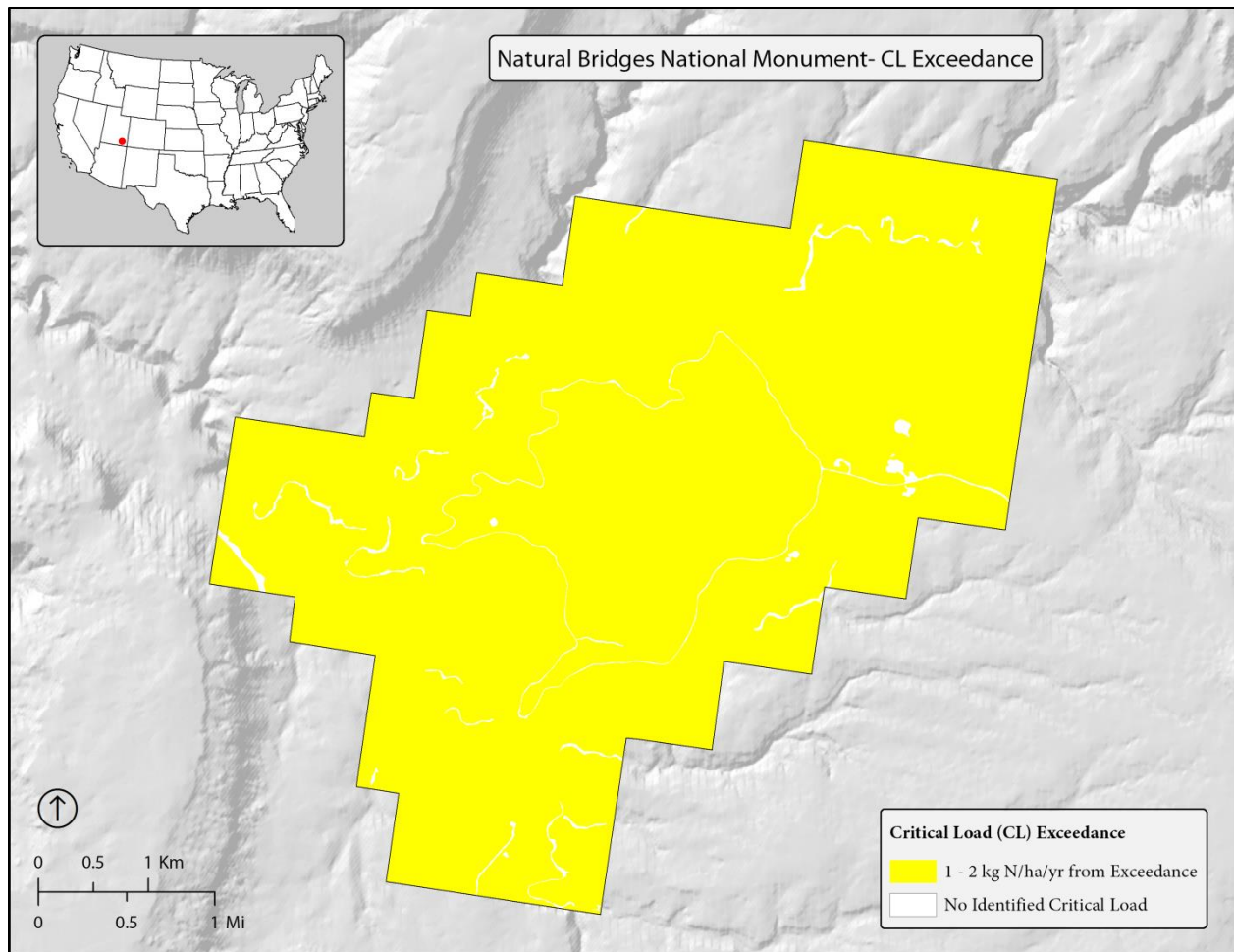
Map 24. Locations of vegetation types in Colorado National Monument that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas showing the background color do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.



Map 25. Locations of vegetation types in Dinosaur National Monument that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas showing the background color do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.



Map 26. Locations of vegetation types in Hovenweep National Monument that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas showing the background color do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.



Map 27. Locations of vegetation types in Natural Bridges National Monument that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas showing the background color do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.

Sonoran Desert Network

Dose Response and Critical Loads

In the driest desert ecosystems, such as within SODN, water is generally more limiting than N. Nevertheless, enhanced N could play a role in the recently observed invasion of some exotic plant species within parts of the Sonoran and nearby Mojave deserts. Brooks (2003) found that plant responses were more influenced by specific rainfall events rather than by average annual rainfall, with the annual plants thriving in a year when high rainfall events triggered germination. In the Mojave desert, creosote bush showed no increased growth response to experimental N additions (at 10 and 40 kg N/ha/yr as $\text{Ca}(\text{NO}_3)_2$), but did respond to increased water (Barker et al. 2006). Invasive annuals showed a greater response to elevated N than did native plant species.

Saguaro National Park

The SODN contains one park (SAGU) that was included in this analysis. Parts of SAGU occur within the Sonoran Desert Level III ecoregion. In the lowland areas throughout the Sonoran Desert, N deposition would be expected to contribute to increased cover of non-native grasses and increased fire frequency and severity (Fenn and Allen 2011). Non-native grass invasion is an important management issue in SAGU.

Critical loads of atmospheric N deposition are analyzed below for SAGU. Desert lichens may be especially sensitive to N addition. Lichens near a large coal-fired plant in Page, Arizona showed chlorophyll degradation and reduced N fixation (Belnap 1991). In contrast, Marsh and Nash (1979) did not find effects on lichens near the Four Corners Power Plant on the Colorado Plateau.

Model simulations using the Patch Arid Land Simulator (PALS) suggested that plant biomass in the desert near Phoenix can increase with only a small increase in N supply (Shen et al. 2008). The issue of increased plant biomass with increased N input is further confounded by the presence of nonnative invasive grass species, which are common in portions of the Sonoran Desert network.

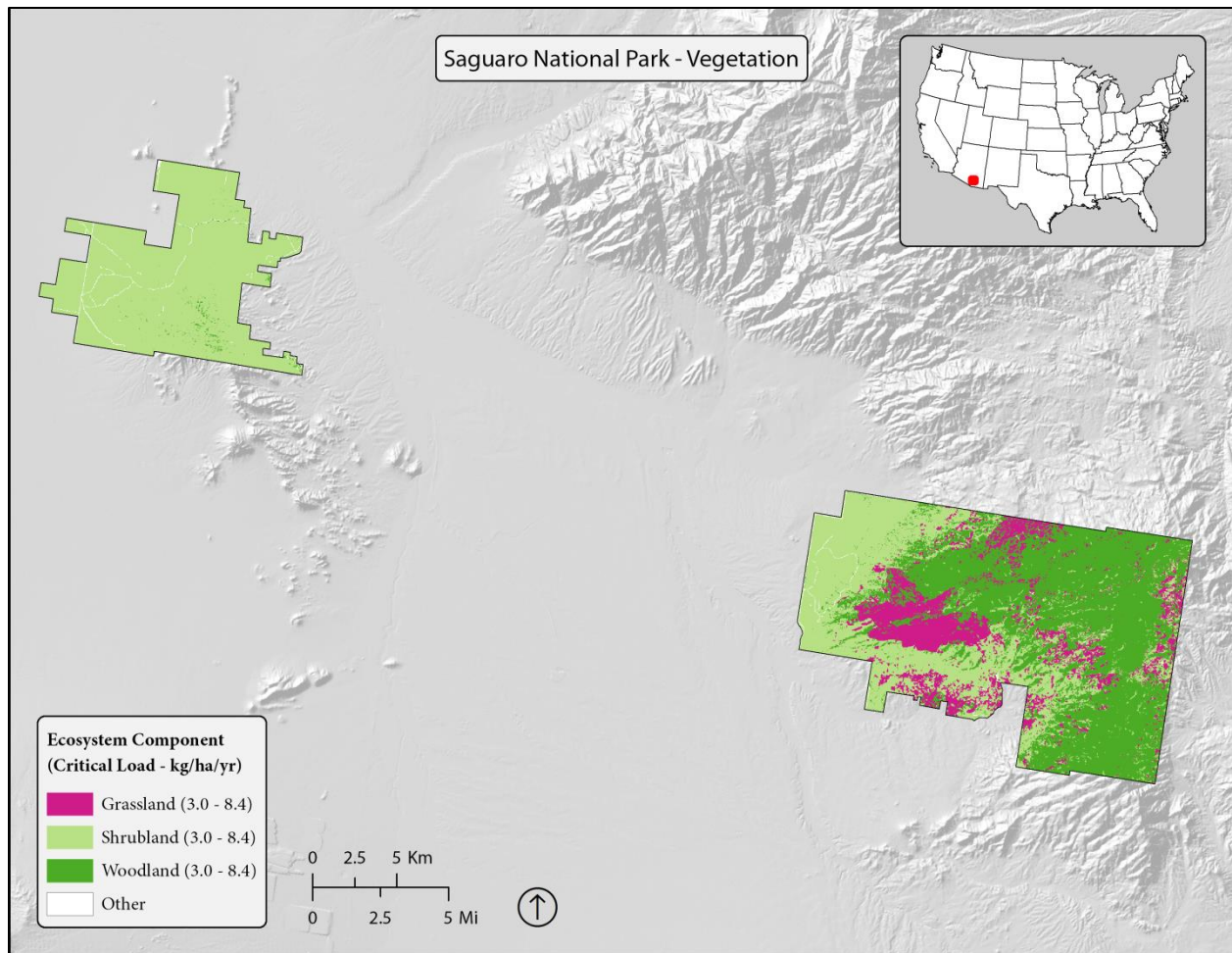
Portions of SAGU covered by woodland, shrubland, and grassland are shown in Map 28. Each of these plant community types was estimated by Allen and Geiser (2011) to be sensitive to N deposition and to have CL in the range of 3 to 8.4 kg N/ha/yr. Locations in the park where these plant communities occur and where ambient N deposition is higher than 3 kg N/ha/yr are in exceedance of the CL for protecting these potentially N-sensitive plant communities against change in community composition. This same CL (3 kg N/ha/yr) was also judged by Allen and Geiser (2011) to be applicable to protection of lichen community composition in desert plant communities such as are found in SAGU.

Deposition

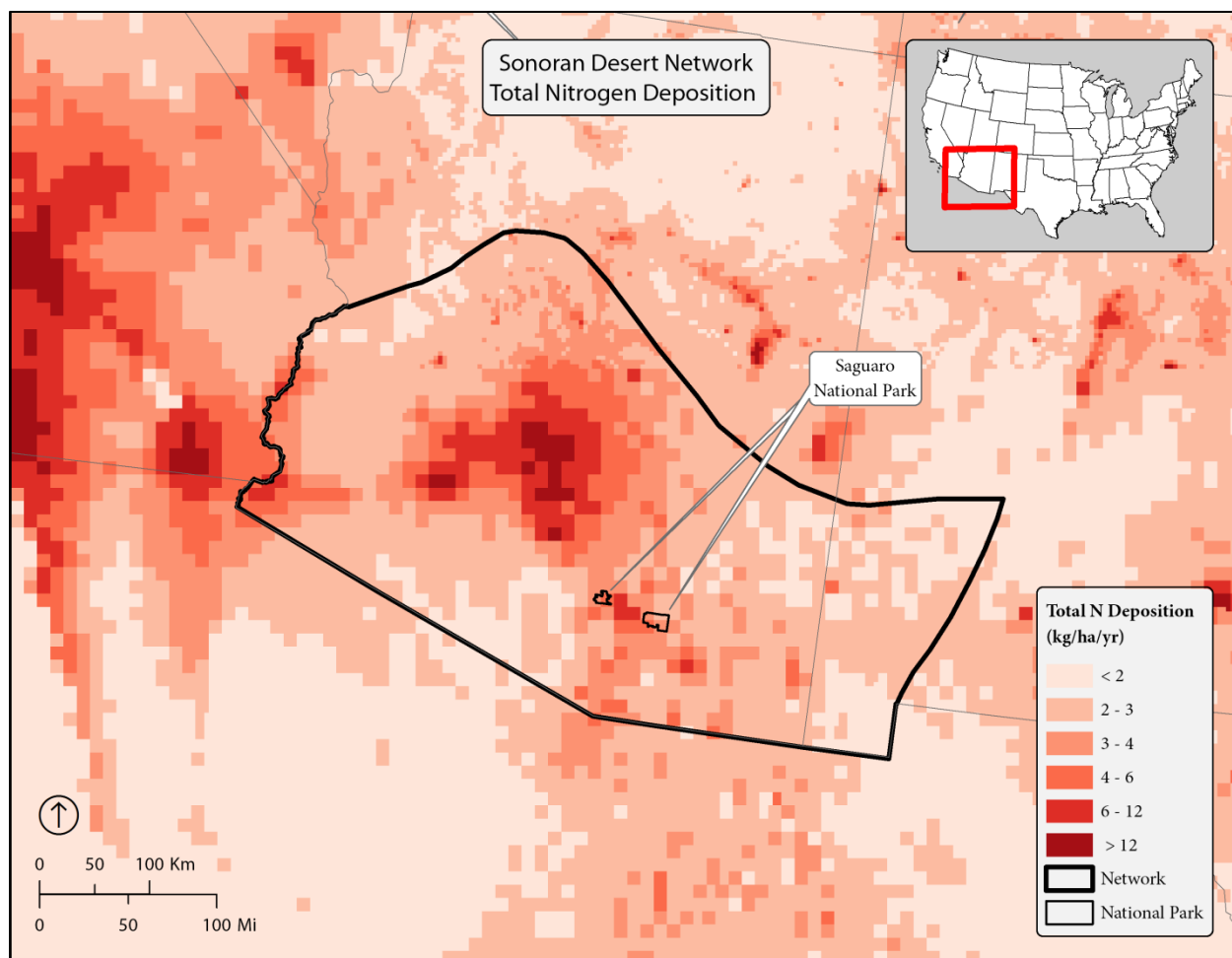
Total wet plus dry N deposition in SODN was less than 3 kg N/ha/yr at most locations. However, estimated N deposition was much higher around Phoenix and other portions of south central Arizona, in some areas in excess of 12 kg N/ha/yr (Map 29).

Exceedance

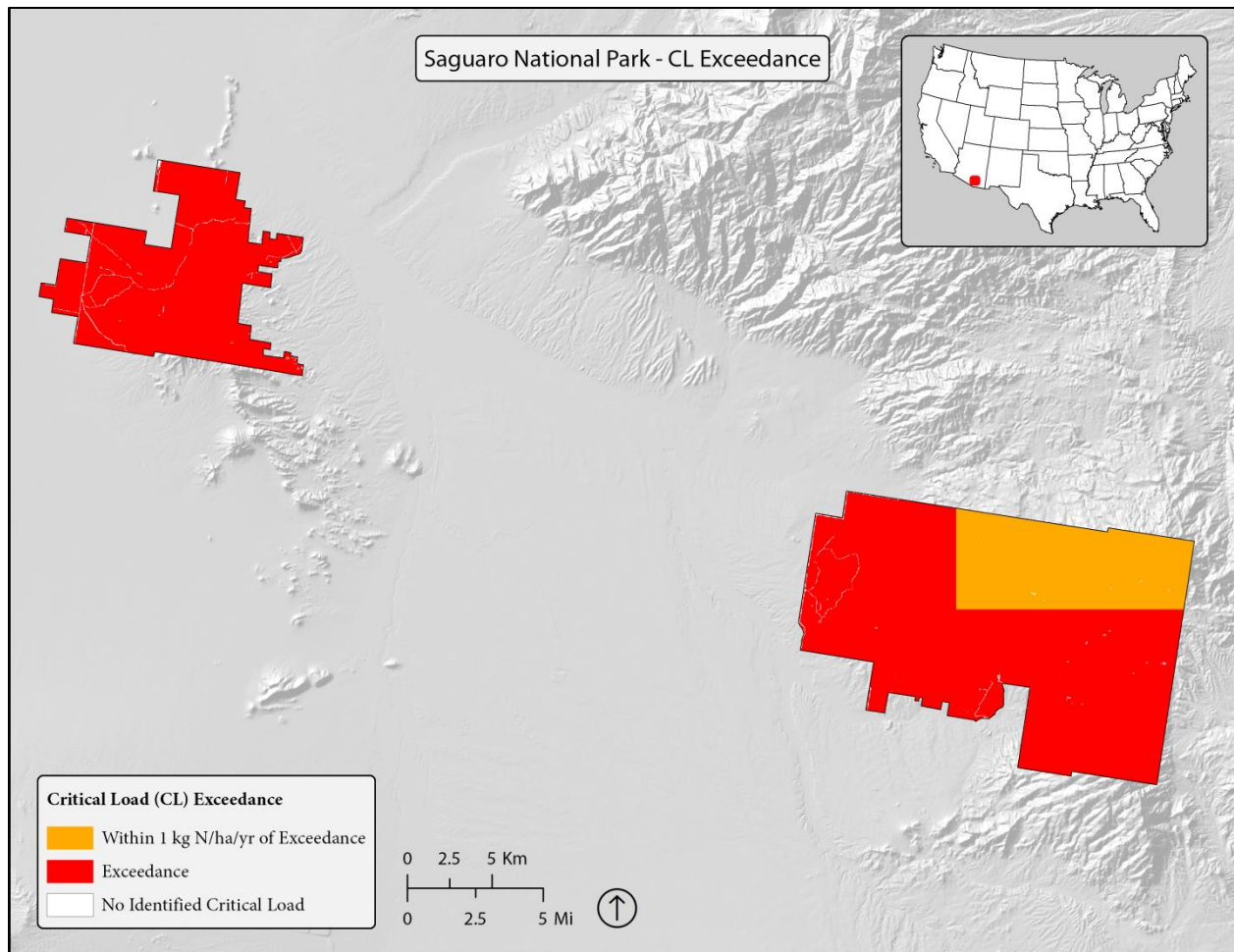
The majority of the parkland in SAGU, in both the East and West units, received ambient N deposition that was in exceedance of the N CL (Map 30). The remainder of the park received N deposition below, but within 1 kg N/ha/yr of, the CL. Thus, there is a reasonable likelihood of adverse impacts at SAGU under ambient N deposition loading and an increased likelihood that further increases in N emissions in and near SAGU could cause ecological changes related to excess N deposition.



Map 28. Locations in Saguaro National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Allen and Geiser (2011).



Map 29. CAMx model estimates of total wet plus dry N deposition (kg/ha/yr) for the year 2011 throughout the Sonoran Desert Network.



Map 30. Locations of vegetation types in Saguaro National Park considered sensitive to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Orange indicates areas that are within 1 kg N/ha/yr of exceedance. Yellow indicates areas that are between 1 and 2 kg N/ha/yr from exceedance. Green represents areas that are not within 2 kg N/ha/yr of exceedance. Areas showing the background color do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.

Northwest Forested Mountains Ecoregion

Rocky Mountain Network

Dose-Response and Critical Load

Aquatic Nutrient Enrichment

Addition of N can stimulate algal growth in N-limited lakes (Lafrancois et al. 2003, Sickman et al. 2003, Bergström et al. 2005, Bergström and Jansson 2006), which are common in ROMN. However, not all species of diatoms or other algae are equally responsive to N supply. Differences in resource requirements allow some species to gain a competitive advantage over others upon nutrient addition. In response, shifts in algal assemblages have been observed (Wolfe et al. 2001, Wolfe et al. 2003, Lafrancois et al. 2004, Saros et al. 2005). Species diversity can decline with increasing availability of

N (Interlandi and Kilham 2001). Sediment cores from lakes in the Colorado Front Range showed increasing representation of mesotrophic diatom taxa in recent times, as compared with pre-development conditions (Wolfe et al. 2001). Community shifts in phytoplankton were also observed in the Snowy Range, with chrysophytes favored in lakes having lower N and cyanophytes and chlorophytes favored in lakes having higher N (Lafrancois et al. 2003). These results corroborate earlier work on resource requirements for these algal species (Tilman 1981).

Two species of diatom, *Asterionella formosa* and *Fragilaria crotonensis*, now dominate the flora of some alpine and montane Rocky Mountain lakes (Interlandi and Kilham 1998, Baron et al. 2000, Wolfe et al. 2001, Saros et al. 2003, Wolfe et al. 2003, Saros et al. 2005). *A. formosa* and *F. crotonensis* have extremely low resource requirements for P and moderate requirements for N, allowing for rapid response to increased N availability (Michel et al. 2006). Studies of diatom remains in lake sediments (Wolfe et al. 2003) have shown declines in the oligotrophic diatom species *Aulacoseria perglabra*, *Cycotella stelligera*, and *Achnanthes* spp. coincident with increases in abundance of *A. formosa* and *F. crotonensis*. The growth of *A. formosa* has been stimulated with N amendments during *in situ* incubations, using bioassays and mesocosms (6.4 to 1616 μM N/L, McKnight et al. 1990, 76 μM N/L, Lafrancois et al. 2004, 18 μM N/L, Saros et al. 2005). Mesocosm enrichments in Wyoming lakes found positive responses of *A. formosa* and *F. crotonensis* to N, but not to P or Si enrichment (Saros et al. 2005).

Increased N deposition can change the species composition of algal communities in oligotrophic lakes. Baron (2006) found that diatom reconstructions from lake sediment cores in ROMO during the period 1850 to 1964 suggested changes in algal abundance associated with wet N deposition of only about 1.5 kg N/ha/yr. Similar results were found by Saros et al. (2003) in the Beartooth Mountains in Wyoming. The freshwater algae thought to be most sensitive to effects of increased N deposition included *A. formosa* and *F. crotonensis*. These are considered to be opportunistic species that can respond rapidly to slight nutrient enrichment.

Terrestrial Nutrient Enrichment

The potential impacts of nutrient N deposition on terrestrial resources within ROMO, especially those at high elevation in the alpine and subalpine zones, is an important concern. The major issues appear to be 1) terrestrial eutrophication, with excess fertilization leading to increased ecosystem productivity, increased spread of exotic plant species, and decreased native plant species diversity (cf., Huston 1994); and 2) N saturation, where N supply exceeds the vegetative uptake capacity and NO_3^- leaches out of the soil in high concentrations in soil water.

Factors that govern the sensitivity of high-elevation plant communities to N deposition include low rates of primary production, short growing season, low temperature, and wide variation in moisture (Bowman and Fisk 2001). Alpine plant communities have developed under conditions of low nutrient supply, in part because soil-forming processes are poorly developed, and this also contributes to their N-sensitivity. Nitrogen cycling in Rocky Mountain alpine environments is strongly influenced by variations in moisture (Bowman et al. 1993, Bowman 1994, Fisk et al. 1998). Blowing snow is transported across alpine landscapes by wind and accumulates in depression areas, which receive much higher levels of moisture and winter season N deposition than other more wind-

swept portions of the alpine environment (Bowman 1992). Fenn et al. (2003) suggested that as much as 10 kg N/ha/yr may leach through the snow during the initial phases of snowmelt in some of the alpine areas in Colorado that accumulate substantial snowpack. It is these moist meadow areas that may be most affected by N deposition, and they are also the areas most likely to show changes in plant species composition and impacts on N cycling (Bowman and Steltzer 1998).

Baron et al. (1994) estimated N uptake by plants and soil in Colorado using the CENTURY model. Simulated N export increased in alpine ecosystems at relatively low levels of N deposition (3.4 kg N/ha/yr). The adjacent subalpine forests had more substantial forest N retention. Analyses by Baron et al. (2000) suggested that the eastern slope of the Colorado Front Range may be at the beginning of a trajectory of N saturation change.

Alpine ecosystems are adapted to cold temperature, short growing season, periodically high soil moisture, and periodically low soil oxygen level. Plants respond to reduced N availability by changing the allocation of biomass to increase root growth (Bloom et al. 1985) or changing the efficiency with which N is used or stored (Chapin 1980). Increased abundance of high N demand plant species has been demonstrated in alpine plant communities at the Niwot Ridge Long Term Ecological Research site, about 10 km south of ROMO (Korb and Ranker 2001). The experimental site receives slightly higher atmospheric N deposition than does Loch Vale (Burns 2003). Results of fertilization experiments suggested that the lowest amount of atmospheric N deposition expected to alter alpine plant communities at Niwot Ridge and Loch Vale is about 4 kg N/ha/yr (Bowman et al. 2006, 2012). This deposition level is similar to ambient deposition measured at Loch Vale.

Changes in alpine plant species composition can precede detectable changes in soil chemistry in response to increased N deposition (Sverdrup et al. 2012). Changes in species composition of dry meadows (among the most sensitive alpine plant community types) are probably ongoing along the Front Range (Bowman et al. 2006, 2012), in response to ambient N deposition, which varies from about 3 to 6 kg N/ha/yr.

Rueth and Baron (2002) compared N dynamics of Engelmann spruce (*Picea engelmannii*) forest stands east and west of the Continental Divide in Colorado. Nitrogen deposition was moderate (3 to 5 kg N/ha/yr) on the east slope, but only 1 to 2 kg N/ha/yr on the west slope. East slope sites showed lower soil organic horizon C:N, lower foliar C:N, higher potential net mineralization, and higher percent N and N:Mg and N:P ratios in foliage. These results suggested that even moderate levels of N deposition input can cause measurable changes in spruce forest biogeochemistry. It is unclear, however, to what extent such biogeochemical changes affect forest species composition, growth, or health. Results of a modeling study by Baron et al. (1994) suggested that subalpine forest soils in the Front Range would exhibit increased N leaching at N deposition above about 4 kg N/ha/yr.

Addition of 25 kg N/ha at Niwot Ridge during summer caused a community shift towards greater dominance of hairgrass (*Deschampsia* sp.) in wet alpine meadows, but the increase in plant biomass (+67%) and plant N content (+107%) following N fertilization was higher in graminoid-dominated dry meadows than in forb-dominated wet meadows (+53% plant biomass, +64% standing N crop; Bowman et al. 1995, Burns 2004).

Additions of 20, 40, and 60 kg N/ha/yr in addition to ambient N deposition (near 5 kg N/ha/yr) over an eight-year period to a dry alpine meadow at Niwot Ridge caused a change in plant species composition, an increase in species diversity and plant biomass, and an increase in tissue N concentration at all treatment levels within three years of application. Much of the response was due to increased cover and total biomass of *Carex* spp. There was a significant decrease in *Kobresia* sp. biomass with increasing N input. Vegetation composition appeared to respond at lower N input levels than those that caused measurable changes in soil inorganic N content.

Effects of N deposition on terrestrial alpine ecosystems in the Rocky Mountain Network region are thought to include community-level changes in vascular plants, lichens, and mycorrhizae. Subtle effects have been shown to occur at levels of N deposition about 4 kg/ha/yr (Bowman et al. 2006). Bowman et al. (2006, 2012) concluded that alpine plants may be more sensitive indicators of the effects of increased N inputs than soils. Changes in the sedge species *Carex rupestris* were estimated to occur at deposition levels near 4 kg N/ha/yr. Changes in the overall plant community, based on the first axis of a detrended correspondence analysis, were estimated to occur at deposition levels near 10 kg N/ha/yr. In contrast, increases in NO_3^- leaching, soil solution NO_3^- concentration, and net nitrification occurred at levels above 20 kg N/ha/yr.

Nitrogen deposition to the alpine tundra of Niwot Ridge provided the potential for replacement of some plant species by more competitive, faster-growing species (Bowman and Steltzer 1998, Baron et al. 2000, Bowman 2000). Many plants that grow in low resource environments have some similar characteristics, including slow growth rate and low stature, photosynthetic rate, capacity for nutrient uptake, and soil microbial activity (Bowman and Steltzer 1998, Bowman 2000). Such plants generally continue to grow slowly when provided with an optimal supply and balance of resources (Pearcy et al. 1987, Chapin 1991). In addition, plants adapted to cold, moist environments grow more leaves than roots as the relative availability of N increases. These patterns of vegetative development and their response to added N affect plant capacity to respond to variation in available resources and to environmental stresses such as frost, high winds, and drought.

Changes in alpine plant species composition on Niwot Ridge have included increased cover of the plant species that tend to be most responsive to N fertilization in some of the long-term monitoring plots (Korb and Ranker 2001, Fenn et al. 2003). These changes have probably developed in response to changes in N availability. However, the influences of other drivers, such as changes in precipitation (Williams et al. 1996) or pocket gopher disturbance (Sherrod and Seastedt 2001) could not be ruled out as contributors to vegetation change (Fenn et al. 2003). Other environmental factors can also affect the species make-up of alpine ecosystems, but long-term experimental fertilization plots demonstrated a clear response of alpine flora to N, including shifts toward graminoid plants that shade smaller forb species, and accompanying changes in soil N cycling (Bowman et al. 2006).

Bowman et al. (2012) added ammonium NO_3^- at rates of 5, 10, and 30 kg N/ha/yr to an alpine dry meadow plant community in ROMO. Three years after fertilization, they measured aboveground biomass, plant N concentration, and soil and soil solution chemistry. Plant species composition was measured annually. Plant species richness and diversity did not change in response to the N addition, but one species of sedge, *C. rupestris*, increased in cover from 34% to 125%. Based on the rate of

change in *C. rupestris* in the N treatment plots and the ambient control plots (receiving 4 kg N/ha/yr), and assuming that the change in sedge cover was attributable solely to N addition, Bowman et al. (2012) estimated the CL of nutrient N loading to protect plant community composition to be 3 kg N/ha/yr. Inorganic N in soil solution increased above ambient levels at input rates (experimental addition plus ambient loading) between 9 (resin bag measurements) and 14 (lysimeter measurements) kg N/ha/yr, suggesting N saturation at these levels of N loading. There was no indication of change after three years in soil pH or extractable base cations, suggesting that soil acidification had not occurred.

McDonnell et al. (2014) evaluated potential long-term impacts of N deposition and climate change on a subalpine plant community at Loch Vale, using the ForSAFE-VEG model. ForSAFE-VEG is a coupled biogeochemical, vegetation niche and plant competition model. The model had earlier been applied in a generalized fashion to the Rocky Mountain region (Porter et al. 2012, Sverdrup et al. 2012). Simulated changes in N deposition, temperature, and precipitation over the previous century caused pronounced changes in model projections of plant species cover. The model estimate of the CL of N deposition required to protect against a change in plant cover of 10% was between 1.9 and 3.5 kg N/ha/yr. Ambient N deposition is slightly higher than that, suggesting that the CL for protection against nutrient N enrichment has been exceeded at Loch Vale.

Data compiled by Pardo et al. (2011a) suggest that ambient N deposition may exceed the lower limit of the expected CLs to protect against nutrient enrichment effects in ROMO. These potential exceedances were reported for the protection of lichens, herbaceous plants, and forest vegetation, and to limit NO_3^- leaching in drainage waters.

Ellis et al. (2013) estimated the CL for N deposition to protect the most sensitive ecosystem receptors in 45 national parks. The lowest terrestrial CL of N is generally estimated for protection of lichens (Geiser et al. 2010). Changes to lichen communities may signal the beginning of other changes to the ecosystem that might affect structure and function (Pardo et al. 2011c). Ellis et al. (2013) estimated the N CL for ROMO in the range of 2.5-7.1 kg N/ha/yr for protection of lichens.

Rocky Mountain National Park Initiative

Documented and potential future impacts from atmospheric N deposition on sensitive aquatic and terrestrial resources in ROMO led to the formation of the Rocky Mountain National Park Initiative, a collaborative process involving the NPS, the U.S. EPA, and the Colorado Department of Public Health and Environment. Through this initiative process, a CL target of N deposition has been developed in order to protect aquatic resources in the park against eutrophication (Porter and Johnson 2007). The NPS established a wet N deposition CL of 1.5 kg N/ha/yr for protecting high-elevation lakes in ROMO against biological effects associated with nutrient enrichment. The agency also entered into a Memorandum of Understanding with the EPA and the Colorado Department of Public Health and Environment to address harmful impacts of N deposition in this park (Cheatham 2011). The Memorandum of Understanding was intended to facilitate interagency cooperation in reversing N CL exceedance in ROMO. The Nitrogen Deposition Reduction Plan was endorsed by the three participating agencies and the Colorado Air Quality Control Commission (<http://www.colorado.gov/cdphe/rmnpinitiative>). The NPS adopted and the Memorandum of

Understanding agencies endorsed a CL of wet N deposition of 1.5 kg N/ha/yr at the Loch Vale deposition monitoring site. In order to achieve this resource management goal, a glidepath approach was selected, as described by Morris et al. (2014). The baseline wet N deposition for the period 2002-2006 was 3.1 kg N/ha/yr. Although some progress has been made, the target five-year rolling average value for 2012 of 2.7 kg N/ha/yr was not met; the measured five-year rolling average in 2012 was slightly higher (2.9 kg N/ha/yr; (Morris et al. 2014).

Nanus et al. (2012) calculated regional estimates of nutrient N deposition for the Rocky Mountains using a geostatistical approach. They established the response of sensitive diatom species to variation in surface water NO_3^- concentration and identified a threshold NO_3^- concentration above which ecological effects were observed. Response of the diatom *A. formosa* to changes in NO_3^- concentration during nutrient addition experiments was determined. Nanus et al. (2012) found that surface water NO_3^- concentration was positively correlated with north-facing aspect, elevation, slope, and N deposition. Growth experiments using *A. formosa* showed maximum algal growth at 0.5 μM NO_3^- , and this level was specified as the threshold for algal growth, which was used to determine nutrient CLs. The lowest estimated CL levels (< 1.5 kg N/ha/yr) occurred at high elevation locations having steep slope, sparse vegetation, abundant exposed rock, and talus. Such areas were commonly in exceedance of the CL by more than 1.5 kg N/ha/yr. Atmospheric N deposition exceeded the CL in $21 \pm 8\%$ of the Rocky Mountain study area; this estimate was sensitive to selection of the NO_3^- threshold of ecological effects (Nanus et al. 2012).

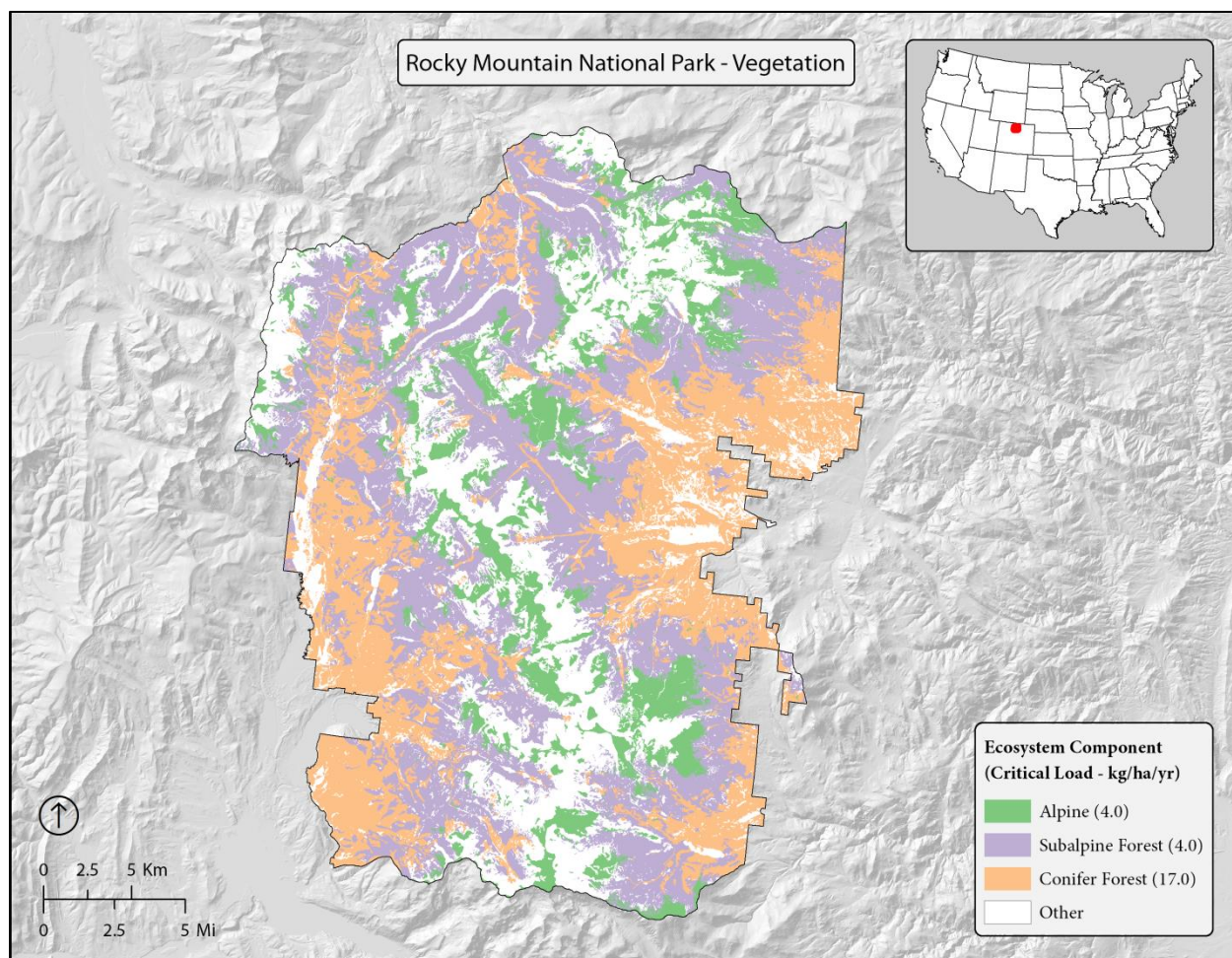
Locations in ROMO that have vegetation types characterized by plant communities expected to be most sensitive to N deposition, based on nutrient CL values compiled by Bowman et al. (2011) are shown in Map 31. The most sensitive vascular plant communities were alpine meadows (4-10 kg N/ha/yr) and subalpine forest (4 kg N/ha/yr). The former CL was specified to protect plant species composition; the latter was specified to protect against changes in N cycling, including increase in foliar N and N leaching. Mixed conifer forests had an identified CL of 17 kg N/ha/yr to protect against N leaching. These sensitive vegetation types cover much of the park.

Deposition

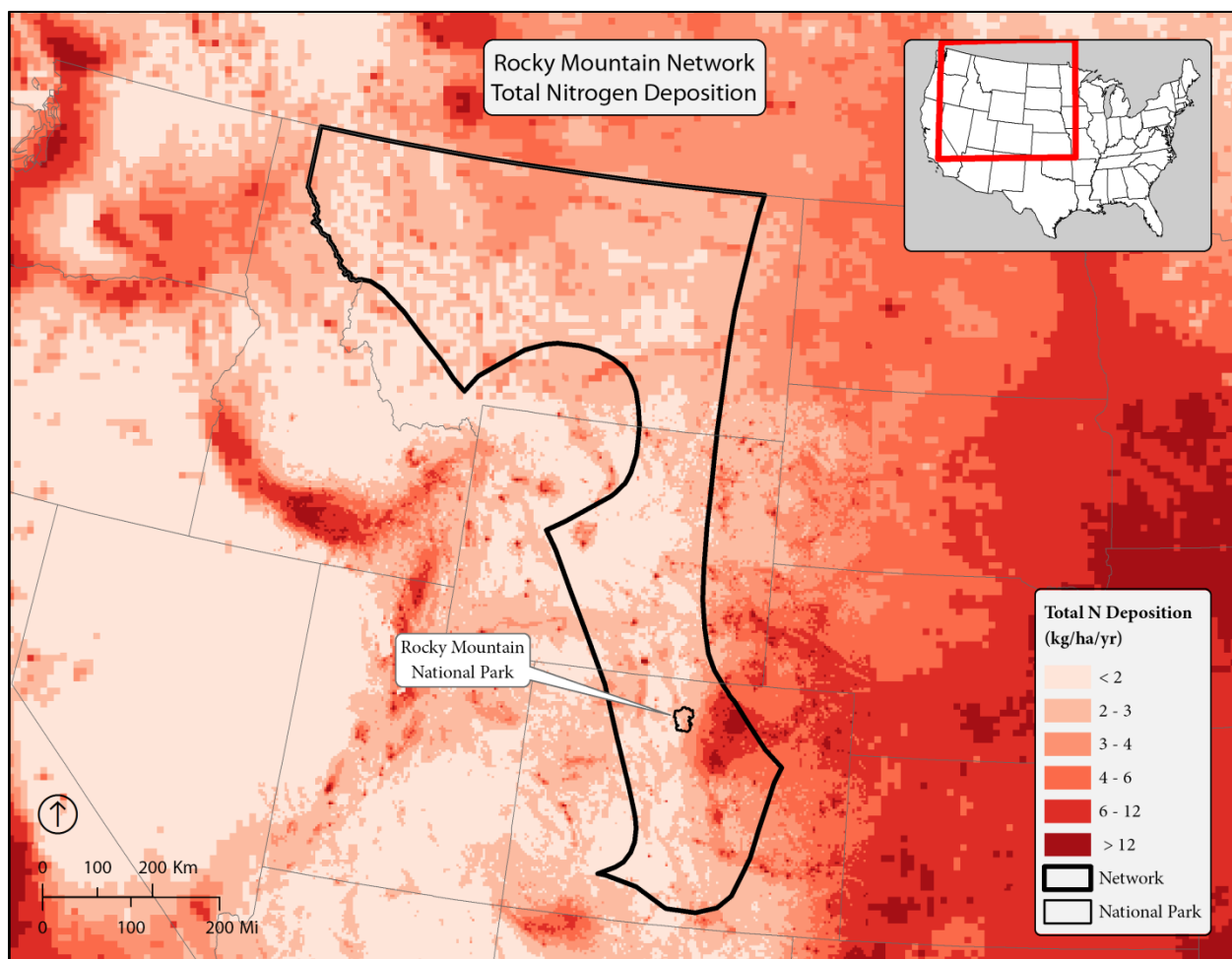
Model estimates of total wet plus dry N deposition, generated with the CAMx model for 2011, are shown in Map 32. Modeled N deposition in ROMO was generally below 3 kg N/ha/yr, lower to the west of the park and higher to the east.

Exceedance

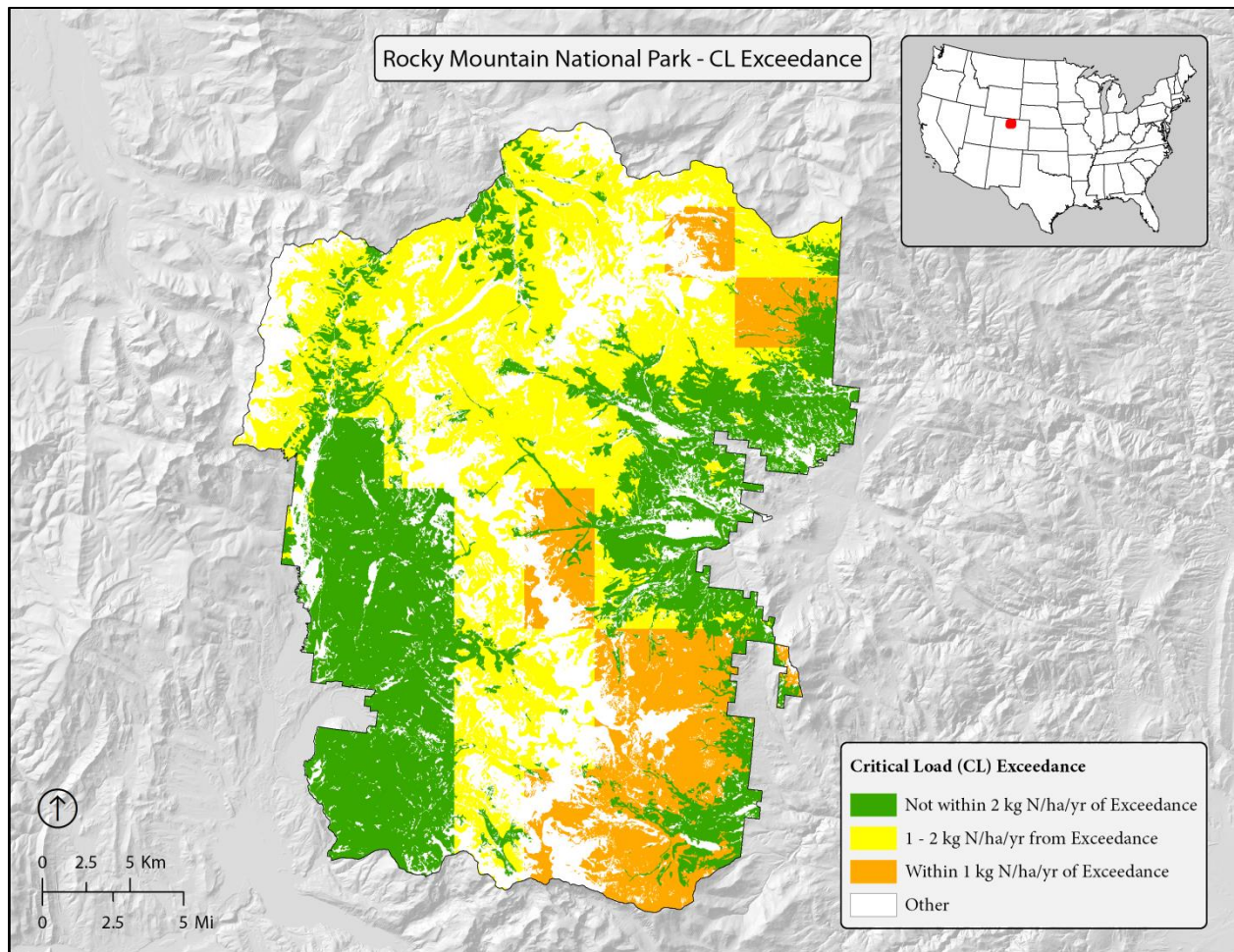
None of the sensitive vegetation types in ROMO were found to be in exceedance of the nutrient N CLs (Map 33), although much of the southeastern portion of the park was within 1 kg N/ha/yr of exceedance. The majority of the park was within 2 kg N/ha/yr of exceedance.



Map 31. Locations in Rocky Mountain National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Bowman et al. (2011).



Map 32. CAMx model estimates of total wet plus dry N deposition (kg/ha/yr) for the year 2011 throughout the Rocky Mountain Network.



Map 33. Locations of vegetation types in Rocky Mountain National Park that exhibit CL exceedance due to N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Allen and Geiser (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas showing the background color do not contain vegetation types identified by Allen and Geiser (2011) as being highly sensitive to N enrichment.

Great Plains Ecoregion

Northern Great Plains Network

Dose-Response and Critical Loads

Research studies conducted on the Great Plains (and further corroborated by studies in Europe) have shown that excess N can alter grassland biodiversity, promote growth of non-native grasses, enhance insect infestation, and promote loss of grassland ecosystems at landscape scales by favoring encroachment of trees and shrubs. Many of these studies were considered in the review of Pardo et al. (2011b). Much of the work on nutrient enrichment effects of N deposition on grasslands has been conducted in Europe. Nitrophilous plant species have been shown to have increased in abundance, and N- sensitive species to have declined in European grasslands over approximately the last half of the 20th century (Bobbink et al. 1998). It is believed that these changes were caused, at least in part, by atmospheric N deposition. Recent data were compiled for the review of Pardo et al. (2011a) and

are summarized below. The clearest evidence that atmospheric N deposition over a large region has actually impacted terrestrial biodiversity was provided by Stevens et al. (2004), who reported results of 68 plot (4 m²) surveys across a range of atmospheric N deposition from 5 to 35 kg N/ha/yr. Species richness in grasslands was found to decline as a linear function of N deposition, with a reduction on average of one plant species for every 2.5 kg N/ha/yr of N input.

N enrichment can alter the species composition and biodiversity in grassland communities in the Great Plains. Grasslands in the northern Great Plains are mainly N-limited or co-limited by N, P and/or water. Many grassland species respond rapidly to changing environmental conditions (Vitousek and Howarth 1991, Hooper and Johnson 1999, Knapp and Smith 2001, Clark 2011). It is difficult to ascertain the likely effects of N addition to these ecosystems without also considering the effects of periodic disturbance (especially fire, drought, and herbivory; Seastedt and Knapp 1993, Knapp et al. 1998).

Many studies of the effects of N enrichment on grasslands of the Great Plains have involved experimental addition of very high amounts of N (> 30 kg N/ha/yr; Clark 2011). Some experiments included lower levels of N addition to grassland ecosystems, mainly in Minnesota. For example, Tilman (1987) added N to four sites in Minnesota at levels ranging from 10 to 270 kg N/ha/yr. At the lower rates of experimental N addition (10 to 20 kg N/ha/yr) to two old fields, much of the added N was retained in the soil after 22 years of treatment (Wedin and Tilman 1996). Nevertheless, the N retention efficiency decreased, soil extractable NO₃⁻ increased, and plant species composition shifted over time in response to N addition (Clark and Tilman 2008, Clark et al. 2009).

Reduced species richness and biodiversity in response to N addition are of concern for grassland communities, in large part because of the potential interactions among diversity and ecosystem processes and functioning. It is more likely that a species-poor plant community may exhibit compromised ecosystem functioning as compared with a species-rich community. There are also interactions with the availability of other resources. For example, shortgrass prairie is considered to be less sensitive to N addition than tallgrass prairie because the former is more likely to experience water limitation (Lauenroth et al. 1978, Hooper and Johnson 1999, Clark 2011).

In tallgrass prairie, C₃ grasses such as *Elymus virginicus* and *E. canadensis* showed a greater positive growth response to N additions than C₄ grasses (*Andropogon gerardii*, *Schizachyrium scoparium*) and forbs (*Solidago nemoralis*, *S. rigida*; Lane and BassiriRad 2002). Species with smaller initial biomass exhibited the greatest increase in biomass, with a sevenfold to eightfold increase in *S. nemoralis* and *E. canadensis* and only a threefold increase in *S. rigida* (Lane and BassiriRad 2002). In experiments where N fertilization to simulate increased N deposition was applied to common ragweed (*Ambrosia artemisiifolia*), simulated N deposition led to increased vegetative and seed biomass and decreased root:shoot ratios (Throop 2005).

In another study, experimental N addition for 12 years to two Minnesota old fields at levels of 10 and 20 kg N/ha/yr decreased the abundance of four grasses by almost 20%, and increased the abundance of invasive Kentucky bluegrass (*Poa pratensis*) and quackgrass (*Agropyron repens*; Knops and Reinhart 2000). Losses of grass species and changes in species composition generally increased over

time with experimental N addition, especially at lower addition levels (Clark 2011). After 22 years of N addition at a level of 10 kg N/ha/yr, the number of species declined by 17% (Clark and Tilman 2008). Tilman (1993) hypothesized that species loss was caused mainly by increased litter mass, although light limitation from competing plants was also likely important (Hautier et al. 2009).

Experimental N addition at > 50 kg N/ha/yr to tallgrass prairie increased productivity and decreased species richness, probably as a consequence of reduced light penetration and increased litter biomass (Baer et al. 2003). Wedin and Tilman (1996) presented results of 12 years of experimental N addition to 162 grassland plots in Minnesota. N loading dramatically changed plant species composition, decreased species diversity, and increased aboveground productivity in their treatment plots. Species richness declined by more than 50% across the N-deposition gradient, with the greatest losses at levels of N input of 10 to 50 kg N/ha/yr. This loss of species diversity was accompanied by large changes in plant species composition, with C₄ grasses declining and the weedy Eurasian C₃ grass quackgrass becoming dominant at high N addition rates (Wedin and Tilman 1996). The authors concluded that N loading is a major threat to grassland ecosystems and causes loss of diversity, increased abundance of non-native species, and the disruption of ecosystem functioning. A major uncertainty, however, is the rate of N loading at which such changes may be manifested. There is relatively little information on the effects of low levels of N addition from the atmosphere to prairie ecosystem in NGPN.

Effects of N fertilization, in turn, can influence faunal populations. For example, fertilization in a Minnesota old-field at moderate rates (≤ 20 kg N/ha/yr) for 14 years resulted in decreased species diversity of insects in response to decreased diversity of plant food sources. Plant species richness decreased, and quackgrass and Kentucky bluegrass became dominant in response to the N addition (Haddad et al. 2000). Changes in the abundance of insect functional groups were also observed. Herbivores (especially the dominant species) increased in numbers; parasitoid insect species decreased. Over the long term, changes in plant species composition would be expected to either increase or decrease insect herbivore activity, depending on whether there is a shift toward or away from herbivore-preferred plant species (Throop et al. 2004, Clark 2011).

Increased availability of N to grasses can affect herbivores that feed on grasses by altering food quality, quantity, and phenology, and also perhaps by changing the relationships between herbivores and their predators (Throop and Lerdau 2004). Nitrogen fertilization at very high rates of 54 and 170 kg N/ha/yr (as NH₄NO₃) led to a decline in plant species composition in an oak savanna site (Avis et al. 2003). In the control plots, five species collectively accounted for more than 40% of the plant cover versus four plant species in the lower N addition plots. In the higher N addition plots, a single plant species accounted for more than 40% of the plant cover.

Experimental N addition for five years at a rate of 16.3 kg N/ha/yr to a mixed-grass prairie in Oklahoma caused an increase in soil NO₃⁻; leaching of N increased about 12-fold (Jorgensen et al. 2005, Clark 2011). Total plant biomass increased, and the cover of tall fescue (*Schedonorus phoenix*) increased twofold (Clark et al. 2003, Jorgensen et al. 2005). Shortgrass prairie is considered to be less sensitive to N addition than tallgrass prairie because the former is more likely to experience water limitation (Lauenroth et al. 1978, Hooper and Johnson 1999, Clark 2011).

Grasslands of the Great Plains have also experienced invasions of woody plant species (Kleb and Wilson 1997) that appear to be driven, at least in part, by N enrichment of soil (Tilman 1987). Fertilization may increase the water use efficiency of woody species (Bert et al. 1997), and enable them to colonize temperate grassland sites (Köchy and Wilson 2001). Accelerated rates of N cycling (Carreiro et al. 2000) may increase competition for light (Wilson and Tillman 1991) and give advantage to woody plants (Aerts et al. 1999, Köchy and Wilson 2001). High N deposition has been shown to be correlated with an increase of tall plant species in nutrient-poor European grasslands (Bobbink et al. 1998). Köchy and Wilson (2001) quantified forest invasion of aspen trees into grasslands in six national parks in western Canada that received a range of levels of atmospheric N deposition. The rate of aspen expansion was measured from aerial photographs taken over a period of six decades. Forests in high-deposition parks expanded 10 times faster than forests in low-deposition parks. The average forest expansion rate was 1% per year in high-deposition parks (Köchy and Wilson 2001).

Three parks within the Northern Great Plains Network were included in the I&M vegetation mapping effort to date: THRO, BADL, and WICA (Cogan et al. 1999, Von Loh et al. 1999, Von Loh et al. 2000). These are the parks assessed here. Grassland communities in these parks labeled by USGS and NPS as medium-tall were mapped for this study as having CL appropriate to tallgrass prairie as estimated by Clark (2011). This was done in order to err on the side of resource protection by assigning the lower CL range of tallgrass prairie (5-15 kg N/ha/yr) to these communities rather than the CL range of the less sensitive shortgrass or mixed-grass prairie (10-25 kg N/ha/yr).

Badlands National Park

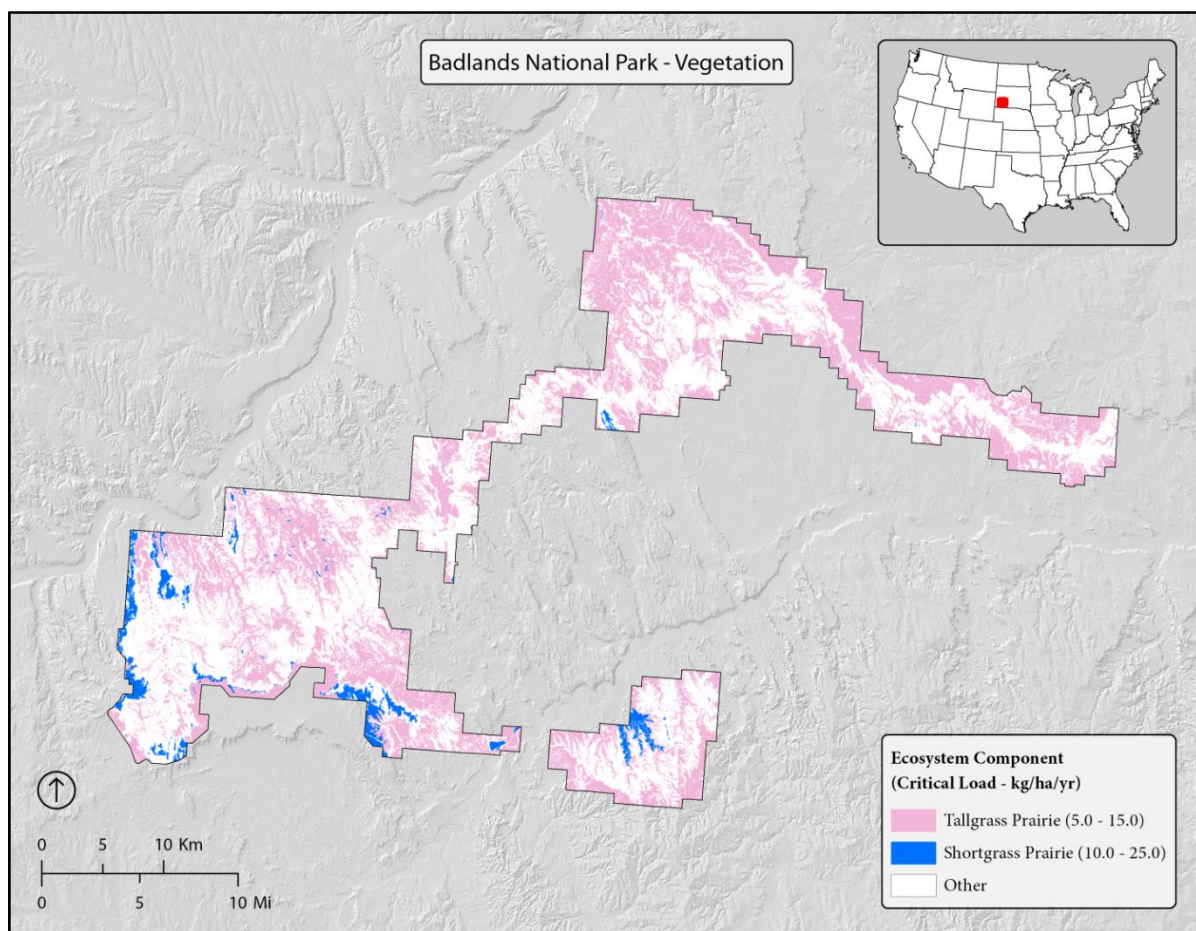
The dominant vegetation of BADL is a moderately dense short to medium tallgrass prairie, although this designation encompasses a variety of grassland communities (Cushman and Jones 1988, Froiland and Weedon 1990). These in-park prairies constitute important AQRVs that are sensitive to nutrient enrichment impacts from atmospheric N deposition. They are mainly dominated by western wheatgrass (*Agropyron smithii*), green needlegrass (*Stipa viridula*), blue grama, and needle-and-thread (*Stipa comata*). Associated species include fringed sage (*Artemisia frigida*), prairie junegrass (*Koeleria pyramidata*), little bluestem (*Andropogon scoparius*), silky wormwood (*Artemisia dracunculus*), purple coneflower (*Echinacea angustifolia*), and various other forbs. Blue grama and buffalo grass (*Bouteloua dactyloides*) form a mosaic of patches in combination with western wheatgrass and green needlegrass. The vegetation of BADL is an example of these highly valued mixed and tallgrass prairie ecosystems, which have largely been extirpated from their former ranges.

Von Loh et al. (1999) identified vegetation map units in BADL, based on aerial photographs. Data from 137 observation points, selected to sample the range of habitat and vegetation variability, were collected during field surveys to verify and refine the aerial interpretation. Of the 33 vegetation map units developed in BADL, we identified for the purposes of this report the following plant community types as belonging to prairie categories:

- Shortgrass prairie
 - blue grama grassland

- Tallgrass prairie
 - introduced grassland
 - little bluestem-grama grasses – threadleaf sedge (*Carex filigolia*) grassland
 - seeded mixed-grass prairie
 - switchgrass (*Panicum virgatum*) grassland
 - western wheatgrass grassland alliance
 - western wheatgrass – green needlegrass grassland

Portions of BADL covered by the tallgrass and shortgrass prairies listed above are shown in **Map 34**. These are the plant community types present in BADL that are expected to be most sensitive to N enrichment.



Map 34. Locations in Badlands National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Clark (2011).

Several of the map units classified here as tallgrass prairie likely contain a mix of short and tallgrass species (i.e., the two western wheatgrass units and the seeded mixed-grass prairie unit). These map units are classified as the more sensitive tallgrass prairie type. Thus, they are considered here to have

CL in the low range (5-15 kg N/ha/yr) reported by Clark (2011) in order to err on the side of resource protection.

Theodore Roosevelt National Park

Von Loh et al. (2000) identified seven vegetation map units in THRO that represent grassland types. Of those, the following can be classified as tallgrass prairie, or containing some elements of tallgrass prairie:

- introduced grassland
- little bluestem – sideoats grama (*Bouteloua curtipendula*) herbaceous alliance
- needle and thread herbaceous alliance
- prairie sandreed (*Calamovilfa longifolia*) herbaceous alliance
- seeded mixed-grass prairie
- western wheatgrass herbaceous alliance

Additionally, the following was classified as representing mixed-grass prairie:

- Prairie cordgrass (*Spartina pectinata*) temporarily flooded

Locations in THRO having plant community types expected to be most sensitive to N deposition are shown in Map 35. Tallgrass and shortgrass prairies have estimated N CLs of 5-15 and 10-25 kg N/ha/yr, respectively, based on analyses reported by Clark (2011).

Wind Cave National Park

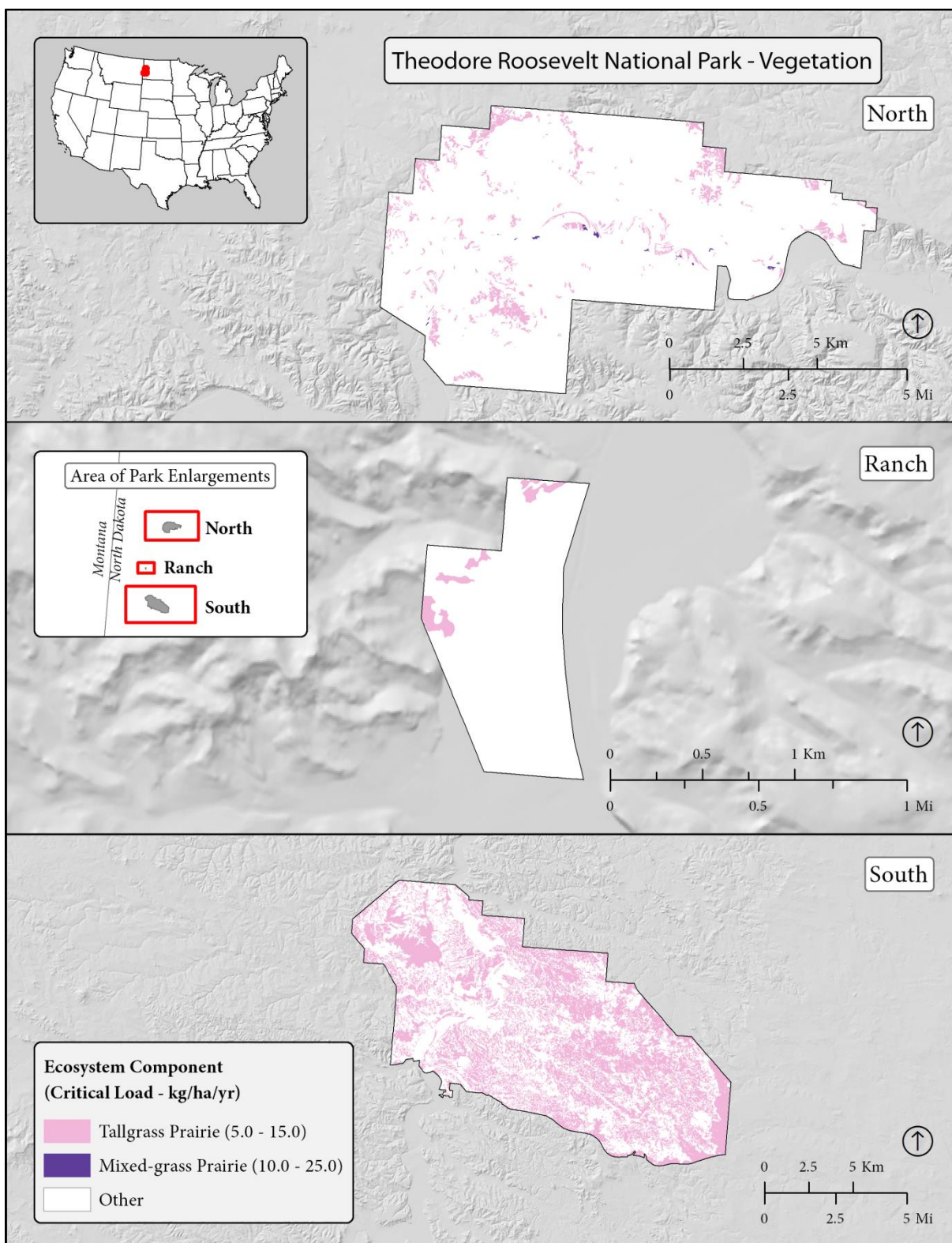
Cogan et al. (1999) identified vegetation map units in WICA, based on aerial photography. Field surveys were conducted at 134 observation points, selected to sample the range of habitat and vegetation variability in the park. The following vegetation map units in WICA were identified as tallgrass prairie or as containing elements of tallgrass prairie:

- little bluestem – grama grass herbaceous vegetation
- little bluestem sideoats grama herbaceous alliance (with burned ponderosa pine)
- needle and thread – blue grama-threadleaf sedge herbaceous vegetation
- western wheatgrass – Kentucky bluegrass complex
- western wheatgrass – Kentucky bluegrass complex (with burned ponderosa pine)

Additionally, the following were classified as representing short or mixed-grass prairie:

- introduced weedy graminoid herbaceous vegetation
- purple three-awn fetid marigold herbaceous vegetation

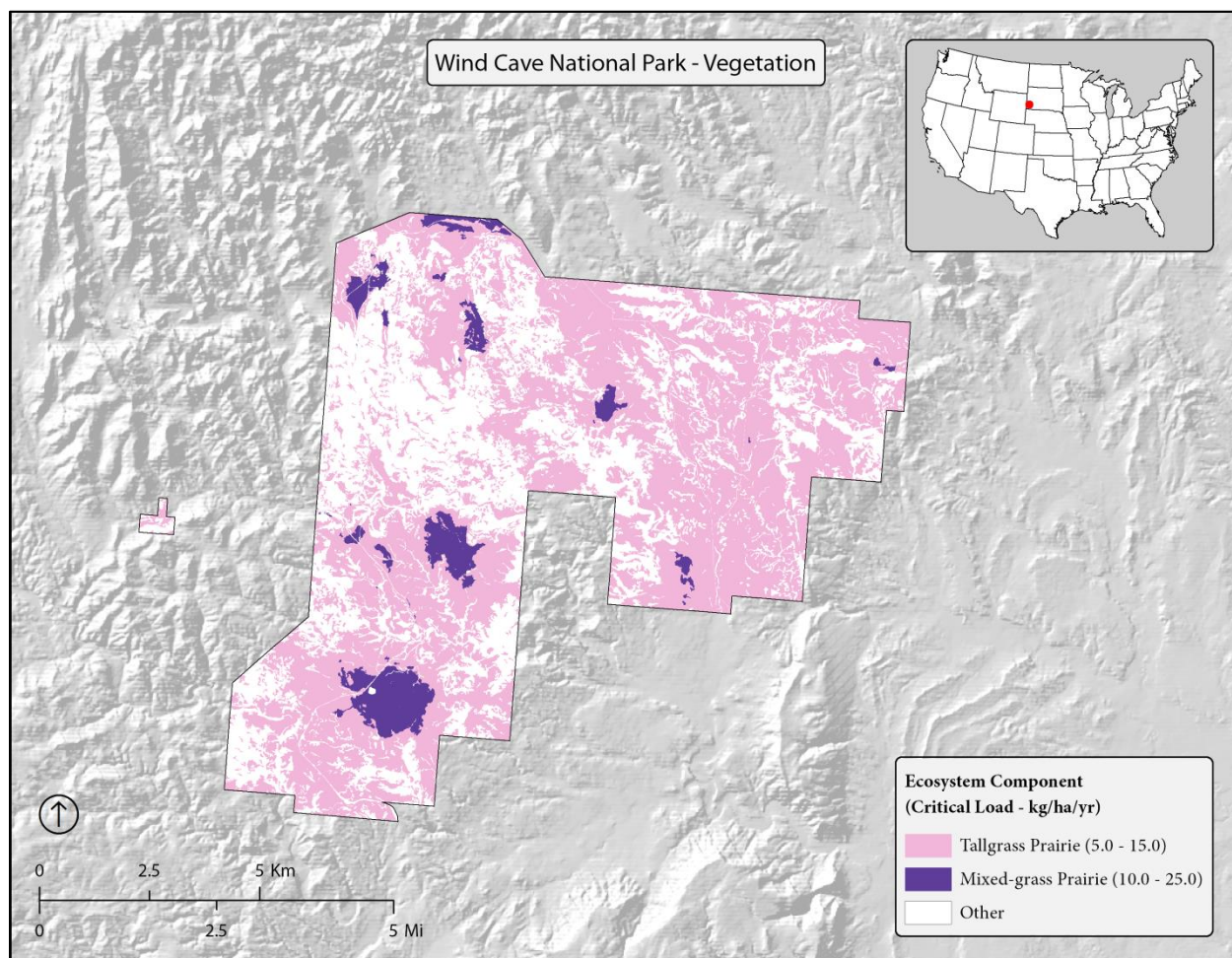
Locations in WICA having these plant community types expected to be most sensitive to N deposition are shown in Map 36. Tallgrass and shortgrass prairies in THRO have estimated nutrient critical N loads of 5-15 and 10-25 kg N/ha/yr, respectively, based on analyses reported by Clark (2011).



Map 35. Locations in Theodore Roosevelt National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Clark (2011).

Deposition

Total N deposition in the NGPN region varied from west to east, with levels generally below 4 kg N/ha/yr in the west to greater than 6 kg N/ha/yr throughout the eastern and southern portions of the network region. Deposition in the vicinity of the NGPN parks ranged between about 3 and 6 kg N/ha/yr based on CAMx estimates shown on Map 37.

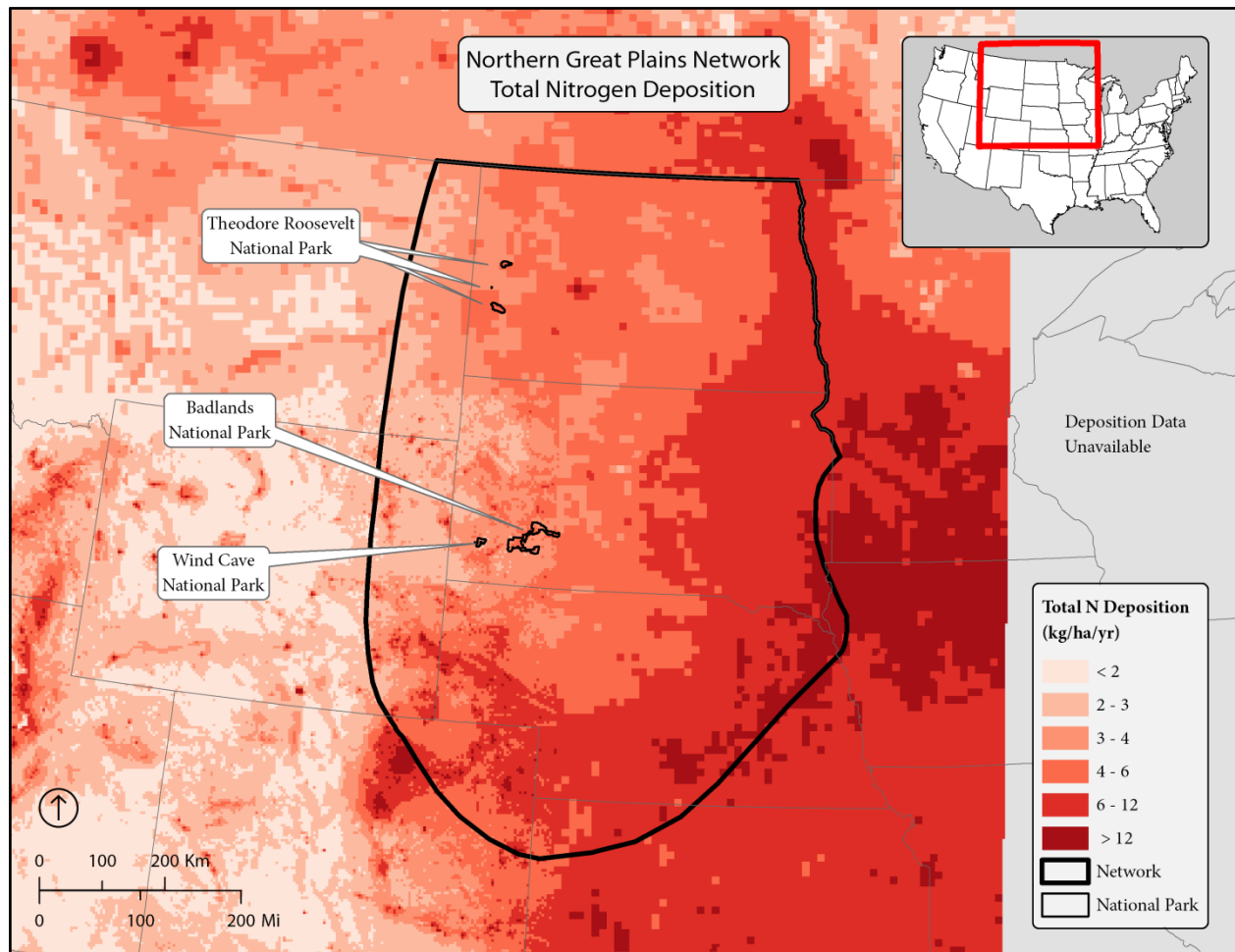


Map 36. Locations in Wind Cave National Park having vegetation types characterized by the presence of plant communities expected to be most sensitive to N deposition, based on nutrient critical load values compiled by Clark (2011).

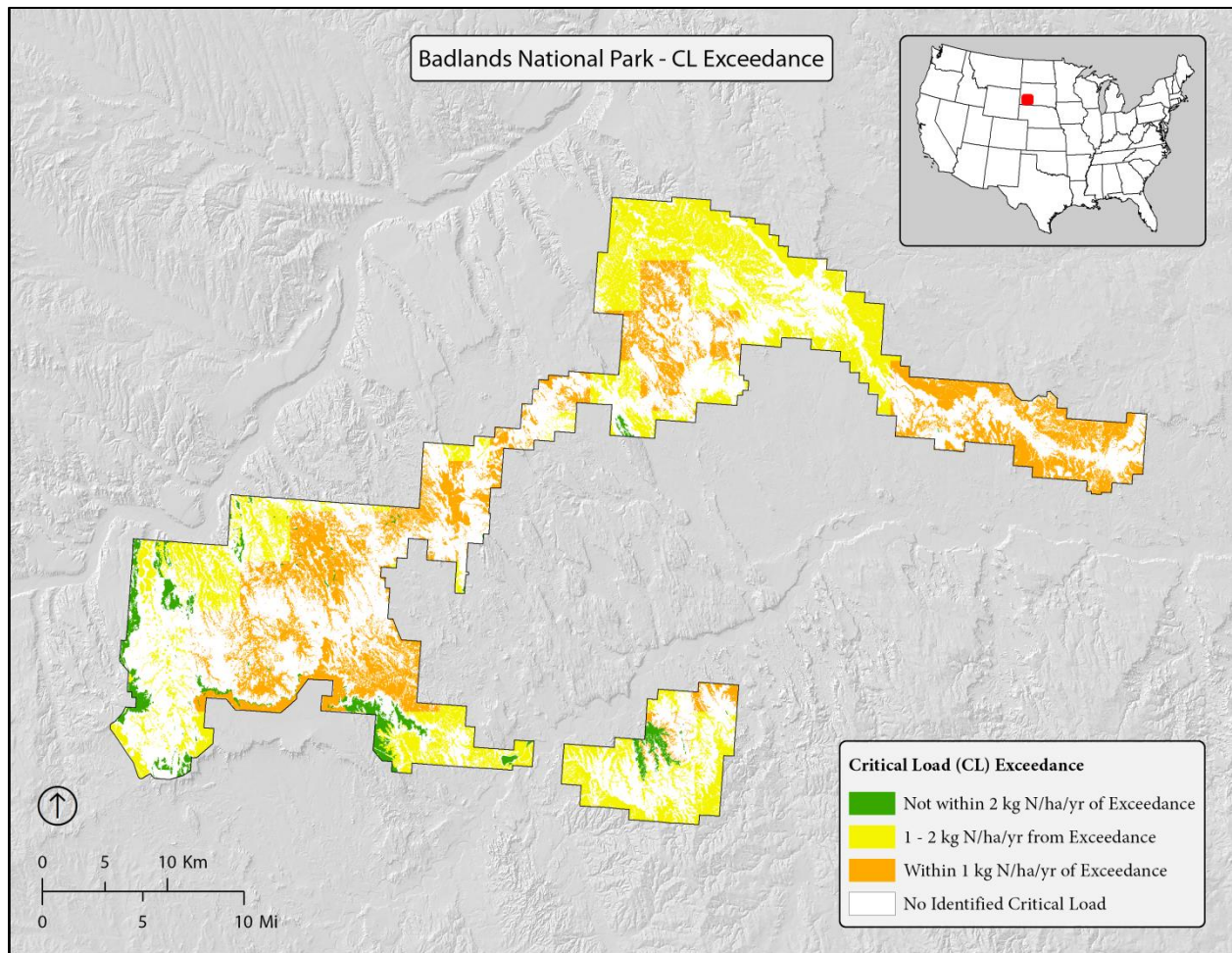
Exceedance

Based on CAMx modeling for 2011, none of the park lands in BADL or WICA are in exceedance (Maps 38 and 39). Only a very small portion of THRO is in exceedance (Map 40). Nevertheless, more than half of BADL, WICA, and much of the southern unit of THRO received ambient N deposition (in 2011) below, but within 1 kg N/ha/yr of, the lower CL estimate (5 kg N/ha/yr) compiled by Clark (2011). Thus, any appreciable increase in NO_x emissions from O&G exploration and production, or other sources, will increase the likelihood of exceedance and consequent

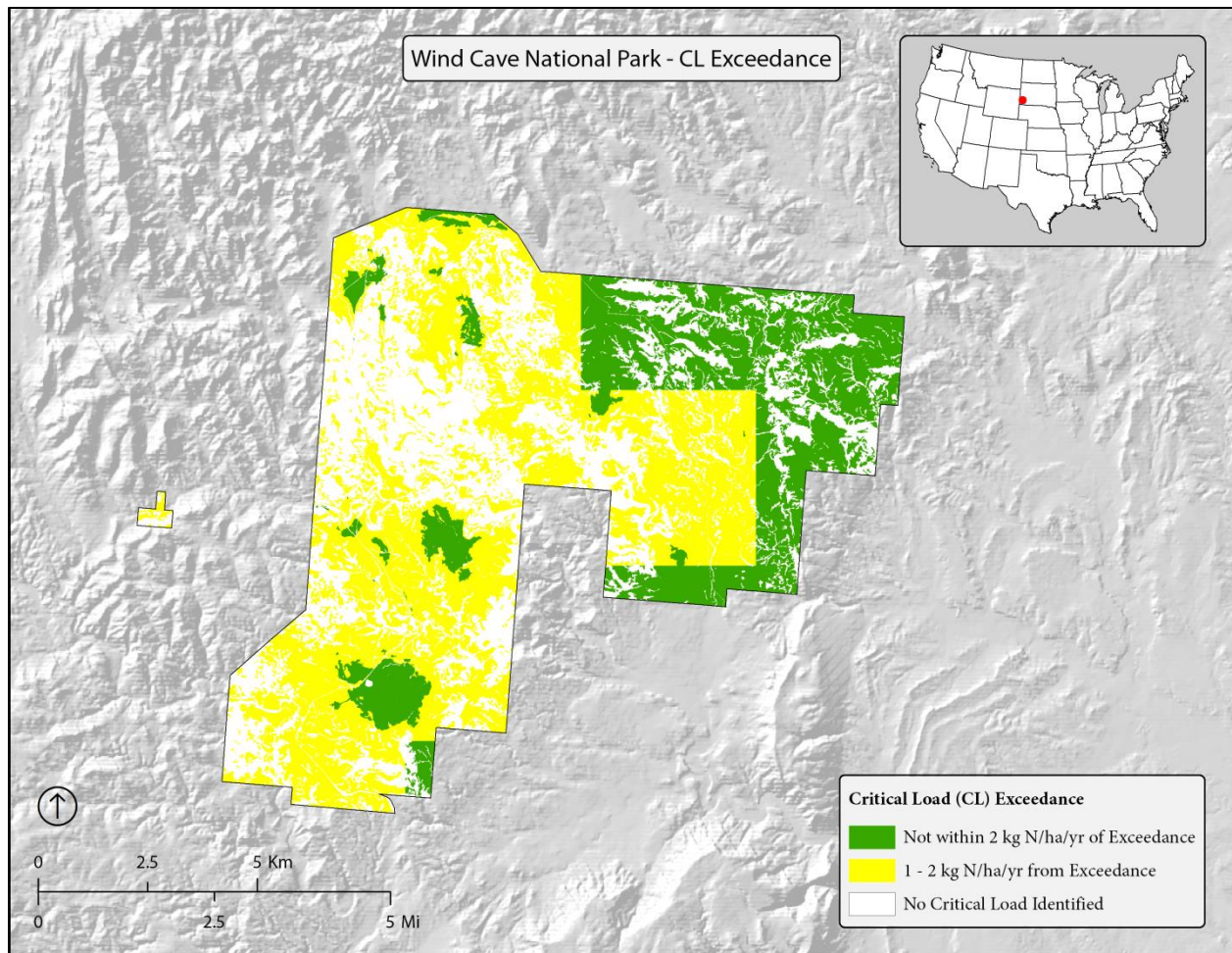
ecological changes associated with excess N supply. Substantial portions of BADL and the south unit of THRO are within 1 kg N/ha/yr of exceedance.



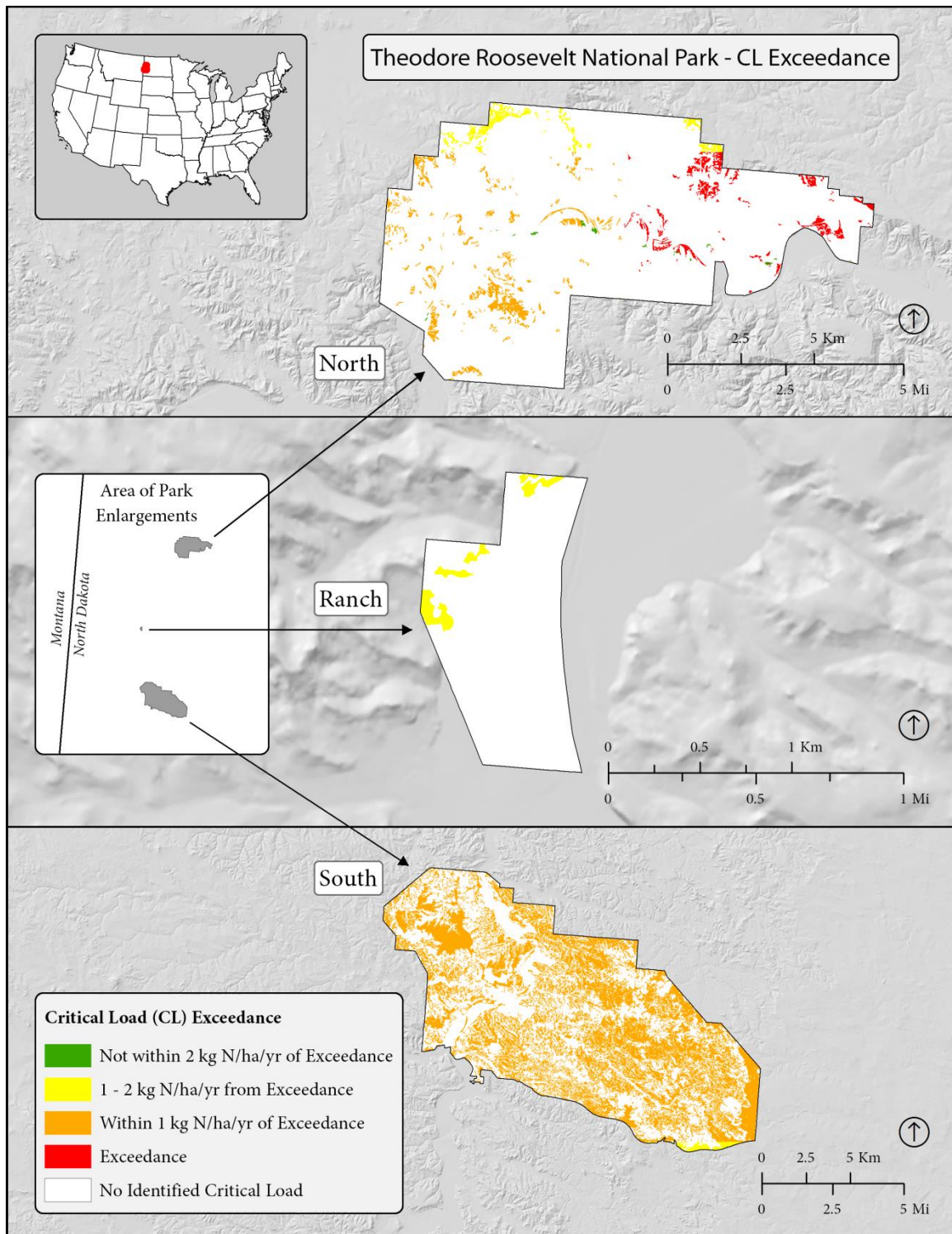
Map 37. CAMx model estimates of total wet plus dry N deposition (kg/ha/yr) for the year 2008 throughout the Northern Great Plains Network.



Map 38. Locations of vegetation types in Badlands National Park in exceedance or close to being in exceedance of the CL (5 kg N/ha/yr) to protect against N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Clark (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas in white do not contain vegetation types identified by Clark (2011) as being highly sensitive to N enrichment.



Map 39. Locations of vegetation types in Wind Cave National Park in exceedance or close to being in exceedance of the CL (5 kg N/ha/yr) to protect against N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Clark (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas in white do not contain vegetation types identified by Clark (2011) as being highly sensitive to N enrichment.



Map 40. Locations of vegetation types in Theodore Roosevelt National Park in exceedance or close to being in exceedance of the CL (5 kg N/ha/yr) to protect against N enrichment. The area of sensitive vegetation is labeled red if total N deposition in year 2011 is in exceedance of the lower limit of the critical load (CL) estimated by Clark (2011). The remaining areas of sensitive vegetation are classified according to the extent to which total N deposition is below the CL. Areas in white do not contain vegetation types identified by Clark (2011) as being highly sensitive to N enrichment.

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Appendix A. Source Apportionment

The CAMx model is able to estimate source contributions to downwind receptors by “tagging” emissions from specified sectors (e.g., oil and gas development, automobiles, power plants) and/or regions (e.g., individual counties), and following these tagged emissions as they are transported and chemically transformed in the atmosphere. This study used CAMx’s Particulate Source Apportionment Tool (PSAT) to estimate at 4 km resolution the contribution from emissions associated with oil and gas development to nitrogen deposition at national parks under study here. This was done because the oil and gas sector is considered to be an ongoing and potentially important threat that is poorly understood. The suite of nitrogen-containing compounds that are treated within PSAT include nitrogen oxides (NO_x), nitrate radical (NO_3), nitrous acid (HONO), dinitrogen pentoxide (N_2O_5), peroxy acetyl nitrate (PAN), organic nitrates (R-NO_3), nitric acid (HNO_3), ammonia (NH_3), and particulate ammonium (NH_4^+) and nitrate (NO_3^-). Both wet and dry deposition are included.

Nitrogen (oxidized and reduced) emissions source apportionment are represented in Tables A1 and A2, respectively, for the oil and gas emissions sector and for all emissions sectors. Source apportionment results for total (oxidized plus reduced) N are given in Table A3. In general, it was estimated that oil and gas emissions contributed only a relatively small fraction of the total N deposition at most of the national parks that are subjects of this analysis. The maximum oil and gas contribution (25% of oxidized N deposition) was estimated for parts of DINO, followed by parts of MEVE (24%) and HOVE (20%). Oil and gas accounted for more than 10% of average total N deposition only in these same three parks. These estimates should be considered preliminary and are based on an uncertain emissions inventory and uncertain modeling. In addition, emissions and the relative importance of oil and gas contributions to in-park deposition are changing over time.

The percent of the estimated average total N deposition in each study park derived from oil and gas emissions, modeled for 2011 using CAMx, is shown on Map A1. Parks having highest oil and gas contributions to N emissions were clustered in the central part of the study area, generally between DINO in the north and MEVE and HOVE in the south.

Table A1. Oxidized nitrogen emissions source apportionment.

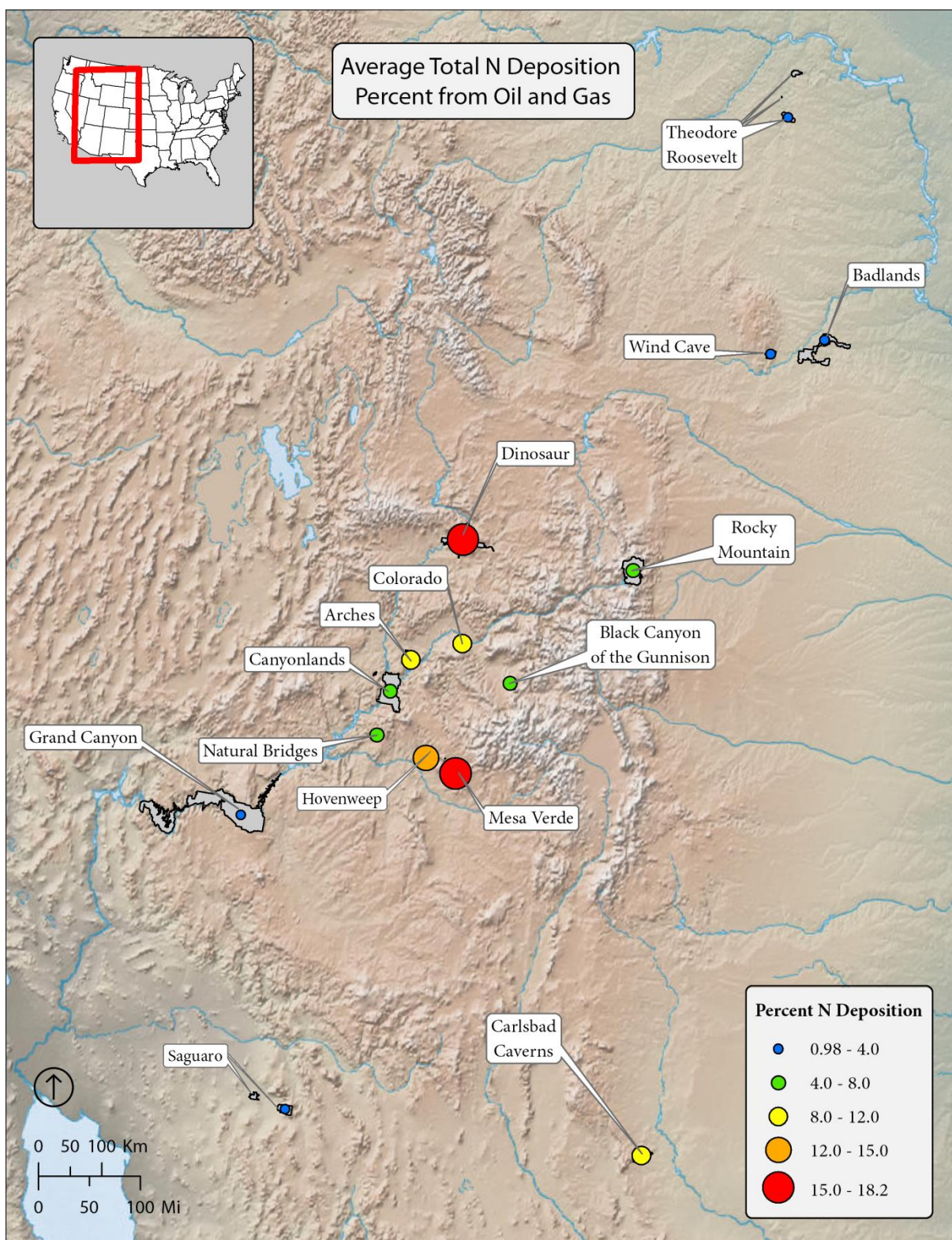
Park Code	Park Name	Maximum Oxidized N Deposition (kg N/ha/yr)			Average Oxidized N Deposition (kg N/ha/yr)		
		All Sources	O&G Sources Only	% from O&G Sources	All Sources	O&G Sources Only	% from O&G Sources
ARCH	Arches	1.50	0.18	12.03	1.37	0.16	11.39
BADL	Badlands	2.07	0.12	5.83	1.84	0.07	3.84
BLCA	Black Canyon of the Gunnison	1.57	0.19	12.04	1.35	0.15	11.36
CANY	Canyonlands	1.65	0.17	10.18	1.25	0.10	7.66
CAVE	Carlsbad Caverns	1.96	0.34	17.31	1.75	0.25	14.30
COLM	Colorado	1.78	0.23	13.08	1.58	0.19	12.29
DINO	Dinosaur	2.32	0.58	25.01	1.68	0.38	22.69
GRCA	Grand Canyon	2.17	0.06	2.63	1.39	0.02	1.45
HOVE	Hovenweep	2.13	0.43	20.15	1.80	0.34	18.76
MEVE	Mesa Verde	2.58	0.61	23.51	2.25	0.47	21.03
NABR	Natural Bridges	1.62	0.16	9.59	1.47	0.13	8.96
ROMO	Rocky Mountain	2.36	0.26	11.16	1.85	0.20	10.74
SAGU	Saguaro	2.91	0.04	1.41	2.37	0.03	1.40
THRO	Theodore Roosevelt	2.07	0.14	6.95	1.82	0.11	6.11
WICA	Wind Cave	2.23	0.13	5.81	1.82	0.10	5.45

Table A2. Reduced nitrogen emissions source apportionment.

Park Code	Park Name	Maximum Reduced N Deposition (kg N/ha/yr)			Average Reduced N Deposition (kg N/ha/yr)		
		All Sources	O&G Sources Only	% from O&G Sources	All Sources	O&G Sources Only	% from O&G Sources
ARCH	Arches	0.34	0.00	0.00	0.29	0.00	0.00
BADL	Badlands	3.30	0.00	0.04	2.12	0.00	0.00
BLCA	Black Canyon of the Gunnison	1.81	0.00	0.00	1.03	0.00	0.00
CANY	Canyonlands	0.40	0.00	0.00	0.28	0.00	0.00
CAVE	Carlsbad Caverns	1.21	0.00	0.00	0.85	0.00	0.00
COLM	Colorado	0.65	0.00	0.00	0.51	0.00	0.00
DINO	Dinosaur	1.26	0.00	0.00	0.41	0.00	0.00
GRCA	Grand Canyon	1.62	0.00	0.01	0.48	0.00	0.00
HOVE	Hovenweep	1.06	0.00	0.00	0.46	0.00	0.00
MEVE	Mesa Verde	0.64	0.00	0.00	0.54	0.00	0.00
NABR	Natural Bridges	0.30	0.00	0.00	0.29	0.00	0.00
ROMO	Rocky Mountain	0.90	0.00	0.00	0.71	0.00	0.00
SAGU	Saguaro	1.33	0.00	0.07	1.02	0.00	0.00
THRO	Theodore Roosevelt	3.04	0.00	0.00	2.54	0.00	0.00
WICA	Wind Cave	1.74	0.00	0.00	1.45	0.00	0.00

Table A3. Total nitrogen emissions source apportionment.

Park Code	Park Name	Maximum Total N Deposition (kg N/ha/yr)			Average Total N Deposition (kg N/ha/yr)		
		All Sources	O&G Sources Only	% from O&G Sources	All Sources	O&G Sources Only	% from O&G Sources
ARCH	Arches	1.82	0.18	9.88	1.66	0.16	9.37
BADL	Badlands	4.89	0.12	2.50	3.96	0.07	1.79
BLCA	Black Canyon of the Gunnison	2.88	0.19	6.57	2.38	0.15	6.46
CANY	Canyonlands	2.04	0.17	8.23	1.52	0.10	6.27
CAVE	Carlsbad Caverns	2.84	0.33	11.75	2.60	0.25	9.43
COLM	Colorado	2.42	0.23	9.61	2.08	0.19	9.31
DINO	Dinosaur	2.98	0.58	19.52	2.09	0.38	18.22
GRCA	Grand Canyon	3.75	0.06	1.52	1.87	0.02	1.08
HOVE	Hovenweep	3.10	0.43	13.84	2.25	0.34	14.95
MEVE	Mesa Verde	3.14	0.61	19.31	2.80	0.47	16.94
NABR	Natural Bridges	1.92	0.16	8.10	1.76	0.13	7.50
ROMO	Rocky Mountain	3.24	0.26	8.14	2.56	0.20	7.76
SAGU	Saguaro	4.15	0.04	1.01	3.39	0.03	0.98
THRO	Theodore Roosevelt	5.12	0.13	2.59	4.35	0.11	2.45
WICA	Wind Cave	3.85	0.13	3.37	3.27	0.10	3.04



Map A1. Percent of the estimated average total N deposition in each study park derived from oil and gas sources.

Oil and gas shale basins are widely distributed across many parts of the United States. One region where such shale formations predominate runs in the intermountain West from the Canadian border north of THRO to the desert southwest in and around CANY (National Parks Conservation Association [NPCA] 2013). Many thousands of new wells have been installed in some basins, most since about 2008, and relatively recent estimates suggested that the installation rate might continue to increase (<http://cogcc.state.co.us/Home/gismain.cfm>; NPCA 2013). The NPCA (2013) reported an increase in the number of active wells in the vicinity of THRO from about 1,000 in 2008 to over 6,000 in 2012 (North Dakota Industrial Commission 2012; <http://www.dmr.nd.gov/oilgas/maps/2012>). The Uintah Basin of Utah, including the area adjacent to DINO, is another center of recent O&G development with thousands of wells (<http://gis.utah.gov/data/energy/oil-gas/>). Between December, 2008 and December, 2015, the number of producing wells in North Dakota increased from 4,271 to 13,119 (<https://www.dmr.nd.gov/oilgas/stats/statisticsvw.asp>).

Emissions of NO_x from an individual well, CAFO, or industrial source may be insignificant to the broader landscape. However, the cumulative effects of many sources may be substantial. Because the number of O&G sources has increased rapidly in these key regions, additional data with which to assess the magnitude of effects on N deposition, ozone (O₃) formation, or other air or water pollution issues is necessary. There is an accelerating need to compile and evaluate data on emissions, deposition, and effects.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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