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Risk to Epiphytic Lichen Communities in NPS Units from Atmospheric Nitrogen and Sulfur Pollution

Changes in Critical Load Exceedances from 2001–2016

Natural Resource Report NPS/NRSS/ARD/NRR—2021/2299



ON THE COVER
Epiphytic lichen growing on a tree trunk at North Cascades National Park
Kelly McCoy / NPS Photo

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Natural Resource Report NPS/NRSS/ARD/NRR—2021/2299

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Executive Summary

Human caused nitrogen (N) and sulfur (S) pollutants travel from their sources (power plants, oil & gas developments, mobile emissions, and agriculture) to national park lands and cause harm to ecosystems through fertilization and acidification. Scientists have developed critical loads of N and S deposition to communicate the levels of pollution that prevent ecosystem harm. One of the ecosystem components most sensitive to air pollution are epiphytic lichen communities. Geiser et al. (2019) developed a dose-response relationship between deposition of N and S and four metrics of epiphytic lichen species communities: total species richness, N/S sensitive species richness, forage lichens abundance, and cyanolichens abundance. From each relationship they established a critical load at a 20% loss in richness. Here the critical loads are compared to current deposition to identify areas at risk of community decline. To accomplish this, we extrapolated the dose-response relationships and applied critical loads to forested areas within national park units to assess risk from current deposition levels as well as changes in conditions from 2000–2017. Within this analysis forested areas were chosen as a proxy for the presence of epiphytic lichen communities as tree trunks, branches, and boles are the most common surface for them to grow.

The National Park Service (NPS) protects 423 units across the United States, preserving natural and cultural resources. At the time of this analysis, there are 280 Inventory and Monitoring Parks with significant natural resources and 169 of these areas have forested areas greater than 1 km within the contiguous United States (CONUS). Of these 168 have modeled deposition to assess risk to lichen communities.

Generally, the risk to lichen communities from both N and S deposition declined across national parks between 2000–2002 (2001) and 2015–2017 (2016). The average difference in N deposition within national parks was a reduction of 2.9 kg-N ha^{-1} yr^{-1} of deposition. The average difference in S deposition within national parks was a decrease of 5.8 kg-S ha^{-1} yr^{-1}.

The rate of species richness loss attributed to N deposition decreased for 88% of national parks between 2001 and 2016, and yet in 2016 89% of CONUS I&M National Park Service units (149 national parks) remained above the critical load of N for a decline in species richness (CLN-SR) of 3.5 kg-N ha^{-1} yr^{-1}. The total forested area in the 168 parks that was in exceedance of the CLN-SR decreased from 2001 to 2016, indicating that the health of forests is improving. There was an increase of two NPS units that had any forested area below the CLN-SR (with improving conditions at Chaco Culture National Historical Park, Curecanti National Recreation Area, and Black Canyon of the Gunnison National Park, and deteriorating conditions at Nez Perce National Historical Park). As of 2016, 95 parks are predicted to have 100% of the forested area in exceedance of the CLN-SR.

Sulfur deposition decreased more dramatically between 2001 and 2016 than did nitrogen deposition, which is demonstrated by the large number of parks and total forested area trending below the critical load of S for a decline in species richness (CLS-SR) of 6.0 kg-S ha^{-1} yr^{-1}. Risk to lichen species richness from S deposition decreased in 98% of CONUS I&M National Park Service units between 2001 and 2016. By 2016, there are only 6 parks that were predicted to exceed the CLS-SR and only 9

parks that had any forested area that was at or above the CLS-SR. However, all of these parks have experienced improving conditions since 2001 in regard to S deposition.

The geospatial response of epiphytic lichen species richness loss and risk to forested ecosystems from N deposition against acid deposition was evaluated for 10 case study national parks: Acadia National Park, Glacier National Park, Grand Teton National Park, Great Smoky Mountains National Park, Joshua Tree National Park, North Cascades National Park, Rocky Mountain National Park, Sleeping Bear Dunes National Lakeshore, Theodore Roosevelt National Park, and Yosemite National Park. The national parks were chosen to represent a snapshot of different regions and forested ecosystems in the United States. They demonstrate the spatial variability of changes in N and S deposition between 2001 and 2016.

Several parks, such as Great Smoky Mountains National Park, experienced highly improved conditions caused by a decrease N and/or S deposition levels. Other parks, such as Theodore Roosevelt National Park, saw increases in N deposition from 2001 to 2016. No parks experienced degrading conditions from S deposition between 2001 and 2016. The percentage of forested area in exceedance of the CLN-SR ranged from <1% to 100% in 2001. There was no forested area in any of the 10 park case studies that exceeded the CLS-SR in 2016.

NPS units where deposition has decreased to the level where critical loads of lichen species richness are no longer exceeded should consider establishing field surveys to understand potential recovery. Studies in Europe have found a slow rate of return of lichen to an area after extirpation from atmospheric pollution, so understanding if or when lichen return can help highlight the importance of reducing deposition before harm occurs.

List of Terms

Lichen descriptions and ecological roles are taken from Geiser et al. (2019).

cyano-lichens (large): Primary nitrogen-fixing epiphytes achieving high biomass in moist, temperate, old-growth forests, contributing significant amounts of new nitrogen to the forest floor. Nutrient-rich food for mollusks and other invertebrates; habitat and cover for invertebrates.

cyano-lichens (small to medium): Nitrogen-fixing lichens, but typically low biomass, due to the small size and low abundance. Habitat and nutrient rich food for invertebrates.

forage lichens (pendant): Critical winter forage for ungulates in areas with deep snow; primary winter forage for flying squirrels, voles, other rodents. Nesting materials for rodents and birds. Habitat and food for invertebrates.

forage lichens (shrubby): Winter forage for flying squirrels, voles, other rodents. Nesting materials for birds. Habitat and food for invertebrates.

matrix lichens (medium to large): Nesting materials for birds; habitat, cover and food for invertebrates.

matrix lichens (small): Exposed habitat and food for invertebrates

N/S sensitive lichens: Species were considered sensitive if the sensitivity rating (deposition at peak detection frequency) was <4.2 kg-N or <2.7 kg-S ha^{-1} y^{-1}. These cut-offs correspond to minimum deposition levels for the East; a practical decision that allowed eastern 'decreasers' to be rated sensitive, while minimizing the inclusion of intermediately tolerant species from the west with 'hump-shaped' responses to deposition.

Introduction

Atmospheric nitrogen (N) and sulfur (S) are emitted from both natural (wildfire, lightning) and human sources (industry, energy production, and agriculture). In normal quantities, these nutrients help balance soil and water chemistry, but when human-caused emissions overload an area, they can cause fertilizing (N) and acidifying (N+S) effects that harm the ecosystem function (Pardo et al, 2011). The level of deposition below which harmful effects do not occur is called a critical load (Nilsson and Grennfelt 1988). Critical loads are used by policy makers and land managers to communicate the risk to natural ecosystems based on current levels of pollution (Porter et al. 2005).

Within terrestrial systems many critical loads for N and S have been defined. N often causes a fertilization effect by increasing N in the soil, which leads to positive growth responses by vegetation; e.g. increased alpine sedge growth (Bowman et al. 2012), increased tree growth and survival (Horn et al. 2018), and increased herbaceous plant growth (Clark et al. 2019). Alternatively, some species have evolved to thrive in low nutrient conditions, so the increase in N leads to a decline in health, like with soil mycorrhiza and epiphytic lichens (Pardo et al. 2011, Geiser et al. 2019). Sulfur deposition, as well as deposition of nitric acid compounds, causes an acidifying effect to the soils, leading to a decrease in ecosystem health; e.g. decrease in tree growth and survival (Horn et al, 2018), decreased herbaceous plant abundance (Clark et al. 2019), and a decrease in epiphytic lichen species richness (Geiser et al. 2019).

Epiphytic macrolichens are a diverse category of lichens that grow on tree trunks, branches, and boles. Since these lichens grow above the ground, they get all their nutrients directly from precipitation and the air. Therefore, many epiphytic lichen species have narrow environmental niches and are extremely sensitive to changes in air pollution (Conti and Cecchetti 2001). Changes in lichen community composition with decreased air quality has been documented in climates across the United States (Fenn et al. 2008; Geiser et al. 2010; Cleavitt et al. 2015; McMurray et al. 2015). Additionally, lichen that are less sensitive to pollution can integrate atmospheric deposition into their structures and act as bioindicators of deposition (Root et al. 2013).

Using data from over 8,000 plots spanning the conterminous United States, Geiser et al. (2019) identified relationships between lichen communities and deposition gradients of reactive N and S. These relationships allowed them to develop dose-response curves to calculate the expected decline of the lichen community at increasing levels of deposition. They identified unique responses to N and S deposition for a decline in four metrics of epiphytic lichen species communities: total species richness, N/S sensitive species richness, forage lichens abundance, and cyanolichens abundance. The critical load of each category was set as a 20% decline in maximum richness as the researchers felt that this was the level at which the ecological integrity of the lost species would cascade through the forest.

Sulfur deposition levels in the United States peaked in the 1970s prior to being regulated by the Clean Air Act (Nopmongcol et al 2020). Additional regulations were adopted as the Clean Air Act Amendments of 1990 that hastened the decline of sulfur and led to the beginning of the decline of nitrogen as nitric acid (Greaver et al. 2012). The steady decline has led to reductions in acid rain and

the general improvement of ecosystem health (Sullivan et al. 2018). The highest concentration of pollutants has historically been in the eastern United States, but as agriculture and oil and gas operations increase in the west, more western national parks are at risk of ecosystem harm (NADP 2019). The continual decline of both pollutants has improved conditions for lichen communities, but many areas are still above the critical load.

As most of the plots used to establish lichen critical loads are outside of National Park Service boundaries, the relationships must be extrapolated to understand the risk to these areas. This analysis evaluates where epiphytic lichen communities are expected to occur within NPS units and if there is a risk of community decline due to air pollution. We use modeled three-year averages of total N and total S from 2000–2002 and 2015–2017 to evaluate if critical loads of N and critical loads of S for the four lichen community metrics are exceeded in forested areas of NPS units. The comparison allows us to determine how conditions have changed over the past 17 years. We then perform a detailed analysis on 10 case-study parks to discuss regional differences in response to N and S deposition.

Methods

Application of lichen species response curves

Critical loads of N and critical loads of S for declines in epiphytic macrolichen, and the related species response curves, developed by Geiser et al. (2019), were applied to total N and total S results from TDep models to predict risk to lichen species in 168 National Parks in the contiguous United States (CONUS). In brief, Geiser et al. (2019) used data from lichen surveys from 1990–2012 at 8855 sites to develop relationships between lichen communities and nitrogen and sulfur deposition. Across all climates, maximal responses to N and S peaked at the lowest deposition value and decreased in a curvilinear pattern with increasing deposition. Thus, they used a 90% quantile regression to represent the response to deposition alone under all conditions.

They developed response equations for four lichen categories: lichen species richness, forage lichens, cyanolichens, oligotrophic and S-sensitive species (Oligotrophic species will be referred to as 'N-Sensitive species' throughout this document). The critical load for each lichen community metric was set at a 20% decline in lichen richness or abundance from an unimpacted site (Table 1) The equations applied to the N and S TDep data to determine expected community condition are listed in Table 2.

Table 1. Critical loads of N and S to protect the epiphytic macrolichen community against a 20% decline in richness or abundance (Geiser et al. 2019).

Lichen Metric	N Deposition (kg-N ha^{-1} yr^{-1})	S Deposition (kg-S ha^{-1} yr^{-1})
Species Richness	3.5	6.0
N- and S-Sensitive Lichen Richness	3.1	2.5
Forage Lichens Abundance	1.9	2.6
Cyanolichens Abundance	1.3	2.3

Table 2. Equations from (Geiser et al. 2019) for the expected percent loss of each lichen community metric with increasing N and S deposition.

Lichen Metric	N Deposition Response Equation	S Deposition Response Equation
Species Richness	$1 - (32.97 - (N*2.19) + (N^2 * 0.07))/32.97$	$1 - (29.61 - (S*1.18) + (S^2 *0.03))/29.61$
N- and S-Sensitive Lichens Richness	$1 - (18.39 - (N*1.27) + (N^2 * 0.02))/18.39$	$1 - (17.62 - (S*1.66) + (S^2 *0.05))/17.62$
Forage Lichens Abundance	$1 - (30.36 - (N*3.51) + (N^2 *0.11))/30.36$	$1 - (23.99 - (S*2.1) + (S^2 *0.05))/23.99$
Cyanolichens Abundance	$1 - (13.68 - (N*2.31) + (N^2 *0.1))/13.68$	$1 - (9.95 - (S*1.03) + (S^2 *0.03))/9.95$

As per Geiser et al. (2019), the maximum N and S deposition used in the below species richness, forage lichen, and cyanolichen equations was 12 kg-N ha^{-1} yr^{-1} and 20 kg-S ha^{-1} yr^{-1}. The N- and S-sensitive lichen richness equations used a maximum deposition level of 20 kg-N ha^{-1} yr^{-1} and 16.6 kg-S ha^{-1} yr^{-1}. Beyond these N and S disposition levels for the different lichen categories Geiser et al. (2019) did not have enough data to accurately predict lichen richness and abundance loss, thus if deposition exceeded those values the response at these maximum values was used.

The response equations in Table 2 are used to calculate the potential risk of decline in each of the lichen community types based on the amount of deposition at a location within a national park. Figure 1 shows how the rates of decline differ among community types with increasing nitrogen and sulfur deposition. For both types of deposition, total species richness is the most resilient to change, while cyanolichen communities are most sensitive.

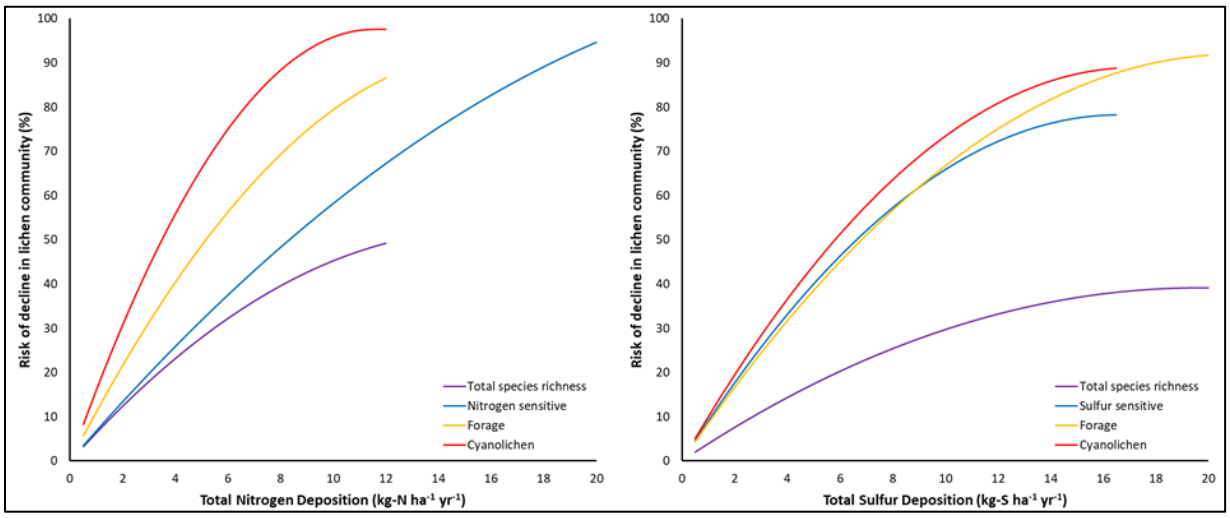


Figure 1. Nitrogen (left) and sulfur (right) response curves for the equations in Table 2 showing the rates of decline to lichen community types with increasing deposition.

Atmospheric deposition models

Modeled total N and total S estimates were retrieved from the National Atmospheric Deposition Program (NADP) Total Deposition Model (TDep; v.2018.02). The TDep model uses concentration measurements of HNO_3 and NO_3 and wet deposition measurements of NO_3 and NH_4 to adjust the results of the CMAQ model (v.5.0.2) and then incorporates modeled dry deposition of gaseous NH_3, PAN, N_2O_5, NO, NO_2, HONO, and organic nitrates (Schwede and Lear, 2014). Two sets of deposition data, representing the earliest and latest data available, averaged over three years, were used for spatial and temporal analyses for both N and S deposition levels. Annual deposition of these three-year averages are represented by the years 2001 (2000–2002) and 2016 (2015–2017). The data was downloaded as a raster with 4.1344 kilometer (km) spatial resolution. The spatial distribution of N and S deposition are shown in Figure 2 and Figure 3, respectively.

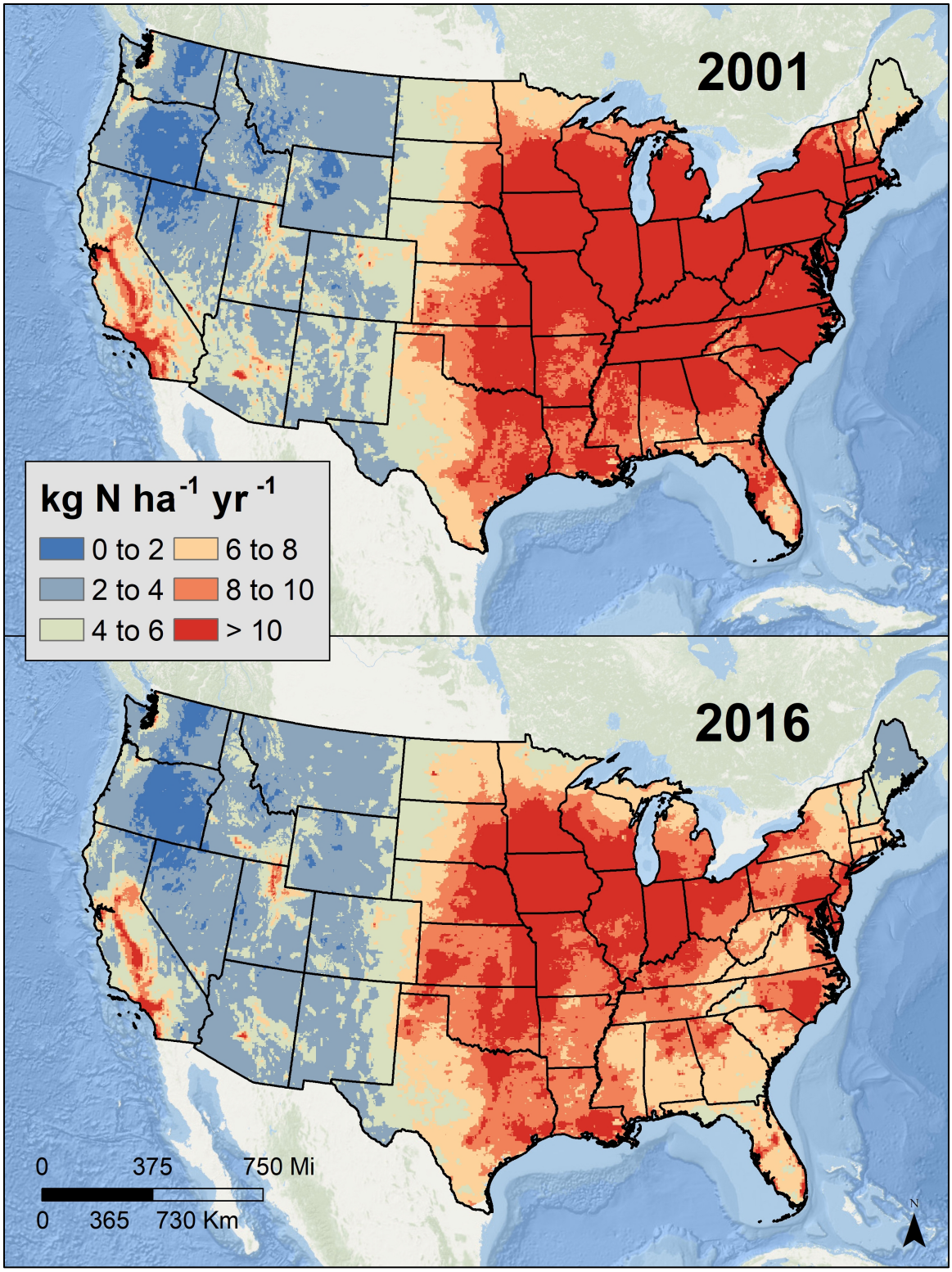


Figure 2. Total nitrogen deposition across the United States in 2001 (top) and 2016 (bottom).

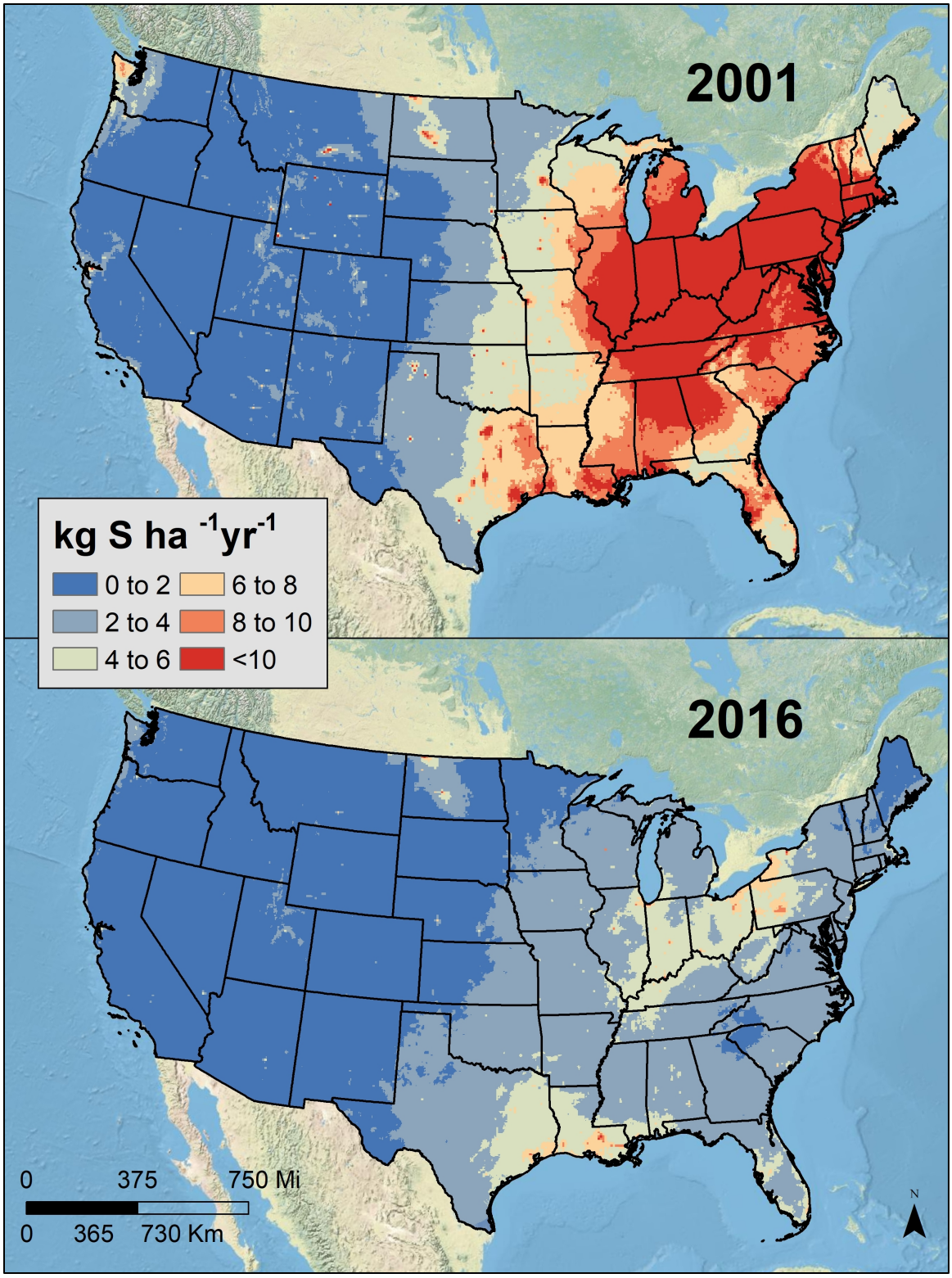


Figure 3. Total sulfur deposition levels are shown across the United States in 2001 (top) and 2016 (bottom).

Epiphytic macrolichen communities need a forested habitat to survive. Therefore, our study area was limited to NPS units that contain at least 1 kilometer of forested ecosystems. Forested areas were determined using the National Land Cover located on the Multi-Resolution Land Characteristics Consortium (NLCD; Homer et al. 2020). The NLCD data has a spatial resolution of 30 m. ArcGIS version 10.6 was used to create a layer that included only deciduous, evergreen, and mixed forests in CONUS. Based on assumptions stated in Geiser et al. (2019), the risk analysis of cyanolichens was further limited to Level 1 US EPA Ecoregions of West Coast Marine Forests, Northern Forests, and Eastern Temperate Forests. The number of NPS units included in the cyanolichen analysis was reduced to 94 as a result of the additional restrictions.

Evaluation of lichen critical load exceedances

The National Park Service manages 423 units across the United States, preserving natural and cultural resources. At the time of this analysis, there were 265 units where the NPS systematically inventories and monitors natural resources within the contiguous (CONUS) United States and 169 of these areas have forested areas greater than 1 km. Risk to epiphytic lichen communities in each unit is assessed by comparing the maximum total N and S deposition to each lichen community critical load. Critical load exceedance was calculated as total N or S deposition minus the critical load, and categorized as below the critical load value for each lichen metric (<CL−0.5 kg-N ha^{-1} yr^{-1}), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}). These qualitative ranges around the CL values were chosen to account for limitations of data collection, inherent uncertainty that accompanies modeling deposition levels, and to highlight the leading edge of risk from deposition. The TDep model represents the deposition best data available that can be applied consistently across CONUS in multiple years. There are known uncertainties that impact the modeled total N value including the fact that outputs are summarized at a 4-km grid (Walker et al. 2019). Temporal comparisons were made to evaluate changes in exceedance type at a NPS unit specific scale and to identify areas of improvement, degradation, and continued high risk. The maximum critical load exceedances in each unit in 2001 and 2016 were compared to evaluate how the highest risk areas within forested ecosystems has changed over time.

A case study analysis was completed for 10 NPS units (Acadia National Park, Glacier National Park, Grand Teton National Park, Great Smoky Mountains National Park, Joshua Tree National Park, North Cascades National Park, Rocky Mountain National Park, Sleeping Bear Dunes National Lakeshore, Theodore Roosevelt National Park, and Yosemite National Park) to assess the spatial variability of species richness critical load exceedances with respect to total N deposition and total S deposition in 2001 and 2016 (Figure 4). Additionally, the minimum and maximum deposition were used as an input into the response equations to calculate the range of expected decline in lichen communities. Difference in responses between 2001 and 2016 were used to assess potential recovery or increased harm.

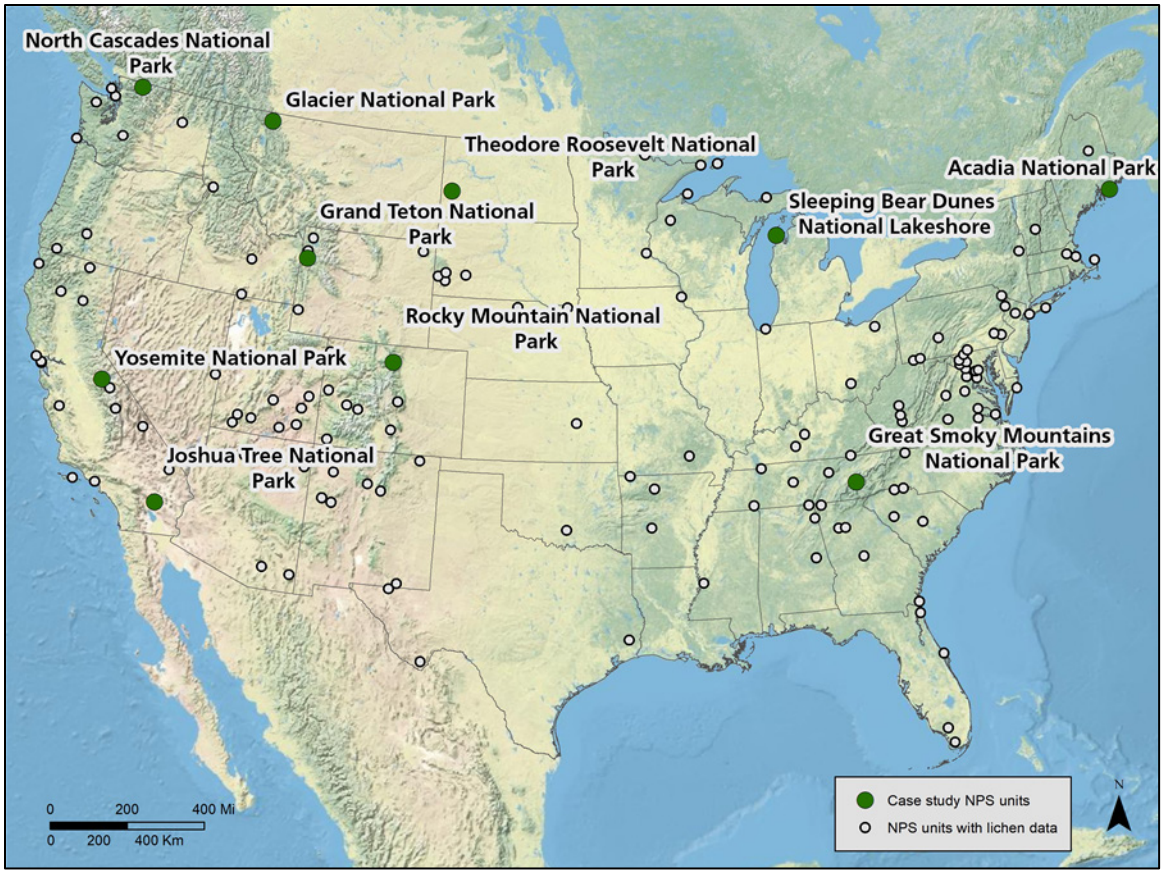


Figure 4. The 10 NPS units depicted in green will be explored in further depth in terms of the predicted species richness response to nitrogen deposition levels. The NPS units depicted in gray were included in the study and results are included in Appendices A and B.

Results

Lichen critical load exceedances

Deposition coverage

Focus was placed on assessing the risk to total lichen species richness from both N and S deposition because the critical loads for a decline in species richness provide broad range protection for lichen in forested ecosystems and is applicable across all NPS units. The critical load of N for a decline in species richness (CLN-SR) is 3.5 kg-N ha^{-1} yr^{-1} and critical load of S for a decline in species richness is 6.0 kg-S ha^{-1} yr^{-1} (CLS-SR).

Generally, the risk to lichen communities improved from both N and S deposition across NPS units between 2001 and 2016. The average change in N deposition within units was a reduction of 2.9 kg-N $ha^{-1}yr^{-1}$ of deposition. The maximum increase in deposition was at Assateague Island National Seashore in Maryland, at 3.6 kg-N ha^{-1} yr^{-1}. The maximum decline in deposition occurred in Kennesaw Mountain National Battlefield Park in Georgia, with a decrease of 12.6 kg-N ha^{-1} yr^{-1}. There were three NPS units that did not experience any change in maximum N deposition levels.

The average change in S deposition within NPS units was a decrease of 5.8 kg-S ha^{-1} yr^{-1}. The maximum increase in deposition from 2000–2002 (2001) to 2015–2017 (2016) was at Fossil Butte National Monument in Wyoming, with a 0.8 kg-S ha^{-1} yr^{-1} increase. The maximum decline in S deposition occurred in Fort Necessity National Battlefield in Pennsylvania, with a decrease of 35.6 kg-S ha^{-1} yr^{-1}. There were no units that did not experience any change in S deposition levels.

Of the 265 Inventory and Monitoring units, 169 are in the contiguous US (CONUS) and have forested areas greater than 1 km where epiphytic lichen may be impacted by air pollution. Due to coverage issues along the coast, Biscayne National Park does not have N or S deposition data associated with it and therefore 168 NPS units were included in the study. The total forested area in these units is 29,906 km^2. The largest park in the analysis has 3,481 km^2 of forest (Yellowstone National Park) and the smallest has 1.01 km^2 (Lake Mead National Recreation Area).

Critical load of nitrogen for a decline in lichen species richness

Between 2001 and 2016, N deposition levels decreased across CONUS NPS units. The risk of species richness loss attributed to N deposition decreased for 88% of units between 2001 and 2016. However, in 2016, 89% of the assessed National Park Service units (149 NPS units) remained above the CLN-SR of 3.5 kg-N ha^{-1} yr^{-1} (Table 3).

The total forested area in exceedance of the CLN-SR decreased from 2001 to 2016 (Table 3), indicating that the general risk to lichen communities from air pollution is decreasing. There was an increase of two units that had any forested area below the CLN-SR (with improving conditions at Chaco Culture National Historical Park, Curecanti National Recreation Area, and Black Canyon of the Gunnison National Park, and deteriorating conditions at Nez Perce National Historical Park). As of 2016, of NPS units with any area in exceedance, 95 are predicted to have 100% of the forested area above the CLN-SR.

Table 3. Forested area in exceedance of the critical load of N for a decline in epiphytic lichen species richness (CLN-SR) based on 3-year TDep Total N.

Deposition Compared to CL	Area in 2001 (km^2)	Area in 2016 (km^2)	Number of NPS units in 2001 (deposition in any area)	Number of NPS units in 2016 (deposition in any area)
Below CLN-SR	2,449	5,389	4	6
At CLN-SR	6,815	6,762	11	13
Exceedance: Above CLN-SR	20,096	17,209	153	149

Using the equations from Table 2, Figure 5 shows how the condition of epiphytic lichen communities change within NPS units based on maximum N deposition levels between 2001 to 2016; a downward arrow representing a declining condition (increased N) and an upward arrow representing an improving condition (decreased N). 122 units experienced improved conditions between 2001 and 2016. For example, Acadia National Park experienced the largest percentage decrease in predicted forested area above the CLN-SRL (−51.77 km^2; 99.8% improvement). The units that showed the largest improvement are located in the west coast, northwest, and eastern parts of the United States (Figure 5). Twenty-three NPS units experienced degrading conditions between 2001 and 2016. NPS units with deteriorating conditions are generally located in the Great Basin, Rocky Mountains, and Great Plains areas. Change in exceedance classifications for individual units can be found in Appendix A.

Extrapolating the results to the overlap of deposition and forested area, Figure 6 shows the current CLN-SR exceedance category for CONUS based on 2016 TDep total N deposition. Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}). The bottom panel of Figure 6 shows the corresponding calculated decline in species richness based on the amount of deposition at each location using the equations for Table 2.

The remaining three lichen categories provide specific targets for management teams to focus recovery and protection efforts, depending on the individual needs of the unit. These three critical loads are more sensitive than the species richness critical load. The risk to N- and S-sensitive species, forage lichens, and cyanolichens from N and S was therefore higher than risk to total lichen species richness.

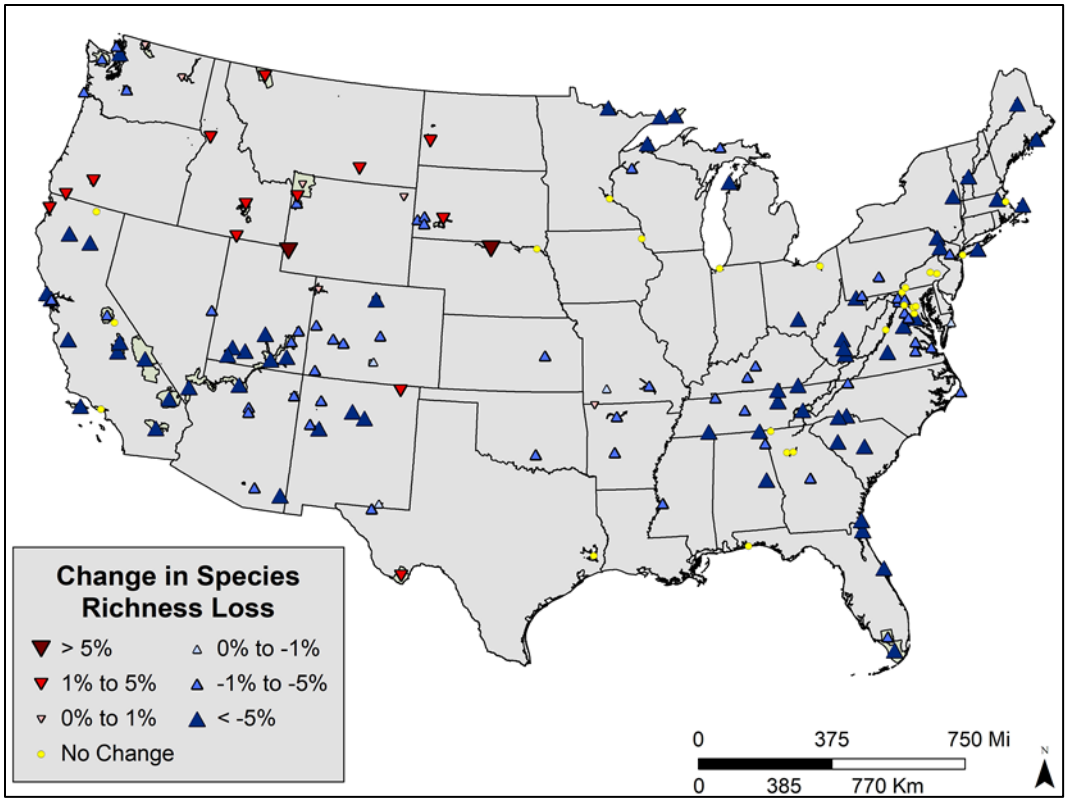


Figure 5. Change in species richness response to N deposition from 2001 to 2016 in individual NPS units is depicted as either degrading (red downward triangle) or improving (blue upward triangle) between 2001 and 2016. The magnitude of the change is shown by increasing shape size and color darkness. No change is shown by a yellow circle.

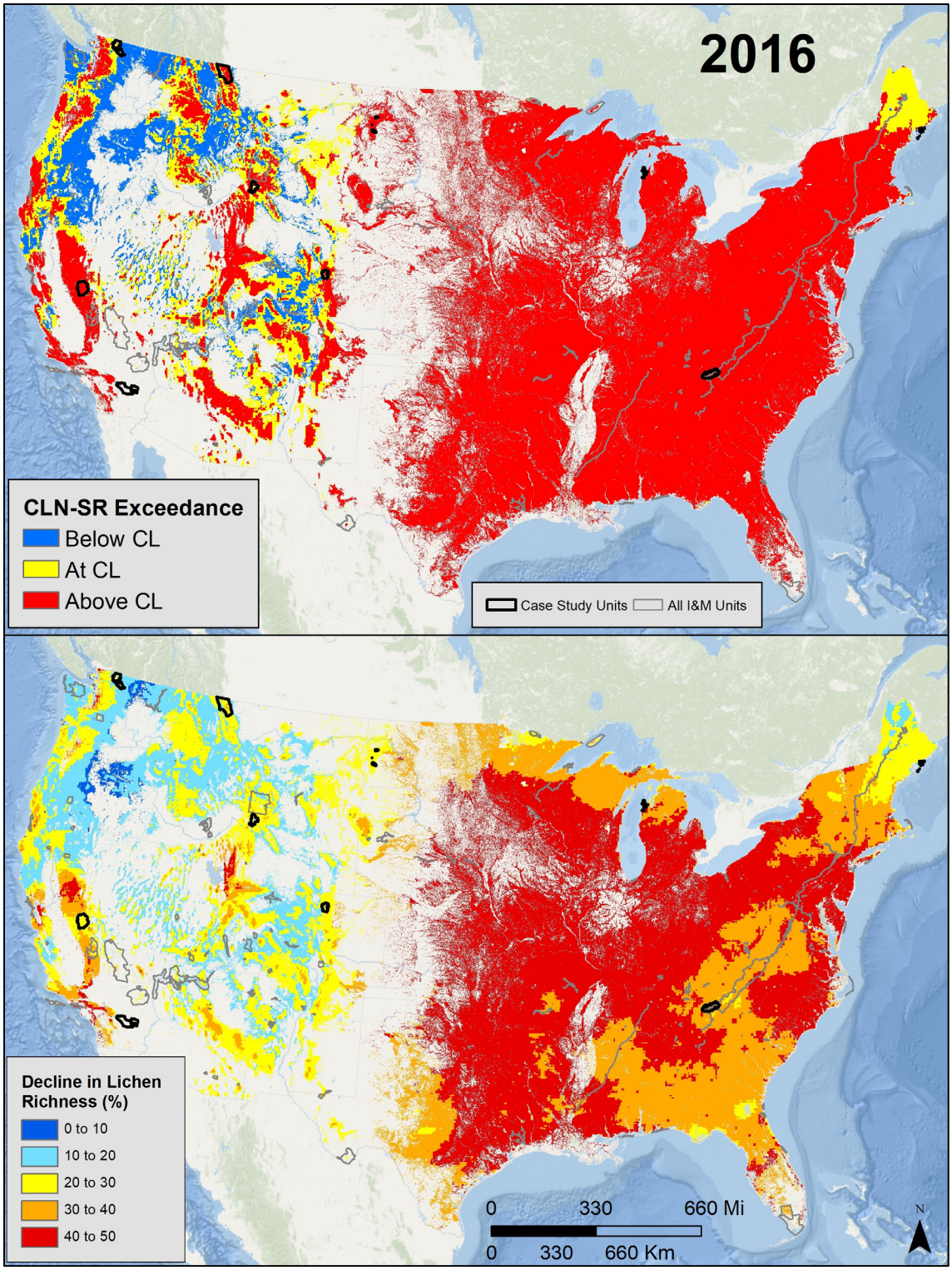


Figure 6. Critical load exceedance category for all forested areas in CONUS (top) and the expected percent loss of total lichen species richness (bottom) based on TDep total N 3-year average from 2015–2017. Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

N-sensitive, forage lichens, and cyanolichens

The number of NPS units with areas above the critical load of N (CLN) for a decline in N-sensitive species decreased between 2001 and 2016 (Table 4). However, Fossil Butte National Monument experienced deteriorating conditions where forested area shifted from below the critical load to at the critical load. One NPS unit (Craters of the Moon National Monument and Preserve) had forested areas shift from at to above the CLN for decline in forage lichen abundance. No NPS units in either 2001 or 2016 were below the CLN for decline in forage lichen. All 94 NPS units within the relevant ecoregions were above the CLN for decline in cyanolichen abundance in both 2001 and 2016.

Table 4. Exceedances of the critical load of N (CLN) for each lichen community category based on 3-year TDep Total N.

	Number of NPS units (deposition in any area)					
Deposition Compared to CL	**N-sensitive lichens (2001)**	**N-sensitive lichens (2016)**	**Forage lichens (2001)**	**Forage lichens (2016)**	**Cyanolichens (2001)**	**Cyanolichens (2016)**
Below CLN	2	1	0	0	0	0
At CLN	9	13	2	1	0	0
Above CLN	157	154	166	167	94	94

Critical load of sulfur for a decline in lichen species richness

Sulfur deposition decreased more dramatically between 2000–2002 (2001) and 2015–2017 (2016) than did nitrogen deposition. This is demonstrated by the large number of units and total forested area trending below the critical load of S for a decline in species richness (CLS-SR) of 6.0 kg-S $ha^{-1}yr^{-1}$. Risk to lichen species richness from S deposition decreased in 98% of NPS units between 2001 and 2016. By 2016, there are only 6 units that were predicted to exceed the CLS-SR and only 9 units that had any forested area that was at or above the CLS-SR (Table 5). However, all of these units have experienced improving conditions since 2001 in regard to S deposition.

Table 5. Forested area in exceedance of the critical load of S for a decline in epiphytic lichen species richness (CLS-SR) based on 3-year TDep Total S.

Deposition Compared to CL	**Area in 2001 (km^2)**	**Area in 2016 (km^2)**	**Number of NPS units in 2001 (deposition in any area)**	**Number of NPS units in 2016 (deposition in any area)**
Below CLS-SR	19,587	29,141	82	159
At CLS-SR	784	111	5	3
Above CLS-SR	8,988	108	81	6

The total NPS forested area below the CLS-SR increased by over 10,000 square kilometers (km^2). In 2016, there were only 3 units predicted to have greater than 50% of their forested area exceeding the

CLS-SR (Fort Necessity National Battlefield, Indian Dunes National Park, and Big Thicket National Preserve).

Using the equations from Table 2, Figure 7 shows how the condition of epiphytic lichen communities change within NPS units based on maximum S deposition between 2001 to 2016; a downward arrow representing a declining condition (increased S) and an upward arrow representing an improving condition (decreased S). 165 NPS units experienced improved conditions for lichen species richness, with 52 units improving the species richness condition by 20% or more. Kennesaw Mountain National Battlefield Park had the greatest improvement of species richness condition (30% increase in expected total species richness). There were 4 units in the western and central United States that had decreased conditions with the maximum sulfur deposition; however, all were still below the CLS-SR. The 6 units in exceedance of the CLS-SR had decreases in maximum deposition and thus improving conditions.

The top panel of Figure 8 shows the current CLS-SR exceedance category for CONUS based on 2016 TDep total S deposition. Exceedances are categorized as Below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}), At the critical load (CL±0.5 kg-S ha^{-1} yr^{-1}), or Above the critical load (>CL+0.5 kg-S ha^{-1} yr^{-1}). The bottom panel of Figure 8 shows the corresponding expected condition of species richness condition based on the response equations from Table 2.

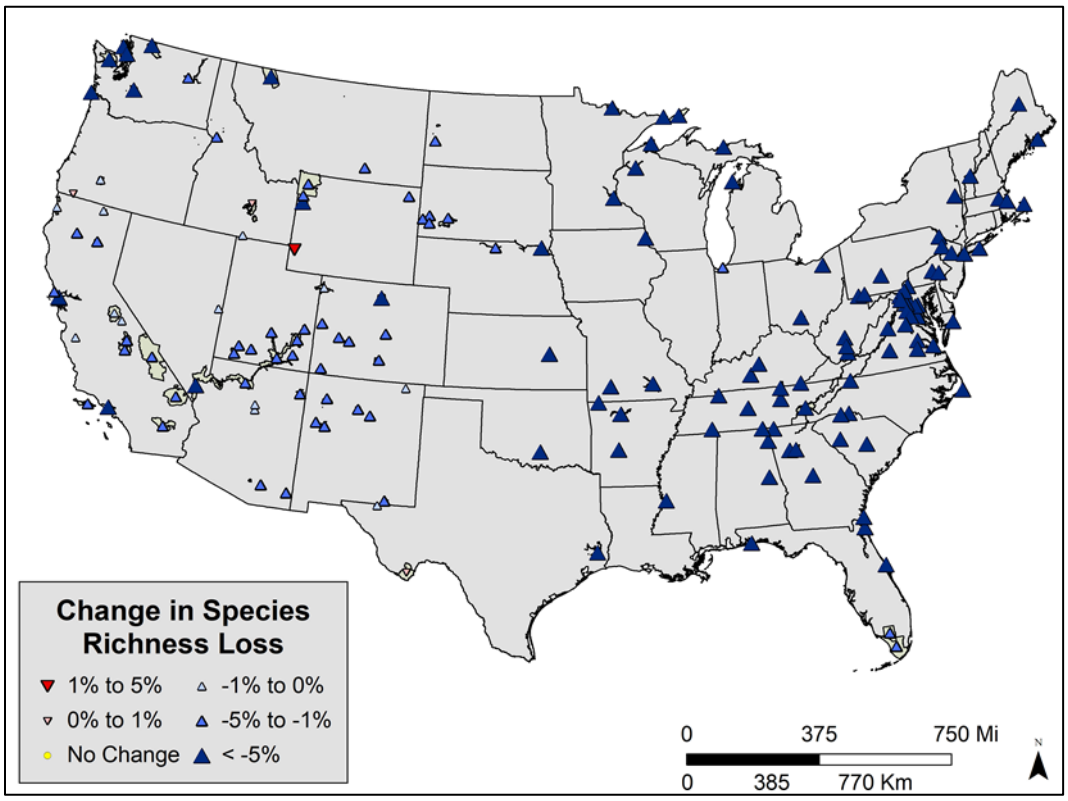


Figure 7. Change in species richness response to S deposition from 2001 to 2016 in individual NPS units is depicted as either degrading (red downward triangle) or improving (blue upward triangle) between 2001 and 2016. The magnitude of the change is shown by increasing shape size and color darkness.

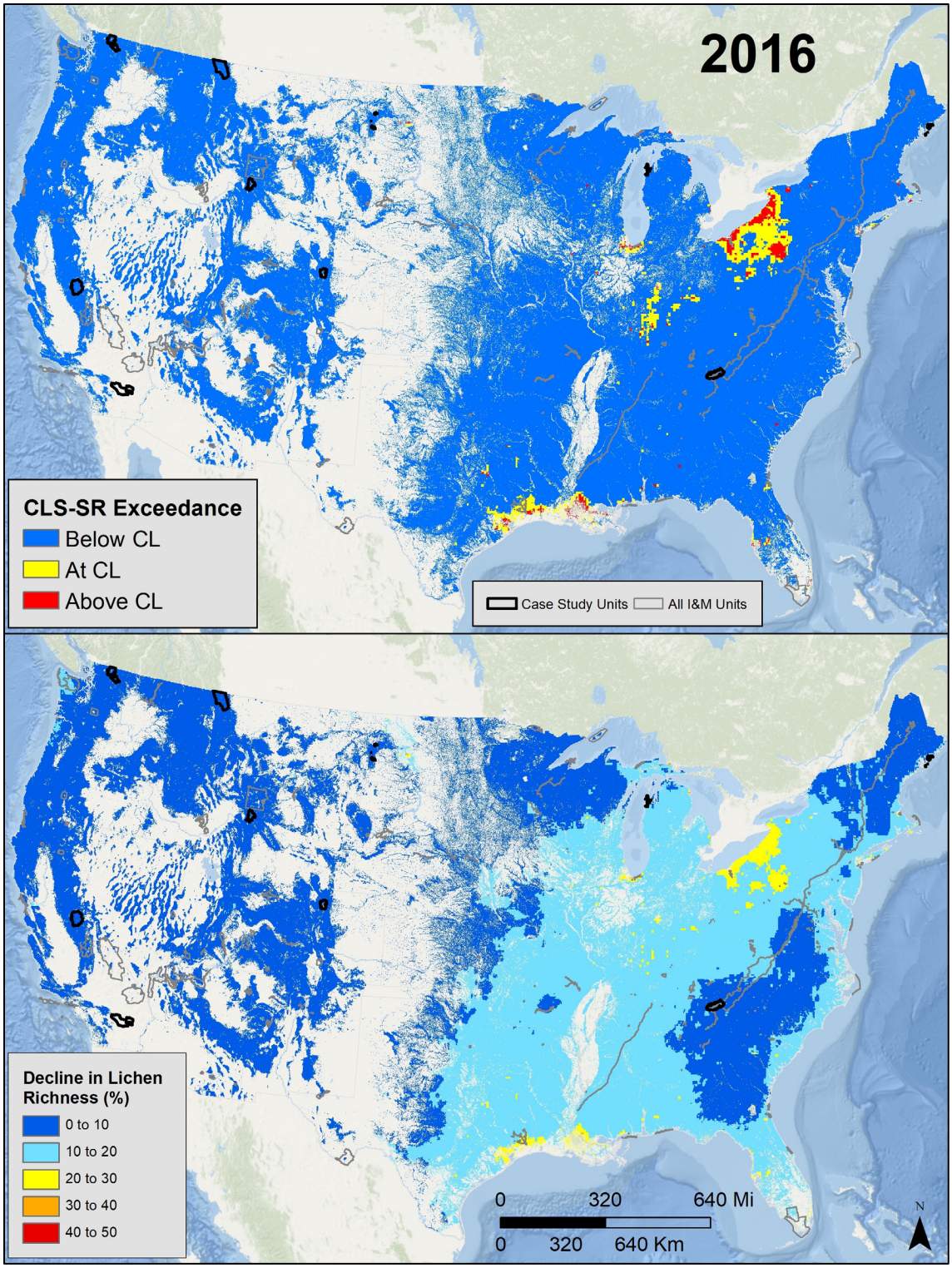


Figure 8. Critical load exceedance category for all forested areas in CONUS (top) and the expected percent loss of total lichen species richness (bottom) based on TDep total S 3-year average from 2015–2017. Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

S-sensitive, forage lichens, and cyanolichens

The critical load of sulfur (CLS) for a decline in S-sensitive species (2.5 kg-S ha^{-1} yr^{-1}), the CLS for a decline in forage lichen abundance (2.6 kg-S ha^{-1} yr^{-1}), and the CLS for a decline in cyanolichen abundance (2.3 kg-S ha^{-1} yr^{-1}) all have similar critical loads and thus showed similar exceedance patterns (Table 6). There was a decrease in the number of NPS units that experienced S deposition Above the S CL across all categories. In 2001 no units were predicted to have forested area below the cyanolichen S CL, however by 2016 two units, Voyageurs National Park and Cowpens National Battlefield, were below this threshold.

Table 6. Exceedance of the critical load of S (CLS) for each lichen community category based on 3-year TDep Total S.

	Number of NPS units (deposition in any area)					
Deposition compared to CL	**S-sensitive lichens (2001)**	**S-sensitive lichens (2016)**	**Forage lichens (2001)**	**Forage lichens (2016)**	**Cyanolichens (2001)**	**Cyanolichens (2016)**
Below S CL	44	71	47	74	0	2
At S CL	16	34	13	38	1	21
Above S CL	108	63	108	56	93	71

National Park Service unit case studies

The spatial variation in the rate of epiphytic lichen species richness loss and risk of critical load exceedance of forested ecosystems from N and S deposition was evaluated for all relevant national park units based on the overlap of the TDep deposition model and forested area. Data from ten of the units is shown here representing a snapshot of different regions and forested ecosystems in the United States and the spatial variability of N and S deposition changes between 2001 and 2016. (Figure 6; Acadia National Park (ACAD), Glacier National Park (GLAC), Grand Teton National Park (GRTE), Great Smoky Mountains National Park (GRSM), Joshua Tree National Park (JOTR), North Cascades National Park (NOCA), Rocky Mountain National Park (ROMO), Sleeping Bear Dunes National Lakeshore (SLBE), Theodore Roosevelt National Park (THRO), and Yosemite National Park (YOSE)). Data for all NPS units with forested area can be found in Appendix A and Appendix B. Regional case-studies were chosen to highlight units with a broad range of temperature, precipitation, and geographic locations. A park like Joshua Tree National Park has very little forested area relative to North Cascades, but based on the surveys used in Geiser et al. (2019), lichen still exist in aird tree communities and respond to air pollution.

Table 7 extracts data from Figure 6 on the exceedance category and expected decline of lichen species richness from total N deposition in 2016 and how the risk has changed since 2001 for each of the selected units. Table 8 extracts data from Figure 8 on the exceedance category and expected decline of lichen species richness from total S deposition in 2016 and how the risk has changed since 2001 for each of the selected units.

Table 7. The rate of response for total epiphytic lichen species richness from maximum N deposition within NPS unit boundaries and the percent of the forest area above the critical load. Responses are based on TDep 3-year averages 2000–2002 (2001) and 2015–2017 (2016).

NPS unit	2016 max deposition (kg-N ha^{-1} yr^{-1})	Change in max deposition 2001–2016[B] (kg-N ha^{-1} yr^{-1})	2016 max decline in species richness (%)	Change in max decline in species richness 2001–2016 (%)[C]	2016 forest area above CL (%)	Decrease in area above CL 2001–2016 (%)
ACAD[A]	5.0	−4.8	27.7	−16.9	0.18	99.82
GLAC[A]	7.4	−0.2	37.4	−0.9	56.14	7.05
GRSM	8.4	−7.5	40.8	−8.3	98.51	0.00
GRTE	7.4	−2.0	37.5	−3.7	59.28	6.09
JOTR	5.4	−4.6	29.8	−14.4	100.00	0.00
NOCA[A]	4.3	−0.3	24.8	0.7	3.71	1.97
ROMO	6.5	−3.7	34.0	−9.6	77.52	22.48
SLBE[A]	8.9	−4.5	42.2	−7.0	100.00	0.00
THRO	5.2	0.1	28.7	1.4	100.00	0.00
YOSE	6.2	−1.5	33.1	−1.9	100.00	0.00

[A] NPS units located on the border (land or water) of the United States often do not have complete coverage of TDep data. The units indicated are associated with incomplete TDep coverage.

[B] A negative value of deposition in this column indicates that between 2001 and 2016, average annual deposition decreased and N-related air quality in the unit improved.

[C] A negative value indicates that the predicted lichen species richness in the unit increased as air quality improved. A positive value indicates that the predicted lichen species richness in the unit decreased as air quality deteriorated.

Several places, such as Great Smoky Mountains National Park, experienced highly improved conditions caused by a decrease N and/or S deposition levels (Table 7). Other places, such as Theodore Roosevelt National Park, saw increases in N deposition from 2001 to 2016. No units experienced degrading conditions from S deposition between 2001 and 2016 (Table 8). The percentage of forested area in exceedance of the CLN-SR ranged from <1% to 100% in 2016. There was no forested area in any of the 10 NPS unit case studies that exceeded the CLS-SR in 2016. The conditions of each unit are described in further detail in the following sections. For additional maps and analyses for each case study unit, please see Appendix C.

Table 8. The rate of response for total epiphytic lichen species richness from maximum sulfur deposition level within NPS unit boundaries and the percent of the forest area above the critical load. Responses are based on TDep three-year averages 2000–2002 (2001) and 2015–2017 (2016).

NPS unit	2016 max deposition (kg-S ha^{-1} yr^{-1})	Change in max deposition 2001–2016[B] (kg-S ha^{-1} yr^{-1})	2016 max decline in species richness (%)	Change max decline in species richness 2001–2016 (%)[C]	2016 forest area above CL (%) (%)	Decrease in area above CL 2001–2016 (%)
ACAD[A]	4.3	−7.7	15.2	−18.1	0.0	100
GLAC[A]	1.8	−1.5	7.0	−5.2	0.0	0.0
GRSM	3.1	−15.2	11.5	−27.5	0.0	100
GRTE	2.3	−1.6	8.6	−5.5	0.0	0.0
JOTR	0.7	−0.3	2.9	−1.0	0.0	0.0
NOCA[A]	1.9	−1.5	7.0	−5.1	0.0	0.0
ROMO	1.7	−2.9	6.4	−9.8	0.0	0.0
SLBE[A]	3.3	−7.8	12.0	−19.7	0.0	100
THRO	2.0	−1.3	7.6	−4.5	0.0	0.0
YOSE	1.5	−0.2	5.6	−0.7	0.0	0.0

[A] NPS units located on the border (land or water) of the United States often do not have complete coverage of TDep data. The units indicated are associated with incomplete TDep coverage.

[B] A negative value of deposition in this column indicates that between 2001 and 2016, average annual deposition decreased and S-related air quality in the unit improved.

[C] A negative value indicates that the predicted lichen species richness in the unit increased as air quality improved. A positive value indicates that the predicted lichen species richness in the unit decreased as air quality deteriorated.

Observations and Recommendations

National trends in critical load exceedances

This study applied critical loads of nitrogen (N) and critical loads of sulfur (S) for a decline in total lichen species richness, N- and S- sensitive lichen species richness, forage lichen abundance, and cyanolichens abundance developed by Geiser et al. (2019) to forested ecosystems across 168 CONUS NPS units to assess risk from acid deposition from 2001–2016. Most units experienced improved conditions to N and S deposition between 2001 and 2016. The largest improvements for both N and S deposition were found along the east coast and in the southeast, and in response to N deposition in the southwest. By 2016, fewer than 50% of NPS units were in exceedance of the critical load of S (CLS) for decline in species richness, S-sensitive lichens, or forage lichens. However, the majority of units (>75%) were still experiencing an exceedance of a critical load of N (CLN) for a decline in all lichen categories and for the CLS for a decline in cyanolichens.

Deteriorating conditions for N deposition were seen primarily in the northcentral and northwestern United States and in the west for S deposition. Further research is needed in these areas to understand the source of the increased N and S deposition. Particular attention should be placed on areas that have both an increase on S and N deposition such as Fossil Butte National Monument (Wyoming), Craters of the Moon National Monument and Preserve (Idaho), and Big Bend National Park (Texas). It would also be useful to study the combined effects of N and S deposition not only in NPS units that experienced critical load exceedances in both, but also units that experienced CL exceedances in only one form of deposition or units that did not experience an CLN or CLS exceedances. It is possible that the even in NPS units with no exceedances that the combined effects of N and S deposition may lead to a decline in lichen community health.

Focus was placed on critical loads protective of lichen species richness, which offers the broadest protection of lichen communities. While S deposition was primarily found to be below the CLS-SR in many of the NPS units included in the study (96%), N deposition remained above the CLN-SR in most units (89%). The remaining lichen categories provide more stringent criteria that can be used to target the recovery and protection of specific areas within individual NPS units as needed. Therefore, there were more units and larger forested areas that experienced exceedances of these critical loads (Appendix A).

N deposition in 2016 posed a high risk to N-sensitive species (92% of NPS units), forage lichens (99% of NPS units), and cyanolichens (100% of NPS units). There was a small decrease in the number of units where the maximum N deposition exceeded the CLN for decline in N-sensitive species and forage lichens. High risk to lichen species from 2016 S deposition was predicted in fewer NPS units for S-sensitive species (38%), forage lichens (33%), and cyanolichens (76%) than N deposition. NPS units where N- and S- sensitive lichen species, forage lichens, and cyanolichens play important ecosystem roles will be especially impacted by elevated N and S deposition levels in 2016 and will require specific management goals to protect and restore full ecosystem function.

Summary of case study NPS units results

The case study NPS units provide insights into the different spatial trends in different regions and ecosystems in the contiguous United States. The maximum deposition in all the 10-case study NPS units was below the CLS-SR. Therefore, we determined that there is currently low risk to lichen species richness from S deposition, with no predicted decline in species richness from S deposition above 15.2%. However, the maximum N deposition was above the CLN-SR for all of the case study NPS units.

NOCA and ACAD were the only two NPS units with less than 50% of the forested area above the CLN-SR in 2016 (Table 7). The remaining 8 units had greater than 50% of the forested area above the CLN-SR. 100% of the forested area in five units (GRSM, JOTR, SLBE, THRO, and YOSE) exceeded the CLN-SR in 2016. These same units were also above the CLN-SR in 2001. However, 7 of the units experienced improved conditions for lichen species richness based on the change in maximum N deposition in the unit (ACAD, ROMO, GRTE, GRSM, JOTR, SLBE, YOSE). Contrary to the trend of improving conditions, several units experienced an increase forested area that was above the CLN-SR (GLAC, GRTE, NOCA, and THRO).

There were several units that experienced shifts in the status of forested area below, at, or above the CLN-SR. ROMO (Colorado) demonstrated clear improvements in conditions for lichen species richness in respect to N deposition with both a decrease in maximum N deposition, predicted species richness loss, and forested area above the CLN-SR (see Appendix C, Figure C25). In 2001, there was no area below or at the CLN-SR, however, by 2016 there was an obvious improvement in lichen community conditions in the western part of the park.

On the other hand, some NPS units, such as NOCA (Washington), showed variable results in different areas of the park (see Appendix C, Figure C21). Based on the TDep model, the northwestern and north central parts of the park showed increased levels of deposition and areas above the critical load. Conversely, the eastern border of the park has shifted from at the CLN to below the CLN-SR, representing improved conditions. A park specific study comparing deposition and lichen community responses would be useful for future research to investigate N deposition sources and provide management guidance for protection and restoration efforts.

GRTE (Wyoming) would be expected to have improved conditions with respect to a decrease in maximum N deposition. However, the forested area above the CLN-SR increased and there was no longer any area predicted to be below the CLN-SR in 2016 (see Appendix C, Figure C13). GRTE is an example of why it was important to evaluate both the maximum N deposition and area in exceedance of the CLN to determine risk to lichen species from N deposition. Other parks, such as GLAC (Montana) demonstrated clear degrading conditions in both maximum N deposition and forested area above the CLN-SR (see Appendix C, Figure C5). Based on the TDep model, we expect that lichen species in GLAC are at higher risk to N deposition in 2016 than in 2001.

Comparing other critical loads for a decline in lichen richness

The CLN and CLS for decline in species richness used in this analysis came from a national dataset and were applied universally to forested areas because they act as a proxy for the presence of

epiphytic lichen communities as tree trunks, branches, and boles are the most common surface for them to grow. Previous studies were limited to regional analyses of critical loads of N for decline in epiphytic lichen species, and most resulted in critical loads of N higher than those developed by Geiser et al. (2019). The following sections will compare the national CLN-SR developed by Geiser et al., 2019 (3.5 kg-N ha^{-1} yr^{-1}) to previously published regional critical loads of N for decline in lichen species, community composition, or lichen health. TDep total N deposition from 2016 will be used as a reference for the comparison.

Critical loads from eastern ecosystems

Pardo et al., 2011 developed regional critical loads of N deposition in Eastern Temperate Forests and Northern Forests. The critical loads of N in the eastern ecoregions of the United States were between 4 and 8 kg-N ha^{-1} yr^{-1}. Similarly, Cleavitt et al. (2015) studied Class I areas in the northeastern U.S. and developed critical loads of N for decline in species richness, abundance of N-sensitive species, and thallus conditions. The critical load ranged between 4 and 6 kg-N ha^{-1} yr^{-1}. Both studies developed critical loads above the national critical load of N applied in this study which was 3.5 kg-N ha^{-1} yr^{-1}. However, critical loads developed for the eastern United States were less reliable because of factors such as historical S deposition, acidification, and unknown N and S deposition background levels (Pardo et al. 2011).

Of the 10 case-study NPS units, three are located in the eastern United States: ACAD (Maine), GRSM (North Carolina/Tennessee), and SLBE (Michigan). ACAD and GRSM are in the Eastern Temperate Forests and SLBE is located in the Northern Forests. According to the Pardo et al. (2011) critical load, only lichen species in the central part of GRSM are at high risk to N deposition. However, unlike with the Geiser et al. (2019) critical load, the entire park is not in exceedance. Cleavitt et al. (2015) predicted similar levels of risk to lichen in GRSM as the Geiser et al. (2019). Only a small area near the southern border of the park is not in exceedance of this critical load. Both the Pardo et al. (2011) and Cleavitt et al. (2015) critical loads predict lower risk to lichen species in SLBE than the Geiser et al. (2019) critical load. The risk of exceedance within ACAD from N deposition in 2016 is expected to be the similar using any of the above critical loads of N and the Geiser et al. (2019) critical load.

Critical loads from western ecosystems

Fenn et al. (2003) developed critical loads of N deposition for changes in lichen community composition in the western United States, which ranged from 3 to 8 kg-N ha^{-1} yr^{-1}. The deleterious effects were mainly observed around hotspots of elevated N deposition near urban and agricultural areas. The critical loads presented in Pardo et al., 2011 for the Northwest Forested Mountains and Marine West Coast Forests range from 2.5 to 9.2 kg-N ha^{-1} yr^{-1}. Geiser et al. (2010) developed critical loads for decline in sensitive species in temperate forests in Western Oregon and Washington ranging from 3 to 9 kg-N ha^{-1} yr^{-1}. Compared to the Geiser et al. (2019) critical load of N for decline in species richness, the Fenn et al. (2003), Pardo et al. (2011), and Geiser et al. (2010) critical loads are generally higher. These critical loads are applied at an Ecoregion I scale and predict low risk to THRO (South Dakota, Great Plains), GLAC (Montana, Northwestern Forested Mountains), GRTE (Wyoming, Northwestern Forested Mountains), YOSE (California, Mediterranean California),

NOCA (Washington, Northwestern Forested Mountains), and ROMO (Colorado, Northwestern Forested Mountains) while Geiser et al. (2019) predicts the all or the majority of the forested area to be exceeded within these parks (Omernik and Griffith 2014).

However, Fenn et al. (2008) described a critical load of N for change in lichen community composition with a decline in N-sensitive species at 3.1 kg-N ha^{-1} yr^{-1}. The critical load applies to epiphytic lichen species in mixed conifer forests in California and is complimentary to the Geiser et al. (2019) critical load.

The critical load for North American Deserts was similar in both Pardo et al. (2011) (3 kg-N ha^{-1} yr^{-1}) and Geiser et al. (2019) (3.5 kg-N ha^{-1} yr^{-1}). JOTR was the only case study park located in this ecoregion where the predicted risk to lichen species is the same when using either critical load. However, the Pardo et al. (2011) study stated lower confidence in the critical loads applicable to the North American Desert ecoregion due to limited data from arid environments.

Glavich and Geiser (2008) was one of the few studies that developed a critical load of N deposition for decline in N-sensitive lichen communities that was lower than the 3.1 kg-N ha^{-1} yr^{-1} applied in this study. The critical load developed was 0.26–0.33 kg inorganic N ha^{-1} yr^{-1} and is applicable in coastal Oregon and Washington. McMurray et al. (2015) developed a critical load of N deposition for deleterious effects to lichen communities of 4 kg-N ha^{-1} yr^{-1} for the Northern Rocky Mountains. While higher than the one applied in this study, both the McMurray et al. (2015) and Glavich and Geiser (2008) critical loads are also lower than the range developed by Pardo et al. (2011) for Northwest Forested Mountains and Marine West Coast Forests. Lower critical loads of N for change in lichen community composition is further supported by Root et al. (2015). This study compared nitrogen content of lichen tissue with measured N deposition to develop a critical load ranging from 1.54 to 2.51 kg-N ha^{-1} yr^{-1}, applicable to forested ecosystems in the Pacific Northwest.

Limitations of this analysis for broader application

TDep data is not available for NPS units outside of CONUS, including those located in Alaska, Hawaii, and Puerto Rico. Although, given the strong relationship between community richness and deposition, the lichen community should be able to be used to predict deposition gradients in these areas. TDep data is summarized to an approximately 4-km grid and therefore cannot provide a fine-scale assessment at an individual unit level. The known uncertainties within the model, outside of the scale, include overestimating wet deposition to high deposition areas, underestimating deposition to forests when mixed land use is present, and unknown error in dry deposition measurements (Walker et al. 2019). Even with these unknowns, it provides a snapshot of risk and allows land managers to identify high risk areas and hotspots and focus monitoring, management, and restoration efforts at these locations and how the risk changes over time. The TDep data is also not available for all forested area within units located on the borders of CONUS. The largest discrepancies within the study are found in Apostle Islands National Lakeshore (Wisconsin), Isle Royale National Park (Michigan), and Acadia National Park (Maine).

NPS units located in dry ecoregions such as JOTR (California), located in both North American Desert and Mediterranean California ecoregions, and THRO (North Dakota), located in the Great

Plains ecoregion do not benefit from the use of these CLs as much as the other units included in the case study. JOTR and THRO have sparse forest cover and few epiphytic lichen species are found within the parks. Although, they do have many crustose lichens on rocks and soils that need to be studied for responses to air pollution. Resources within these parks and those with similar ecosystems will be more effectively distributed on management efforts focused on CLs protecting species specific to those ecosystems. Pardo et al. (2011) also identified the North American Deserts as an ecoregion where there was lower confidence in the associated critical loads because of the lack of research in the area.

Recommended future research

NPS units with consistent or emerging hotspots should investigate the sources of air pollution that may be affecting forest ecosystem health. Our study used TDep measurement-model fusion outputs to predict risk to lichen species. TDep is known to overpredict deposition in high elevation mountainous environments, which may infer an exceedance in some areas where it does not exist (Williams et al. 2017). Most NPS units do not have lichen Forest Inventory and Analysis plots from which these critical loads were developed, thus units with identified risk should consider supplementing this analysis with field studies to increase confidence in the results and provide data to compare with the surrounding area. This is especially important in NPS units in which lichens have not been extensively studied, like those in the Eastern Temperate Forests and Northern Forests ecoregions.

NPS units where deposition has decreased to the level where critical loads of lichen species richness are no longer exceeded should consider establishing field surveys to understand potential recovery. Studies in Europe have found a slow rate of return of lichen to an area after extirpation from atmospheric pollution (Weldon and Grandin, 2021), so understanding if or when lichen return can help highlight the importance of reducing deposition before harm occurs.

Literature Cited

Bowman, W. D., J. Murgel, T. Blett, and E. Porter. 2012. Nitrogen critical loads for alpine vegetation and soils in Rocky Mountain National Park. Journal of Environmental Management **103**:165–171.

Clark, C. M., S. M. Simkin, E. B. Allen, W. D. Bowman, J. Belnap, M. L. Brooks, S. L. Collins, L. H. Geiser, F. S. Gilliam, S. E. Jovan, L. H. Pardo, B. K. Schulz, C. J. Stevens, K. N. Suding, H. L. Throop, and D. M. Waller. 2019. Potential vulnerability of 348 herbaceous species to atmospheric deposition of nitrogen and sulfur in the United States. Nature Plants **5**:697–705.

Cleavitt, N. L., J. W. Hinds, R. L. Poirot, L. H. Geiser, A. C. Dibble, B. Leon, R. Perron, and L. H. Pardo. 2015. Epiphytic macrolichen communities correspond to patterns of sulfur and nitrogen deposition in the northeastern United States. The Bryologist **118**:304–324.

Conti, M. E. and G. Cecchetti. 2001. Biological monitoring: lichens as bioindicators of air pollution assessment — a review. Environmental Pollution **114**:471–492.

Fenn, M. E., J. S. Baron, E. B. Allen, H. M. Rueth, K. R. Nydick, L. Geiser, W. D. Bowman, J. O. Sickman, T. Meixner, D. W. Johnson, and P. Neitlich. 2003. Ecological effects of nitrogen deposition in the western United States. BioScience **53**:404–420.

Fenn, M. E., S. Jovan, F. Yuan, L. Geiser, T. Meixner, and B. S. Gimeno. 2008. Empirical and simulated critical loads for nitrogen deposition in California mixed conifer forests. Environmental Pollution **155**:492–511.

Geiser, L. H., S. E. Jovan, D. A. Glavich, and M. K. Porter. 2010. Lichen-based critical loads for atmospheric nitrogen deposition in Western Oregon and Washington Forests, USA. Environmental Pollution **158**:2412–2421.

Geiser, L. H., P. R. Nelson, S. E. Jovan, H. T. Root, and C. M. Clark. 2019. Assessing Ecological Risks from Atmospheric Deposition of Nitrogen and Sulfur to US Forests Using Epiphytic Macrolichens. Diversity **11**:87.

Glavich, D. A. and L. H. Geiser. 2008. Potential Approaches to Developing Lichen-Based Critical Loads and Levels for Nitrogen, Sulfur and Metal-Containing Atmospheric Pollutants in North America. The Bryologist **111**:638–649, 612.

Greaver, T. L., T. J. Sullivan, J. D. Herrick, M. C. Barber, J. S. Baron, B. J. Cosby, M. E. Deerhake, R. L. Dennis, J.-J. B. Dubois, C. L. Goodale, A. T. Herlihy, G. B. Lawrence, L. Liu, J. A. Lynch, and K. J. Novak. 2012. Ecological effects of nitrogen and sulfur air pollution in the US: what do we know? Frontiers in Ecology and the Environment **10**:365–372.

Horn, K. J., R. Q. Thomas, C. M. Clark, L. H. Pardo, M. E. Fenn, G. B. Lawrence, S. S. Perakis, E. A. H. Smithwick, D. Baldwin, S. Braun, A. Nordin, C. H. Perry, J. N. Phelan, P. G. Schaberg, S. B. St. Clair, R. Warby, and S. Watmough. 2018. Growth and survival relationships of 71 tree species with nitrogen and sulfur deposition across the conterminous U.S. PLoS ONE **13**:e0205296.

Homer, C., J. Dewitz, S. Jin, G. Xian, C. Costello, P. Danielson, L. Gass, M. Funk, J. Wickham, S. Stehman, R. Auch, and K. Riitters. 2020. Conterminous United States land cover change patterns 2001–2016 from the 2016 National Land Cover Database. ISPRS Journal of Photogrammetry and Remote Sensing **162**:184–199.

McMurray, J. A., D. W. Roberts, and L. H. Geiser. 2015. Epiphytic lichen indication of nitrogen deposition and climate in the northern rocky mountains, USA. Ecological Indicators **49**:154–161.

National Atmospheric Deposition Program (NADP). 2019. National Atmospheric Deposition Program 2018 Annual Summary. Wisconsin State Laboratory of Hygiene, University of Wisconsin-Madison, WI

Nilsson, J. and P. Grennfelt. 1988. Critical loads for sulphur and nitrogen. UNECE/Nordic Council workshop report, Skokloster, Sweden. March 1988.

Nopmongcol, U., R. Beardsley, N. Kumar, E. Knipping, and G. Yarwood. 2019. Changes in United States deposition of nitrogen and sulfur compounds over five decades from 1970 to 2020. Atmospheric Environment 209:144–151.

Omernik, J. M. and G. E. Griffith. 2014. Ecoregions of the Conterminous United States: Evolution of a Hierarchical Spatial Framework. Environmental Management 54:1249–1266.

Pardo, L. H., M. E. Fenn, C. L. Goodale, L. H. Geiser, C. T. Driscoll, E. B. Allen, J. S. Baron, R. Bobbink, W. D. Bowman, C. M. Clark, B. Emmett, F. S. Gilliam, T. L. Greaver, S. J. Hall, E. A. Lilleskov, L. Liu, J. A. Lynch, K. J. Nadelhoffer, S. S. Perakis, M. J. Robin-Abbott, J. L. Stoddard, K. C. Weathers, and R. L. Dennis. 2011. Effects of nitrogen deposition and empirical nitrogen critical loads for ecoregions of the United States. Ecological Applications **21**:3049–3082.

Porter, E., T. Blett, D. U. Potter, and C. Huber. 2005. Protecting Resources on Federal Lands: Implications of Critical Loads for Atmospheric Deposition of Nitrogen and Sulfur. BioScience **55**:603–612.

Root, H. T., L. H. Geiser, M. E. Fenn, S. Jovan, M. A. Hutten, S. Ahuja, K. Dillman, D. Schirokauer, S. Berryman, and J. A. McMurray. 2013. A simple tool for estimating throughfall nitrogen deposition in forests of western North America using lichens. Forest Ecology and Management **306**:1–8.

Schwede, D. B. and G. G. Lear. 2014. A novel hybrid approach for estimating total deposition in the United States. Atmospheric Environment **92**:207–220.

Sullivan, T. J., C. T. Driscoll, C. M. Beier, D. Burtraw, I. J. Fernandez, J. N. Galloway, D. A. Gay, C. L. Goodale, G. E. Likens, G. M. Lovett, and S. A. Watmough. 2018. Air pollution success stories in the United States: The value of long-term observations. Environmental Science & Policy **84**:69–73.

Weldon, J. and U. Grandin. 2021. Weak recovery of epiphytic lichen communities in Sweden over 20 years of rapid air pollution decline. The Lichenologist 53:203–213.

Walker, J. T., M. D. Bell, D. Schwede, A. Cole, G. Beachley, G. Lear, and Z. Wu. 2019. Aspects of uncertainty in total reactive nitrogen deposition estimates for North American critical load applications. Science of the Total Environment 690:1005–1018.

Williams, J. J., S. H. Chung, A. M. Johansen, B. K. Lamb, J. K. Vaughan, and M. Beutel. 2017. Evaluation of atmospheric nitrogen deposition model performance in the context of U.S. critical load assessments. Atmospheric Environment **150**:244–255.

Appendix A – All NPS unit area above CL

Nitrogen Deposition Response

This table reports the current expected forested area at risk of exceedance of the critical load of nitrogen (CLN) for a decline in each of the four lichen community categories defined by Geiser et al. (2019) based on 2015–2017 TDep total nitrogen deposition. These conditions are compared to 2000–2002 TDep total nitrogen deposition to calculate improvement or decline of conditions. All NPS units listed below have greater than 1 km^2 of forest cover.

Table A1. The current and change of the percent of forested area that is above the critical load of nitrogen for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-N ha^{-1} yr^{-1} above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max N dep.	Δ max N dep	2016 area above CLN spp. rich.	Δ area above CLN spp. rich	2016 area above CLN N-sens. lichen	Δ area above CLN N-sens. lichen loss	2016 area above CLN forage lichen	Δ area above CLN forage lichen	2016 area above CLN cyano lichen	Δ area above CLN cyano lichen
ABLI	10.0	−3.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
ACAD	5.0	−4.8	0.2	−99.8	0.2	−99.8	100.0	0.0	100.0	0.0
ALPO	10.4	−6.7	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
ANTI	10.1	−4.6	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
APCO	7.4	−3.7	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
APIS	7.5	−1.8	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
APPA	14.8	−8.3	93.3	−6.7	96.3	−3.7	100.0	0.0	100.0	0.0
ARCH	3.0	−0.9	0.0	0.0	0.0	0.0	100.0	0.0	NA	NA
BADL	6.1	0.3	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
BAND	4.2	−1.4	16.1	−39.7	28.1	−62.2	100.0	0.0	NA	NA
BIBE	5.1	−0.2	98.2	45.9	99.5	0.4	100.0	0.0	NA	NA
BICA	3.7	0.0	0.0	0.0	0.1	0.0	93.2	4.5	NA	NA
BICY	7.1	−1.2	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
BISO	8.3	−5.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
BITH	14.5	−8.2	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
BLCA	2.9	−0.4	0.0	0.0	0.0	0.0	73.6	−26.4	NA	NA
BLRI	9.8	−7.2	98.6	0.0	98.6	0.0	98.6	0.0	98.6	0.0
BLUE	7.7	−5.6	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
BRCA	4.7	−1.6	13.9	−67.8	41.8	−58.2	100.0	0.0	NA	NA

Table A1 (continued). The current and change of the percent of forested area that is above the critical load of nitrogen for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-N ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max N dep.	Δ max N dep	2016 area above CLN spp. rich.	Δ area above CLN spp. rich	2016 area above CLN N-sens. lichen	Δ area above CLN N-sens. lichen loss	2016 area above CLN forage lichen	Δ area above CLN forage lichen	2016 area above CLN cyano lichen	Δ area above CLN cyano lichen
BUFF	9.7	−1.7	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CACH	4.0	−1.0	10.5	−53.7	15.2	−73.1	100.0	0.0	NA	NA
CACO	3.8	−2.9	0.0	0.0	85.0	−15.0	100.0	0.0	100.0	0.0
CAHA	6.8	−0.9	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CANA	5.7	−2.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CANY	3.2	−1.2	0.0	0.0	0.0	0.0	83.7	−16.3	NA	NA
CARE	4.2	−1.2	3.3	−20.5	17.3	−29.1	100.0	0.0	NA	NA
CATO	12.0	−8.2	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CAVE	4.4	−0.2	80.5	0.3	100.0	0.0	100.0	0.0	NA	NA
CAVO	5.6	1.0	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
CEBR	5.8	−1.5	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
CHAT	15.2	−12.4	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CHCH	12.3	−7.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CHCU	2.6	−0.7	0.0	0.0	0.0	0.0	100.0	0.0	NA	NA
CHIC	10.5	−1.9	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
CHIR	5.5	−1.5	11.0	−89.0	98.3	−1.7	100.0	0.0	NA	NA
CHIS	6.5	−3.7	48.1	−32.9	48.1	−50.9	100.0	0.0	NA	NA
CHOH	13.2	−7.1	99.6	0.0	99.6	0.0	99.6	0.0	99.6	0.0
CIRO	5.1	0.5	27.4	5.9	99.9	78.3	100.0	0.0	NA	NA
COLM	3.3	−0.6	0.0	0.0	0.0	0.0	95.3	−4.7	NA	NA
COLO	10.0	−4.6	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CONG	7.8	−6.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
COWP	6.8	−2.9	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CRLA	3.6	0.1	0.0	0.0	2.8	0.0	85.7	5.3	NA	NA
CRMO	3.0	0.5	0.0	0.0	0.0	0.0	100.0	0.0	NA	NA

Table A1 (continued). The current and change of the percent of forested area that is above the critical load of nitrogen for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-N ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max N dep.	Δ max N dep	2016 area above CLN spp. rich.	Δ area above CLN spp. rich	2016 area above CLN N-sens. lichen	Δ area above CLN N-sens. lichen loss	2016 area above CLN forage lichen	Δ area above CLN forage lichen	2016 area above CLN cyano lichen	Δ area above CLN cyano lichen
CUGA	7.5	−5.4	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CUIS	4.9	−1.9	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
CURE	3.0	−0.7	0.0	0.0	0.0	0.0	81.6	−4.7	NA	NA
CUVA	13.5	−6.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
DEPO	5.8	0.0	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
DETO	4.4	0.2	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
DEVA	6.1	−3.7	77.6	−22.4	95.6	−4.4	100.0	0.0	NA	NA
DEWA	9.4	−5.2	94.8	0.0	94.8	0.0	94.8	0.0	94.8	0.0
DINO	3.5	−0.2	0.0	0.0	0.0	0.0	100.0	1.1	NA	NA
EBLA	4.0	−1.1	6.7	−93.3	100.0	0.0	100.0	0.0	100.0	0.0
EFMO	13.8	−0.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
ELMA	4.3	−1.2	8.9	−72.5	9.9	−86.8	100.0	0.0	NA	NA
ELMO	3.4	−0.5	0.0	0.0	0.0	0.0	100.0	0.0	NA	NA
EVER	7.4	−2.2	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
FIIS	8.7	−7.5	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
FLFO	4.0	−0.6	36.2	−41.3	100.0	0.0	100.0	0.0	NA	NA
FOBU	4.2	1.0	98.6	0.0	100.0	0.0	100.0	0.0	NA	NA
FODO	10.4	−4.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
FONE	10.0	−5.9	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
FRHI	8.5	−4.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
FRSP	8.9	−4.8	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
GARI	7.8	−4.9	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
GETT	12.0	−4.7	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
GLAC	7.4	−0.2	56.4	7.0	70.2	6.1	98.4	6.6	NA	NA
GLCA	3.8	−1.3	0.0	0.0	8.0	−75.4	94.4	−5.6	NA	NA

Table A1 (continued). The current and change of the percent of forested area that is above the critical load of nitrogen for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-N ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max N dep.	Δ max N dep	2016 area above CLN spp. rich.	Δ area above CLN spp. rich	2016 area above CLN N-sens. lichen	Δ area above CLN N-sens. lichen loss	2016 area above CLN forage lichen	Δ area above CLN forage lichen	2016 area above CLN cyano lichen	Δ area above CLN cyano lichen
GOGA	10.0	−4.4	99.8	3.3	99.8	0.0	100.0	0.0	100.0	0.0
GRBA	4.3	−1.3	15.6	−71.1	76.4	−22.7	100.0	0.0	NA	NA
GRCA	6.2	−3.1	37.4	−34.3	45.2	−40.3	97.5	−2.5	NA	NA
GREE	14.2	−5.2	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
GRPO	6.4	−1.8	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
GRSA	6.0	−0.2	69.1	0.0	83.8	3.5	100.0	0.0	NA	NA
GRSM	8.4	−7.5	98.5	0.0	98.5	0.0	98.5	0.0	98.5	0.0
GRTE	7.4	−2.0	59.3	6.1	71.5	5.6	100.0	0.0	NA	NA
GUMO	5.6	−0.4	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
GWMP	13.2	−7.1	99.5	0.0	99.5	0.0	99.5	0.0	99.5	0.0
HAFE	9.8	−4.5	92.4	0.0	92.4	0.0	92.4	0.0	92.4	0.0
HOBE	7.4	−4.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
HOCU	9.3	−5.5	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
HOFR	8.1	−5.1	99.9	0.0	99.9	0.0	99.9	0.0	99.9	0.0
HOFU	12.2	−4.7	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
HOSP	9.1	−2.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
INDU	16.7	−3.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
ISRO	6.8	−1.7	96.6	−3.4	100.0	0.0	100.0	0.0	100.0	0.0
JECA	5.2	−0.6	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
JODR	5.4	0.2	100.0	51.6	100.0	0.0	100.0	0.0	NA	NA
JOTR	5.4	−4.6	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
KAWW	4.0	−2.0	1.0	−99.0	31.7	−68.3	100.0	0.0	100.0	0.0
KEMO	12.7	−12.6	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
KICA	8.5	−4.0	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
KIMO	7.8	−3.9	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0

Table A1 (continued). The current and change of the percent of forested area that is above the critical load of nitrogen for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-N ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max N dep.	Δ max N dep	2016 area above CLN spp. rich.	Δ area above CLN spp. rich	2016 area above CLN N-sens. lichen	Δ area above CLN N-sens. lichen loss	2016 area above CLN forage lichen	Δ area above CLN forage lichen	2016 area above CLN cyano lichen	Δ area above CLN cyano lichen
LABE	2.8	−0.1	0.0	0.0	0.0	0.0	9.8	0.0	NA	NA
LAKE	4.1	−2.1	0.1	−99.4	11.5	−88.5	100.0	0.0	NA	NA
LARO	2.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
LAVO	4.2	−1.8	10.0	−74.9	31.9	−67.8	100.0	0.0	NA	NA
LEWI	3.6	−0.8	0.0	0.0	0.0	0.0	88.3	0.0	100.0	0.0
LIRI	9.8	−5.5	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
MABI	5.6	−2.9	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
MACA	10.4	−4.6	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
MANA	9.7	−3.9	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
MEVE	4.1	−0.6	19.1	−44.0	98.5	−1.5	100.0	0.0	NA	NA
MIMA	7.7	−6.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
MISS	18.5	−3.2	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
MNRR	12.7	0.5	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
MOJA	4.7	−2.7	86.8	−13.2	98.8	−1.2	100.0	0.0	NA	NA
MONO	10.2	−4.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
MORA	4.4	−0.9	1.1	−7.5	6.3	−27.0	99.8	−0.2	NA	NA
MORR	11.0	−6.7	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
MORU	5.9	−0.6	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
MUWO	7.7	−3.1	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
NABR	4.1	−1.5	3.0	−97.0	76.4	−23.6	100.0	0.0	NA	NA
NATR	12.5	−5.2	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
NEPE	3.1	0.1	0.0	0.0	0.0	0.0	95.5	10.0	NA	NA
NERI	8.3	−6.8	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
NIOB	9.2	1.6	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
NISI	6.5	−3.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0

Table A1 (continued). The current and change of the percent of forested area that is above the critical load of nitrogen for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-N ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max N dep.	Δ max N dep	2016 area above CLN spp. rich.	Δ area above CLN spp. rich	2016 area above CLN N-sens. lichen	Δ area above CLN N-sens. lichen loss	2016 area above CLN forage lichen	Δ area above CLN forage lichen	2016 area above CLN cyano lichen	Δ area above CLN cyano lichen
NOCA	4.3	−0.3	3.7	2.0	11.6	−5.2	93.7	−1.7	NA	NA
OBRI	8.3	−5.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
OCMU	10.2	−5.4	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
OLYM	4.1	−1.9	0.1	−39.1	1.5	−63.4	61.6	−37.0	92.9	7.1
ORCA	4.3	0.5	100.0	0.0	100.0	18.6	100.0	0.0	NA	NA
OZAR	9.5	−2.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
PARA	4.6	−2.5	26.3	−63.7	58.0	−40.4	100.0	0.0	NA	NA
PECO	4.3	−1.3	74.9	−25.1	100.0	0.0	100.0	0.0	NA	NA
PERI	12.4	−0.2	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
PETE	10.7	−4.5	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
PINN	3.0	−1.9	0.0	0.0	0.0	0.0	100.0	0.0	NA	NA
PIRO	9.6	−1.8	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
PORE	5.7	−2.7	99.2	−0.7	99.3	−0.7	100.0	0.0	NA	NA
PRWI	9.8	−5.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
REDW	6.3	0.3	93.6	49.5	100.0	12.4	100.0	0.0	100.0	0.0
RICH	11.1	−6.6	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
ROCR	13.2	−6.8	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
ROMO	6.5	−3.7	77.5	−22.5	80.3	−19.7	100.0	0.0	NA	NA
ROVA	7.9	−4.9	13.9	0.0	13.9	0.0	13.9	0.0	13.9	0.0
RUCA	8.9	−5.4	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
SACN	10.9	−2.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
SAGU	5.4	−1.0	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
SAJH	4.0	−0.6	0.0	0.0	82.7	0.0	82.7	0.0	82.7	0.0
SAMO	22.1	−5.6	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
SARA	7.6	−4.2	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0

Table A1 (continued). The current and change of the percent of forested area that is above the critical load of nitrogen for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-N ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max N dep.	Δ max N dep	2016 area above CLN spp. rich.	Δ area above CLN spp. rich	2016 area above CLN N-sens. lichen	Δ area above CLN N-sens. lichen loss	2016 area above CLN forage lichen	Δ area above CLN forage lichen	2016 area above CLN cyano lichen	Δ area above CLN cyano lichen
SEKI	8.7	−4.2	57.8	0.0	57.8	0.0	57.8	0.0	NA	NA
SEQU	8.4	−2.8	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
SHEN	12.1	−8.2	94.7	0.0	94.7	0.0	94.7	0.0	94.7	0.0
SHIL	7.5	−3.6	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
SLBE	8.9	−4.5	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
STRI	9.7	−4.8	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
SUCR	4.9	−1.1	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
TAPR	9.7	−1.4	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
THRO	5.2	0.1	100.0	1.6	100.0	0.0	100.0	0.0	NA	NA
THST	8.8	−5.5	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
TIMU	7.5	−3.8	99.9	0.0	99.9	0.0	99.9	0.0	99.9	0.0
UPDE	8.1	−5.3	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
VAFO	12.8	−4.6	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
VICK	10.2	−3.5	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
VOYA	4.9	−2.2	92.2	−7.8	100.0	0.0	100.0	0.0	100.0	0.0
WACA	6.2	−0.9	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
WHIS	4.3	−1.3	23.5	−76.1	80.6	−19.4	100.0	0.0	NA	NA
WICA	5.5	−0.2	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
WICR	11.9	−0.1	100.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
YELL	6.1	0.0	50.2	15.8	73.0	17.7	100.0	3.8	NA	NA
YOSE	6.2	−1.5	100.0	0.0	100.0	0.0	100.0	0.0	NA	NA
ZION	4.5	−1.6	35.6	−62.0	75.3	−24.7	100.0	0.0	NA	NA

Sulfur Deposition Response

This table reports the current expected forested area at risk of exceedance of the critical load of sulfur (CLS) for a decline in each of the four lichen community categories defined by Geiser et al. (2019) based on 2015–2017 TDep total sulfur deposition. These conditions are compared to 2000–2002 TDep total sulfur deposition to calculate improvement or decline of conditions. All NPS units listed below have greater than 1 km^2 of forest cover

Table A2. The current and change of the percent of forested area that is above the critical load of sulfur for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-S ha^{-1} yr^{-1} above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max S dep.	Δ max S dep	2016 area above CLS spp. rich.	Δ area above CLS spp. Rich	2016 area above CLS sens. Lichen	Δ area above CLS S-sens. lichen loss	2016 area above CLS forage lichen	Δ area above CLS forage lichen	2016 area above CLS cyano lichen	Δ area above CLS cyano lichen
ABLI	3.9	−11.5	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
ACAD	4.3	−7.7	0.0	−100.0	0.4	−99.6	0.2	−99.8	11.9	−88.1
ALPO	9.3	−32.2	85.5	−14.5	100.0	0.0	100.0	0.0	100.0	0.0
ANTI	3.1	−12.0	0.0	−100.0	100.0	0.0	0.0	−100.0	100.0	0.0
APCO	2.2	−7.7	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
APIS	2.4	−3.2	0.0	0.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
APPA	5.4	−16.9	0.0	−84.5	29.9	−70.1	25.4	−74.6	42.3	−57.7
ARCH	1.0	−0.7	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
BADL	1.1	−0.5	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
BAND	1.0	−0.8	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
BIBE	1.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
BICA	1.2	−0.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
BICY	4.5	−1.6	0.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
BISO	3.1	−11.2	0.0	−100.0	8.7	−91.3	0.4	−99.6	76.1	−23.9
BITH	6.7	−6.4	0.2	−99.8	100.0	0.0	100.0	0.0	100.0	0.0
BLCA	0.7	−0.3	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
BLRI	3.8	−11.7	0.0	−100.0	21.7	−78.3	20.6	−79.4	35.8	−64.2
BLUE	4.2	−16.4	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
BRCA	1.0	−0.7	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
BUFF	3.1	−2.7	0.0	0.0	11.6	−88.4	2.0	−98.0	28.0	−72.0
CACH	1.0	−0.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA

Table A2 (continued). The current and change of the percent of forested area that is above the critical load of sulfur for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-S ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max S dep.	Δ max S dep	2016 area above CLS spp. rich.	Δ area above CLS spp. Rich	2016 area above CLS sens. Lichen	Δ area above CLS S-sens. lichen loss	2016 area above CLS forage lichen	Δ area above CLS forage lichen	2016 area above CLS cyano lichen	Δ area above CLS cyano lichen
CACO	4.6	−7.3	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
CAHA	4.7	−7.0	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
CANA	4.1	−4.7	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
CANY	1.1	−0.9	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
CARE	1.2	−0.7	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
CATO	3.9	−16.4	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
CAVE	1.6	−0.4	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
CAVO	1.2	−0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
CEBR	1.3	−1.1	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
CHAT	2.5	−17.1	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
CHCH	2.8	−11.4	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.1	−99.9
CHCU	0.7	−0.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
CHIC	3.4	−2.1	0.0	0.0	100.0	0.0	100.0	0.0	NA	NA
CHIR	1.1	−0.8	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
CHIS	3.2	−1.1	0.0	0.0	48.3	−51.7	48.3	−51.7	NA	NA
CHOH	3.3	−12.1	0.0	−100.0	63.1	−36.9	22.7	−77.3	77.0	−23.0
CIRO	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
COLM	1.0	−0.4	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
COLO	3.8	−9.9	0.0	−100.0	95.2	−4.8	86.6	−13.4	100.0	0.0
CONG	4.1	−9.9	0.0	−100.0	68.6	−31.4	68.6	−31.4	68.6	−31.4
COWP	1.7	−6.5	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
CRLA	1.1	−0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
CRMO	0.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
CUGA	2.8	−12.4	0.0	−100.0	0.0	−100.0	0.0	−100.0	6.1	−93.9
CUIS	3.2	−4.8	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
CURE	0.7	−0.4	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA

Table A2 (continued). The current and change of the percent of forested area that is above the critical load of sulfur for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-S ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max S dep.	Δ max S dep	2016 area above CLS spp. rich.	Δ area above CLS spp. Rich	2016 area above CLS sens. Lichen	Δ area above CLS S-sens. lichen loss	2016 area above CLS forage lichen	Δ area above CLS forage lichen	2016 area above CLS cyano lichen	Δ area above CLS cyano lichen
CUVA	7.2	−19.6	96.7	−3.3	100.0	0.0	100.0	0.0	100.0	0.0
DEPO	1.1	−0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
DETO	1.0	−0.9	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
DEVA	1.9	−0.5	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
DEWA	3.1	−12.3	0.0	−100.0	5.5	−94.5	0.0	−100.0	100.0	0.0
DINO	1.0	−0.2	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
EBLA	2.0	−1.7	0.0	0.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
EFMO	3.1	−4.6	0.0	−100.0	95.8	−4.2	0.0	−100.0	100.0	0.0
ELMA	1.0	−0.7	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
ELMO	0.9	−0.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
EVER	5.6	−1.3	0.0	0.0	100.0	0.0	100.0	0.0	NA	NA
FIIS	5.6	−9.9	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
FLFO	1.0	−0.5	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
FOBU	1.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
FODO	4.3	−9.6	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
FONE	5.8	−35.6	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
FRHI	4.4	−22.8	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
FRSP	2.5	−9.3	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
GARI	4.2	−16.3	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
GETT	3.4	−13.8	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
GLAC	1.8	−1.5	0.0	0.0	0.0	−1.9	0.0	−0.9	NA	NA
GLCA	1.1	−1.1	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
GOGA	3.2	−4.9	0.0	−1.4	12.1	−66.7	12.0	−64.0	12.1	−70.1
GRBA	1.2	−0.3	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
GRCA	1.3	−1.0	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
GREE	2.8	−11.4	0.0	−100.0	0.0	−100.0	0.0	−100.0	100.0	0.0

Table A2 (continued). The current and change of the percent of forested area that is above the critical load of sulfur for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-S ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max S dep.	Δ max S dep	2016 area above CLS spp. rich.	Δ area above CLS spp. Rich	2016 area above CLS sens. Lichen	Δ area above CLS S-sens. lichen loss	2016 area above CLS forage lichen	Δ area above CLS forage lichen	2016 area above CLS cyano lichen	Δ area above CLS cyano lichen
GRPO	2.0	−2.4	0.0	0.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
GRSA	1.8	−0.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
GRSM	3.1	−15.2	0.0	−100.0	8.3	−91.7	2.5	−97.5	23.9	−76.1
GRTE	2.3	−1.6	0.0	0.0	0.0	−3.1	0.0	−2.2	NA	NA
GUMO	2.0	−0.2	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
GWMP	3.1	−11.9	0.0	−100.0	8.1	−91.9	0.0	−100.0	63.4	−36.6
HAFE	3.1	−10.9	0.0	−100.0	64.9	−35.1	0.0	−100.0	100.0	0.0
HOBE	2.9	−9.3	0.0	−100.0	0.0	−100.0	0.0	−100.0	100.0	0.0
HOCU	5.3	−18.8	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
HOFR	3.1	−8.9	0.0	−100.0	5.2	−94.8	5.2	−94.8	5.2	−94.8
HOFU	3.2	−12.3	0.0	−100.0	100.0	0.0	22.5	−77.5	100.0	0.0
HOSP	3.6	−2.2	0.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
INDU	13.2	−15.2	20.4	−79.6	100.0	0.0	100.0	0.0	100.0	0.0
ISRO	2.7	−2.4	0.0	0.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
JECA	1.1	−0.9	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
JODR	1.8	−0.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
JOTR	0.7	−0.3	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
KAWW	1.8	−3.6	0.0	0.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
KEMO	2.4	−17.4	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
KICA	1.9	−1.2	0.0	0.0	0.0	−0.2	0.0	−0.2	NA	NA
KIMO	1.9	−7.5	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
LABE	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
LAKE	0.6	−1.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
LARO	0.7	−0.5	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
LAVO	1.1	−0.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
LEWI	2.6	−2.1	0.0	0.0	0.0	−100.0	0.0	−100.0	0.0	−100.0

Table A2 (continued). The current and change of the percent of forested area that is above the critical load of sulfur for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-S ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max S dep.	Δ max S dep	2016 area above CLS spp. rich.	Δ area above CLS spp. Rich	2016 area above CLS sens. Lichen	Δ area above CLS S-sens. lichen loss	2016 area above CLS forage lichen	Δ area above CLS forage lichen	2016 area above CLS cyano lichen	Δ area above CLS cyano lichen
LIRI	2.9	−11.7	0.0	−100.0	0.0	−100.0	0.0	−100.0	39.7	−60.3
MABI	2.1	−6.1	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
MACA	3.9	−12.1	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
MANA	2.6	−10.0	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
MEVE	1.0	−0.8	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
MIMA	3.1	−9.0	0.0	−100.0	98.9	−1.1	5.5	−94.5	99.0	−1.0
MISS	4.6	−13.2	0.0	−90.5	60.9	−39.1	52.0	−48.0	66.1	−33.9
MNRR	2.2	−3.4	0.0	0.0	0.0	−73.7	0.0	−73.7	NA	NA
MOJA	0.6	−0.8	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
MONO	2.9	−12.4	0.0	−100.0	8.2	−91.8	0.0	−100.0	100.0	0.0
MORA	2.2	−3.2	0.0	0.0	0.0	−94.0	0.0	−90.8	NA	NA
MORR	3.2	−12.3	0.0	−100.0	100.0	0.0	62.9	−37.1	100.0	0.0
MORU	1.1	−1.0	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
MUWO	2.6	−2.3	0.0	0.0	0.0	−100.0	0.0	−100.0	NA	NA
NABR	1.3	−1.0	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
NATR	4.0	−8.7	0.0	−100.0	96.4	−3.6	92.7	−7.3	100.0	0.0
NEPE	0.6	−0.3	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
NERI	4.6	−19.9	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
NIOB	1.5	−0.7	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
NISI	2.0	−5.8	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
NOCA	1.9	−1.5	0.0	0.0	0.0	−5.4	0.0	−3.9	NA	NA
OBRI	3.0	−10.9	0.0	−100.0	0.0	−100.0	0.0	−100.0	1.3	−98.7
OCMU	2.5	−8.7	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
OLYM	5.1	−4.5	0.0	−73.2	57.2	−42.8	52.8	−47.2	62.0	−38.0
ORCA	1.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
OZAR	3.8	−4.7	0.0	−98.3	100.0	0.0	100.0	0.0	100.0	0.0

Table A2 (continued). The current and change of the percent of forested area that is above the critical load of sulfur for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-S ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max S dep.	Δ max S dep	2016 area above CLS spp. rich.	Δ area above CLS spp. Rich	2016 area above CLS sens. Lichen	Δ area above CLS S-sens. lichen loss	2016 area above CLS forage lichen	Δ area above CLS forage lichen	2016 area above CLS cyano lichen	Δ area above CLS cyano lichen
PARA	0.9	−0.7	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
PECO	0.9	−0.7	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
PERI	3.4	−1.8	0.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0
PETE	3.0	−10.4	0.0	−100.0	0.1	−99.9	0.0	−100.0	0.1	−99.9
PINN	0.7	−0.2	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
PIRO	5.2	−4.9	0.0	−31.9	37.7	−62.3	31.9	−68.1	53.0	−47.0
PORE	2.6	−1.1	0.0	0.0	0.0	−4.9	0.0	−4.9	NA	NA
PRWI	2.8	−10.2	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
REDW	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RICH	3.0	−12.0	0.0	−100.0	0.0	−100.0	0.0	−100.0	69.8	−30.2
ROCR	3.1	−11.7	0.0	−100.0	94.7	−5.3	0.0	−100.0	100.0	0.0
ROMO	1.7	−2.9	0.0	0.0	0.0	−2.4	0.0	−2.4	NA	NA
ROVA	2.8	−9.0	0.0	−100.0	3.9	−96.1	3.9	−96.1	9.0	−91.0
RUCA	2.9	−11.1	0.0	−100.0	0.0	−100.0	0.0	−100.0	95.8	−4.2
SACN	2.3	−3.2	0.0	0.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
SAGU	1.3	−0.8	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
SAJH	2.4	−1.8	0.0	0.0	0.0	−82.8	0.0	−82.8	0.0	−82.8
SAMO	1.9	−1.9	0.0	0.0	0.0	−11.2	0.0	−10.4	NA	NA
SARA	2.5	−7.8	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
SEKI	1.7	−0.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
SEQU	1.4	−0.5	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
SHEN	2.7	−12.0	0.0	−100.0	0.0	−100.0	0.0	−100.0	0.0	−100.0
SHIL	4.0	−6.7	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
SLBE	3.3	−7.8	0.0	−100.0	3.6	−96.4	0.8	−99.2	23.5	−76.5
STRI	3.6	−7.6	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
SUCR	1.0	−0.2	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA

Table A2 (continued). The current and change of the percent of forested area that is above the critical load of sulfur for each lichen category. Above CL is calculated as deposition greater than 0.5 kg-S ha−1 yr−1 above the critical load. Negative numbers in the change columns represent improving conditions.

NPS unit	2016 max S dep.	Δ max S dep	2016 area above CLS spp. rich.	Δ area above CLS spp. Rich	2016 area above CLS sens. Lichen	Δ area above CLS S-sens. lichen loss	2016 area above CLS forage lichen	Δ area above CLS forage lichen	2016 area above CLS cyano lichen	Δ area above CLS cyano lichen
TAPR	2.3	−2.0	0.0	0.0	0.0	−100.0	0.0	−100.0	NA	NA
THRO	2.0	−1.3	0.0	0.0	0.0	−42.6	0.0	−42.6	NA	NA
THST	2.8	−11.3	0.0	−100.0	0.0	−100.0	0.0	−100.0	26.4	−73.6
TIMU	4.5	−5.5	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
UPDE	3.1	−12.5	0.0	−100.0	4.8	−95.2	0.5	−99.5	25.2	−74.8
VAFO	3.2	−12.1	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
VICK	3.9	−4.0	0.0	−100.0	100.0	0.0	100.0	0.0	100.0	0.0
VOYA	1.4	−1.8	0.0	0.0	0.0	−59.1	0.0	−46.9	0.0	−98.4
WACA	1.2	−0.3	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
WHIS	1.1	−0.5	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
WICA	1.0	−0.8	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
WICR	3.3	−3.7	0.0	−8.6	15.0	−85.0	8.6	−91.4	100.0	0.0
YELL	2.0	−0.6	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
YOSE	1.5	−0.2	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA
ZION	1.0	−0.7	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA

Appendix B – All NPS Unit Response Data

Nitrogen Deposition Response

This table reports the current expected maximum rate of community decline for each of the four lichen community categories defined by Geiser et al. (2019) based on maximum 2015–2017 TDep total nitrogen deposition within a unit's boundary. All NPS units listed below have greater than 1 km^2 of forest cover.

Table B1. The maximum nitrogen (N) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha^{-1} yr^{-1}) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions and positive values indicate improving conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS Unit	2016 max N dep.	Δ max N dep	2016 spp. rich. loss	Δ spp. rich loss	2016 N-sens. lichen loss	Δ N-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
ABLI	10.0	−3.1	45.1	4.0	58.0	13.3	79.2	7.3	95.7	1.7
ACAD	5.0	−4.8	27.7	16.9	31.5	25.5	48.4	29.9	65.7	29.5
ALPO	10.4	−6.7	46.2	2.9	60.2	26.2	81.2	5.3	96.6	0.8
ANTI	10.1	−4.6	45.4	3.7	58.6	19.2	79.8	6.8	96.0	1.4
APCO	7.4	−3.7	37.4	9.7	44.9	17.3	65.4	17.4	84.7	12.5
APIS	7.5	−1.8	37.8	5.5	45.5	9.1	66.1	9.8	85.3	8.3
APPA	14.8	−8.3	49.1	0.0	78.2	16.4	86.6	0.0	97.5	0.0
ARCH	3.0	−0.9	18.2	2.6	20.0	3.1	31.8	4.6	44.5	6.0
BADL	6.1	0.3	32.8	−3.7	38.3	−5.0	57.3	−6.6	76.1	−7.6
BAND	4.2	−1.4	24.0	6.1	26.9	7.8	41.9	10.8	57.7	13.1
BIBE	5.1	−0.2	28.4	−2.1	32.4	−2.6	49.6	−3.6	67.2	−4.4
BICA	3.7	0.0	21.5	−1.1	23.8	−1.3	37.5	−1.9	52.0	−2.5
BICY	7.1	−1.2	36.3	2.7	43.4	4.1	63.6	4.8	82.8	4.6
BISO	8.3	−5.1	40.4	8.8	49.6	22.9	70.8	15.8	89.6	7.9
BITH	14.5	−8.2	49.1	0.0	77.5	17.2	86.6	0.0	97.5	0.0
BLCA	2.9	−0.4	17.3	2.0	19.0	2.3	30.2	3.4	42.5	4.6
BLRI	9.8	−7.2	44.8	4.4	57.4	25.3	78.6	7.9	95.4	2.2
BLUE	7.7	−5.6	38.7	10.5	46.9	25.6	67.7	18.8	86.9	10.6
BRCA	4.7	−1.6	26.7	6.9	30.3	9.2	46.7	12.1	63.7	14.1
BUFF	9.7	−1.7	44.5	3.2	56.8	6.7	78.1	5.8	95.1	2.4

Table B1 (continued). The maximum nitrogen (N) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions and positive values indicate improving conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS Unit	2016 max N dep.	Δ max N dep	2016 spp. rich. loss	Δ spp. rich loss	2016 N-sens. lichen loss	Δ N-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
CACH	4.0	−1.0	23.3	4.6	26.1	5.7	40.7	8.0	56.2	9.9
CACO	3.8	−2.9	22.0	12.9	24.5	16.8	38.5	22.6	53.3	26.9
CAHA	6.8	−0.9	35.4	2.4	41.9	3.6	61.9	4.3	81.0	4.3
CANA	5.7	−2.0	31.0	7.5	35.9	10.8	54.2	13.3	72.6	14.1
CANY	3.2	−1.2	18.9	4.6	20.7	5.5	32.9	8.0	46.1	10.4
CARE	4.2	−1.2	24.2	5.3	27.2	6.8	42.3	9.4	58.2	11.4
CATO	12.0	−8.2	49.1	0.0	67.3	27.3	86.6	0.0	97.5	−0.1
CAVE	4.4	−0.2	25.2	0.7	28.4	0.8	44.1	1.2	60.4	1.5
CAVO	5.6	1.0	30.6	−4.6	35.3	−5.9	53.4	−8.0	71.7	−9.6
CEBR	5.8	−1.5	31.4	5.9	36.5	8.4	55.0	10.5	73.5	11.2
CHAT	15.2	−12.4	49.1	0.0	79.9	14.7	86.6	0.0	97.5	−0.1
CHCH	12.3	−7.1	49.1	0.0	68.5	19.4	86.6	0.0	97.4	0.0
CHCU	2.6	−0.7	16.1	3.4	17.5	4.0	28.0	6.0	39.5	8.0
CHIC	10.5	−1.9	46.4	2.7	60.7	6.6	81.6	4.9	96.8	0.7
CHIR	5.5	−1.5	30.0	6.0	34.5	8.3	52.4	10.6	70.4	11.7
CHIS	6.5	−3.7	34.3	11.5	40.4	19.0	59.9	20.5	79.0	17.3
CHOH	13.2	−7.1	49.1	0.0	72.1	22.4	86.6	0.0	97.5	0.0
CIRO	5.1	0.5	28.4	−2.3	32.5	−2.9	49.6	−4.0	67.2	−4.8
COLM	3.3	−0.6	19.5	1.8	21.5	2.2	34.0	3.2	47.5	4.2
COLO	10.0	−4.6	45.2	4.0	58.2	18.8	79.4	7.2	95.7	1.6
CONG	7.8	−6.1	38.7	10.4	47.0	28.0	67.8	18.7	87.0	10.5
COWP	6.8	−2.9	35.2	9.1	41.7	14.7	61.5	16.1	80.7	14.1
CRLA	3.6	0.1	21.3	−2.0	23.6	−2.3	37.2	−3.5	51.6	−4.5
CRMO	3.0	0.5	17.9	−4.1	19.6	−4.7	31.3	−7.2	43.9	−9.7
CUGA	7.5	−5.4	38.0	11.2	45.8	24.8	66.5	20.1	85.7	11.8

Table B1 (continued). The maximum nitrogen (N) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions and positive values indicate improving conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS Unit	2016 max N dep.	Δ max N dep	2016 spp. rich. loss	Δ spp. rich loss	2016 N-sens. lichen loss	Δ N-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
CUIS	4.9	−1.9	27.5	7.6	31.3	10.3	48.1	13.4	65.3	15.3
CURE	3.0	−0.7	17.8	3.8	19.5	4.5	31.0	6.7	43.5	8.8
CUVA	13.5	−6.0	49.1	0.0	73.3	16.3	86.6	0.0	97.5	−0.1
DEPO	5.8	0.0	31.4	0.0	36.5	0.0	54.9	0.0	73.4	−0.1
DETO	4.4	0.2	25.2	−0.8	28.4	−0.9	44.0	−1.3	60.4	−1.6
DEVA	6.1	−3.7	32.7	9.4	38.2	14.3	57.2	16.6	76.0	16.1
DEWA	9.4	−5.2	43.6	5.5	55.2	20.7	76.5	10.0	94.0	3.3
DINO	3.5	−0.2	20.6	−0.5	22.8	−0.5	36.0	−0.8	50.1	−1.0
EBLA	4.0	−1.1	23.2	5.2	25.9	6.5	40.5	9.1	55.9	11.2
EFMO	13.8	−0.1	49.1	0.0	74.6	−0.2	86.6	0.0	97.4	0.0
ELMA	4.3	−1.2	24.6	5.2	27.6	6.7	43.0	9.2	59.0	11.2
ELMO	3.4	−0.5	20.1	2.7	22.1	3.3	35.0	4.8	48.8	6.2
EVER	7.4	−2.2	37.7	6.5	45.4	10.8	66.0	11.5	85.2	9.5
FIIS	8.7	−7.5	41.7	7.4	51.9	31.3	73.2	13.4	91.6	5.8
FLFO	4.0	−0.6	23.3	2.3	26.0	2.8	40.6	4.0	56.1	5.1
FOBU	4.2	1.0	24.3	−5.4	27.2	−6.5	42.4	−9.5	58.3	−12.3
FODO	10.4	−4.0	46.0	3.1	59.8	16.3	80.9	5.7	96.5	0.9
FONE	10.0	−5.9	45.2	3.9	58.3	24.3	79.5	7.1	95.8	1.6
FRHI	8.5	−4.0	41.0	8.1	50.7	16.5	71.9	14.6	90.6	6.9
FRSP	8.9	−4.8	42.4	6.7	53.1	20.7	74.4	12.2	92.5	5.0
GARI	7.8	−4.9	38.8	10.4	47.1	22.7	67.9	18.6	87.1	10.4
GETT	12.0	−4.7	49.1	0.0	67.3	16.1	86.6	0.0	97.5	−0.1
GLAC	7.4	−0.2	37.4	−0.9	44.9	−1.3	65.5	−1.6	84.7	−1.6
GLCA	3.8	−1.3	22.1	6.0	24.6	7.5	38.6	10.5	53.5	13.1
GOGA	10.0	−4.4	45.2	3.9	58.2	18.5	79.4	7.1	95.8	1.7

Table B1 (continued). The maximum nitrogen (N) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions and positive values indicate improving conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS Unit	2016 max N dep.	Δ max N dep	2016 spp. rich. loss	Δ spp. rich loss	2016 N-sens. lichen loss	Δ N-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
GRBA	4.3	−1.3	24.8	4.6	27.9	5.9	43.3	8.1	59.4	9.8
GRCA	6.2	−3.1	33.0	9.1	38.6	13.9	57.7	16.1	76.5	15.5
GREE	14.2	−5.2	49.1	0.0	76.0	16.9	86.6	0.0	97.4	0.0
GRPO	6.4	−1.8	33.9	5.9	39.9	8.9	59.3	10.5	78.3	10.4
GRSA	6.0	−0.2	32.4	0.7	37.7	1.0	56.6	1.3	75.3	1.5
GRSM	8.4	−7.5	40.8	8.3	50.4	31.5	71.6	15.0	90.3	7.2
GRTE	7.4	−2.0	37.5	3.7	45.0	5.8	65.6	6.6	84.8	5.9
GUMO	5.6	−0.4	30.6	1.4	35.3	1.8	53.4	2.4	71.7	2.8
GWMP	13.2	−7.1	49.1	0.0	72.1	22.4	86.6	0.0	97.5	−0.1
HAFE	9.8	−4.5	44.7	4.4	57.3	18.9	78.5	8.0	95.3	2.1
HOBE	7.4	−4.1	37.7	10.5	45.4	19.4	66.0	18.9	85.2	12.3
HOCU	9.3	−5.5	43.5	5.6	55.0	23.0	76.4	10.2	94.0	3.4
HOFR	8.1	−5.1	39.8	9.3	48.7	21.8	69.8	16.8	88.8	8.6
HOFU	12.2	−4.7	49.1	0.0	67.9	14.3	86.6	0.0	97.4	0.0
HOSP	9.1	−2.0	42.8	4.7	53.6	9.4	75.0	8.5	93.0	4.4
INDU	16.7	−3.1	49.1	0.0	84.8	9.3	86.6	0.0	97.5	−0.1
ISRO	6.8	−1.7	35.5	5.6	42.1	8.7	62.1	10.0	81.3	9.4
JECA	5.2	−0.6	28.8	2.2	33.0	2.9	50.3	3.8	68.1	4.5
JODR	5.4	0.2	29.8	−1.0	34.3	−1.3	52.1	−1.7	70.2	−2.0
JOTR	5.4	−4.6	29.8	14.4	34.3	22.0	52.1	25.5	70.1	24.6
KAWW	4.0	−2.0	23.3	7.8	26.1	10.0	40.7	13.8	56.2	16.7
KEMO	12.7	−12.6	49.1	0.0	70.1	24.5	86.6	0.0	97.4	0.0
KICA	8.5	−4.0	41.0	5.9	50.6	11.0	71.8	10.5	90.5	6.5
KIMO	7.8	−3.9	39.0	9.2	47.4	17.4	68.3	16.5	87.4	10.1
LABE	2.8	−0.1	16.8	−0.1	18.4	−0.2	29.4	−0.2	41.3	−0.3

Table B1 (continued). The maximum nitrogen (N) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions and positive values indicate improving conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS Unit	2016 max N dep.	Δ max N dep	2016 spp. rich. loss	Δ spp. rich loss	2016 N-sens. lichen loss	Δ N-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
LAKE	4.1	−2.1	23.7	7.3	26.5	9.3	41.4	12.7	57.0	15.4
LARO	2.4	0.1	14.7	−0.8	15.9	−1.0	25.6	−1.5	36.3	−2.0
LAVO	4.2	−1.8	23.9	7.9	26.8	10.2	41.7	13.9	57.5	16.7
LEWI	3.6	−0.8	21.1	3.3	23.3	4.1	36.7	5.9	51.1	7.5
LIRI	9.8	−5.5	44.7	4.4	57.2	22.2	78.5	8.1	95.3	2.1
MABI	5.6	−2.9	30.6	10.6	35.3	15.6	53.5	18.7	71.7	19.1
MACA	10.4	−4.6	46.1	3.0	60.0	18.2	81.0	5.6	96.5	0.8
MANA	9.7	−3.9	44.4	4.7	56.7	17.0	78.0	8.6	95.0	2.4
MEVE	4.1	−0.6	23.5	2.2	26.3	2.7	41.0	3.9	56.5	4.8
MIMA	7.7	−6.1	38.7	10.4	47.0	27.3	67.8	18.8	86.9	10.4
MISS	18.5	−3.2	49.1	0.0	90.6	4.1	86.6	0.0	97.4	0.0
MNRR	12.7	0.5	49.1	0.0	70.4	−3.3	86.6	−0.1	97.5	0.0
MOJA	4.7	−2.7	26.6	10.2	30.2	14.0	46.5	18.0	63.5	20.3
MONO	10.2	−4.0	45.6	3.6	58.9	17.1	80.0	6.5	96.1	1.3
MORA	4.4	−0.9	25.3	2.1	28.6	2.7	44.3	3.8	60.6	4.6
MORR	11.0	−6.7	47.4	1.7	62.9	25.0	83.4	3.1	97.3	0.1
MORU	5.9	−0.6	31.7	1.2	36.8	1.7	55.5	2.2	74.0	2.4
MUWO	7.7	−3.1	38.7	8.3	47.0	14.9	67.8	14.8	86.9	10.2
NABR	4.1	−1.5	23.4	6.6	26.2	8.4	40.9	11.6	56.5	14.2
NATR	12.5	−5.2	49.1	0.0	69.3	18.8	86.6	0.0	97.4	0.1
NEPE	3.1	0.1	18.4	−1.0	20.2	−1.2	32.1	−1.8	45.0	−2.4
NERI	8.3	−6.8	40.4	8.7	49.7	29.7	70.9	15.7	89.7	7.7
NIOB	9.2	1.6	43.2	−5.1	54.5	−8.5	75.9	−9.1	93.6	−7.7
NISI	6.5	−3.0	34.0	9.8	40.0	15.5	59.5	17.4	78.5	15.8
NOCA	4.3	−0.3	24.8	−0.7	27.9	−0.9	43.4	−1.2	59.6	−1.5

Table B1 (continued). The maximum nitrogen (N) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions and positive values indicate improving conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS Unit	2016 max N dep.	Δ max N dep	2016 spp. rich. loss	Δ spp. rich loss	2016 N-sens. lichen loss	Δ N-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
OBRI	8.3	−5.0	40.4	8.8	49.6	20.0	70.8	15.8	89.6	7.9
OCMU	10.2	−5.4	45.7	3.5	59.1	19.4	80.2	6.4	96.2	1.2
OLYM	4.1	−1.9	23.7	3.5	26.6	4.4	41.5	6.1	57.1	7.6
ORCA	4.3	0.5	24.6	−3.0	27.6	−3.7	43.0	−5.3	59.0	−6.8
OZAR	9.5	−2.0	43.9	3.9	55.7	8.2	77.0	7.1	94.4	3.1
PARA	4.6	−2.5	25.9	8.8	29.3	11.8	45.2	15.5	61.8	18.0
PECO	4.3	−1.3	24.7	5.3	27.8	6.7	43.1	9.2	59.3	11.2
PERI	12.4	−0.2	49.1	−0.3	68.8	−2.3	86.6	−0.5	97.5	0.0
PETE	10.7	−4.5	46.7	2.5	61.3	18.1	82.1	4.5	96.9	0.6
PINN	3.0	−1.9	18.2	9.1	19.9	11.1	31.7	16.0	44.4	20.4
PIRO	9.6	−1.8	44.3	3.2	56.4	6.6	77.8	5.8	94.8	2.5
PORE	5.7	−2.7	31.0	10.0	35.9	14.7	54.2	17.7	72.6	18.0
PRWI	9.8	−5.1	44.8	4.4	57.4	21.5	78.6	7.9	95.3	2.0
REDW	6.3	0.3	33.4	−4.9	39.2	−6.6	58.4	−8.7	77.3	−10.0
RICH	11.1	−6.6	47.6	1.5	63.3	23.2	83.7	2.8	97.4	0.1
ROCR	13.2	−6.8	49.1	0.0	72.3	22.3	86.6	0.0	97.4	0.0
ROMO	6.5	−3.7	34.0	9.6	40.0	15.1	59.5	17.0	78.5	15.5
ROVA	7.9	−4.9	39.3	9.9	47.9	22.8	68.8	17.7	87.9	9.5
RUCA	8.9	−5.4	42.2	6.9	52.7	23.2	74.0	12.5	92.2	5.1
SACN	10.9	−2.1	47.1	2.0	62.2	6.7	82.8	3.7	97.2	0.3
SAGU	5.4	−1.0	29.7	3.3	34.1	4.5	51.9	5.9	69.9	6.7
SAJH	4.0	−0.6	23.1	2.9	25.8	3.6	40.3	5.1	55.6	6.4
SAMO	22.1	−5.6	49.1	0.0	94.6	0.0	86.6	0.0	97.4	0.0
SARA	7.6	−4.2	38.1	10.7	46.0	20.2	66.7	19.2	85.9	11.6
SEKI	8.7	−4.2	41.6	6.1	51.6	12.0	72.9	11.0	91.4	6.0

Table B1 (continued). The maximum nitrogen (N) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions and positive values indicate improving conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS Unit	2016 max N dep.	Δ max N dep	2016 spp. rich. loss	Δ spp. rich loss	2016 N-sens. lichen loss	Δ N-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
SEQU	8.4	−2.8	40.8	6.1	50.3	11.4	71.5	11.0	90.2	6.8
SHEN	12.1	−8.2	49.1	0.0	67.5	26.0	86.6	0.0	97.5	−0.1
SHIL	7.5	−3.6	37.9	9.5	45.7	17.2	66.3	17.1	85.5	11.8
SLBE	8.9	−4.5	42.2	7.0	52.6	20.0	74.0	12.6	92.2	5.3
STRI	9.7	−4.8	44.3	4.8	56.5	20.5	77.9	8.7	94.9	2.5
SUCR	4.9	−1.1	27.3	4.9	31.0	6.5	47.6	8.7	64.8	10.2
TAPR	9.7	−1.4	44.5	2.1	56.8	4.3	78.1	3.8	95.1	1.8
THRO	5.2	0.1	28.7	−1.4	32.8	−1.8	50.2	−2.5	67.8	−3.0
THST	8.8	−5.5	42.0	7.1	52.3	23.9	73.6	12.9	92.0	5.4
TIMU	7.5	−3.8	37.8	9.8	45.5	17.7	66.2	17.5	85.4	12.0
UPDE	8.1	−5.3	40.0	9.1	49.0	24.0	70.1	16.5	89.0	8.5
VAFO	12.8	−4.6	49.1	0.0	70.7	16.7	86.6	0.0	97.4	0.0
VICK	10.2	−3.5	45.8	3.4	59.4	15.1	80.4	6.1	96.3	1.1
VOYA	4.9	−2.2	27.2	8.4	31.0	11.4	47.6	14.9	64.7	16.9
WACA	6.2	−0.9	32.9	2.9	38.5	4.1	57.6	5.1	76.4	5.5
WHIS	4.3	−1.3	24.6	6.0	27.7	7.7	43.0	10.5	59.0	12.7
WICA	5.5	−0.2	30.0	1.0	34.5	1.4	52.4	1.8	70.5	2.1
WICR	11.9	−0.1	49.0	0.1	66.9	0.2	86.4	0.1	97.4	0.0
YELL	6.1	0.0	32.4	−0.7	37.8	−1.0	56.7	−1.3	75.4	−1.5
YOSE	6.2	−1.5	33.1	1.9	38.7	2.7	57.8	3.4	76.6	3.6
ZION	4.5	−1.6	25.7	5.7	29.1	7.4	45.0	10.0	61.5	12.0

Sulfur Deposition

This table reports the current expected community response rate based on 2015–2017 TDep total sulfur deposition for each of the four lichen community categories defined by Geiser et al. (2019). These conditions are compared to 2000–2002 TDep total sulfur deposition to calculate improvement or decline of conditions. All NPS units listed below have greater than 1 km^2 of forest cover.

Table B2. The maximum sulfur (S) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha^{-1} yr^{-1}) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS unit	2016 max S dep.	Δ max S dep	2016 spp. rich. loss	Δ spp. rich loss	2016 S-sens. lichen loss	Δ S-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
ABLI	3.89	−11.49	13.98	−23.35	32.37	−45.41	30.91	−54.42	35.72	−52.17
ACAD	4.26	−7.73	15.15	−18.07	35.00	−37.17	33.53	−41.48	38.65	−42.13
ALPO	9.33	−32.17	28.37	−10.81	63.22	−14.98	63.55	−28.15	70.36	−16.07
ANTI	3.08	−12.02	11.32	−25.75	26.35	−51.21	25.00	−59.66	29.05	−58.52
APCO	2.21	−7.74	8.31	−21.30	19.44	−46.19	18.33	−48.12	21.41	−51.72
APIS	2.41	−3.22	9.01	−10.21	21.04	−22.98	19.87	−22.79	23.18	−25.52
APPA	5.44	−16.91	18.67	−20.52	42.83	−35.37	41.43	−50.27	47.37	−41.48
ARCH	1.01	−0.73	3.93	−2.72	9.24	−6.34	8.64	−6.00	NA	NA
BADL	1.07	−0.52	4.15	−1.92	9.75	−4.47	9.12	−4.23	NA	NA
BAND	0.99	−0.83	3.83	−3.06	9.02	−7.13	8.43	−6.75	NA	NA
BIBE	1.86	0.22	7.06	0.82	16.53	1.89	15.55	1.80	NA	NA
BICA	1.15	−0.64	4.46	−2.36	10.48	−5.51	9.81	−5.22	NA	NA
BICY	4.45	−1.62	15.74	−4.71	36.34	−10.39	34.86	−10.60	34.47	−14.34
BISO	3.12	−11.21	11.44	−24.86	26.62	−50.11	25.27	−57.37	29.35	−57.07
BITH	6.70	−6.37	22.15	−12.63	50.38	−24.28	49.29	−29.52	55.82	−27.98
BLCA	0.72	−0.29	2.81	−1.11	6.61	−2.60	6.17	−2.44	NA	NA
BLRI	3.84	−11.70	13.81	−23.66	31.99	−45.88	30.54	−55.17	35.31	−52.75
BLUE	4.19	−16.37	14.91	−24.27	34.46	−43.74	32.99	−58.71	38.05	−50.80
BRCA	1.04	−0.69	4.05	−2.57	9.52	−6.00	8.91	−5.68	NA	NA
BUFF	3.12	−2.67	11.45	−8.23	26.65	−18.40	25.30	−18.41	29.38	−20.46
CACH	0.98	−0.61	3.81	−2.26	8.95	−5.26	8.37	−4.98	NA	NA

Table B2 (continued). The maximum sulfur (S) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS unit	2016 max S dep.	Δ max S dep	2016 spp. rich. loss	Δ spp. rich loss	2016 S-sens. lichen loss	Δ S-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
CACO	4.63	−7.31	16.29	−16.85	37.56	−34.48	36.08	−38.73	41.49	−39.13
CAHA	4.74	−6.99	16.63	−16.19	38.31	−33.17	36.84	−37.19	42.33	−37.63
CANA	4.05	−4.67	14.49	−12.57	33.53	−27.08	32.06	−28.47	37.01	−30.37
CANY	1.12	−0.92	4.32	−3.36	10.16	−7.82	9.51	−7.43	NA	NA
CARE	1.19	−0.67	4.59	−2.46	10.78	−5.73	10.10	−5.44	NA	NA
CATO	3.92	−16.40	14.08	−25.11	32.59	−45.61	31.14	−60.56	35.97	−51.83
CAVE	1.65	−0.44	6.29	−1.57	14.75	−3.64	13.86	−3.48	NA	NA
CAVO	1.21	−0.08	4.66	−0.29	10.94	−0.69	10.25	−0.65	NA	NA
CEBR	1.34	−1.08	5.17	−3.88	12.14	−9.00	11.38	−8.58	NA	NA
CHAT	2.50	−17.05	9.34	−29.85	21.80	−56.40	20.61	−70.87	24.02	−64.83
CHCH	2.81	−11.44	10.39	−25.82	24.22	−52.40	22.94	−59.46	26.69	−59.59
CHCU	0.71	−0.59	2.77	−2.23	6.52	−5.22	6.08	−4.91	NA	NA
CHIC	3.36	−2.11	12.26	−6.52	28.48	−14.58	27.08	−14.58	NA	NA
CHIR	1.08	−0.85	4.19	−3.13	9.84	−7.28	9.21	−6.90	NA	NA
CHIS	3.20	−1.07	11.71	−3.45	27.24	−7.80	25.87	−7.68	NA	NA
CHOH	3.26	−12.06	11.92	−25.36	27.71	−50.03	26.33	−58.86	30.55	−57.27
CIRO	1.20	−0.05	4.65	−0.17	10.93	−0.40	10.23	−0.38	NA	NA
COLM	0.99	−0.44	3.83	−1.63	9.01	−3.81	8.42	−3.60	NA	NA
COLO	3.77	−9.95	13.58	−22.02	31.48	−44.36	30.04	−50.82	34.74	−50.53
CONG	4.08	−9.92	14.56	−21.37	33.68	−42.58	32.21	−49.46	37.18	−48.63
COWP	1.68	−6.48	6.40	−19.36	15.01	−42.95	14.10	−43.43	16.52	−47.85
CRLA	1.07	−0.13	4.15	−0.48	9.77	−1.11	9.14	−1.05	NA	NA
CRMO	0.78	0.16	3.06	0.61	7.21	1.44	6.74	1.35	NA	NA
CUGA	2.84	−12.43	10.51	−26.72	24.50	−53.20	23.21	−61.87	27.00	−60.77
CUIS	3.21	−4.79	11.76	−13.65	27.34	−29.90	25.97	−30.75	30.15	−33.41
CURE	0.74	−0.43	2.91	−1.62	6.84	−3.80	6.39	−3.58	NA	NA

Table B2 (continued). The maximum sulfur (S) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS unit	2016 max S dep.	Δ max S dep	2016 spp. rich. loss	Δ spp. rich loss	2016 S-sens. lichen loss	Δ S-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
CUVA	7.18	−19.65	23.40	−15.78	53.03	−25.17	52.13	−39.57	58.81	−27.62
DEPO	1.11	−0.12	4.29	−0.43	10.10	−1.01	9.45	−0.95	NA	NA
DETO	1.01	−0.85	3.91	−3.15	9.20	−7.33	8.61	−6.94	NA	NA
DEVA	1.92	−0.47	7.26	−1.68	17.00	−3.88	16.00	−3.72	NA	NA
DEWA	3.08	−12.35	11.31	−26.05	26.32	−51.49	24.97	−60.46	29.01	−58.92
DINO	1.04	−0.25	4.04	−0.93	9.50	−2.16	8.89	−2.04	NA	NA
EBLA	1.96	−1.67	7.41	−5.72	17.34	−13.11	16.33	−12.70	19.10	−14.50
EFMO	3.09	−4.55	11.34	−13.20	26.40	−29.03	25.05	−29.68	29.10	−32.40
ELMA	0.95	−0.72	3.71	−2.68	8.72	−6.25	8.15	−5.91	NA	NA
ELMO	0.86	−0.60	3.35	−2.26	7.88	−5.27	7.36	−4.97	NA	NA
EVER	5.64	−1.31	19.25	−3.54	44.10	−7.64	42.73	−8.01	NA	NA
FIIS	5.59	−9.89	19.12	−18.30	43.81	−34.03	42.44	−43.14	48.46	−39.54
FLFO	0.99	−0.54	3.85	−2.03	9.06	−4.74	8.47	−4.48	NA	NA
FOBU	1.87	0.79	7.09	2.90	16.60	6.75	15.62	6.40	NA	NA
FODO	4.34	−9.62	15.39	−20.50	35.55	−40.67	34.07	−47.52	39.26	−46.50
FONE	5.84	−35.63	19.82	−19.36	45.34	−32.86	44.01	−47.69	50.17	−36.26
FRHI	4.45	−22.81	15.71	−23.47	36.28	−41.92	34.80	−56.90	40.06	−46.37
FRSP	2.54	−9.31	9.46	−23.53	22.07	−49.70	20.86	−53.57	24.32	−55.99
GARI	4.24	−16.31	15.08	−24.10	34.86	−43.34	33.38	−58.32	38.49	−49.66
GETT	3.42	−13.80	12.45	−26.13	28.92	−49.28	27.52	−61.42	31.90	−56.96
GLAC	1.84	−1.51	7.00	−5.24	16.40	−12.03	15.43	−11.61	NA	NA
GLCA	1.14	−1.06	4.40	−3.85	10.35	−8.95	9.69	−8.51	NA	NA
GOGA	3.24	−4.89	11.85	−13.84	27.56	−30.26	26.19	−31.19	30.39	−15.98
GRBA	1.22	−0.25	4.71	−0.94	11.07	−2.19	10.37	−2.07	NA	NA
GRCA	1.32	−0.97	5.07	−3.51	11.90	−8.14	11.15	−7.75	NA	NA
GREE	2.80	−11.36	10.37	−25.74	24.18	−52.33	22.90	−59.26	26.65	−59.48

Table B2 (continued). The maximum sulfur (S) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS unit	2016 max S dep.	Δ max S dep	2016 spp. rich. loss	Δ spp. rich loss	2016 S-sens. lichen loss	Δ S-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
GRPO	1.97	−2.42	7.45	−8.08	17.44	−18.43	16.41	−17.98	19.20	−20.41
GRSA	1.81	−0.65	6.88	−2.31	16.13	−5.33	15.17	−5.11	NA	NA
GRSM	3.14	−15.17	11.53	−27.47	26.82	−51.38	25.46	−64.95	29.57	−59.28
GRTE	2.29	−1.65	8.59	−5.52	20.08	−12.60	18.95	−12.27	NA	NA
GUMO	1.99	−0.25	7.51	−0.89	17.59	−2.05	16.56	−1.96	NA	NA
GWMP	3.06	−11.93	11.24	−25.73	26.16	−51.31	24.82	−59.57	28.84	−58.59
HAFE	3.08	−10.88	11.32	−24.57	26.35	−49.87	25.01	−56.58	29.05	−56.71
HOBE	2.90	−9.32	10.71	−22.86	24.94	−47.80	23.64	−52.20	27.49	−53.97
HOCU	5.27	−18.77	18.20	−20.99	41.80	−36.40	40.37	−51.33	46.21	−42.09
HOFR	3.10	−8.89	11.39	−21.83	26.50	−45.66	25.15	−49.84	29.22	−51.56
HOFU	3.18	−12.26	11.63	−25.74	27.06	−50.76	25.70	−59.77	29.83	−58.12
HOSP	3.60	−2.23	13.02	−6.74	30.21	−15.02	28.79	−15.11	33.33	−16.72
INDU	13.25	−15.23	35.02	−4.16	75.01	−3.19	79.39	−12.31	84.23	−4.62
ISRO	2.72	−2.38	10.08	−7.60	23.50	−17.13	22.24	−16.95	25.90	−19.02
JECA	1.10	−0.87	4.25	−3.18	9.99	−7.40	9.35	−7.03	NA	NA
JODR	1.82	−0.58	6.93	−2.06	16.24	−4.77	15.27	−4.57	NA	NA
JOTR	0.74	−0.27	2.89	−1.02	6.81	−2.39	6.35	−2.25	NA	NA
KAWW	1.81	−3.59	6.87	−11.68	16.10	−26.47	15.14	−26.03	17.72	−29.36
KEMO	2.43	−17.41	9.08	−30.11	21.20	−57.00	20.02	−71.61	23.35	−65.33
KICA	1.95	−1.16	7.38	−4.02	17.27	−9.24	16.25	−8.91	NA	NA
KIMO	1.93	−7.53	7.32	−21.31	17.14	−46.58	16.13	−48.02	18.87	−52.07
LABE	0.62	0.00	2.42	−0.01	5.70	−0.03	5.31	−0.03	NA	NA
LAKE	0.57	−1.57	2.22	−5.83	5.24	−13.59	4.88	−12.86	NA	NA
LARO	0.71	−0.46	2.79	−1.76	6.57	−4.13	6.13	−3.89	NA	NA
LAVO	1.13	−0.58	4.38	−2.14	10.30	−4.99	9.64	−4.73	NA	NA
LEWI	2.65	−2.07	9.84	−6.70	22.95	−15.16	21.72	−14.92	25.29	−16.81

Table B2 (continued). The maximum sulfur (S) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS unit	2016 max S dep.	Δ max S dep	2016 spp. rich. loss	Δ spp. rich loss	2016 S-sens. lichen loss	Δ S-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
LIRI	2.85	−11.69	10.55	−25.97	24.58	−52.41	23.29	−59.93	27.09	−59.68
MABI	2.08	−6.07	7.85	−17.90	18.36	−39.57	17.29	−40.20	20.21	−44.12
MACA	3.88	−12.11	13.94	−23.88	32.28	−45.80	30.83	−55.85	35.63	−52.80
MANA	2.62	−9.96	9.74	−24.37	22.71	−50.90	21.48	−55.66	25.03	−57.49
MEVE	1.05	−0.77	4.07	−2.83	9.57	−6.59	8.95	−6.24	NA	NA
MIMA	3.11	−8.99	11.41	−21.98	26.55	−45.91	25.20	−50.22	29.27	−51.85
MISS	4.61	−13.17	16.22	−22.61	37.40	−40.80	35.92	−53.83	41.31	−47.46
MNRR	2.18	−3.39	8.20	−10.84	19.17	−24.47	18.07	−24.19	NA	NA
MOJA	0.59	−0.78	2.32	−2.95	5.47	−6.91	5.10	−6.51	NA	NA
MONO	2.89	−12.43	10.68	−26.60	24.87	−52.86	23.57	−61.62	27.41	−60.42
MORA	2.20	−3.25	8.28	−10.42	19.37	−23.54	18.26	−23.24	NA	NA
MORR	3.16	−12.25	11.59	−25.77	26.96	−50.84	25.60	−59.81	29.72	−58.20
MORU	1.11	−1.01	4.30	−3.71	10.12	−8.63	9.47	−8.20	NA	NA
MUWO	2.61	−2.31	9.70	−7.43	22.64	−16.80	21.41	−16.57	NA	NA
NABR	1.29	−0.99	4.98	−3.57	11.70	−8.29	10.97	−7.89	NA	NA
NATR	4.03	−8.65	14.40	−19.84	33.33	−40.51	31.86	−45.62	36.78	−46.00
NEPE	0.62	−0.30	2.43	−1.15	5.72	−2.71	5.33	−2.54	NA	NA
NERI	4.59	−19.94	16.17	−23.02	37.29	−40.91	35.82	−55.88	41.20	−46.00
NIOB	1.55	−0.65	5.92	−2.35	13.88	−5.45	13.03	−5.20	NA	NA
NISI	1.98	−5.77	7.49	−17.30	17.52	−38.42	16.50	−38.79	19.29	−42.79
NOCA	1.85	−1.47	7.04	−5.07	16.48	−11.66	15.50	−11.25	NA	NA
OBRI	2.96	−10.93	10.89	−24.91	25.36	−50.74	24.05	−57.31	27.96	−57.64
OCMU	2.51	−8.71	9.35	−22.60	21.83	−48.13	20.63	−51.33	24.06	−54.12
OLYM	5.13	−4.50	17.78	−11.20	40.87	−23.54	39.42	−25.55	45.17	−26.55
ORCA	1.09	0.06	4.22	0.21	9.94	0.49	9.30	0.46	NA	NA
OZAR	3.84	−4.75	13.80	−12.95	31.97	−27.99	30.52	−29.27	35.28	−31.37

Table B2 (continued). The maximum sulfur (S) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions. NPS units not expected to have cyanolichen are labeled as NA.

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PARA	0.94	−0.67	3.64	−2.48	8.56	−5.80	8.00	−5.48	NA	NA
PECO	0.88	−0.67	3.45	−2.50	8.11	−5.84	7.58	−5.51	NA	NA
PERI	3.43	−1.83	12.48	−5.67	28.99	−12.70	27.59	−12.68	31.97	−14.12
PETE	3.04	−10.42	11.18	−24.11	26.02	−49.39	24.68	−55.39	28.68	−56.04
PINN	0.68	−0.23	2.66	−0.89	6.26	−2.09	5.84	−1.96	NA	NA
PIRO	5.21	−4.89	18.02	−11.90	41.39	−24.82	39.96	−27.19	45.76	−28.04
PORE	2.62	−1.06	9.74	−3.56	22.73	−8.12	21.50	−7.91	NA	NA
PRWI	2.77	−10.17	10.26	−24.34	23.91	−50.48	22.64	−55.73	26.35	−57.11
REDW	1.98	−0.03	7.48	−0.10	17.52	−0.24	16.49	−0.23	19.29	−0.26
RICH	2.96	−12.01	10.92	−26.03	25.43	−52.01	24.11	−60.22	28.03	−59.37
ROCR	3.08	−11.68	11.32	−25.43	26.34	−50.89	25.00	−58.80	29.04	−58.06
ROMO	1.67	−2.92	6.36	−9.79	14.92	−22.33	14.02	−21.75	NA	NA
ROVA	2.83	−8.96	10.46	−22.44	24.37	−47.25	23.09	−51.14	26.86	−53.27
RUCA	2.87	−11.09	10.61	−25.27	24.73	−51.49	23.43	−58.15	27.25	−58.50
SACN	2.26	−3.16	8.50	−10.14	19.87	−22.90	18.74	−22.63	21.88	−25.42
SAGU	1.33	−0.79	5.12	−2.88	12.04	−6.68	11.28	−6.36	NA	NA
SAJH	2.42	−1.78	9.06	−5.90	21.15	−13.42	19.98	−13.12	23.30	−14.86
SAMO	1.88	−1.93	7.12	−6.59	16.68	−15.10	15.69	−14.64	NA	NA
SARA	2.53	−7.75	9.45	−20.83	22.05	−44.83	20.85	−47.15	24.30	−50.29
SEKI	1.74	−0.57	6.63	−2.03	15.54	−4.69	14.61	−4.48	NA	NA
SEQU	1.42	−0.48	5.46	−1.75	12.83	−4.06	12.03	−3.86	NA	NA
SHEN	2.68	−11.96	9.95	−26.67	23.21	−53.89	21.96	−61.51	25.58	−61.34
SHIL	4.00	−6.71	14.33	−16.73	33.17	−35.18	31.70	−38.14	36.61	−39.67
SLBE	3.27	−7.77	11.96	−19.70	27.81	−41.64	26.43	−44.84	30.66	−46.90
STRI	3.63	−7.55	13.14	−18.76	30.48	−39.40	29.05	−42.80	33.63	−44.45
SUCR	1.04	−0.19	4.04	−0.70	9.51	−1.63	8.89	−1.54	NA	NA

Table B2 (continued). The maximum sulfur (S) deposition recorded within the boundaries of each NPS unit from TDep 2015–2017 (2016) and the change from 2000–2002 values (kg ha−1 yr−1) are used to calculate the percentage of decline expected for each lichen category and the change in rate of decline between 2001 and 2016 (%). Negative values in the change column represent declining conditions. NPS units not expected to have cyanolichen are labeled as NA.

NPS unit	2016 max S dep.	Δ max S dep	2016 spp. rich. loss	Δ spp. rich loss	2016 S-sens. lichen loss	Δ S-sens. lichen loss	2016 forage lichen loss	Δ forage lichen loss	2016 cyano lichen loss	Δ cyano lichen loss
TAPR	2.28	−2.03	8.55	−6.75	19.98	−15.37	18.85	−15.02	NA	NA
THRO	2.02	−1.32	7.62	−4.54	17.84	−10.41	16.80	−10.07	NA	NA
THST	2.84	−11.32	10.51	−25.61	24.49	−52.02	23.20	−58.98	26.99	−59.15
TIMU	4.51	−5.49	15.91	−13.81	36.70	−29.12	35.23	−31.46	40.54	−32.82
UPDE	3.13	−12.55	11.47	−26.10	26.68	−51.27	25.33	−60.67	29.42	−58.77
VAFO	3.16	−12.07	11.58	−25.62	26.93	−50.74	25.57	−59.40	29.69	−58.03
VICK	3.89	−4.01	13.98	−11.18	32.38	−24.34	30.93	−25.23	35.74	−27.23
VOYA	1.38	−1.84	5.30	−6.49	12.45	−14.97	11.68	−14.38	13.70	−16.54
WACA	1.16	−0.26	4.48	−0.98	10.54	−2.28	9.86	−2.15	NA	NA
WHIS	1.08	−0.48	4.17	−1.79	9.80	−4.19	9.17	−3.96	NA	NA
WICA	1.02	−0.83	3.94	−3.06	9.28	−7.14	8.68	−6.76	NA	NA
WICR	3.27	−3.66	11.94	−10.81	27.76	−23.90	26.39	−24.27	30.62	−26.65
YELL	2.02	−0.63	7.63	−2.21	17.87	−5.08	16.83	−4.88	NA	NA
YOSE	1.46	−0.20	5.60	−0.73	13.13	−1.70	12.32	−1.61	NA	NA
ZION	1.02	−0.70	3.97	−2.58	9.33	−6.01	8.73	−5.69	NA	NA

Appendix C – Case Study Analysis

Acadia National Park (ACAD)

Complete TDep coverage was not available for 33 NPS units in the study, including ACAD. This is due to limitations in the model's ability to predict deposition along coast lines. Deposition data is available for 43% of ACAD's forested area (Figure C1). Maximum deposition, species richness response, and percentages are based on the area of forested land where TDep data is available, not for the entire forested area of ACAD. The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C1. Summary of deposition values and expected loss of total epiphytic lichen species richness in Acadia National Park based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	51.9	4.3	9.8	24.5	44.6	7.1	12.0	23.1	33.2
2016	51.9	2.5	5.0	15.2	27.7	2.5	4.3	9.5	15.1

2001 N and S conditions

N deposition in 2001 ranged from 4.3 kg-N ha^{-1} yr^{-1} in the northern section of the park to 9.8 kg-N ha^{-1} yr^{-1} in the western part of the park (Table C1). The CLN-SR exceedance was between 0.8 and 6.3 kg-N ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the western portion of the park. S deposition in 2001 ranged from 7.1 kg-S ha^{-1} yr^{-1} to 12.0 kg-S ha^{-1} yr^{-1} (Table C1). The CLS-SR exceedance in ACAD was between 1.2 and 6.0 kg-S ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the western portion of the park. 100% of the forested area included in the study exceeded both the CLN-SR and CLS-SR in 2001 (Figure C1, Figure C3).

The geography of N and S exceedances across the park in 2001 was broadly similar, with the highest exceedances in the western portion of the park for both forms of deposition.

2016 N and S conditions

N deposition in 2016 ranged from 2.5 kg-N ha^{-1} yr^{-1} in the eastern part of the park to 5.0 kg-N ha^{-1} yr^{-1} in the western part of Mount Desert Island in the park (Table C1). Only 0.18% of the forested area exceeded the critical load (Figure C1). The maximum CLN-SR exceedance was 1.45 kg-N ha^{-1} yr^{-1}. Approximately 98% of the park was projected to experience between 10 and 20% predicted species richness loss (Figure C2). The minimum predicted species richness loss was 15.14%, the

maximum was 27.70%, and the mean was 15.67%. The maximum predicted loss occurred in the northwestern part of ACAD (Figure C2).

S deposition in 2016 was between 2.5 kg-S ha^{-1} yr^{-1} and 4.3 kg-S ha^{-1} yr^{-1} (Table C1). 100% of the forested area was below the CLS-SR in 2016 (Figure C3). Approximately 51% of the park was predicted to experience less than 10% lichen species richness loss (Figure C4). The minimum predicted species richness loss from sulfur deposition in 2016 was 9.45%, the maximum predicted loss was 15.15% and the mean was 10% predicted species richness loss.

Change over time in N and S conditions

Maximum N deposition at ACAD decreased 4.8 kg-N ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum N deposition represents improved conditions for lichen species richness across the majority of the forested ecosystem by decreasing the area above the CLN-SR. 2016 conditions improved from 2001 by a 16.9% decrease in risk of species richness loss attributable to N deposition. Compared to the 51.87 km^2 of forested area that exceeded the CLN-SR in 2002, in 2016 less than 1 km^2 on the northwestern side of the park exceeded the CLN-SR.

Maximum S deposition at ACAD decreased 7.7 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum S deposition represents improved conditions for lichen species richness across the forested ecosystem by decreasing the area above the CLS-SR. 2016 conditions improved from 2001 by a 18.1% decrease in risk of species richness loss attributable to S deposition. Forested area in ACAD experienced dramatic change from 2001 to 2016, in respect to CLS-SR exceedance, where 100% of the forest exceeded the CLS-SR in 2001 and 0% exceeded the CLS-SR in 2016.

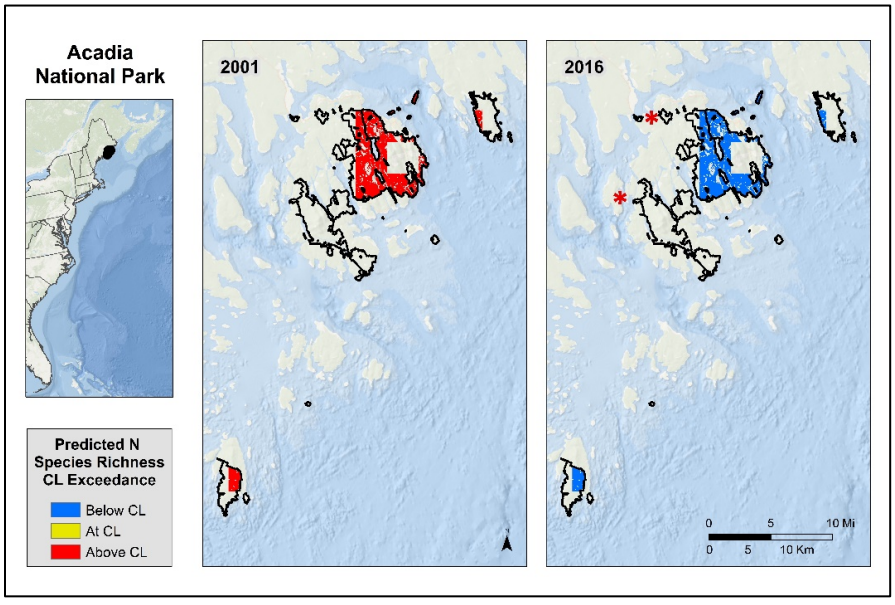


Figure C1. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in Acadia National Park in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red). The red asterisks denote the locations where the CLN-SR is expected to be exceeded in 2016, as the area in exceedance is too small to appear at this scale.

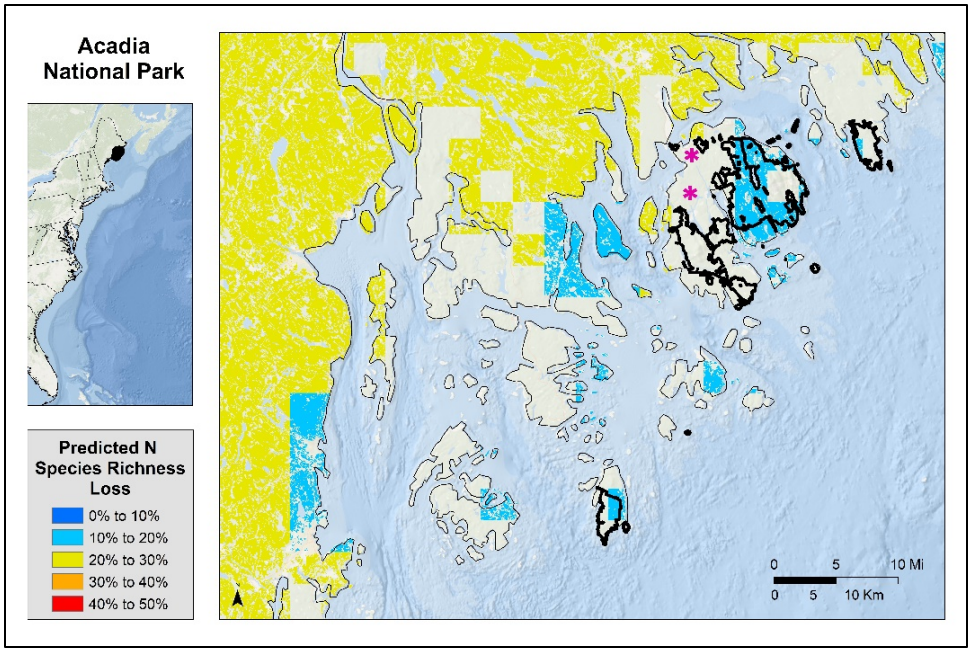


Figure C2. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in Acadia National Park. The highest levels of predicted species richness loss are indicated by pink asterisks since they are not visible at this resolution.

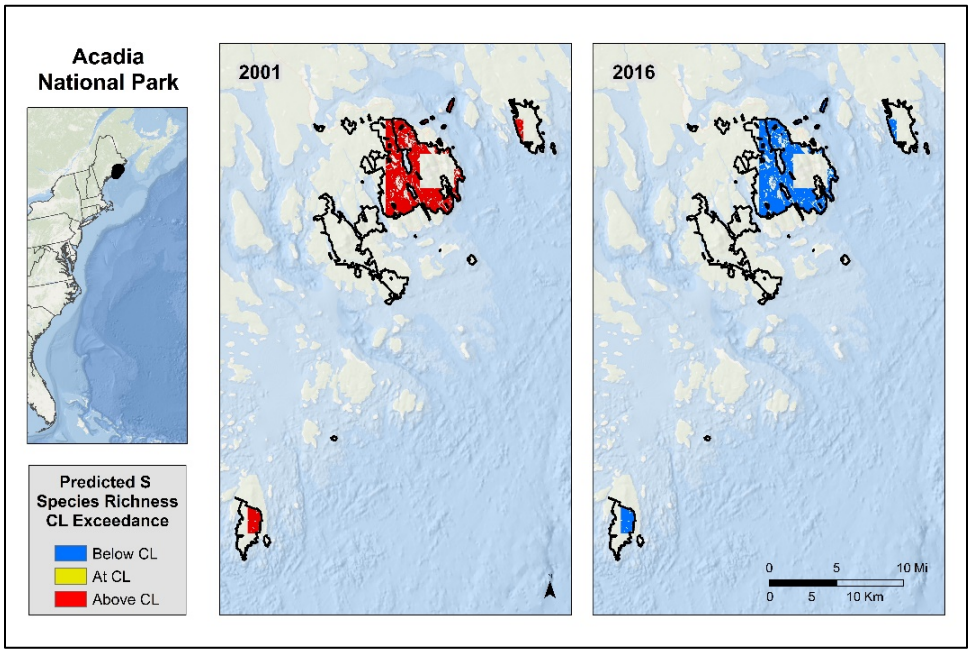


Figure C3. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in Acadia National Park in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

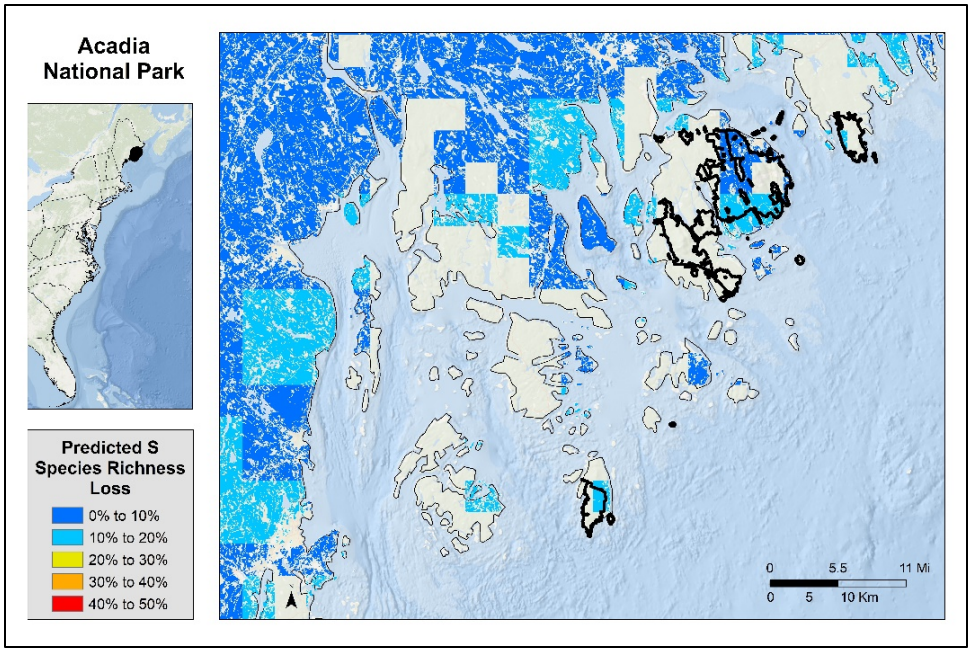


Figure C4. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in Acadia National Park.

Glacier National Park (GLAC)

Complete TDep coverage was not available for 33 national NPS units in the study, including GLAC. This is due to limitations in the model's ability to predict deposition along the United States' borders. Deposition data is available for 97% of GLAC's forested area (Figure C5). Maximum deposition, species richness response, and percentages are based on the area of forested land where TDep data is available, not for the entire forested area of GLAC. The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C2. Summary of deposition values and expected loss of total epiphytic lichen species richness in Glacier National Park based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	2126.8	1.8	7.1	11.3	36.5	0.9	3.4	3.5	12.2
2016	2126.8	2.2	7.4	13.7	37.4	0.6	1.8	2.2	7.0

2001 N and S conditions

N deposition in 2001 ranged from 1.8 kg-N ha^{-1} yr^{-1} in the western section of the park to 7.1 kg-N ha^{-1} yr^{-1} in the central and eastern part of the park (Table C2). The maximum CLN-SR exceedance was 3.6 kg-N ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the central portion of the park. Approximately, 49% of the forested area included in the study exceeded the CLN-SR in 2001, while 25% of the forested area was predicted to be below the critical load (Figure C5).

S deposition in 2001 ranged from 0.9 kg-S ha^{-1} yr^{-1} to 3.4 kg-S ha^{-1} yr^{-1} (Table C2). In 2001, the CLS-SR was not exceeded and 100% of the forested area included in the study was below the CLS-SR (Figure C7).

2016 N and S conditions

N deposition in 2016 ranged from 2.2 kg-N ha^{-1} yr^{-1} in the western part of the park to 7.4 kg-N ha^{-1} yr^{-1} in the central part of the park (Table C2). 56.41% of the forested area exceeded the critical load and 14.37% was predicted to be below the CLN-SR (Figure C5). The maximum CLN-SR exceedance was 3.86 kg-N ha^{-1} yr^{-1}. Approximately 65% of the park was projected to experience between 20 and 30% predicted species richness loss (Figure C6). The minimum predicted species richness loss was 13.69%, the maximum was 37.69%, and the mean was 23.63%. The maximum predicted loss occurred in the central and eastern sections of GLAC (Figure C6).

S deposition in 2016 was between 0.6 kg-S ha^{-1} yr^{-1} and 1.8 kg-S ha^{-1} yr^{-1} (Table C2). 100% of the forested area was below the CLS-SR in 2016 (Figure C7). 100% of the park was predicted to experience less than 10% lichen species richness loss (Figure C8). The minimum predicted species richness loss from sulfur deposition in 2016 was 2.17%, the maximum predicted loss was 7% and the mean was 4.02% predicted species richness loss.

Change over time in N and S conditions

Maximum N deposition at GLAC increased 0.25 kg-N ha^{-1} yr^{-1} from 2001 to 2016. The increase in maximum N deposition represents slightly degraded conditions for lichen species richness across the forested ecosystem with deposition data in GLAC. 2016 conditions degraded from 2001 by a 0.9% increase in risk of species richness loss attributable to N deposition. The forested area above the CLN-SR increase from 1,050 km^2 in 2001, to 1,200 km^2 in 2016 (Figure C5).

Maximum S deposition at GLAC decreased 1.52 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum S deposition represents improved conditions for lichen species richness across the forested ecosystem with deposition data in GLAC. 2016 conditions improved from 2001 by a 5.2% decrease in risk of species richness loss attributable to S deposition. There was no change in forested area predicted to be below the CLS-SR in GLAC, as 100% of forested area was predicted to be below the CLS-SR in 2001 and 2016 (Figure C7).

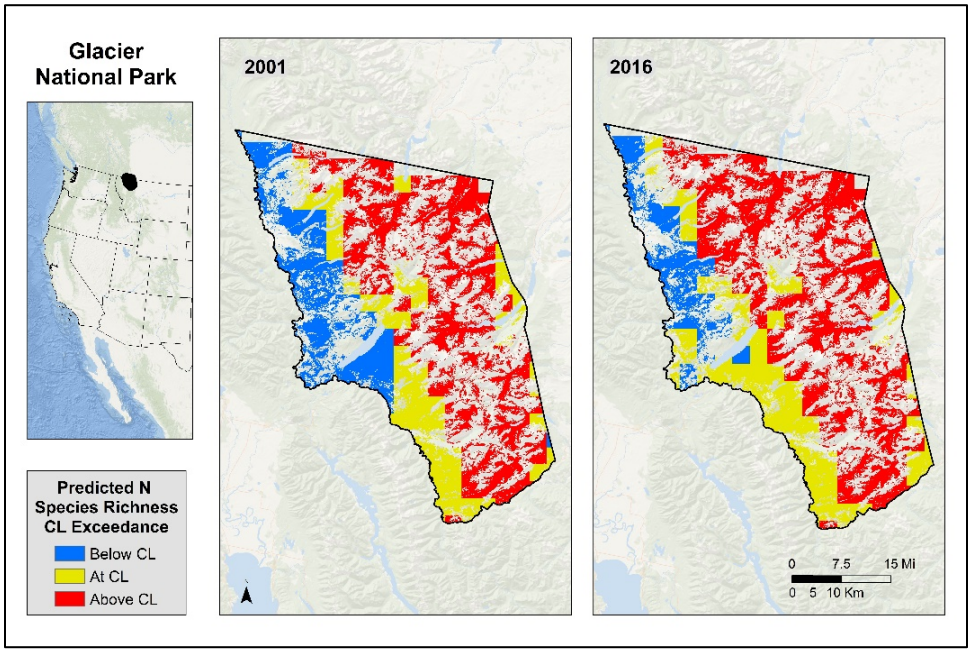


Figure C5. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in Glacier National Park in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

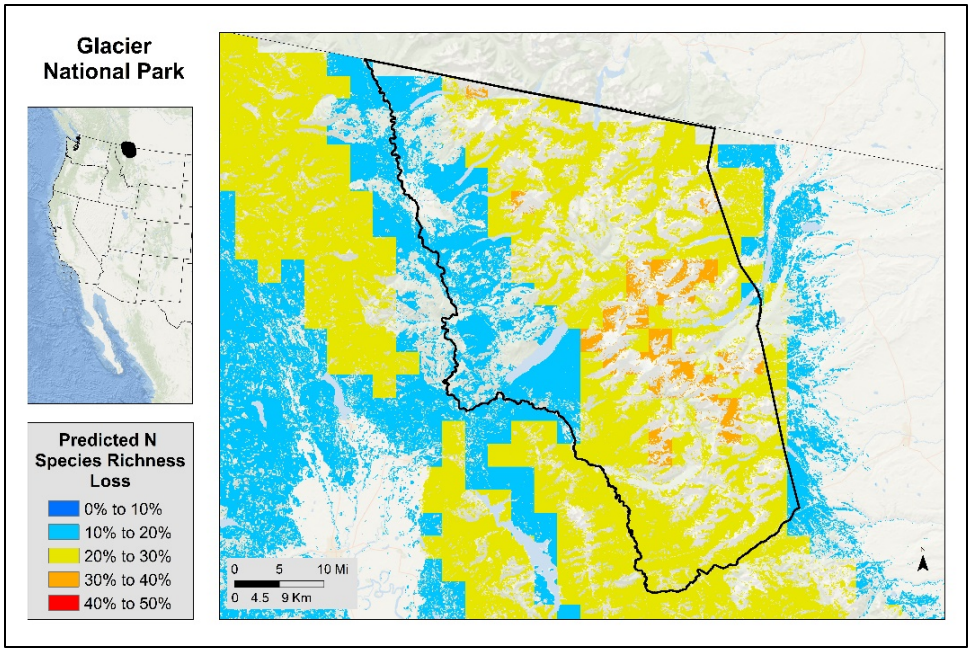


Figure C6. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in Glacier National Park.

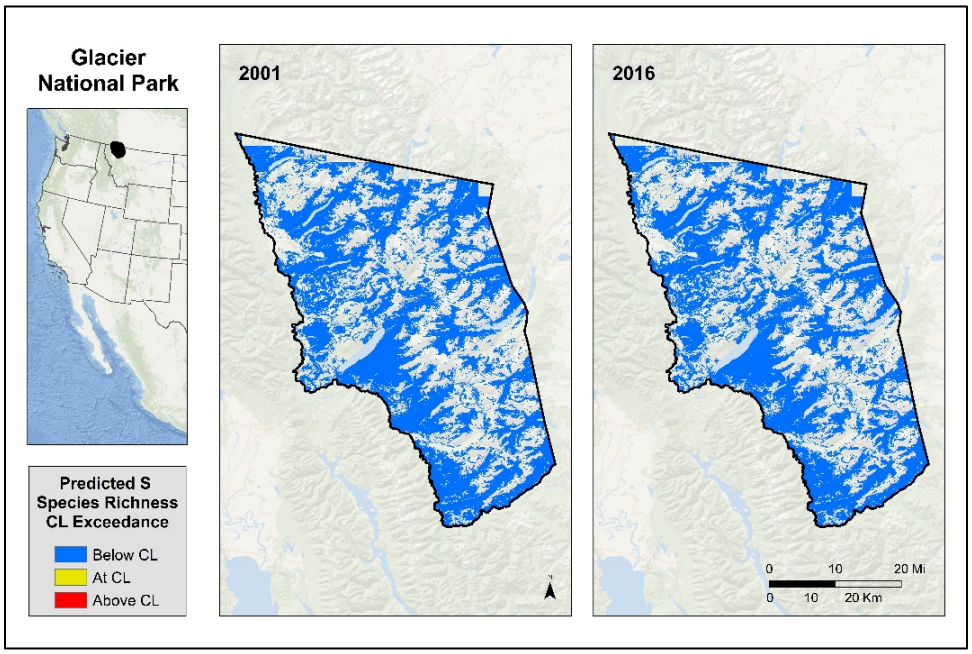


Figure C7. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in Glacier National Park is depicted in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

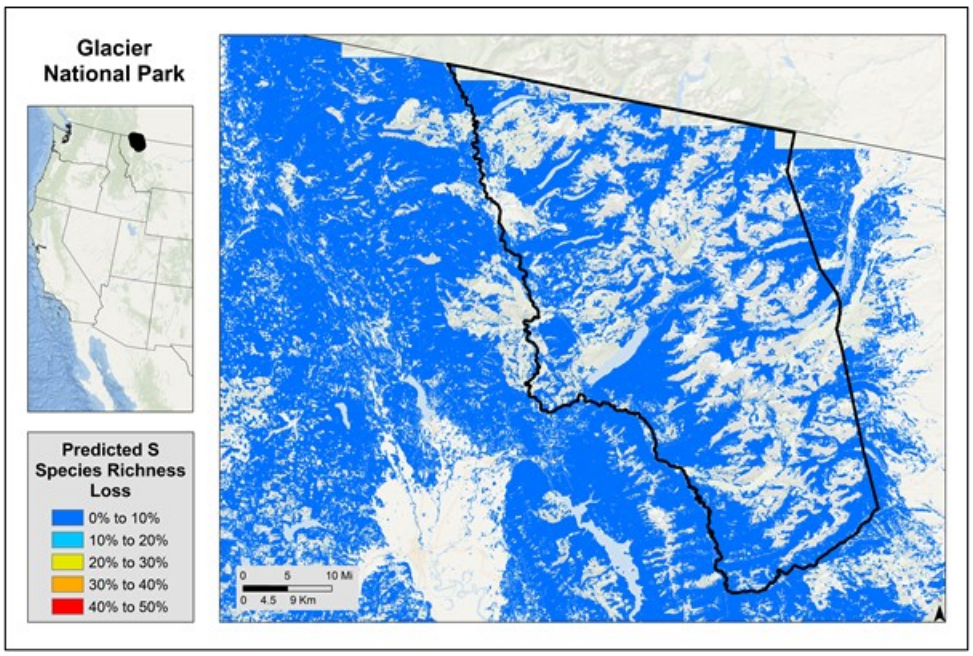


Figure C8. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in Glacier National Park.

Great Smoky Mountains National Park (GRSM)

100% of the forested area within GRSM has N and S deposition cover. The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C3. Summary of deposition values and expected loss of total epiphytic lichen species richness in Great Smoky Mountains National Park based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	2053.4	7.9	15.8	39.3	52.0	7.5	18.3	24.1	39.0
2016	2053.4	5.6	8.4	30.4	40.8	1.9	3.1	7.3	11.5

2001 N and S conditions

N deposition in 2001 ranged from 7.9 kg-N ha^{-1} yr^{-1} in the south central section of the park to 15.8 kg-N ha^{-1} yr^{-1} in the southwestern part of the park (Table C3). Overall, N deposition was highest in the northwestern and central portions of the park. The CLN-SR exceedance was between 4.4 and 12.3 kg-N ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the southeastern portion of the park.

S deposition in 2001 ranged from 7.5 kg-S ha^{-1} yr^{-1} to 18.3 kg-S ha^{-1} yr^{-1} (Table C3). The CLS-SR exceedance in GRSM was between 1.5 and 12.3 kg-S ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the central portion of the park. 100% of the forested area included in the study exceeded both the N and CLS-SR in 2001 (Figure C9).

The geography of N and S exceedances across the park in 2001 was broadly similar, with the highest exceedances in the central portion of the park and a general spatial pattern of lower deposition levels on the eastern and southeastern edges of GRSM for both N and S deposition (Figure C11).

2016 N and S conditions

N deposition in 2016 ranged from 5.6 kg-N ha^{-1} yr^{-1} in the south central part of the park to 8.4 kg-N ha^{-1} yr^{-1} in the central part of the park (Table C3). 100% of the forested area exceeded the critical load (Figure C9). The CLN-SR exceedance ranged from 2.1 kg-N ha^{-1} yr^{-1} to 4.9 kg-N ha^{-1} yr^{-1}. Approximately 81% of the park was projected to experience between 30 and 40% species richness loss (Figure C10). The minimum predicted species richness loss was 30.36%, the maximum was 40.83%, and the mean was 37.76%. The maximum predicted loss occurred in the northwestern part of GRSM (Figure C10).

S deposition in 2016 was between 1.9 kg-S ha^{-1} yr^{-1} and 3.1 kg-S ha^{-1} yr^{-1} (Table C3). 100% of the forested area was below the CLS-SR in 2016 (Figure C11). Approximately 61% of the park was predicted to experience less than 10% lichen species richness loss (Figure C12). The minimum predicted species richness loss from sulfur deposition in 2016 was 7.35%, the maximum predicted loss was 11.53% and the mean was 9.73% predicted species richness loss.

Change over time in N and S conditions

Maximum N deposition at GRSM decreased 7.35 kg-N ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum N deposition represents improved conditions for lichen species richness across the majority of the forested ecosystem within the park. 2016 conditions improved from 2001 by an 8.3% decrease in risk of species richness loss attributable to N deposition. However, there was no change in the area above the CLN-SR (100%; Figure C9).

Decreases in CLS-SR exceedances and changes in species richness response to sulfur deposition were more apparent and represented a clear success story. Maximum S deposition at GRSM decreased 15.18 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum S deposition shows drastically improved conditions for lichen species richness across the forested ecosystem with deposition data in GRSM. 2016 conditions improved from 2001 by a 27.5% decrease in risk of species richness loss attributable to S deposition. Forested area in GRSM experienced dramatic change from 2001 to 2016, in respect to CLS-SR exceedance, where 100% of the forest exceeded the CLS-SR in 2001 and 0% exceeded the CLS-SR in 2016 (Figure C11).

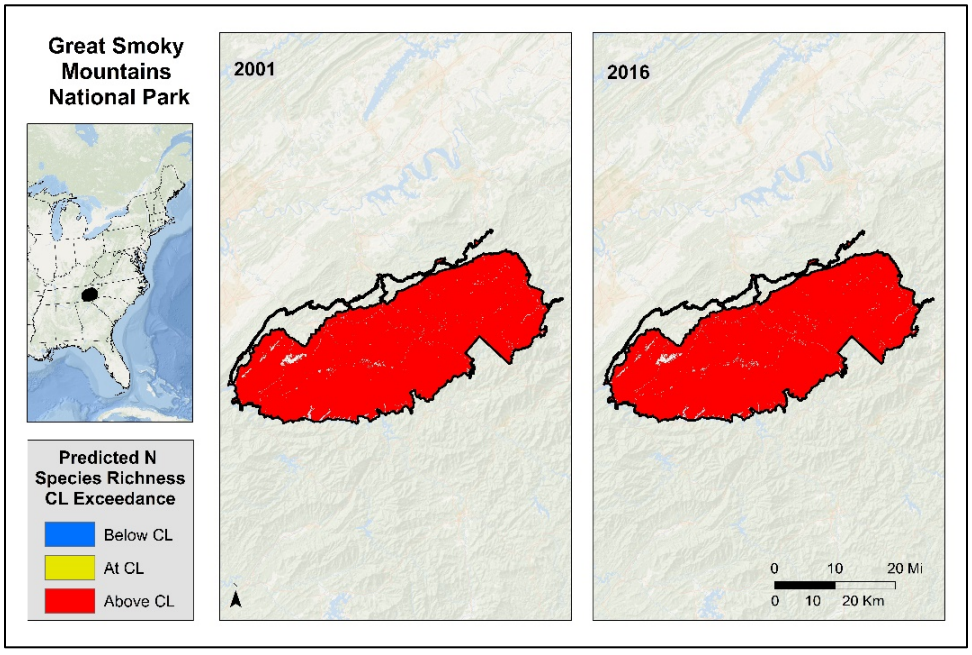


Figure C9. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in Great Smoky Mountains National Park in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

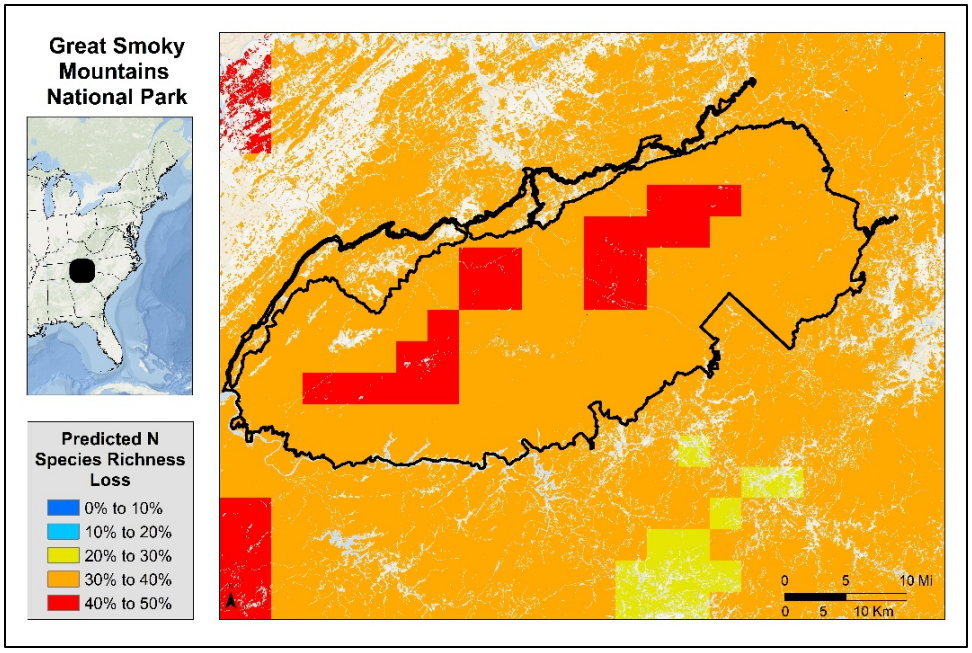


Figure C10. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in Great Smoky Mountains National Park.

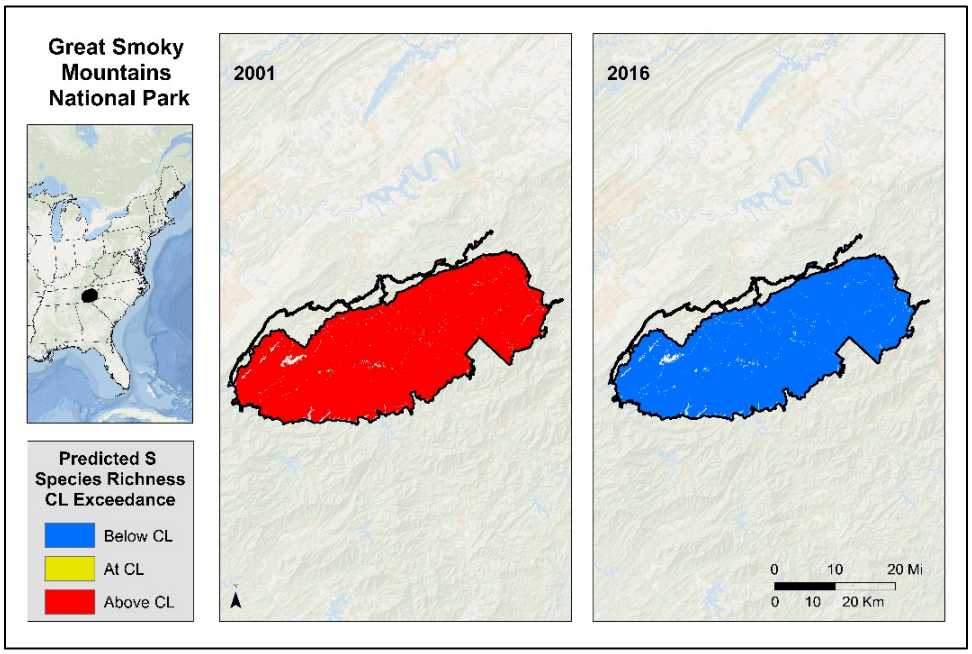


Figure C11. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in Great Smoky Mountains National Park is depicted in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

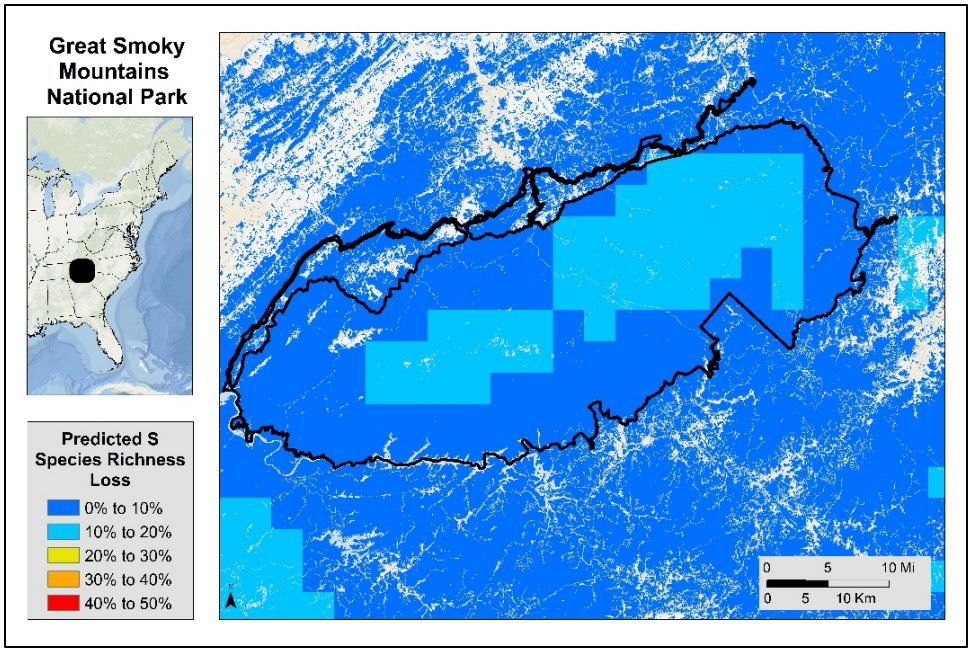


Figure C12. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in Great Smoky Mountains National Park.

Grand Teton National Park (GRTE)

There was 100% N and S deposition coverage for the forested area in GRTE (Figure C13). The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C4. Summary of deposition values and expected loss of total epiphytic lichen species richness in Grand Teton National Park based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	398.9	2.8	8.5	16.9	41.2	1.4	3.9	5.3	14.1
2016	398.9	3.1	7.4	18.4	37.5	0.9	2.3	3.3	8.6

2001 N and S conditions

N deposition in 2001 ranged from 2.8 kg-N ha^{-1} yr^{-1} in the eastern section of the park to 8.5 kg-N ha^{-1} yr^{-1} in the western part of the park (Table C4). The maximum CLN-SR exceedance was 5 kg-N ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the central, western portion of the park. 53.19% of the forested area in GRTE was above the CLN-SR in 2001 (Figure C13).

S deposition in 2001 ranged from 1.4 kg-S ha^{-1} yr^{-1} to 3.9 kg-S ha^{-1} yr^{-1} (Table C4). 100% of the forested area was below the CLS-SR in 2001 (Figure C15).

2016 N and S conditions

N deposition in 2016 ranged from 3.1 kg-N ha^{-1} yr^{-1} in the eastern part of the park to 7.38 kg-N ha^{-1} yr^{-1} in the southwestern part of the park (Table C4). 59.28% of the forested area exceeded the critical load (Figure C13). The maximum CLN-SR exceedance was 3.88 kg-N ha^{-1} yr^{-1}. Approximately 70% of the park was projected to experience between 20 and 30% predicted species richness loss (Figure C14). The minimum predicted species richness loss was 18.42%, the maximum was 37.46%, and the mean was 24.7%. The maximum predicted loss occurred in the southwestern part of GRTE (Figure C14).

S deposition in 2016 was between 0.9 kg-S ha^{-1} yr^{-1} and 2.3 kg-S ha^{-1} yr^{-1} (Table C4). 100% of the forested area was below the CLS-SR and predicted to experience less than 10% lichen species richness loss in 2016 (Figure C15 and Figure C16). The minimum predicted species richness loss from sulfur deposition in 2016 was 3.32%, the maximum predicted loss was 8.59% and the mean was 5.43% predicted species richness loss.

Change over time in N and S Conditions

Maximum N deposition at GRTE decreased 1.1 kg-N ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum N deposition represents overall improved conditions for lichen species richness across the forested ecosystem in GRTE. 2016 conditions improved from 2001 by a 3.7% decrease in risk of species richness loss attributable to N deposition. However, the decrease in maximum N deposition and the improved condition of species richness was not complemented by a decrease in forested area above the CLN-SR. In fact, there was 2.69% decrease in forested area that was below the CLN-SR from 2001 to 2016 (Figure C13).

Maximum S deposition at GRTE decreased 1.65 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum S deposition represents improved conditions for lichen species richness across the forested ecosystem with deposition data in GRTE. 2016 conditions improved from 2001 by a 5.5% decrease in risk of species richness loss attributable to S deposition. However, there was no change in the forested area in GRTE that exceeded the CLS-SR from 2001 to 2016, as 100% of the forest was below the CL in both years (Figure C15).

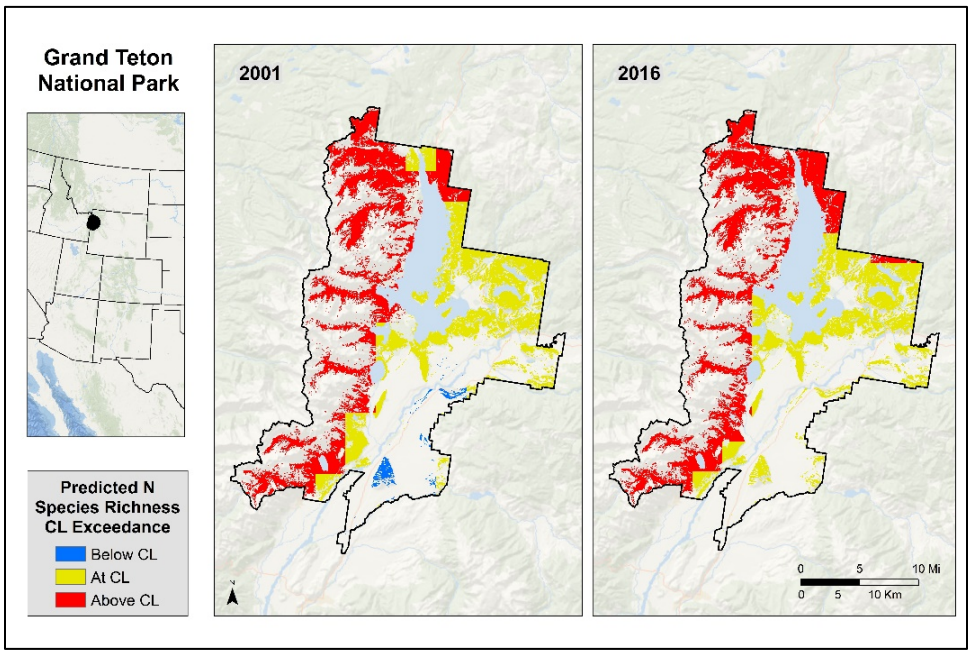


Figure C13. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in Grand Teton National Park in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

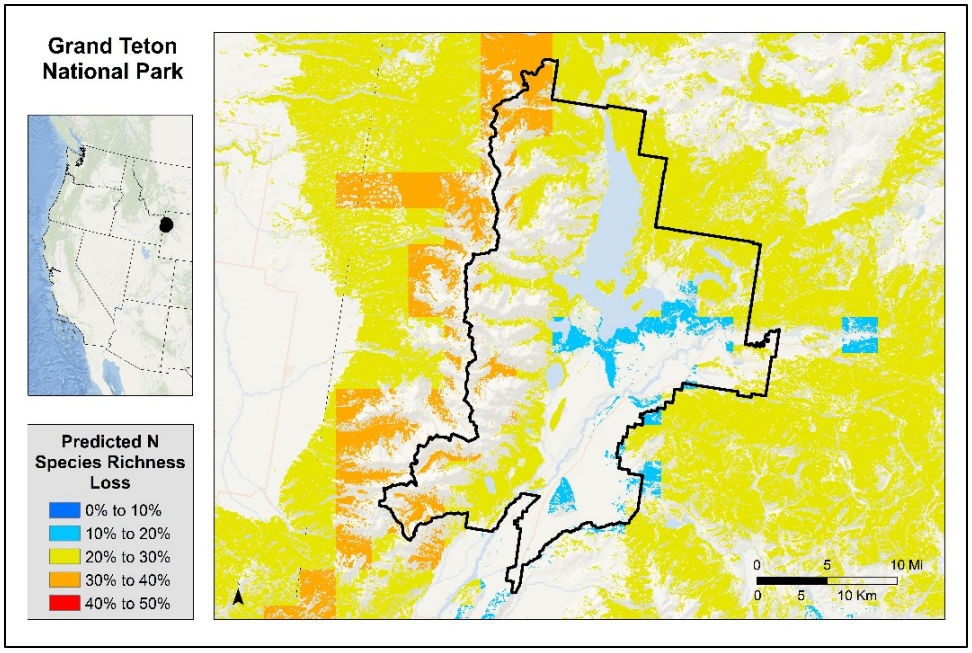


Figure C14. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in Grand Teton National Park.

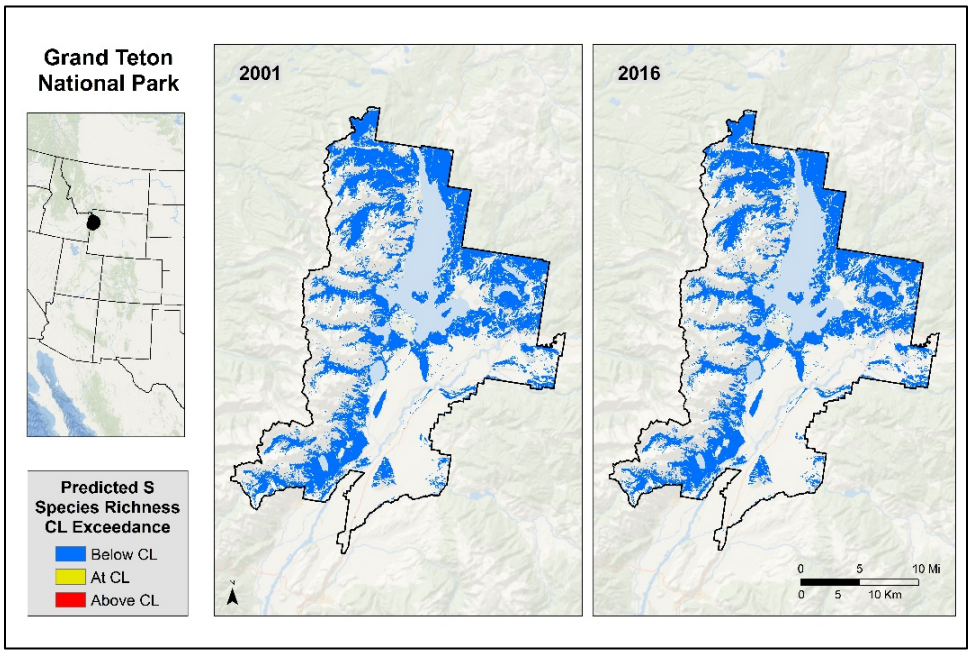


Figure C15. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in Grand Teton National Park is depicted in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

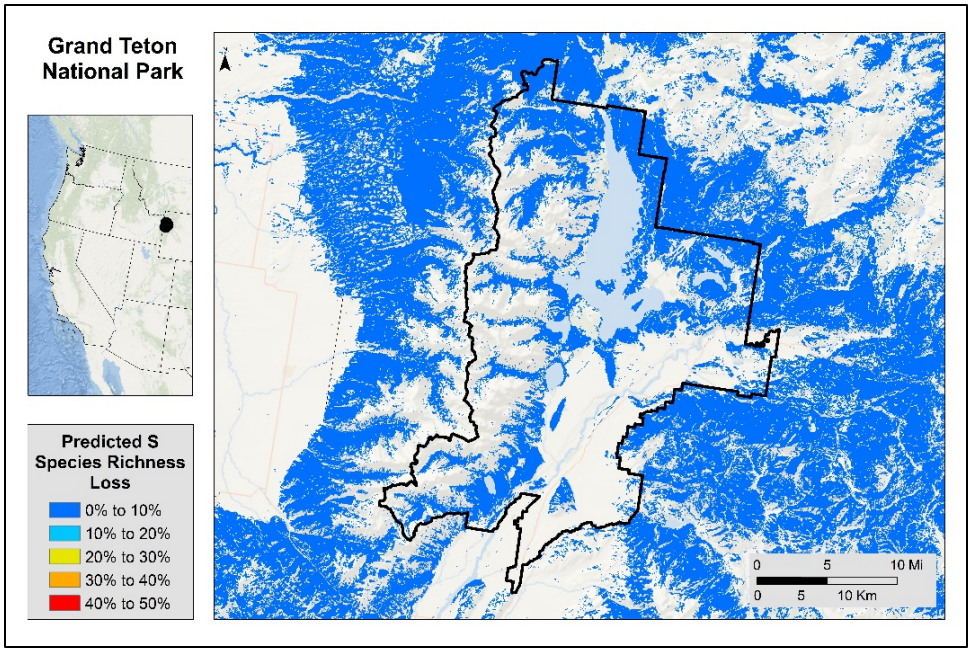


Figure C16. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in Grand Teton National Park.

Joshua Tree National Park (JOTR)

Deposition data is available for 100% of JOTR's forested area (Figure C17). However, less than 1% of the total area in JOTR is forested (3.2 km^2). The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C5. Summary of deposition values and expected loss of total epiphytic lichen species richness in Joshua Tree National Park based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	3.2	7.7	9.6	38.7	44.2	0.7	1.0	2.6	3.9
2016	3.2	4.3	5.4	24.4	29.8	0.4	0.7	1.7	2.9

2001 N and S conditions

N deposition in 2001 ranged from 7.7 kg-N ha^{-1} yr^{-1} in the southern section of the park to 9.6 kg-N ha^{-1} yr^{-1} in the northern part of the park (Table C5). The CLN-SR exceedance was between 4.2 and 6.1 kg-N ha^{-1} yr^{-1} over the CL. While, the highest critical load exceedances were located in the northern portion of the park, similar critical load exceedances could be found throughout the forested area in JOTR. 100% of the forested area exceeded the CLN-SR in 2001 (Figure C17).

S deposition in 2001 ranged from 0.7 kg-S ha^{-1} yr^{-1} to 1.0 kg-S ha^{-1} yr^{-1} (Table C5). 100% of the forested area included was below the CLS-SR in 2001 (Figure C19).

2016 N and S conditions

N deposition in 2016 ranged from 4.3 kg-N ha^{-1} yr^{-1} in the southern part of the park to 5.4 kg-N ha^{-1} yr^{-1} in the north, central part of the park (Table C5). 100% of the forested area exceeded the critical load (Figure C17). The CLN-SR exceedance was between 0.8 kg-N ha^{-1} yr^{-1} and 1.9 kg-N ha^{-1} yr^{-1}. 100% of the park was projected to experience between 20 and 30% predicted species richness loss (Figure C18). The minimum predicted species richness loss was 24.44%, the maximum was 29.80%, and the mean was 26.92%. The maximum predicted loss occurred in the northwestern and north central part of JOTR (Figure C18).

S deposition in 2016 was between 0.4 kg-S ha^{-1} yr^{-1} and 0.7 kg-S ha^{-1} yr^{-1} (Table C5). 100% of the forested area was below the CLS-SR in 2016 (Figure C19). 100% of the park was predicted to experience less than 10% lichen species richness loss (Figure C20). The minimum predicted species richness loss from sulfur deposition in 2016 was 1.75%, the maximum predicted loss was 2.89% and the mean was 2.14% predicted species richness loss.

Change over time in N and S Conditions

Maximum N deposition at JOTR decreased 4.16 kg-N ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum N deposition represents improved conditions for lichen species richness across the forested ecosystems in JOTR, even though 2016 N deposition levels area above the CLN-SR. 2016 conditions improved from 2001 by a 14.4% decrease in risk of species richness loss attributable to N deposition.

Maximum S deposition at JOTR decreased 0.3 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The slight decrease in maximum S deposition represents minor condition improvements for lichen species richness across JOTR. 2016 conditions improved from 2001 by a 1.0% decrease in risk of species richness loss attributable to S deposition. There was no change in the forested area below the CLS-SR because 100% of the forested area was below the CLS-SR in 2001 and 2016.

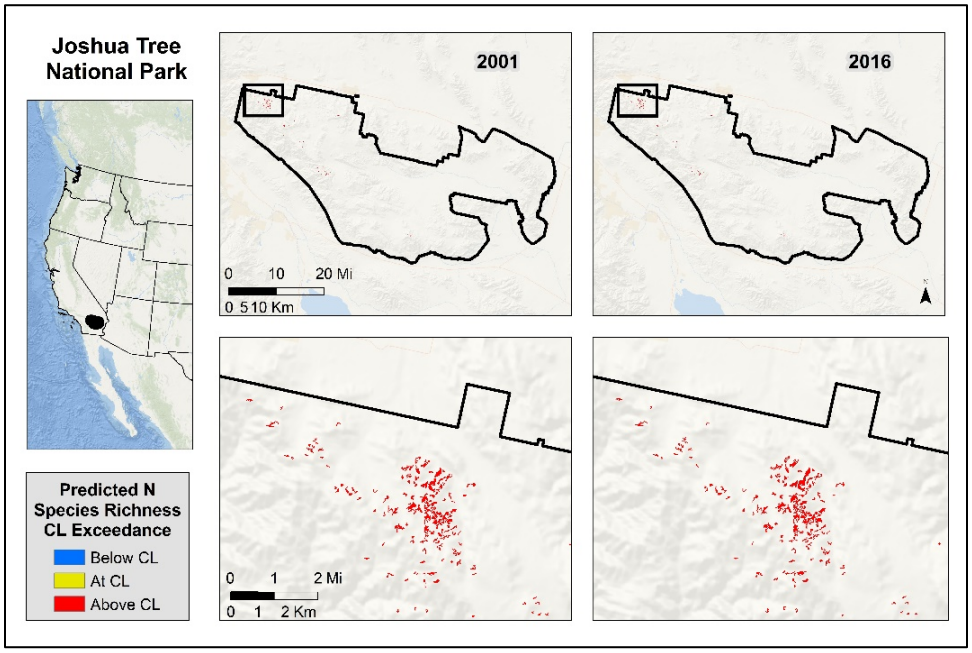


Figure C17. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in Joshua Tree National Park in 2001 (left top and bottom) and 2016 (right top and bottom). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

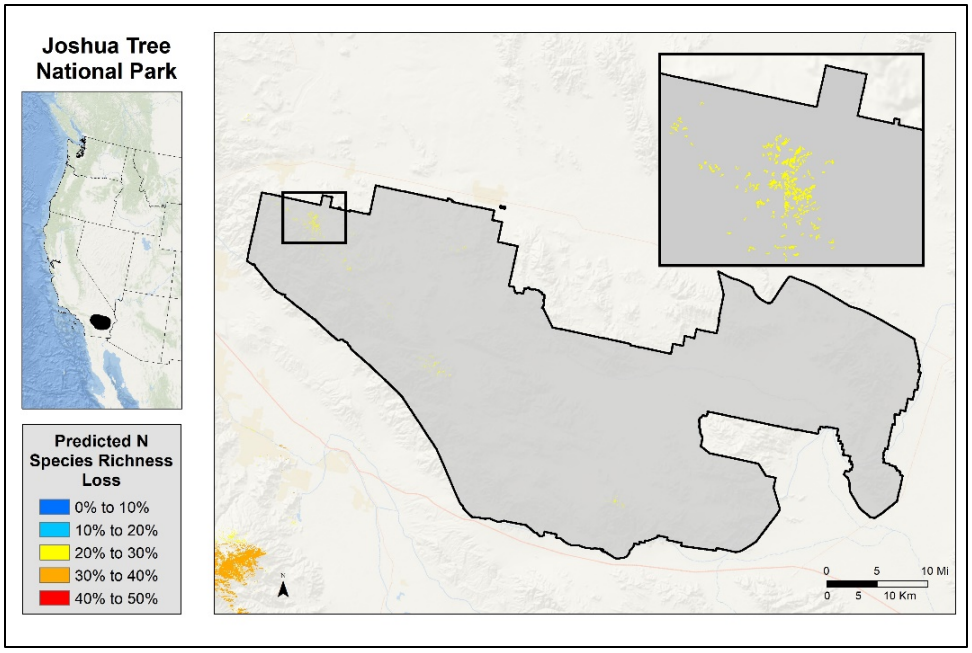


Figure C18. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in Joshua Tree National Park.

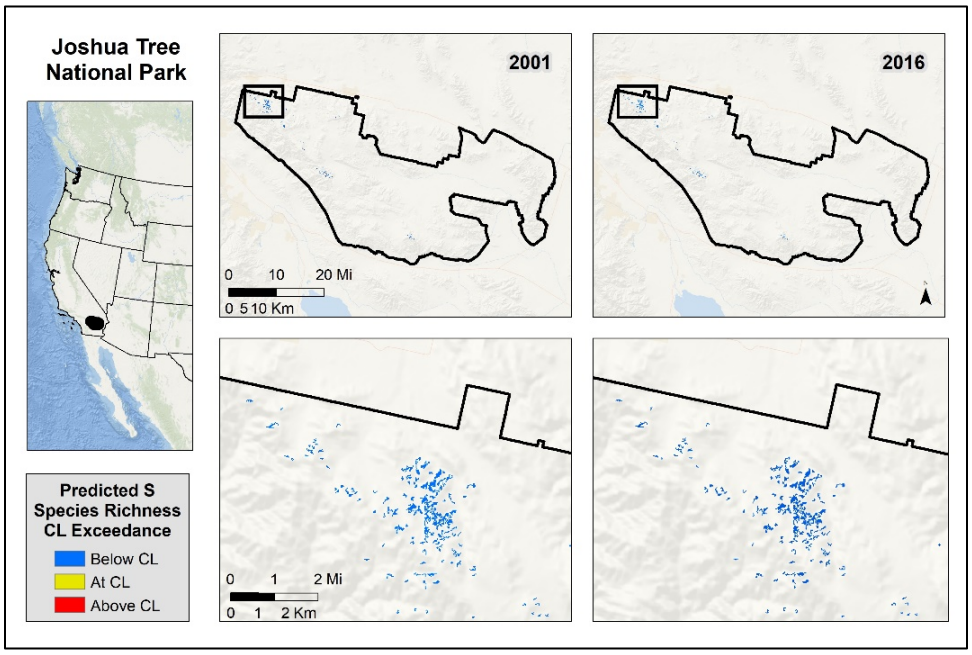


Figure C19. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in Joshua Tree National Park is depicted in 2001 (left top and bottom) and 2016 (right top and bottom). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

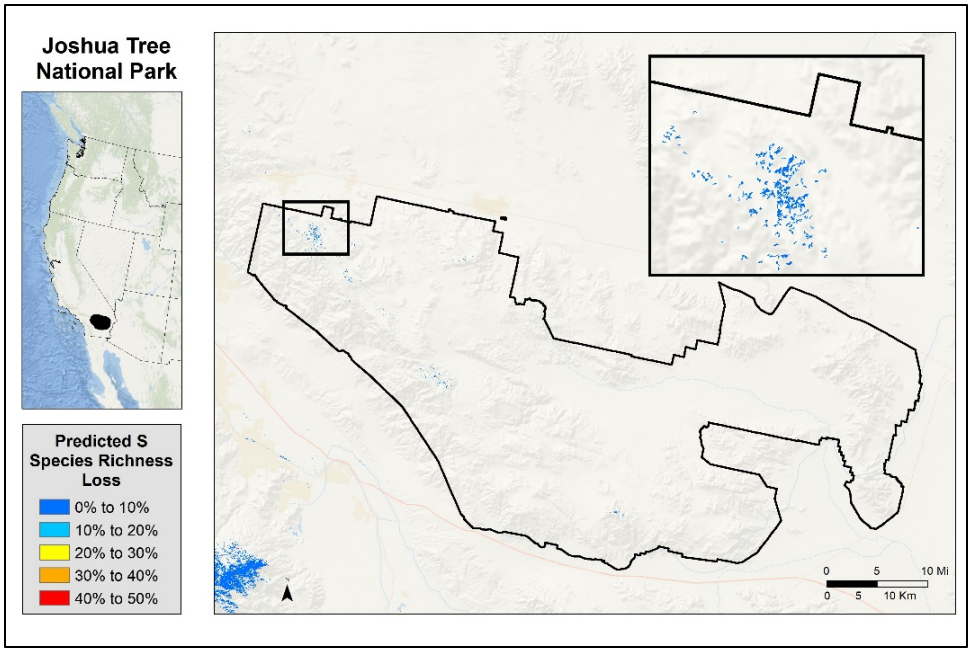


Figure C20. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in Joshua Tree National Park.

North Cascades National Park (NOCA)

Complete TDep coverage was not available for 33 national parks in the study, including NOCA. This is due to limitations in the model's ability to predict deposition along the United States border. Deposition data is available for 99% of NOCA's forested area (Figure C21). Maximum deposition, species richness response, and percentages are based on the area of forested land where TDep data is available, not for the entire forested area of NOCA. The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C6. Summary of deposition values and expected loss of total epiphytic lichen species richness in North Cascades National Park based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	1031.5	2.1	4.2	12.9	24.2	1.4	3.3	5.5	12.1
2016	1031.5	2.1	4.3	13.2	24.8	0.7	1.9	2.9	7.0

2001 N and S conditions

N deposition in 2001 ranged from 2.08 kg-N ha^{-1} yr^{-1} in the northeastern section of the park to 4.20 kg-N ha^{-1} yr^{-1} in the northwestern part of the park (Table C6). The maximum CLN-SR exceedance was between 0.7 kg-N ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the northwestern portion of the park. 1.74% of the forested area exceeded the CLN-SR in 2001 (Figure C21).

S deposition in 2001 ranged from 1.4 kg-S ha^{-1} yr^{-1} to 3.3 kg-S ha^{-1} yr^{-1} (Table C6). 100% of the forested area in NOCA was below the CLS-SR (Figure C23).

2016 N and S conditions

N deposition in 2016 ranged from 2.13 kg-N ha^{-1} yr^{-1} in the northeastern and southeastern parts of the park to 4.34 kg-N ha^{-1} yr^{-1} in the northwestern part of the park (Table C6). 3.71% of the forested area exceeded the critical load (Figure C21). The maximum CLN-SR exceedance was 0.84 kg-N ha^{-1} yr^{-1}. Approximately 72% of the park was projected to experience between 10 and 20% predicted species richness loss (Figure C22). The minimum predicted species richness loss was 13.17%, the maximum was 24.85%, and the mean was 18.3%. The maximum predicted loss occurred in the northwestern part of NOCA (Figure C22).

S deposition in 2016 was between 0.7 kg-S ha^{-1} yr^{-1} and 1.9 kg-S ha^{-1} yr^{-1} (Table C6). 100% of the forested area was below the CLS-SR in 2016 (Figure C23). 100% of the park was predicted to experience less than 10% lichen species richness loss (Figure C24). The minimum predicted species richness loss from sulfur deposition in 2016 was 2.90%, the maximum predicted loss was 7.04% and the mean was 4.66% predicted species richness loss.

Change over time in N and S conditions

Maximum N deposition at NOCA increased 0.14 kg-N ha^{-1} yr^{-1} from 2001 to 2016, resulting in a 0.7% increase in predicted species richness loss from N deposition. There was also a 1.97% increase in forested area above the CLN-SR. While there was an increase in area that was predicted to be in exceedance of the CLN-SR, there was also a 6.53% increase in area below the CLN-SR between 2001 and 2016. Figure C21 depicts an increase in area exceeding the critical load from 2001 and 2016 in the northwestern and north central areas of NOCA and a shift from areas at the critical load to below the critical load near the western CL threshold within NOCA.

Maximum S deposition at NOCA decreased 1.47 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum S deposition represents improved conditions for lichen species richness across the forested ecosystem with deposition data in NOCA. 2016 conditions improved from 2001 by a 5.1% decrease in risk of species richness loss attributable to S deposition. There was no change in forested area exceeding the CLS-SR between 2001 and 2016, as 100% of the forested area was below the CLS-SR in both 2001 and 2016 (Figure C23).

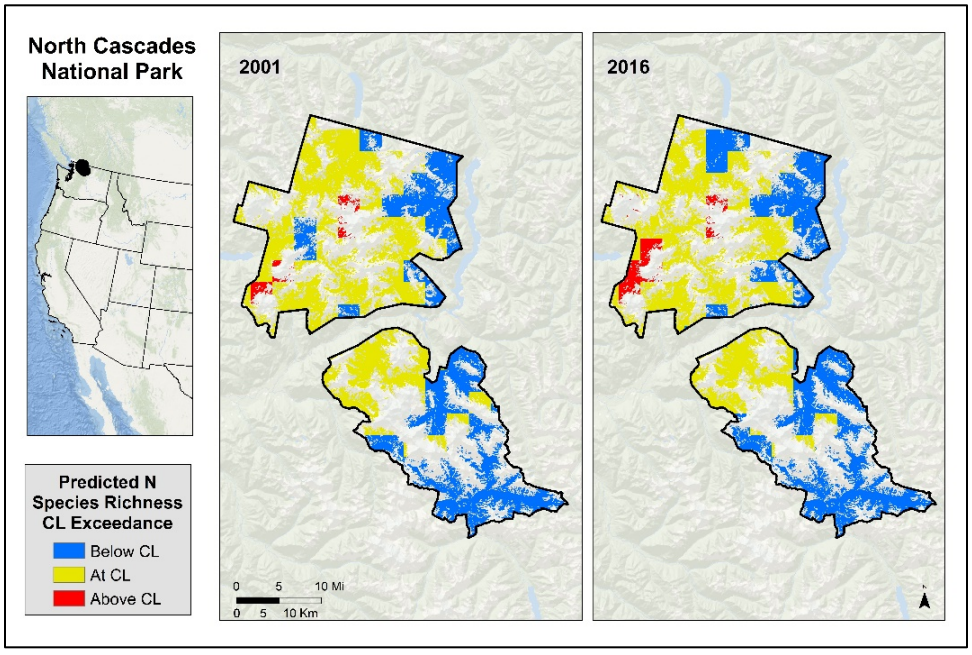


Figure C21. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in North Cascades National Park in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

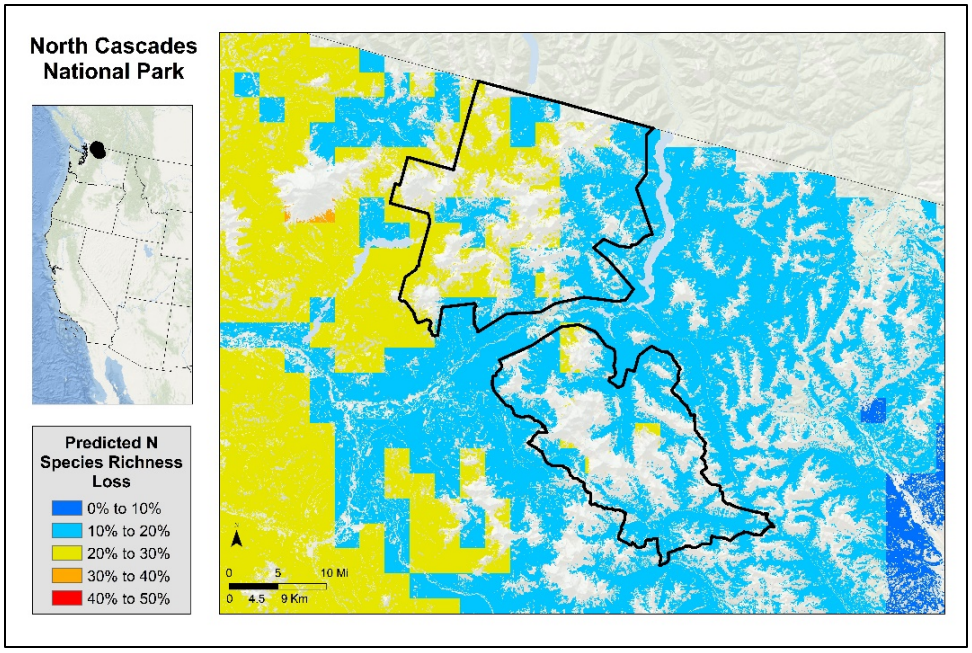


Figure C22. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in North Cascades National Park.

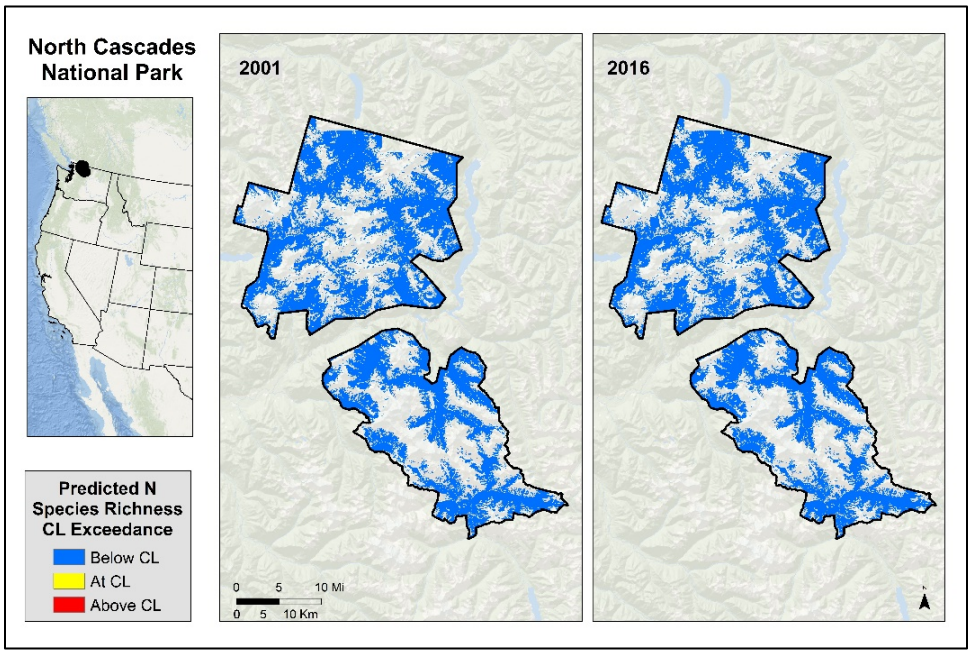


Figure C23. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in North Cascades National Park is depicted in 2001 (left top and bottom) and 2016 (right top and bottom). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

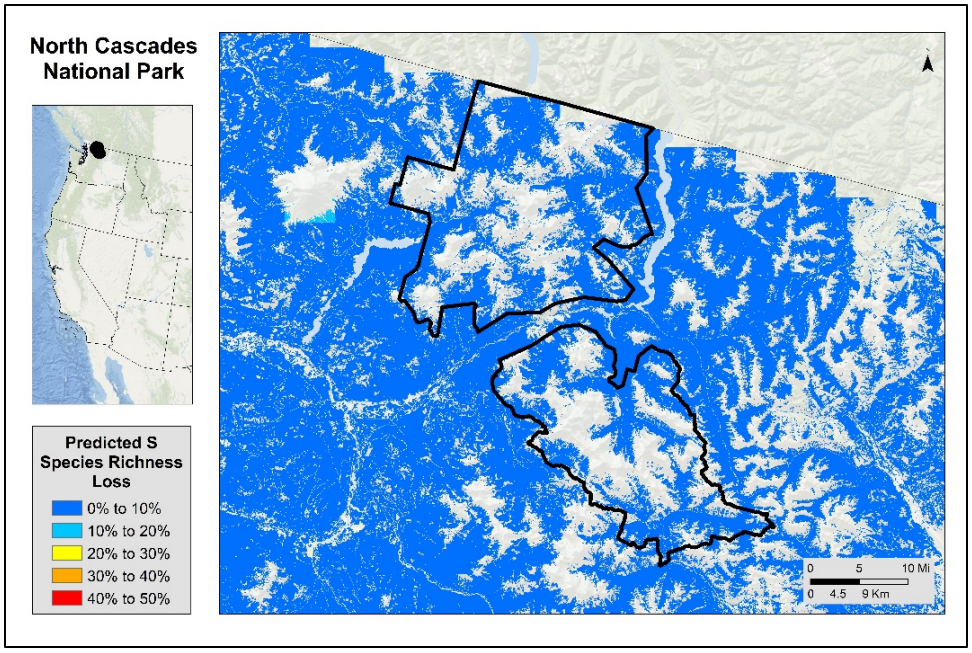


Figure C24. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in North Cascades National Park. Predicted lichen species richness loss from S deposition is between 0% and 10% for all forested area within the park.

Rocky Mountain National Park (ROMO)

Deposition data is available for 100% of ROMO's forested area (Figure C25). The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C7. Summary of deposition values and expected loss of total epiphytic lichen species richness in Rocky Mountain National Park based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	594.5	4.4	9.4	25.0	43.6	1.4	4.6	5.3	16.2
2016	594.5	2.8	6.5	16.9	34.0	0.6	1.7	2.5	6.4

2001 N and S conditions

N deposition in 2001 ranged from 4.4 kg-N ha^{-1} yr^{-1} in the southwest corner of the park to 9.4 kg-N ha^{-1} yr^{-1} in the southern part of the park (Table C7). The CLN-SR exceedance was between 0.9 and 5.9 kg-N ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located across the central portion of the park from north to south. 100% of the forested area in NOCA is above the CLN-SR (Figure C25).

S deposition in 2001 ranged from 1.4 kg-S ha^{-1} yr^{-1} to 4.6 kg-S ha^{-1} yr^{-1} (Table C7). 100% of the forested area included in the study exceeded both the CLS-SR in 2001 (Figure C27).

2016 N and S conditions

N deposition in 2016 ranged from 2.8 kg-N ha^{-1} yr^{-1} in the southeastern corner of the park to 6.5 kg-N ha^{-1} yr^{-1} in the east central part of the park (Table C7). 78% of the forested area exceeded the critical load Figure C25). The maximum CLN-SR exceedance was 2.95 kg-N ha^{-1} yr^{-1}. Approximately 60% of the park was projected to experience between 20 and 30% predicted species richness loss (Figure C26). The minimum predicted species richness loss was 16.88%, the maximum was 34.01%, and the mean was 26.60%. The maximum predicted loss occurred in the east central part of ROMO (Figure C26).

S deposition in 2016 was between 0.6 kg-S ha^{-1} yr^{-1} and 1.7 kg-S ha^{-1} yr^{-1} (Table C7). 100% of the forested area was below the CLS-SR in 2016 (Figure C27). 100% of the park was predicted to experience less than 10% lichen species richness loss (Figure C28). The minimum predicted species richness loss from sulfur deposition in 2016 was 2.49%, the maximum predicted loss was 6.36% and the mean was 4.20% predicted species richness loss.

Change over time in N and S conditions

Maximum N deposition at ROMO decreased 2.91 kg-N ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum N deposition represents improved conditions for lichen species richness across the majority of the forested ecosystem with deposition data in ROMO. 2016 conditions improved from 2001 by a 9.6% decrease in risk of species richness loss attributable to N deposition. There was a decrease of 22.48% of forested area in ROMO in exceedance of the CLN-SR from 2001 to 2016. Approximately 461 km^2 are predicted to have been above the CLN-SR in 2016, compared to the approximately 595 km^2 in 2001 (Figure C25).

Maximum S deposition at ROMO decreased 2.92 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum S deposition represents improved conditions for lichen species richness across the forested ecosystem with deposition data in ROMO. 2016 conditions improved from 2001 by a 9.8% decrease in risk of species richness loss attributable to S deposition. There was no change in forested area in exceedance of the CLS-SR between 2001 and 2016. Both years were predicted to experience S deposition levels below the CLS-SR for all forested area (Figure C27).

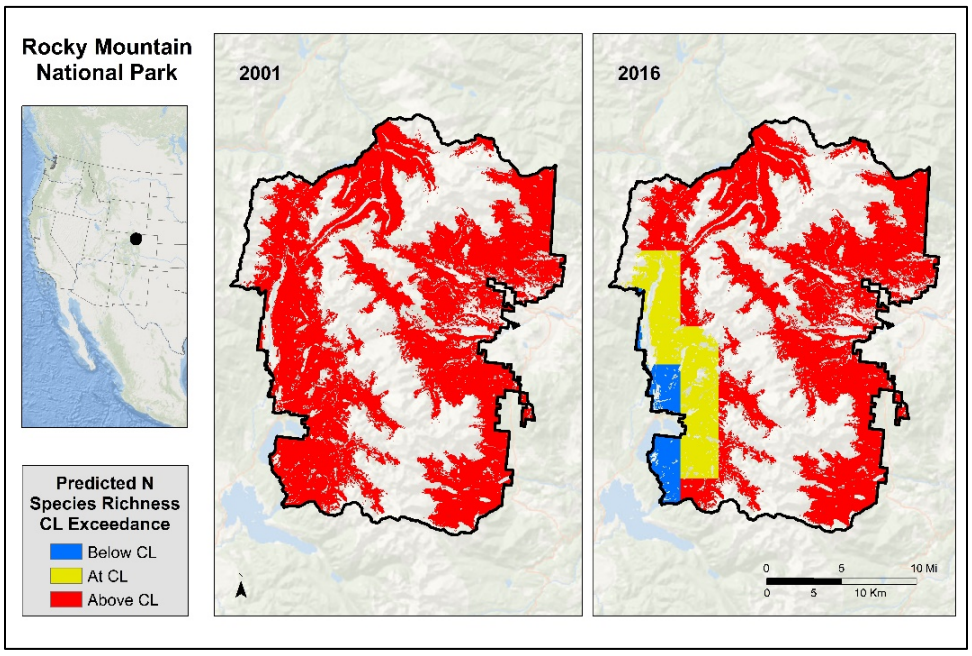


Figure C25. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in Rocky Mountain National Park in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

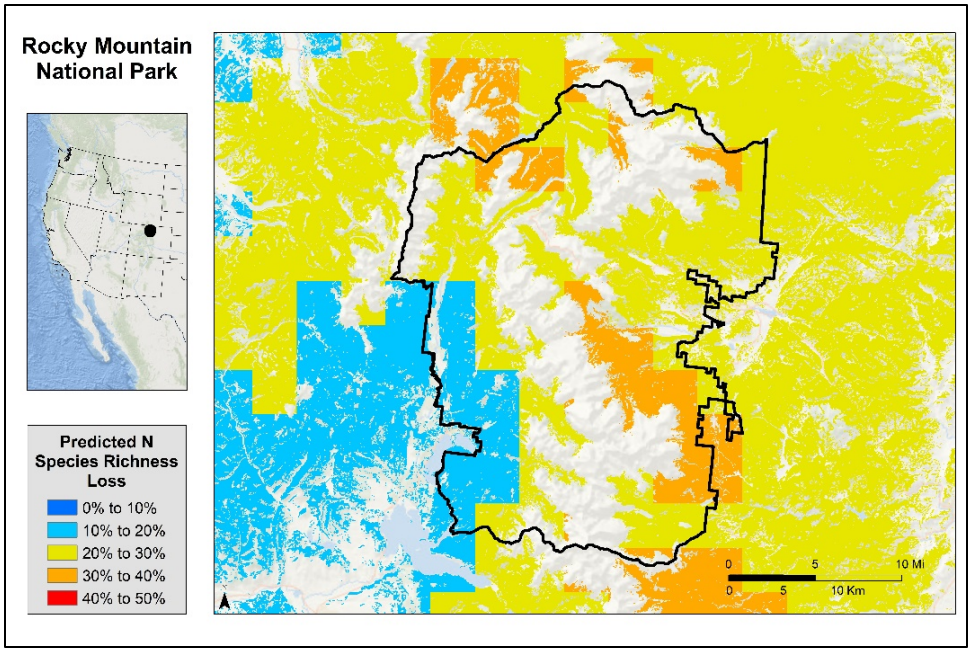


Figure C26. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in Rocky Mountain National Park.

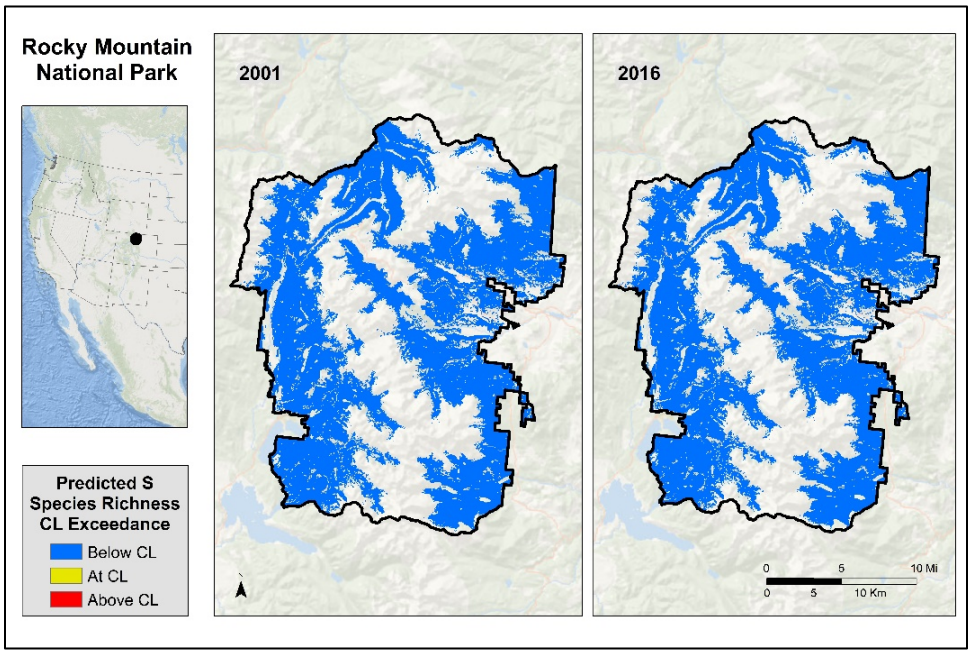


Figure C27. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in Rocky Mountain National Park is depicted in 2001 (left top and bottom) and 2016 (right top and bottom). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

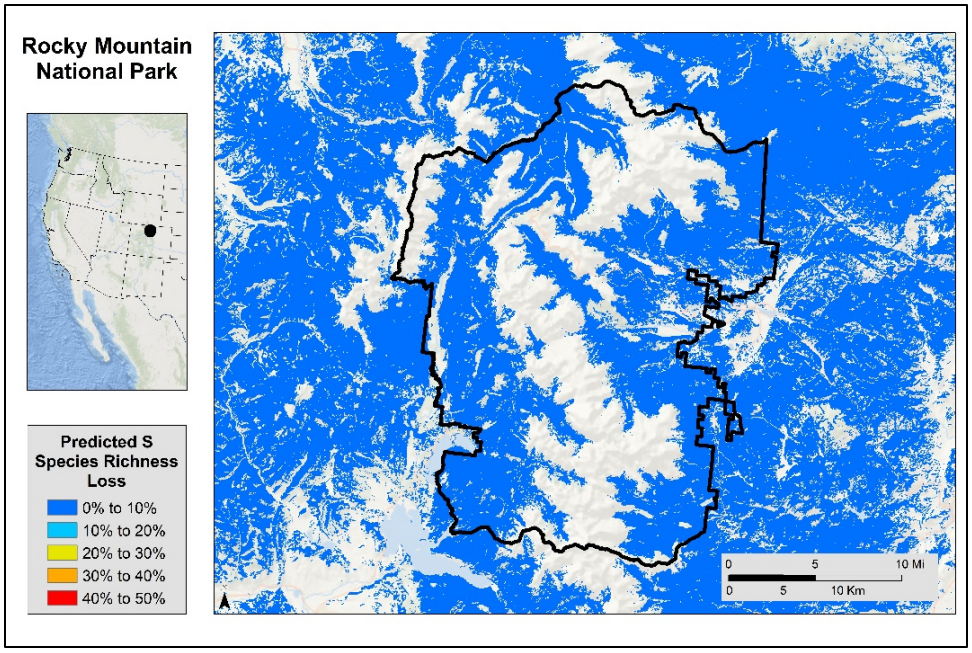


Figure C28. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in Rocky Mountain National Park.

Sleeping Bear Dunes National Lakeshore (SLBE)

Complete TDep coverage was not available for 33 NPS units in the study, including SLBE. This is due to limitations in the model's ability to predict deposition along coast lines and the United States' border. Deposition data is available for 82% of SLBE's forested area (Figure C29). Maximum deposition, species richness response, and percentages are based on the area of forested land where TDep data is available, not for the entire forested area of SLBE. The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C8. Summary of deposition values and expected loss of total epiphytic lichen species richness in Sleeping Bear Dunes National Lakeshore based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	129.5	7.3	13.3	37.3	50.8	7.3	11.1	23.6	31.7
2016	129.5	5.5	8.9	29.9	42.2	2.5	3.3	9.4	11.9

2001 N and S conditions

N deposition in 2001 ranged from 7.3 kg-N ha^{-1} yr^{-1} in the eastern section of the park to 13.3 kg-N ha^{-1} yr^{-1} in the southern part of the park (Table C8). The CLN-SR exceedance was between 3.8 and 9.8 kg-N ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the southern and southeastern portion of the park.

S deposition in 2001 ranged from 7.3 kg-S ha^{-1} yr^{-1} to 11.1 kg-S ha^{-1} yr^{-1} (Table C8). The CLS-SR exceedance in SLBE was between 1.3 and 5.1 kg-S ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the southern portion of the park on the mainland. 100% of the forested area included in the study exceeded both the N and CLS-SR in 2001 (Figure C29, Figure C31).

The geography of N and S exceedances across the park in 2001 was broadly similar, with the highest exceedances in the southern and southeastern portion of the park for both N and S deposition.

2016 N and S conditions

N deposition in 2016 ranged from 5.5 kg-N ha^{-1} yr^{-1} in the northern part of the park to 8.9 kg-N ha^{-1} yr^{-1} in the southern part of the park on the mainland (Table C8). 100% of the forested area exceeded the N critical load (Figure C29). The CLN-SR exceedance was between 1.95 kg-N ha^{-1} yr^{-1} and 5.4 kg-N ha^{-1} yr^{-1}. Approximately 84% of the park was projected to experience between 30 and 40% predicted species richness loss (Figure C30). The minimum predicted species richness loss was

29.90%, the maximum was 42.17%, and the mean was 32.44%. The maximum predicted loss occurred in the southern part of SLBE (Figure C30).

S deposition in 2016 was between 2.5 kg-S ha^{-1} yr^{-1} and 3.3 kg-S ha^{-1} yr^{-1} (Table C8). 100% of the forested area was below the CLS-SR in 2016 (Figure C31). Approximately 83% of the park was predicted to experience between 10 and 20% lichen species richness loss (Figure C32). The minimum predicted species richness loss from sulfur deposition in 2016 was 9.42%, the maximum predicted loss was 11.96% and the mean was 10.19% predicted species richness loss.

Change over time in N and S conditions

Maximum N deposition at SLBE decreased 4.5 kg-N ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum N deposition represents improved conditions for lichen species richness across the majority of the forested ecosystem with deposition data in SLBE. 2016 conditions improved from 2001 by a 7% decrease in risk of species richness loss attributable to N deposition. However, there was no change in the forested area that exceeded the CLN-SR. In both 2001 and 2016, 100% of the forested area was above the critical load (Figure C29).

Maximum S deposition at SLBE decreased 7.8 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum S deposition represents improved conditions for lichen species richness across the forested ecosystem with deposition data in SLBE. 2016 conditions improved from 2001 by a 19.7% decrease in risk of species richness loss attributable to S deposition. Forested area in SLBE experienced dramatic change from 2001 to 2016 in respect to CLS-SR exceedance. 100% of the forest exceeded the CLS-SR in 2001 and 0% exceeded the CLS-SR in 2016 (Figure C31).

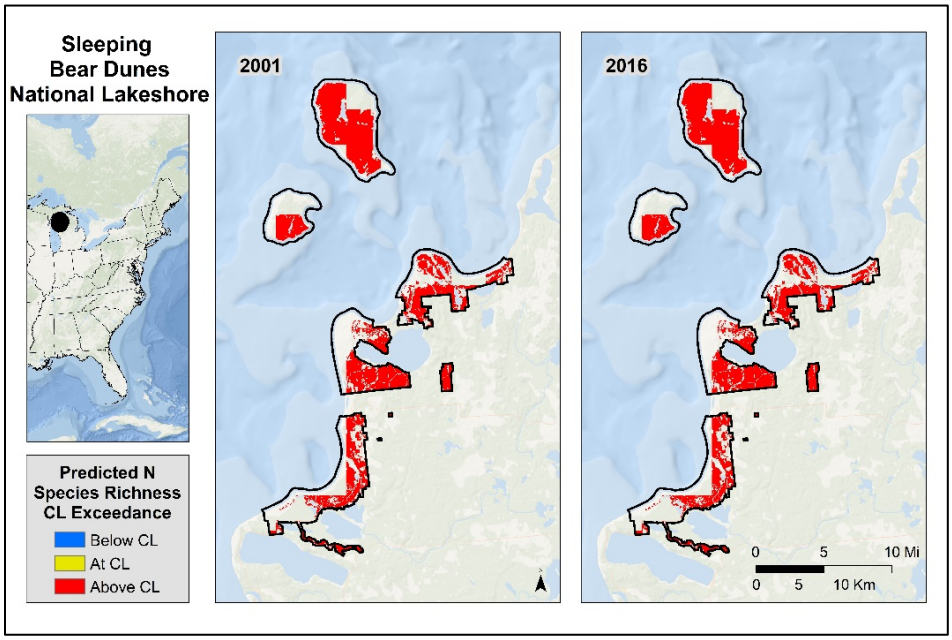


Figure C29. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in Sleeping Bear Dunes National Lakeshore in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

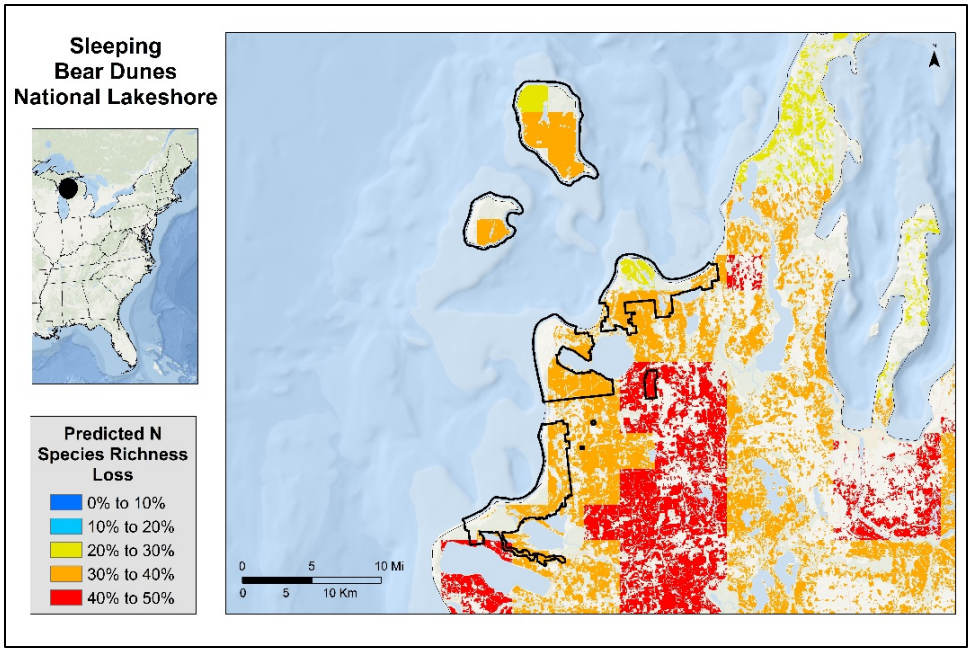


Figure C30. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in Sleeping Bear Dunes National Lakeshore.

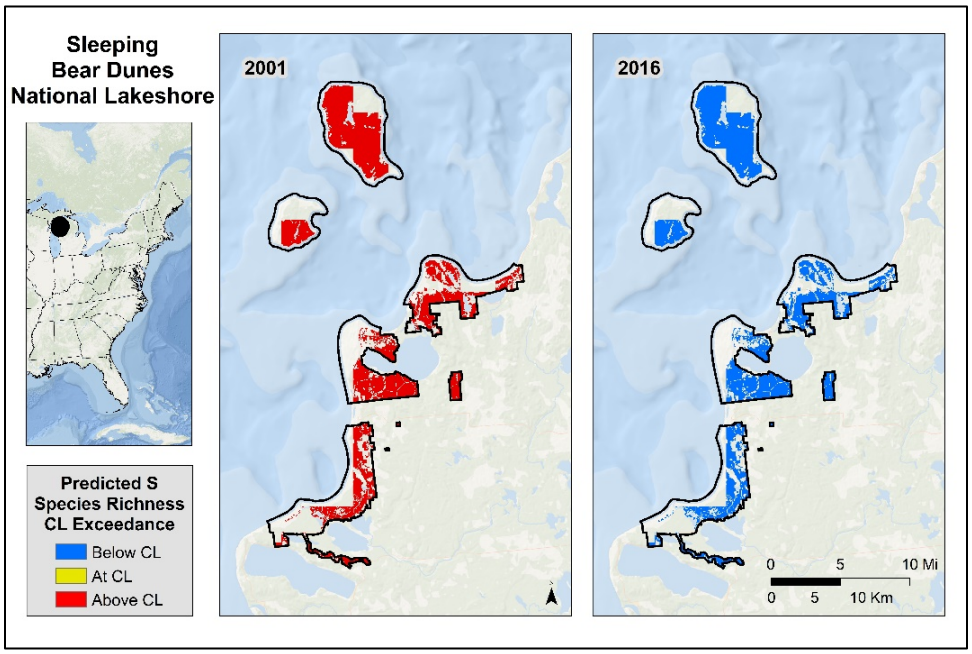


Figure C31. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in Sleeping Bear Dunes National Lakeshore is depicted in 2001 (left top and bottom) and 2016 (right top and bottom). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

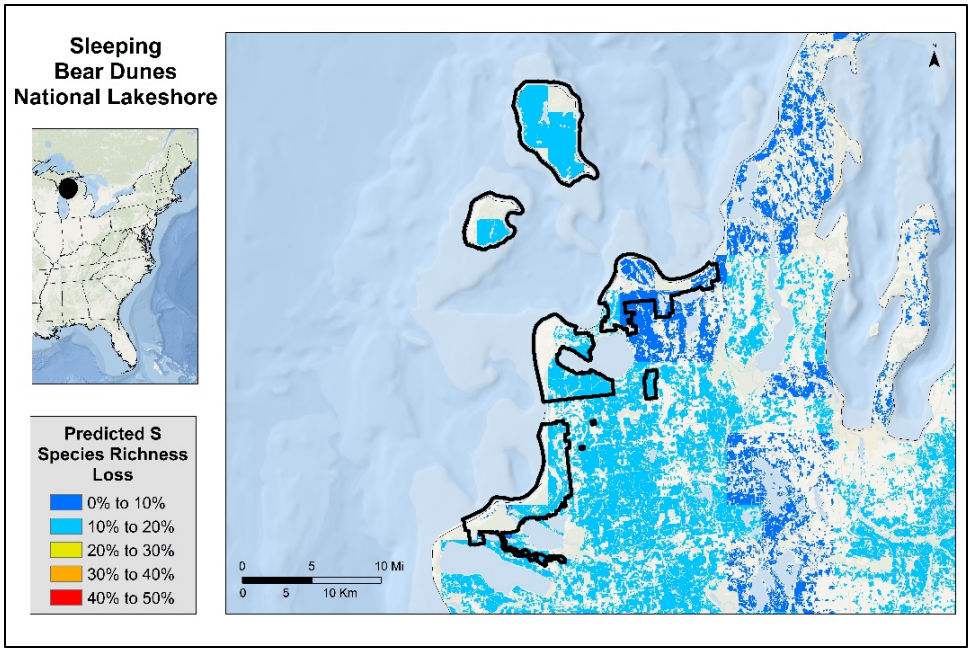


Figure C32. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in Sleeping Bear Dunes National Lakeshore.

Theodore Roosevelt National Park (THRO)

Deposition data is available for 100% of THRO's forested area (Figure C33). The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C9. Summary of deposition values and expected loss of total epiphytic lichen species richness in Theodore Roosevelt National Park based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	51.7	4.0	4.9	23.1	27.3	2.5	3.3	9.4	12.1
2016	51.7	4.4	5.2	24.9	28.7	1.5	2.0	5.6	7.6

2001 N and S conditions

N deposition in 2001 ranged from 4.0 kg-N ha^{-1} yr^{-1} near the western border of the park to 4.9 kg-N ha^{-1} yr^{-1} at the eastern edge of the park (Table C9). The CLN-SR exceedance was between 0.5 and 1.4 kg-N ha^{-1} yr^{-1} over the CL. The maximum predicted loss occurred in the southeastern and northern part of THRO. Approximately 99% of the forested area was above the CLN-SR in 2016 (Figure C33).

S deposition in 2001 ranged from 2.5 kg-S ha^{-1} yr^{-1} to 3.3 kg-S ha^{-1} yr^{-1} (Table C9). 100% of the forested area in THRO was below the CLS-SR in 2001 (Figure C35).

2016 N and S conditions

N deposition in 2016 ranged from 4.4 kg-N ha^{-1} yr^{-1} in the central unit of the park to 5.2 kg-N ha^{-1} yr^{-1} in the southeastern part of THRO (Table C9). 100% of the forested area exceeded the critical load (Figure C33). The CLN-SR exceedance was between 0.9 kg-N ha^{-1} yr^{-1} and 1.7 kg-N ha^{-1} yr^{-1}. 100% of the park was projected to experience between 20 and 30% predicted species richness loss (Figure C34). The minimum predicted species richness loss was 24.88%, the maximum was 28.71%, and the mean was 27.29%. The maximum predicted loss occurred in the southeastern and northern part of THRO (Figure C34).

S deposition in 2016 was between 1.5 kg-S ha^{-1} yr^{-1} and 2.0 kg-S ha^{-1} yr^{-1} (Table C9). 100% of the forested area was below the CLS-SR in 2016 (Figure C35). 100% of the park was predicted to experience less than 10% lichen species richness loss (Figure C36). The minimum predicted species richness loss from sulfur deposition in 2016 was 5.57%, the maximum predicted loss was 7.62% and the mean was 6.66% predicted species richness loss.

Change over time in N and S conditions

Maximum N deposition at THRO increased 0.3 kg-N ha^{-1} yr^{-1} from 2001 to 2016. The increase in maximum N deposition represents slightly degraded conditions for lichen species richness across the majority of the forested ecosystem in THRO. 2016 conditions degraded from 2001 by a 1.4% increase in risk of species richness loss attributable to N deposition. In 2001, less than 1% of the forested area was below the CLN-SR. By 2016, 0% of the forested area was below the CLN-SR. The southwestern edge of THRO shifted from at the CLN-SR in 2001 to above the CLN-SR in 2016 (Figure C33).

Maximum S deposition at THRO decreased 1.3 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum S deposition represents improved conditions for lichen species richness across the forested ecosystem with deposition data in THRO. 2016 conditions improved from 2001 by a 4.5% decrease in risk of species richness loss attributable to S deposition. In both 2001 and 2016 the forested area was 100% below the CLS-SR and thus there was no change in forested area exceedance over this time period (Figure C35).

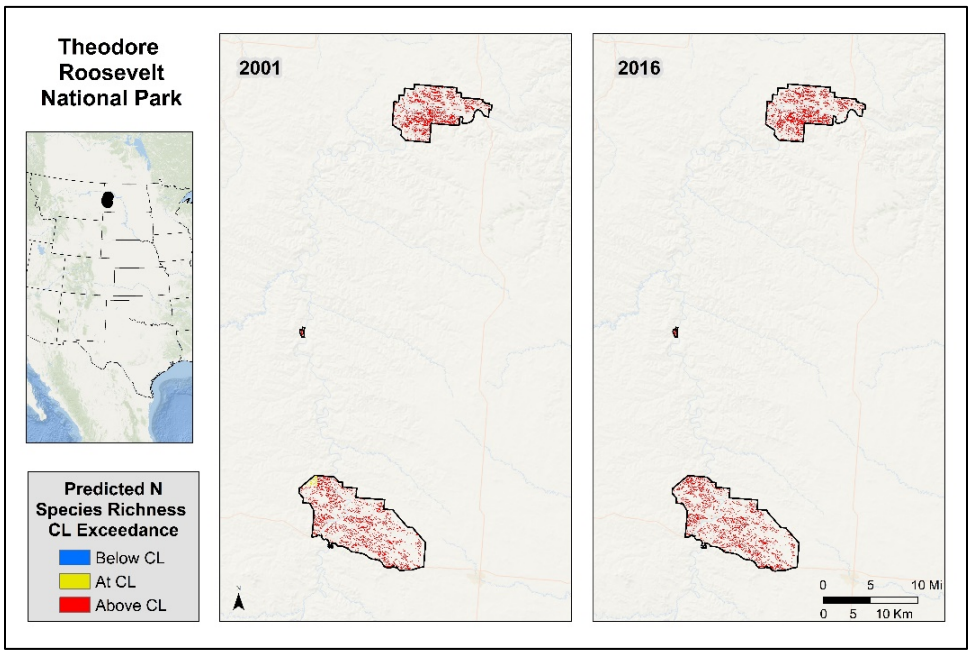


Figure C33. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in Theodore Roosevelt National Park in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

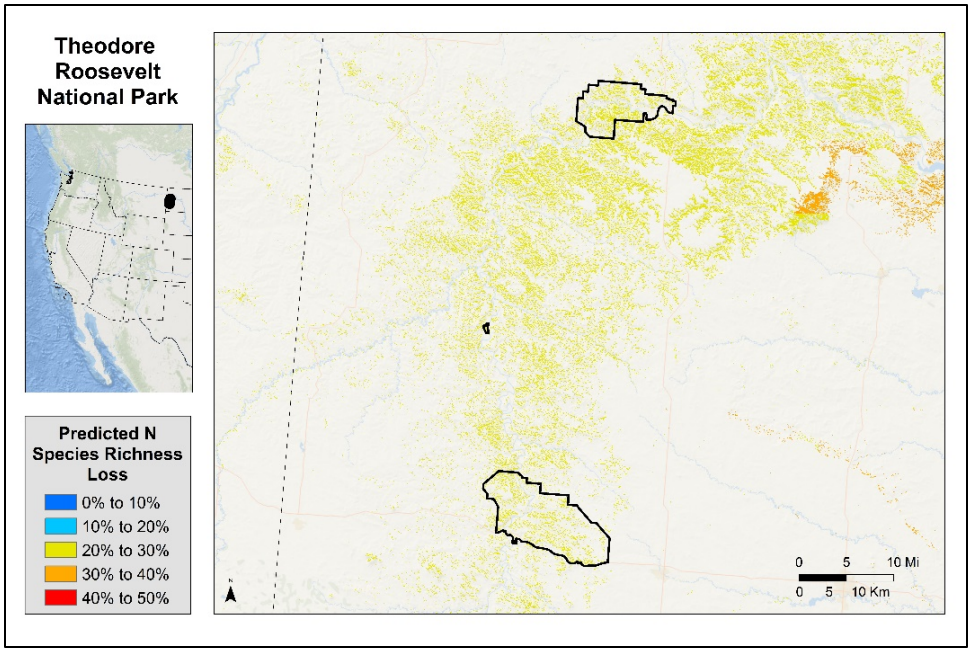


Figure C34. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in Theodore Roosevelt National Park.

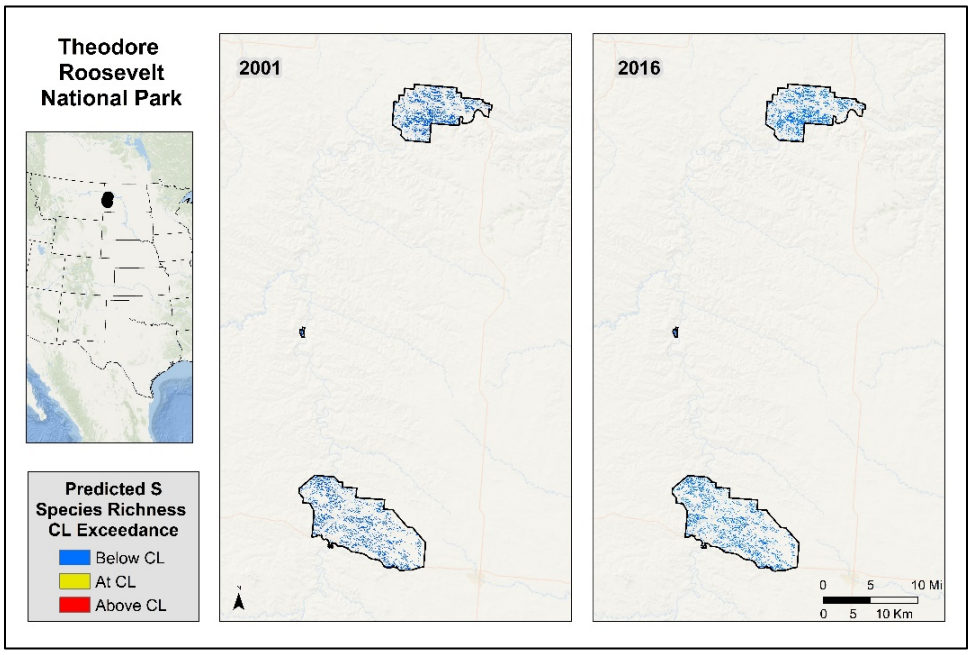


Figure C35. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in Theodore Roosevelt National Park is depicted in 2001 (left top and bottom) and 2016 (right top and bottom). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

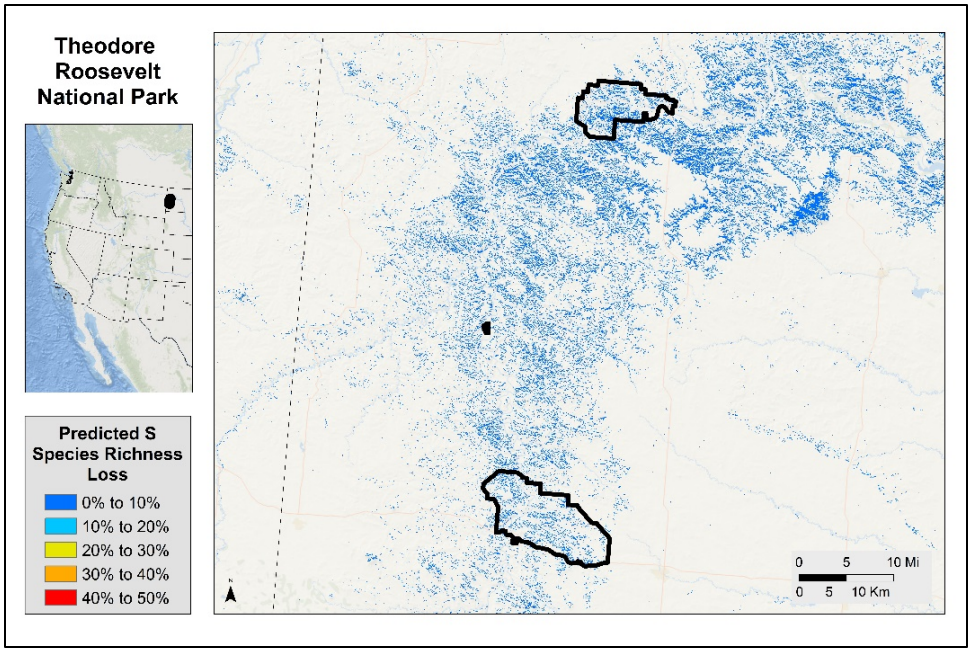


Figure C36. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in Theodore Roosevelt National Park.

Yosemite National Park (YOSE)

Deposition data is available for 100% of YOSE's forested area (Figure C37). The critical load of N for a decline in species richness (CLN-SR) which is protective of the lichen community is 3.5 kg-N ha^{-1} yr^{-1}. The critical load of S for a decline in species richness (CLS-SR) which is protective of the lichen community is 6.0 kg-S ha^{-1} yr^{-1}. The percent decline in species richness number reported below are relative to the maximum from the response equations (Table 2). Given that the equations summarize all data, and curves were consistent across ecosystems, these values are relative to the maximum expected at each site.

Table C10. Summary of deposition values and expected loss of total epiphytic lichen species richness in Yosemite National Park based on 3-year TDep total N and total S (kg-N/S ha^{-1} yr^{-1}).

Year	Forest cover (km^2)	Min N dep.	Max N dep.	Min N - % decline in species richness	Max N - % decline in species richness	Min S Dep.	Max S Dep.	Min S - % decline in species richness	Max S - % decline in species richness
2001	1435.8	4.6	6.7	26.1	35.0	1.1	1.7	4.1	6.3
2016	1435.8	4.0	6.2	23.2	33.1	0.9	1.5	3.5	5.6

2001 N and S conditions

N deposition in 2001 ranged from 4.6 kg-N ha^{-1} yr^{-1} in the eastern edge of the park, near the Tioga Pass Entrance to 6.7 kg-N ha^{-1} yr^{-1} in the western part of the park (Table C10). The CLN-SR exceedance was between 1.1 and 2.1 kg-N ha^{-1} yr^{-1} over the CL. The highest critical load exceedances were located in the western edge of the park and the southern tip. 100% of the forested area in YOSE was above the CLN-SR in 2001 (Figure C37).

S deposition in 2001 ranged from 1.1 kg-S ha^{-1} yr^{-1} to 1.7 kg-S ha^{-1} yr^{-1} (Table C10). 100% of the forested area in YOSE was below the CLS-SR in 2001 (Figure C39).

2016 N and S conditions

N deposition in 2016 ranged from 4.0 kg-N ha^{-1} yr^{-1} in the north central part of the park to 6.2 kg-N ha^{-1} yr^{-1} in the northern part of the park (Table C10). 100% of the forested area exceeded the critical load (Figure C37). The CLN-SR exceedance was between 0.5 kg-N ha^{-1} yr^{-1} and 2.7 kg-N ha^{-1} yr^{-1}. Approximately 97% of the park was projected to experience between 20 and 30% predicted species richness loss (Figure C38). The minimum predicted species richness loss was 23.23%, the maximum was 33.05%, and the mean was 26.66%. The maximum predicted loss occurred in the northern part of YOSE (Figure C38).

S deposition in 2016 was between 0.9 kg-S ha^{-1} yr^{-1} and 1.5 kg-S ha^{-1} yr^{-1} (Table C10). 100% of the forested area was below the CLS-SR in 2016 (Figure C39). 100% of the park was predicted to experience less than 10% lichen species richness loss (Figure C40). The minimum predicted species richness loss from sulfur deposition in 2016 was 3.55%, the maximum predicted loss was 5.60% and the mean was 4.08% predicted species richness loss.

Change over time in N and S conditions

Maximum N deposition at YOSE decreased 0.5 kg-N ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum N deposition represents improved conditions for lichen species richness across the majority of the forested ecosystem with deposition data in YOSE. 2016 conditions improved from 2001 by a 1.9% decrease in risk of species richness loss attributable to N deposition. However, 100% of the forested area in YOSE remained above the CLN-SR from 2001 to 2016 (Figure C37).

Maximum S deposition at YOSE decreased 0.2 kg-S ha^{-1} yr^{-1} from 2001 to 2016. The decrease in maximum S deposition represents improved conditions for lichen species richness across the forested ecosystem with deposition data in YOSE. 2016 conditions improved from 2001 by a 0.7% decrease in risk of species richness loss attributable to S deposition. There was no change in the forested area in exceedance of the CLS-SR. In both 2001 and 2016, 100% of the forested area was below the CLS-SR (Figure C39).

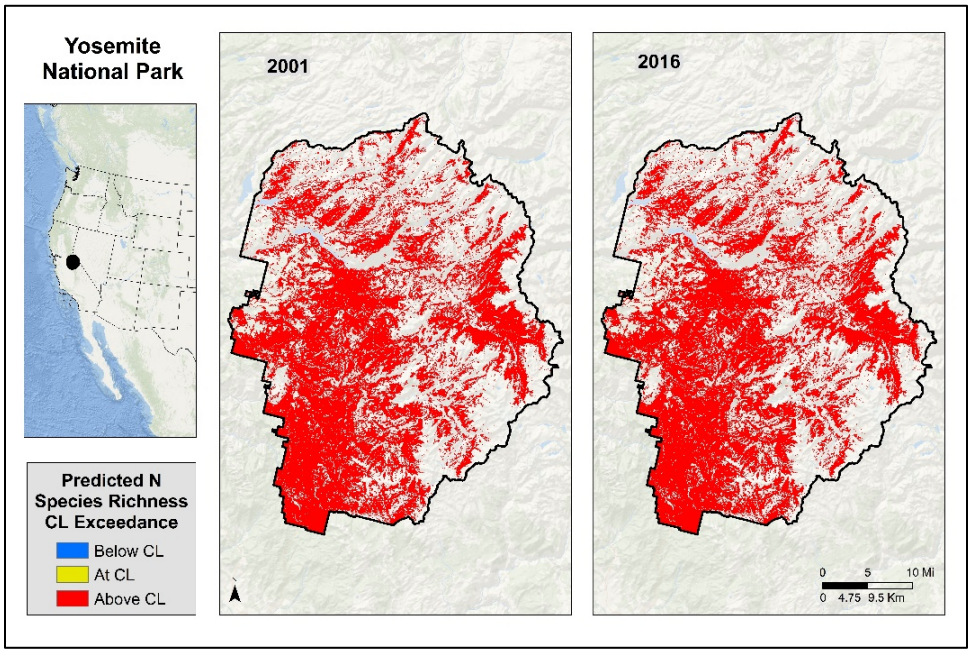


Figure C37. Exceedance of the critical load of N for a decline in epiphytic lichen species richness in Yosemite National Park in 2001 (left) and 2016 (right). Exceedances are categorized as below the critical load (<CL−0.5 kg-N ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-N ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-N ha^{-1} yr^{-1}; red).

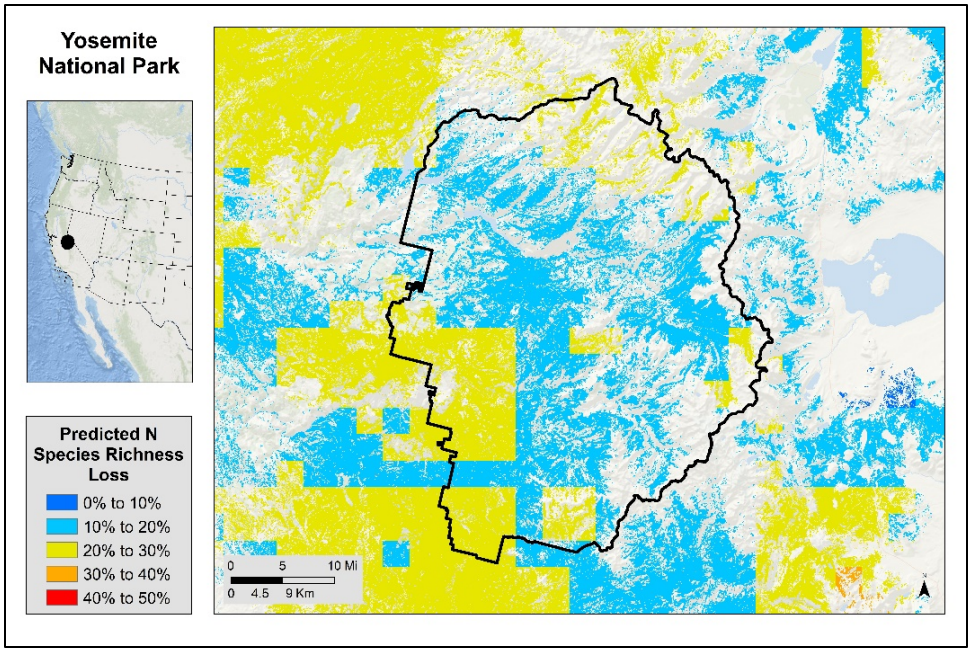


Figure C38. Level of decline of epiphytic lichen species richness based on 2016 TDep total N deposition in Yosemite National Park.

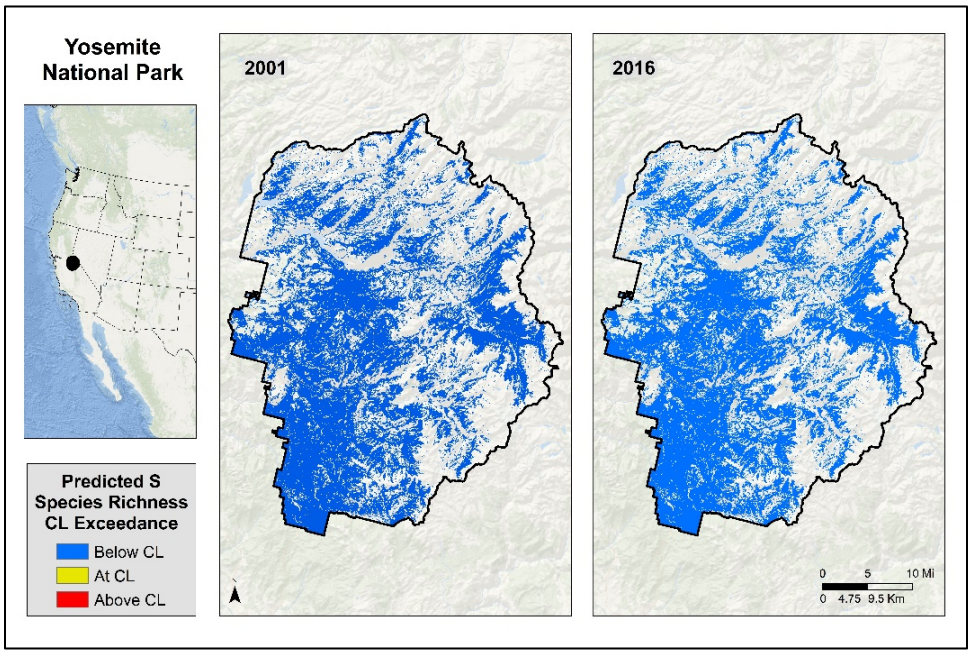


Figure C39. Exceedance of the critical load of S for a decline in epiphytic lichen species richness in Yosemite National Park is depicted in 2001 (left top and bottom) and 2016 (right top and bottom). Exceedances are categorized as below the critical load (<CL−0.5 kg-S ha^{-1} yr^{-1}; blue), at the critical load value (CL±0.5 kg-S ha^{-1} yr^{-1}; yellow), or above the critical load value (>CL+0.5 kg-S ha^{-1} yr^{-1}; red).

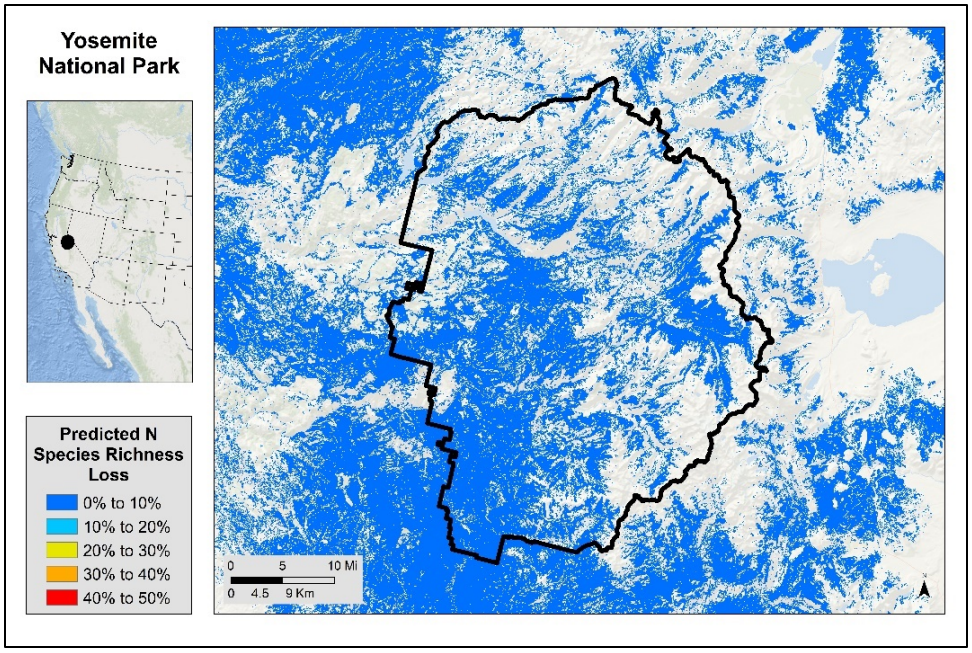


Figure C40. Level of decline of epiphytic lichen species richness based on 2016 TDep total S deposition in Yosemite National Park.

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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