



Critical Loads of Nitrogen and Critical Loads of Sulfur for Herbaceous Species in National Parks

Natural Resource Report NPS/NRSS/ARD/NRR—2022/2442



ON THE COVER

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Critical Loads of Nitrogen and Critical Loads of Sulfur for Herbaceous Species in National Parks

Natural Resource Report NPS/NRSS/ARD/NRR—2022/2442

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Executive Summary

Herbaceous species comprise large portions of plant biodiversity and play a pivotal role in maintaining ecosystem health and function. Excessive deposition of atmospheric pollutants, such as nitrogen (N) and sulfur (S), can have harmful effects on herbaceous species leading to changes in community composition and disruptions in ecosystem services. To monitor the effects of deposition, critical loads—deposition thresholds below which harmful ecosystem effects do not occur—have been established for herbaceous species for ecoregions and open and closed canopy environments. While useful, these broad categorizations cannot capture the variation of individual species responses to deposition. Clark et al. (2019) developed critical loads of N and of S for a decline in probability of occurrence of 348 individual herbaceous species using species locations and local pH, temperature, and precipitation data. Species specific critical loads allow land managers to assess overall risk to herbaceous species communities as well as monitor individual species that may be sensitive to N or S deposition. This report applies the critical loads developed by Clark et al. (2019) to assess risk to herbaceous species in national parks. It uses the 198 focal herbaceous species from the original 348 herbaceous species, that were shown to have a strong and statistically significant responses to nitrogen and sulfur deposition.

Species presence-absence data was used to identify the park occurrences of the 198 focal herbaceous species from Clark et al. The critical loads for these species were then compared to long-term N and S deposition from 1985–2011 and short-term deposition from 2016–2018 summarized to national parks. Critical load percentiles at the minimum, 10th percentile, median, and maximum levels were also calculated for each park. Tenth percentile critical loads were emphasized in this study as they provide a level of deposition at which 90% of species in a park are protected and highlights the species in a park that are most sensitive to deposition.

Plant species responded to the over fertilization of N deposition or the soil acidification of S deposition. Greater atmospheric concentrations of N and S were experienced in the Midwestern and Eastern parks exposing more plant species in those parks to higher N and S deposition resulting in more Clark et al. species reached threshold deposition in parks in those areas.

The highest number of species with N deposition in exceedance of their critical load of N were in national parks in the eastern United States and the Midwest. The greatest decline in the number of N critical load exceedances between the two deposition datasets were in parks in the eastern United States while the greatest increase in N critical load exceedances were in midwestern parks. Exceedances of S critical loads declined in all parks across the United States, with the largest declines in eastern parks.

Of the 198 species in this analysis, 135 had their critical load of N exceeded in at least one national park and 95 had their critical load of S exceeded in at least one national park. Although there has been widespread improvement in deposition, there are still parks with large numbers of herbaceous species N and S critical load exceedances that may be likely to experience shifts in plant species composition. Direct intervention and management are needed to prevent detrimental effects to ecosystem services and visual resources in parks. Identifying species sensitive to N and S within

parks allows park resource managers to make informed management decisions and assists in restoration efforts and curbing invasive species. This study also contributes a dataset comprised of the critical load values and percentiles which park resource managers can use to monitor species and develop focused intervention strategies. While the application of species-level critical loads to national parks revealed parks and species that may need additional monitoring or intervention, the responses of species within parks could not be assessed. Additional research using vegetation plot locations of species within parks is needed to provide a more accurate and detailed analysis of herbaceous species response to N and S deposition.

Introduction

The National Park Service is responsible for protecting a wide variety of ecosystems in lands across the United States. Herbaceous plant species are an integral part of national parks and are present in numerous ecosystems including forests, deserts, woodlands, shrublands, and grasslands. ‘Herbs’ are defined by their growth form: vascular plants with non-woody stems such as grasses, flowering plants, and ferns. Herbs dominate plant communities in grasslands and alpine communities above the tree line and comprise the majority of plant biodiversity even in forested systems. In all environments where they are found, they serve important roles for maintaining biodiversity and ecosystem function. Some species of herbaceous plants are sensitive to environmental stressors such as air pollution. The deposition of atmospheric pollutants, including nitrogen (N) and sulfur (S) compounds, can have detrimental effects on herbaceous plant species and the ecosystems they occupy (Porter et al 2013, Pardo et al. 2011). In this study we evaluate the risk presented to herbaceous species by N and S deposition across national parks.

While N is an essential nutrient for plant growth, excess N can have negative impacts on herbaceous plants. Surplus N entering an ecosystem through deposition can cause eutrophication, excessive nutrient presence, which has a fertilizing effect on some plant species. This fertilization can change plant community composition as some species show increased growth with additional N in the environment while others do not. Thus, N deposition causes increased competition between plant species and can lead to the decline of species adapted to low-N conditions in favor of nitrophilous species (Bobbink et al., 2010; Dupré et al., 2010; Isbell et al., 2013; Stevens et al., 2004). Heightened competition for light and declines in root biomass due to N input can further favor the presence of certain species in eutrophied environments (Hautier et al., 2009; Li et al., 2015). This impact on plant species can be seen most intensely in N limited environments such as grassland ecosystems (Porter et al., 2013). In these N limited environments, even small additions of N through deposition can have dramatic effects on community composition through the loss of species richness (Clark and Tilman, 2008; De Shrijver et al., 2011; Stevens et al., 2010). Due to their evolution under specific environmental conditions, native plants may be more susceptible to negative effects of increased N, allowing the further spread of invasive species which are often environmental generalists (Allen et al., 2009; Isbell et al., 2013; Ren et al., 2019).

S is also a plant nutrient, but its availability in most terrestrial ecosystems matches or exceeds plant demand, so S deposition primarily affects plant communities via acidification of groundwater, soils, and aquatic environments. Both N and S deposition contribute to the acidification of aquatic environments and soils. N deposition in the form of nitrogen oxides and ammonium and S deposition in the form of sulfur oxides can move through the soil solution and deplete essential base cations like calcium, magnesium, and potassium (Beier et al., 2012; Gilliam, 2006). The loss of base cations leads to a decrease in the pH of the soil and the unavailability of these base cations for vegetation growth (Sullivan, 2016). Decreased soil pH can increase concentrations of soluble aluminum (Al) which impairs nutrient and water uptake by plants (Rahman et al., 2018). Acidified soils and toxic concentrations of Al damage plant species that are intolerant of acidic conditions and contribute to further losses in ecosystem biodiversity.

Declines in herbaceous species richness can impact overall ecosystem productivity and stability including the inhibition of the full delivery of ecosystem services (Isbell et al., 2013; Tilman et al., 2016). Changes in herbaceous species composition due to deposition can also have cascading impacts on trophic levels. The declining abundance of certain plant species can affect microclimates, plant-pollinator interactions, and the availability of prey species and nesting materials (Stevens et al., 2018). Simkin et al. (2016) found that plants in grasslands and open canopy were more sensitive to N deposition than plants in forested ecosystems. These varied responses to deposition highlight the need for more detailed research into the response to deposition of individual species. Species specific responses are important to characterize as they may provide insight into which species in a particular ecosystem may be most at risk to decline when exposed to heightened levels of deposition. Addressing the far-reaching and species-specific effects of N and S deposition on herbaceous species is vital for the National Park Service to fulfill its mission of preserving natural resources.

Protecting natural resources within national parks requires monitoring deposition sources and intervention to reduce deposition. The main human sources of N and S deposition include power plants, industrial facilities, and agriculture. Nitrate (NO_3^-), ammonia (NH_3), and sulfur dioxide (SO_2) are the main forms of N and S deposition produced by these sources. The National Atmospheric Deposition Program (NADP) was created to measure atmospheric deposition from these sources. As a part of NADP, the Total Deposition Science Committee (TDep) develops models which estimate N and S deposition across the contiguous United States. These estimates allow land managers, researchers, and decisionmakers to assess the impacts of deposition on important natural resources. Along with programs dedicated toward monitoring deposition, federal air quality policy has also impacted deposition monitoring and research. The Clean Air Act significantly reduced N and S deposition across the United States, particularly in the eastern portion of the country. Clean Air Act regulations led to a substantial decline in deposition due to fossil fuels in the forms of nitrate and sulfur dioxide. However, as nitrate has declined as a source of N deposition, ammonia from intensive agriculture operations has increased its contribution to N deposition (Li et al. 2016). While S deposition has decreased broadly across the United States, its effects are still a threat to acid-sensitive ecosystems. As such, continued assessment of the impacts of N and S deposition is still important as the nature of atmospheric deposition changes.

To effectively monitor and reduce the effects of deposition on the environment, the idea of a critical load was implemented by researchers and land managers. A critical load is “the quantitative exposure to one or more pollutants below which significant harmful effects on sensitive elements of the environment do not occur, according to present knowledge” (Nilsson and Grennfelt, 1988). In the context of N or S deposition, a critical load establishes a threshold level of deposition that protects elements of an ecosystem from experiencing negative impacts at deposition levels below the threshold (Burns et al., 2008). Critical loads are useful tools for scientists, policy makers, and land managers as they provide a way to assess current ecosystem conditions and set meaningful goals for deposition reduction (Porter et al., 2005). Established for a variety of ecosystem components, critical loads of N deposition have been created for alpine vegetation, lakes, trees, lichen, and mycorrhizal fungi among other components (Baron et al., 2011; Bowman et al., 2012; Geiser et al., 2019; Horn et al., 2018; Pardo et al., 2011). Critical loads of S deposition have primarily been created for the

protection against aquatic and soil acidification effects, but recent analyses have developed responses for trees, epiphytic lichen communities, and herbaceous species using large datasets (Clark et al., 2019, Geiser et al., 2019; Horn et al., 2018; Sullivan et al., 2012). Most critical loads have been created to protect broad ecosystem components or regions (e.g., alpine lakes in the Rockies, forests in the Northeast). However, the effects of deposition on individual species within an ecosystem can vary greatly within these categorizations.

Clark et al. (2019) began to fill this gap by developing critical loads of N and of S for individual herbaceous species across the United States. They developed these critical loads based on a vegetation plot dataset compiled by Simkin et al. (2016), who created critical loads of N for changes in herbaceous plant species richness in open- and closed-canopy ecosystems. Figure 1 shows the vegetation plot locations from Simkin et al. which Clark et al. used to establish individual species critical loads. Based on the presence of species within plots and plot-specific environmental data, Clark et al. modeled species response to N and S deposition for 348 herbaceous species across the United States and developed critical loads of N and of S for a decline in probability of occurrence for a subset of these species.

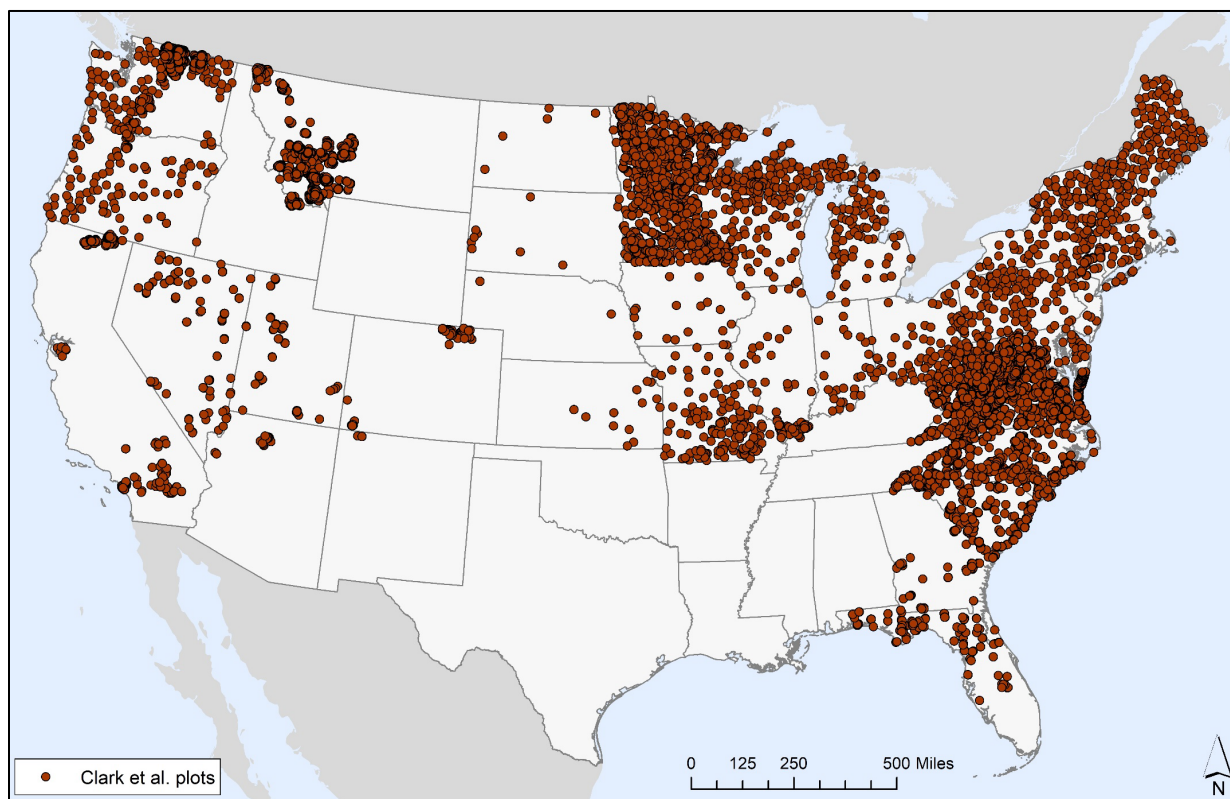


Figure 1. Vegetation plots from Simkin et al. (2016) used to develop critical loads for individual herbaceous species.

Protecting herbaceous plant species in national parks from the detrimental effects that accompany N and S deposition is vital for fulfilling the NPS responsibility to leave natural resources unimpaired.

This study aims to assess the risk to individual herbaceous species from N and S deposition in national parks. To accomplish this, we apply the critical loads of N and of S for individual herbaceous species created by Clark et al. to parks. To ensure accurate results, this study uses 198 focal herbaceous species of the original 348 herbaceous species used by Clark et al. (2019) that were shown to have a strong and statistically significant responses to nitrogen and sulfur deposition. We compare the critical loads of each species to modeled N and S deposition values at each national park to identify parks and species at risk for changes in herbaceous species composition.

Methods

Critical Loads for a Decrease in Herbaceous Species Probability of Occurrence

Critical loads of nitrogen (N) and critical loads of sulfur (S) for a decrease in probability of occurrence of individual herbaceous species were calculated by Clark et al. (2019) using occurrences within 15,136 vegetation plots across the contiguous United States; the same data that Simkin et al. (2016) used to establish critical loads of N for a decline in herbaceous species richness. Clark et al. used herbaceous species locations from this dataset that occurred in at least five plots and had N deposition or S deposition data that spanned a range of at least $7 \text{ kg ha}^{-1} \text{ yr}^{-1}$ across plot occurrences; of the 348 species that fit these requirements, 198 had statistically significant modeled responses to nitrogen or sulfur deposition.

Clark et al. developed the critical loads for this subset of species based on response equations for probability of occurrence using a combination of soil pH, temperature, precipitation, N deposition, and S deposition as predictor variables. Soil pH data were taken from the United States Department of Agriculture Soil Survey Geographic Database (SSURGO) database and temperature and precipitation data were 30-year normals from 1981–2010 collected from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group. The equations used total N and total S deposition, in which each form of deposition was the sum of the National Atmospheric Deposition Program (NADP) Total Deposition model (TDep) mean wet deposition from 1985–2011 and Community Multiscale Air Quality (CMAQ) mean dry deposition from 2002–2011. To estimate total nitrogen, the models incorporate measured NH_4 (wet), NO_3 (wet/dry) and HNO_3 (dry) deposition, and modeled dry deposition of NH_3 PAN, N_2O_5 , NO_2 , HONO, and organic nitrates (Schwede and Lear, 2014).

Response curves for changes in probability of occurrence across deposition gradients were created for each species for both N and S deposition based on the results of the probability of occurrence equations. Critical loads of N and of S were then derived for each species from these response curves.

Critical Loads of Nitrogen

In response to N deposition, plant species occurrence fell into five response categories: Decreasing, increasing, U-shaped, hump-shaped (threshold), or no response (Figure 2). A critical load of N for a decline in an herbaceous species' maximum probability of occurrence (CLN-HS) was established for species that had a hump shaped, increasing, or decreasing response. This critical load indicates the level of N deposition above which the probability of occurrence of a species begins to decline. A CLN-HS was set for 158 of the 198 herbaceous species in the analysis. Species with a saddle or no response do not indicate a continuous decline in probability of occurrence at any measured level of deposition, so a CLN-HS could not be calculated for these species. Table 1 shows the number of species that fit into each N response type.

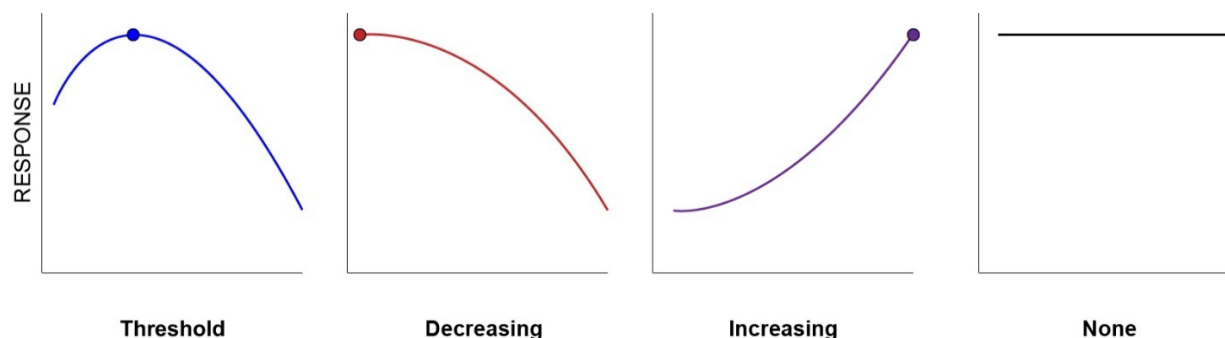


Figure 2. Possible shapes of species response to increasing N deposition. The points on the curves for threshold (hump), decreasing, and increasing response types indicate the level of N deposition at which the critical load is calculated for each response type.

Table 1. Number of species per N response type and whether it was assigned a CLN-HS.

N Response Type	Number of Species	Has CLN-HS
Increase	29	Yes
Decrease	21	Yes
Hump (threshold)	107	Yes
Flat	1	Yes
Saddle/increase	11	No
Saddle/decrease	9	No
Saddle/flat	1	No
None	19	No

CLN-HS values were established for species with a hump-shaped response at the level of deposition corresponding to the highest probability of occurrence, or the peak of the response curve. Species exhibiting a monotonically increasing or decreasing response are presumed to have a hump-shaped relationship over the full range of possible N deposition amounts where the peak species occurrence probability is at a level of N deposition below (for decreasing species) or above (for increasing species) the gradient of N deposition used to build the species response curves. As this peak, which would represent the CLN-HS, is beyond the range of plot deposition, the critical load was instead set as lower than the known minimum N deposition identified for species with decreasing responses, and as higher than the known maximum N deposition identified for species with increasing responses. Figure 2 shows each of the different response types a species could have to N deposition and the point where the CLN-HS was set for each response.

Critical Loads of Sulfur

In response to S deposition, plant species fell into three response categories: increasing, decreasing, or no response. The original analysis did not develop sulfur models for hump-shaped responses based on an assumption that S deposition contributes to soil acidification but not nutrient enrichment, and

that species are either acidophilic (increasing) or acid-sensitive (decreasing in response to S deposition). Species with an increasing and decreasing response to S deposition were assigned a critical load of S for a decline in an herbaceous species' maximum probability of occurrence (CLS-HS). Clark et al. calculated CLS-HS values for 131 of the 198 herbaceous species in the data.

As with species with an increasing or decreasing responses to N deposition, the CLS-HS was set below the minimum S deposition experienced by a species for decreasing responses, and above the maximum S deposition experienced by a species for increasing responses. Table 2 shows the number of species that fit into each S response type.

Table 2. Number of species per S response type and whether it was assigned a CLS-HS.

S Response Type	Number of Species	Has CLS-HS
Increase	34	Yes
Decrease	97	Yes
Saddle/increase	9	No
Saddle/decrease	26	No
Flat	1	No
None	31	No

National Park Service NPSpecies Database

Species occurrence data from the NPSpecies database were used to evaluate risk to herbaceous species in all NPS units. We refer to NPS units including national parks, monuments, seashores, lakeshores, battlefields, and historical sites as “parks” throughout the remainder of this document. The NPSpecies database records the presence and status of species at each park. Each park creates and maintains its own list and each species is recorded as present, probably present, unconfirmed, or not present. The database was queried for a list of the 198 species using species/genus nomenclature from the Clark et al. analysis and each park in which a species is recorded as present or probably present. All sub-species and varieties were lumped into the base taxa. Of the 381 parks in the United States, 288 recorded at least one of the 198 species from the Clark et al. analysis. As the deposition data used in this study are only available for the 48 contiguous states, parks outside the contiguous 48 states were excluded, resulting in a final tally of 267 parks with at least one Clark et al. species. The CLN-HS and CLS-HS for each species created by Clark et al. were then joined to the park species occurrence list.

Exceedances of Critical Loads for Herbaceous Species

N or S deposition in quantities greater than the critical load of a species indicates that the species is at risk for experiencing negative effects from deposition. Deposition in exceedance of a species' CLN-HS or CLS-HS means that the species may experience a decline in probability of occurrence at those levels of deposition. For this analysis, a species' critical load was considered to be in exceedance if the comparison deposition value was greater than the critical load by any amount.

Exceedances of CLN-HS and CLS-HS in parks were calculated using two deposition datasets. Mean deposition from 1985–2011 was used so critical loads could be evaluated with the same deposition values used by Clark et al. to create the probability of occurrence equations. Deposition from 2016–2018 was also used to assess critical loads with more recent deposition values. Figure 3 and Figure 4 compare deposition values across the United States from both datasets for N and S respectively.

Given that precise species ranges within parks cannot be determined from the NPSpecies dataset, we evaluated the CLN-HS and CLS-HS against the minimum and maximum deposition values found within a park, thus providing the full range of potential responses given modeled deposition. Exceedances calculated based on the minimum deposition value within parks highlights the most sensitive species at risk across an entire park, while exceedances calculated from maximum deposition shows the range of species within a park that may be at risk. Additional investigation using species locations within parks from vegetation surveys and deposition mapping will be necessary to evaluate species with critical loads between the minimum and maximum deposition values at each park.

To find the minimum and maximum deposition values at each park, a NPS unit boundary polygon layer was overlaid on the N and S deposition raster layers from both 1985–2011 and 2016–2018 in *ArcMap 10.7.1*. The Grid Statistics for Polygons tool from *SAGA GIS 7.6.3* was imported into *ArcMap* and was used to calculate the minimum and maximum value of the N and S deposition raster cells from both time periods that fell within each park unit boundary. Two of the 267 parks that contain at least one Clark et al. species in the contiguous United States did not have deposition data available. These two parks are along the coast of the United States where the TDep model does not completely cover the land area so exceedances could not be calculated.

The CLN-HS and CLS-HS values for each herbaceous species determined to be present in each park by the NPSpecies database were then compared to the minimum and maximum N and S deposition within each park for both deposition datasets. Species were flagged as experiencing deposition in or not in exceedance of their critical loads for minimum and maximum N and S deposition at each park for both deposition datasets. This resulted in four exceedance determinations for N (minimum N 1985–2011, maximum N 1985–2011, minimum N 2016–2018, maximum N 2016–2018) and four exceedance determinations for S (minimum S 1985–2011, maximum S 1985–2011, minimum S 2016–2018, maximum S 2016–2018) for each plant species. The number of species with their critical load in exceedance per park and the number of times the critical load of each species was exceeded across parks were evaluated to identify parks and species most at risk.

Along with the comparison of individual species critical loads to N and S deposition, the 10th percentile CLN-HS and CLS-HS at each park were calculated. The 10th percentile critical load is based on all species' critical loads within a park and is the level of deposition that protects 90% of species within a park from critical load exceedance. Species with a CLN-HS or CLS-HS higher than the 10th percentile critical load at a park would be protected from negative impacts of deposition at levels below the 10th percentile critical load. Using 10th percentile critical loads provides a target level of N deposition for protecting most species at a park and identifying species that may be sensitive to low levels of N deposition.

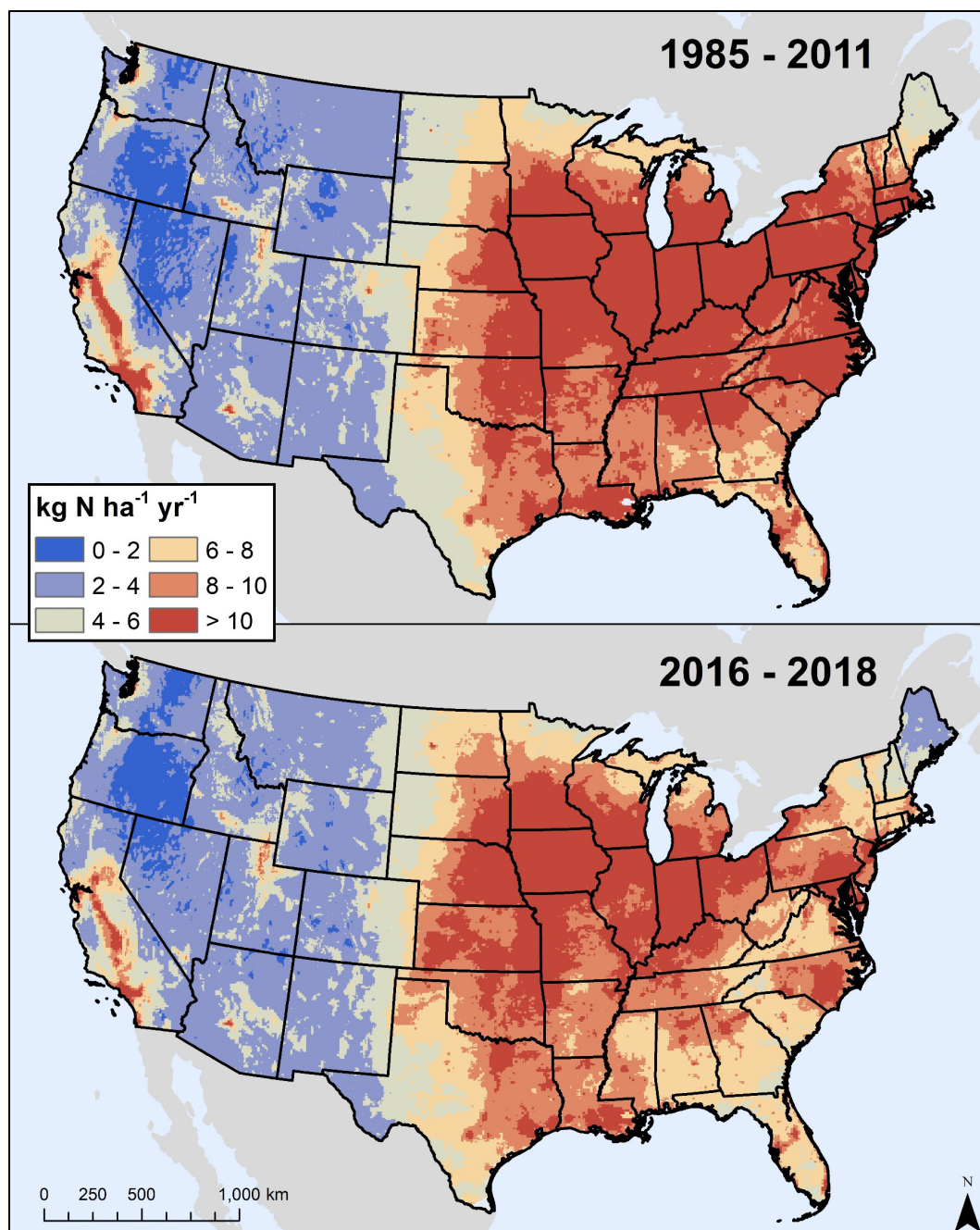


Figure 3. Average total N deposition across the United States from 1985–2011 (top) and 2016–2018 (bottom). Total N deposition is generally higher in eastern and central United States. N deposition decreased overall between 1985–2011 and 2016–2018.

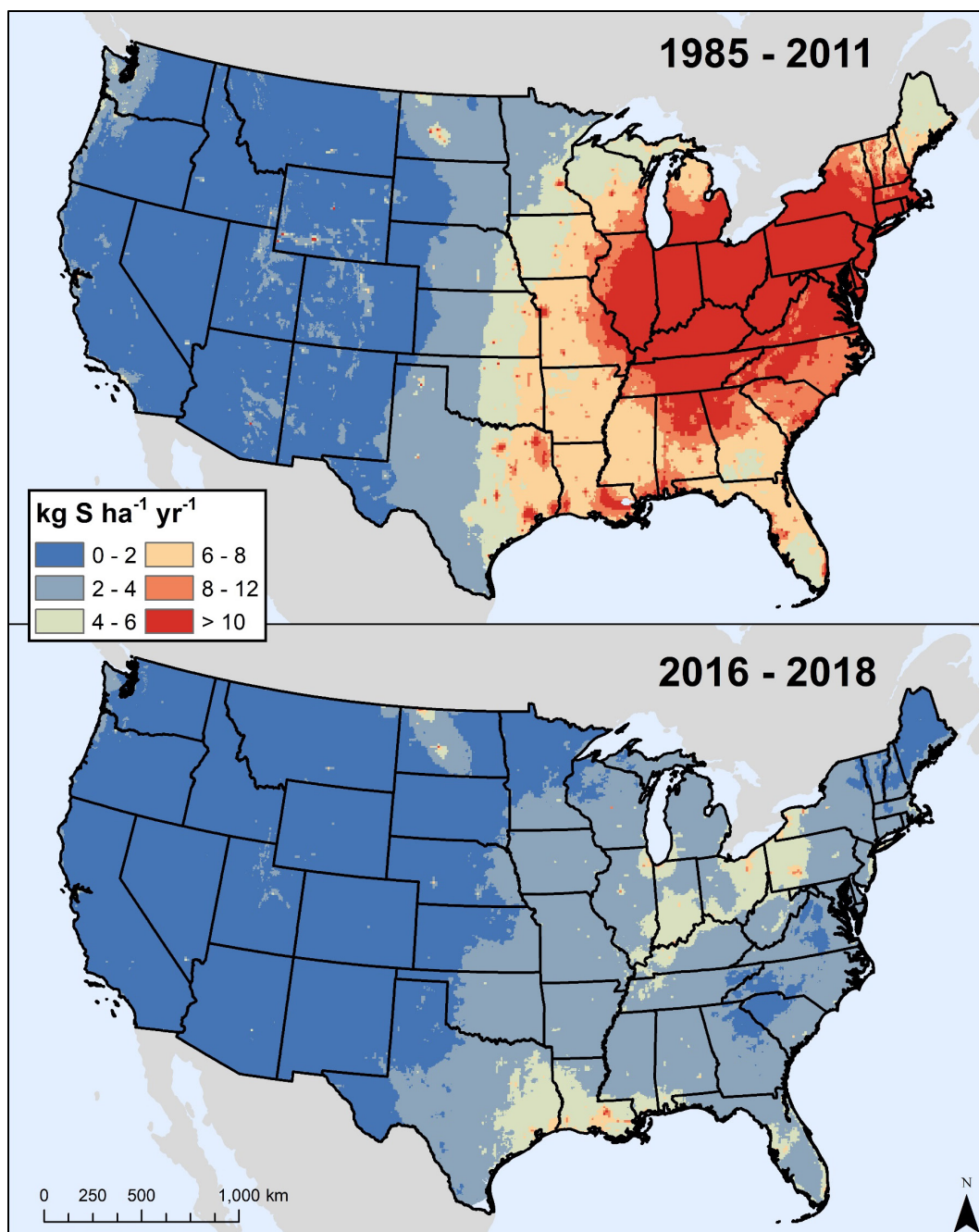


Figure 4. Average total S deposition across the United States from 1985–2011 (top) and 2016–2018 (bottom). Total S deposition is generally higher in the eastern United States. S deposition has decreased significantly across the United States in recent years.

Results

Parks with Critical Loads of Nitrogen for Herbaceous Species

At least one species from the Clark et al. analysis was present in 267 parks in the contiguous United States. Figure 5 shows the locations of the parks with at least one herbaceous species evaluated by Clark et al. present. Shenandoah National Park contained the most Clark et al. species with 144 of the 198 species present. Casa Grande Ruins National Monument, Chamizal National Memorial, and Dry Tortugas National Park contained the fewest number of Clark et al. species with only one species each. A full list of Clark et al. species occurrences and critical load exceedances can be found in Russell et al. (2022).

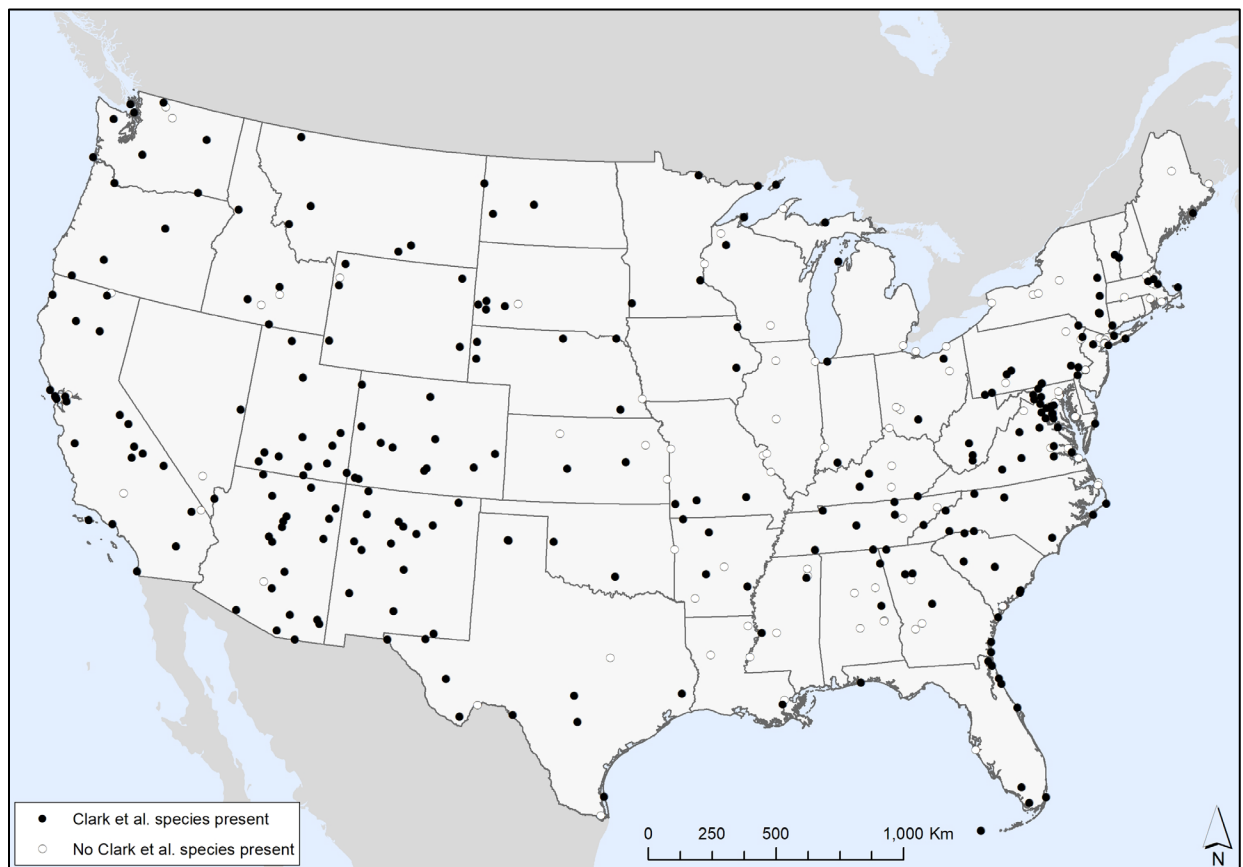


Figure 5. NPS units with a known occurrence of an herbaceous species with a critical load of N or a critical load of S. Black points indicate parks that contain at least one species (n=381) and white points indicate parks that do not contain any species (n=114).

The number of Clark et al. species that had a critical load of nitrogen (N) for a decline in an herbaceous species' maximum probability of occurrence (CLN-HS) within parks ranged from 1 to 121 species. Mississippi National River and Recreation Areas contained the highest number, 121, of species with CLN-HS values (Table 3). The average number of species with a CLN-HS per park was

34 species. Parks to the east of the Rocky Mountains had an average of 46 species with a CLN-HS while parks to the west of the Rocky Mountains had an average of 14 species with a CLN-HS.

Table 3. The ten parks with the most species with a CLN-HS. Included are the minimum, 10th percentile, median, and maximum CLN-HS at each park. The last column indicates the number of species that have a CLN-HS above the 10th percentile CLN-HS. These values are available for each park unit evaluated in Russell et al. (2022).

Park Name	Clark Species with CLN-HS	Min CLN-HS (kg-N ha ⁻¹ yr ⁻¹)	10 th Percentile CLN-HS (kg-N ha ⁻¹ yr ⁻¹)	Median CLN-HS (kg-N ha ⁻¹ yr ⁻¹)	Max CLN-HS (kg-N ha ⁻¹ yr ⁻¹)	Species Protected by 10 th Percentile CLN-HS
Mississippi National River and Recreation Areas	121	1.3	5.9	11.0	18.9	109
Saint Croix National Scenic River	120	1.3	5.8	10.9	18.9	108
Shenandoah National Park	118	1.3	5.2	11.5	19.3	106
Great Smoky Mountains National Park	117	1.6	5.8	11.7	19.3	105
Indiana Dunes National Park	116	2.0	6.4	11.4	18.9	106
Blue Ridge Parkway	115	1.3	4.9	11.5	19.3	103
New River Gorge National River	113	1.3	6.1	11.7	19.3	101
Delaware Water Gap National Recreation Area	107	1.3	5.9	11.5	18.9	96
Cuyahoga Valley National Park	103	2.0	6.1	11.5	18.9	92
Appalachian National Scenic Trail	103	1.3	5.9	11.1	18.9	92

Minimum CLN-HS values at each park ranged from 1.3 kg-N ha⁻¹ yr⁻¹ to 18.9 kg-N ha⁻¹ yr⁻¹ (Table 3). This value indicates the CLN-HS of the species most sensitive to N deposition at each park. Parks with a minimum CLN-HS over 10 kg-N ha⁻¹ yr⁻¹ all had three or fewer CLN-HS species. Across all parks, the average minimum CLN-HS was 2.7 kg-N ha⁻¹ yr⁻¹, indicating that most parks contain at least one species sensitive to low levels of N deposition. Minimum and maximum CLN-HS were the same at four parks as these parks contain only one species with a CLN-HS.

Tenth percentile CLN-HS were calculated to identify the level of N deposition at each park at which 90% of species would be protected. Across parks, 10th percentile CLN-HS values ranged from 1.9 kg-N ha⁻¹ yr⁻¹ to 11.0 kg-N ha⁻¹ yr⁻¹ (Table 3). The average 10th percentile CLN-HS for parks was 5.8 kg-N ha⁻¹ yr⁻¹. An average of 37 species at each park were protected by the 10th percentile CLN-HS, meaning that their CLN-HS values were higher than the 10th percentile CLN-HS.

Evaluation of Exceedances of Critical Load of Nitrogen for Herbaceous Species

CLN-HS exceedances were calculated using minimum and maximum N deposition within the boundaries of each park with data averaged across both 1985–2011 and 2016–2018. Table 4 shows the ten parks containing the most CLN-HS exceedances from 2016–2018 maximum deposition, along with exceedances from minimum and maximum deposition from the 1985–2011 deposition dataset. Comparing minimum deposition exceedances to maximum deposition exceedances provides detailed insight into species risk to N deposition within individual parks. An exceedance at the minimum deposition in a park indicates that a species is at risk in all areas of the park while an exceedance at the maximum deposition warrants a more thorough analysis to determine if species presence overlaps with high deposition areas in the park. A similar number of exceedances from both the minimum and maximum deposition within a park could indicate that the range of deposition at that park is small. For example, Effigy Mounds National Monument has the same number of exceedances from minimum and maximum 2016–2018 N deposition. Minimum 2016–2018 N deposition at the park was 14.1 kg-N ha⁻¹ yr⁻¹ and maximum N deposition was 14.3 kg-N ha⁻¹ yr⁻¹. Parks with few exceedances based on minimum deposition compared to many exceedances from maximum deposition could indicate that the minimum deposition at a park is low. Appalachian National Scenic Trail had just six species in exceedance of minimum 2016–2018 N deposition compared to 84 species in exceedance of maximum N deposition. Minimum 2016–2018 N deposition at the park was 3.4 kg-N ha⁻¹ yr⁻¹ and maximum deposition was 14.9 kg-N ha⁻¹ yr⁻¹. This indicates that most species present within Appalachian National Scenic Trail have CLN-HS higher than the minimum deposition and are not sensitive to very low levels of N.

Focus was placed on CLN-HS exceedances calculated based on maximum deposition as these provide more comprehensive protection to herbaceous species within a park that may be at risk. Maximum deposition exceedances of species' CLN-HS are explored in more detail below for both deposition datasets.

Table 4. The ten park units with the most herbaceous species present. Included are the number of species from the Clark et al. analysis within each park, the number of species with a CLN-HS at each park, and the number of species at each park with exceedances of their CLN-HS from minimum and maximum N deposition from both deposition datasets.

Park Name	Clark Species with CLN-HS	Species in Exceedance of min N Deposition (1985–2011)	Species in Exceedance of max N Deposition (1985–2011)	Species in Exceedance of min N Deposition (2016–2018)	Species in Exceedance of max N Deposition (2016–2018)
Mississippi National River and Recreation Areas	121	65	110	72	110
Saint Croix National Scenic River	120	23	51	30	58
Shenandoah National Park	118	42	83	22	62
Great Smoky Mountains National Park	117	23	76	11	25
Indiana Dunes National Park	116	29	109	29	102
Blue Ridge Parkway	115	26	80	13	42
New River Gorge National River	113	30	61	20	25
Delaware Water Gap National Recreation Area	107	50	66	19	34
Cuyahoga Valley National Park	103	84	103	52	76
Appalachian National Scenic Trail	103	10	84	6	84

1985–2011 Nitrogen Deposition Exceedances

The number of species at each park whose CLN-HS were exceeded by maximum N deposition from 1985–2011 are shown in Figure 6. Parks in the eastern United States had more species in exceedance than parks in the western portion of the country. This was due to higher quantities of N deposition in the eastern United States and the bias towards species with eastern US distribution included in the original analysis.

Across all parks, an average of 17 species were in exceedance of the CLN-HS at maximum N deposition from 1985–2011. Mississippi National River and Recreation Areas had the most species in exceedance with 110 CLN-HS exceedances. Indiana Dunes National Park and Cuyahoga Valley National Park also had over 100 species with CLN-HS in exceedance (Table 4). There were 27 parks where the CLN-HS of all the species occurring at those parks was not exceeded by maximum N deposition from 1985–2011. Expectedly, parks with few or no species in exceedance are mainly

located in the west and southwest United States. Of the parks with more than 10 species, 67 had CLN-HS exceedances for less than 20% of herbaceous species present and 69 had CLN-HS exceedances for greater than 50% of the herbaceous species present.

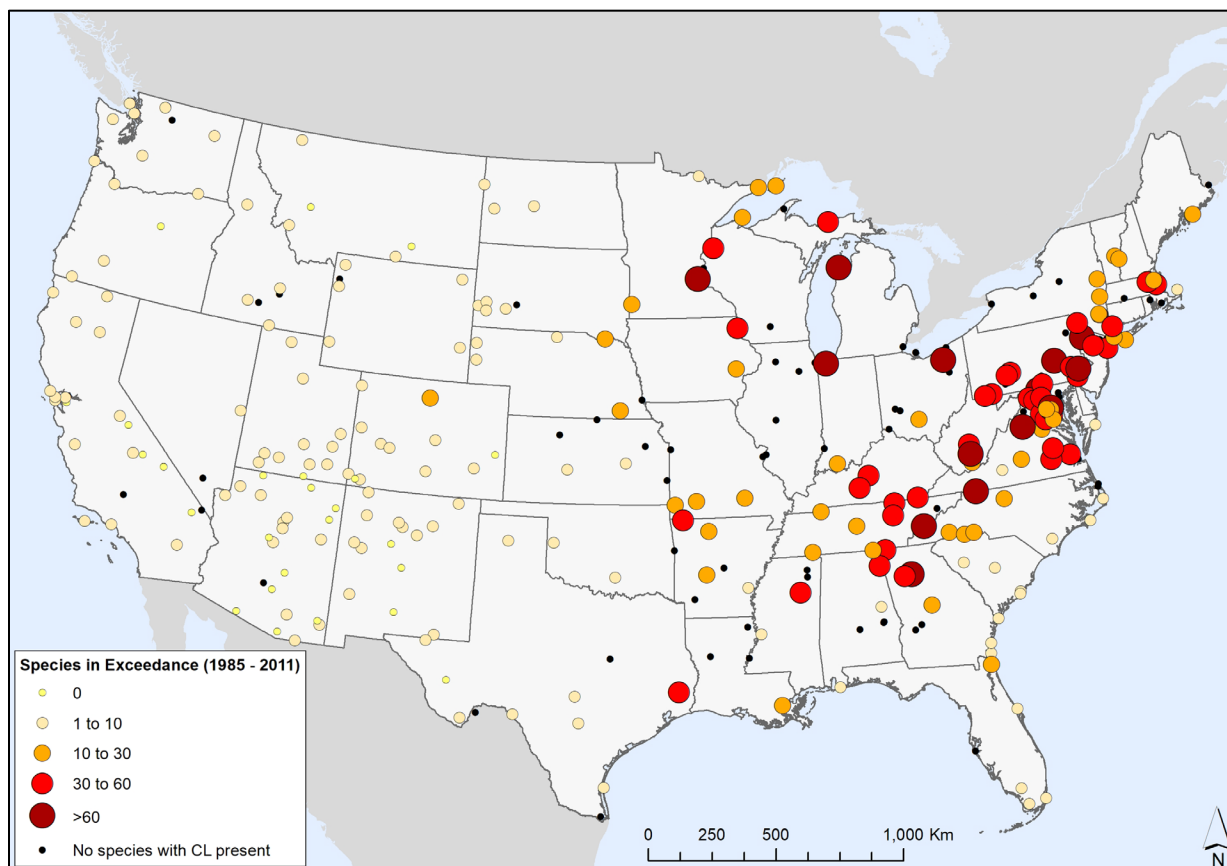


Figure 6. Number of species whose CLN-HS are exceeded by maximum N deposition from 1985–2011. Larger and darker circles represent parks with a higher number of species with CLN-HS exceedances. Grey points indicate parks that did not have any Clark et al. species present.

2016–2018 Nitrogen Deposition Exceedances

Figure 7 shows the number of species at each park whose critical loads were exceeded by maximum N deposition from 2016–2018. The overall number of species at risk declined in most parks compared to the exceedance evaluation with the 1985–2011 N deposition data. The average number of species with CLN-HS in exceedance from maximum 2016–2018 N deposition at each park was 11; 6 fewer than 1985–2011. Mississippi National River and Recreation Areas still had the most species in exceedance with 110 species. The number of species in exceedance at Indiana Dunes National Park remained over 100, but decreased by 7 compared to exceedances calculated with the 1985–2011 deposition data. Twenty-five parks contained no species with maximum deposition from 2016–2018 in exceedance of the species’ CLN-HS. This indicates that two additional parks had at least one species in exceedance compared to exceedances calculated with the 1985–2011 N deposition data, which had 27 parks with no exceedances.

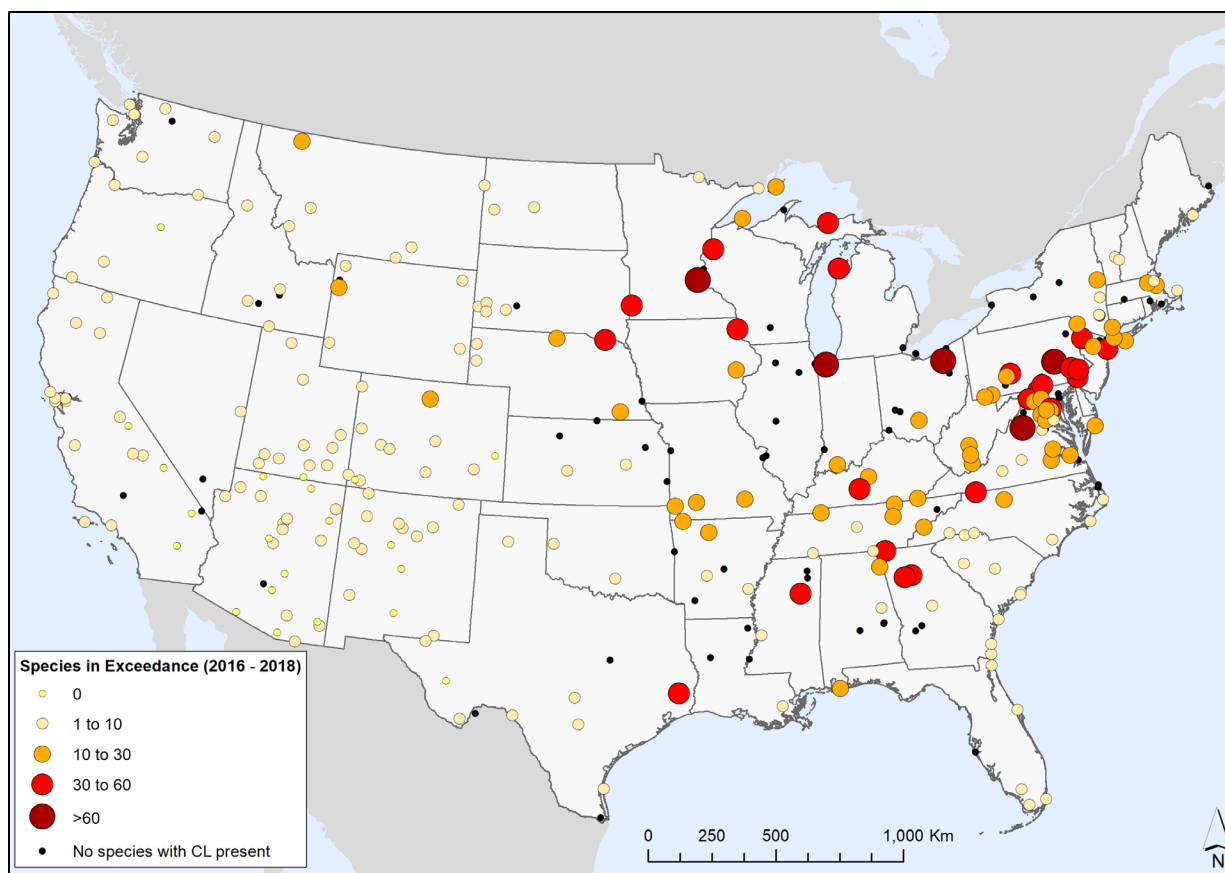


Figure 7. Number of species whose CLN-HS were exceeded by maximum N deposition from 2016–2018. Larger and darker circles represent parks with a higher number of species with CLN-HS exceedances. Grey points indicate parks that did not have any Clark et al. species present.

The number of parks with more than 10 species and CLN-HS exceedances for less than 20% of the herbaceous species increased from 67 to 94 between the 1985–2011 and 2016–2018 deposition datasets. The decrease in exceedances highlights the overall decrease in N deposition across the United States. Thirty-one parks with more than 10 species had CLN-HS exceedances for 50% or more of the species present. Mississippi National River and Recreation Areas had the highest percentage of exceedances with 91% of present species in exceedance.

Trends in Exceedance of CLN-HS

Figure 8 compares the number of exceedances at each park between the 1985–2011 and the 2016–2018 deposition datasets and identifies trends in conditions at each park. Blue upward facing arrows indicate a park with an improving condition or a decrease in the number of exceedances. Red downward facing arrows indicate a park with a deteriorating condition or an increase in the number of exceedances. Yellow circles indicate a park with no change in the number of exceedances. Parks in the eastern United States had the greatest decrease in the number of species in exceedance between the 1985–2011 N deposition data and the 2016–2018 N deposition data. Parks in the northern Midwest showed the greatest increase in the number of species in exceedance. Higher quantities of CLN-HS exceedances in this area were due to continued increases in N deposition due to agricultural

emissions in the region. Great Smoky Mountains National Park had the largest decline in the number of species in exceedance with 51 fewer species in exceedance based on 2016–2018 N deposition values. Effigy Mounds National Monument and Missouri National Recreational River had the greatest increase in exceedances with 13 additional species in exceedance.

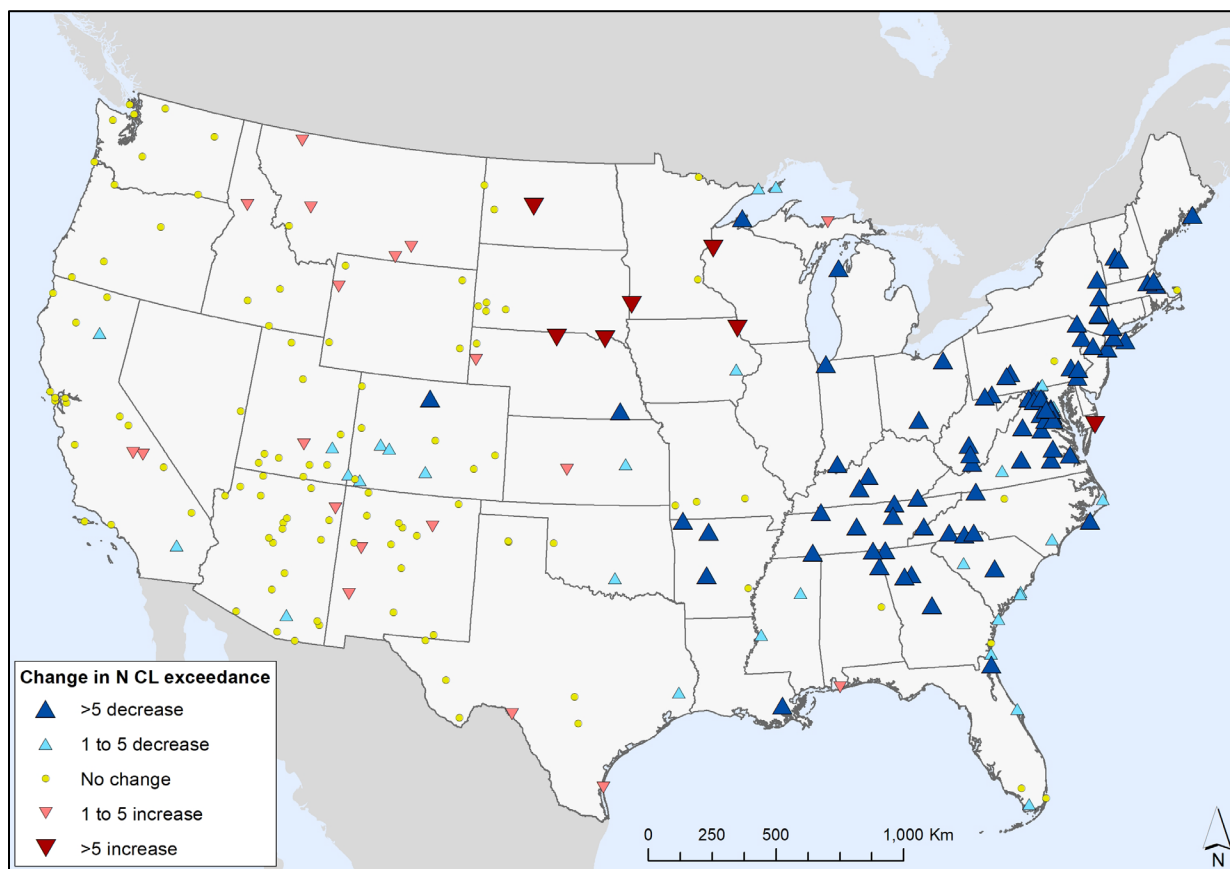


Figure 8. Change in the number of species at each park with CLN-HS exceedances between maximum 1985–2011 N deposition and maximum 2016–2018 N deposition. Blue upward facing arrows indicate a park with an improving condition or a decrease in the number of exceedances. Red downward facing arrows indicate a park with a deteriorating condition or an increase in the number of exceedances.

Four parks (Manzanar National Historic Site, Little Bighorn Battlefield National Monument, Canyon De Chelly National Monument, and Grant-Kohrs Ranch National Historic Site) had no exceedances when evaluated with the 1985–2011 deposition data but had at least one exceedance from the 2016–2018 data. Conversely, Joshua Tree National Park had one exceedance when evaluated with the 1985–2011 data and had no species with their CLN-HS in exceedance from the 2016–2018 data.

Summary of Herbaceous Species Presence in Parks

Conyza canadensis was the most common species with a CLN-HS of the 198 species included in this analysis, occurring in 209 parks (Table 5). *Oligoneuron riddelii* was the least common, occurring in only 3 parks. A full list of species occurrence within parks can be found in the accompanying database (Russell et al. 2022).

Table 5. The ten species with the most CLN-HS exceedances across parks. Included are the total number of park occurrences, the percent of occurrences in exceedance, the CLN-HS, and the species' N response type.

Species	Number of CLN-HS Exceedances	Park Occurrences	Percent of Park Occurrences in Exceedance	CLN-HS (kg-N ha ⁻¹ yr ⁻¹)	N Response Type
<i>Verbascum thapsus</i>	183	184	99	2.0	Decrease
<i>Juncus effusus</i>	130	130	100	2.3	Decrease
<i>Conyza canadensis</i>	116	209	55	6.1	Decrease
<i>Cirsium arvense</i>	98	109	89	3.2	Hump
<i>Rudbeckia hirta</i>	93	118	78	6.4	Decrease
<i>Fragaria virginiana</i>	82	122	67	6.9	Hump
<i>Goodyera pubescens</i>	68	68	100	4.1	Decrease
<i>Onoclea sensibilis</i>	54	95	56	9.7	Hump
<i>Asplenium platyneuron</i>	54	92	58	9.7	Hump
<i>Galium triflorum</i>	51	127	40	9.5	Hump

Species level exceedances were evaluated against maximum N deposition at each park from 2016–2018. Species level CLN-HS exceedances indicate the number of parks containing a species where maximum N deposition at the parks is greater than the species' CLN-HS (Table 5). The species *Verbascum thapsus*, with a CLN-HS of 2.0 kg-N ha⁻¹ yr⁻¹, had the most CLN-HS exceedances with 183 of the 184 parks in exceedance. Fourteen species, with occurrence ranging from 3 to 130 parks, had N deposition in exceedance of their CLN-HS in 100% of the parks they were found to be present in. Of these 14 species, 13 have a decreasing response to N deposition, one has a hump response to N deposition, and all have CLN-HS values ranging from 1.3 kg-N ha⁻¹ yr⁻¹ to 9.8 kg-N ha⁻¹ yr⁻¹. There are 23 species with no exceedances across all parks. Most of these species have an increasing response to N deposition and have a CLN-HS of greater than 15 kg-N ha⁻¹ yr⁻¹.

Of the 198 species in this analysis, 158 have a CLN-HS; of the CLN-HS species, 135 have at least one park occurrence where maximum N deposition is in exceedance of the species' CLN-HS. Of the 154 species with at least one CLN-HS exceedance, 106 have a hump-shaped response, 21 have a decreasing response, and 8 have an increasing response. Species with a decreasing response had the highest number of park occurrences in exceedance per species with an average of 48 exceedances.

Species with a threshold response averaged 18 exceedances and species with an increasing response averaged 1 exceedance. This distribution of species exceedances by response type is expected as CLN-HS values are lowest for species with a decreasing response and highest for species with an increasing response.

Parks with Critical Loads of Sulfur for Herbaceous Species

The number of Clark et al. species that have a critical load of sulfur (S) for a decline in an herbaceous species' maximum probability of occurrence (CLS-HS) ranged from 1–97 across parks. Mississippi National River and Recreation Areas had the most species with a CLS-HS at 97 species (Table 6). The average number of species across parks with a CLS-HS was 30 species. The higher number of sampled sites in the eastern United States increases species counts and skews the data where parks to the east of the Rocky Mountains had an average of 37 species with a CLS-HS compared to an average of 12 species to the west of the Rocky Mountains.

Minimum CLS-HS values across parks ranged from $0.4 \text{ kg-S ha}^{-1} \text{ yr}^{-1}$ to $15.0 \text{ kg-S ha}^{-1} \text{ yr}^{-1}$ (Table 6). Six parks had a minimum CLS-HS of $15.0 \text{ kg-S ha}^{-1} \text{ yr}^{-1}$ and five of these parks contained only one species with a CLS-HS. For all five of these parks this species was *Conyza canadensis* which has an increasing response to S deposition. Across all parks, the average minimum CLS-HS was $0.8 \text{ kg-S ha}^{-1} \text{ yr}^{-1}$, indicating that most parks contain at least one species that is sensitive to low levels of S deposition.

Tenth percentile CLS-HS were calculated to identify the level of S deposition at each park where 90% of species would be protected. Tenth percentile CLS-HS had the same range as minimum CLS-HS from $0.4 \text{ kg-S ha}^{-1} \text{ yr}^{-1}$ to $15.0 \text{ kg-S ha}^{-1} \text{ yr}^{-1}$. This is likely due to parks with less than ten Clark et al. species with a CLS-HS present, as the 10th percentile CLS-HS will be close to or identical with the minimum CLS-HS for these parks. The average 10th percentile CLS-HS across parks was $0.8 \text{ kg-S ha}^{-1} \text{ yr}^{-1}$. This low value reflects that most Clark et al. species with a CLS-HS have a decreasing response to S and have low critical loads. An average of 36 species at each park are protected by the 10th percentile CLS-HS.

Table 6. The ten parks with the most species with CLS-HS. Included are the minimum, 10th percentile, median, and maximum CLS-HS at each park. The last column indicates the number of species that have a CLS-HS above the 10th percentile CLS-HS. These values are available for each park unit evaluated in Russell et al. (2022).

Park Name	Clark Species with CLS-HS	Min CLS-HS (kg-S ha ⁻¹ yr ⁻¹)	10 th percentile CLS-HS (kg-S ha ⁻¹ yr ⁻¹)	Median CLS-HS (kg-S ha ⁻¹ yr ⁻¹)	Max CLS-HS (kg-S ha ⁻¹ yr ⁻¹)	Species protected by 10 th percentile CLS-HS
Mississippi National River and Recreation Areas	97	0.4	0.4	0.5	42.5	93
Saint Croix National Scenic River	96	0.4	0.4	0.5	42.5	92
Shenandoah National Park	94	0.4	0.4	2.3	42.5	92
Blue Ridge Parkway	94	0.4	0.4	2.4	42.5	92
Indiana Dunes National Park	93	0.4	0.4	1.3	42.5	91
New River Gorge National River	92	0.4	0.4	2.3	42.5	91
Great Smoky Mountains National Park	90	0.4	0.4	2.5	42.5	89
Delaware Water Gap National Recreation Area	83	0.4	0.4	2.2	42.5	81
Sleeping Bear Dunes National Lakeshore	82	0.4	0.4	0.5	42.5	81
Appalachian National Scenic Trail	81	0.4	0.4	1.3	42.5	80

Evaluation of Exceedances of Critical Loads of Sulfur for Herbaceous Species

CLS-HS exceedances were calculated in the same manner as CLN-HS exceedances. CLS-HS at each park were compared against minimum and maximum deposition at each park using S deposition data from both 1985–2011 and 2016–2018. Table 7 shows the ten parks that have the most species with maximum S deposition from 2016–2018 in exceedance of their CLS-HS. Compared to CLN-HS exceedances, more parks tend to have a similar number of CLS-HS exceedances between minimum and maximum S deposition. This indicates the presence of species that are sensitive to S deposition or narrow ranges of S deposition within parks. As with CLN-HS exceedances, focus was placed on evaluating exceedances with maximum deposition from the 1985–2011 and 2016–2018 to identify all species that may be at risk in each park. Maximum S deposition exceedances are discussed in more detail below.

Table 7. The ten park units with the most herbaceous species present. Included are the number of species from the Clark et al. analysis within each park, the number of species with a CLS-HS at each park, and the number of species at each park with exceedances of their CLS-HS from minimum and maximum N deposition from both deposition datasets.

Park Name	Clark Species with CLS-HS	Species in Exceedance of min S Deposition (1985–2011)	Species in Exceedance of max S Deposition (1985–2011)	Species in Exceedance of min S Deposition (2016–2018)	Species in Exceedance of max S Deposition (2016–2018)
Mississippi National River and Recreation Areas	97	77	81	65	76
Saint Croix National Scenic River	96	74	74	50	50
Shenandoah National Park	94	69	69	41	50
Blue Ridge Parkway	94	68	69	40	61
Indiana Dunes National Park	93	75	93	73	73
New River Gorge National River	92	68	70	62	62
Great Smoky Mountains National Park	90	63	66	39	58
Delaware Water Gap National Recreation Area	83	63	64	48	58
Sleeping Bear Dunes National Lakeshore	82	60	61	53	59
Appalachian National Scenic Trail	81	58	62	40	58

1985–2011 Sulfur Deposition Exceedances

The number of species whose CLS-HS were exceeded by maximum S deposition from 1985–2011 at each park are shown in Figure 9. Eastern parks tended to have more species with maximum S deposition from 1985–2011 in exceedance of their CLS-HS. This is due to higher S deposition in the eastern United States. However, parks in the western United States had comparatively more species in exceedance of CLS-HS than in exceedance of CLN-HS. Species which are highly sensitive to S and have lower CLS-HS are likely the cause of this difference.

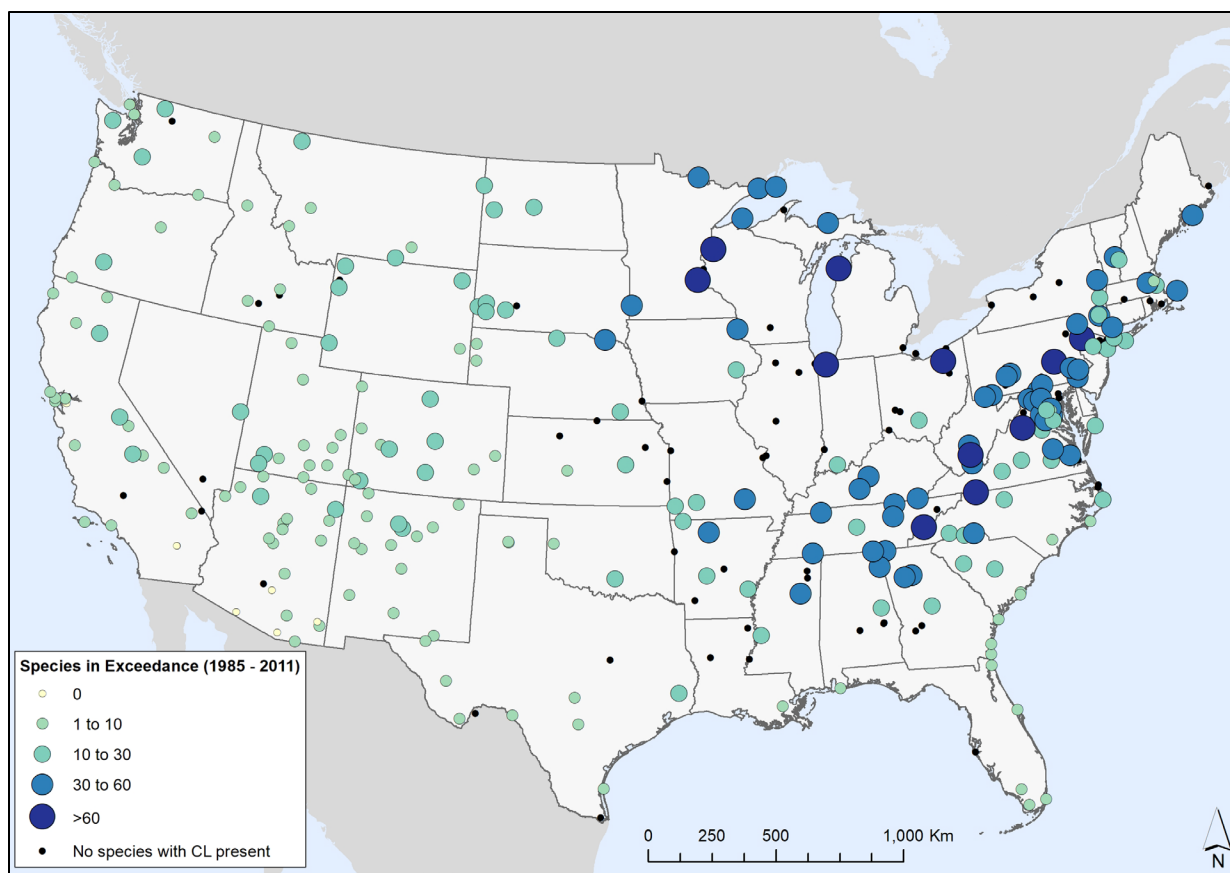


Figure 9. Number of species whose CLS-HS were exceeded by maximum S deposition from 1985–2011. Larger and darker circles represent parks with a higher number of species with exceeded critical loads. Grey points indicate parks that did not have any Clark et al. species present.

Across all parks, the average number of species with maximum S deposition from 1985–2011 in exceedance of their CLS-HS was 20 species. Indiana Dunes National Park had the most species in exceedance with 93 CLS-HS exceedances (Table 7). Parks with the fewest species in exceedance are mainly located in the southwest United States. Five parks had no species with maximum deposition from 1985–2011 in exceedance of their CLS-HS.

Zero parks with more than 10 species had CLS-HS exceedances for less than 20% of species analyzed for a response to sulfur. One-hundred-seventy parks with more than 10 species had CLS-HS exceedances for over 50% of the species listed by the park as present. Of these parks, Indiana Dunes National Park, Allegheny Portage Railroad National Historic Site, and Fort Necessity National Battlefield had every species (100%) in exceedance. The average exceedance percentage of parks with more than 10 species was 69%. This distribution of exceedances in national parks reflects the range of CLS-HS values across species. Species with very low CLS-HS are exceeded in most parks they occur in while species with very high CLS-HS values are not in exceedance in any parks.

2016–2018 Sulfur Deposition Exceedances

Figure 10 shows the number of species at each park with maximum S deposition from 2016–2018 in exceedance of their CLS-HS. The overall number of species at risk declined compared to the exceedance evaluation with the maximum 1985–2011 S deposition data. The average number of species with CLS-HS in exceedance from maximum 2016–2018 deposition per park was 34 species. Mississippi National River and Recreation Areas had the most of any park at 76 species with CLS-HS exceedances; five fewer compared to the exceedances based on the 1985–2011 deposition data. Indiana Dunes National Park, New River Gorge National River, and Blue Ridge Parkway all had over 60 species with CLS-HS exceedances. Seven parks had no species with CLS-HS exceedances.

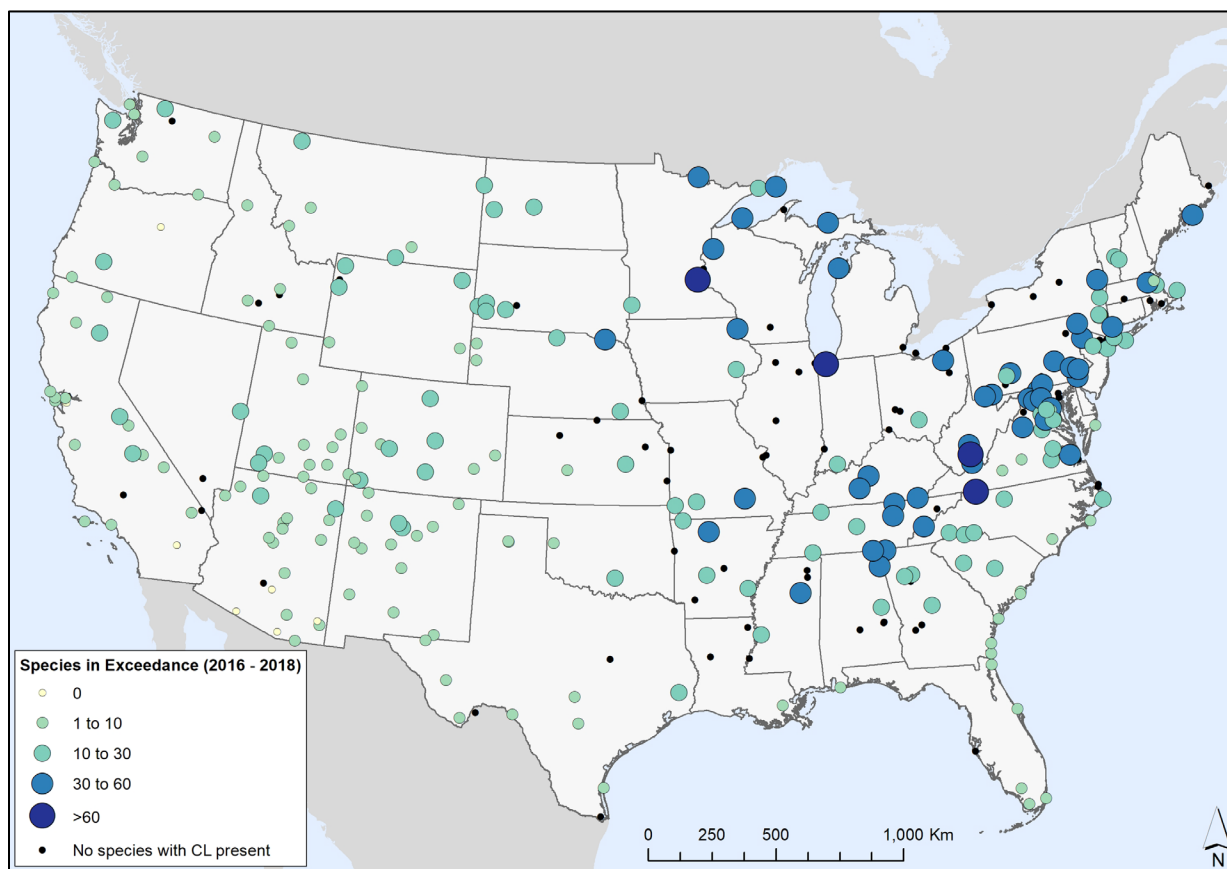


Figure 10. Number of species whose CLS-HS were exceeded by maximum S deposition from 2016–2018. Larger and darker circles represent parks with a higher number of species with exceeded critical loads. Grey points indicate parks that did not have any Clark et al. species present.

Zero parks with over 10 species had CLS-HS exceedances for fewer than 20% of the species present and 144 parks with over 10 species had CLS-HS exceedances for over 50% of species. Eleanor Roosevelt National Historic Site had the highest percentage of species in exceedance with 88%. The average species exceedance percentage at each park was 60%. More parks had fewer exceedances from 2016–2018 deposition in comparison to the 1985–2011 exceedances, reflecting the overall decrease in S deposition between the time periods.

Trends in Exceedance of CLS-HS

Comparing the number of CLS-HS exceedances per parks between the two deposition datasets further shows the nationwide improvement in S deposition as levels generally decreased between the deposition datasets. Figure 11 shows the change in the number of species in exceedance at each park. The greatest decrease in exceedances was seen in the eastern and midwestern United States. Saint Croix National Scenic River had the greatest improvement with 24 fewer species in exceedance from the 2016–2018 S deposition data compared to the 1985–2011 S deposition data. Parks in the western United States showed a smaller reduction of exceedances, likely due to the low number of Clark et al. species present within parks in this region.

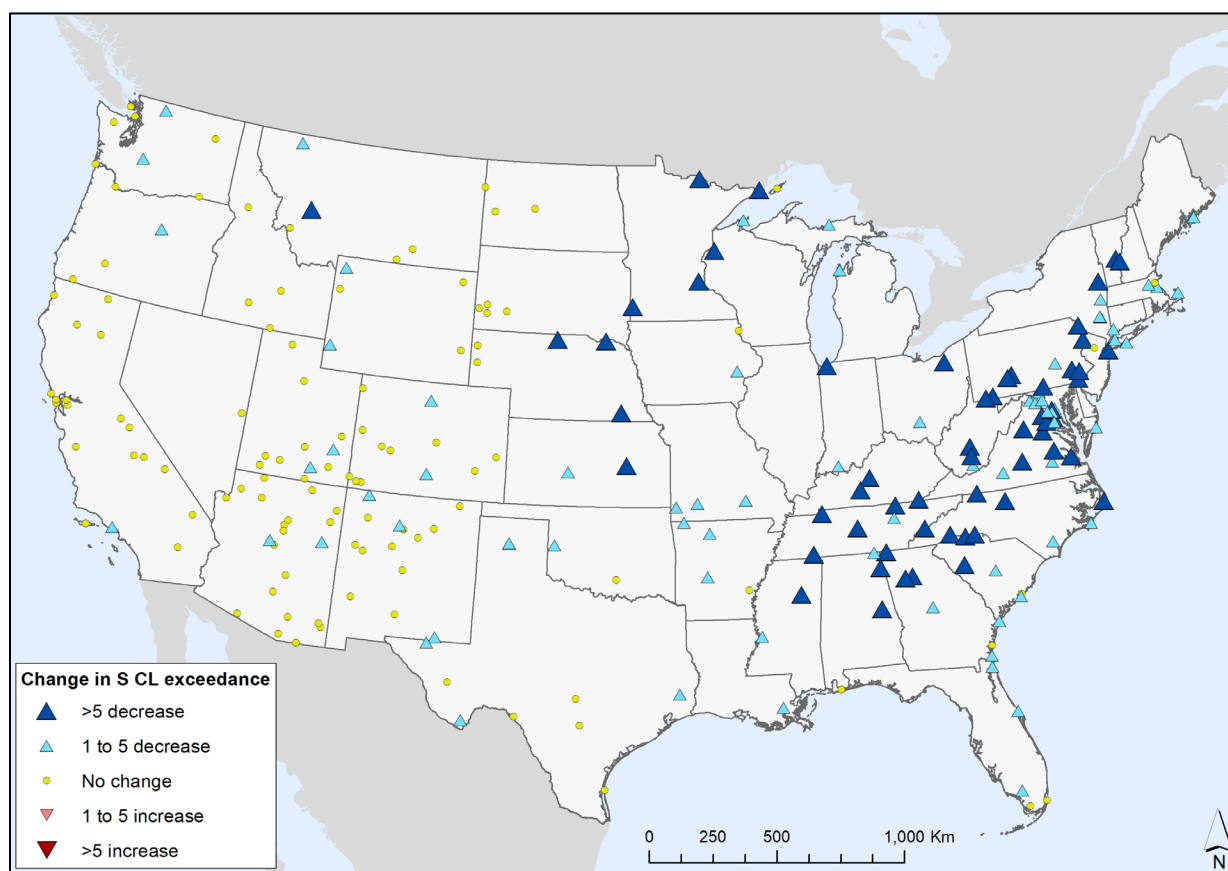


Figure 11. Change in the number of species at each park with CLS-HS exceedances between 1985–2011 maximum S deposition and 2016–2018 maximum S deposition. Blue upward facing arrows indicate a park with an improving condition or a decrease in the number of exceedances. Red downward facing arrows indicate a park with a deteriorating condition or an increase in the number of exceedances.

Summary of Herbaceous Species Presence in Parks

Conyza canadensis was the most common species that has a CLS-HS and was present in 209 parks. *Sericocarpus tortifolius* was the most rarely occurring of the species with a CLS-HS, occurring in just seven parks. See the supplemental data for a full list of species occurrence in parks (Russell et al. 2022).

CLS-HS species level exceedances were evaluated using maximum S deposition at each park from 2016–2018. Table 8 shows the ten species with the most CLS-HS exceedances across parks. The species *Poa pratensis* had the highest number of exceedances with maximum 2016–2018 S deposition exceeding its CLS-HS in 188 of the parks in which it occurs. *P. pratensis* has a decreasing response to S deposition and a CLS-HS of 0.4 kg-S ha⁻¹ yr⁻¹. It is present in 189 parks and its CLS-HS was exceeded by maximum 2016–2018 S deposition in 99% of the parks it occurs in. Forty-nine species, with park occurrence ranging from 9–137, had CLS-HS exceedances in 100% of the parks they occur in. Thirty-nine species had no CLS-HS exceedances across all parks. Species with no CLS-HS exceedances across all parks had an average CLS-HS of 29.3 kg-S ha⁻¹ yr⁻¹ while species with at least one CLS-HS exceedance had an average CLS-HS of 1.4 kg-S ha⁻¹ yr⁻¹.

Table 8. The ten species with the most CLS-HS exceedances across parks. Included are the total number of park occurrences, the percent of occurrences in exceedance, the CLS-HS, and the species S response type.

Species	Number of CLS-HS Exceedances	Park Occurrences	Percent of Park Occurrences in Exceedance	CLS-HS (kg-S ha ⁻¹ yr ⁻¹)	S Response Type
<i>Poa pratensis</i>	188	189	99	0.4	Decrease
<i>Schizachyrium scoparium</i>	137	137	100	0.4	Decrease
<i>Pteridium aquilinum</i>	133	133	100	0.4	Decrease
<i>Bromus inermis</i>	128	129	99	0.4	Decrease
<i>Galium triflorum</i>	127	127	100	0.4	Decrease
<i>Athyrium filix-femina</i>	111	111	100	0.4	Decrease
<i>Geum canadense</i>	108	108	100	0.4	Decrease
<i>Viola sororia</i>	106	106	100	0.4	Decrease
<i>Danthonia spicata</i>	100	100	100	0.4	Decrease
<i>Polygonatum biflorum</i>	96	96	100	0.4	Decrease

Of the 131 species that have a CLS-HS, 92 species had at least one occurrence in a park where maximum 2016–2018 S deposition was in exceedance of their CLS-HS. Only species with a decreasing response to S deposition had CLS-HS exceedances. The 34 species with a CLS-HS and an increasing response to S deposition had no exceedances across all parks. CLS-HS for species with an increasing response ranged from 8.6 kg-S ha⁻¹ yr⁻¹ to 42.5 kg-S ha⁻¹ yr⁻¹ and had an average of 32.4 kg-S ha⁻¹ yr⁻¹. These high CLS-HS values explain why species with increasing responses to S deposition did not have any exceedances.

Discussion

This study applied critical loads of nitrogen (N) and critical loads of sulfur (S) for 198 herbaceous species developed by Clark et al. (2019) for a decline in probability of occurrence to parks. Critical loads were compared to total N and total S deposition from 1985–2011 and 2016–2018 to evaluate species at risk for negative impacts within parks. Critical loads were evaluated within and across parks to identify species at risk regionally and nationwide. This section will synthesize the important findings from this analysis, provide recommendations for using the dataset developed in this study, present considerations regarding the scope of the data used in this study, and discuss the trajectories for future research.

Exceedances of Critical Load for Herbaceous Species in Parks

Two deposition datasets were used in this analysis to provide a snapshot of critical load exceedances over time. The 1985–2011 dataset is the original deposition data used to develop the critical loads and represents a direct application of the information from the original study, while the 2016–2018 dataset is the most recent data available and represents current deposition conditions. The long-term deposition data in the 1985–2011 dataset reflects the understanding that N accumulates within ecosystems. Effects from low levels of deposition can take many years to appear, and effects from historically high levels of deposition can take years to disappear. Thus, cumulative deposition across thirty-year time periods can be better for evaluating eutrophication impacts to natural resources (Payne et al., 2019). However, three-year averages, like the 2016–2018 dataset, are more functional for management goals as they can show short-term changes in deposition and the impacts of any actions taken to reduce deposition.

Most parks saw a decline in total N and total S deposition between 1985–2011 and 2016–2018. S deposition improved broadly across the United States, with the largest improvements in the northeastern and central Appalachian regions. Reductions in N deposition were primarily seen in the southeast and northeast regions of the United States. Changes in herbaceous species critical loads reflect these trends in deposition. Exceedances of critical loads of N for a decline in an herbaceous species' maximum probability of occurrence (CLN-HS) at parks showed improvements primarily in the southeast and the east coast of the United States. Exceedances of critical loads of S for a decline in an herbaceous species' maximum probability of occurrence (CLS-HS) improved across the United States and showed the strongest improvement in the eastern and midwestern United States. While the number of exceedances improved overall, 91% of parks contained at least one species whose CLN-HS was exceeded by 2016–2018 N deposition and 97% of parks contained at least one species whose CLS-HS was exceeded. This indicates that most parks contain herbaceous species that are sensitive to low levels of N or S deposition and may experience detrimental effects.

Risk to herbaceous species in parks from N deposition worsened in the northern Midwest and northern Great Plains regions. The six parks with the largest increase in CLN-HS exceedances were all found in this region (Effigy Mounds National Monument, Missouri National Recreational River, Pipestone National Monument, Saint Croix National Scenic River, Niobrara National Scenic River, and Knife River Indian Villages National Historic Site). Deteriorating N conditions in the upper

Midwest and northern plains are likely due to intensified industrial agriculture in the region and the resulting increase in reduced nitrogen (NH_y) deposition as seen at NADP-NTN site IA08 (NADP 2021). N deposition due to NO_x emissions from fossil fuel combustion has broadly declined while agricultural emissions in the form of NH₃ contribute to a more prominent proportion of N deposition (Nopmongcol et al., 2019). Some parks in the northern Rocky Mountains and the Southwest also showed moderate increases in CLN-HS exceedances. Increases in N deposition in these parks may be due to nearby oil and gas development, increasing human development in the West, or to a lesser extent increased visitation and vehicle traffic within the parks (Hoffman et al 2017, Root et al 2021)

While park conditions improved overall, there is still risk to herbaceous species in parks where the number of exceedances decreased. This reveals that parks with a minor decrease in exceedances between the two deposition datasets may simply reflect small fluctuations in N or S deposition rather than a continual declining trend. The distribution of CLN-HS values across all parks was close to normal but skewed toward higher values, indicating that the majority of species evaluated are tolerant of N deposition. This suggests that making small improvements to air quality in parks with high deposition levels can reduce the number of exceedances and improve herbaceous community condition. As easier air quality improvements are made, reductions in deposition become harder to achieve and thus that active management on the ground must be paired with policy changes to protect against continued harm. Detailed understanding about the local sources of N and S is needed to assess where further decreases in specific emissions can assist in the protection of sensitive herbaceous species.

These results show that herbaceous species in parks are impacted by N and S deposition, and some may be at risk for declines in occurrence. Particularly in parks with a large or increasing number of exceedances, the negative impacts of N and S deposition may lead to decreases in herbaceous species community composition and broad changes in biodiversity. These changes can negatively affect the function of ecosystem services within parks and the integrity of the visual resources enjoyed by park visitors. As such, parks with large numbers and increases of CLN-HS or CLS-HS exceedances require specific management focus to protect herbaceous species and the broader ecosystems within these parks.

Exceedances of Critical Loads for Herbaceous Species across Parks

Assessing species across park occurrences reveals trends in occurrence and response types. The 10 most common species with a CLN-HS had an average CLN-HS of 11.0 kg-N ha⁻¹ yr⁻¹ and all but three of these species had hump-shaped or increasing responses to N deposition. This suggests that most of these common species have general environmental requirements and are less responsive to small changes in N above background levels. The most common species with a CLS-HS had both very high and very low CLS-HS values. This is expected as only increasing and decreasing responses were modeled for S. Species such as *Verbascum Thapsus* have low CLN-HS or CLS-HS values suggesting that they are sensitive to soil acidification and may not be responding to the fertilizing properties of N. An additional analysis based on reduced and oxidized N deposition would help determine the mechanism of change. Deposition levels at the locations of these species within parks would provide more information as to why such sensitive species are so common.

Species with increasing responses to deposition had the lowest number of exceedances across parks. Evaluating critical loads for species with increasing responses is challenging as it is difficult to designate harm to the ecosystem for increasing species. While a species that has an increase in probability of occurrence as N deposition increases may not experience any negative effects itself, its growth could intensify competition for light and other resources for nearby species. The responses of nearby species to deposition and information about whether the increaser species are invasive or native would provide needed context to evaluate whether the impacts of N deposition on increaser species are causing ecosystem harm. For example, two of the most common species across parks had increasing responses to N deposition and were non-native species. *Bromus inermis* and *Urtica dioica* are both invasive species with increasing responses to N deposition and are present in over 120 parks. The presence of these increaser invasive species in many parks suggests that small changes in N deposition, that may be detrimental to native species with hump-shaped or decreasing responses, would encourage further growth for the invasive species. More geographically specific context about the presence of increaser invasive species alongside native decreaser or hump-shaped species in parks is needed to fully understand the impacts of these species on the ecosystem around them.

Applying Critical Load Percentiles

While the NPS mission is to protect parks unimpaired, it is unlikely that pollution will be reduced below the most sensitive species' critical load in the near term. A critical load metric representative of the larger herbaceous community may provide a more realistic management goal. Along with the measurement of exceedances for individual species within parks, percentile critical loads at each park were evaluated. Critical load percentiles are determined by identifying values along the distribution of critical loads from all species present at each park. Minimum (0%), 10th percentile (10%), median (50%), and maximum (100%) critical loads were calculated for each park. These percentiles can provide benchmarks of protection and help identify the proportion of the herbaceous community affected by deposition, as well as which sensitive species should be targeted for active management.

Minimum critical loads signify the level of deposition at which all herb species, even the most sensitive, would be protected from deposition. For most parks, the minimum critical load was determined by a species with a decreasing response to N or S deposition. Thus, the minimum critical load for these parks is equal to the minimum level of deposition at which a species with a decreasing response occurred in the original Clark et al. dataset. This sets the minimum critical load for a park at a potentially artificially low level, given that the model does not allow for no response prior to a decrease, and in this analysis does not consider environmental cofactors (Perring et al., 2018). Decreasing species that set the minimum critical load at a park may experience different environmental conditions or management history in the park than the plots surveyed and used to create the critical load in the Clark et al. study. Minimum critical load values may be useful to parks in which the species with the minimum critical load is of conservation value, or in pristine parks considering permits for new sources.

The 10th percentile critical loads indicate the critical load at which 90% of herb species within a park are protected. This 90% protection value is useful as it both provides a threshold of deposition at which most herbaceous species within a park are protected and highlights particularly sensitive

species with critical loads below the 10th percentile. As some parks have less than 10 species with a CLN-HS or CLS-HS present, or the number of species present is not divisible by 10, the 10th percentile critical loads do not always correspond to an actual species' critical load and its underlying species-specific relationship. 10th percentile critical loads may be useful to parks where deposition far exceeds the critical load of the most sensitive species as they set glide paths toward recovery, or for parks considering deposition in the context of other disturbances (climate change, invasions) and their effect on plant communities.

Median critical loads identify the level of deposition at a park where half of the present herbaceous species are protected from the negative impacts of deposition. Like 10th percentile critical loads, median critical loads provide an intermediate metric for park managers to assess the condition of species within parks. In parks with large numbers of exceedances, these critical load percentiles can be useful as target thresholds of deposition as they set a concrete level of deposition and proportion of herb species to protect.

The maximum critical load at a park identifies the level of deposition at which no herbaceous species are protected from detrimental effects from deposition. This value is useful as it provides a cap for the amount of deposition that any herbaceous species in a park can tolerate. Maximum critical loads may be less applicable in parks that contain species with critical loads far above measured deposition in the area. For example, some species have CLS-HS values of over 40 kg-S ha⁻¹ yr⁻¹ while the highest maximum deposition in parks from 2016–2018 was 12.9 kg-S ha⁻¹ yr⁻¹. Overall, these percentile critical loads will allow park managers to easily evaluate and monitor the condition of herbaceous species in parks. Go to the supplementary dataset to see minimum, 10th percentile, median, and maximum critical loads for each park assessed in this study.

Recommendation for Using the Dataset for Individual Parks

The dataset created for this analysis identifies critical loads percentiles and exceedances within parks is available with this report. This dataset will allow park managers to identify herbaceous species in critical load exceedance within their parks and the expected response of those species to increasing deposition. Sensitive and ecologically important species can be directly called out as in need of monitoring and focused efforts can be implemented to protect these species.

The dataset also provides a list of species exceedances across parks. The NPS Air Resources Division will use the species exceedances to contribute to our annual and long-term evaluation of conditions and trends in each park (<https://www.nps.gov/subjects/air/park-conditions-trends.htm>). Critical load data is currently being added to the system which will allow for a quick evaluation of critical load exceedances from deposition over time and will be updated when new data becomes available.

This list is also useful for Inventory and Monitoring regions to identify common species from the dataset that are in exceedance of nitrogen or sulfur deposition. Regional summaries of species at risk could help create collective efforts to mitigate negative impacts on sensitive species across multiple parks within a region.

Along with these potential uses, application of this dataset within parks would provide ground-truthing for the modeled species responses. As this analysis did not identify individual species locations within parks, location-specific environmental conditions were not considered in species' response. If a species with a decreasing response to deposition is found to be thriving in a park where maximum deposition exceeds its critical load, that indicates that the modeled response may not be applicable in that area. This can provide useful information for future research and inform how researchers modeling species responses incorporate environmental cofactors into their analyses.

Knowing which species are responsive to N and S deposition can assist planning restoration and management projects and target invasive species. This can be particularly useful when working near roadsides or high-use areas that are known to create local deposition (Bettez et al., 2013; Kenkel et al., 2013). This approach gives a broad overview of risk and can be enhanced using species survey data that can link location, soil chemistry, and environmental factors into the expected response.

As deposition was summarized to each park and species locations were not known, the deposition values used to measure exceedances in this study differ from the deposition actually experienced by individual species. This national and park level data is useful for broadly identifying species that may be at risk and parks where deposition is a particular threat to herbaceous species. However, a local analysis using deposition values at the location where each species is present will provide a more accurate view into species at risk. Given the different spatial scales, the local analysis would produce different results than this park level analysis and provide additional confidence in the accuracy of results.

Scope of this Dataset

The vegetation plots used by Clark et al. (2019) to create the herbaceous species critical loads were sampled more heavily from the eastern and midwestern regions of the United States. Few plots were located in the Rocky Mountains, Southwest, and Great Plains regions. Herbaceous species in these regions are underrepresented in the Clark et al. data and parks in these regions had fewer species present that could be used in the analysis. We found that parks to the east of the Rocky Mountains had more Clark et al. species present than parks to the west of the Rocky Mountains. Given this divide, evaluations of conditions and trends of N and S in western parks may not be as representative of the conditions of herbaceous species commonly found in those parks.

This research applies the herbaceous species critical loads developed by Clark et al. outside of the original contexts within which they were created. Species in parks far from the original plots may experience different environmental conditions that could influence species response to N and S. For example, few plots were sampled near montane parks in the western United States, such as Rocky Mountain National Park, Yellowstone National Park, and Glacier National Park. Herbaceous species' response to deposition in these parks are likely influenced by elevation. High-elevation ecosystems may be particularly sensitive to N and S deposition as they are often N limited (Bowman et al., 2006). The potential sensitivity of herbaceous species in high-elevation areas was not considered in the original models used to create the critical loads as no plots from these areas were included. In addition, TDep overestimates inorganic wet deposition at high elevation sites (Williams et al., 2017). Thus, critical load exceedances for herbaceous species in high elevation parks may be overestimated.

Along with this, some species occurrences in parks may experience levels of the environmental variables used to calculate the critical loads at levels outside of the range of environmental conditions experienced by the species in the Clark et al. dataset. That is, precipitation, soil pH, temperature, or N or S deposition in a park may be outside of the range of the input data used to create the critical load for a species in that park. Further research is needed to understand whether these critical loads can be accurately applied to areas with environmental conditions outside of what was considered in the response equations.

Narrowing the spatial scope of the critical load evaluations to measure exceedances at individual points within parks would alleviate some of these issues. Vegetation plots within parks containing the Clark et al. species could be identified and used to compare critical loads to point specific deposition rather than parkwide summary values. Point location data would also allow for the models used to create the critical loads to be expanded to include plot-specific environmental data. This would potentially give a better understanding of the true response of species along N or S deposition gradients.

Future Research

This analysis provided a synopsis of the risk to herbaceous species in parks as a whole. Identifying the specific locations of herbaceous species could provide more specific insight into the responses of herbaceous species to N and S within parks. Applying the Clark et al. critical loads to vegetation plot data from the National Park Service would allow for this detail and for the consideration of the environmental conditions where species are found. The use of vegetation plot data would allow for the species response equations from Clark et al. to be applied using the exact ranges of deposition and cofactor data each species experiences within parks. Understanding the response of, and risk to, individual species at specific locations within parks would provide land managers the ability to confidently identify species and areas within parks that are most at risk and may need intervention. Additionally, further work on developing critical loads for individual species would allow for the expansion of this research to other important resources within parks.

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