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

Natural Resource Report NPS/NRSS/ARD/NRR—2022/2468



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Vegetation in Acadia National Park
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Site-specific Critical Loads of Nitrogen and Critical Loads of Sulfur for Herbaceous Species in National Parks

Natural Resource Report NPS/NRSS/ARD/NRR—2022/2468

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Executive Summary

Herbaceous species (vascular plants with non-woody stems such as grasses, flowering plants, and ferns) in national parks play an integral role in maintaining biodiversity and ecosystem function. The diversity and distribution of herbaceous species are dependent on local climate and soil conditions, some of which are altered by deposition of anthropogenic air pollutants nitrogen (N) and sulfur (S). Clark et al. (2019) developed critical loads of N (CLN-HS) and critical loads of S (CLS-HS) for 198 herbaceous species which represent the maximum annual deposition that an herbaceous species can tolerate with no decrease in the probability of occurrence. Here we apply critical loads for the 198 species to location data from the NPS Vegetation Mapping Inventory (VMI) for 209 park units and assess the risk of decline based on current deposition.

This report is a companion to a report which used park species lists from NPSpecies and park-wide estimates of deposition to assess risk from deposition to park herbaceous communities (Russell et al. 2022). By contrast, this report uses site-specific species presence and deposition levels based on the plot location. For the 106 herbaceous species with a threshold response to N deposition, soil pH, temperature, and precipitation data specific to VMI plot locations were used to calculate site-specific CLN-HS, which reflect the influence of other environmental factors on plant sensitivity to deposition. Species with an increasing or decreasing response to N or S deposition have static CLs that do not incorporate other environmental factors into their CL calculations. Deposition exceedances of plot level critical loads of N and of S were assessed against total N and S deposition from 2016–2018 to determine expected decline in probability of occurrence.

The plots used to determine the critical loads are mostly distributed in the Midwest and eastern United States which limits the number of species within the study for western parks; especially in the desert southwest. Across all parks, there was an average of 24 species with a CLN-HS and 20 species with a CLS-HS. Parks to the east of the Rocky Mountains had an average of 45 species with a CLN-HS and 48 species with a CLS-HS, while parks to the west of the Rocky Mountains had an average of 11 species with a CLN-HS and 12 species with a CLS-HS. The difference in these numbers are due to the plots within the original dataset from which the CLs were calculated being weighted towards the east coasts and thus the western species may not be represented in the dataset.

Nine case study parks were selected to evaluate regional differences in CLN-HS and CLS-HS exceedances and provide an example of how the data can be used assess the spatial distribution of species at risk to negative impacts from N and S deposition. From the case study parks, midwestern and eastern parks had over 10% of their flora represented by the species in the analysis, while parks west of the Rocky Mountains all had under 10% of their flora represented.

Along with establishing local responses to deposition, park and resource managers can use site-specific critical loads to develop targeted management plans for species or sensitive areas at risk within their parks. Each site has a species list of occurrences and risk of response to current deposition that can assist in active management of biodiversity and ecosystem health. Additionally, the NPS VMI survey plots can be used to expand the number of species that meet minimum model requirements and increase the number of species for which we can model critical load responses.

Introduction

The mission of the National Park Service is to preserve unimpaired natural and cultural resources within national parks for current and future generations. Natural resources include herbaceous species (vascular plants with non-woody stems such as grasses, flowering plants, and ferns) which play an integral role in maintaining biodiversity and ecosystem function. The diversity and distribution of herbaceous species are dependent on local environmental conditions, some of which are altered by the deposition of anthropogenic air pollutants. Nitrogen (N) and sulfur (S) deposition can have detrimental effects on herbaceous species leading to changes in community composition and ecosystem stability (Clark et al. 2019). This report uses species location data from field surveys to assess how current N and S deposition are impacting herbaceous species in National Park Service units.

N is an essential nutrient for plant growth, but excess N can cause eutrophication and favor the growth of nitrophilous species over the growth of species adapted to baseline conditions (Bobbink et al., 2010; Isbell et al., 2013; Stevens et al., 2004; Valliere et al. 2017, Symstad et al. 2019). Additionally, N and S deposition both can cause acidification of soils; deposited nitrogen oxides, ammonia/ammonium, and sulfur oxides can move through the soil solution and leach essential base cations, like calcium, from the soil while also releasing toxic levels of aluminum from soil minerals (Beier et al., 2012; Gilliam, 2006; Sullivan, 2016). The changes in vegetation communities in response to eutrophication and soil acidification can affect overall ecosystem productivity and stability (Isbell et al., 2013; Tilman et al., 2016).

Researchers developed the concept of a critical load to identify a threshold of deposition at which harmful environment impacts occur and better communicate the effects (Porter et al., 2005). 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). Early critical loads were developed to protect broad ecosystem components or regions (Baron et al., 2011; Bowman et al., 2012; Clark et al., 2019; Geiser et al., 2019; Pardo et al., 2011, Sullivan et al., 2012). However, recent research has been conducted using surveys across a species' range to establish individual species responses to N and S and develop species-specific critical loads (Clark et al., 2019; Horn et al., 2018). Using vegetation plot data to develop critical loads for individual species provides a more accurate representation of how local environmental conditions in addition to deposition contribute to plant responses. This novel approach can inform resource managers about specific locations and species at risk, and lead to improvements in air protection policies by providing precise and context-enriched results about risk to vital ecosystem components.

Clark et al. (2019) developed critical loads of N and critical loads of S for a decrease in probability of occurrence of individual herbaceous species across the United States. The analysis used a vegetation plot dataset compiled by Simkin et al. (2016), which had previously established critical loads for a decline in herbaceous community richness under open- and closed-canopies. Based on the presence of species within plots and plot-specific environmental data, Clark et al. modeled individual 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. A previous report was published applying the average herbaceous species critical loads to national park species lists (Russell et al. 2022).

The threshold and rate of response for each species can be more or less sensitive to N or S deposition based on other environmental constraints, including precipitation, temperature, and soil chemistry. For example, N addition increases plant biomass in many herbaceous species, and this response amplifies with increasing precipitation (Xia and Wan, 2008), although some tolerant plant species are unresponsive to N even under different precipitation regimes (Hall et al., 2011). Generally, species richness increases with increasing temperature (Currie et al., 2004), although plant growth response to N addition peaks at a mean annual temperature of 8° C, and plants respond less strongly to N addition at lower or higher temperatures (Tian et al., 2016). Soil pH is controlled by multiple factors, including underlying geology and organic matter produced by plants, and changes in soil pH can change the availability of and chemical form of nutrients in the soil (Chapin et al., 2011). Soil pH and its effects on nutrients can alter plant growth because different plant functional groups vary in their response to different chemical forms of available N (Yan et al., 2019), or because plant species can have different nutrient requirements under common environmental conditions (Roem et al., 2003). When these factors are relevant to a plant's response to N or S deposition, they were included in the models developed by Clark et al. (2019). By using known species locations within national parks, we are able to better assess the risk posed by deposition while taking into account other environmental variables.

This study aims to provide a detailed assessment of the expected response of herbaceous species to N and S deposition occurring in national parks. Many of the critical loads that Clark et al. (2019) calculated are contingent upon soil pH or precipitation. We use vegetation surveys paired with available environmental information for each plots to calculate plot-specific critical loads of N and critical loads of S from response equations. We compare the critical loads of each location to modeled N and S deposition to identify species in exceedance. Along with establishing local responses to deposition, park and resource managers can use site-specific critical loads to develop targeted management plans for species or sensitive areas at risk within their parks.

Methods

Critical Loads for a Decline 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 modeled by Clark et al. (2019) using local soil pH, temperature, precipitation, N deposition, and S deposition as predictor variables at 15,136 vegetation plots across the contiguous United States (Figure 1). For a critical load to be calculated, the species had to occur in at least five plots and had N deposition data that spanned a range of at least 7 kg-N ha^{-1} yr^{-1} across plot occurrences; 348 species fit these requirements—198 of which were determined to be statistically significant. The distribution of these plots is weighted towards the midwestern and eastern United States which limits the applicability to western parks but provides information at these locations that can be used to guide future research.

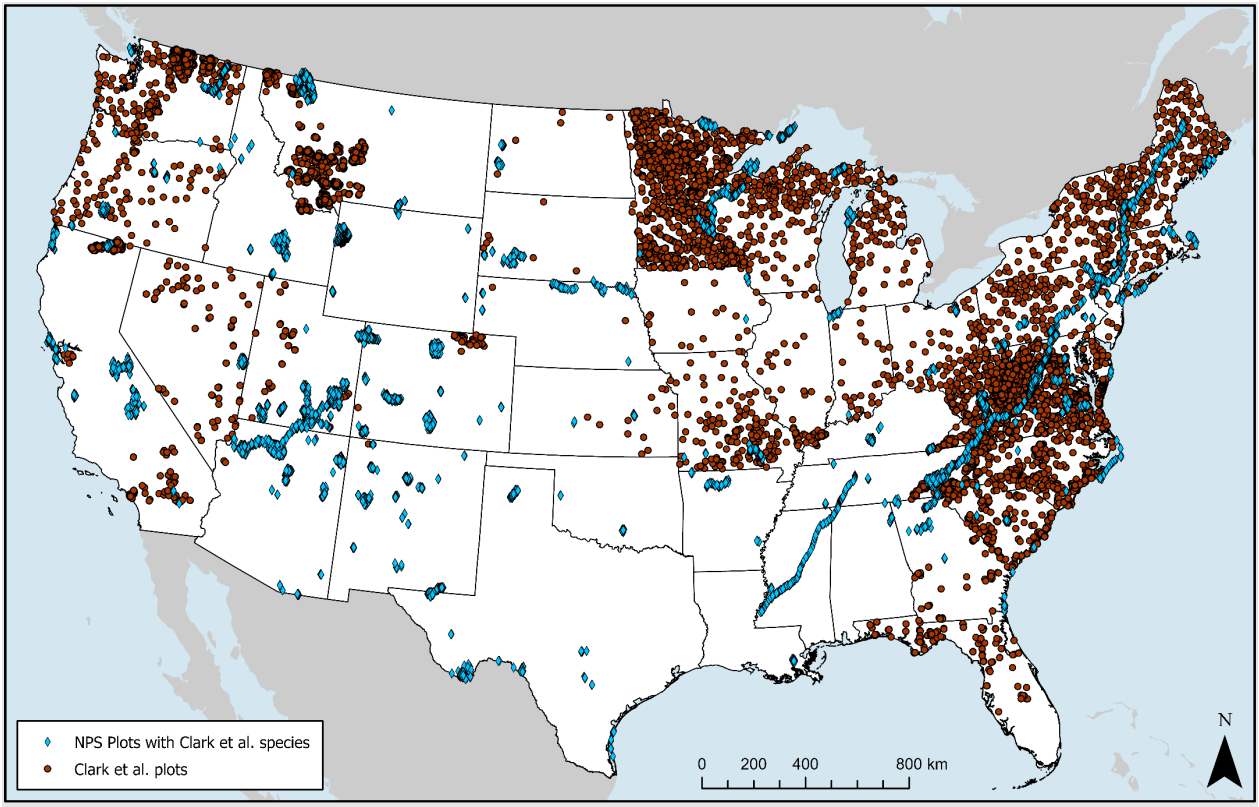


Figure 1. Comparison of NPS Vegetation Mapping Inventory plots that contain at least one Clark et al. species (blue squares) and the plots used by Clark et al. to create the herbaceous species critical loads (red circles).

Critical Loads of Nitrogen

Herbaceous species probability of occurrence had a threshold, decreasing, increasing, saddle, or flat response to increasing N deposition. A single critical load of N to protect against a decline in an herbaceous species' maximum probability of occurrence (abbreviated as CLN-HS) was established for species that had a threshold, increasing, or decreasing response (Figure 2). Saddle responses

change the direction of response when a threshold of a second environmental variable (e.g. soil pH) is exceeded; they are not included in this analysis as a single CL cannot be set and further research is needed to assess the ecological accuracy.

Models from Clark et al. identified a CLN-HS for 157 of the 198 herbaceous species in the analysis. The CL for species with threshold response is set at the level of N deposition at which a species probability of occurrence begins to decline or the peak of the response curve. For species with a decreasing response, the CLN-HS was set lower than the minimum N deposition experienced by that species in the Clark et al. plots, and for species with an increasing response, the CLN-HS was set higher than the maximum N deposition experienced by the species. Figure 2 shows where the CLN-HS was set for each of species' probability of occurrence response. Table 1 shows the number of species that fit into each N response type.

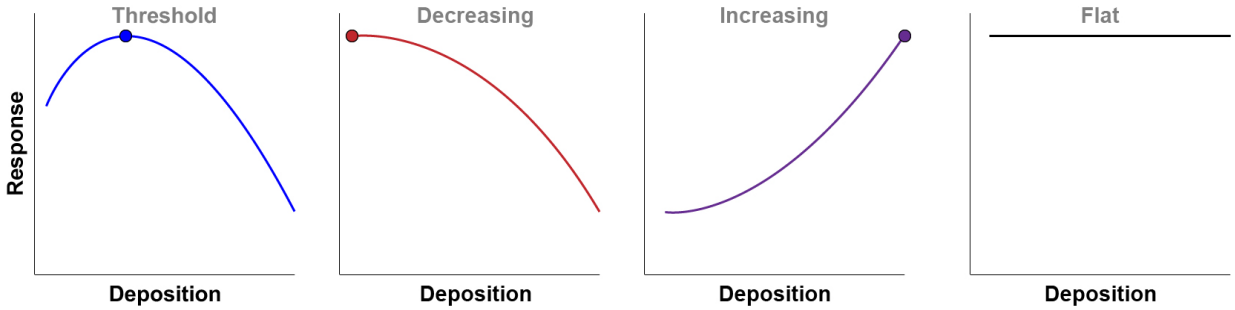


Figure 2. Possible shapes of species response to increasing N deposition. The points on the curves for threshold, decreasing, and increasing response types indicate the level of N deposition at which the critical load would be placed. A saddle response type has no point of consistent decline so no critical load can be established.

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

N Response Type	Number of Species	Has CLN-HS
Increase	29	Yes
Decrease	21	Yes
Threshold	106	Yes
Flat	1	No
Saddle/increase	11	No
Saddle/decrease	9	No
Saddle/flat	1	No
None	19	No

Critical Loads of Sulfur

Herbaceous species had an increasing, decreasing, saddle, or flat response to increasing S deposition. The analysis did not allow for threshold responses from the model 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 increasing and decreasing responses to S deposition were assigned a critical load of S for a decline in an herbaceous species' maximum probability of occurrence (CLS-HS). As with N, saddle responses were excluded from this analysis.

Models identified a CLS-HS value for 131 of the 198 herbaceous species in the dataset. 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 species within a response type were 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 Vegetation Mapping Inventory

Vegetation plot data from the NPS Vegetation Mapping Inventory (VMI) was used to map the presence of herbaceous species within 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 VMI classifies, describes, and maps vegetation in parks and provides species presence information at vegetation plots within parks. Vegetation plot data from the VMI is available from each park as a geodatabase containing a point feature class of all vegetation plots in a park and an excel file with a matching ID field describing the species that are present within each plot. Additionally, each park had a Microsoft Access Database with plot and species information. Geodatabases and excel files from 200 parks were retrieved from the VMI and compiled into a single point feature class and excel file describing all vegetation plots across parks. The Microsoft Access Database was downloaded and used to export species and plot data to an excel file for parks that did not have a prepared downloadable excel file of that information. Some parks could not be included as the inventories were still in progress or the species data in the excel file or Microsoft Access Database did not have a useable ID field to match to the point feature class. The

final geodatabase and excel file were then queried for all plots containing at least one species from the 198 species included in the Clark et al. analysis and combined with the location data from the dataset used to develop the critical load models. All plots without a Clark et al. species were filtered out of the dataset. The resulting data included 68,252 occurrences of Clark et al. species within 18,658 plots from 209 parks. Of these 209 parks, 200 are represented in the VMI dataset and 9 parks are included based on the data from Clark et al. (2019). The number of species present within each plot ranged from 1–31 species. Figure 1 shows the locations of the plots from the VMI in comparison to the original plots used by Clark et al. (2019).

Calculating Location-based Critical Loads

Threshold responses to increasing N deposition can vary with local environmental conditions, meaning a species in one plot with one set of environmental conditions may have a different CLN-HS than that same species in a different plot with different environmental conditions. The threshold responses were evaluated for 39,273 occurrences of the 106 threshold response species across 14,086 NPS VMI plots using the same environmental factors as the Clark study (soil pH, temperature, precipitation, and N and S deposition).

The results of the threshold calculation produced a negative CLN-HS for 62 species occurrences, indicating that the environmental data input into the partial derivative expressions were outside of the range of the environmental data used by Clark et al. to create the models. Of the 62 species occurrences with a negative CLN-HS, 22 were from species whose models were driven solely by the term for S deposition and in which annual S deposition is relatively high. As such, the CLN-HS for these 22 species occurrences were changed to 0, indicating that since S was high in these plots and the addition of any level of N would lead to a decline in probability of occurrence. Forty of the species occurrences with negative CLN-HS values had models that included both S and pH variables. The negative CLN-HS values for these occurrences were changed to null as it cannot be determined if changes in pH or S are the sole drivers of sensitivity to N for these occurrences.

Species with decreasing or increasing relationships were given the lowest or highest, respectively, amount of N deposition experienced by the species in the Clark et al. plots. For example, *Carex disperma* has a decreasing response to N deposition so it was assigned a critical load of 1.6 kg-N ha^{-1} yr^{-1} by Clark et al. All occurrences of *C. disperma* across the plots, regardless of other environmental conditions, are given the CLN-HS of 1.6 kg-N ha^{-1} yr^{-1}.

Since the CLS-HS values applied to VMI plots are all decreasing or increasing relationships, they were given the lowest or highest, respectively, amount of S deposition experienced by the species in the Clark et al. plots. and applied uniformly across sites.

Evaluating Herbaceous Species Plot Specific Critical Load Exceedances

N or S deposition in quantities greater than or equal to a species' critical load indicate an exceedance of the critical load and may lead to a decline in probability of occurrence for that species. Exceedances of plot level critical loads of N and of S were assessed against TDep total N and total S deposition from 2016–2018 (Figure 3 and Figure 4; NADP 2018).

CLN-HS and CLS-HS exceedances were evaluated at species and plot levels. First, the plot-based CLN-HS and CLS-HS values for each species were compared to the corresponding total 2016–2018 N or S deposition value. Species in each plot were flagged as experiencing deposition in exceedance or not in exceedance of their critical loads for N and S from each deposition dataset. Second, the minimum CLN-HS and CLS-HS of all species within each plot was calculated and compared to modeled N and S deposition at each plot location. Three designations were given to each plot based on the deposition comparison. Plots were flagged as below the minimum critical load if deposition was lower than the minimum critical load by 0.5 kg-N ha^{-1} yr^{-1}, at the minimum critical load if deposition was within ± 0.5 kg-N ha^{-1} yr^{-1} of the minimum critical load, and above the minimum critical load if deposition exceeded the minimum critical load by more than 0.5 kg-N ha^{-1} yr^{-1}.

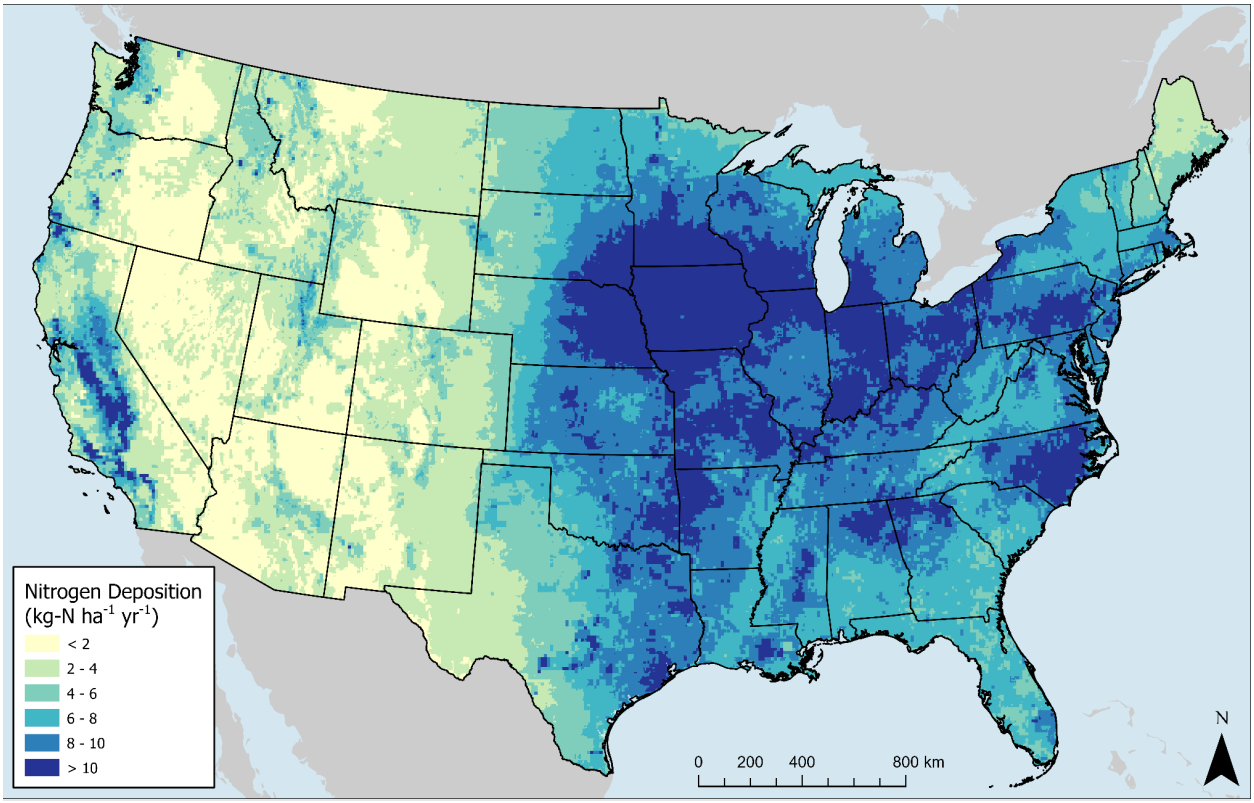


Figure 3. Average total N deposition across the United States from 2016–2018. Total N deposition is generally higher in the eastern and central United States and in the Central Valley in California.

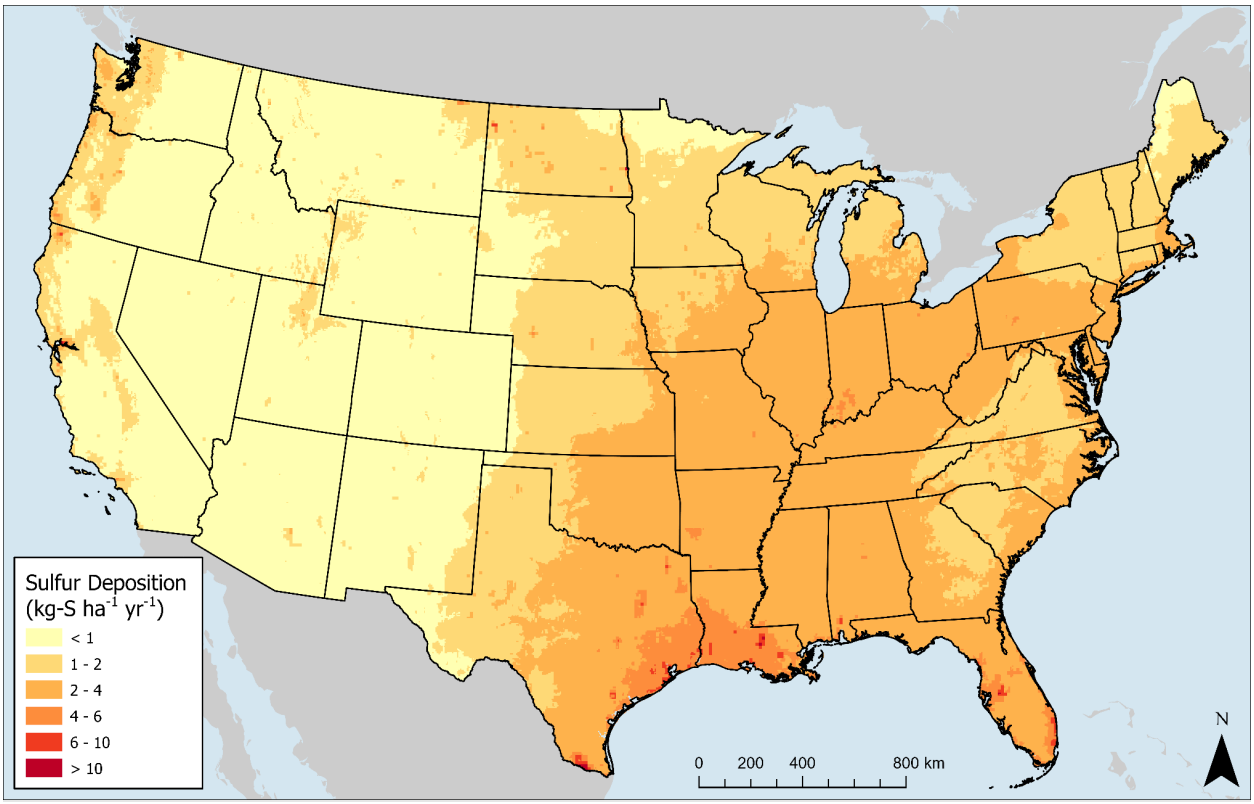


Figure 4. Average total S deposition across the United States from 2016–2018. Total S deposition is generally higher in the eastern and southeastern United States.

Nine case study national parks (Acadia National Park, Glacier National Park, Grand Teton National Park, Great Smoky Mountains National Park, Joshua Tree National Park, Rocky Mountain National Park, Sleeping Bear Dunes National Lakeshore, Theodore Roosevelt National Park, Yosemite National Park) are highlighted below analyze patterns in exceedance and assess the spatial variation of CLN-HS and CLS-HS exceedances within the parks and across ecosystems within the contiguous US (Figure 5). The distribution of plots with sensitive species and plots with the most CLN-HS or CLS-HS exceedances were also evaluated for the case study parks.

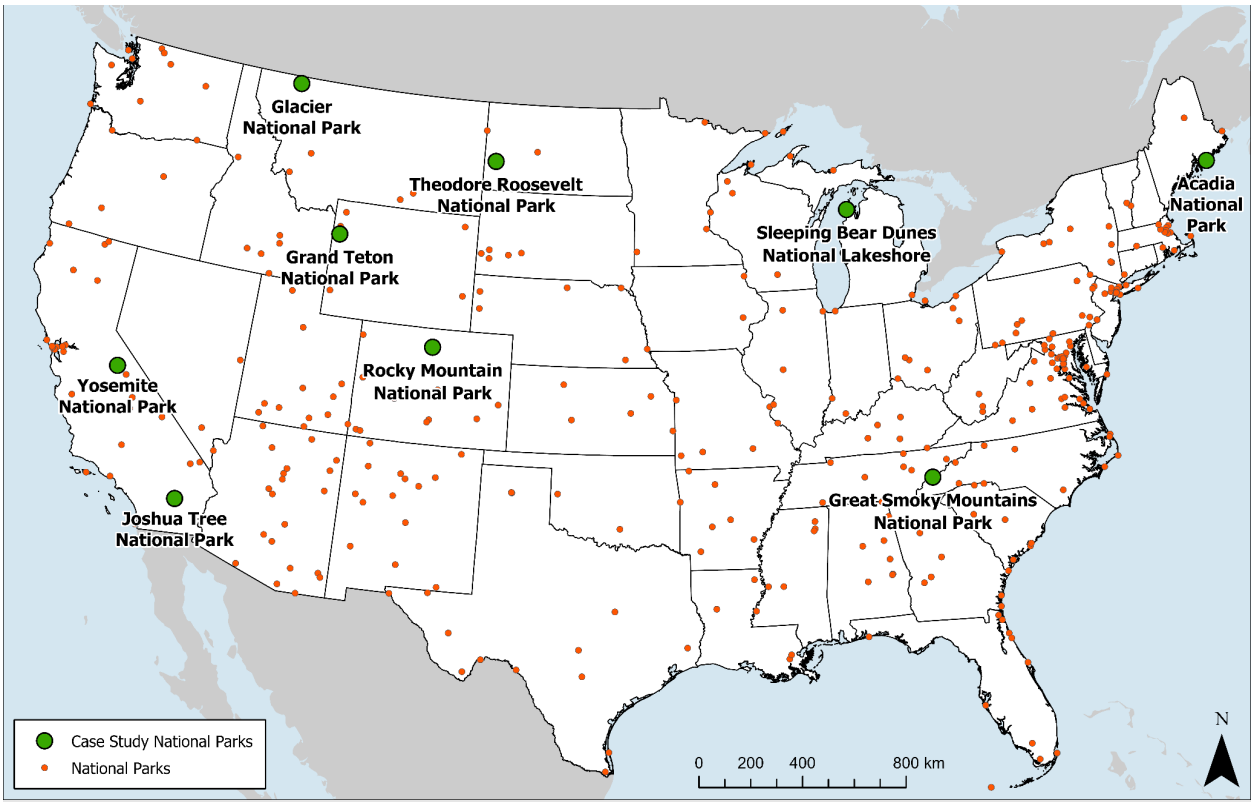


Figure 5. The location of the nine case study parks (green circles) and the other parks included in this study (red dots).

Results

Herbaceous Species in Parks

The National Park Service Vegetation Mapping Inventory (VMI) dataset combined with the plot data from Clark et al. (2019) has 209 parks that contain at least one herbaceous species with a critical load. Of the 198 species from the Clark et al. analysis 197 were found within the plots; *Oligoneuron riddellii* was not present in any plot. 89% (15,377) of the 18,658 total plots contained at least one Clark et al. species. Table 3 shows the ten parks with the most Clark et al. species present. Appalachian National Scenic Trail contained the most Clark et al. species with 132 of the 198 species present while 10 parks contained a single species with a critical load. Information for all parks is found in the full database (Clemens et al, 2022).

Table 3. Parks with the ten highest number of Clark et al. species present within VMI plots.

Park Name	Total VMI plots	Total Clark et al. plots	Total species	Plots with Clark et al. species	Number of Clark et al. species
Appalachian National Scenic Trail	1216	262	151	1478	151
Grand Teton National Park	837	0	34	837	34
Glacier National Park	648	0	44	648	44
Grand Canyon National Park	536	53	29	589	29
Great Smoky Mountains National Park	461	30	104	491	104
Bandelier National Monument	429	0	36	429	36
El Malpais National Monument	403	0	12	403	12
Shenandoah National Park	393	317	122	710	122
New River Gorge National Park and Preserve	318	152	119	470	119
Guadalupe Mountains National Park	307	0	14	307	14

Appalachian National Scenic Trail had the highest number of species with N response and S response relationships—127 CLN-HS species and 100 CLS-HS species (Table 4 and Table 5). Across all parks, the average number of species with a CLN-HS per park was 24 species and the average number of species with a CLS-HS was 20 species. Parks to the east of the Rocky Mountains had an average of 33 species with a CLN-HS and 27 species with a CLS-HS, while parks to the west of the Rocky Mountains had an average of 8 species with a CLN-HS and 7 species with a CLS-HS. These numbers are lower than from the species identified within the NPSpecies analysis where the average number of species with a CLN-HS and a CLS-HS were 34 and 30 for the entire dataset, 46 and 37 for eastern parks, and 14 and 12 for western parks (Russell et al. 2022).

Table 4. 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. All values are in kg-N ha^{-1} yr^{-1}. Data for all parks can be found in the full database (Clemens et al., 2022a).

Park Name	Number of species with a CLN-HS	Minimum CLN-HS	10th percentile CLN-HS	Median CLN-HS	Maximum CLN-HS
Appalachian National Scenic Trail	127	0.0	4.1	12.1	30.4
Shenandoah National Park	105	0.0	4.1	13.0	28.5
Saint Croix National Scenic Riverway	96	0.0	3.4	8.7	24.3
New River Gorge National Park and Preserve	95	0.0	4.1	13.0	33.2
Great Smoky Mountains National Park	89	0.0	4.1	11.8	23.3
Blue Ridge Parkway	86	1.6	7.1	12.4	26.7
Delaware Water Gap National Recreation Area	84	0.0	7.6	13.3	27.4
George Washington Memorial Parkway	81	0.0	8.6	16.0	32.0
Mammoth Cave National Park	76	0.0	10.2	13.4	28.1
Gauley River National Recreation Area	74	0.0	1.5	12.5	18.9

Table 5. The ten parks with the most species with a CLS-HS. Included are the minimum, 10th percentile, median, and maximum CLS-HS at each park. All values are in kg-S ha^{-1} yr^{-1}. Data for all parks can be found in the full database (Clemens et al., 2022a).

Park Name	Number of species with a CLS-HS	Minimum CLS-HS	10th percentile CLS-HS	Median CLS-HS	Maximum CLS-HS
Appalachian National Scenic Trail	100	0.0	0.4	0.4	42.5
Shenandoah National Park	80	0.0	0.4	0.4	42.5
New River Gorge National Park and Preserve	78	0.4	0.4	0.4	42.5
Saint Croix National Scenic Riverway	76	0.4	0.4	0.4	42.5
Great Smoky Mountains National Park	72	0.4	0.4	2.5	42.5
Blue Ridge Parkway	69	0.4	0.4	0.4	42.5
George Washington Memorial Parkway	65	0.0	0.4	0.4	42.5
Mammoth Cave National Park	64	0.4	0.4	2.5	42.5
Delaware Water Gap National Recreation Area	63	0.4	0.4	0.4	42.5
Gauley River National Recreation Area	62	0.4	0.4	2.2	42.5

Minimum CLN-HS or CLS-HS values indicate the species occurrence in each park with the lowest CLN-HS or CLS-HS. Minimum CLN-HS ranged from 0 kg-N ha^{-1} yr^{-1} to 18.9 kg-N ha^{-1} yr^{-1} and the average minimum CLN-HS across parks was 2.6 kg-N ha^{-1} yr^{-1}. Minimum CLN-HS values of 0 at a park represent the occurrence of species whose response to N is driven solely by S in a plot with high levels of S: any addition of N would lead to a decline in probability of occurrence for that species at that plot. Minimum CLS-HS ranged from 0 kg-S ha^{-1} yr^{-1} to 31.8 kg-S ha^{-1} yr^{-1} and the average minimum CLS-HS across parks was 0.9 kg-S ha^{-1} yr^{-1}. These values indicate that while minimum CLN-HS and CLS-HS had a wide range across species, most parks contain at least one sensitive species at risk of a negative response from low levels of N and S deposition.

10^{th} percentile CLN-HS and CLS-HS represent the value of deposition below which 90% of species at a park are protected from negative effects. 10^{th} percentile CLN-HS ranged from 0.0 kg-N ha^{-1} yr^{-1} to 14.2 kg-N ha^{-1} yr^{-1} and 10^{th} percentile CLS-HS ranged from 0.4 kg-S ha^{-1} yr^{-1} to 2.6 kg-S ha^{-1} yr^{-1}. 10^{th} percentile CLN-HS and CLS-HS have similar ranges across parks to the minimum CLN-HS and CLS-HS and were only calculated for plots with 10 or more species present.

Herbaceous Species Across Parks

Bouteloua gracilis was the most common species across plots, occurring in 2164 plots and 60 parks (Table 6). The least common species was *Sericocarpus tortifolius*, occurring in only 1 plot. *Poa pratensis* was the most common species with a CLN-HS, occurring in 2045 plots (Table 7). *Goodyera pubescens* had the most plots with N deposition in exceedance of its CLN-HS values with 599 of the 600 plots in exceedance. Thirteen species had N deposition in exceedance of their CLN-HS at over 90% of the plots in which they occur. On average, species experienced N deposition in exceedance of their CLN-HS in 22% of the plots in which they occur.

As species with CLS-HS all have increasing or decreasing responses to S deposition based on the response equations from Clark et al., CLS-HS values for a species are the same across plot occurrences regardless of environmental conditions (Table 8). *Poa pratensis* was also the most common species with a CLS-HS and had the highest number of plot occurrences where 2016–2018 S deposition was above its CLS-HS, with 1405 of its 2045 plot occurrences in exceedance. Thirty-two species had S deposition above their CLS-HS values in over 90% of the plots in which they occur.

Table 6. Overview of the ten most common species across VMI plots and parks.

Species	Number of Plots	Number of Parks	N Response Type	S Response Type
Bouteloua gracilis	2164	60	Saddle/decrease	Saddle/decrease
Poa pratensis	2045	101	Threshold	Decrease
Galium triflorum	1584	76	Threshold	Decrease
Bouteloua curtipendula	1509	59	Threshold	None
Schizachyrium scoparium	1429	100	Threshold	Decrease
Koeleria macrantha	1371	55	Threshold	Increase
Sporobolus cryptandrus	1310	61	Saddle/increase	Saddle/increase
Maianthemum canadense	1264	40	Threshold	Decrease
Fragaria virginiana	1245	69	Threshold	Saddle/increase
Pteridium aquilinum	1119	68	Threshold	Decrease

Table 7. Summary of top ten most common species with CLN-HS values across VMI plots. Included are the minimum and maximum CLN-HS of each species across parks and the number of plots where 2016–2018 N deposition was below, at, and above the CLN-HS of a species at each plot.

Species	N response type	Number of Plots	Minimum CLN-HS (kg-N ha^{-1} yr^{-1})	Maximum CLN-HS (kg-N ha^{-1} yr^{-1})	Below CLN-HS	At CLN-HS	Above CLN-HS
Poa pratensis	Threshold	2045	0.0	78.1	1913	0	114
Galium triflorum	Threshold	1584	0.0	15.7	1170	128	235
Bouteloua curtipendula	Threshold	1509	0.0	11.4	1338	31	103
Schizachyrium scoparium	Threshold	1429	0.0	14.2	1157	18	142
Koeleria macrantha	Threshold	1371	0.0	12.0	1309	4	43
Maianthemum canadense	Threshold	1264	0.0	18.9	888	79	95
Fragaria virginiana	Threshold	1245	6.9	6.9	1004	23	157
Pteridium aquilinum	Threshold	1119	0.0	22.7	870	81	73
Carex pensylvanica	Threshold	1061	0.0	17.6	874	40	121
Athyrium filix-femina	Threshold	971	0.0	17.3	856	9	70

Table 8. Summary of top ten most common species with CLS-HS values across VMI plots. Included are the CLS-HS of each species across parks and the number of plots where 2016–2018 total S deposition was below, at, and above the CLS-HS of a species at each plot.

Species	S response type	Number of Plots	CLS-HS (kg-S ha^{-1} yr^{-1})	Below CLS-HS	At CLS-HS	Above CLS-HS
Poa pratensis	Decrease	2045	0.4	0	622	1405
Galium triflorum	Decrease	1584	0.4	0	82	1451
Schizachyrium scoparium	Decrease	1429	0.4	0	353	964
Koeleria macrantha	Increase	1371	17.1	1356	0	0
Maianthemum canadense	Decrease	1264	0.4	0	0	1062
Pteridium aquilinum	Decrease	1119	0.4	0	103	921
Carex pensylvanica	Decrease	1061	0.4	0	0	1035
Athyrium filix-femina	Decrease	971	0.4	0	21	914
Asplenium platyneuron	Decrease	968	0.4	0	0	962
Polygonatum biflorum	Decrease	966	0.4	0	0	961

Case Study Parks

Nine case study parks (Acadia National Park, Glacier National Park, Grand Teton National Park, Great Smoky Mountains National Park, Joshua Tree National Park, Rocky Mountain National Park, Sleeping Bear Dunes National Lakeshore, Theodore Roosevelt National Park, and Yosemite National Park) were selected to evaluate regional differences in CLN-HS and CLS-HS exceedances within plots and to assess the spatial distribution of species at risk to negative impacts from N and S deposition (Table 9). Data presented for the case study parks is available for all parks in Clemens et al. (2022a). Midwestern and Eastern parks had over 10% of their flora represented by the species in the analysis, while parks west of the Rocky Mountains all had under 10% of their flora represented. To highlight the lack of desert species in the analysis, only five of the 296 plots within Joshua Tree National Park contained at least one Clark et al. species.

Table 9. Summary of plots and species at each case study national park. Included are the number of VMI plots at each national park that contain at least one Clark et al. species, the number of Clark et al. species present in each national park, and the total number of VMI plots and species in each national park.

Park Name	Total VMI Plots	Total Clark et al. Plots	Total Species	Plots with Clark et al. Species	Number of Clark et al. species
Grand Teton National Park	837	0	837	1421	34
Glacier National Park	648	0	648	752	44
Great Smoky Mountains National Park	461	30	491	795	104
Rocky Mountain National Park	220	0	220	514	36
Acadia National Park	142	0	142	159	32
Theodore Roosevelt National Park	135	0	135	144	35
Sleeping Bear Dunes National Lakeshore	93	2	95	117	72
Yosemite National Park	83	0	83	237	15
Joshua Tree National Park	5	0	5	289	2

CLN-HS Exceedances

Table 10 shows the number of plots within each case-study park with at least one species with a CLN-HS, the number of species with at least one site in exceedance, and the number of plots in each exceedance category based on the minimum CLN-HS and 2016–2018 N deposition for each plot. Great Smoky Mountains National Park had the highest number of species whose CLN-HS were exceeded by current deposition, with 89 species across the park experiencing at least one CLN-HS exceedance (See Appendix A, Figure A8). Great Smoky Mountains National Park also had 265 plots where the minimum CLN-HS of all species at each plot was exceeded by N deposition, the most across the case study parks (See Appendix A, Figure A8). Only two species from the Clark et al. analysis were present within Joshua Tree National Park, none of which had any plot occurrences where N deposition exceeded their CLN-HS (See Appendix A, Figure A14).

Parks with a large number of plots with minimum CLN-HS exceedances but low numbers of unique species in exceedance indicate the widespread presence of species that are sensitive to N deposition. For example, only nine of the 36 herbaceous species present in plots within Glacier National Park have CLN-HS exceedances while 162 plots have minimum CLN-HS exceedances. This indicates that a small number of species set the minimum CLN-HS in plots across the park.

Table 10. Number of plots in each case study park that contain at least one species with a CLN-HS, the minimum CLN-HS across all plots within each park, the number of unique species whose CLN-HS were exceeded at least once in each park, and the number of plots in each exceedance category relative to the minimum CLN-HS in a plot. NPSpecies Exceedances compares results to Russell et al. (2022).

Park Name	Plots containing a species with a CLN-HS	Minimum CLN-HS (kg-N ha^{-1} yr^{-1})	Unique Species with CLN-HS exceedance	NPSpecies with CLN-HS exceedance	Plots below min CLN-HS	Plots at min CLN-HS	Plots above min CLN-HS
Grand Teton National Park	830	0.0	17	11	717	19	94
Glacier National Park	643	0.0	9	12	409	72	162
Great Smoky Mountains National Park	490	0.0	21	23	215	10	265
Rocky Mountain National Park	202	0.0	11	9	165	3	34
Acadia National Park	140	0.0	9	7	63	55	22
Theodore Roosevelt National Park	127	3.8	2	3	114	11	2
Sleeping Bear Dunes National Lakeshore	90	0.0	23	29	22	38	30
Yosemite National Park	81	2.3	1	2	76	0	5
Joshua Tree National Park	5	10.9	0	0	5	0	0

To assess the spatial distribution of CLN-HS exceedances within parks a series of maps were created for each case study park. These maps show the distribution of species with CLN-HS across plots, the minimum CLN-HS within each plot, the number of CLN-HS exceedances per plot, and whether the minimum CLN-HS is exceeded by modeled 2016–2018 N deposition at each plot. Figure 6 and Figure 7 provide an example of these maps for Glacier National Park. The maps for the other case study parks can be found in Appendix A.

The map on the left in Figure 6 shows the number of species at each plot within Glacier National Park that have a CLN-HS. Generally, plots on the eastern side of the park have more species with CLN-HS. The map on the right shows the minimum CLN-HS at each plot in Glacier National Park. Plots in the central and western portion of the park have the lowest minimum CLN-HS. This

indicates the presence of one or more species in these areas that are sensitive to low levels of N deposition.

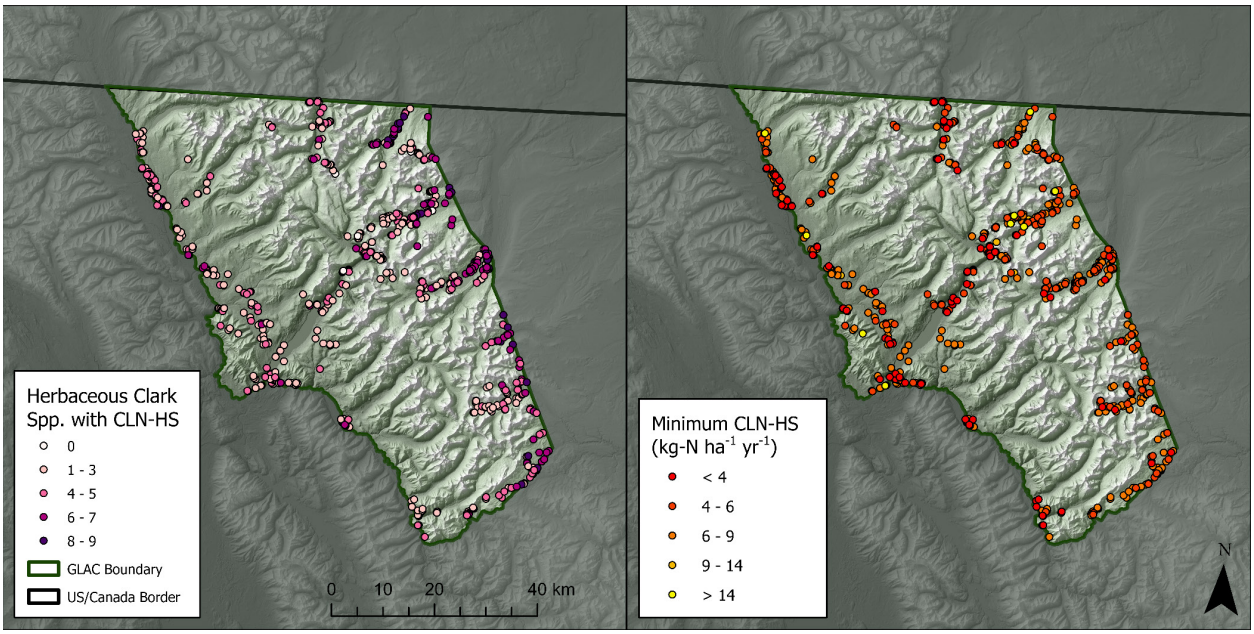


Figure 6. Number of species (spp.) at each vegetation plot with a CLN-HS at Glacier National Park (left) and the minimum CLN-HS at each plot (right).

The map on the left in Figure 7 shows the number of species whose CLN-HS were exceeded by 2016–2018 N deposition at each of the 643 plots in Glacier National Park. Four-hundred and seventy-two plots did not have any species in exceedance and 147 plots had just one species in exceedance. Plots in the central and southwestern parts of the park had the most species in exceedance.

The map on the right in Figure 7 compares 2016–2018 TDep total N deposition to the minimum CLN-HS in each plot. One-hundred and sixty-two plots across the park had N deposition in exceedance of the minimum CLN-HS by at least 0.5 kg-N ha^{-1} yr^{-1} at each plot and 72 plots had N deposition at (within ±0.5 kg-N ha^{-1} yr^{-1} of) the minimum CLN-HS at the plot. Although the lowest CLN-HS values were in the western and central regions of the park (Figure 6), exceedances of the minimum CLN-HS were common in eastern plots as well as in central and western plots. Plots that experienced N deposition at the same level as the CLN-HS (within 0.5 kg-N ha^{-1} yr^{-1}) indicate plots where herbs may be at risk for negative impacts if deposition were to increase in the area.

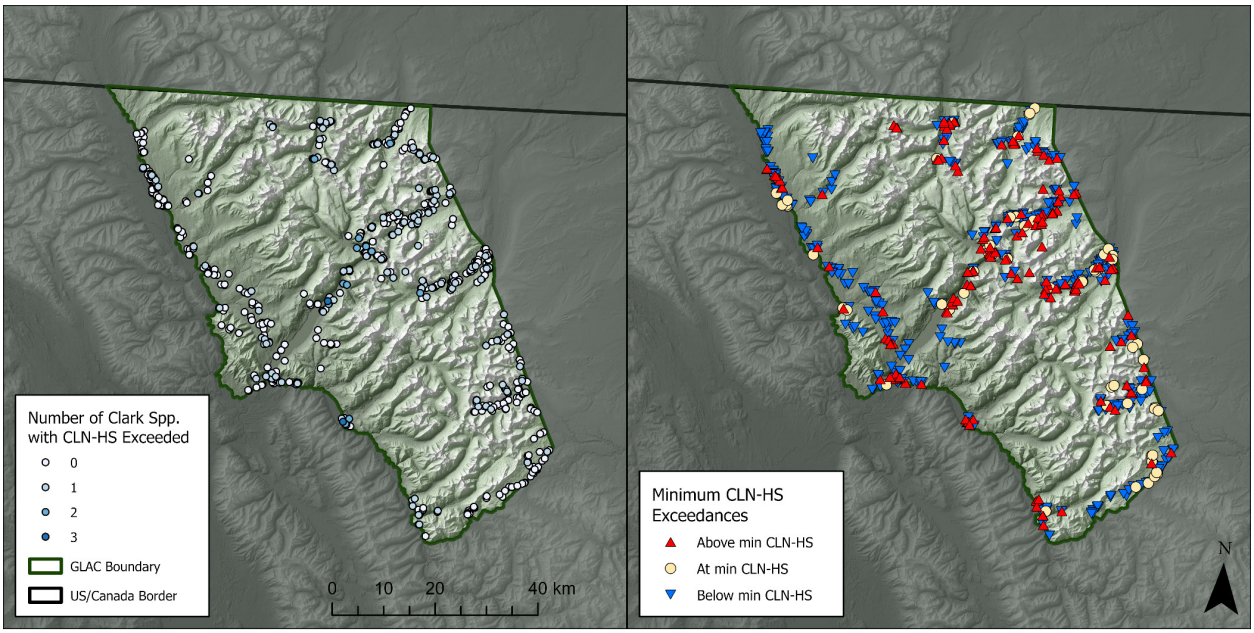


Figure 7. Number of species at each vegetation plot with 2016–2018 N deposition in exceedance of their CLN-HS at Glacier National Park (left) and plots with 2016–2018 N deposition above, at, and below the minimum CLN-HS at each plot (right).

CLS-HS Exceedances

Species' CLS-HS were compared to 2016–2018 TDep total S deposition at each plot to assess S critical load exceedances within parks. Table 11 summarizes the number of plots in each case study park that contain at least one species with a CLS-HS, the number of species with at least one CLS-HS exceedance, and the number of plots that experienced S deposition in exceedance of the minimum CLS-HS at each plot. Of the case study parks, Grand Teton National Park had the most plots where the minimum CLS-HS was exceeded by S deposition (range of deposition in plots, 0.8 to 2.3 kg-S ha^{-1} yr^{-1}), with 712 of the 754 plots in exceedance. Great Smoky Mountains National Park, where deposition in plots ranged from 1.7 kg-S ha^{-1} yr^{-1} to 2.5 kg-S ha^{-1} yr^{-1}, had the highest number of individual species whose CLS-HS were exceeded by S deposition with 32 species in exceedance. Plots in these parks contain species that have low CLS-HS and are sensitive to low levels of S deposition.

Compared to the evaluation of CLN-HS in the case study parks, S deposition causes more exceedances in terms of plots or species per park. This indicates that all case study parks contain multiple species that are sensitive to S deposition and reflects that CLS-HS are set at the lowest experienced levels of deposition for decreaser species.

Table 11. Number of plots in each case study park that contain at least one species with a CLS-HS, the minimum CLS-HS across all plots within each park, the number of unique species whose CLS-HS were exceeded at least once in each park, and the number of plots in each exceedance category relative to the minimum CLS-HS in a plot. NPSpecies Exceedances compares results to Russell et al. (2022).

Park Name	Plots containing a species with a CLS-HS	Minimum CLS-HS (kg-S ha^{-1} yr^{-1})	Unique species with CLS-HS exceedance	NPSpecies with CLN-HS exceedance	Plots below min CLS-HS	Plots at min CLS-HS	Plots above min CLS-HS
Grand Teton National Park	754	0.4	17	22	36	6	712
Glacier National Park	588	0.4	18	19	59	198	331
Great Smoky Mountains National Park	465	0.4	32	42	77	101	287
Rocky Mountain National Park	175	0.4	13	23	14	99	62
Acadia National Park	132	0.4	10	35	0	54	78
Theodore Roosevelt National Park	127	0.4	15	20	12	9	106
Sleeping Bear Dunes National Lakeshore	88	0.4	25	54	8	32	48
Yosemite National Park	78	0.4	9	13	6	5	67
Joshua Tree National Park	2	5.4	0	0	2	0	0

Figure 8 shows the number of species with a CLS-HS per plot (left) and the minimum CLS-HS value (right) at each plot in Great Smoky Mountains National Park. Plots in the north-central and western portion of the park contain the most species with CLS-HS. The majority of plots in Great Smoky Mountains National Park had minimum CLS-HS values below 0.43 kg-S ha^{-1} yr^{-1} which highlights the presence of at least one species with a decreasing response to S deposition in each plot.

Figure 9 shows the number of species at each plot whose CLS-HS were exceeded by 2016–2018 total S deposition (left) and the category of exceedance (above, at, below) for each plot based on the minimum CLS-HS (right) in Great Smoky Mountains National Park. Plots with the highest number of species in exceedance were located in the north-central and western portions of the park. Of the

465 plots with a CLS-HS in Great Smoky Mountains National Park, 287 were in exceedance of the minimum CLS-HS.

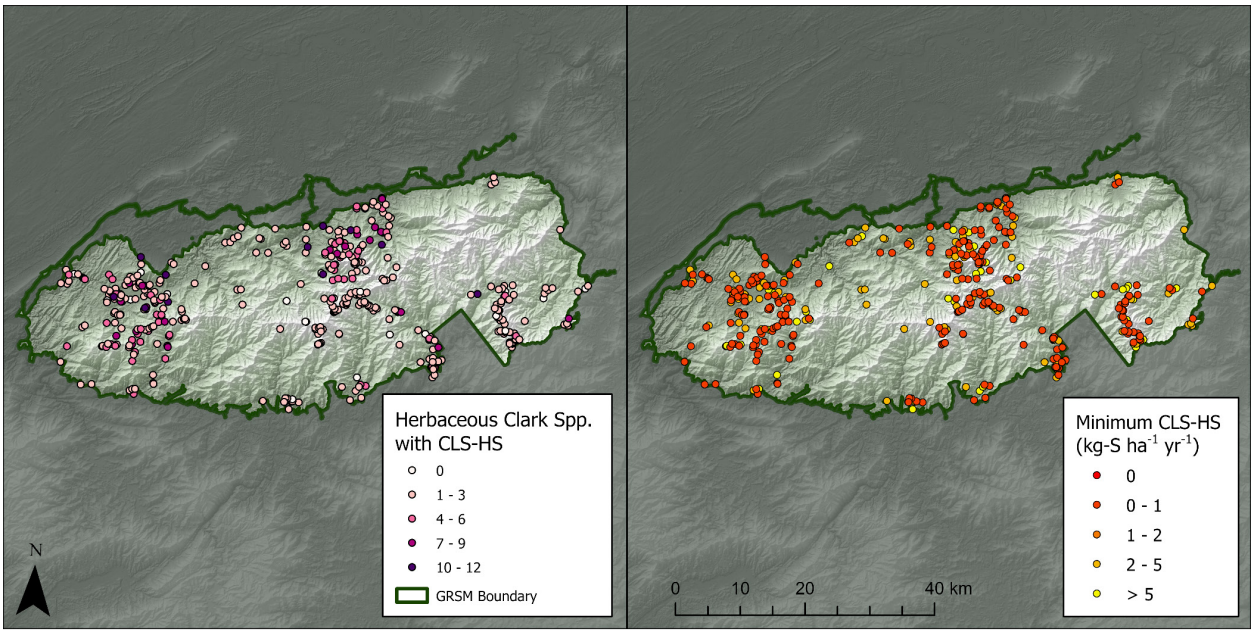


Figure 8. Number of species at each vegetation plot with a CLS-HS at Great Smoky Mountains National Park (left) and the minimum CLS-HS at each plot (right).

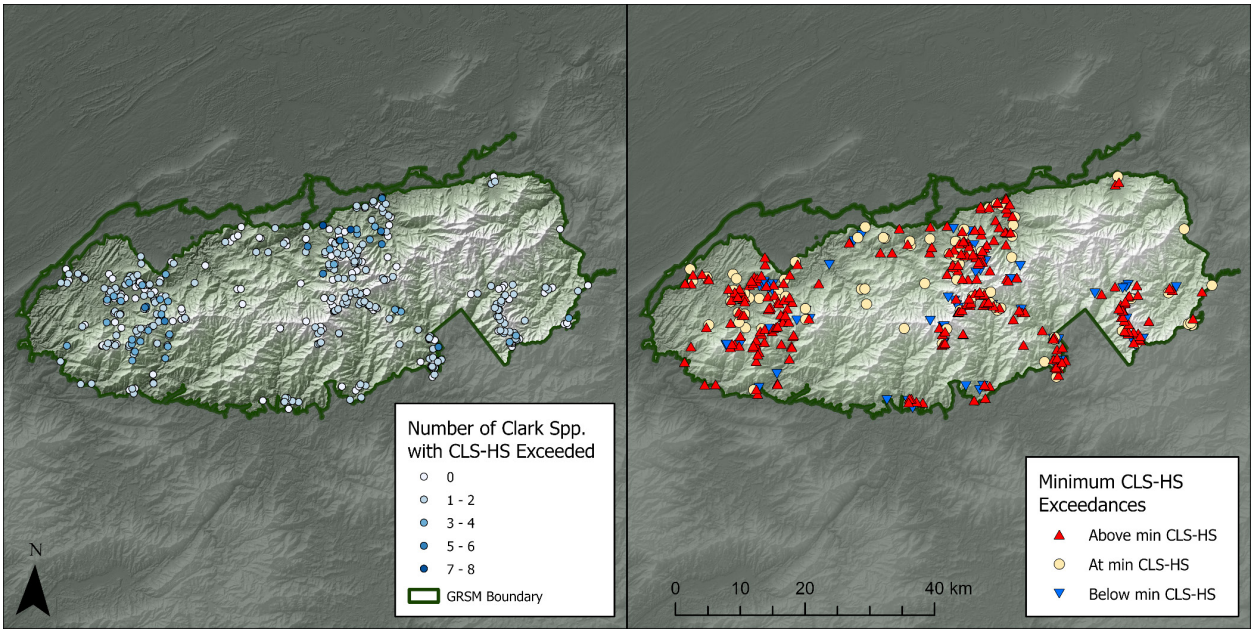


Figure 9. Number of species at each vegetation plot with 2016–2018 S deposition in exceedance of their CLS-HS at Great Smoky Mountains National Park (left) and plots with 2016–2018 S deposition above, at, and below the minimum CLS-HS at each plot (right).

Discussion

This study applied critical loads of nitrogen (N) and critical loads of sulfur (S) for a decline in probability of occurrence for individual species (CLN-HS, CLS-HS) at vegetation plots surveyed for the NPS Vegetation Mapping Inventory and plots from the original study (Clark et al., 2019). Site-specific critical loads were compared to TDep modeled total N and total S deposition from 2016–2018 to identify plots and species at risk of harm due to air pollution (NADP 2018).

The key outcomes of this analysis are site specific responses for 197 species in 209 parks from 18,658 plots that are summarized within a data table for quick access to park level summaries. Below we discuss the value of site-specific data over using average species response values, how exceedances of critical loads vary regionally, and how to use the database to interpret information for a park or region of interest.

Distribution of VMI Plots

Parks to the east of the Rocky Mountains had an average of 33 species with a CLN-HS and 27 species with a CLS-HS while parks to the west of the Rocky Mountains had an average of 8 species with a CLN-HS and 7 species with a CLS-HS. This was highlighted by the total number of Clark et al. (2019) species (Table 3), total species with a CLN-HS (Table 4), and the total species with a CLS-HS (Table 5) all occurring in parks east of the Rocky Mountains.

In terms of herbaceous species occurrence within the continental United States, the VMI dataset adds a significant number of plots and species locations to the southwest and mountainous west (Figure 1). The southwest sites are likely to have higher uncertainty, and fewer species represented from their flora, in applying current herbaceous CLs due to higher temperature and lower precipitation in the Southwest compared to the plots that were used to build the herbaceous CL models. New western mountain sites in California, Colorado, and Wyoming are all south of the western mountain areas included in the Clark et al. (2019) dataset. While these sites have conditions in common, elevation effects on temperature, precipitation, and plant communities vary with latitude.

The distribution of Clark et al. plots influences which species within western parks have been analyzed for CLN-HS and CLS-HS. These areas are biologically diverse and are likely to have additional herbaceous species that respond to nitrogen (Baez et al., 2007; Rao et al., 2010). The lack of plots from the original dataset in the southwest limits the ability to compare CLs with previous studies showing desert grass and herbaceous response to N deposition (Rao et al. 2010). The NPS VMI survey plots can be used to expand the number of species that meet minimum model requirements and thus provide an opportunity for future model analyses.

Value of Site-Specific Data in Critical Load Development and Evaluation

A previous analysis applied published CLN-HS and CLS-HS to parks based on herbaceous species lists from NPSpecies (Russell et al., 2022). Published herbaceous species critical loads based on average environmental conditions give a comparable picture of species response and risk across parks. However, that application did not include smaller-scale variation in species distribution or microclimate, creating uncertainty in species locations, critical load values, and exceedance

calculations. Site-specific critical loads calculated for threshold herbaceous species in plots incorporate local climate and soil conditions that may make a park herbaceous population more sensitive to deposition. Conversely, local soil pH, temperature, or precipitation regimes may buffer and protect herbaceous species against deposition effects. Regardless of whether the critical loads for herbaceous species incorporate environmental data, the exceedances applied within this project can be considered site-specific, as CLs are compared to the deposition estimate for the TDep grid cell estimate for the plot, rather than to the park minimum or maximum TDep value as in Russell et al. (2022). This spatial granularity should better reflect the species response to N or S deposition given the plot-specific environmental conditions.

The level of detail in this analysis will allow some consideration of how changes in environmental conditions within parks (e.g., increases in temperature or decreases in precipitation due to climate change) impact species responses to deposition. Additional environmental cofactors not considered in this analysis, like elevation, could be included in models of herbaceous occurrence to further capture how changes in environmental conditions influence species' response to N and S deposition (e.g., disruption of existing elevation vegetation zones due to changing precipitation and temperature regimes).

In most cases, the analysis of species from the NPSpecies database by Russell et al. (2022) showed more species in exceedance than the analysis of the VMI plots (Table 10 and Table 11). This is expected due to plots not necessarily capturing the entire park flora and all species being compared to the highest level of deposition in the NPSpecies analysis versus that which occurs at a plot.

VMI plots are designed to document specific plant species within each vegetation alliance as defined by the US National Vegetation Classification (USNVC, 2021). Each plot intends to capture the characteristic species at a site and thus those where a change would impact plant communities. The previous park-wide critical load comparison used the NPSpecies database rather than VMI plots to identify herbaceous species within a park. NPSpecies reports species presence from a multitude of surveys and other species lists, and often serves as a flora, documenting all of the plant species present in a park regardless of their abundance. The VMI dataset can give a quick assessment of where risk (low CLs) and deposition overlap but considering the species that occur in the park based on NPSpecies without appearing in the VMI plots could yield information about how locally rare species in a park might respond to N or S deposition.

Exceedances in this analysis are calculated based on the species present within a plot and the deposition rate that TDep predicts for the grid cell in which the plot resides. The previous park-wide critical load comparison used the maximum deposition that TDep predicts within park boundaries to calculate exceedances. As a result, most parks had more species in exceedance of their CLN-HS in the NPSpecies analysis than in this analysis based on VMI plots, except for YOSE, which had three species in exceedance in both analyses (Table 10). In comparing exceedances of CLS-HS, most parks had more species exceedance based on the park-wide NPSpecies dataset rather than the VMI plots; YOSE was again the exception, with one more species in exceedance based on VMI than on NPSpecies (Table 11).

Summarizing the critical loads at the plot level by the minimum CLN-HS showed about 45% of the plots per park had at least one species above the CL based on 2016–2018 TDep total N deposition. Although N deposition is higher than S deposition on a kilogram-by-kilogram basis at most continental US sites, there were more species in exceedance of the CLS-HS than CLN-HS. From the case-study parks, 68% of the plots classified as above the minimum CLS-HS, with THRO and GRTE having 84% and 95% of their plots in exceedance, respectively.

Updating critical load models

The herbaceous species data from the NPS VMI plots could be incorporated in a future update of the models used to establish the CLN-HS and CLS-HS. This would extend the occurrence count of some species into new regions not sampled by the original Simkin et al paper. The environmental parameters of the new sites are mostly within the bounds previously identified for pH, precipitation, temperature, and deposition, but often exist in gaps in the previous data which more evenly distributes occurrence data across environmental niches and could strengthen or change the currently defined relationships between deposition and species response. Additionally, VMI only represents one of many datasets available from the NPS. The application of these CLs can be expanded where other NPS datasets are available, such as network surveys to monitor particular herbaceous species, or by crosswalking between VMI plot occurrences and vegetation classes within parks.

Potential models for critical loads of sulfur deposition were only evaluated for a negative or decreasing relationship with herbaceous species occurrence. This was consistent with previous research conducted in natural systems which found strong negative effects of decades of high S deposition. Some recent work has found more complex relationships between sulfur deposition and plant growth (Fenn et al., 2020). Given this research, current low rates of S deposition, and the established science that S deposition causes acidification only under particular soil conditions, future analyses could consider analyzing S deposition in a threshold relationship to herbaceous species occurrence.

Recommendations for using these datasets

Along with establishing local responses to deposition, park and resource managers can use site-specific critical loads to develop targeted management plans for species or areas at risk. This analysis produced two separate databases that can be used to see the data for a specific NPS unit. Using these datasets, park managers can identify plots containing sensitive species in exceedance of their critical loads to locate areas in the greatest need of monitoring or intervention. Additionally, species- and plot-specific critical loads allow managers to directly assess the risk of decline for important species, such as locally rare or culturally important species. The underlying species abundance data and information requirements in the models that determined the critical loads may not include endemic or extremely sensitive herbaceous species that occur within a park. A species' exclusion from the critical loads indicates unknown sensitivity to deposition within the terms of this analysis, not a species tolerant of N or S deposition.

These data will be utilized within the NPS Air Resources Division Conditions and Trends page soon (https://www.nps.gov/subjects/air/park-conditions-trends.htm).

Excel Database

The first data product is a Microsoft Excel file that includes copies of each of the tables from this report expanded to all 209 parks in the analysis (Clemens et al. 2022a). It also includes the core dataset that includes the species occurrences within each plot labeled by the park that it falls within. This data is also summarized by park creating a species list for each unit with the range of critical loads and exceedances within the boundaries. The critical loads within the dataset are compared against 2016–2018 TDep total N or total S deposition but can be compared to newer deposition data using the geodatabase below to assess how risk of species harm changes through time or compare to historic deposition estimates to assess recovery.

The 'Plot x Species' sheet provides the list of species found at each plot, the shape of the response to deposition, the critical load calculated from the local environmental conditions, and the level of exceedance based on 2016–2018 TDep total N or total S. It also includes columns for whether the points were included in the east/west calculations from this report and whether the plot is from the VMI dataset or the Clark et al. dataset.

The 'Park x Species' sheet provides a list of species that occur within a park and the CL data for those specific sites. This is useful for a park when you have a target species that acts as habitat, forage, or a species you're interested in controlling. The columns in this dataset are the number of plot occurrences, the range of critical loads calculated within a park, and the number of sites where a species is in exceedance based on 2016–2018 TDep total N or total S deposition.

This dataset is useful to provide a quick summary of known species that respond to N and S deposition and understand if they are at risk of increasing or decreasing based on current conditions. It can also be used to assess which species are on a park's list of species but are not contained in the VMI plots.

Geospatial datasets

The second data product are two geospatial shapefiles; one of all point locations and the species within them, and the second a summary of species within the plot with summary statistics of the critical loads (Clemens et al. 2022b).

The Plot x Species shapefile includes all species present at each location along with the relevant critical load data. This dataset can be used to extract updated deposition data to calculate current exceedances of each species as well as to extract data and map

The Plot Summary shapefile includes the environmental data extracted from each of the base data layers as well as the minimum, 10^{th} percentile, median, and maximum of the critical load information for the species found at each plot location. This dataset can be used with current deposition data to show the risk to the overall plant community at each location.

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Appendix A: Case Study Park Maps

Case study park maps similar to Figure 6, Figure 7, Figure 8, and Figure 9 in the main text.

Acadia National Park

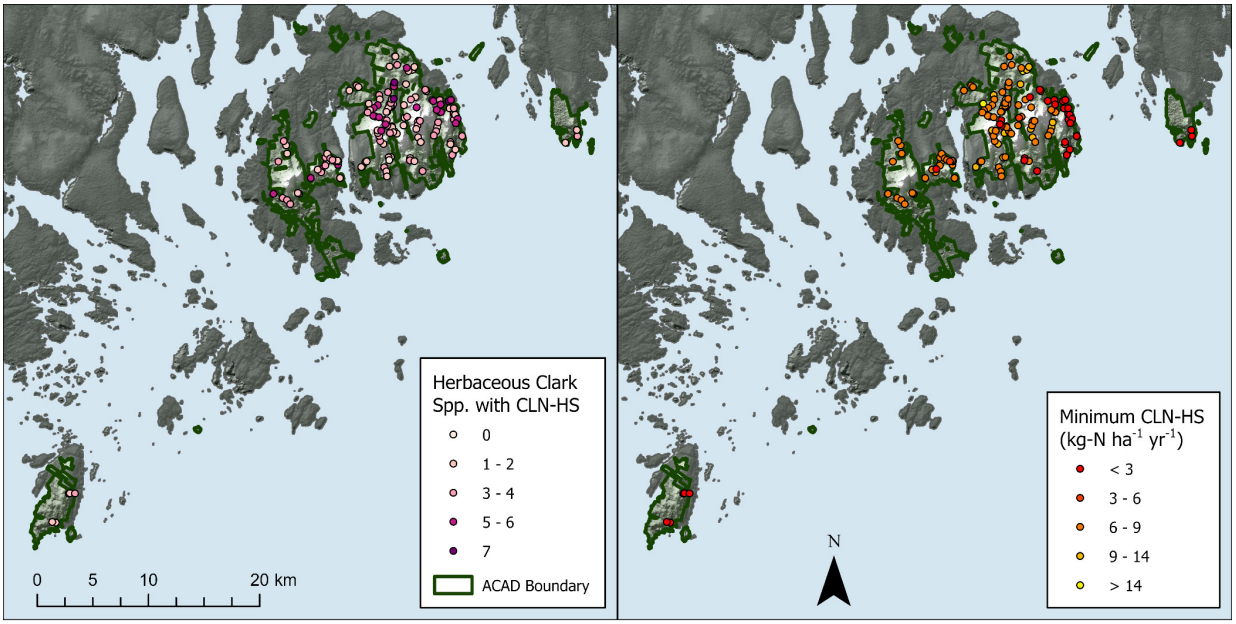


Figure A1. Number of species at each vegetation plot with a CLN-HS at Acadia National Park (left) and the minimum CLN-HS at each plot (right).

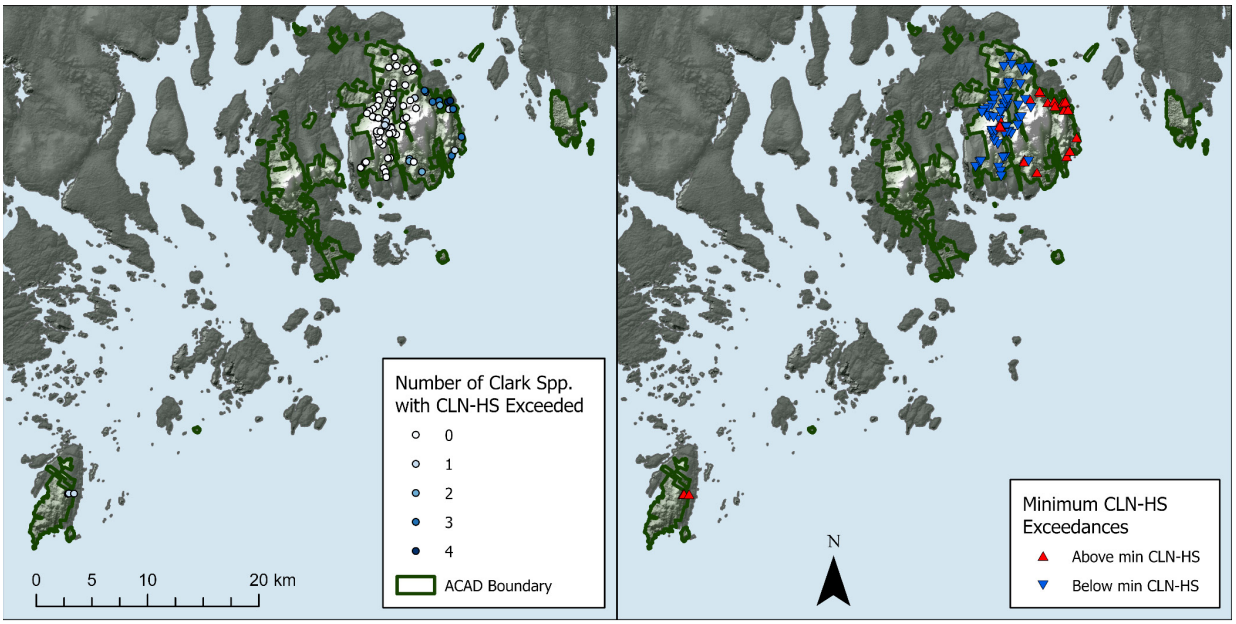


Figure A2. Number of species at each vegetation plot with 2016–2018 N deposition in exceedance of their CLN-HS at Acadia National Park (left) and plots with 2016–2018 N deposition above, at, and below the minimum CLN-HS at each plot (right).

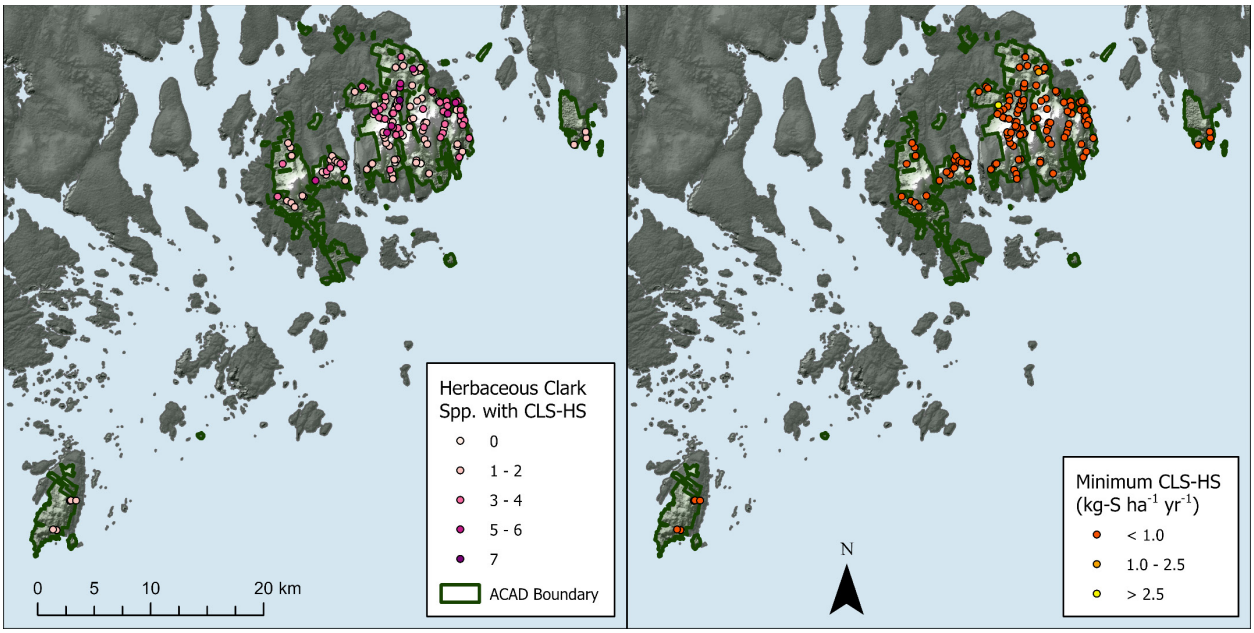


Figure A3. Number of species at each vegetation plot with a CLS-HS at Acadia National Park (left) and the minimum CLS-HS at each plot (right).

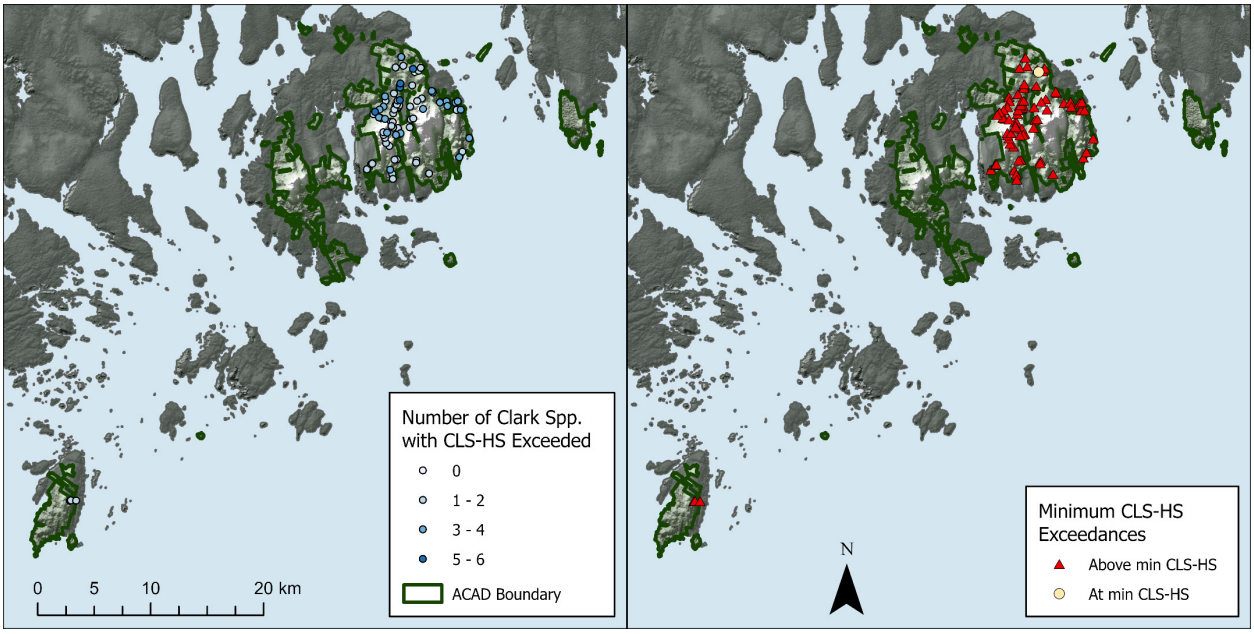


Figure A4. Number of species at each vegetation plot with 2016–2018 S deposition in exceedance of their CLS-HS at Acadia National Park (left) and plots with 2016–2018 S deposition above, at, and below the minimum CLS-HS at each plot (right).

Glacier National Park

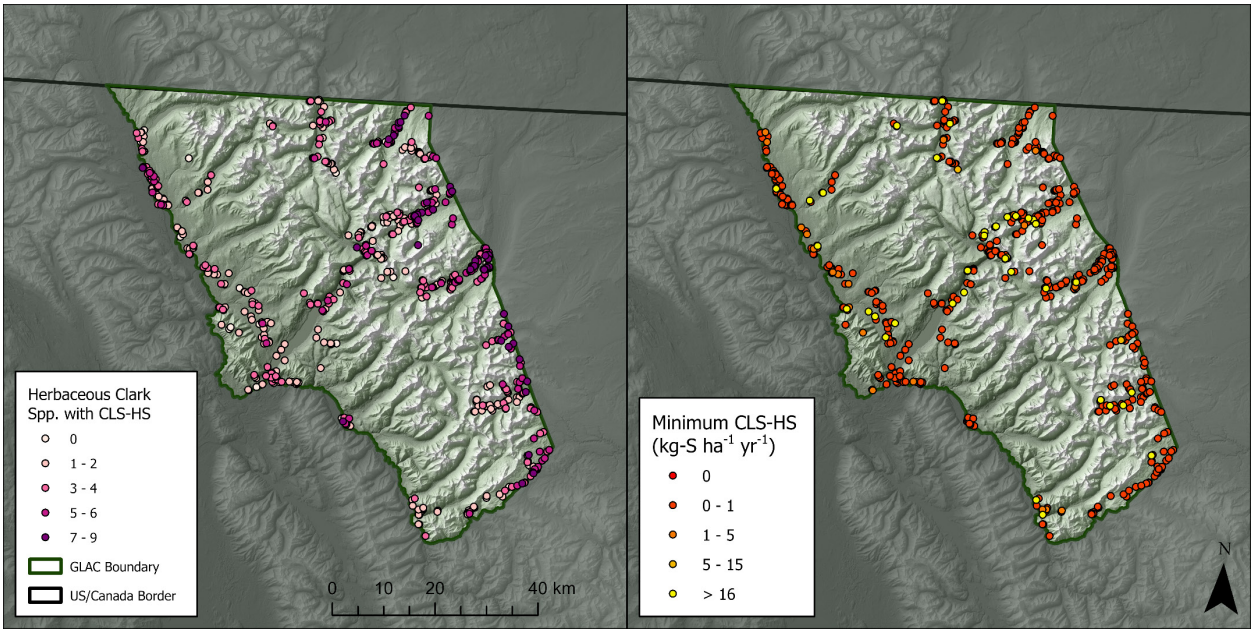


Figure A5. Number of species at each vegetation plot with a CLS-HS at Glacier National Park (left) and the minimum CLS-HS at each plot (right).

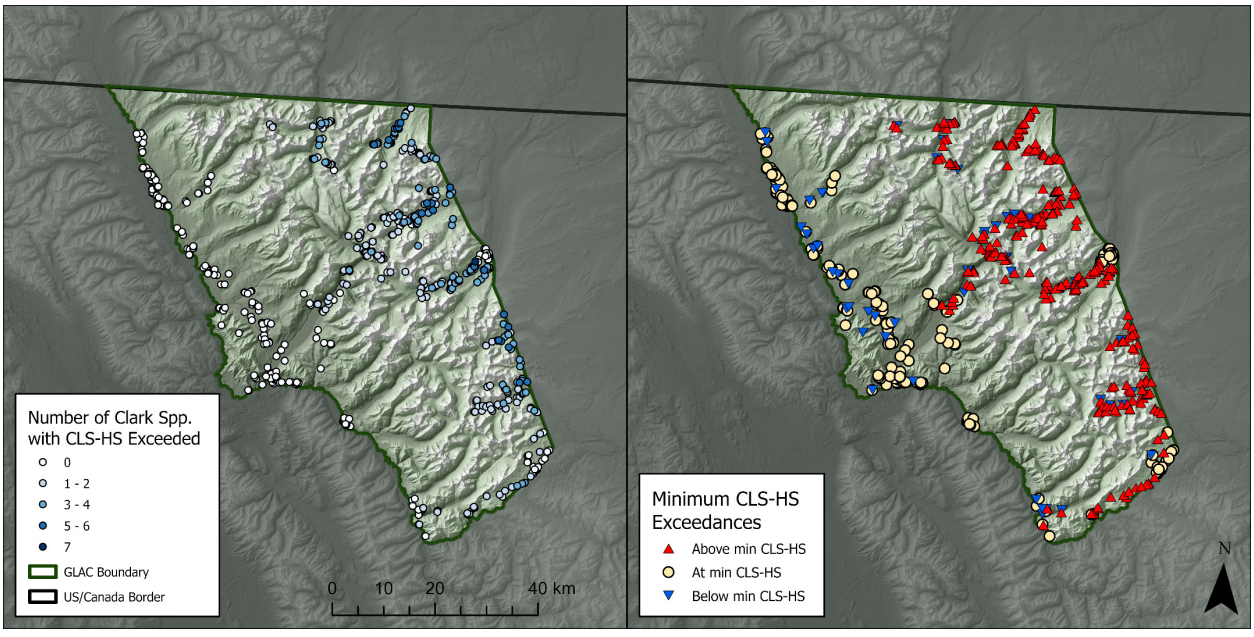


Figure A6. Number of species at each vegetation plot with 2016–2018 S deposition in exceedance of their CLS-HS at Glacier National Park (left) and plots with 2016–2018 S deposition above, at, and below the minimum CLS-HS at each plot (right).

Great Smoky Mountains National Park

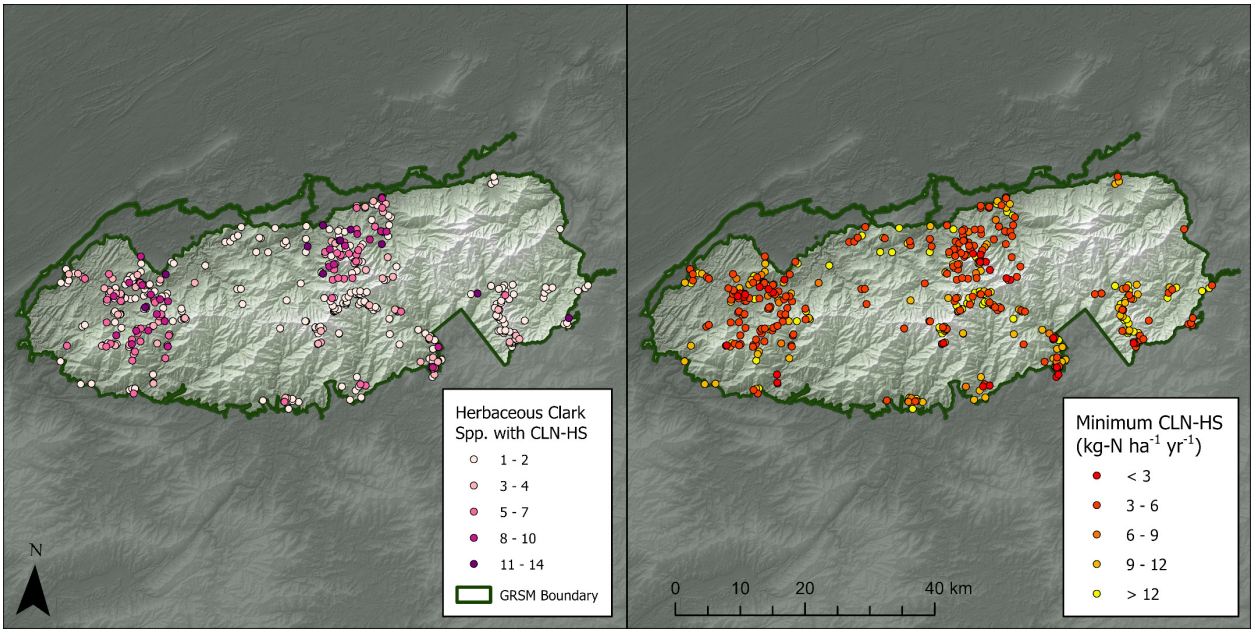


Figure A7. Number of species at each vegetation plot with a CLN-HS at Great Smoky Mountains National Park (left) and the minimum CLN-HS at each plot (right).

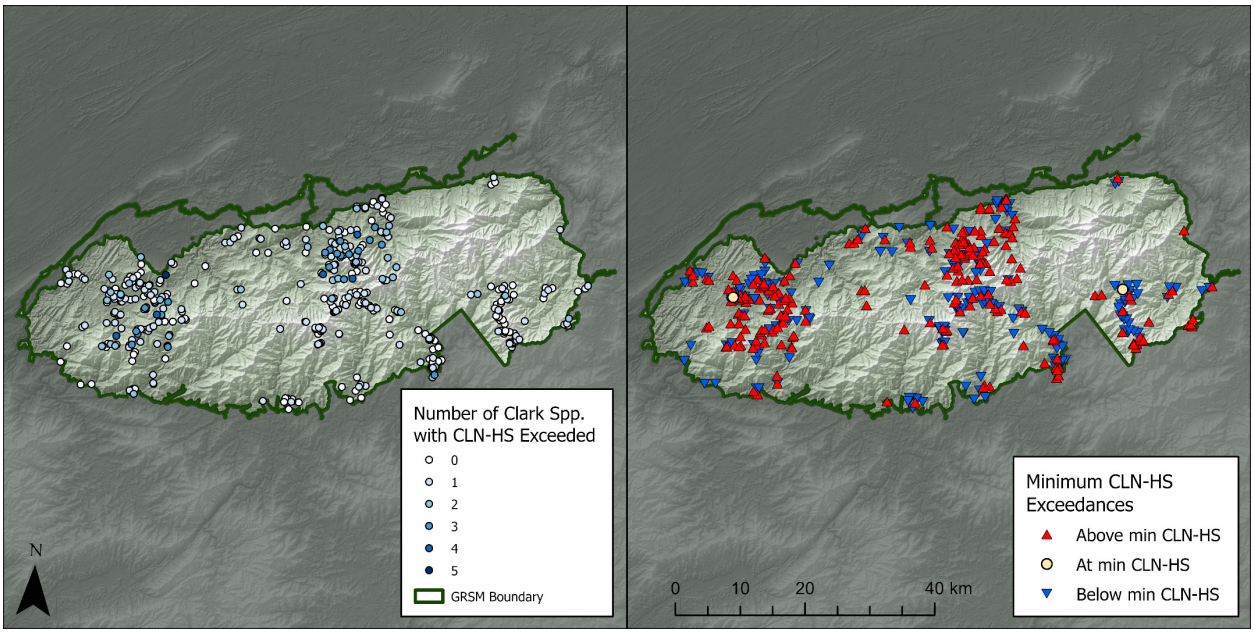


Figure A8. Number of species at each vegetation plot with 2016–2018 N deposition in exceedance of their CLN-HS at Great Smoky Mountains National Park (left) and plots with 2016–2018 N deposition above, at, and below the minimum CLN-HS at each plot (right).

Grand Teton National Park

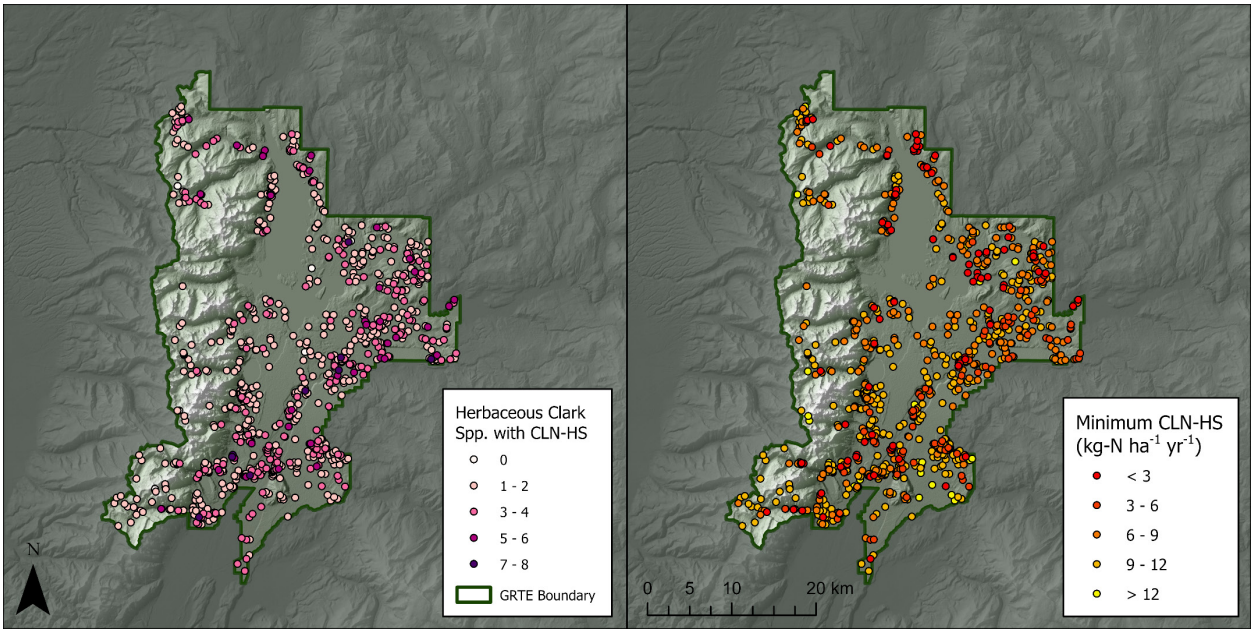


Figure A9. Number of species at each vegetation plot with a CLN-HS at Grand Teton National Park (left) and the minimum CLN-HS at each plot (right).

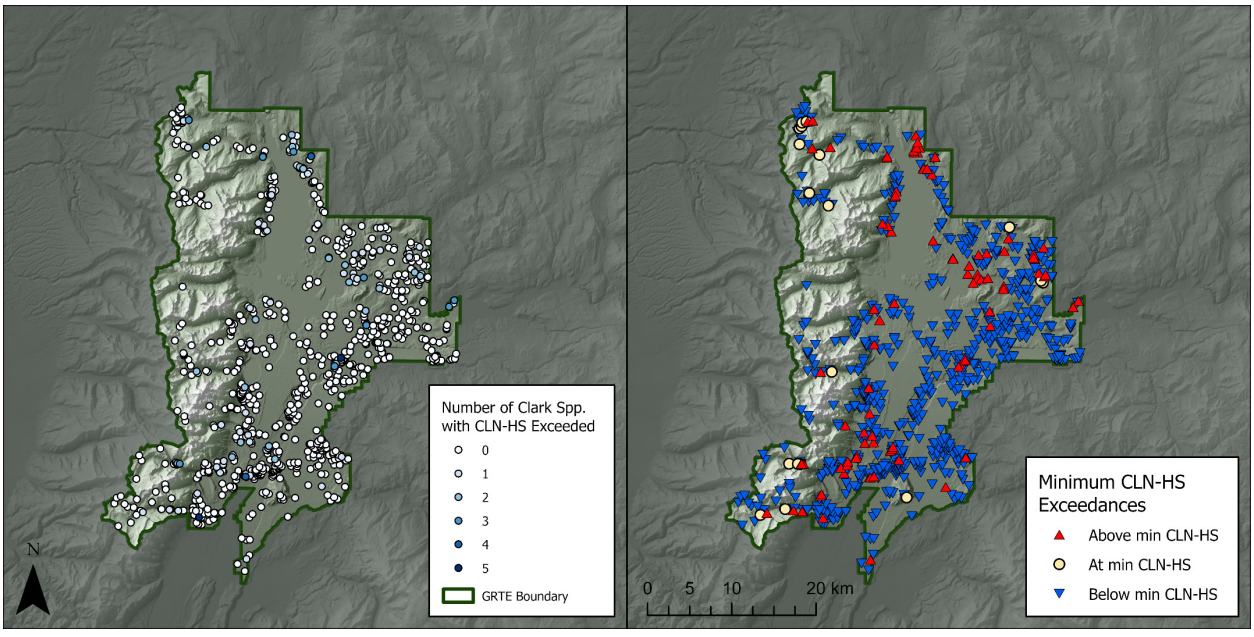


Figure A10. Number of species at each vegetation plot with 2016–2018 N deposition in exceedance of their CLN-HS at Grand Teton National Park (left) and plots with 2016–2018 N deposition above, at, and below the minimum CLN-HS at each plot (right).

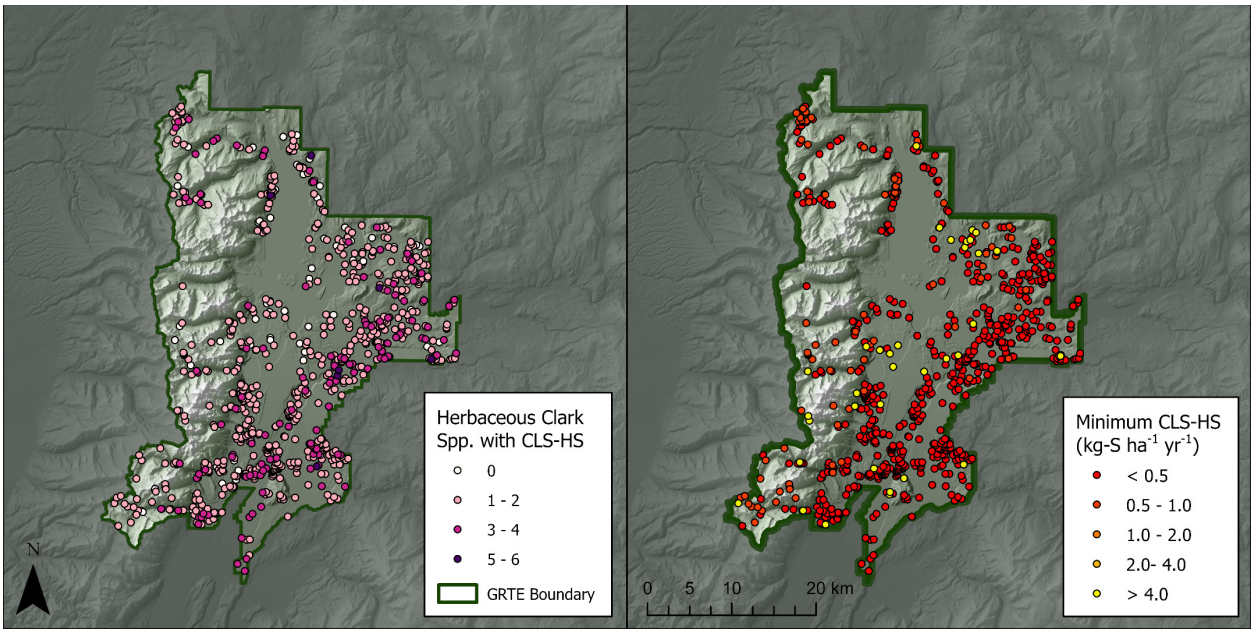


Figure A11. Number of species at each vegetation plot with a CLS-HS at Grand Teton National Park (left) and the minimum CLS-HS at each plot (right).

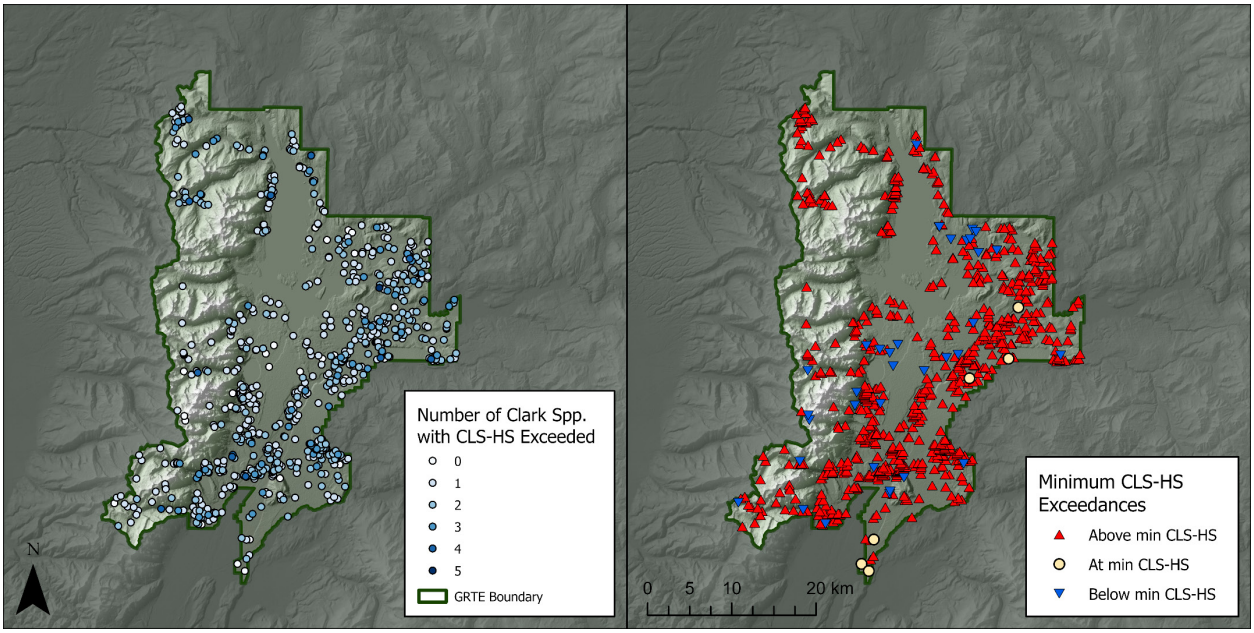


Figure A12. Number of species at each vegetation plot with 2016–2018 S deposition in exceedance of their CLS-HS at Grand Teton National Park (left) and plots with 2016–2018 S deposition above, at, and below the minimum CLS-HS at each plot (right).

Joshua Tree National Park

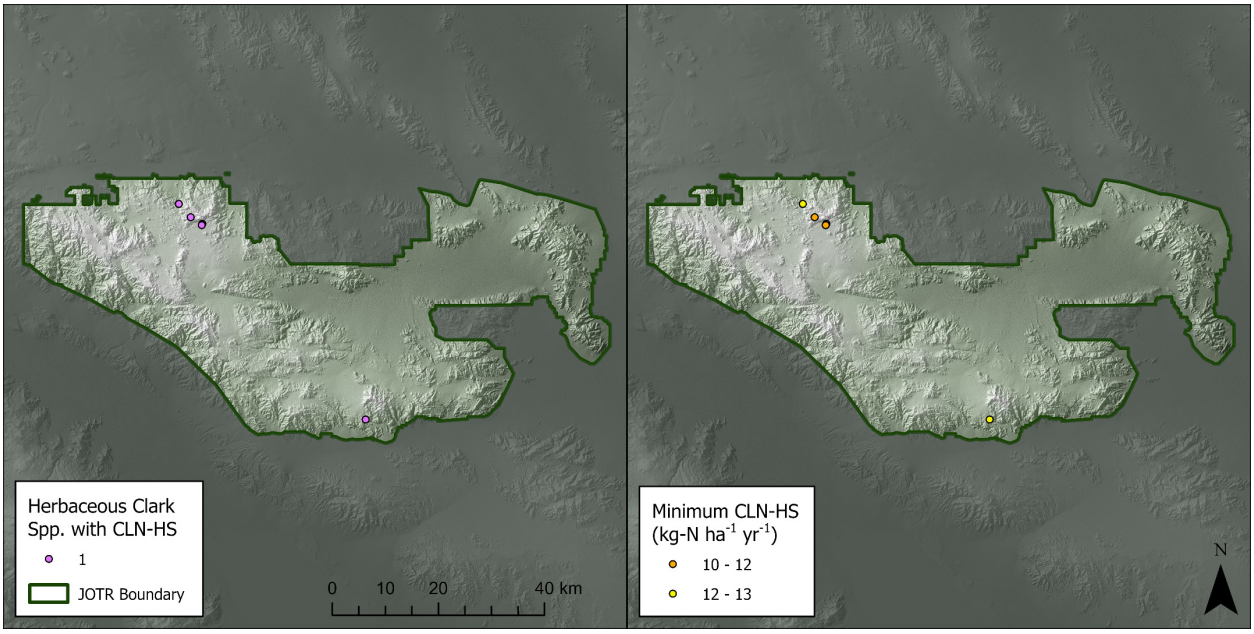


Figure A13. Number of species at each vegetation plot with a CLN-HS at Joshua Tree National Park (left) and the minimum CLN-HS at each plot (right).

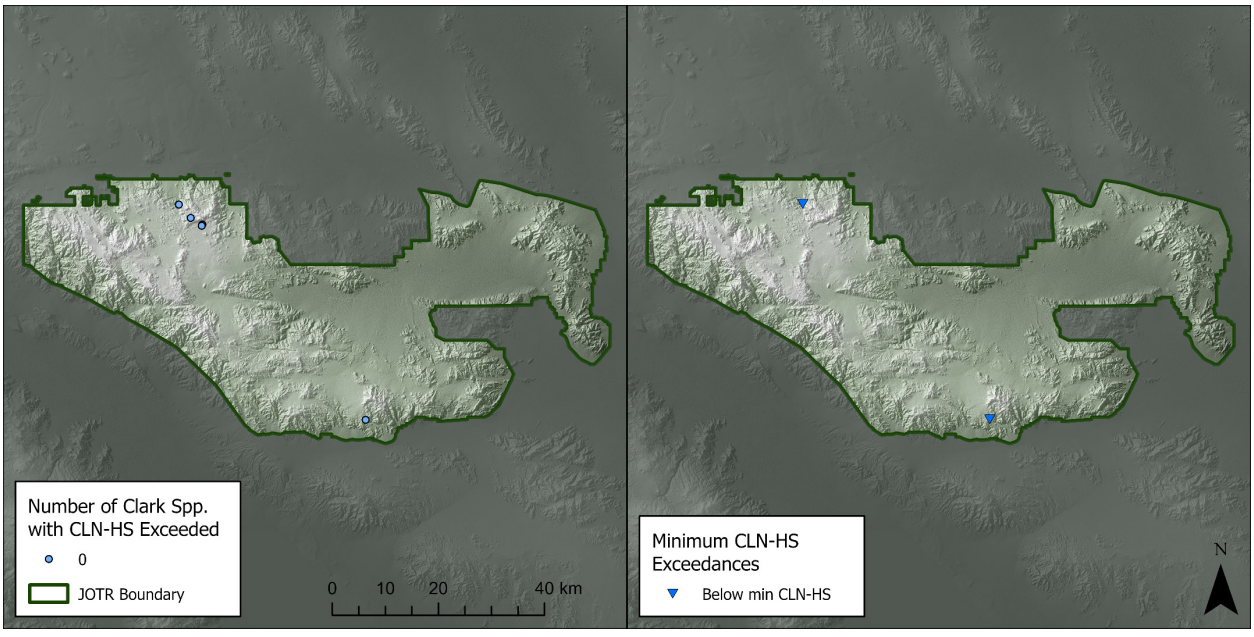


Figure A14. Number of species at each vegetation plot with 2016–2018 N deposition in exceedance of their CLN-HS at Joshua Tree National Park (left) and plots with 2016–2018 N deposition above, at, and below the minimum CLN-HS at each plot (right).

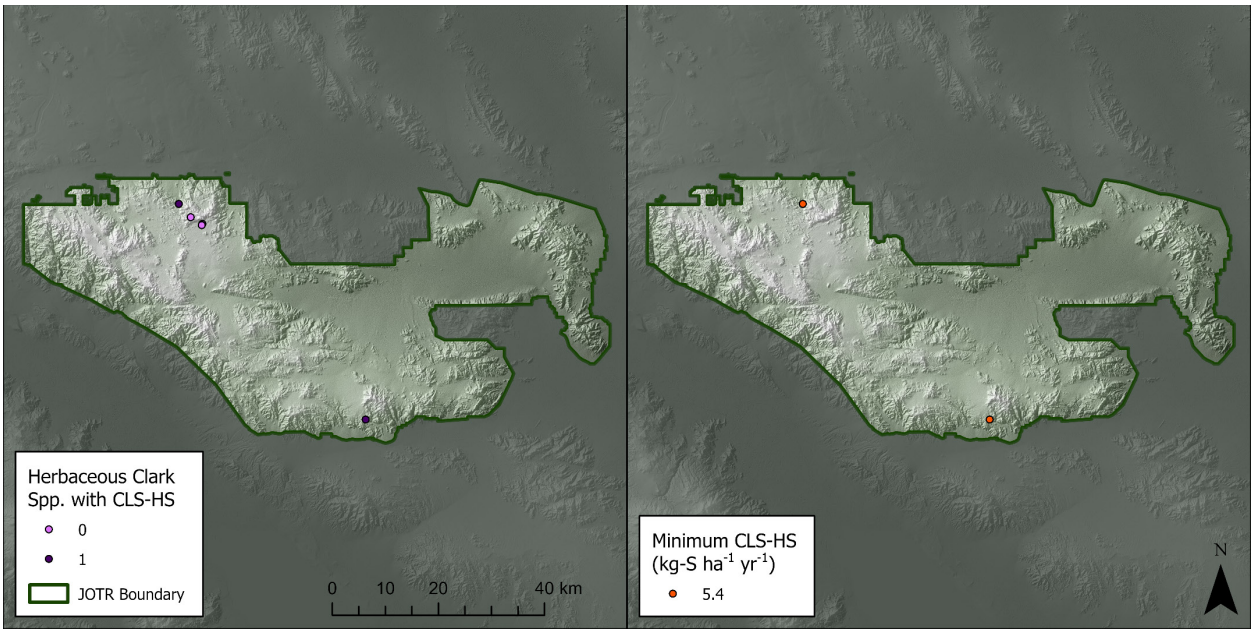


Figure A15. Number of species at each vegetation plot with a CLS-HS at Joshua Tree National Park (left) and the minimum CLS-HS at each plot (right).

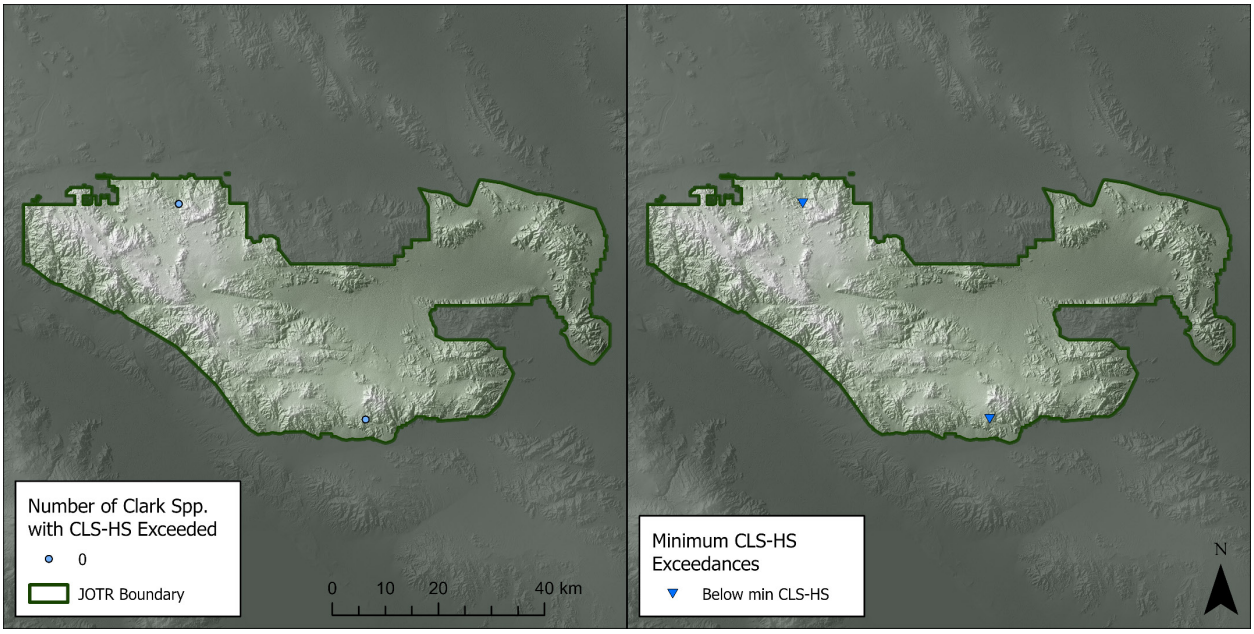


Figure A16. Number of species at each vegetation plot with 2016–2018 S deposition in exceedance of their CLS-HS at Joshua Tree National Park (left) and plots with 2016–2018 S deposition above, at, and below the minimum CLS-HS at each plot (right).

Rocky Mountain National Park

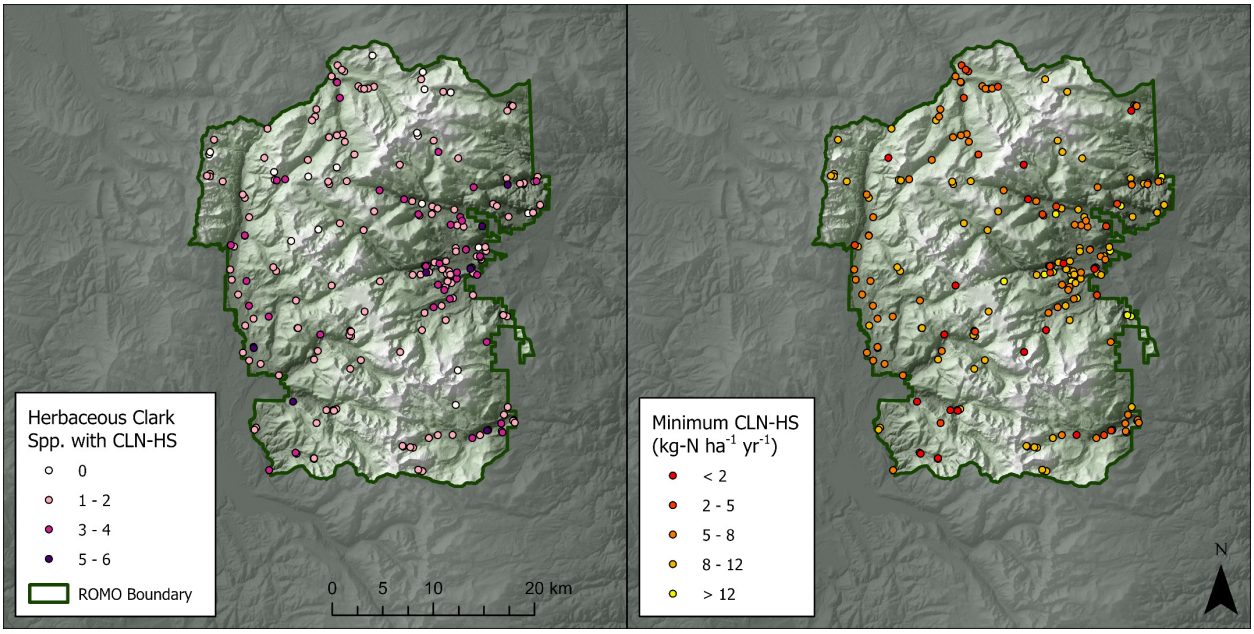


Figure A17. Number of species at each vegetation plot with a CLN-HS at Rocky Mountain National Park (left) and the minimum CLN-HS at each plot (right).

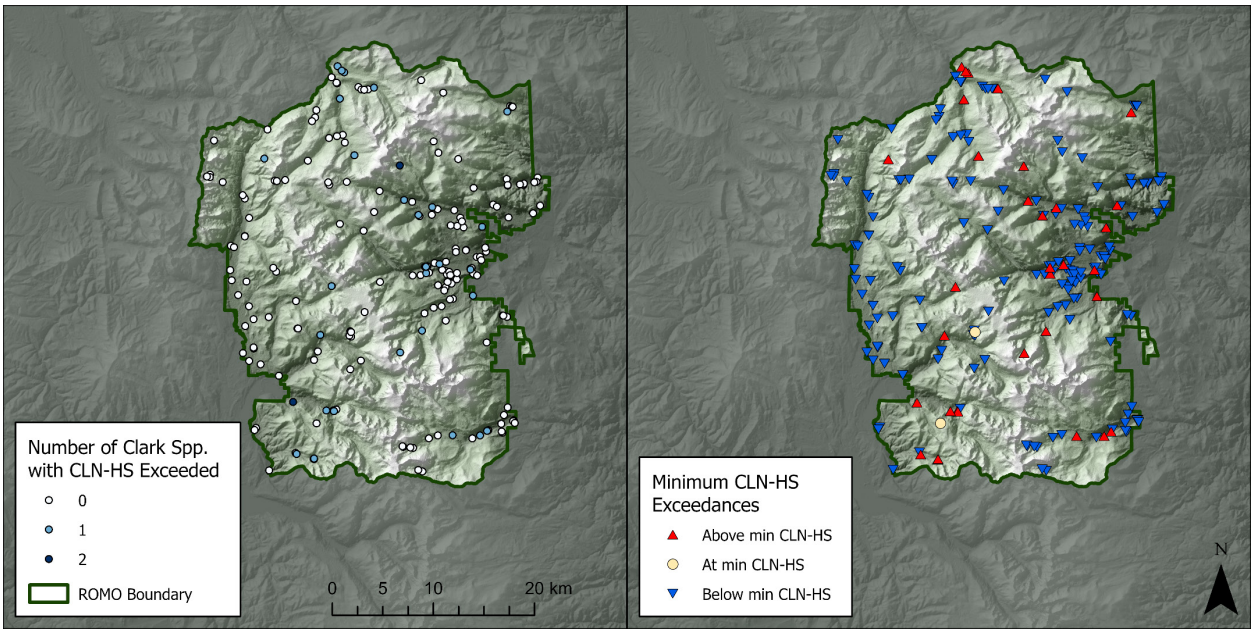


Figure A18. Number of species at each vegetation plot with 2016–2018 N deposition in exceedance of their CLN-HS at Rocky Mountain National Park (left) and plots with 2016–2018 N deposition above, at, and below the minimum CLN-HS at each plot (right).

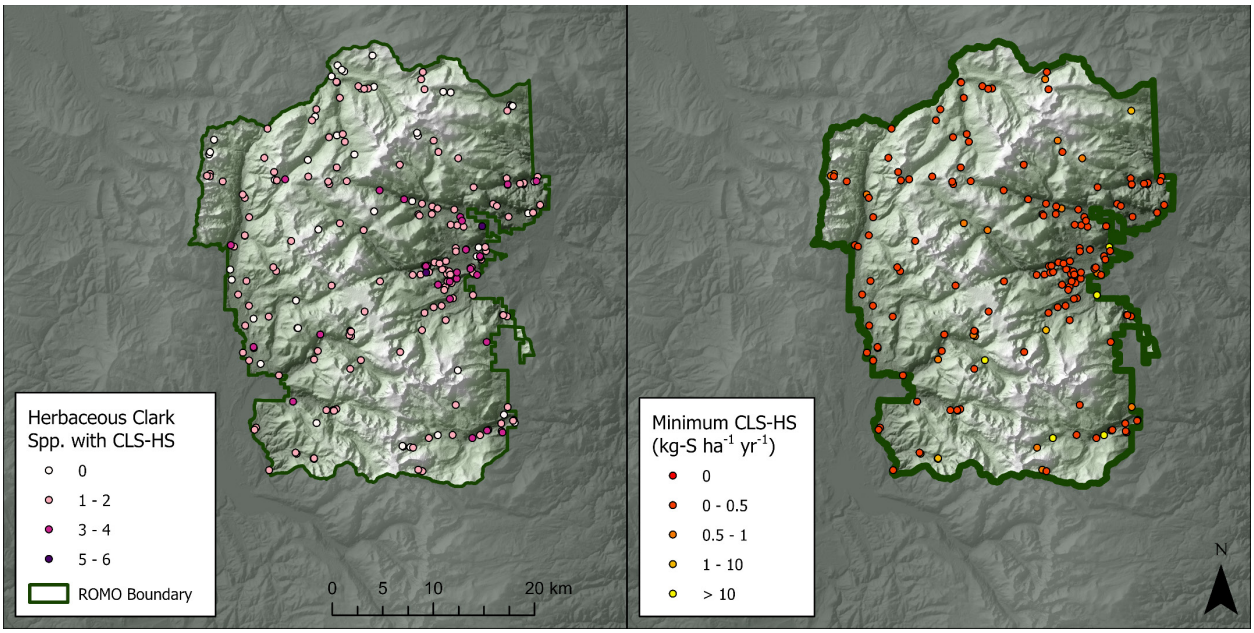


Figure A19. Number of species at each vegetation plot with a CLS-HS at Rocky Mountain National Park (left) and the minimum CLS-HS at each plot (right).

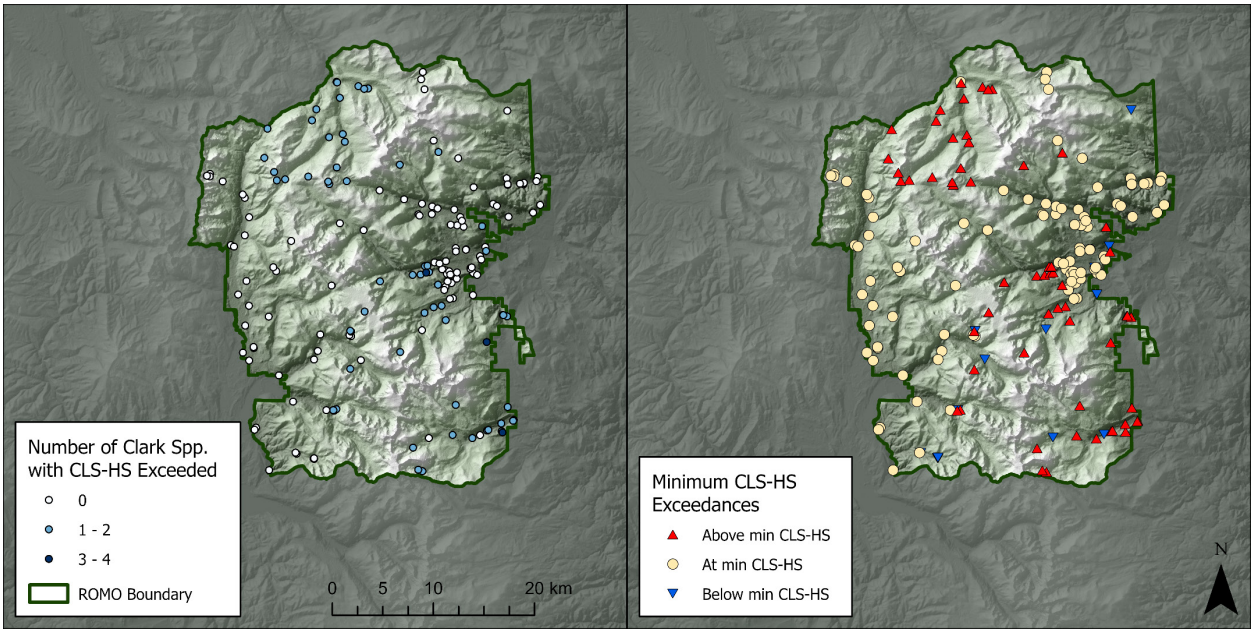


Figure A20. Number of species at each vegetation plot with 2016–2018 S deposition in exceedance of their CLS-HS at Rocky Mountain National Park (left) and plots with 2016–2018 S deposition above, at, and below the minimum CLS-HS at each plot (right).

Sleeping Bear Dunes National Lakeshore

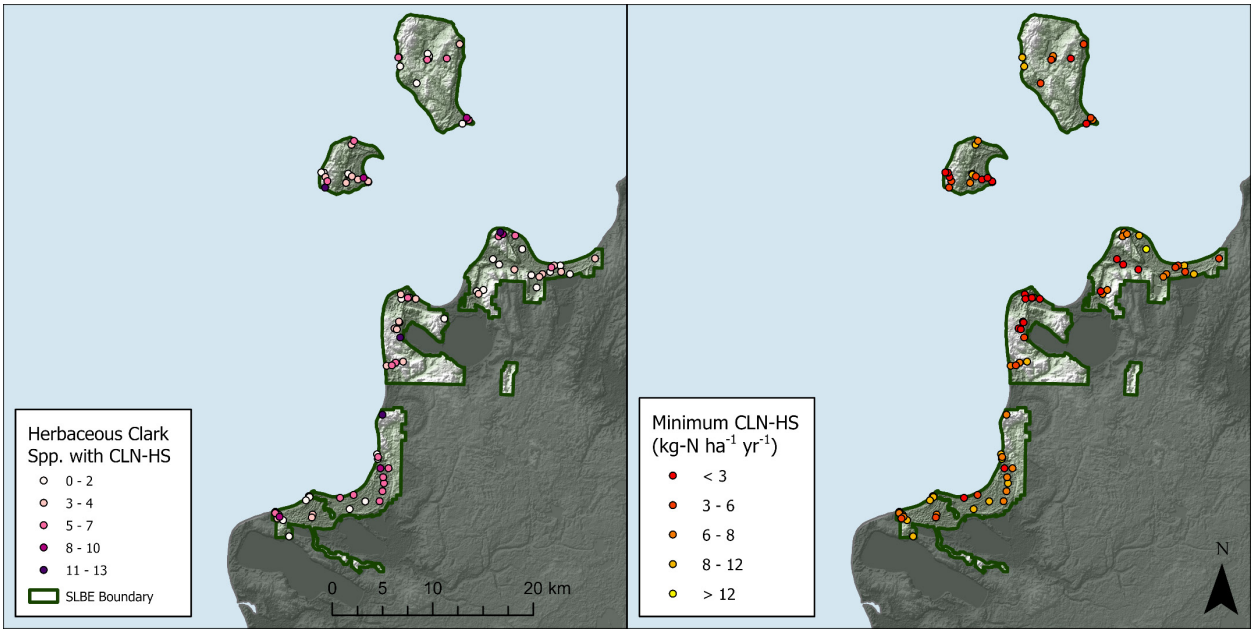


Figure A21. Number of species at each vegetation plot with a CLN-HS at Sleeping Bear Dunes National Lakeshore (left) and the minimum CLN-HS at each plot (right).

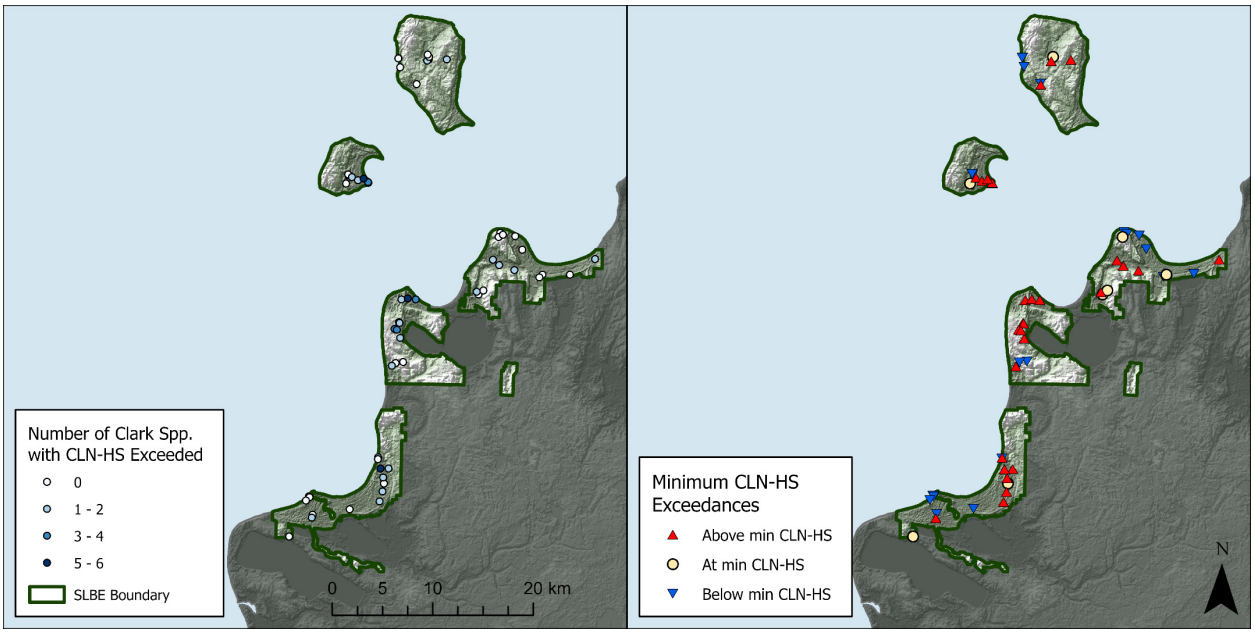


Figure A22. Number of species at each vegetation plot with 2016–2018 N deposition in exceedance of their CLN-HS at Sleeping Bear Dunes National Lakeshore (left) and plots with 2016–2018 N deposition above, at, and below the minimum CLN-HS at each plot (right).

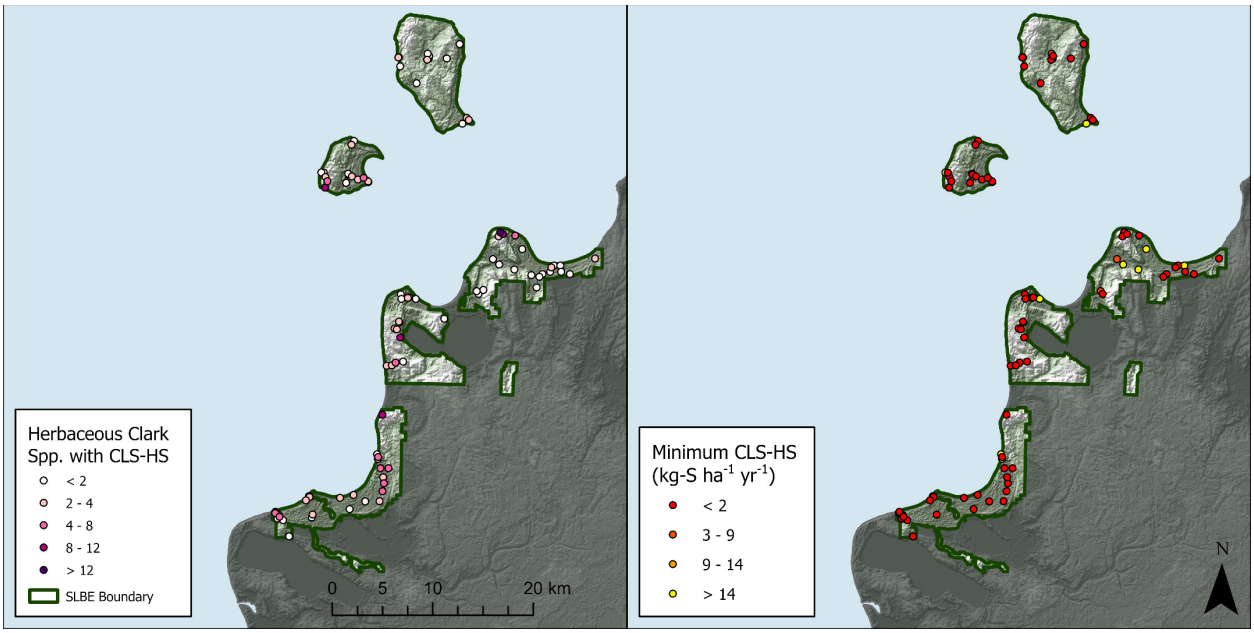


Figure A23. Number of species at each vegetation plot with a CLS-HS at Sleeping Bear Dunes National Lakeshore (left) and the minimum CLS-HS at each plot (right).

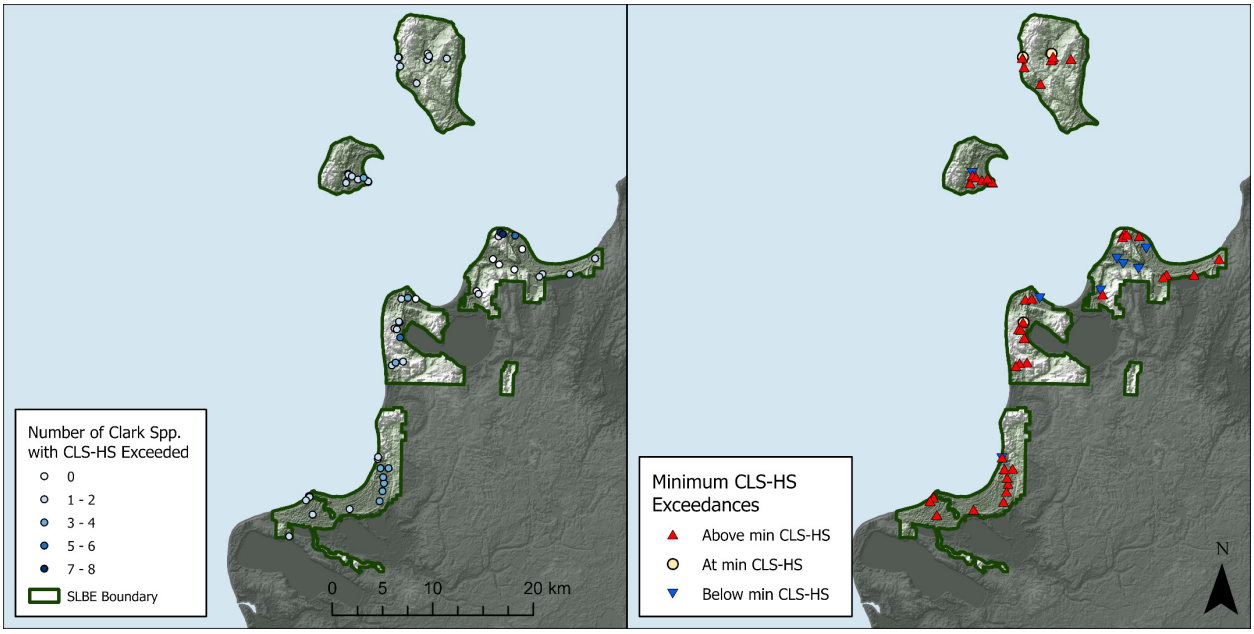


Figure A24. Number of species at each vegetation plot with 2016–2018 S deposition in exceedance of their CLS-HS at Sleeping Bear Dunes National Lakeshore (left) and plots with 2016–2018 S deposition above, at, and below the minimum CLS-HS at each plot (right).

Theodore Roosevelt National Park

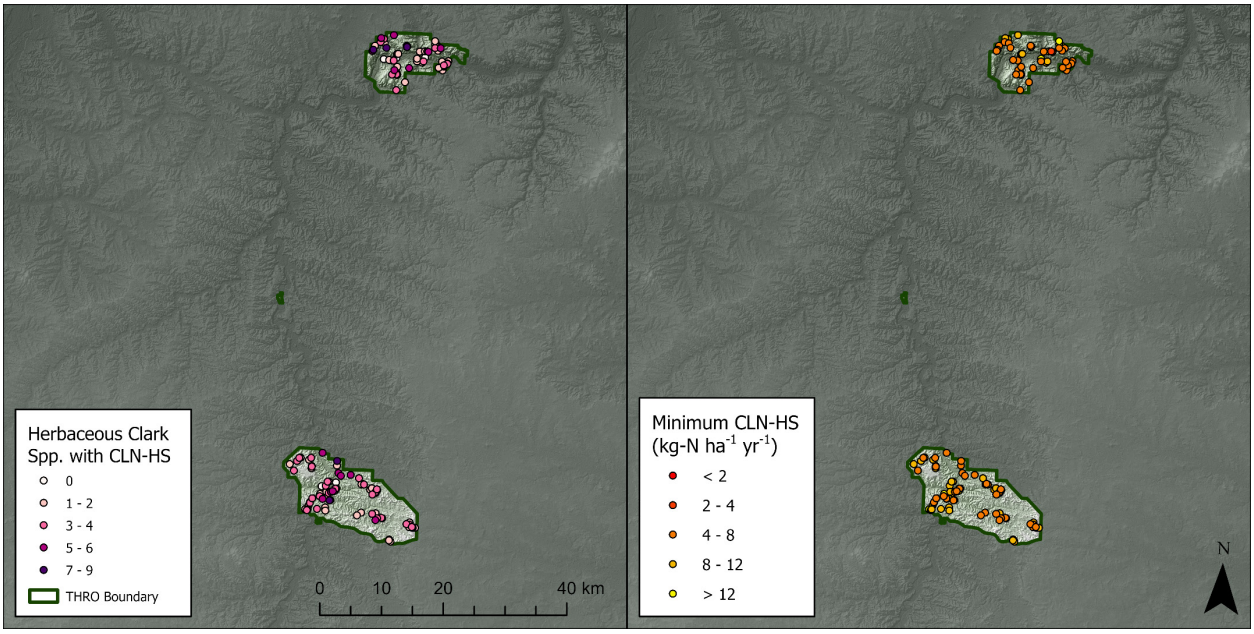


Figure A25. Number of species at each vegetation plot with a CLN-HS at Theodore Roosevelt National Park (left) and the minimum CLN-HS at each plot (right).

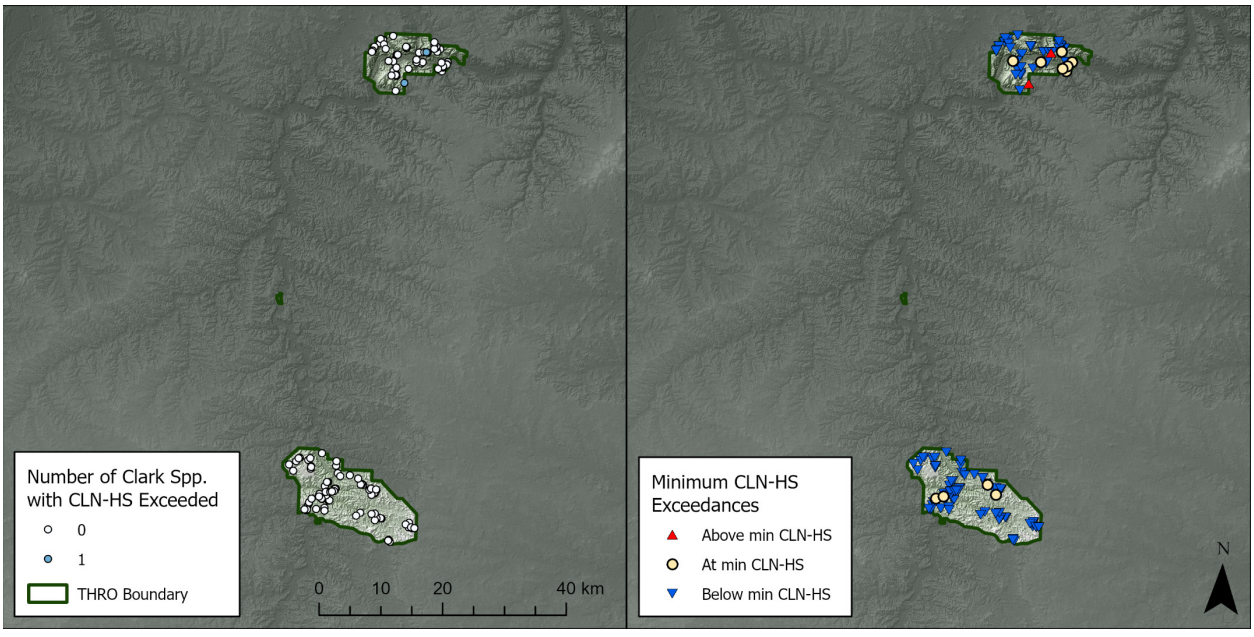


Figure A26. Number of species at each vegetation plot with 2016–2018 N deposition in exceedance of their CLN-HS at Theodore Roosevelt National Park (left) and plots with 2016–2018 N deposition above, at, and below the minimum CLN-HS at each plot (right).

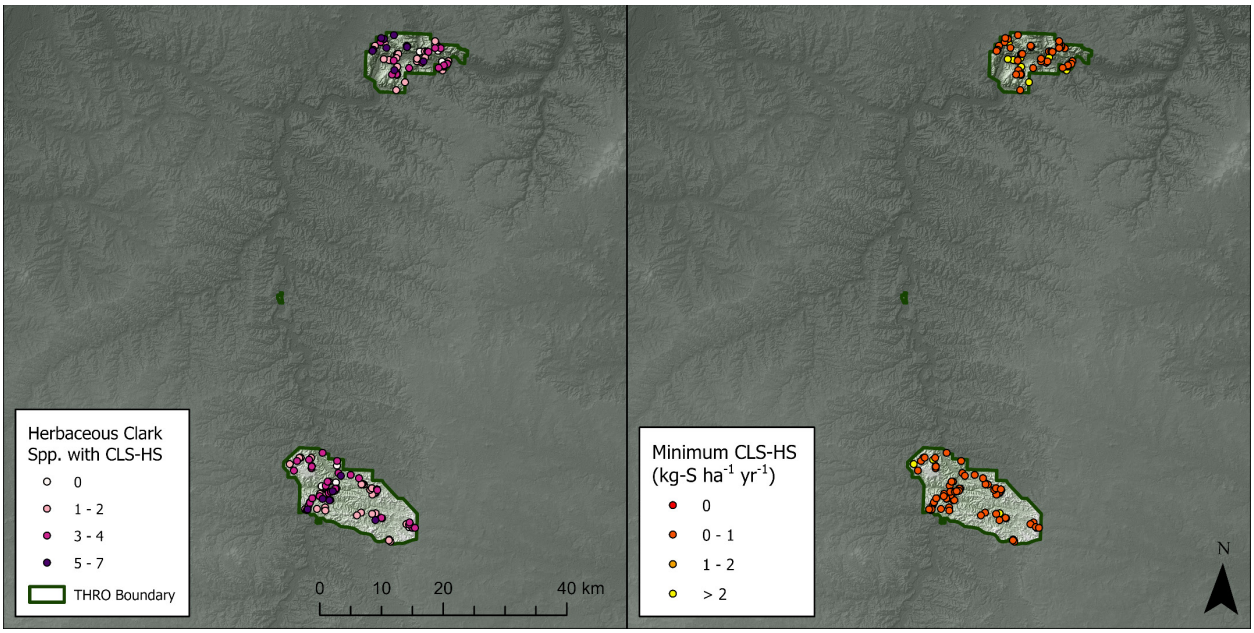


Figure A27. Number of species at each vegetation plot with a CLS-HS at Theodore Roosevelt National Park (left) and the minimum CLS-HS at each plot (right).

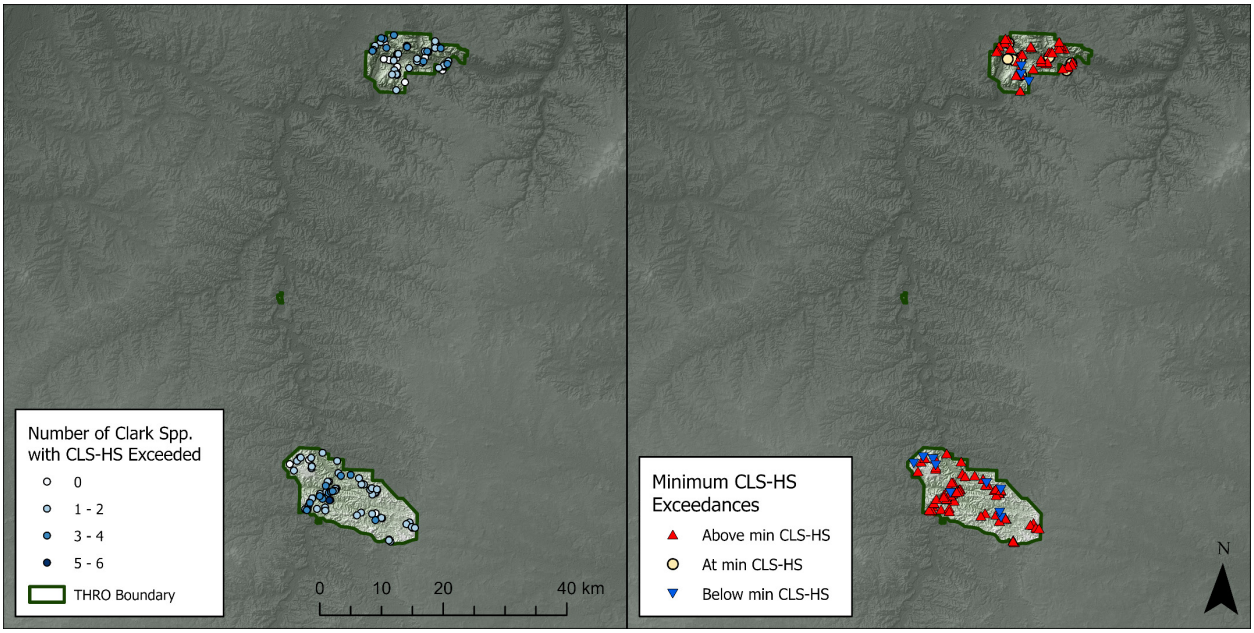


Figure A28. Number of species at each vegetation plot with 2016–2018 S deposition in exceedance of their CLS-HS at Theodore Roosevelt National Park (left) and plots with 2016–2018 S deposition above, at, and below the minimum CLS-HS at each plot (right).

Yosemite National Park

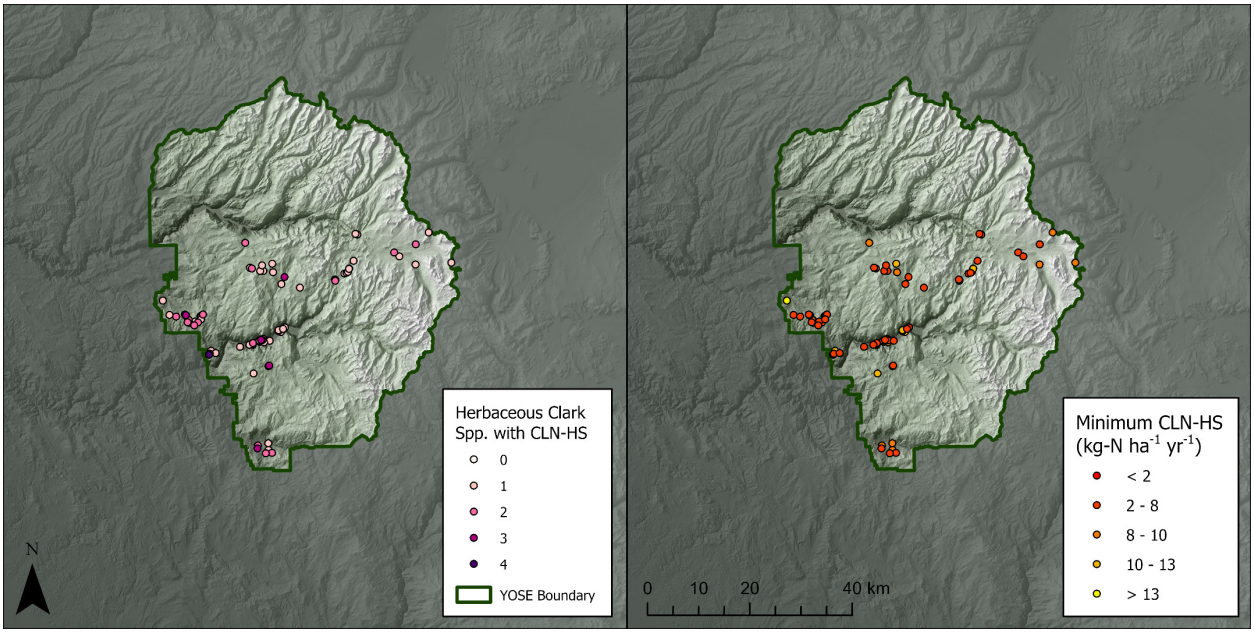


Figure A29. Number of species at each vegetation plot with a CLN-HS at Yosemite National Park (left) and the minimum CLN-HS at each plot (right).

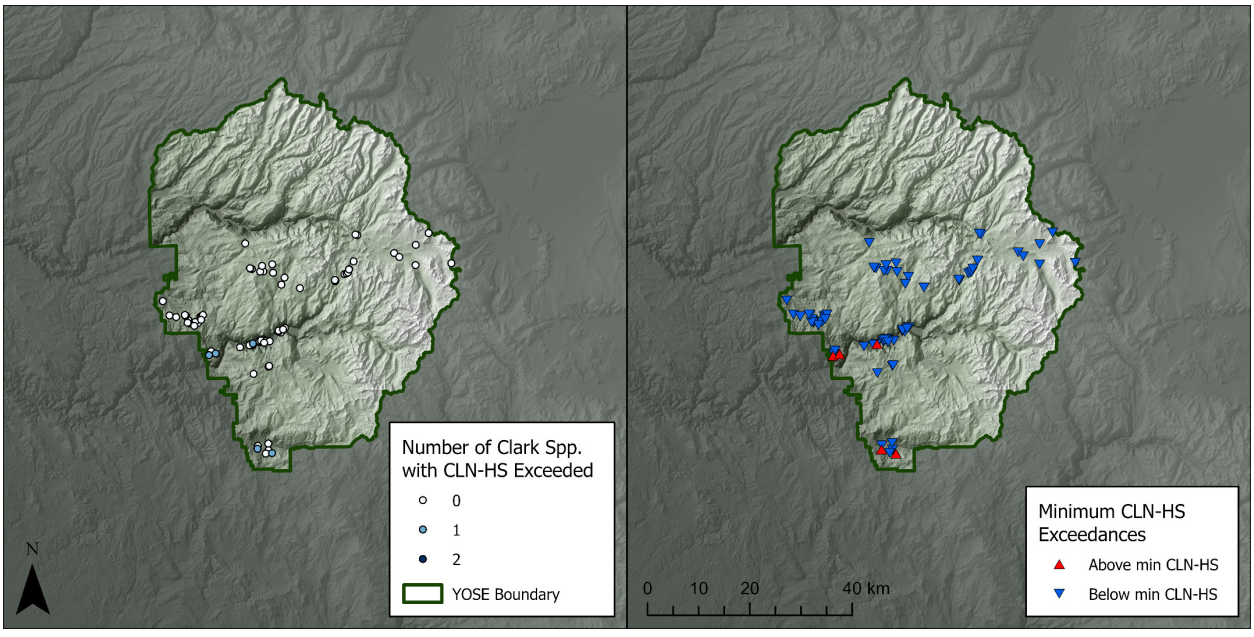


Figure A30. Number of species at each vegetation plot with 2016–2018 N deposition in exceedance of their CLN-HS at Yosemite National Park (left) and plots with 2016–2018 N deposition above, at, and below the minimum CLN-HS at each plot (right).

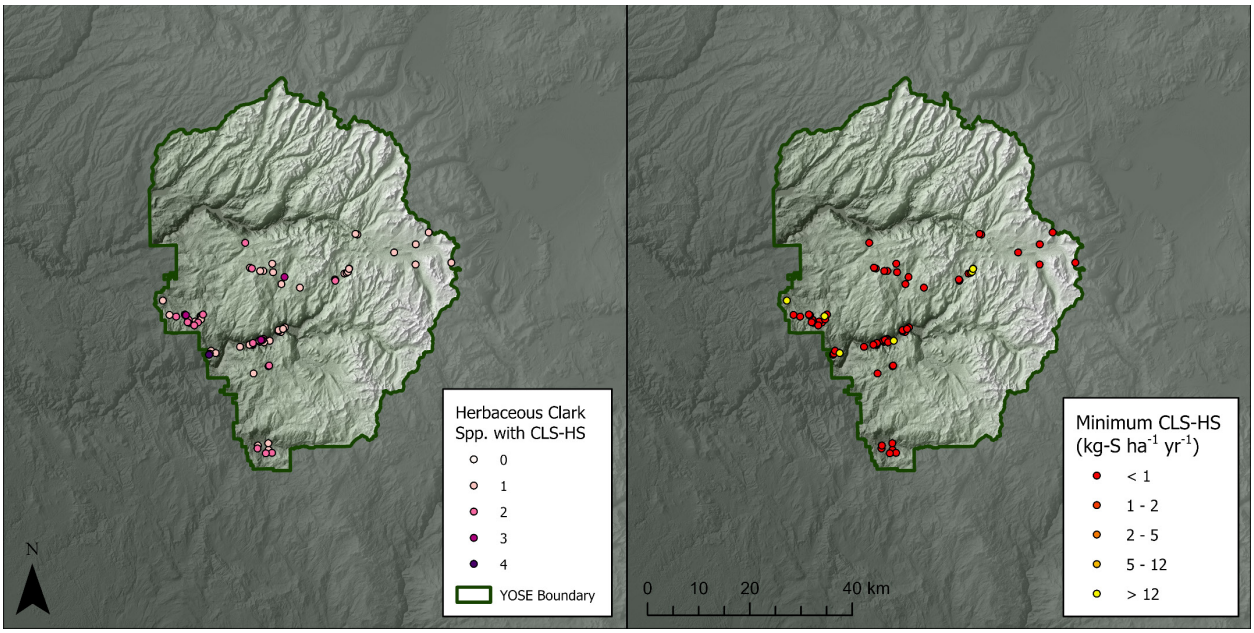


Figure A31. Number of species at each vegetation plot with a CLS-HS at Yosemite National Park (left) and the minimum CLS-HS at each plot (right).

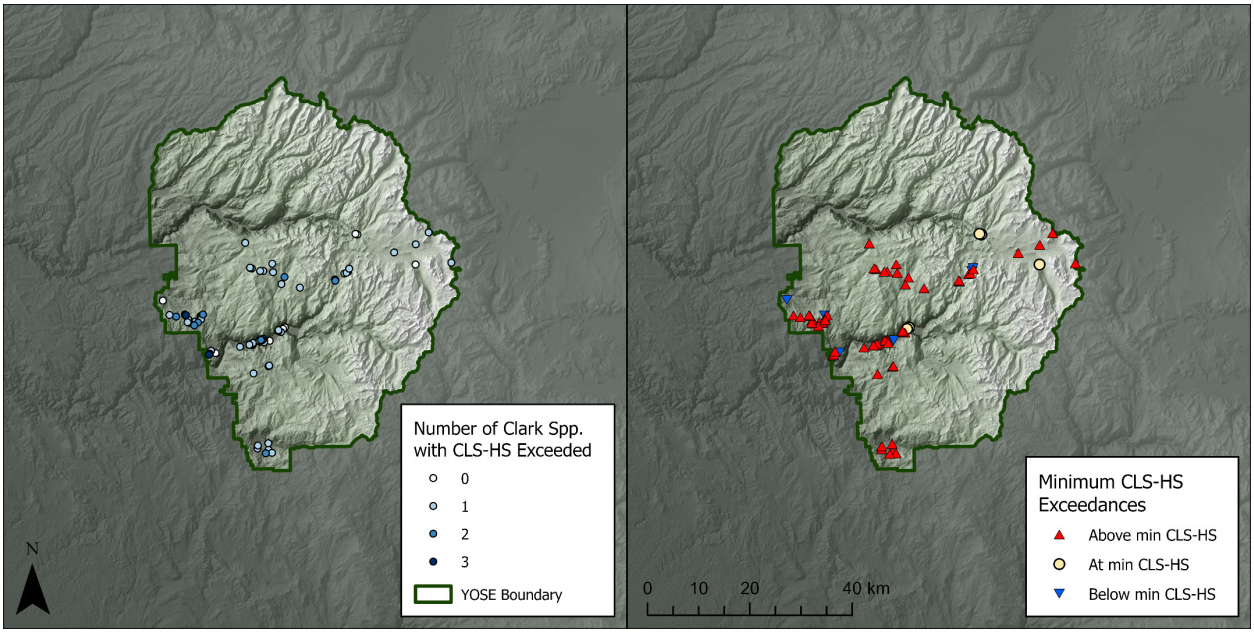


Figure A32. Number of species at each vegetation plot with 2016–2018 S deposition in exceedance of their CLS-HS at Yosemite National Park (left) and plots with 2016–2018 S deposition above, at, and below the minimum CLS-HS at each plot (right).

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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