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Effects of Climate Change and Atmospheric Nitrogen Deposition on Forest Understory Vegetation Communities in Selected U. S. National Parks

Wildflowers near the mountains in Grand Teton National Park.
NPS / JANE GAMBLE

Effects of climate change and atmospheric nitrogen deposition on forest understory vegetation communities in selected U. S. national parks

Science Report NPS/SR—2024/169

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Abstract

Climate change and elevated atmospheric nitrogen (N) deposition can have adverse effects on biodiversity, leading to acidification of soil and surface waters, reductions in tree growth and survival, alteration of aquatic food webs, and changes in biodiversity across landscapes. The objectives of this study were to implement the United States Probability of Occurrence of Plant Species model to evaluate species-level CLs and responses to N deposition under three potential future climate scenarios at eight national parks located across the continental United States. Model application results were used to make comparisons of CLs and magnitudes of change in species responses across parks.

Critical loads of N deposition and changes in occurrence probability were determined for current climate conditions and three potential future climate scenarios to reflect change in occurrence probability under simulated air temperature increases of +0.5, +1.0, +1.5 °C in eight NPS units. Under a future air temperature scenario of +0.5 °C, occurrence probability of the most sensitive species to air temperature changes at Acadia NP and Sleeping Bear Dunes National Lakeshore decreased by at least 50% for approximately half of the map classes. Four other national parks (Glacier, Rocky Mountain, Theodore Roosevelt, and Yosemite) showed a 50% reduction in occurrence probability for the most sensitive species at approximately half of the map classes under a warming scenario of +1.0 °C. Some species may either be extirpated or nearly extirpated (i.e., more than 95% reduction in occurrence probability) with a 1.5 °C future increase in air temperature at Acadia, Glacier, Sleeping Bear Dunes, and Yosemite.

Critical loads of atmospheric N deposition were less than 5 kg N/ha/yr for most vegetation species and map classes included in this study. Protection of the most sensitive species within vegetation classes typically requires N deposition to be lower than 2.5 kg N/ha/yr. Median CLs across map classes were nearly always indeterminable under climate change scenarios (i.e., maximum occurrence probability under ambient climate was no longer attainable even if annual N deposition was reduced to zero). This indicates that at least one-half of the map classes at each NPS unit are expected to experience reductions in occurrence probability from climate change that cannot be compensated for by reductions in N deposition. Although these adverse effects of climate change are expected to outweigh benefits of decreased N pollution, reductions in N deposition would still be expected to benefit vegetation species in exceedance of the designated CL.

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Introduction

Emissions of greenhouse gases, ammonia (NH_3), nitrogen oxides (NO_x), and other nitrogen (N)-containing pollutants can result in elevated N deposition and climate change, which can lead to adverse effects on biodiversity (Sala et al. 2000, Lu et al. 2008). These widespread environmental stressors affect terrestrial and aquatic ecosystems, leading to acidification of soil and surface waters, reductions in tree growth and survival, alteration of aquatic food webs, and changes in biodiversity across landscapes. Over the past several decades, estimates of critical loads (CLs) of atmospheric deposition have been developed as protective thresholds for a variety of environmental components. The CL is the deposition load below which harmful effects on ecosystems are not expected to occur according to present knowledge (Nilsson and Grennfelt 1988). In the United States, initial CLs for terrestrial systems were established at an ecoregion level to summarize responses within similar community types (Pardo et al. 2011). As larger observed response datasets have been analyzed relative to deposition exposure, community level responses for herbaceous species and lichen communities have been generated at regional to national scales (Simkin et al. 2016, Geiser et al. 2019). Initial species-level responses and CLs for over 300 herbaceous plant species and 94 tree species have been established (Horn et al. 2018, Clark et al. 2019). These species-level CL datasets are most useful when one species dominates a landscape. However, they are less useful for informing natural resource management of diverse ecosystems. The United States Probability of Occurrence of Plant Species (US-PROPS) model uses more than 1,500 statistical models for estimating the probability of plant species occurrence according to environmental drivers such as N deposition and air temperature have been developed and has been used for site-level applications in eastern U.S. forests (McDonnell et al. 2020). Based on a case study at Great Smoky Mountains National Park (NP), an approach for regional US-PROPS model application has been developed to utilize this expansive set of vegetation response models within other regions of the United States (McDonnell et al. 2022).

The National Park Service (NPS) is legislatively mandated to protect park resources from adverse impacts caused by air pollution and sustain unimpaired conditions for future generations (Shaver et al. 1994). Research and monitoring in national parks of the United States have shown that air pollution has impacted biota and ecosystem function in some parks. Although air quality has improved since the 1970s under the Clean Air Act and its amendments along with other state and federal legislation, air pollution continues to cause adverse effects on sensitive park resources. The objectives of this study were to implement the US-PROPS model to evaluate species-level CLs and responses to N deposition under three potential future climate scenarios at eight national parks located across the continental United States. Model application results were used to make comparisons of CLs and magnitudes of change in species responses across parks.

Approach

Characteristic Species of Study Parks

The eight NPS units included in this assessment are Acadia NP (ACAD), Glacier NP (GLAC), Grand Teton NP (GRTE), Joshua Tree NP (JOTR), Rocky Mountain NP (ROMO), Sleeping Bear Dunes National Lakeshore (SLBE), Theodore Roosevelt NP (THRO), and Yosemite NP (YOSE; Figure 1). Vegetation maps developed by the NPS Vegetation Mapping Inventory (VMI; https://www.nps.gov/im/vmi-products.htm) were used as the basis for spatial representation of CLs and vegetation response across each study park. The VMI effort delineated vegetation map classes throughout each park boundary, each of which represent one or more National Vegetation Classification plant associations. For each VMI dataset, vegetation surveys were completed within map class polygons. For this analysis, species were considered characteristic of the vegetation map class if they were identified on at least 25% of the VMI plots located within the map class. Individual species can occur in multiple map classes.

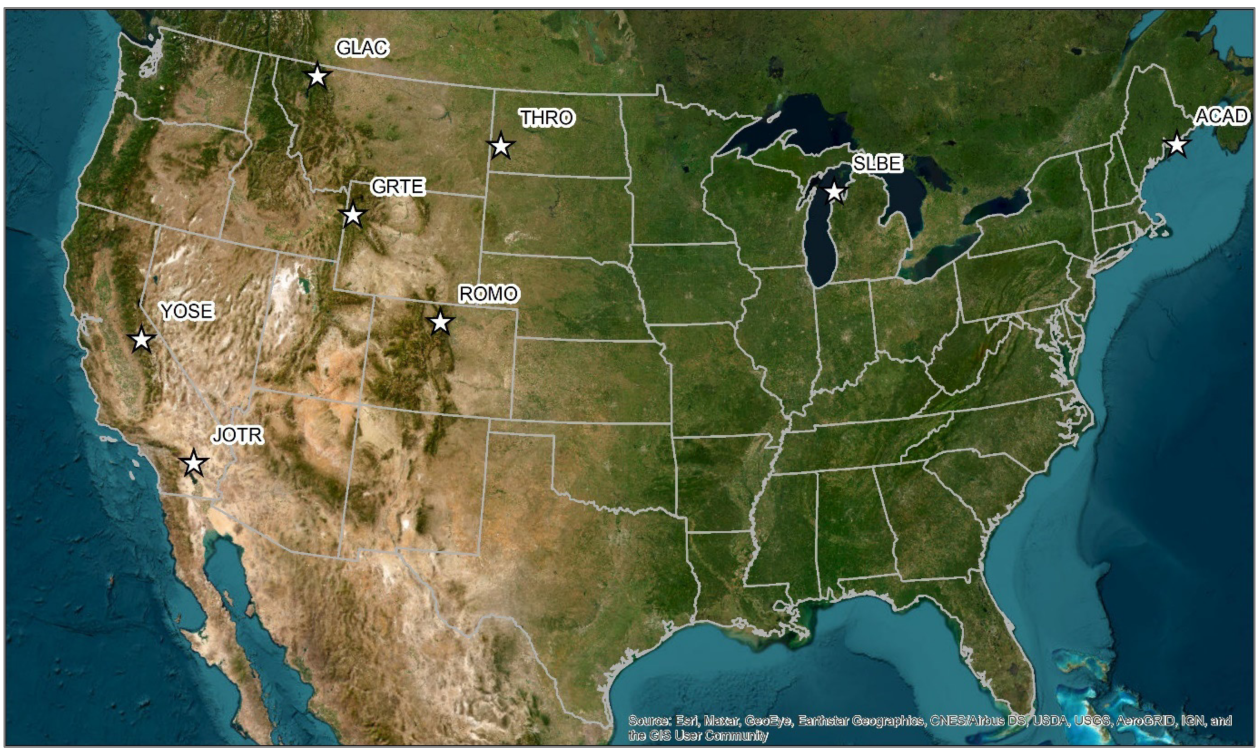

Figure 1. Locations of the eight National Park Service units included in this assessment.

Among the 322 unique map classes across all eight parks, 41% (n = 132) had between 10 and 20 characteristic species (Table 1). Less than 15% of the map classes had either more than 40 (n = 6) or less than 5 (n = 37) characteristic species. JOTR had the fewest total number of characteristic species (n = 29) and SLBE had the most (n = 200; Table 2). Further details related to the total number of species identified by the VMI and species that were characterized with US-PROPS models are included in McDonnell et al. (2024).

Table 1. Number of map classes characterized by various ranges of characteristic species.

Number of Characteristic Species per Map Class	Number of Map Classes
1 to 5	37
5 to 10	82
10 to 20	132
20 to 30	43
30 to 40	22
40 to 50	5
50 to 60	1

Table 2. Total number of characteristic species that occur in each park, the number of vegetation map classes in each park, and the minimum and maximum number of characteristic species attributed to a map class for each study NPS unit.

NPS Unit Code	NPS Unit Name	# of Characteristic Species	# of Map Classes	Min # of Characteristic Species for a Map Class	Max # of Characteristic Species for a Map Class
ACAD	Acadia National Park	72	26	3	36
GLAC	Glacier National Park	164	36	2	44
GRTE	Grand Teton National Park	104	48	2	25
JOTR	Joshua Tree National Park	29	36	3	18
ROMO	Rocky Mountain National Park	113	39	3	35
SLBE	Sleeping Bear Dunes National Lakeshore	200	43	3	55
THRO	Theodore Roosevelt National Park	84	24	2	35
YOSE	Yosemite National Park	134	70	1	25

PROPS Model

The United States Probability of Plant Species (US-PROPS) models are based on nine predictor datasets to calculate the occurrence probability for a given species including annual precipitation total, average annual air temperature, average 30-year annual N deposition, soil pH, soil percent clay, available water storage, soil rooting depth, canopy cover, and incoming solar radiation during May – July (McDonnell et al. 2020). These models were used to evaluate changes in occurrence probability and determine CLs for the eight NPS units considered.

Vegetation Response

Scenarios

Critical loads of N deposition and changes in occurrence probability were determined under ambient climate conditions (i.e., no simulated future trends in air temperature). Model results for three potential future scenarios of air temperature were also generated to reflect change in occurrence probability under simulated air temperature increases of +0.5, +1.0, +1.5 °C (Table 3).

Table 3. Scenarios of changing air temperature.

Scenario ID	Air Temperature Condition (°C)
Scen01	Ambient + 0.5
Scen02	Ambient + 1.0
Scen03	Ambient + 1.5

Occurrence Probability

Occurrence probability for each characteristic species was determined at 30-m grid cell locations for each map class where the species was found. Species-level occurrence probabilities were estimated based on 0.5 kg N/ha/yr intervals of N deposition between 0.5 and 20 kg N/ha/yr and the location-specific values of the other eight predictor variables. For each interval of N deposition, a spatial average of occurrence probability among all grid cells was determined for each characteristic species of each map class. Changes in occurrence probability were presented based on the minimum percent change (Figure 2) and the average percent change (Figure 3) in the maximum occurrence probability, which occurs at the CL of N deposition (see ‘Critical Loads’ section below), among characteristic species of each map class. In the event that at least one species responds negatively, the “minimum percent change” refers to the most negative value among all characteristic species responses for that map class. If all species respond positively, the “minimum percent change” is the lowest positive value. The “average percent change” represents the average change among all characteristic species of a map class.

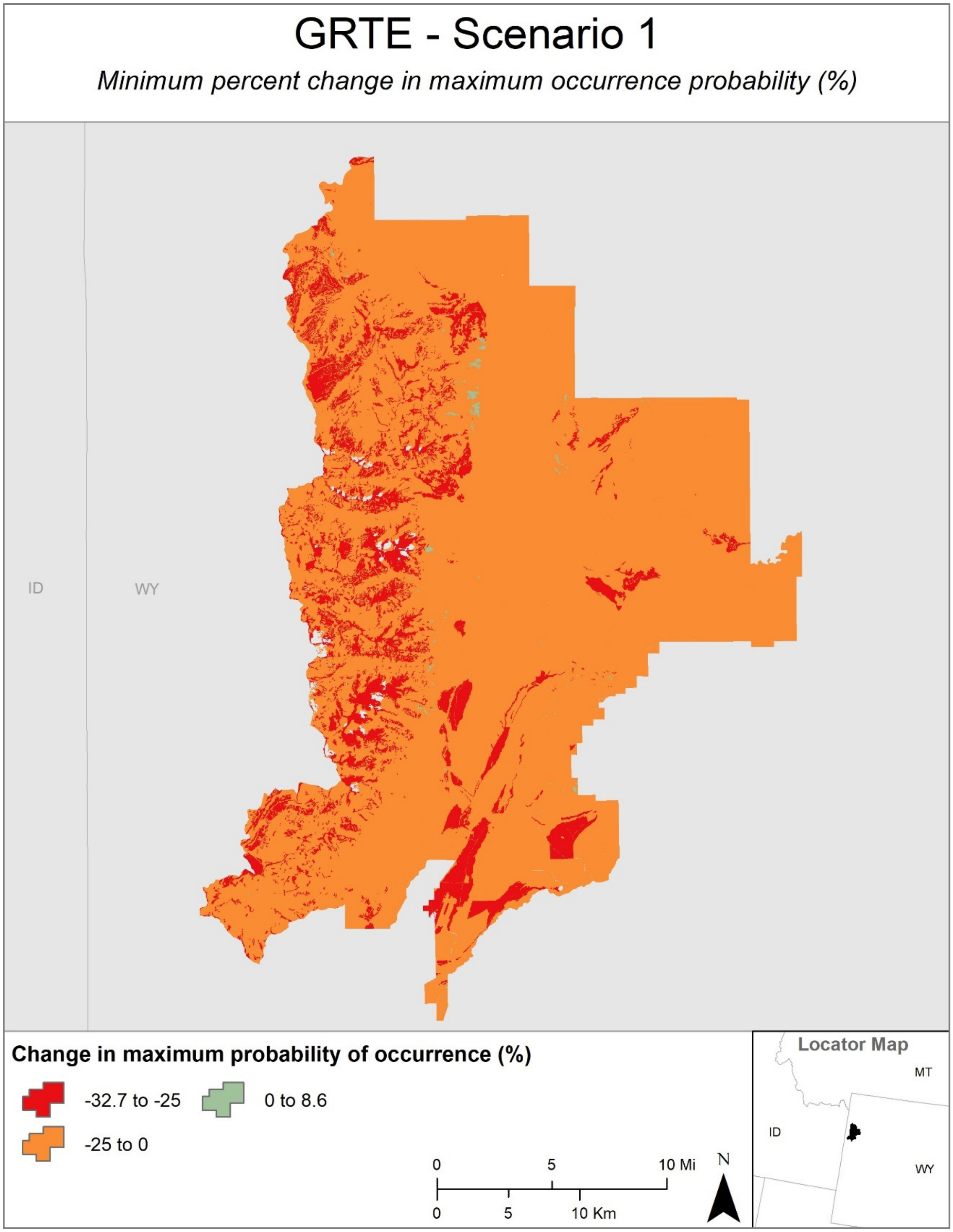

Figure 2. Example map showing results of the "minimum percent change" in the maximum occurrence probability among all species in a map class under Scenario 1 (+0.5 °C) relative to ambient climate at Grand Teton National Park (GRTE).

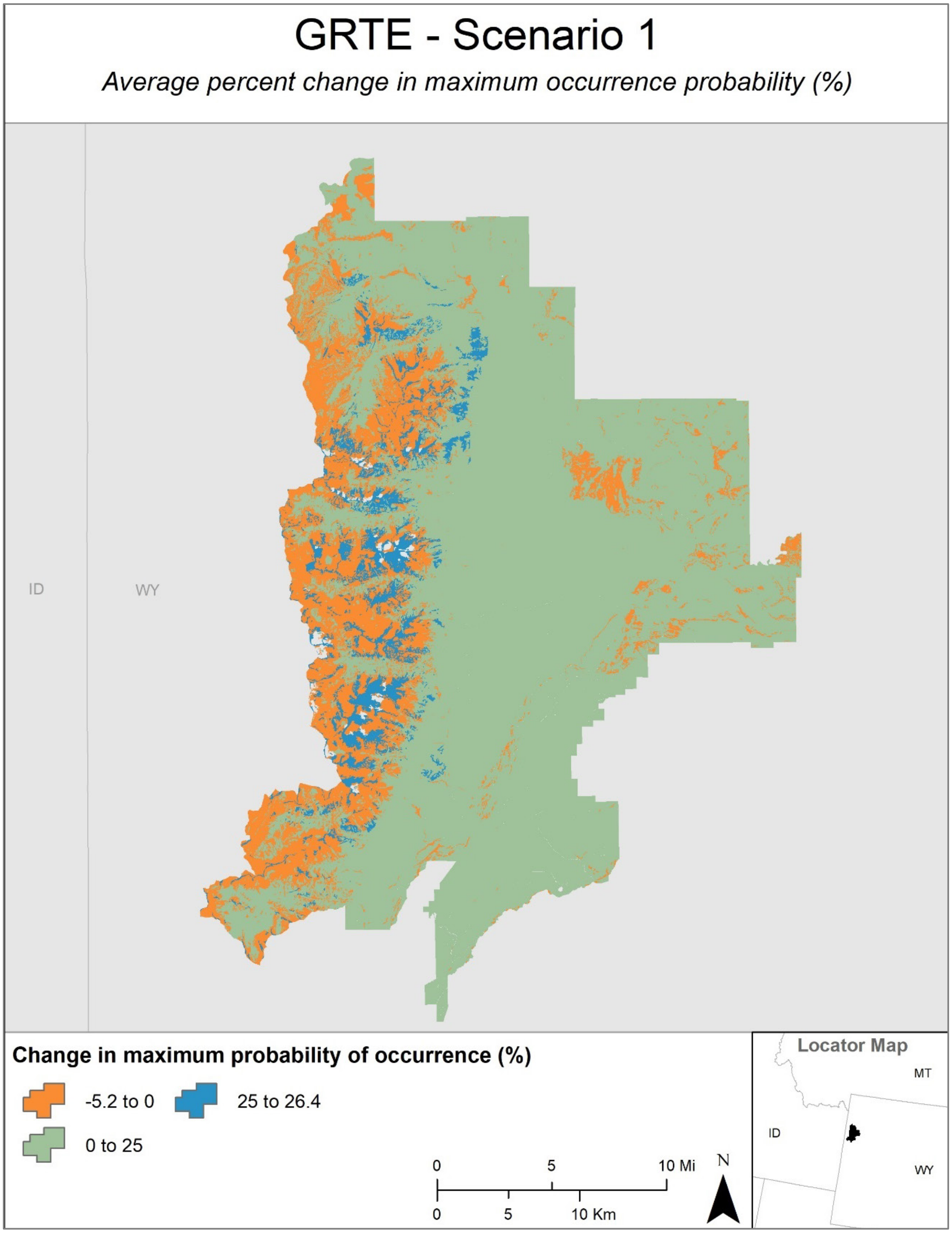

Figure 3. Example map showing results of the "average percent change" in the maximum occurrence probability among all species in a map class under Scenario 1 (+0.5 °C) relative to ambient climate at Grand Teton National Park (GRTE).

Critical Loads

Species-level occurrence probability functions (US-PROPS; McDonnell et al. 2020) were assessed to develop CLs of N deposition to represent the characteristic understory vegetation community of each map class. Under ambient climate, the CL was defined as the level of N deposition associated with the maximum occurrence probability for a given species. For a species modeled with decreasing occurrence probability as N deposition increases, the CL is at the lowest level of N deposition considered. Occurrence probability increases for other species as N deposition increases, and CLs for these species are assumed to be at the highest level of N deposition considered. Critical loads for species with unimodal (i.e., "hump-shaped") responses are designated at the level of N deposition associated with the highest level of occurrence probability of the response curve. If N deposition was not included as a significant predictor for a given species model, then the response to N deposition is considered "flat" and there are no CLs of N deposition for this species.

The CL of N deposition was defined as the level of N deposition expected to maintain maximum occurrence probability under ambient climate conditions. However, the maximum occurrence probability under ambient climate may not be attainable under simulated increases in future air temperature. In other words, a simulated increase in air temperature may decrease occurrence probability to an extent that reductions in N deposition are not be able to compensate for the negative effect of the increase in air temperature. In these cases, the CL is indeterminable (i.e., not attainable; NA) because there is no level of N deposition that can maintain maximum occurrence probability expected under ambient climate conditions.

The level of N deposition associated with the maximum occurrence probability within the range of 0.5 – 20 kg N/ha/yr was designated as the CL for each species. The CL for each map class can be derived from the distribution of CLs among the associated set of characteristic species. For example, the CL for a given map class can be specified as the minimum species-level CL, which would be the most conservative CL. Alternatively, the CL can be specified as the level of N deposition at which 90% of the species-level CLs are above (i.e., the CL at which 90% of the species are protected). Another option would be to set the CL for a given map class to that of a focal species for management. For this study, the distribution of CLs is reported for each map class in tabular format, and the minimum, 10^{th} percentile (protective of 90% of species), and median (protective of 50% of species) CLs are mapped. A comprehensive list of CLs for characteristic species used to characterize each NPS study unit is included in McDonnell et al. (2024).

Climate Change Effects on Occurrence Probability

Vegetation responses and critical loads within each park were summarized and compared across the eight study parks and reported in this section.

Under a future air temperature scenario of +0.5 °C, occurrence probability of the most sensitive species to air temperature decreased by at least 50% for approximately half of the map classes at ACAD and SLBE (Figure 4). Four other parks (GLAC, ROMO, THRO, and YOSE) showed a 50% reduction in occurrence probability for the most sensitive species at approximately half of the map classes under a warming scenario of +1.0 °C. Some species may either be extirpated or nearly extirpated (i.e., more than 95% reduction in occurrence probability) with a 1.5 °C future increase in air temperature at ACAD, GLAC, SLBE, and YOSE (Table 4).

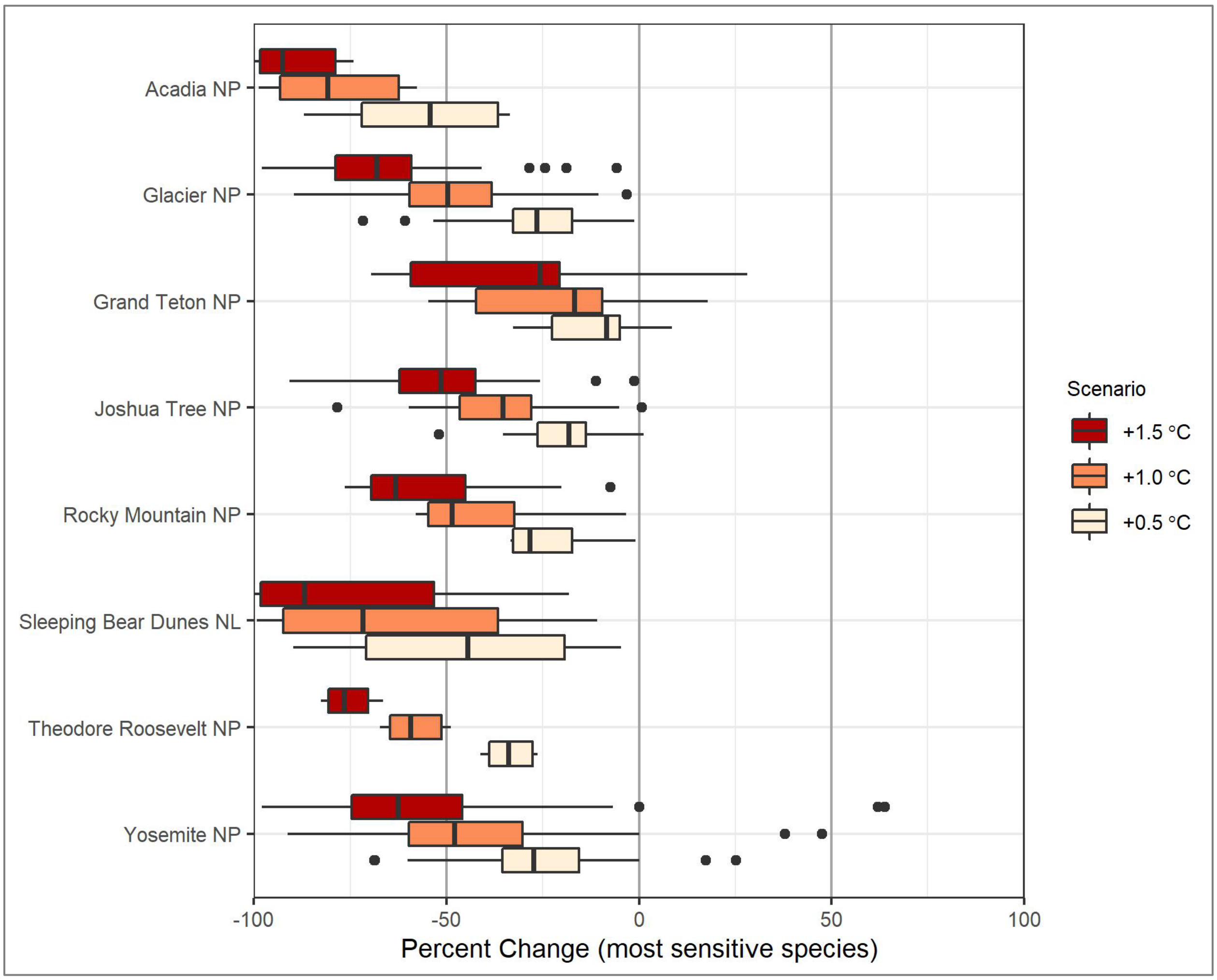

Figure 4. Distribution of the percent change in the occurrence probability of the most sensitive species per map class under future scenarios of increased air temperature.

Other relatively climate-sensitive species showed reductions in occurrence probability of greater than 80% but less than 95% (Table 5), some of which are known to presently occur in more than one study park, including *Alnus viridis, Argentina anserina, Carex filifolia, Cornus canadensis, Danthonia intermedia, Equisetum sylvaticum, Mimulus guttatus, Mitella nuda, Oreostemma alpigenum, Oryzopsis asperifolia, Pinus contorta, Potentilla gracilis, Rubus pubescens, Shepherdia canadensis, Spiraea splendens,* and *Vaccinium myrtilloides*.

Table 4. Species, by NPS Unit, that showed a reduction in occurrence probability of ≥ 95% with a simulated 1.5 °C increase in future air temperature.

NPS Unit Code	Species Name
ACAD	*Picea glauca*
	Gaultheria hispidula
	Ledum groenlandicum
GLAC	*Potentilla gracilis*
	Valeriana dioica
SLBE	*Picea glauca*
	Gaultheria hispidula
	Lonicera canadensis
	Lycopodium complanatum
	Rosa acicularis
	Carex arctata
	Equisetum scirpoides
YOSE	*Agastache urticifolia*
	Ribes inerme
	Symphoricarpos mollis
	Aquilegia formosa

Table 5. Species, by NPS Unit, that showed a reduction in occurrence probability of between 80 and 95% with a simulated 1.5 °C increase in future air temperature.

NPS Unit Code	Species Name
ACAD	*Alnus viridis*
	Cornus canadensis
	Rubus pubescens
	Vaccinium myrtilloides
	Oryzopsis asperifolia
GLAC	*Potentilla gracilis*

Table 5 (continued). Species, by NPS Unit, that showed a reduction in occurrence probability of between 80 and 95% with a simulated 1.5 °C increase in future air temperature.

NPS Unit Code	Species Name
GLAC (continued)	*Achnatherum richardsonii*
	Arnica sororia
	Danthonia intermedia
JOTR	*Gutierrezia microcephala*
SLBE	*Cornus canadensis*
	Lycopodium obscurum
	Pyrola elliptica
	Rubus pubescens
	Shepherdia canadensis
	Vaccinium myrtilloides
	Argentina anserina
	Carex pedunculata
	Epipactis helleborine
	Equisetum sylvaticum
	Mitella nuda
	Oryzopsis asperifolia
	Potamogeton gramineus
THRO	*Carex filifolia*
YOSE	*Pinus contorta*
	Rubus ursinus
	Spiraea splendens
	Symphoricarpos mollis
	Holcus lanatus
	Mimulus guttatus
	Oreostemma alpigenum

The distribution of the average (across all species in a map class) percent change in species occurrence probability among map classes is shown in Figure 5 for each NPS study unit. These distributions are represented by a box plot for each of the three climate scenarios. The left end of each box plot (i.e., either the tip of the left whisker or the left-most outlier point) indicates the most negative average percent change among map classes. The right ends of the plots show the most positive percent change in average occurrence probability. Among all parks, nearly all map classes showed reductions in average occurrence probability with warming of +0.5 °C, and some map classes showed greater than 25% reductions in average species response. Although additional map classes showed reductions in occurrence probability greater than 25% under the more extensive warming scenarios of +1.0 °C and +1.5 °C, YOSE was the only NPS Unit with map classes showing average reductions greater than 50%. These relatively large changes for YOSE are expected to occur within the Canyon Live Oak/Whiteleaf Manzanita Forest Association (Zone 2) and Mountain Misery Dwarf-shrubland Alliance (Zone 2) map classes. Although most species responded negatively to warming scenarios, some map classes showed positive responses, particularly at GRTE, ROMO, and YOSE. This reflects the relatively high level of vegetation species diversity found across these parks characterized by broad ranges of elevation.

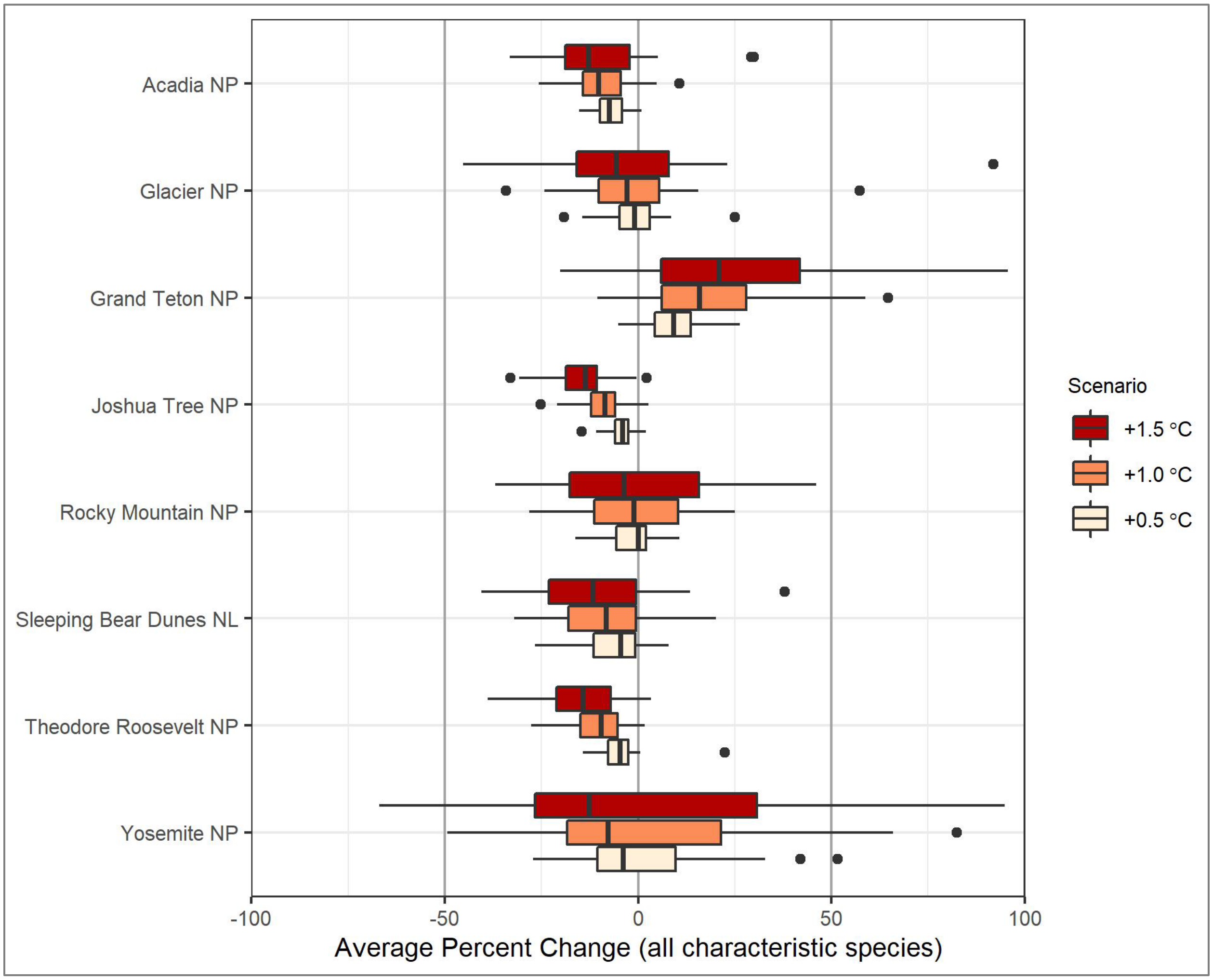

Figure 5. Distribution of the average percent change in species occurrence probability among map classes under future scenarios of increased air temperature for each NPS study unit.

Critical Loads of Atmospheric Nitrogen Deposition

Minimum CLs were less than 2.5 kg N/ha/yr for nearly all map classes across all parks, except for JOTR where the vast majority of map classes showed slightly higher minimum CLs of less than 5 kg N/ha/yr (Figure 6). Parks located in the mountainous terrain of the western United States (i.e., YOSE, GLAC, GRTE, and ROMO) had median CLs of less than 5 kg N/ha/yr for the majority of map classes, whereas median CLs for JOTR, SLBE, and ACAD were mostly between 5 and 10 kg N/ha/yr. THRO reflected the least sensitivity, with median CLs mostly higher than 10 kg N/ha/yr (Figure 6).

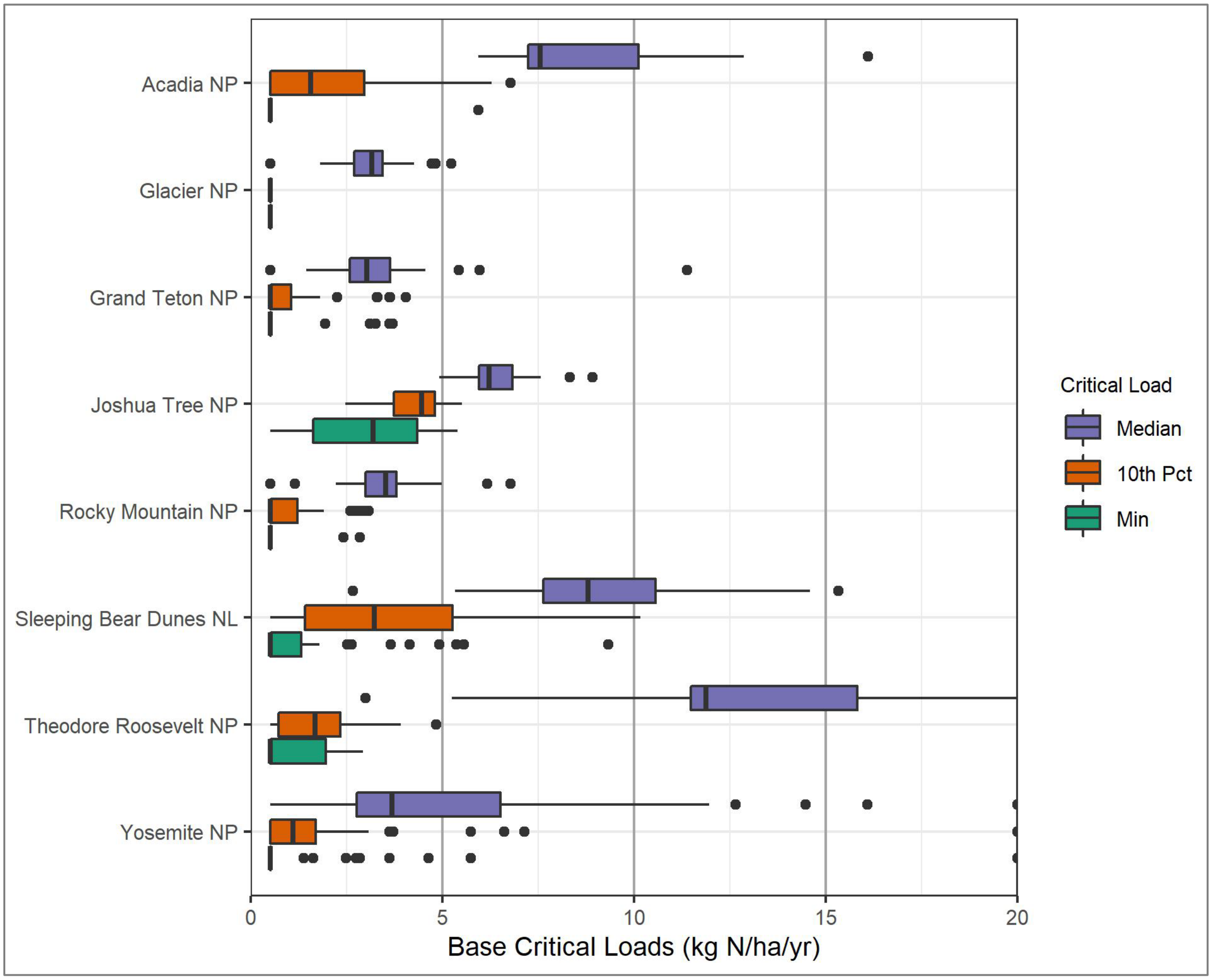

Figure 6. Distribution of the minimum, 10th percentile, and median critical load (kg N/ha/yr) among map classes to protect characteristic understory vegetation under ambient climate conditions for each NPS study unit.

Median CLs among the distributions of the minimum, 10th percentile, and median CLs across map classes were nearly always indeterminable (i.e., maximum occurrence probability under ambient climate was no longer attainable even if annual N deposition was reduced to zero) under climate change scenarios (Table 6). This indicates that at least half of the map classes at each NPS unit are expected to experience reductions in occurrence probability from climate change that cannot be compensated for by reductions in N deposition. Although these adverse effects of climate change are expected to outweigh the benefits of decreased N pollution, reductions in N deposition would still be expected to benefit vegetation species that experience deposition above the designated CL.

More than 90% of map classes of each NPS study unit had minimum CLs (i.e., CLs that protect all characteristic species of a map class) that could not be determined under future climate change scenarios because the effects of increased air temperature were greater than the benefit that can be provided by N deposition reductions (Table 7). Map class-level CLs based on the median CL among characteristic species were indeterminable for more than half of the map classes under all scenarios of increased air temperature at each of the NPS study units, except for GRTE. These results further indicate that substantial impacts on ambient occurrence probability are expected under climate change, which cannot be expected to be fully compensated for by reductions in N deposition.

Table 6. Median value (kg N/ha/yr) of the minimum, 10th percentile, and median critical loads among map classes for each climate scenario and NPS study unit.

NPS Unit Code	# of Map Classes	Ambient Climate Median of the:			+0.5 °C Median of the:			+1.0 °C Median of the:			+1.5 °C Median of the:		
		Min CL	10th Pct CL	Median CL	Min CL	10th Pct CL	Median CL	Min CL	10th Pct CL	Median CL	Min CL	10th Pct CL	Median CL
ACAD	26	0.5	1.5	7.6	NA	NA	NA	NA	NA	NA	NA	NA	NA
GLAC	36	0.5	0.5	3.2	NA	NA	NA	NA	NA	NA	NA	NA	NA
GRTE	48	0.5	0.5	3.0	NA	NA	0.5	NA	NA	0.5	NA	NA	0.5
JOTR	36	3.2	4.4	6.2	NA	NA	NA	NA	NA	NA	NA	NA	NA
ROMO	39	0.5	0.5	3.5	NA	NA	NA	NA	NA	NA	NA	NA	NA
SLBE	43	0.5	3.2	8.8	NA	NA	NA	NA	NA	NA	NA	NA	NA
THRO	24	0.5	1.7	11.9	NA	NA	NA	NA	NA	NA	NA	NA	NA
YOSE	70	0.5	1.1	3.7	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 7. Percent of the total number of map classes for which the critical load is indeterminable (i.e., maximum occurrence probability under ambient climate is not attainable) under each climate scenario. Results are shown based on the minimum, 10th percentile, and median CLs among map classes.

NPS Unit Code	# of Map Classes	+0.5 °C			+1.0 °C			+1.5 °C		
		Min CL	10th Pct CL	Median CL	Min CL	10th Pct CL	Median CL	Min CL	10th Pct CL	Median CL
ACAD	26	100	100	77	100	100	77	100	100	77
GLAC	36	100	100	58	100	100	64	100	100	69
GRTE	48	94	71	8	98	79	13	98	83	19
JOTR	36	97	94	67	97	94	78	100	94	83
ROMO	39	100	95	64	100	95	77	100	95	82
SLBE	43	100	98	61	100	98	61	100	98	63
THRO	24	100	96	75	100	96	83	100	96	92
YOSE	70	96	86	64	96	86	69	96	86	69

Conclusions

Critical loads of atmospheric N deposition were less than 5 kg N/ha/yr for the vast majority of vegetation species and map classes included in this study of eight NPS units distributed across the conterminous United States. Protection of the most sensitive species within vegetation classes typically requires N deposition to be lower than 2.5 kg N/ha/yr. Projected increases in air temperature were shown to have variable effects on vegetation species among the NPS parks with predominantly negative effects, particularly for mountainous NPS units. Reductions in atmospheric N deposition and greenhouse gas emissions would be expected to contribute to preservation of existing biodiversity within U.S. national parks.

Summaries of climate change responses and interactions with N deposition are described for each NPS study unit in the following sub-sections.

Acadia National Park (ACAD)

Nearly all vegetation map classes at ACAD showed negative responses to simulated air temperature increases, with some of the most temperature-sensitive species expected to be nearly extirpated with +1.5 °C of warming. Among vegetation map classes at ACAD, the median CL of N deposition to protect ambient occurrence probability for 90% of characteristic species was 1.5 kg N/ha/yr (min $CL_{90\%}$ = 0.5 kg N/ha/yr; max $CL_{90\%}$ = 6.8 kg N/ha/yr).

Glacier National Park (GLAC)

Although vegetation responses to air temperature increases among map classes at GLAC were mixed, the majority of map classes showed a negative response. The most temperature-sensitive species of each map class showed substantial incremental declines in occurrence probability for each simulated +0.5 °C increase in air temperature. Among vegetation map classes at GLAC, the median CL of N deposition to protect ambient occurrence probability for 90% of characteristic species was 0.5 kg N/ha/yr (min $CL_{90\%}$ = 0.5 kg N/ha/yr; max $CL_{90\%}$ = 0.5 kg N/ha/yr).

Grand Teton National Park (GRTE)

Characteristic species at GRTE generally showed positive responses to simulated air temperature increases. However, decreases in occurrence beyond 50% are expected for some of the most sensitive species with +1.5 °C of warming. Among vegetation map classes at GRTE, the median CL of N deposition to protect ambient occurrence probability for 90% of characteristic species was 0.5 kg N/ha/yr (min $CL_{90\%}$ = 0.5 kg N/ha/yr; max $CL_{90\%}$ = 4.0 kg N/ha/yr).

Characteristic species at GRTE generally showed positive responses to simulated air temperature increases. However, decreases in occurrence beyond 50% are expected for some of the most sensitive species with +1.5 °C of warming. Among vegetation map classes at GRTE, the median CL of N deposition to protect ambient occurrence probability for 90% of characteristic species was 0.5 kg N/ha/yr (min $CL_{90\%}$ = 0.5 kg N/ha/yr; max $CL_{90\%}$ = 4.0 kg N/ha/yr).

Joshua Tree National Park (JOTR)

Nearly all vegetation map classes at JOTR showed negative responses to simulated air temperature increases, with declines in occurrence probability of greater than 50% for some of the most temperature-sensitive species with +1.5 °C of warming. Among vegetation map classes at JOTR, the median CL of N deposition to protect ambient occurrence probability for 90% of characteristic species was 4.4 kg N/ha/yr (min $CL_{90\%}$ = 2.5 kg N/ha/yr; max $CL_{90\%}$ = 5.5 kg N/ha/yr).

Rocky Mountain National Park (ROMO)

Vegetation responses to air temperature increases among map classes at ROMO were nearly evenly split between negative and positive among map classes, with increasing spread in the magnitude of response with each simulated +0.5 °C increase in air temperature. Although relatively small decreases in occurrence are expected for the most temperature-sensitive species of some map classes with +0.5 °C of warming, more substantial increases in air temperature are expected to result in declines of up to 75% for some characteristic species. Among vegetation map classes at ROMO, the median CL of N deposition to protect ambient occurrence probability for 90% of characteristic species was 0.5 kg N/ha/yr (min $CL_{90\%}$ = 0.5 kg N/ha/yr; max $CL_{90\%}$ = 3.1 kg N/ha/yr).

Sleeping Bear Dunes National Lakeshore (SLBE)

Nearly all vegetation map classes at SLBE showed negative responses to simulated air temperature increases. Wide variation in the magnitude of decline in occurrence for the most sensitive species of each map class is expected, with some of these most sensitive species expected to be nearly extirpated with either +1.0 or +1.5 °C of warming. Among vegetation map classes at SLBE, the median CL of N deposition to protect ambient occurrence probability for 90% of characteristic species was 3.2 kg N/ha/yr (min $CL_{90\%}$ = 0.5 kg N/ha/yr; max $CL_{90\%}$ = 10.2 kg N/ha/yr).

Theodore Roosevelt National Park (THRO)

Nearly all vegetation map classes at THRO showed negative responses to simulated air temperature increases. The most temperature-sensitive species of each map class showed substantial incremental declines in occurrence probability for each simulated +0.5 °C increase in air temperature. Among vegetation map classes at THRO, the median CL of N deposition to protect ambient occurrence probability for 90% of characteristic species was 1.7 kg N/ha/yr (min $CL_{90\%}$ = 0.5 kg N/ha/yr; max $CL_{90\%}$ = 4.8 kg N/ha/yr).

Yosemite National Park (YOSE)

Vegetation responses to air temperature increases among map classes at YOSE showed wide variation (both negative and positive) among map classes, with increasing spread in the magnitude of response with each simulated +0.5 °C increase in air temperature. Declines in occurrence for some of the most temperature-sensitive species were beyond 75% under simulated warming of 1.0 and +1.5 °C. Among vegetation map classes at YOSE, the median CL of N deposition to protect ambient occurrence probability for 90% of characteristic species was 1.1 kg N/ha/yr (min $CL_{90\%}$ = 0.5 kg N/ha/yr; max $CL_{90\%}$ = > 20 kg N/ha/yr).

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