Critical Loads Summary
for Bridger-Teton National Forest

Contents

1 Summary for Bridger-Teton National Forest

A critical load (CL) is the atmospheric deposition level expected to result in harmful ecosystem changes. Exceedance is the amount by which local deposition goes beyond an established CL.

1.1 Estimated deposition range

Table 1: Estimated deposition range for this location, from the 2017-2019 three-year average of total nitrogen or total sulfur modeled by Total Deposition (TDep). Units: kg ha^{-1} y^{-1}.

Deposition	Minimum	Maximum
Nitrogen	2.6	7.5
Sulfur	0.6	2.0

1.2 Short summary of critical loads

Table 2: Abbreviated summary of critical loads used to establish conditions and trends by ecosystem component. Units: kg ha^{-1} y^{-1}.

Ecosystem component	Nitrogen CL	Sulfur CL
Alpine minimum:	3.0	–
Alpine maximum:	10.0	–
Aquatic minimum:	1.0	–
Aquatic maximum:	4.1	–
Herb minimum:	1.5	0.4
Herb median:	8.7	0.4
Herb maximum:	20.8	43.0
Tree growth minimum:	1.4	–
Tree growth median:	12.7	–
Tree growth maximum:	17.5	–
Tree survival minimum:	2.0	–
Tree survival median:	4.2	–
Tree survival maximum:	9.0	–
Lichen minimum:	1.3	2.3
Lichen maximum:	3.5	6.0

1.3 Extended summary of critical loads

Ecosystem component	Source	Name	Nitrogen CL	Sulfur CL
Deposition	Model	Deposition minimum	2.6	0.6
Deposition	Model	Deposition maximum	7.5	2.0
Alpine	Area	Alpine minimum	3.0	–
Alpine	Area	Alpine maximum	10.0	–
Aquatic	Plot	Aquatic eutrophication minimum	1.0	–
Aquatic	Plot	Aquatic eutrophication maximum	3.0	–
Aquatic	Plot	Aquatic N- to P-limitation, fixed	4.1	–
Herb	Plot	Herb richness (open, plot min.)	–	–
Herb	Model	Herb richness (open, surface min.)	7.7	–
Herb	Model	Herb richness (open, surface 10% decline)	10.1	–
Herb	Plot	Herb richness (closed, plot min.)	–	–
Herb	Model	Herb richness (closed, surface min.)	11.4	–
Herb	Model	Herb richness (closed, surface 10% decline)	15.4	–
Herb	Area	Pardo herb minimum	–	–
Herb	Area	Pardo herb maximum	–	–
Herb	Plot	Herb occurrence minimum	1.5	0.4
Herb	Plot	Herb occurrence median	8.7	0.4
Herb	Plot	Herb occurrence maximum	20.8	43.0
Forest	Area	Forest minimum	–	–
Forest	Area	Forest maximum	–	–
Tree	Plot	Tree growth minimum	1.4	–
Tree	Plot	Tree growth minimum	1.4	–
Tree	Plot	Tree growth median	12.7	–
Tree	Plot	Tree growth maximum	17.5	–
Tree	Plot	Tree survival minimum	2.0	–
Tree	Plot	Tree survival median	4.2	–
Tree	Plot	Tree survival maximum	9.0	–
Lichen	Model	Lichen minimum	1.3	2.3
Lichen	Model	Lichen maximum	3.5	6.0
Lichen	Model	Lichen total richness	3.5	6.0
Lichen	Model	Lichen total richness 30% decline	5.5	10.1
Lichen	Model	Sensitive lichen richness	3.1	2.5
Lichen	Model	Sensitive lichen richness 30% decline	4.7	3.6
Lichen	Model	Forage lichen abundance	1.9	2.6
Lichen	Model	Forage lichen abundance 30% decline	2.8	3.8
Lichen	Model	Cyanolichen abundance	1.3	2.3
Lichen	Model	Cyanolichen abundance 30% decline	1.9	3.2
Lichen	Model	Lichen community airscores	1.5	2.7
Soil	Area	Mycorrhizal fungi minimum	–	–
Soil	Area	Mycorrhizal fungi maximum	–	–
Soil	Area	Nitrate leaching minimum	–	–
Soil	Area	Nitrate leaching maximum	–	–

2 Deposition from TDep

Citation: Schwede and Lear (2014)

Description: Deposition of N- and S-containing compounds was modeled with the National Atmospheric Deposition Program Total Deposition Model (TDep). For total N deposition, the TDep model (version 2018.02) uses measurements of HNO_3 (dry), NO_3 (wet/dry) and NH_4 (wet) to modify the CMAQ model (v.5.0.2), and then incorporates modeled dry deposition of gaseous NH_3, PAN, N_2O_5, NO, NO_2, HONO, and organic nitrates (Schwede and Lear 2014). For total S deposition, the TDep model (v.2018.02) uses measurements of SO_2 (dry), pSO_4 (dry) and SO_4 (wet) to modify outputs of the CMAQ model (version 5.0.2). To smooth year-to-year variation, we report mean annual deposition for the three-year period 2017-2019.

Cell size: 4134 m

Most recent data: 2017-2019

Uncertainty: A weighted deposition uncertainty metric (WDUM) helps scientists and decision-makers assess CL exceedances (Walker et al. 2019). The WDUM applied to National Atmospheric Deposition Program (NADP) Total Deposition (TDep) estimates shows greater uncertainty where dry deposition makes a larger contribution to the deposition budget, particularly ammonia (NH_3) in agricultural areas and oxidized nitrogen (NO_x) in urban areas. Organic N deposition is an important source of uncertainty over much of the US. The WDUM can help assess spatial patterns of deposition uncertainty and inform CL assessments at the local scale.

Table 4: Estimated deposition minimum, median and maximum for this location, from the 2017-2019 three-year average of total nitrogen or total sulfur modeled by Total Deposition (TDep). Percent wet deposition values are provided for clarity of deposition types. Units: kg ha^{-1} y^{-1}.

Type	Minimum	Median	Maximum
Total N deposition (kg N ha^{-1} y^{-1})	2.6	4.6	7.5
Percent wet N deposition (%)	38.7	61.5	75.2
Percent oxidized N (%)	36.8	43.0	56.6
Total S deposition (kg S ha^{-1} y^{-1})	0.6	1.2	2.0
Percent wet S deposition (%)	40.0	64.7	81.0

3 Alpine vegetation

Citation: Bowman et al. (2012)

Description: Researchers fertilized alpine vegetation with increasing levels of N to determine the level of deposition that changed community compositions. Plots were located in multiple sites on the eastern edge of the Rocky Mountains of Colorado. Models calculated a 2.5% increase in *Carex rupestris* cover per year at 3.0 kg N ha^{-1} y^{-1}, and increases in NO_3 leaching below the rooting zone at 10.0 kg N ha^{-1} y^{-1}.

Response: Response curves were not calculated in this analysis.

Notes: This CL is specific to alpine meadow habitats, but is applied more broadly due to lack of additional data and because alpine vegetation occurs in a range of habitats above treeline. The sedge species in the N-fertilization experiment occurs across the Rocky Mountains but not elsewhere. The CL is extrapolated because similar CLs exist in harsh, low-nutrient ecosystems.

Critical load of N for an increase in alpine sedge growth: 3.0 kg N ha^{-1} y^{-1}

Critical load of N for an increase in soil N leaching: 10.0 kg N ha^{-1} y^{-1}

Data type: surface

Cell size: 30 m

Most recent data: xxxx-xxxx

Data description: The critical loads are applied to all areas above sea level within each land unit because national datasets were inconsistent in identifying vegetated areas relative to local surveys (McClung et al. 2021). The alpine dataset is extracted from the USGS Gap Analysis Project.

Table 5: Alpine area (km^2) below, at or above critical loads of N for alpine ecosystems.

Type	Alpine area (km^2)	Area < CL (km^2)	Area at CL (km^2)	Area > CL (km^2)
Increased sedge growth	3158	0	46.1	3112
Increased NO_3 leaching	3158	3158	0.0	0

4 Aquatic systems: shift from N- to P-limitation

Citation: Williams et al. (2017)

Description: Critical loads of N for shifts from N to P limitation of phytoplankton biomass growth in high elevation lakes are from Williams et al. (2017), who showed accurate prediction of NO_3 threshold exceedance in 69% of lakes at a critical load of 4.1 kg ha^{-1} y^{-1}.

To define the CL, Williams et al. (2017) first selected a biological measure of nutrient limitation shifts, and defined its threshold value. Second, logistic regression defined lake water chemical thresholds for nitrate, dissolved inorganic nitrogen (DIN), and DIN-to-total phosphorus (TP) mass ratio DIN:TP associated with 50% and 70% probability of exceeding the biological threshold. Third, logistic regression models described the mathematical relationship between nitrogen deposition and exceedance of biological thresholds (an empirical critical load) or chemical thresholds (a modeled critical load). Logistic regression was appropriate to identify critical loads because lake water NO_3 responses to N deposition typically show a dog-leg rather than linear pattern (see Williams et al. 2017).

Data from bioassays in 47 mountain lakes (>1200m) within federal land units were used to define biological (RR-N/RR-P = 1) and chemical (NO_3, DIN, DIN:TP) thresholds above which biomass P limitation exceeds N limitation. Williams et al. (2017) applied this critical load to an independent sample of 385 mountain lakes with NO_3 data to estimate the frequency it would fail to predict a limitation shift. Lake chemistry data used in analyses were obtained from the Georeferenced Lake Nutrient Chemistry (GLNC) database (Williams and Labou 2017).

Response: Across models, estimated critical loads ranged from 2.8 to 5.2 kg N ha^{-1} y^{-1}. The best-performing model, a univariate logistic model with N deposition as the only predictor of NO_3 threshold exceedance, gave a critical load of 4.1 kg N ha^{-1} y^{-1}, and accurately predicted NO_3 threshold exceedance in 69% of lakes.

Notes: The false-negative rate of the 385 mountain lakes was 13% across the western United States, but was slightly higher (22%) in the Sierras. Performance analyses suggest a 2.0 kg N ha^{-1} y^{-1}critical load may avoid false negatives entirely. Critical load of N for shifts from N to P limitation of phytoplankton biomass growth in high elevation lakes was identified at 4.1 kg N ha^{-1} y^{-1}.

Data type: Point

Data description: To extrapolate results beyond the lakes identified in the manuscript, we used the USGS National Hydrography Dataset Plus High Resolution to identify lakes in the western United States above 1,200 m and 1–70 ha in size. Each point was given a critical load of 4.1 kg N ha^{-1} y^{-1}, and local N deposition was extracted from the 2017-2019 TDep total N model to calculate exceedances.

Table 6: Number of high-elevation lakes in exceedance of the N $\rightarrow$ P shift critical loads, based on 2017-2019 TDep total N.

Critical load	Total number of lakes	Number of lakes < CL	Number of lakes at CL	Number of lakes > CL
4.1 kg N ha^{-1} y^{-1}	1958	259	1059	640

5 Aquatic systems: eutrophication

Citation: Baron et al. (2012)

Description: Baron et al. summarize the aquatic eutrophication literature

Response: The critical load for nutrient enrichment (increase in lake NO_3) in western lakes ranged from 1.0–3.0 kg N ha^{-1} y^{-1}, reflecting the nearly nonexistent vegetation in complex, snowmelt-dominated watersheds. The same critical load for northeastern lakes ranged from 3.5–6.0 kg N ha^{-1} y^{-1}.

Notes: Keep in mind that the threshold will differ between lakes of strongly vs. weakly vegetated catchments. For eastern lakes, where ecosystems currently experience elevated N deposition, the ability to attribute biological changes directly to N deposition is confounded by decades of elevated atmospheric N deposition and land-use change.

Data type: Point

Data description: To extrapolate results beyond the lakes identified in the manuscript, we used the USGS National Hydrography Dataset Plus High Resolution to identify lakes in the western United States above 1,200 m and 1–70 ha in size. Each point was given a corresponding critical load, and local N deposition was extracted from the 2017-2019 TDep total N model to calculate exceedances.

Table 7: Number of high-elevation lakes in exceedance of the nutrient enrichment critical loads, based on 2017-2019 TDep total N.

Critical load	Total number of lakes	Number of lakes < CL	Number of lakes at CL	Number of lakes > CL
Low (1.0 kg ha^{-1} y^{-1})	1958	0	186	1772
High (3.0 kg ha^{-1} y^{-1})	1958	0	0	1958

6 Herbaceous plants: species richness

Citation: Simkin et al. (2016)

Description: This analysis used 15,136 vegetation survey plots from Simkin et al. (2016) to evaluate how plant species richness varies with nitrogen deposition, soil pH, mean annual precipitation, and mean annual temperature. Plots were classified as open-canopy (3,317) or closed-canopy (11,819) based on tree canopy cover at plot locations. Each plot has a CL value based on a modeled response with pH (for closed-canopy) or pH, precipitation and temperature (for open-canopy). Plot locations were distributed non-randomly across the continental US, with implications discussed below.

Response: Total species richness initially increases with increasing N deposition under all soil pH, temperature, and precipitation conditions. The critical load is modeled to occur at the highest level of species richness based on environmental conditions. The rate of decline in species richness varies with pH in closed-canopy sites.

Notes: Species richness increases at lower levels of deposition before reaching the critical load at maximum richness based on soil pH, precipitation, and temperature. Increases in richness are expected to be of species that are tolerant of N deposition. The critical is set at max richness as an estimate of when the increase in tolerant species leads to the loss of other species. Ecological harm may occur prior to the critical load but is not able to be determined by this dataset.

Critical load of N for a decline in herbaceous species richness under a closed canopy: variable, changes with pH

Critical load of N for a decline in herbaceous species richness under an open canopy: variable, changes with pH, precipitation, temperature

Data type: point

Plot size: variable, xxx-xxx ha

Most recent data: xxxx-xxxx

Point data description: A sample size analysis was completed to determine if there were enough points to accurately estimate a CL for a specific land unit (Lynch et al. 2020). The deposition level at which species richness declines 10% is calculated via the maximum potential richness using pH, precip, and temperature data. When a point is in exceedance of the critical load, the expected decline was calculated using TDep Total N data from 2017-2019.

Data type: surface

Cell size: 240 m

Most recent data: xxxx-xxxx

Surface data description: Equations from Simkin et al. (2016) were used to develop a continuous surface of critical loads using PRISM 800-m 30-y mean annual precipitation and temperature, and 30-m gNATSGO DCP soil pH 0-20 cm. Each dataset was clipped to the appropriate ecosystem type using National Land Cover Database (NLCD) data. Open-canopy systems were defined by the 2016 NLCD as grassland, shrubland, and woodland, with alpine areas removed; closed-canopy systems were made up of deciduous forest, evergreen forest, and mixed forest. The deposition level at which species richness declines 10% is calculated via the max potential richness using pH, precipitation, and temperature data. When a point is in exceedance of the critical load, the expected decline was calculated using TDep Total N data from 2017-2019.

Table 8: Critical loads based on point data from Simkin et al. (2016).

Status
No point data available

Table 9: Exceedances based on point data from Simkin et al. (2016).

Status
No point data available

Table 10: Critical loads of N for decline in herbaceous plant species richness, and the deposition at which a 10% loss of richness occurs, based on modeled surfaces using equations from Simkin et al. (2016).

Canopy	Min CL	Median CL	Max CL	Min 10% decline	Med 10% decline	Max 10% decline
Open	7.7	9.0	10.9	10.1	11.6	13.8
Closed	11.4	15.8	20.0	15.4	20.9	26.1

Table 11: The exceedance of critical loads of N, and the expected decline in richness, for modeled surface data based on 2017-2019 TDep total N.

Canopy	Area (km^2)	Area < CL (km^2)	Area at CL (km^2)	Area > CL (km^2)	Min richness decline	Max richness decline
Open	7191.8	7191.8	0	0	10.1	13.8
Closed	10016.8	10016.8	0	0	Inf	-Inf

7 Herbaceous plants: single-species probability of occurrence

Citation: Clark et al. (2019) and Russell et al. (2021)

Description: This analysis used individual species presence and cover from the 15,136 vegetation survey plots from Simkin et al. (2016) to determine the critical load of N and of S for the probability of occurrence of 358 herbaceous species. Each point/species combination has a CL value that is based on a modeled response that can include pH, precip, and temp. The plots in Clark et al. (2019) are distributed non-randomly across the lower 48-states, the implications of which are discussed below.

Response: The probability of occurrence (POC) of each herbaceous species responds to N and S deposition in one of five ways. "Increasers" increase in POC as deposition increases; the critical load is set at maximum deposition of measured points as a harmful response has not yet been reached. "Decreasers" decrease in POC as deposition increases; the critical load is set at the minimum deposition of measured points since a harmful response is continuous across the distribution. A "Threshold" response (N only) initially increases as deposition increases, but then reaches a maximum POC before decreasing across the rest of the range; the critical load is set at the maximum POC since harmful responses are identified as those that reduce POC. "Saddle" responses can either increase or decrease and are dependent of passing a threshold of pH, temp, precip, or deposition; no critical load was set for these responses in this analysis. "U-shaped" responses initially decrease as deposition increases, but then reaches a minimum POC before increasing across the rest of the range; no critical load was set for these responses as additional information is needed to justify the response.

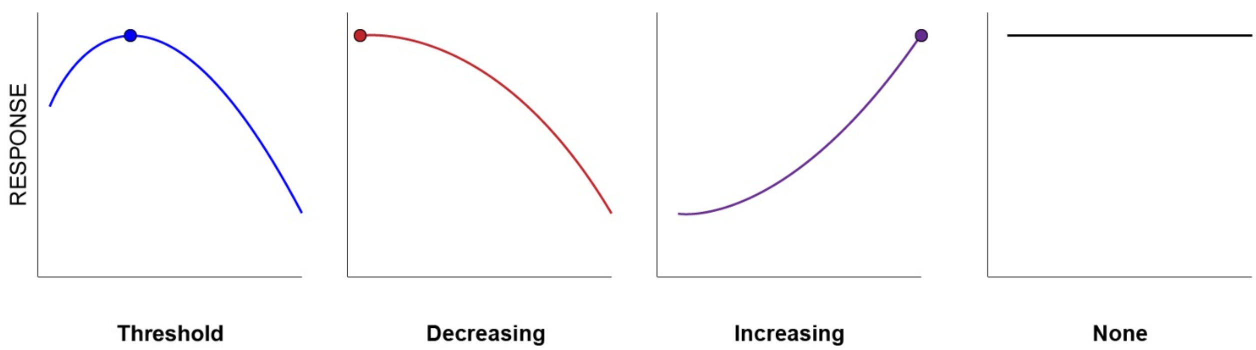

Figure 1: Example of four possible herbaceous plant species responses. Deposition (of N or S) increases from left to right on horizontal axis. Species probability of occurrence is on vertical axis. Each circle symbol, at peak probability of occurrence, is the critical load. Sulfur response shapes are limited to decreasing, increasing, or none.

Notes: If a critical load was calculated to be negative based on the partial derivative equation, then the critical load was set to zero.

Critical load of N for a decline in POC of individual herbaceous species: variable; varies by species and pH, temperature, precipitation, and N deposition.

Critical load of S for a decline in POC of individual herbaceous species: variable; varies by species and pH, temperature, precipitation, and S deposition.

Data type: Point

Data description: Vegetation point data are from two different sources. The first source, Clark et al. (2019), contains the point data used to develop the regression curves. The second source, the National Park Service Vegetation Mapping Inventory program, contains species location data. Covariate data for local pH (gNATSGO), annual precipitation (PRISM), and mean annual temperature (PRISM) were extracted for each point location. In some cases, the geographic distribution of a species occurs beyond the range of environmental conditions used in the CL model.

Table 12: Herbaceous plant species responses (probability of occurrence, POC) to **nitrogen (N)** deposition, from Clark et al. (2019). The CL equations for each species were used to determine the range of CLs based on local environmental conditions. Exceedances are calculated at each point location relative to 2017-2019 TDep total N deposition.

Species	Response	Count	Max CL	Min CL	Min dep	Max dep	Points < CL	Points at CL	Points > CL
Achillea millefolium	U	29	0.0	0.0	3.4	4.7	0	29	0
Actaea rubra	threshold	2	20.3	20.8	3.6	4.1	2	0	0
Agrostis stolonifera	increase	1	14.7	14.7	3.6	3.6	1	0	0
Bromus ciliatus	threshold	7	5.4	6.0	3.5	4.5	7	0	0
Bromus inermis	increase	7	18.9	18.9	3.5	4.5	7	0	0
Campanula rotundifolia	threshold	5	6.7	8.2	3.7	4.7	5	0	0
Cirsium arvense	threshold	2	5.0	5.5	3.6	3.9	2	0	0
Danthonia spicata	threshold	1	4.4	4.4	3.4	3.4	1	0	0
Elymus canadensis	saddle	1	0.0	0.0	3.5	3.5	0	1	0
Elymus trachycaulus	threshold	3	9.5	9.9	3.6	4.7	3	0	0
Equisetum arvense	saddle	3	0.0	0.0	3.4	3.9	0	3	0
Equisetum laevigatum	threshold	1	9.3	9.3	3.6	3.6	1	0	0
Fragaria vesca	threshold	10	1.5	2.0	3.4	3.9	0	0	10
Fragaria virginiana	threshold	7	6.9	6.9	3.6	4.7	7	0	0
Galium triflorum	threshold	1	8.7	8.7	3.4	3.4	1	0	0
Geum triflorum	threshold	4	7.1	9.0	3.4	3.5	4	0	0
Hesperostipa comata	threshold	10	7.5	10.8	3.4	3.6	10	0	0
Koeleria macrantha	threshold	12	8.8	9.6	3.4	4.6	12	0	0
Linnaea borealis	U	2	0.0	0.0	4.0	4.1	0	2	0
Maianthemum racemosum	threshold	1	12.6	12.6	3.6	3.6	1	0	0
Maianthemum stellatum	threshold	5	8.3	8.5	3.5	4.1	5	0	0
Phleum pratense	saddle	8	0.0	0.0	3.5	4.1	0	8	0
Poa compressa	threshold	1	5.8	5.8	3.5	3.5	1	0	0
Poa pratensis	threshold	26	10.6	11.6	3.4	4.5	26	0	0
Pteridium aquilinum	threshold	2	7.8	7.8	3.4	3.5	2	0	0
Solidago canadensis	threshold	1	16.6	16.6	3.6	3.6	1	0	0
Symphyotrichum ciliolatum	threshold	1	8.2	8.2	3.5	3.5	1	0	0
Taraxacum officinale	U	4	0.0	0.0	3.6	4.5	0	4	0
Tragopogon dubius	U	3	0.0	0.0	3.5	4.0	0	3	0
Urtica dioica	increase	1	18.9	18.9	4.1	4.1	1	0	0

Table 13: Herbaceous plant species responses (probability of occurrence, POC) to **sulfur (S)** deposition, from Clark et al. (2019). The CL equations for each species were used to determine the range of CLs based on local environmental conditions. Exceedances are calculated at each point location relative to 2017-2019 TDep total S deposition.

Species	Shape	Count	Max CL	Min CL	Min dep	Max dep	Points < CL	Points at CL	Points > CL
Achillea millefolium	decrease	29	0.4	0.4	1.0	1.4	0	0	29
Actaea rubra	decrease	2	0.4	0.4	1.0	1.2	0	0	2
Agrostis stolonifera	none	1	0.0	0.0	1.0	1.0	0	1	0
Bromus ciliatus	decrease	7	0.4	0.4	1.0	1.3	0	0	7
Bromus inermis	decrease	7	0.4	0.4	1.0	1.3	0	0	7
Campanula rotundifolia	saddle	5	0.0	0.0	1.1	1.4	0	5	0
Cirsium arvense	none	2	0.0	0.0	1.1	1.1	0	2	0
Danthonia spicata	decrease	1	0.4	0.4	1.0	1.0	0	0	1
Elymus canadensis	decrease	1	2.2	2.2	1.0	1.0	1	0	0
Elymus trachycaulus	decrease	3	0.6	0.6	1.0	1.4	0	1	2
Equisetum arvense	decrease	3	0.4	0.4	1.0	1.1	0	0	3
Equisetum laevigatum	saddle	1	0.0	0.0	1.1	1.1	0	1	0
Fragaria vesca	decrease	10	0.4	0.4	1.0	1.1	0	0	10
Fragaria virginiana	saddle	7	0.0	0.0	1.0	1.4	0	7	0
Galium triflorum	decrease	1	0.4	0.4	0.9	0.9	0	0	1
Geum triflorum	decrease	4	0.4	0.4	1.0	1.0	0	0	4
Hesperostipa comata	decrease	10	0.4	0.4	1.0	1.0	0	0	10
Koeleria macrantha	increase	12	17.1	17.1	1.0	1.4	12	0	0
Linnaea borealis	increase	2	27.6	27.6	1.1	1.2	2	0	0
Maianthemum racemosum	decrease	1	0.4	0.4	1.0	1.0	0	0	1
Maianthemum stellatum	decrease	5	0.4	0.4	1.0	1.2	0	0	5
Phleum pratense	decrease	8	0.4	0.4	1.0	1.2	0	0	8
Poa compressa	saddle	1	0.0	0.0	1.0	1.0	0	1	0
Poa pratensis	decrease	26	0.4	0.4	0.9	1.3	0	0	26
Pteridium aquilinum	decrease	2	0.4	0.4	1.0	1.0	0	0	2
Solidago canadensis	increase	1	41.7	41.7	1.0	1.0	1	0	0
Symphyotrichum ciliolatum	decrease	1	0.4	0.4	1.0	1.0	0	0	1
Taraxacum officinale	increase	4	43.0	43.0	1.0	1.3	4	0	0
Tragopogon dubius	none	3	0.0	0.0	1.0	1.1	0	3	0
Urtica dioica	saddle	1	0.0	0.0	1.2	1.2	0	1	0

8 Tree growth and survival

Citation: Horn et al. (2018)

Description: The growth model assumes a maximum potential growth rate (as a function of tree size) modified by competition and climate (Thomas et al. 2010). First, the data were assessed to evaluate whether deposition was important for growth or survival. Several models were assessed to determine whether models with N and/or S deposition terms were more explanatory than models based only on tree size, climate, and competition. If the model with N and/or S deposition was selected over the model without the deposition terms for a given species, the relationship between deposition and growth for that species was included in the assessment.

Response: The shapes of the response curves for N were 1) increasing, 2) unimodal (hump-shaped), 3) decreasing, or 4) no response and thus flat. For S these were constrained to either 1) decreasing or 2) flat. The CL was set at the point with maximum growth or survival, in the following way for the four different response patterns as deposition increased:
1. Threshold–the CL was set at the highest growth/survival level for species with a unimodal (hump-shaped) response.
2. Decreasing– the CL was set at less than lowest deposition level at which the species occurred and labeled decreasing.
3. Increasing— the CL was set as greater than highest deposition level at which the species occurred for response curves that increased across the whole deposition range.
4. No critical load was set if there was no trend in response.

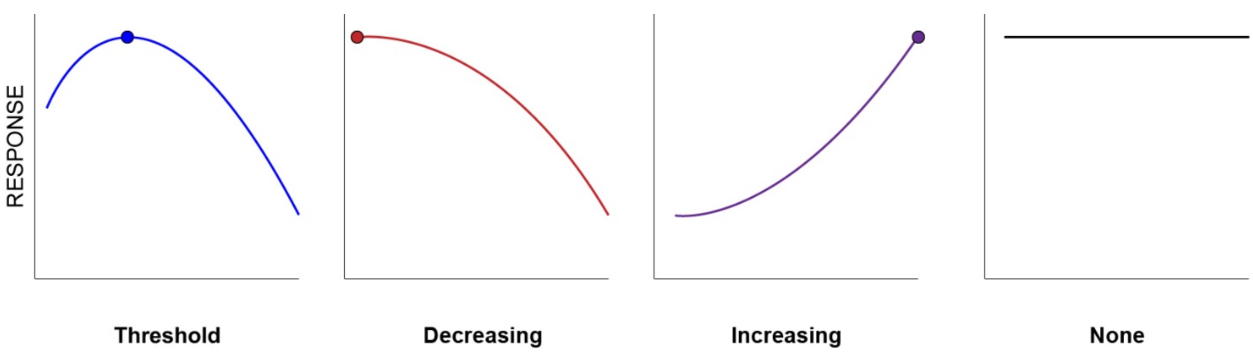

Figure 2: Example of four possible tree species responses. Deposition (of N or S) increases from left to right on horizontal axis. Species growth or survival is on vertical axis. Each circle symbol, at peak probability of occurrence, is the critical load. Sulfur response shapes are limited to decreasing, increasing, or none.

Notes: Species richness increases from lower levels of deposition before reaching the critical load at maximum richness based on soil pH, precipitation, and temperature. Increases in richness are expected to be for species that are tolerant of N deposition. The critical load is set at maximum richness as an estimate of when the increase in tolerant species leads to the loss of other species. Ecological harm may occur prior to the critical load, but cannot be determined by this dataset.

Critical load of N for a decline in tree species survival: single for each tree species, variable in amount and direction of change with a combination of tree size, climate, and competition.

Critical load of N for a decline in tree species growth: single for each tree species, variable in amount and direction of change with a combination of tree size, climate, and competition.

Data type: point

Point data description: Forest Inventory and Analysis plots provide a list of tree species, later paired with nitrogen deposition and environmental covariates in the critical loads models. Level of nitrogen deposition above a critical load was used to calculate the modeled percent decline in growth or survival.

Data type: species list

Species list data description: Using a list of tree species, alongside the range of N deposition within a land unit, allows for the maximum and minimum level of response to be calculated. If the minimum deposition exceeds a species' critical load, then the species is at risk at all locations within the land unit, while if only the maximum deposition is in exceedance, then additional analysis needs to be completed to know if the species exists in the area it would be in exceedance.

Data type: surface

Surface data description: The list of tree species within a land unit is paired with Wilson et al. (2012) species distribution models at 100-m resolution and TDep modeled deposition. This information is used to calculate critical loads exceedances, expected response level, and basal area impacted.

Table 14: Tree species critical loads summary.

Tree CL type	Critical load (kg N ha^{-1} y^{-1})
Tree species with growth CL	4
Minimum growth CL	1.4
Median growth CL	14.3
Maximum growth CL	17.5
Tree species with survival CL	3
Minimum survival CL	2.0
Median survival CL	4.2
Maximum survival CL	9.0

Table 15: Tree species growth and survival responses (based on **point data**). CL and deposition units: kg N ha^{-1} y^{-1}

Species	Response	Shape	Count	CL	Min dep	Max dep	Points < CL	Points at CL	Points > CL	Min response	Max response
Abies lasiocarpa	growth	increase	195	14.3	3.2	7.5	195	0	0		
Abies lasiocarpa	survival	flat	195		3.2	7.5					
Picea engelmannii	growth	decrease	194	1.4	3.2	7.5	0	0	194	-0.1	-0.1
Picea engelmannii	survival	threshold	194	9.0	3.2	7.5	194	0	0	-0.2	-0.0
Pinus contorta	growth	flat	195		2.6	6.1					
Pinus contorta	survival	flat	195		2.6	6.1					
Populus tremuloides	growth	threshold	106	11.1	2.6	6.0	106	0	0	-0.4	-0.1
Populus tremuloides	survival	threshold	106	4.2	2.6	6.0	75	15	16	-0.0	-0.0
Pseudotsuga menziesii	growth	increase	121	17.5	2.6	6.0	121	0	0		
Pseudotsuga menziesii	survival	threshold	121	2.0	2.6	6.0	0	0	121	-0.0	-0.0

Table 16: Tree species growth and survival responses (based on **species list data**).

Status
No data available

9 Lichen communities

Citation: Geiser et al. (2019) and Geiser et al. (2021)

Description: Lichen data are in the publicly accessible USFS national lichen database at https://gis.nacse.org/lichenair. Data originate from the USFS Forest Inventory and Analysis (FIA) and Air Resource Management (ARM) programs. The dataset includes 127,001 voucher specimens of 572 species from 2,156 plots in the eastern US and 6,699 plots in the western US for years 1990–2012. For all species on a plot, field crews assign a rating for ocular abundance on a roughly logarithmic 1–4 scale. Species with abundance ratings of 3 and 4 were considered to provide ecologically substantial contributions to nutrient cycling and to forage, nesting materials, or habitat for forest wildlife and invertebrates.

Response: Five metrics were calculated from lichen survey data:

1. total species richness – the count of all of epiphytic macrolichen species at a site
2. sensitive species richness – the count of N- and S-sensitive species at a site
3. abundance of forage lichens – the sum of abundance ratings for forage lichens at a site, for species with abundance ratings of 3 or 4
4. abundance of cyanolichens – the sum of abundance ratings for cyanolichens detected at a site, for species with abundance ratings of 3 or 4
5. airscores – community-weighted mean of species' deposition optima, showing the central tendency of lichens' tolerance to deposition.

For the abundance-based models (items 1–4 in list above), Geiser et al. (2019) used quantile regression at the 90^{th} percentile to separately model the upper bounds of four lichen responses (total species richness, sensitive species richness, forage lichen abundance and cyanolichen abundance) as a function of N or S deposition. The CL for each lichen response was defined as the point along the prediction response curve resulting in a 20% decline from its maximum value, at which ecological harm would occur. Geiser et al. (2019) reported these CLs at 3.5, 3.1, 1.9, and 1.3 kg N ha^{-1} $y^{-1}$and 6.0, 2.5, 2.6, and 2.3 kg S ha^{-1} y^{-1}, respectively. Each CL is interpreted as the deposition value below which no detrimental change in richness/abundance occurs.

For the composition-based models (item 5 in list above), Geiser et al. (2021) calculated a community composition "airscore" for each plot as the community-weighted mean of species' deposition optima, where optima were calculated as the deposition value at which each species reached its peak detection frequency from 9,000+ nationwide plots. Therefore, airscores depict air quality as the average central tendency of deposition tolerances among all species in a community, weighted by species' abundances. The airscores CL is defined as the uppermost N or S deposition value at which the slope of a nonlinear regression surface did not significantly depart from zero, which occurs at 1.5 kg N ha^{-1} $y^{-1}$and 2.7 kg S ha^{-1} y^{-1}, respectively (Geiser et al. 2021). Each CL is interpreted as the deposition value below which no detrimental change in community compositions occurs.

Deposition data for calculation of lichen CLs are from CMAQ version 5.0.2 (leading up to 2012 for most recent plot visits), and data for estimation of exceedances are from CMAQ version 5.3.2 (most up-to-date data, up to year 2017).

Notes: The geographic distribution of forage lichens and cyanolichens was constrained (masked) by tolerable habitats (must include forested land within suitable climate conditions) further described in Lynch et al. (2020).

Data type: point

Point data description: Plot data from the USFS Forest Inventory and Analysis (FIA) and Air Resource Management (ARM) programs provide a list of epiphytic macrolichen species per site, later paired with N and S deposition originating from CMAQ version 5.3.2 estimated at plot locations.

Table 17: Critical loads for lichens, based on decline in richness/abundance or change in community composition airscores, and the area in exceedance of each CL. Deposition estimates use 2015-2017 CMAQ total N or total S. Deposition units: kg ha^{-1} y^{-1}. Area units: km^2.

Lichen metric	Element	Critical load	Dep. at 30% decline	Dep. at 50% decline	Area < CL (km^2)	Area at CL (km^2)	Area > CL (km^2)	Min response	Max response
Total species richness	N	3.5	5.5	12.0	92	2958	6994	4.0	37.8
Sensitive richness	N	3.1	4.7	8.3	0	1367	8677	4.2	45.6
Forage lichen abundance	N	1.9	2.8	5.2	0	0	9931	6.9	66.2
Cyanolichen abundance	N	1.3	1.9	3.5	0	0	10014	10.0	85.4
Community airscores	N	1.5							
Total species richness	S	6.0	10.1		10044	0	0	2.4	7.4
Sensitive richness	S	2.5	3.6	6.6	10044	0	0	5.6	17.3
Forage lichen abundance	S	2.6	3.8	6.8	9931	0	0	5.3	16.3
Cyanolichen abundance	S	2.3	3.2	5.8	9969	45	0	6.2	19.1
Community airscores	S	2.7							

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