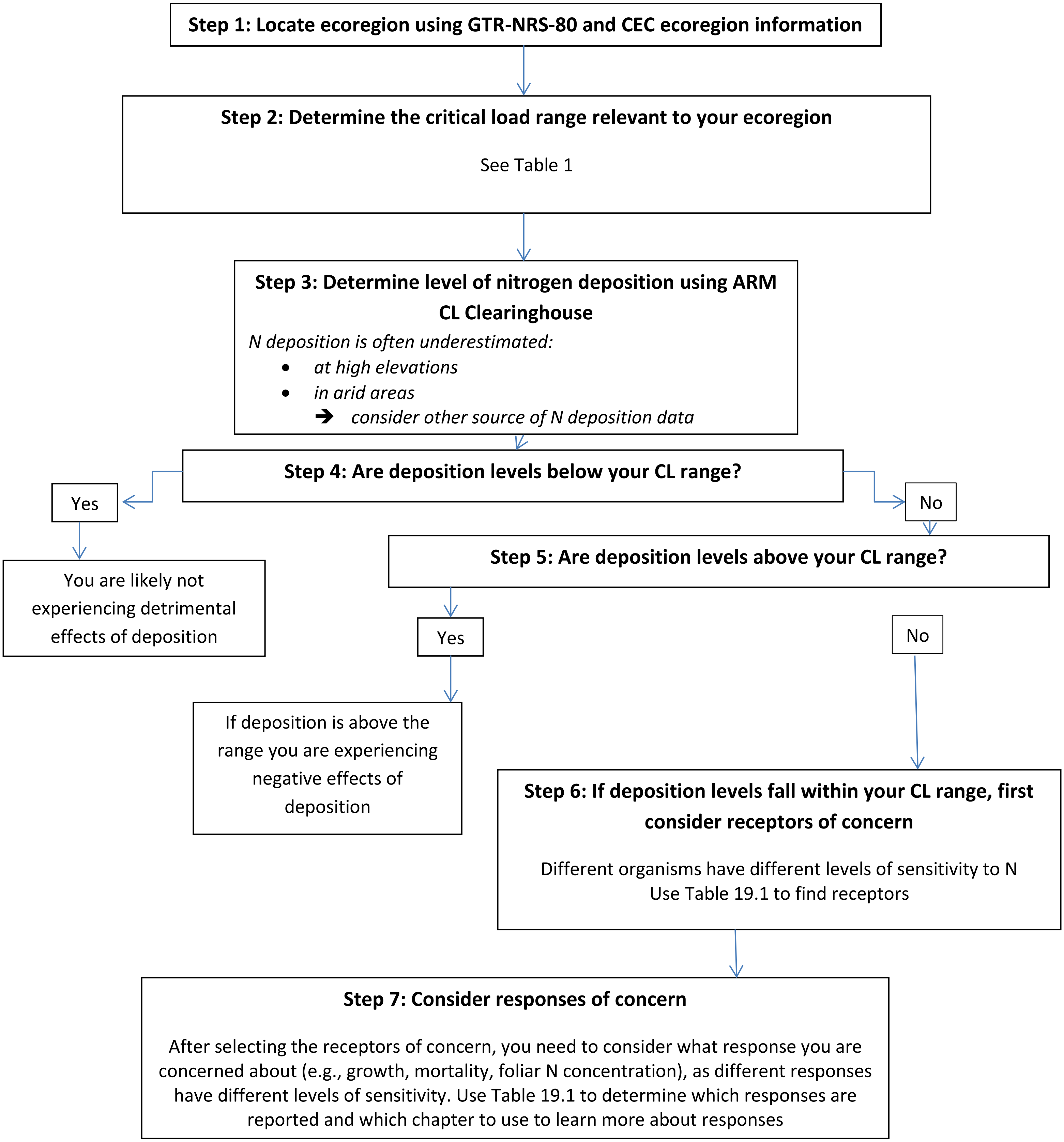
# Users' Guide for Setting Empirical Critical Loads for Nutrient Nitrogen



**Step 8: Review chapter to determine whether specific data relevant to your case are included**

Examine the GTR chapter for your ecoregion and look at the findings cited to determine if certain data are more relevant to your site given proximity, species, or overall comparability.

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**Step 9: Adjust critical loads range based on Table 19.2**

Use Table 19.2 to determine whether any of the factors that affect the critical loads range are relevant to your site. Adjust the CL accordingly.

*Ultimately you should set your CL to protect the most sensitive receptor/response you care about, given the best/most relevant available data.*

**Table 1 Critical loads by ecoregions** for all reported receptors and responses

| Ecoregion | Critical load for N deposition (*kg N ha$^{-1}$ yr$^{-1}$*) |
|---|---|
| Tundra | 1 - 3 |
| Taiga | 1 - 7 |
| Northern Forests | >3 - <26 |
| Northwestern Forested Mountains | 1.2 - 17 |
| Marine West Coast Forests | 2.7 – 9.2 |
| Eastern Temperate Forests | >3 - <17.5 |
| Great Plains | 5 – 25 |
| North American Deserts | 3 – 8.4 |
| Mediterranean California | 3 - 39 |
| Temperate Sierras | 4 – 15 |
| Tropical and Subtropical Humid Forests | <5 – 10 |
| Freshwater Wetlands | 2.7 – 14 |
| Freshwaters | 2 - 8 |

**Table 19.1 – Summary of empirical critical loads of nutrient N for U.S. ecoregions.** Reliability rating: ## reliable; # fairly reliable; (#) expert judgment

| Chapter | Ecoregion | Ecosystem Component | Critical load for N deposition *kg N ha$^{-1}$ yr$^{-1}$* | Reliability | Response | Comments | Study |
|---|---|---|---|---|---|---|---|
| 5 | Tundra | Prostrate dwarf shrubs | 1-3 | ## | Changes in $CO_2$ exchange, cover, foliar N, and community composition of vascular plants | N addition study, Greenland high arctic, P enhanced N effects. | Arens et al. 2008[a] |
| 5 | Tundra | Lichens | 1-3 | (#) | Changes in lichen pigment production and ultrastructure, changes in lichen and bryophyte cover | N addition studies, high and low arctic, P enhanced or moderated N effects. | Arens et al. 2008[a], Hyvärinen et al. 2003[b], Makonen et al. 2007[b] |
| 6 | Taiga | Lichen, moss, and algae | 1-3 | # | Changes in alga, bryophyte, and lichen community composition, cover, tissue N or growth rates. | | Berryman et al. 2004[c], Berryman and Straker 2008[c], Geiser et al. 2010, Moore et al. 2004[c], Poikolainen et al. 1998[b], Strengbom et al. 2003[d], Vitt et al. 2003[c] |
| 6 | Taiga | Mycorrhizal fungi, spruce-fir forests | 5-7 | (#) | Ectomycorrhizal fungi, change in community structure | Expert judgment<br><br>extrapolated from Marine West coast spruce and northern spruce-fir forest | Lilleskov 1999; Lilleskov et al. 2001, 2002, 2008 |
| 6 | Taiga | Shrublands | 6 | ## | Shrub and grass cover, increased parasitism of | Long term, low N addition study: shrub cover | Nordin et al. 2005[d], Strengbom et al. |

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| | | | | | shrubs | decreased, grass cover increased | 2003 [d] |
| 7 | Northern Forests | Hardwood and coniferous forests | >3 | # | Tree growth and mortality | Decreased growth of red pine, and decreased survivorship of yellow birch, scarlet and chestnut oak, quaking aspen, and basswood | Thomas et al. 2010 |
| 7 | Northern Forests | Lichens | 4-6 | (#) | Epiphytic lichen community change | Loss of oligotrophic species. Synergistic/confounding effects of acidic deposition not considered; assumes response threshold similar to Marine West Coast Forest | Geiser et al. 2010 |
| 7 | Northern Forests | Ectomycorhizzal fungi | 5-7 | # | Change in fungal community structure | | Lilleskov et al. 2008 |
| 7 | Northern Forests | Herbaceous cover species | >7 and <21 | # | Loss of prominent species | Response observed in low-level fertilization experiment | Hurd et al. 1998 |
| 7 | Northern Forests | Hardwood and coniferous forests | 8 | ## | Increased surface water $NO_3^-$ leaching | | Aber et al. 2003 |
| 7 | Northern Forests | Old-growth montane red spruce | >10 and <26 | # | Decreased growth and/or induced mortality | Response observed in low-level fertilization experiment | McNulty et al. 2005 |

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| 7 | Northern Forests | Arbuscular mycorrhizal fungi | <12 | (#) | biomass decline and community composition change | | van Diepen 2008, van Diepen et al. 2007 |
| 8 | Northwest Forested Mountains | Alpine lakes | 1.5 | ## | Diatom assemblages | As wet deposition only | Baron 2006 |
| 8 | Northwest Forested Mountains | Lichens | 1.2-3.7 | (#) | Epiphytic lichen community change in mixed-conifer forests, Alaska | Application of western Oregon and Washington model | Geiser et al. 2010 |
| 8 | Northwest Forested Mountains | Lichens | 2.5-7.1 | ## | Epiphytic lichen community change, thallus N enrichment in mixed-conifer forests, non-Alaska | | Fenn et al. 2008, Geiser et al. 2010 |
| 8 | Northwest Forested Mountains | Subalpine forest | 4 | ## | Increase in organic horizon N, foliar N, potential net N mineralization, and soil solution N, initial increases in N leaching below the organic layer | | Rueth and Baron 2002, Baron et al. 1994 |
| 8 | Northwest Forested Mountains | Alpine lakes | 4.0 | # | Episodic freshwater acidification | | Williams and Tonnesson 2000 |
| 8 | Northwest Forested Mountains | Alpine grassland | 4-10 | ## | Plant species composition | | Bowman et al. 2006 |
| 8 | Northwest Forested | Ectomycorrhizal fungi | 5-10 | (#) | Ectomycorrhizal fungi community structure in white, black, and | Expert judgment<br><br>extrapolated from Marine | Lilleskov 1999; Lilleskov et al. |

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| | Mountains | | | | Engelmann spruce forests | West Coast spruce and northern spruce-fir forest | 2001, 2002, 2008 |
| 8 | Northwest Forested Mountains | Mixed conifer forest | 17 | ##<br><br>#| $NO_3^-$ leaching,<br><br>reduced fine root biomass | Fine root biomass in ponderosa pine is reduced by both ozone and elevated soil nitrogen | Fenn et al. 2008 |
| 9 | Marine West Coast Forest | Western OR and WA forests | 2.7-9.2 | ## | Epiphytic lichen community change | Loss of oligotrophic species, enhancement of eutrophic species.<br><br>Critical load increases with regional range in mean annual precipitation from 45-450 cm | Geiser et al. 2010 |
| 9 | Marine West Coast Forest | SE Alaska<br><br>forests | 5 | (#) | Fungal community change; declines in ectomycorrhizal fungal diversity | | Lilleskov 1999; Lilleskov et al. 2001, 2002 ; Whytemare et al. 1997 |
| 10 | Eastern Temperate Forest | Eastern hardwood forest | >3 | # | Decreased growth of red pine, and decreased survivorship of yellow birch, scarlet and chestnut oak, quaking aspen, and basswood | | Thomas et al. 2010 |
| 10 | Eastern Temperate Forest | Lichens | 4-8 | (#) | Epiphytic lichen community change | Loss of oligotrophic species. Synergistic/ confounding effects of acidic deposition not considered; based on application of model and | Geiser et al. 2010 |

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| | | | | | | estimated response threshold | |
| 10 | Eastern Temperate Forest | Southeastern Coastal Plain | 5-10 | (#) | Ectomycorrhizal fungi community response | | Dighton et al. 2004; Lilleskov et al. 2001, 2002, 2008 |
| 10 | Eastern Temperate Forest | Eastern hardwood forests | 8 | ## | Increased surface water loading of $NO_3^-$ | | Aber et al. 2003 |
| 10 | Eastern Temperate Forest | Michigan deposition gradient | <12 | (#) | Arbuscular mycorrhizal fungal biomass decline and community composition change | | van Diepen 2008, van Diepen et al. 2007 |
| 10 | Eastern Temperate Forest | Herbaceous species | <17.5 | (#) | Increases in nitrophilic species, declines in species-rich genera (e.g., *Viola*) | | Gilliam 2006,2007; Gilliam et al. 2006 |
| 11 | Great Plains | Tallgrass prairie | 5-15 | # | Biogeochemical N cycling, plant and insect community shifts | | Clark et al. 2009, Clark and Tilman 2008; Tilman 1993, 1987; Wedin and Tilman 1996 |
| 11 | Great Plains | Mixed-grass prairie | 10-25 | # | Soil $NO_3^-$ pools, leaching, plant community shifts | | Clark et al. 2003, 2005; Jorgenson et al. 2005 |
| 11 | Great Plains | Shortgrass prairie | 10-25 | (#) | | Inferred from mixed grass | Epstein 2001, Barret and Burke 2002 |

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| 11 | Great Plains | Mycorrhizal fungi | 12 | (#) | Decline in arbuscular mycorrhizal fungal activity | | Egerton-Warburton [e] |
| 12 | North American Desert | lichens | 3 | (#) | Lichen community shifts, thallus N concentration | Uncertainty regarding modeled estimates | Geiser et al. 2008, Porter et al. 2007 |
| 12 | North American Desert | shrubland, woodland, desert grassland | 3-8.4 | # | Vegetation response, vascular plant community change | | Allen et al. 2009; Inouye 2006; Rao et al. 2009, 2010 |
| 13 | Mediterranean California | Coastal sage scrub | 7.8-10 | # | Invasive grass cover, native forb richness, arbuscular mycorrhizal fungi richness | Modeled and inferential N deposition estimates and published data for mycorrhizae, unpublished data for vegetation survey. | Allen [f], Egerton-Warburton and Allen 2000, Fenn et al. 2010, Tonnesen et al. 2007 |
| 13 | Mediterranean California | Chaparral; Lichens | 3-6 | # | Epiphytic lichen community change | Lichen critical load is from modeled N deposition data and published data for lichens. | Fenn et al. 2010, Geiser et al. 2010, Jovan 2008, Jovan and McCune 2005 |
| 13 | Mediterranean California | Chaparral, oak woodlands, Central Valley | 10-14 | # | $NO_3^-$ leaching; stimulated N cycling | Critical load for $NO_3^-$ leaching of 10 kg N $ha^{-1}$ $yr^{-1}$ is based on one year of throughfall data in Chamise Creek and an additional year of throughfall data from adjacent Ash Mountain, both in Sequoia National Park. | Fenn et al. 2003a, 2003b, 2003c, 2010; Fenn and Poth 1999; Meixner and Fenn 2004 |
| 13 | Mediterranean | Mixed conifer | 3.1-5.2 | ## | Lichen chemistry and | The lowest critical load is based on lichen tissue | Fenn et al. 2008, |

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| | California | forest; lichens | | | community changes | chemistry above the clean site threshold. | 2010 |
| 13 | Mediterranean California | Mixed conifer forest; plant physiology | 17 | # | Reduced fine root biomass | Fine root biomass in ponderosa pine is reduced by both ozone and elevated soil nitrogen | Fenn et al. 2008; Grulke et al. 1998 |
| 13 | Mediterranean California | Mixed conifer forest; soil processes | 17-25.9 | ##<br><br># | $NO_3^-$ leaching;<br><br>soil acidification | | Breiner et al. 2007, Fenn et al. 2008, 2010 |
| 13 | Mediterranean California | Mixed conifer forest; forest sustainability | 24-39 | (#) | Understory biodiversity; forest sustainability | N deposition from Fenn et al. 2008 | Allen et al. 2007; Grulke and Balduman 1999; Grulke et al. 1998, 2009; Jones et al. 2004 |
| 13 | Mediterranean California | Serpentine grassland | 6 | ## | Annual grass invasion, replacing native herbs | Critical load based on a local roadside gradient; Serpentine grassland site is actually west of the Central Valley. | Weiss 1999; Fenn et al. 2010 |
| 15 | Temperate Sierras | Lichens | 4-7 | (#) | Epiphytic lichen community change | Increase in proportion of eutrophic species. Estimated from MWCF model, response threshold allows ~60% eutrophs due to dry, hot climate, hardwood influence | Geiser et al. 2010 |

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| 15 | Temperate Sierras | Las Cruces and Chichinautzin Ranges S/SW of Mexico City | 15 | # | Elevated $NO_3^-$ in stream and spring waters | Data are from Mexican mountain pine (*Pinus hartwegii*) sites in the Desierto de los Leones National Park and Ajusco | Fenn et al. 1999, 2002 |
| 16 | Tropical and Subtropical Humid Forests | N-rich forests | <5-10 | (#) | $NO_3^-$ leaching, N trace gas emissions | Critical load for N-rich forests should be lower than for N-poor forests based on possibility of N losses. | No direct studies[g] |
| 16 | Tropical and Subtropical Humid Forests | N-poor forests | 5-10 | (#) | Changes in community composition; $NO_3^-$ leaching, N trace gas emissions | Critical load for N-poor forests based on estimates for Southeastern Coastal Plain forests. | No direct studies[g] |
| 17 | Wetlands | Freshwater wetlands | 2.7-13 | # | Peat accumulation and NPP | Critical load for wetlands in the northeastern U.S. and southeastern Canada | Aldous 2002 [c], Moore et al. 2004 [c], Rochefort and Vitt 1990 [c], Vitt et al 2003 [c] |
| 17 | Wetlands | Freshwater wetlands | 6.8-14 | (#) | Pitcher plant community change | Critical load based on northeastern populations | Gotelli and Ellison 2002, 2006 |
| 17 | Wetlands | Intertidal wetlands | 50-100 | ## | Loss of eelgrass | | Latimer and Rego 2010 |
| 17 | Wetlands | Intertidal salt marshes | 63-400 | (#) | Salt marsh community structure, microbial activity and biogeochemistry | | Caffrey et al. 2007, Wigand et al. 2003 |

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| 18 | Aquatic | Western Lakes | 2 | ## | Freshwater eutrophication | | Baron 2006 |
| 18 | Aquatic | Eastern Lakes | 8 | # | $NO_3^-$ leaching | | Aber et al. 2003 |

[a] based on data from Greenland; [b] based on data from Finland; [c] based on data from Canada; [d] based on data from Sweden

[e] see footnote 25 on page 19-11; [f] Allen, E.B. Unpublished data. Professor and Natural Resources Extension Specialist, Department of Botany and Plant Sciences and Center for Conservation Biology, University of California, Riverside, CA 92521;[g] The critical load is based on expert judgment and knowledge of ecosystems which may function similarly.

**Table 19.2 – Assessment and interpretation of empirical critical loads of nutrient N for U.S. ecoregions**

| Chapter | Ecoregion | Factors affecting the range of critical loads[a] | Comparison within Ecoregion[b] |
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| | | | |
| 5 | Tundra | • moisture<br>• competition between vascular plants and cryptogams<br>• P-limitation<br>• temperature<br>• pH | The critical load is higher in wet and P-limited tundra; acidic tundra may be more sensitive to N deposition than non-acidic tundra. Increased N deposition may be more detrimental to lichens in the presence of graminoids and shrubs in the low and mid arctic than to lichens with less competition in the high arctic. Response time increases with latitude due to colder temperatures, less light, and poorer N and P mobilization. |
| 6 | Taiga | • soil depth<br>• vegetation type and species composition<br>• latitude | Morphological damage to lichens has been observed at a lower deposition in forests and woodlands than in shrublands or bogs and fens; cryptogam dominated mats on thin soils become N saturated faster than forest islands. |
| 7 | Northern Forest | • receptor<br>• tree species<br>• stand age<br>• site history<br>• pre-existing N status | Critical loads for lichen are generally lowest, followed by critical loads for ectomycorrhizal fungi and $NO_3^-$ leaching. Critical loads for herbaceous species and forests are generally higher than for other responses. |
| 8 | Northwest Forested Mountains | • biotic receptor<br>• accumulated load of N<br>• ecosystem<br>• region | In alpine regions, diatom changes in lakes are seen at the lowest critical load. Changes in individual plants are seen next, followed by vegetation community change, then soil responses.<br><br>In subalpine forests, the critical load of 4 kg $ha^{-1}$ $yr^{-1}$ for foliar and soil chemistry changes is similar to the lichen critical load of 3.1 – 5.2 for lichen community change. |

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| 9 | Marine West Coast Forest | • background N status<br>• soil type<br>• species composition<br>• fire history<br>• climate | The midrange of responses reported for lichens (2.7 – 9.2 kg $ha^{-1}$ $yr^{-1}$) is broadly comparable to that for plant, soil, and mycorrhizal responses (5 kg $ha^{-1}$ $yr^{-1}$), despite limited studies for non-lichen responses. |
| 10 | Eastern Forests | • precipitation<br>• soil cation fertility and weathering<br>• biotic receptors | The critical load for $NO_3^-$ leaching, lichen community change, and ectomycorrhizal fungal response are within the same range. Arbuscular mycorrhizal fungal and herbaceous critical loads are higher. |
| 11 | Great Plains | • N status<br>• receptor<br>• precipitation | Critical loads are lower in the tall grass prairie than in the mixed- and short-grass prairies. Critical loads in tall- and mixed-grass prairie is lower on N poor sites and sites with very N responsive plant species. Critical loads in the short-grass prairie is likely lower in wet years than in dry years. |
| 12 | North American Deserts | • receptor<br>• interaction of annual grasses with native forb cover<br>• precipitation | The lichen critical load is lowest, at 3 kg N $ha^{-1}$ $yr^{-1}$; vegetation critical load varies from 3-20 kg N $ha^{-1}$ $yr^{-1}$ |

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| 13 | Mediterranean California | • Presence of invasive exotic annual grasses interacting with a highly diverse native forb community<br>• N-sensitivity of mycorrhizal fungi<br>• N-sensitivity of lichens<br>• N retention capacity of catchments, catchment size<br>• co-occurrence of ozone and ozone-sensitive tree species. | The lowest critical loads in Mediterranean California are for sensitive lichen in chaparral and oak woodlands and mixed conifer forests. The critical load for plant and mycorrhizal fungal community change in coastal sage scrub is higher, at 7.8 to 10 kg $ha^{-1}$ $yr^{-1}$.<br><br>Critical load for $NO_3^-$ leaching is lower in chaparral and oak woodlands (10 -14 kg $ha^{-1}$ $yr^{-1}$) than in mixed conifer forests (17 kg $ha^{-1}$ $yr^{-1}$). Critical loads are highest for mixed conifer forest plant community change and sustainability.<br><br>Fine root biomass in ponderosa pine is reduced by both ozone and elevated soil nitrogen. |
| 17 | Wetlands | • vegetation species<br>• the fraction of rainfall in the total water budget<br>• the degree of openness of N cycling | Critical load is much higher for intertidal wetlands (50-400 kg $ha^{-1}$ $y^{-1}$) than for freshwater wetlands (2.7-14 kg $ha^{-1}$ $y^{-1}$), which have relatively closed water and N cycles. |

[a] This explains what factors cause the critical load (CL) to be at the low or high end of the range reported.
[b] Comparison of values and causes for differences if multiple critical loads are reported for an ecoregion.