

Chapter 34

Using Fire Risk and Species Loss to set Critical Loads for Nitrogen Deposition in Southern California Shrublands

**Edith B. Allen, Leela E. Rao, Gail Tonnesen, Robert F. Johnson,
Mark E. Fenn and Andrzej Bytnerowicz**

Abstract Southern California deserts and coastal sage scrub (CSS) are undergoing vegetation-type conversion to exotic annual grassland, especially in regions downwind of urban areas that receive high nitrogen (N), primarily as dry deposition. To determine critical loads (CLs) of N that cause negative impacts, we measured plant and soil responses along N deposition gradients, fertilized vegetation at different N levels, and used biomass production output from the DayCent model. Nitrogen deposition gradients were identified from the CMAQ model and compared with measured N deposition values. Coastal sage scrub receives N deposition as high as $30 \text{ kg ha}^{-1} \text{ year}^{-1}$, while the desert has levels up to $16 \text{ kg ha}^{-1} \text{ year}^{-1}$. These ecosystems are subject to increases in exotic species production, loss of native species diversity, and increased fire risk at relatively low CLs. For instance, a gradient survey in CSS showed that exotic grass cover increased and native plant species richness declined by almost 50% above $10 \text{ kg N ha}^{-1} \text{ year}^{-1}$. Fertiliza-

E. B. Allen (✉) · R. F. Johnson
Department of Botany and Plant Sciences and Center for Conservation Biology,
University of California, Riverside, California, 92521-0124, USA
e-mail: edith.allen@ucr.edu

R. F. Johnson
e-mail: robert.johnson@ucr.edu

L. E. Rao
Center for Conservation Biology, University of California,
Riverside, California, 92521, USA
e-mail: lerao123@gmail.com

G. Tonnesen
Center for Environmental Engineering and Technology,
University of California, Riverside, California, 92521, USA
e-mail: gtonnesen@gmail.com

M. E. Fenn · A. Bytnerowicz
USDA Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Dr.,
Riverside, California, 92507, USA
e-mail: mfenn@fs.fed.us

A. Bytnerowicz
e-mail: abytnerowicz@fs.fed.us

tion studies in desert creosote bush scrub showed a significant increase in exotic species biomass with $5 \text{ kg N ha}^{-1} \text{ year}^{-1}$ in a wet year, and biomass output from DayCent modelling indicated an increased fire risk from exotic grasses with 1 t per ha production during years with moderate to high precipitation at $2.2\text{--}8.8 \text{ kg N ha}^{-1} \text{ year}^{-1}$. The difference in CL between desert and CSS is related to the different criteria used (diversity loss in CSS, productivity and fire risk in desert), as well as responsiveness of native vs. exotic plant species to N and the degree to which precipitation and soil N limits plant growth in the two vegetation types.

Keywords Coastal sage scrub • Desert • Fire risk • Invasive plant species • Plant species richness

34.1 Introduction

There is growing interest in the United States for implementing nitrogen (N) critical loads (CLs) to manage anthropogenic atmospheric N deposition (Porter et al. 2005). Critical loads are defined as the amount of pollutants below which there are no adverse ecological effects (Burns et al. 2008). The criteria for setting CLs may range from species-level impacts of N eutrophication on diversity and species shifts (Bobbink et al. 2010), to ecosystem-level impacts on processes such as nutrient leaching (Fenn et al. 2010). In arid regions with high buffering capacity of the soil, infrequent run-off, and low productivity, the immediate effect of N deposition is often on vegetation productivity, species shifts, and diversity changes from fertilization (Fenn et al. 2003; Allen et al. 2009). The arid and semi-arid regions of the western United States have experienced exotic annual grass invasions that have caused increased fuel for fire, which may be coupled with reduced diversity of native species. We report two different criteria for setting CLs in California deserts and coastal sage scrub (CSS). The CL for desert creosote bush scrub (CB) and pinyon-juniper woodland (PJ) was determined using a biogeochemical process model to calculate exotic annual plant productivity and increased fire risk. The CL for CSS was determined by diversity losses over a N deposition gradient.

34.2 Nitrogen Critical Load Based on Plant Diversity Losses

Coastal sage scrub is a high diversity, Mediterranean-climate vegetation type primarily in southern California, with some 200 sensitive plant species (legally protected by the Endangered Species Act, or under consideration for protection, Skinner and Pavlik 1994). It is highly invaded by exotic Mediterranean annual grasses and forbs and is experiencing vegetation-type conversion and losses in diversity (Allen et al. 2000), and is subject to high levels of N deposition and increased fire frequency (Fenn et al. 2003; Talluto and Suding 2008). The modelling approach used in the desert has not been applied to setting a N CL in CSS. However, assessing diversity losses (Bobbink et al. 2010) has proved useful to setting CLs, as we discovered during a survey along a N deposition gradient.

Table 34.1 Percentage (%) cover and richness of plant groups and extractable soil N (ammonium plus nitrate) along a N deposition gradient in western Riverside County, California. Sites are arranged from north to south along an urban to rural gradient. Nitrogen deposition is total wet plus dry deposition based on the CMAQ model (Tonnesen et al. 2007 and unpublished) and calculated using the inferential method (Fenn et al. 2011)

Site	Exotic grass % cover	Native forb % cover	Shrub % cover	Native forbs species per 3 ha	Soil N μg/g	N deposition kg N ha ⁻¹ year ⁻¹	
						CMAQ	Inferential
Jurupa Hills	63.5	4	2.2	16	37.7	19.6	
Box Springs	69.2	18.5	2.4	31	32.6	14.7	20.2
Botanic Garden	36.0	25.4	0.2	20	28.9	13.4	
Lake Perris	0.5	26.1	2.8	30	20.3	11.1	
Mott Reserve	6.7	14.3	11.2	37	30.6	11.1	8.9
Lopez Canyon	11.1	19.6	19.3	67	9.6	9.0	6.6
Tucalota Hills	1.5	35.7	35	50	10.5	8.7	

Seven sites were selected in CSS vegetation on north-facing slopes along a north to south, urban to rural N deposition gradient. The sites lie in the physiographic region known as the Riverside-Perris Plain along a 70 km stretch with an average 34 cm precipitation annually, and with similar soils on granitic parent material (Padgett et al. 1999). Modelled N deposition using the Multiscale Community Air Quality (CMAQ) model (Tonnesen et al. 2007 and unpublished 4 km² grid data) ranged from 9–20 kg ha⁻¹ year⁻¹. We compared modelled with N deposition values calculated from passive sampler atmospheric concentration data (Fenn et al. 2009), reported here as inferential values (Fenn et al. 2011). At each site percent cover and species richness was assessed in three, 1-ha plots at peak biomass of the growing season (May, 2003). Soil samples were collected during the dry season (October), as extractable soil N concentration is highest in dry soil just prior to the rainy season (Padgett et al. 1999).

Nitrogen deposition (wet plus dry) decreased along an urban to rural gradient from 19.6 to 8.7 kg ha⁻¹ year⁻¹ using the CMAQ model (Table 34.1). Of the three sites where inferential calculations were made, the one at the high end of the gradient had higher N deposition, and two at the lower end had lower deposition than modelled by CMAQ. Soil extractable N was highest at the northern, more polluted end of the gradient, conforming to the deposited N values. Exotic grass cover was highest at the polluted end of the gradient, and native forb and shrub cover were lowest. Forb species richness shown in bold in Table 34.1 shows a rapid drop in richness, suggesting a critical load of 10 kg N ha⁻¹ year⁻¹ using the CMAQ model, and 7.8 kg N ha⁻¹ year⁻¹ by the inferential method.

34.3 Nitrogen Critical Load Based on Fire Risk

Fires have increased in frequency in arid southern California because of increased invasive annual grasses (Brooks and Matchett 2006) coupled with N deposition and wet years that increase productivity above the threshold for carrying fire, which is

about 1 t ha^{-1} of fine fuel (Rao et al. 2010). Because deserts have discontinuous woody fuel, the invasive species now carry fire between shrubs, a function that native annual forb vegetation seldom performed historically except following the wettest periods, which resulted in infrequent fire events. Nitrogen fertilization can elevate this productivity even further, interacting with precipitation to increase biomass to values above the productivity threshold for fire (Allen et al. 2009; Rao and Allen 2010; Rao et al. 2010). Areas of the Mojave and Sonoran Desert have burned once, or in some instances, multiple times in the last two decades, even in areas with relatively low precipitation (Brooks and Matchett 2006). The impacts of elevated N on fire risk was determined for two vegetation types, arid creosote bush scrub (CB) and semiarid pinyon-juniper woodland (PJ). Native shrub and woodland recovery is slow, so multiple or even single fires in invaded vegetation can result in vegetation-type conversion to exotic annual grassland (Brooks et al. 2004).

We used the daily version of the Century model (DayCent) to determine CLs of N deposition for its effects on increasing annual vegetation productivity and fire risk in CB and PJ. This model takes into account changes in soil nutrients, moisture, and texture, thus allowing it to be used to estimate vegetation productivity across landscapes with varying soil and environmental characteristics (Parton et al. 1988). Input parameters were N deposition rates, soil N, C, and P, precipitation using local records, and soil texture (Rao et al. 2010). Biomass was parameterized using annual species productivity measured yearly since 2003 in plots fertilized with N at 0, 5, and $30 \text{ kg N ha}^{-1} \text{ year}^{-1}$ (Allen et al. 2009; Rao et al. 2010). These plots had increased productivity of invasive grasses with $5 \text{ kg N ha}^{-1} \text{ year}^{-1}$ only in the wettest years, and for 30 kg N ha^{-1} in average to wet years, and no consistent decreases in native species richness (Allen et al. 2009).

To determine the CL for a site, the model was run for 100 years at incrementally increasing N deposition loads from background (0.5 kg N ha^{-1}) up to a maximum N deposition load (14 kg N ha^{-1}). The proportion of years in which biomass exceeded the fire threshold, or fire risk, was calculated for each deposition loading. Simulations that produced greater than 1 t ha^{-1} of biomass were assumed to exceed the fire-carrying threshold, as this amount of grass biomass is the minimum to carry fires (Anderson 1982). The CL was defined as the amount of N deposition when the fire risk began to increase exponentially above background levels. We also calculated the N-deposition load at which the fire risk began to level off, or the fire risk stabilization load. For example, fire risk increased from deposition at both CB and PJ calibration sites at CLs of 2.2 and $3.6 \text{ kg N ha}^{-1} \text{ year}^{-1}$ for CB and PJ respectively, stabilizing at a fire risk of 5.5 and $8.8 \text{ kg N ha}^{-1} \text{ year}^{-1}$ (Fig. 34.1).

The values of the CLs and fire stabilization loads in Fig. 34.1 are specific to the model calibration sites. To extrapolate across the landscape, average CLs and fire risk stabilization loads were calculated for multiple precipitation regimes $\times$ soil textures $\times$ N-deposition levels (Rao et al. 2010). In general, CL values decreased with increasing precipitation due to primary limitation by water in this arid system. Averaging across the soil textures evaluated and the range of precipitation common for CB vegetation in this region (mean annual precipitation $< 21 \text{ cm}$) the average CL for CB was 3.2 kg N ha^{-1} and fire risk stabilization occurred with 9.3 kg N ha^{-1} N

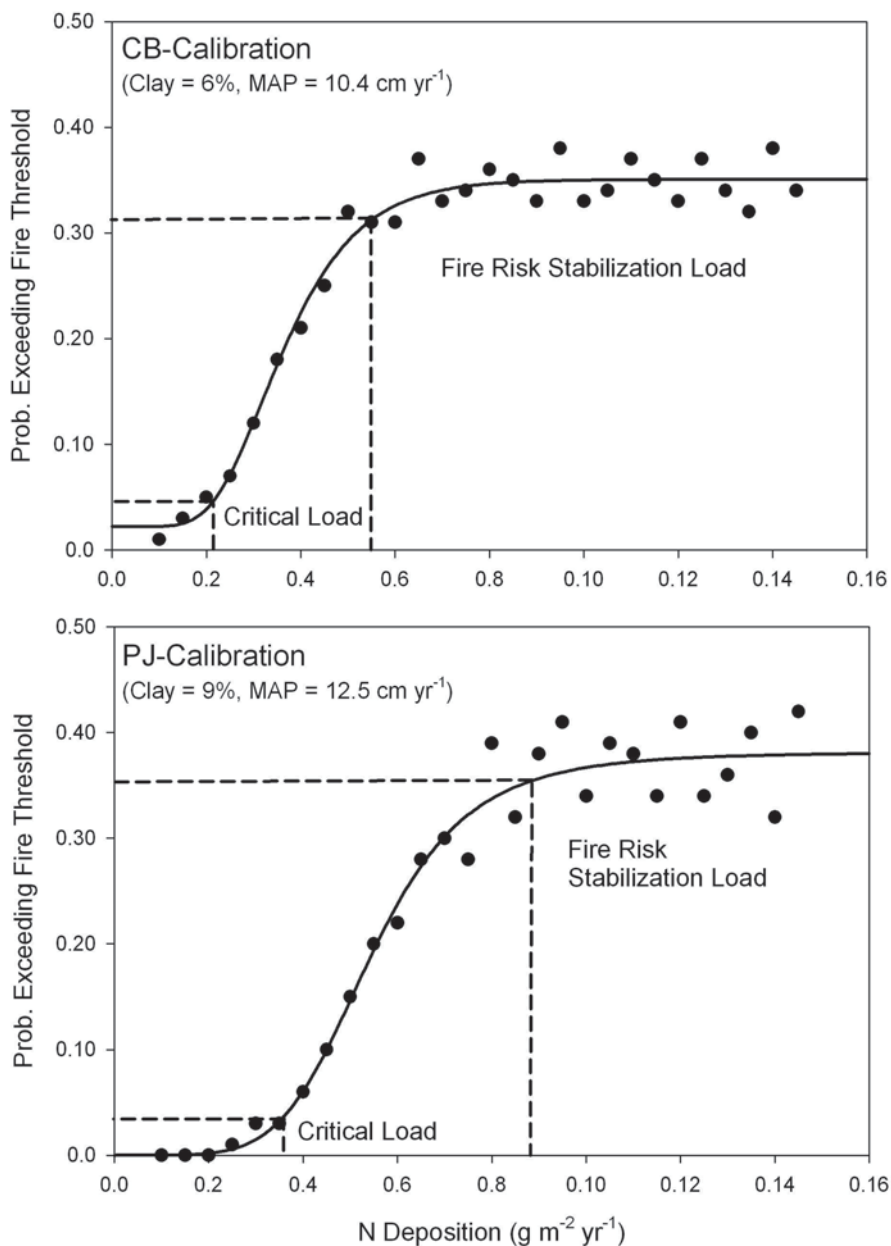


Fig. 34.1 Fire risk for creosote bush scrub (CB) calibration and pinyon-juniper woodland (PJ) calibration sites calculated as the probability that annual biomass will exceed the fire threshold (1 t ha⁻¹) under a given N deposition load. The critical load, the point at which fire risk begins to increase exponentially, is 2.2 and 3.6 kg N ha⁻¹ of N deposition for CB and PJ respectively. The fire risk begins to level out at the fire risk stabilization load, which is 5.5 and 8.8 kg ha⁻¹. Between the critical load and fire risk stabilization load the fire risk changes very rapidly with N deposition (from Rao et al. 2010)

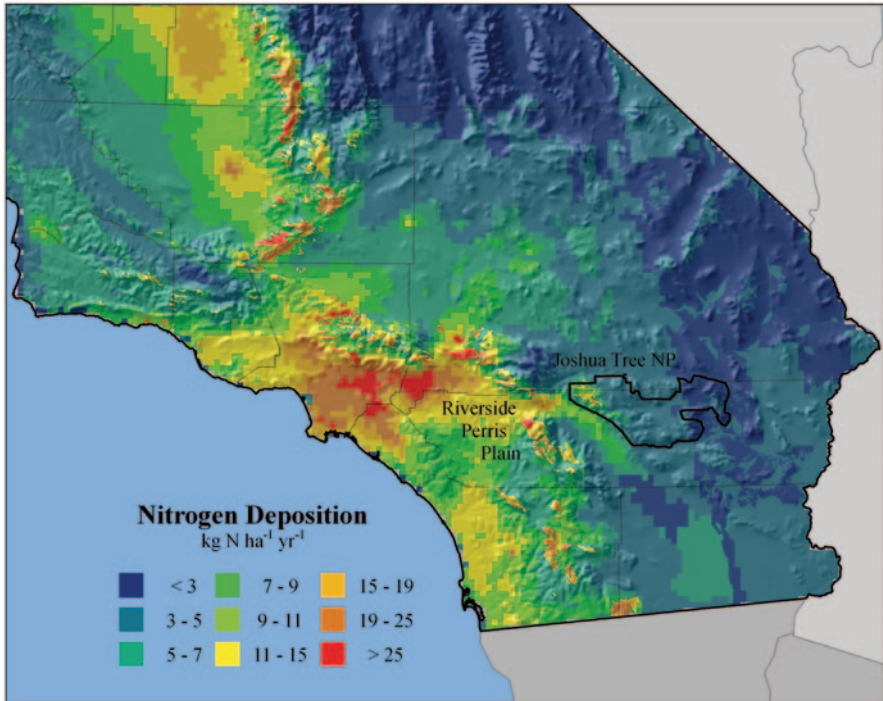


Fig. 34.2 Model of N deposition in southern California (From Tonnesen et al. 2007). Measurements of air quality, soil N, and species composition were taken from N deposition gradients in the Mojave/Colorado deserts (Joshua Tree National Park) and coastal sage scrub (Riverside-Perris Plain)

deposition. Similarly, the average CL for PJ was 3.9 and fire risk stabilization occurred at 8.7 kg ha⁻¹ N deposition.

34.4 Nitrogen Deposition and Critical Load Exceedence in Southern California

Simulated N deposition data from the U.S. Environmental Protection Agency CMAQ (Community Multiscale Air Quality) model were developed for California (Tonnesen et al. 2007). The original model was processed on a 36 km² grid, and was updated on a 4 km² grid to improve local scale accuracy (Fig. 34.2). This model was used as the base map to determine CL exceedence using the CL values for desert and CSS vegetation.

Both modelled and measured values of N deposition are used to estimate CL exceedences for diversity loss in CSS (Fig. 34.3). The rapid loss in native richness between N deposition values of 9–11 (modelled) and 6.6 to 8.9 kg ha⁻¹ year⁻¹ (inferential method) suggests a more stringent 7.8 to a more conservative CL value

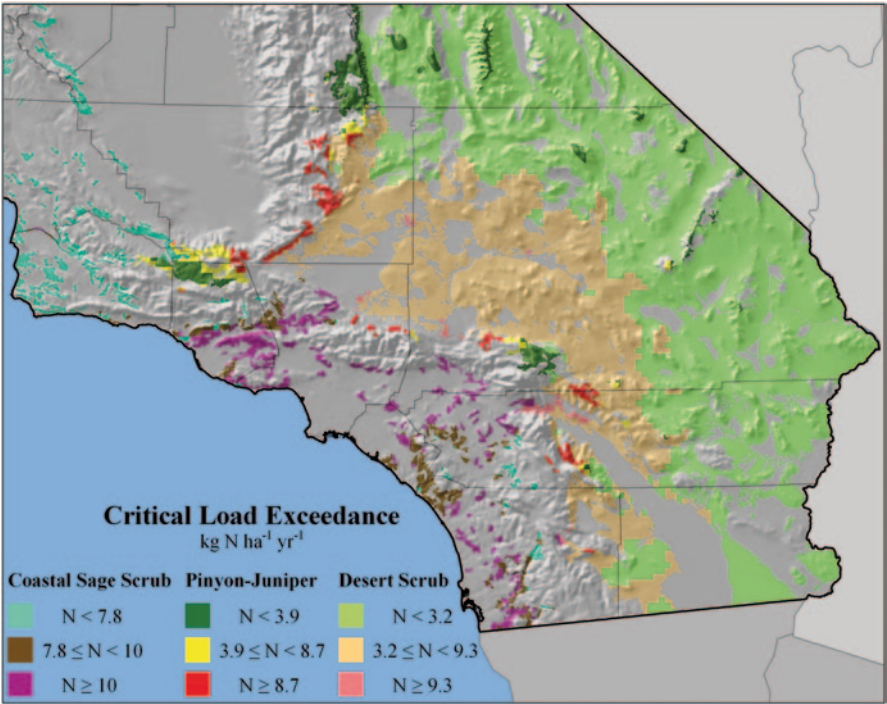


Fig. 34.3 Critical N loads for coastal sage scrub for loss of native forb diversity is 7.8 to 10 kg ha⁻¹ year⁻¹. 33 to 53 % of CSS area exceeds CL using the higher and lower estimates of CL. Critical N loads for CB and PJ for moderate to high fire risk (fine fuel production=1 t ha⁻¹) is 3.2 to 9.3 kg ha⁻¹ year⁻¹ for increased fire hazard (fine fuel=1 t ha⁻¹). 15 to 28 % of PJ, and 0.6 to 31 % of CB land area, exceeds CL using the higher and lower estimates of N deposition

of 10 kg ha⁻¹ year⁻¹ for N deposition. More frequent species richness surveys at a greater number of sites, and more widespread N deposition measurements would confirm which value is more realistic. Of the total 632 km² of CSS in California, 33 % is in exceedance of the higher CL level and 53 % exceeds the lower CL level. CSS is a highly fragmented vegetation type, as shown in Fig. 34.3, that occurs in low elevation sites interspersed by higher elevation chaparral and oak woodlands, and often surrounded by urban and agricultural development. Furthermore, as Table 34.1 shows, many sites designated as CSS are actually dominated by exotic Mediterranean annual grasses with sparse shrubs.

Surrounding chaparral vegetation is more resilient to invasion and recovers more readily from fire, and also has a higher CL for N deposition of 14 kg ha⁻¹ year⁻¹ (Fenn et al. 2010). Chaparral has sclerophyllous evergreen leaves, while CSS is summer drought-deciduous, and therefore more susceptible to invasion. The CL for chaparral is based on nutrient loading of runoff water, while our CL for CSS is based on rapid responses by plants that include many native understory annual species and a seasonally fluctuating canopy. The N CLs for the two desert vegetation

types are based on values averaged over multiple soil texture types, and based on 21 cm precipitation (Fig. 34.3). A more precise map would incorporate variations in mean precipitation and in soil texture classes in different regions. Creosote bush scrub covers some 75,000 km², with CL exceedence on 0.6 to 31 % of the land area using the higher and lower estimates of N deposition. This indicates that under a modest precipitation regime of 21 cm, that is higher than much of the drier western CB area, the vegetation may have increased productivity of invasive annual interspace vegetation and be subject to increased fire because of increased N deposition. Similarly, PJ covers 6,600 km², and CL exceedence occurs in 15 to 28 % of the land area using the higher and lower estimates of N deposition.

The differences in CL between desert and CSS may be related to the different criteria used, plant species richness loss in CSS and exotic species productivity and fire risk in desert, but also to the degree to which precipitation and soil N limits plant growth in the two vegetation types. The more mesic (compared to deserts) CSS soils are deeper and richer in nutrients and organic matter, and native CSS plants are adapted to higher levels of resources than desert plants. Thus they would likely be impacted at higher levels of N deposition than desert plants. While we have observed that native desert plants respond to N with increased productivity, they only do so if invasive plants are inabundant (Allen et al. 2009). Additional studies to refine these CL values are underway. It is hoped that efforts such as this will guide regulatory agencies to control N pollution in these sensitive ecosystem types, and reduce the frequent fires and allow recovery of native species diversity.

Acknowledgments This research was funded by the U.S. National Science Foundation (DEB 04-21530), the National Park Service, the Community Foundation of Riverside and San Bernardino Counties, and the College of Natural and Agricultural Resources, UCR.

References

- Allen, E. B., Eliason, S. A., Marquez, V. J., Schultz, G. P., Storms, N. K., Stylinski, C. D., Zink, T. A., & Allen, M. F. (2000). What are the limits to restoration of coastal sage scrub in southern California? In: Keeley, J.E., Keeley, M.B., & Fotheringham, C.J. (Eds.) *2nd Interface between ecology and land development in California* (pp. 253-262). Sacramento: USGS Open-File Report 00-62.
- Allen, E. B., Rao, L. E., Steers, R. J., Bytnerowicz, A., & Fenn, M. E. (2009). Impacts of atmospheric nitrogen deposition on vegetation and soils in Joshua Tree National Park. In R. H. Webb, L. F. Fenstermaker, J. S. Heaton, D. L. Hughson, E. V. McDonald, & D. M. Miller (Eds.), *The Mojave Desert: Ecosystem processes and sustainability* (pp 78-100). Las Vegas: University of Nevada Press.
- Anderson, H. E. (1982). *Aids to determining fuel models for estimating fire behavior*. General Technical Report INT-122. Ogden, Utah: USDA Forest Service Intermountain Forest and Range Experiment Station. http://www.fs.fed.us/rm/pubs_int/int_gtr122.pdf.
- Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J. W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L., & De Vries, W. (2010). Global assessment of nitrogen deposition effects on terrestrial plant diversity: A synthesis. *Ecological Applications*, 20, 30-59.

- Brooks, M. L., D'Antonio, C. M., Richardson, D. M., Grace, J. B., Keeley, J. E., Di Tomaso, J. M., Hobbs, R. J., Pellant, M., & Pyke, D. (2004). Effects of invasive alien plants on fire regimes. *Bioscience*, 54, 677–688.
- Brooks, M. L., & Matchett, J. R. (2006). Spatial and temporal patterns of wildfires in the Mojave Desert, 1980–2004. *Journal of Arid Environments*, 67, 148–164.
- Burns, D. A., Blett, T., Haeuber, R., & Pardo, L. H. (2008). Critical loads as a policy tool for protecting ecosystems from the effects of air pollutants. *Frontiers in Ecology and the Environment*, 6, 156–159.
- Fenn, M. E., Baron, J. S., Allen, E. B., Rueth, H. M., Nydick, K. R., Geiser, L., Bowman, W. D., Sickman, J. O., Meixner, T., & Johnson, D. W. (2003). Ecological effects of nitrogen deposition in the Western United States. *Bioscience*, 53, 404–420.
- Fenn, M. E., Sickman, J. O., Bytnerowicz, A., Clow, D. W., Molotch, N. P., Pleim, J. E., Tonnesen, G. S., Weathers, K. C., Padgett, P. E., & Campbell, D. H. (2009). Methods for measuring atmospheric nitrogen deposition inputs in arid and montane ecosystems of western North America. In A. H. Legge (ed.), *Developments in Environmental Science, Vol. 9: Air Quality and Ecological Impacts: Relating Sources to Effects* (pp. 179–228). Amsterdam: Elsevier.
- Fenn, M. E., Allen, E. B., Weiss, S. B., Jovan, S., Geiser, L., Tonnesen, G. S., Johnson, R. F., Rao, L. E., Gimeno, B. S., Yuan, F., Meixner, T., & Bytnerowicz, A. (2010). Nitrogen critical loads and management alternatives for N-impacted ecosystems in California. *Journal of Environmental Management*, 91, 2404–2423.
- Fenn, M. E., Allen, E. B., & Geiser, L. H. (2011) Mediterranean California. In L. H. Pardo, M. J. Robin-Abbott, & C. T. Driscoll (Eds.), *Assessment of effects of N deposition and empirical critical loads for nitrogen for ecoregions of the United States* (pp. 143–170). USDA Forest Service General Technical Report NRS–80.
- Padgett, P. E., Allen, E. B., Bytnerowicz, A., & Minnich, R. A. (1999). Changes in soil inorganic nitrogen as related to atmospheric nitrogenous pollutants in Southern California. *Atmospheric Environment*, 33, 769–781.
- Parton, W. J., Stewart, J. W. B., & Cole, C. V. (1988). Dynamics of C, N, P and S in grassland soils: A model. *Biogeochemistry*, 5, 109–131.
- Porter, E., Blett, T., Potter, D. U., & Huber, C. (2005). Protecting resources on federal lands: Implications of critical loads for atmospheric deposition of nitrogen and sulfur. *Bioscience*, 55, 603–612.
- Rao, L. E., & Allen, E. B. (2010). Combined effects of precipitation and nitrogen deposition on native and invasive winter annual production in California deserts. *Oecologia*, 162, 1035–1046.
- Rao, L. E., Allen, E. B., & Meixner, T. (2010). Risk-based determination of critical nitrogen deposition loads for fire spread in southern California deserts. *Ecological Applications*, 20, 1320–1335.
- Skinner, M. W., & Pavlik, B. M. (1994). *CNPS inventory of rare and endangered vascular plants of California*. Sacramento: The California Native Plant Society.
- Talluto, M. V., & Suding, K. N. (2008). Historical change in coastal sage scrub in southern California in relation to fire frequency and air pollution. *Landscape Ecology*, 23, 803–815.
- Tonnesen, G. S., Wang, Z., Omary, M., & Chien, C. J. (2007). Assessment of nitrogen deposition: modeling and habitat assessment. Report number CEC-500-2005-032. California Energy Commission, PIER Energy-Related Environmental Research. <http://www.energy.ca.gov/2006publications/CEC-500-2006-032/CE-500-2006-032.PDF>