# Fog and Soil Weathering as Sources of Nutrients in a California Redwood Forest

**Holly A. Ewing,[1] Kathleen C. Weathers,[2] Amanda M. Lindsey,[2] Pamela H. Templer,[3] Todd E. Dawson,[4] Damon C. Bradbury,[4] Mary K. Firestone,[4] and Vanessa K.S. Boukili[5]**

## Abstract

Fog water deposition is thought to influence the ecological function of many coastal ecosystems, including coast redwood forests. We examined cation and anion inputs from fog and rain, as well as the fate of these inputs, within a Sonoma County, California, coast redwood forest to elucidate the availability of these ions and some of the biotic and abiotic processes that may influence their relative abundance. At this site, the patterns of water and chemical inputs via fog and rain and their movement through the soil-plant ecosystem differed between the summer fog and winter rain seasons. Most (98 percent) of the annual water and more than three quarters of the total ionic load was delivered to the forest during the rain season. Soil water patterns followed those of throughfall. Water for plant use was most available in the rain season; however, after large fog events (fog season) plant-available soil water was also present at the forest edge. Differences between soil water and throughfall chemistry were a function of the mobility of each ion, whether or not an ion was a soil weathering product, and the likely biological demand for the ion. The impact of redwoods as fog catchers, transformers, and redistributors of both water and nutrients may extend all the way into the soil profile: in our plots, organic-rich soil horizons were thicker at the forest edge than in the forest interior. Our data show that, although total fog water inputs were small compared to inputs from rain, fog carried a large proportion of the total aqueous ionic inputs—inputs that, presumably, continued to be biologically available until their loss during the rain season. Cross-seasonal, functional coupling of aboveground (canopy) and belowground (soil) processes are likely to be prevalent in this redwood and other fog-inundated forests.

*Key words*: canopy, fog, input-output, rain, redwoods, soil

## Introduction

Fog water deposition is thought to influence the ecological function—from plant physiology (Burgess and Dawson 2004, Limm et al. 2009, Simonin et al. 2009, Williams et al. 2008) to ecosystem function (Ewing et al. 2009, Weathers et al. 2000)—of many coastal forests, including coast redwood forests. Within California, redwoods inhabit a narrow strip of land from approximately 42 to 35.8 degrees N latitude and a zone fewer than 40 km from the ocean, a region known for its summer fog and winter rain (Noss 2000). Research on soil water and understory plants (Dawson 1998, Limm and Dawson 2010, Limm et al. 2009) and trees (Ambrose et al. 2009, Burgess and Dawson 2004, Ewing et al. 2009, Ingraham and Matthews 1995,

---

[1] Bates College. (hewing@bates.edu).
[2] Cary Institute of Ecosystem Studies. (weathersk@caryinstitute.org; lindseya@caryinstitute.org).
[3] Boston University. (ptempler@bu.edu).
[4] University of California, Berkeley. (tdawson@berkeley.edu; bradbury@nature.berkeley.edu; mkfstone@nature.berkeley.edu)
[5] University of Connecticut. (vanessa.boukili@huskymail.uconn.edu).

Limm et al. 2009, Simonin et al. 2009) has shown that fog water is taken up directly into plant leaves within fog-enshrouded coastal California forests.

Much less is known about the influence of fog on biogeochemical processes, especially in regard to the influence of fog chemistry on ecological function. Nutrients and chemicals are consistently more concentrated in fog than rain (Collett et al. 2002, Weathers et al. 1986, Weathers et al. 1988, Weathers et al. 2000), suggesting that fog could be an important vector of nutrients and pollutants even when it contributes a relatively small fraction of the total water input (Azevedo and Morgan 1974, Ewing et al. 2009, Weathers 1999, Weathers and Likens 1997, Weathers et al. 1988, Weathers et al. 2000). In the redwood forests of California where fog drip is high in the summer, fog brings a fifth (21 percent) of the total nitrogen delivered via atmospheric deposition and below-canopy drip to the forest floor even though it delivers as little as six percent of the water to the same location (Ewing, et al. 2009). Fog in California, like other coastal and inland regions, can carry substantial amounts of calcium, magnesium, potassium, and sodium ($Ca^{+2}$, $Mg^{+2}$, $K^{+}$, and $Na^{+}$; for example, Weathers et al. 1986), and it has been proposed that these elements might influence nutrient cycling, soil fertility, and understory plant growth (Azevedo and Morgan 1974, Weathers 1999, Weathers et al. 1986) by enhancing the availability of essential major or minor nutrients. However, no studies have examined delivery of these nutrients to redwood forests via fog and rain within the same forest nor their abundance in soil water.

We examined fog and rain inputs, as well as the fate of these inputs, within a Sonoma County, California, coast redwood stand to elucidate the potential role of fog in the cycling of major mineral cations and anions. Our objectives were (1) to elucidate the importance of fog as a vector for the delivery of major mineral cations and anions to a redwood forest, and (2) to trace the movement of these ions through soil water to better understand the interplay between inputs, transformations, and translocations within the atmosphere-plant-soil water system.

## Methods

Our research was conducted at a coast redwood forest site in Occidental, Sonoma County, California (see Ewing, et al. 2009 for a more complete description). About 96 percent of the annual precipitation falls between October and May (hereafter rain season); the warm summer season (hereafter fog season) is a time of little rain.

Intensive measurements of fog, bulk precipitation, throughfall (TF), and soil water were made at the Sonoma site from 2003 to 2007 (see Ewing et al. 2009 for full details). Briefly, TF collectors were arrayed from the forest edge to interior in a five-band stratified random design. Two additional (bulk) collectors were placed in open grassy areas outside the forest to the southwest of the forest stand. Fog water was collected outside the forest using a passive fog collector with a plastic mesh collection surface (after Azevedo and Morgan 1974). Soil water was collected using two tension lysimeters (TL; Soil Moisture 1900 series), installed at a depth of 12 cm and set to -50 kPa, and two zero-tension lysimeters (ZTL; PVC trough installed in a soil pit face draining into a collection bottle) at a depth of 70 cm in each of the five bands inside the forest and the clearing. Soil profile descriptions were done in each band in the forest as well as in the field outside the forest at the time of lysimeter installation.

Aqueous TF, bulk, fog, and soil water samples were collected every week during the fog season and every two weeks during the rain season between July 2003 and April 2006. Sampling handling, including nitrogen analysis, is detailed in Ewing et al. (2009). Samples were analyzed at the Cary Institute (IES) for bromide, chloride, phosphate, and sulfate ($Br^-$, $Cl^-$, $PO_4^{3-}$, $SO_4^{2-}$) on a Dionex DX-500 Ion-Chromatograph and for $Ca^{2+}$, $Mg^{2+}$, $K^+$, and $Na^+$ on a Perkin-Elmer P400 inductively coupled plasma emission spectrometer, after Weathers et al. (2001). Samples with concentrations below the method detection limits were set at half the detection limit for data handling.

Seasonal mean, median, minimum, maximum, and first and third quartile ion concentrations for fog, bulk, TF, TL, and ZTL samples were calculated over all sampling periods for each season; TF and bulk ion concentrations were volume-weighted before statistical analysis. Season delineation follows Ewing et al. (2009).

## Results

Nutrients and other chemicals were more concentrated in fog than rain, and fog delivered a substantial proportion of the ionic load to the forest floor even though fog constituted only two percent of the total water delivered via TF (Ewing et al. 2009). On average, ions in fog water collected outside the forest were about 10-fold (range three- to 46-fold) more concentrated than in rain water for all elements, and ions were likewise more concentrated in TF in the fog season (seven- to 22-fold) than in the rain season (*fig. 1*). However, the large amount of precipitation in the rain season meant that the highest per-day inputs of both water and ions were in the rain season rather than the fog season. However, the flux of ions to the forest floor via TF (on a per day basis, charge delivered per unit area; eq/ha) from fog was, on average, approximately 20 percent that of rain (data not shown; Ewing, et al. 2009). The dominant ions were similar for fog, rain, and TF. In all collections, $Na^+$, $K^+$, $Mg^{2+}$, and $Ca^{2+}$ made up the majority of cations, while $Cl^-$ and $SO_4^{2-}$ dominated the anions. Bromide, $PO_4^{3-}$, $NO_3^-$, and $NH_4^+$ made up a relatively small proportion of the total ionic load (*fig. 1*). Nitrate was the only ion that was consistently less concentrated in TF relative to fog. Most other ions had more variable concentrations in TF than in bulk collections, and the non-acid cations in particular were more often more concentrated in TF than in collections outside the forest (*fig. 1*).

Nearly all ions delivered to the soil via TF were also found in lysimeters, but their concentrations differed as a function of lysimeter position within the soil and were variable across fog and rain seasons. As reported in Ewing et al. (2009), soil water was collected throughout the rain season in the near-surface soil (12 cm, TL), but it took approximately a month of rain before water began to drain freely and be collected in the ZTL at 70 cm. Only rain season data are reported here. The non-acid cations $Ca^{2+}$, $Mg^{2+}$, $Na^+$, and $K^+$ and the anions $SO_4^{2-}$ and $NO_3^-$ occurred in higher concentrations in TL than in TF in the rain season (*fig. 2*). Chloride and $Br^-$ appeared in roughly the same concentration in soil water as in TF. Sodium was slightly greater in ZTL than TL samples (median concentration) while $Ca^{2+}$ and $K^+$ were lower in ZTL than TL (*fig. 2*).

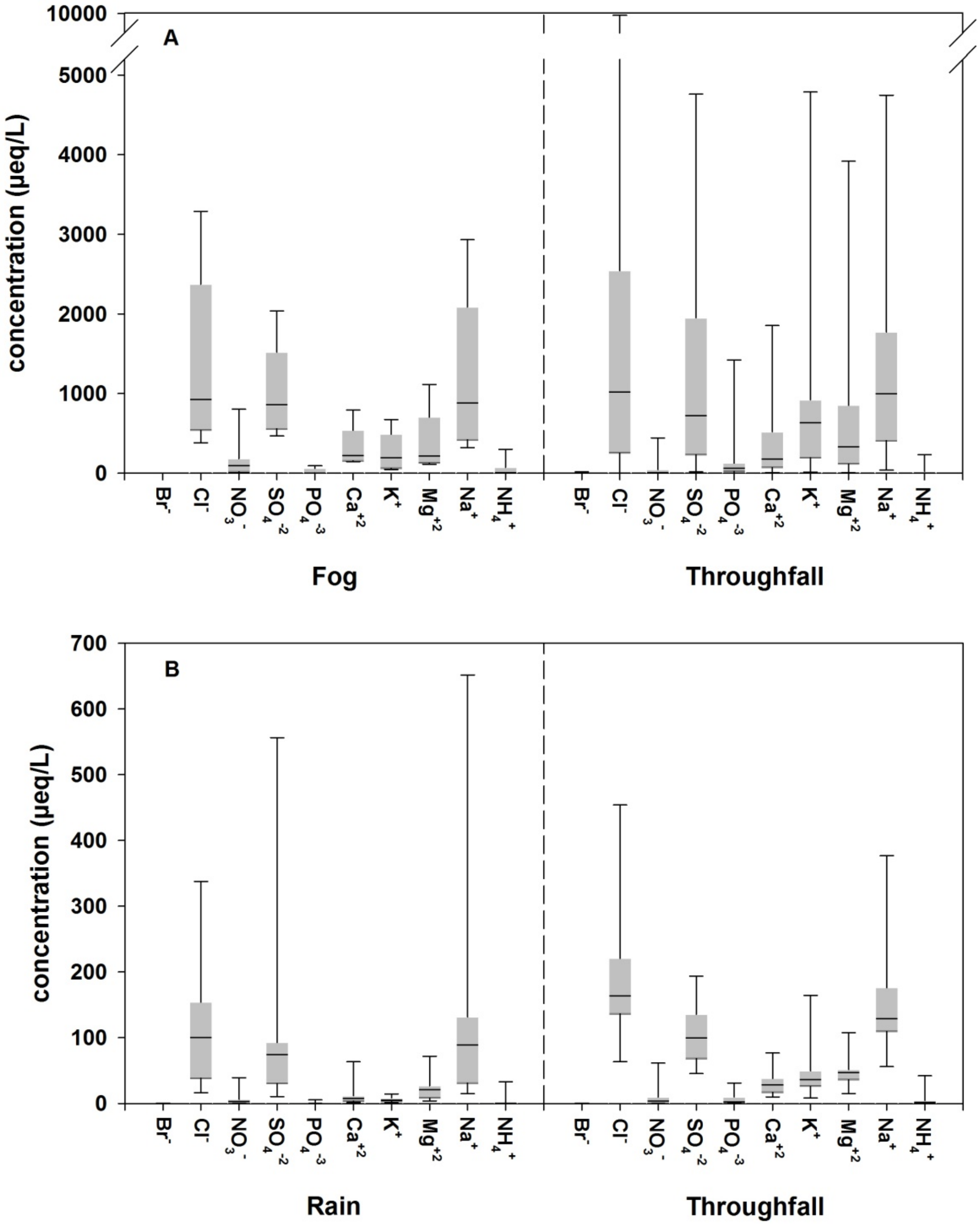

**Figure 1**—Ionic concentration (µeq/L) of (A) fog water and fog season throughfall, and (B) rain water and rain season throughfall collected in a redwood forest in Sonoma County, California. Values for collections at edge and interior sites were averaged before plotting; plots show variability among collections within a season. Note different concentration scales in (A) and (B).

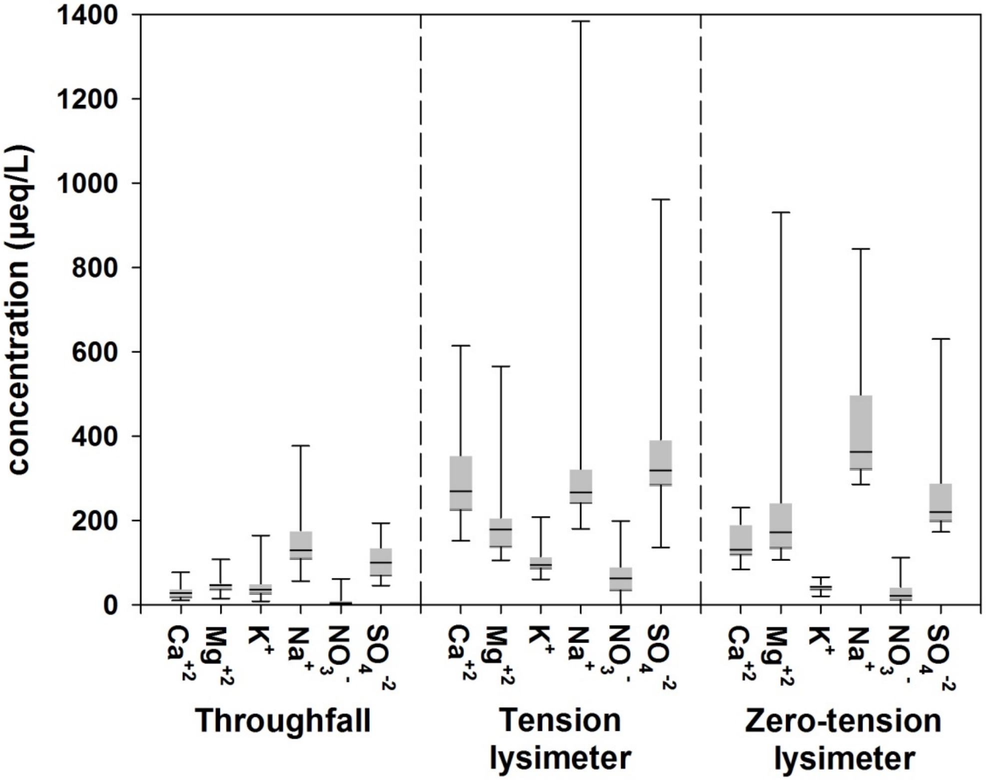

**Figure 2—**Concentration of ions (µeq/L) in throughfall, tension lysimeters and zero-tension lysimeters during the rain season, Sonoma County, CA. Values for collections at edge and interior sites were averaged before plotting; plots show variability among collections within a season.

## Discussion

Fog is an important input vector for both water and nutrients for coast redwood forests; many cation and anion fluxes are influenced by fog despite small fog water fluxes. While water flux outside the forest in the fog season is less than one percent of the rain season flux, high redwood tree surface area results in TF flux at the forest edge that is more than five times greater than in the open, although almost no TF occurred in the forest interior (Ewing et al. 2009). Both the more concentrated nature of fog relative to rain and the change in concentration of water—usually an increase in concentration—as fog passed through the canopy supported observations made in previous studies (for example, Collett et al. 2002, Draaijers et al. 1997, Edmonds et al. 1991, Ewing et al. 2009, Weathers et al. 1988).

Where TF deposition via fog drip is high, fog may deliver a significant amount of ions to soil. Further, through root uptake of water and microbial processing, fog water input has implications for primary production and soil genesis. Root uptake would be possible most of the fog season at the edge of the forest where plant-available water, as evidenced by water found in TLs, was collected from surface soil throughout the fog season. Even in more leeward positions in the forest where fog inputs were less, trees could have access to these ions for the first quarter of the fog season when soil water potentials were high (Ewing et al. 2009). Nevertheless, tree moisture stress was lower at the windward edge of this forest (Ewing et al. 2009), and higher litterfall rates here compared to the interior of the forest indicate that primary production may be greater at the more fog-inundated windward edge of the forest (Ewing et al. 2009). These differences in inputs and tree production are reflected in soil characteristics insofar as soil organic matter concentrations and root densities remain higher deeper into the soil profile at the forest edge (data not shown).

Even in places where fog drip does not occur, fog interception by the canopy can still supply trees with a wide variety of cations and anions; trees have been shown to take in fog water through their needles (Burgess and Dawson 2004, Ewing et al. 2009, Limm et al. 2009, Simonin et al. 2009); they almost certainly are taking in ions in these highly concentrated solutions. Early work predicted that canopy interception of atmospherically-derived nutrients could be a significant source of plant nutrition in some crops (Breazeale et al. 1950, Ingham 1950). While no studies of redwood nutrition as a function of fog exist, our data suggest that redwoods have access to fog water with high concentrations of many nutrient ions.

As indicated by increasing concentrations of some ions as they pass through the soil system, some elements are clearly made available through soil weathering or mineralization in addition to deposition ($Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$), but their fate may depend upon their relative importance as limiting elements for plant growth and their mobility in soils. Of these, $Na^+$, which appears in greatest concentration in ZTL solutions (70 cm depth), is not needed for plant growth and may be in high concentration in the soil either as function of soil weathering or sea salt accumulation (Edmonds et al. 1991). Potassium and $Ca^{2+}$, on the other hand, appear in high concentration in TL (plant-available), but lower concentrations in the ZTL, suggesting that plant or microbial uptake is important. Sulfate and $NO_3^-$, like the non-acid cations, appear in higher concentrations in the soil solution than in TF suggesting a soil source for them as well. Since the parent material at our study site was primarily sandstone (Bradbury 2011), the most likely source for sulfur is mineralization of S from organic matter (Bailey et al. 2004). For $NO_3^-$, high concentrations in TL are also likely a result of organic matter decomposition and subsequent nitrification of $NH_4^+$. Since $NO_3^-$ is an important nutrient for plants and microbes, it is unsurprising that nitrate is in much lower concentration in ZTL, suggesting strong conservation within the forest, as with $Ca^{2+}$ and $K^+$.

## Implications

Both fog water and the chemical constituents within fog are likely to influence biogeochemical cycling in fog- and cloud-dominated forests. Any environmental change that affects the frequency, chemistry, and height and depth of fog layers is likely to impact canopy, soil, and soil water biogeochemical transformation and fluxes (Cavelier and Goldstein 1989, Ingraham and Matthews 1995, Johnstone and Dawson 2010, Ponette-González et al. 2010). Microbial community structure and activity (Bradbury 2011) can also be directly and indirectly affected by fog inputs.

## Acknowledgments

Authorship: We make no distinction in effort and contribution between the first and second authors. Co-authors are listed in order of relative contributions to this paper. S. Simkin assisted with study design, field set-up, and initial sampling; D. Herman contributed to field sampling. Funds were provided by a grant from the A.W. Mellon Foundation.

## References

Ambrose, A.R.; Sillett, S.C.; Dawson, T.E. 2009. **Effects of tree height on branch hydraulics, leaf structure and gas exchange in California redwoods.** Plant Cell and Environment 32(7): 743-757.

Azevedo, J.; Morgan, D.L. 1974. **Fog precipitation in coastal California forests.** Ecology 55(5): 1135-1141.

Bailey, S.W.; Mayer, B.; Mitchell, M.J. 2004. **Evidence for influence of mineral weathering on stream water sulphate in Vermont and New Hampshire (USA).** Hydrological Processes 18(9): 1639-1653.

Bradbury, D.C. 2011. **Climatic and edaphic controllers of soil N transformations and microbial community composition in coast redwood forests.** Berkeley, CA: University of California, Berkeley. Ph.D. thesis.

Breazeale, E.L.; McGeorge, W.T.; Breazeale, J.F. 1950. **Moisture absorption by plants from an atmosphere of high humidity.** Plant Physiology 25(3): 413-419.

Burgess, S.S.O.; Dawson, T.E. 2004. **The contribution of fog to the water relations of *Sequoia sempervirens* (D. Don): foliar uptake and prevention of dehydration.** Plant, Cell and Environment 27(8): 1023-1034.

Cavelier, J.; Goldstein, G. 1989. **Mist and fog interception in elfin cloud forests in Colombia and Venezuela.** Journal of Tropical Ecology 5(3): 309-322.

Collett, J.L.; Bator, A.; Sherman, D.E.; Moore, K.F.; Hoag, K.J.; Demoz, B.B.; Rao, X.; Reilly, J.E. 2002. **The chemical composition of fogs and intercepted clouds in the United States.** Atmospheric Research 64(1-4): 29-40.

Dawson, T.E. 1998. **Fog in the California redwood forest: ecosystem inputs and use by plants.** Oecologia 117(4): 476-485.

Draaijers, G.P.J.; Erisman, J.W.; Van Leeuwen, N.F.M.; Romer, F.G.; Te Winkel, B.H.; Veltkamp, A.C.; Vermeulen, A.T.; Wyers, G.P. 1997. **The impact of canopy exchange on differences observed between atmospheric deposition and throughfall fluxes.** Atmospheric Environment 31(3): 387-395.

Edmonds, R.L.; Thomas, T.B.; Rhodes, J.J. 1991. **Canopy and soil modification of precipitation chemistry in a temperate rain-forest.** Soil Science Society of America Journal 55(6): 1685-1693.

Ewing, H.A.; Weathers, K.C.; Templer, P.H.; Dawson, T.E.; Firestone, M.K.; Elliott, A.M.; Boukili, V.K.S. 2009. **Fog water and ecosystem function: heterogeneity in a California redwood forest.** Ecosystems 12(3): 417-433.

Ingham, G. 1950. **The mineral content of air and rain and its importance to agriculture.** Journal of Agricultural Science 40(1-2): 55-61.

Ingraham, N.L.; Matthews, R.A. 1995. **The importance of fog-drip water to vegetation: Point Reyes peninsula, California.** Journal of Hydrology 164(1-4): 269-285.

Johnstone, J.A.; Dawson, T.E. 2010. **Climatic context and ecological implications of summer fog decline in the coast redwood region.** Proceedings of the National Academy of Sciences of the United States of America 107(10):4533-4538.

Limm, E.B.; Dawson, T.E. 2010. ***Polystichum munitum*** **(Dryopteridaceae) varies geographically in its capacity to absorb fog water by foliar uptake within the redwood forest ecosystem.** American Journal of Botany 97(7): 1121-1128.

Limm, E.B.; Simonin, K.A.; Bothman, A.G.; Dawson, T.E. 2009. **Foliar water uptake: a common water acquisition strategy for plants of the redwood forest.** Oecologia 161(3): 449-459.

Noss, R., editor. 2000. **The redwood forest: history, ecology, and conservation of the coast redwoods.** Washington, DC: Island Press. 339 p.

Ponette-González, A.G.; Weathers, K.C.; Curran, L.M. 2010. **Water inputs across a tropical montane landscape in Veracruz, Mexico: synergistic effects of land cover, rain and fog seasonality, and interannual precipitation variability.** Global Change Biology 16(3): 946-963.

Simonin, K.A.; Santiago, L.S.; Dawson, T.E. 2009. **Fog interception by *Sequoia sempervirens* (D. Don) crowns decouples physiology from soil water deficit.** Plant Cell and Environment 32(7): 882-892.

Weathers, K.C. 1999. **The importance of cloud and fog in the maintenance of ecosystems.** Trends in Ecology & Evolution 14(6): 214-215.

Weathers, K.C.; Cadenasso, M.L.; Pickett, S.T.A. 2001. **Forest edges as nutrient and pollutant concentrators: potential synergisms between fragmentation, forest canopies, and the atmosphere.** Conservation Biology 15(6): 1506-1514.

Weathers, K.C.; Likens, G.E. 1997. **Clouds in southern Chile: an important source of nitrogen to nitrogen-limited ecosystems.** Environmental Science & Technology 31(1): 210-213.

Weathers, K.C.; Likens, G.E.; Bormann, F.H.; Bicknell, S.H.; Bormann, B.T.; Daube, B.C. Jr.; Eaton, J.S.; Galloway, J.N.; Keene, W.C.; Kimball, K.D.; McDowell, W.H.; Siccama, T.G.; Smiley, D.; Tarrant, R.A. 1988. **Cloudwater chemistry from ten sites in North America.** Environmental Science & Technology 22(9): 1018-1026.

Weathers, K.C.; Likens, G.E.; Bormann, F.H.; Eaton, J.S.; Bowden, W.B.; Anderson, J.L.; Cass, D.A.; Galloway, J.N.; Keene, W.C.; Kimball, K.D.; Huth, P.; Smiley, D. 1986. **A regional acidic cloud/fog water event in the eastern United States.** Nature 319(6055): 657-658.

Weathers, K.C.; Lovett, G.M.; Likens, G.E.; Caraco, N.F.M. 2000. **Cloudwater inputs of nitrogen to forest ecosystems in southern Chile: forms, fluxes, and sources.** Ecosystems 3(6): 590-595.

Williams, A.P.; Still, C.J.; Fischer, D.T.; Leavitt, S.W. 2008. **The influence of summertime fog and overcast clouds on the growth of a coastal Californian pine: a tree-ring study.** Oecologia 156(3): 601-611.