



# Reply to Schaberg et al.: Applying stable isotope analyses to examine the influence of acid deposition on *Juniperus virginiana*

Our conclusion that a *Juniperus virginiana* stand in the central Appalachian Mountains is recovering from decades of acid deposition was based on tree ring carbon isotope ratios ( $\delta^{13}\text{C}$ ) that show: (i) close correspondence between the timing of changes in direction of  $\delta^{13}\text{C}$  with declines in  $\text{SO}_2$  emissions occurring after the Clean Air Act; (ii) close similarities between patterns of  $\delta^{13}\text{C}$  after 1980 and during the 1930s Great Depression when  $\text{SO}_2$  emissions were reduced; and (iii) support of our hypothesis that stomatal conductance would increase after the Clean Air Act if trees were recovering from acid deposition (1). The issues outlined by Schaberg et al. (2) do not directly address this conclusion and, thus, do not alter our interpretations of the data.

Schaberg et al. (2) imply that only two species, *Picea rubens* and *Acer saccharum*, are worthy of study. To the contrary, because *Juniperus* is likely neither the most-sensitive nor least-sensitive species to acid deposition, responses by *Juniperus* to changes in acid deposition support our assertion that the Clean Air Act has had important ecological consequences.

Schaberg et al. (2) question that trees responded to acid pollution in the 1930s because acid deposition was not reported in the United States until 1972. Despite a large amount of uncertainty that exists before the 1960s, several lines of evidence point to significant amounts of sulfur pollution by the

early 1900s (3, 4), and thus, observations of these historic effects on *Juniperus* are important (1).

Our isotopic analysis highlights the importance of stomatal conductance but does not address cellular mechanisms of how acid deposition affects stomata (i.e., direct ionic impacts of sulfur or  $\text{H}^+$  acting on stomata). To clarify, tree ring  $\delta^{34}\text{S}$  provides diagnostic information on sulfur sources over the tree ring chronology and strongly supports our observation that the timing of changes in  $\delta^{13}\text{C}$ , and thus changes in tree physiology, corresponds to changes in sulfur pollution received at the tree level (1).

We show that dendroisotopic techniques provide a valuable diagnostic tool to assess historic effects of acid deposition on tree physiology, recovery of trees after the Clean Air Act, and interactions between changing atmospheric  $\text{CO}_2$  and acid deposition (1). Isotopic techniques require a small number of trees to characterize stand-level tendencies, given the typical uniformity of environmental signals reflected in tree rings for a given species and site (5). Our study also benefited from being a subset of a master chronology of *Juniperus* from the surrounding region that shows similar growth patterns (6).

As we state in our report (1), the next step will be to examine the generality of our results from *Juniperus* to determine how widespread these responses to acid deposition are among co-occurring tree species, across wide

geographic areas, and for different soil types in temperate forests. We expect the influence of acid deposition to vary for different species, that some effects are more subtle than the well-documented effects on *Picea* or *Acer*, and that timing of recovery from acid deposition will depend on the resilience of individual tree species.

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**1** Thomas RB, Spal SE, Smith KR, Nippert JB (2013) Evidence of recovery of *Juniperus virginiana* trees from sulfur pollution after the Clean Air Act. *Proc Natl Acad Sci USA* 110(38):15319–15324.

**2** Schaberg PG, Hawley GJ, Rayback SA, Halman JM, Kosiba AM (2013) Evidence of recovery of *Juniperus virginiana* trees from sulfur pollution after the Clean Air Act is inconclusive. *Proc Natl Acad Sci USA*, 10.1073/pnas.1320526111.

**3** National Research Council (1986) *Acid Deposition: Long-Term Trends* (National Academy, Washington, DC).

**4** Charles DF, ed (1991) *Acidic Deposition and Aquatic Ecosystems. Regional Case Studies* (Springer, New York).

**5** McCarroll D, Loader NJ (2004) Stable isotopes in tree rings. *Quat Sci Rev* 23(7–8):771–801.

**6** Maxwell RS, Hessl A, Cook E, Buckley B (2012) A multicentury reconstruction of May precipitation for the mid-Atlantic region using *Juniperus virginiana* tree rings. *J Clim* 25(3):1045–1056.

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The authors declare no conflict of interest.

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