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Interactive comment on "Plant responses to volcanically-elevated CO_2 in two Costa Rican forests" *by* Robert R. Bogue et al.

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We thank the reviewer for highlighting the attractiveness of using volcanically elevated CO2 as an extension of FACE experiments, particularly for assessment of long-term changes in tropical ecosystems. We note that the primary criticism in this study raised by the reviewer echoes that of the other reviewer in our analysis of the wood core isotopes with respect to the time dimension. We agree that this aspect needed further clarification as written. The exact growth chronology was not central to our primary results, so we now reference a range of growth rates from the literature for comparison. We also note that the other major comment of the reviewer was the suggestion to use 14C for the analysis. We agree with the reviewer, though the expense was outside the scope of this investigation. Future studies should expand the scope of this study.

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Discussion paper

"This paper tries to use volcanically elevated CO2 as a substitute for artificially added CO2 gas in FACE experiments. FACE experiments are expensive, because it uses CO2 from gas cylinders to elevate atmospheric CO2 concentrations in the tree canopy. The paper also explores the possibility of using wood carbon-13 isotope to reconstruct past volcanic activity. These ideas seem attractive but unfortunately this paper suffers from serious flaws in the methods applied to draw their conclusions, as pointed out below. Authors have to deal with issues before publication can be considered."

We thank the reviewer for noting the scientific contribution of using volcanically elevated CO2 as an analogue to FACE experiments. We respond to the two major comments below.

"Major concerns: 1) Growth rates of tropical trees can be very different and I do not understand why authors think the wood from the outermost 5cm represents recent growth of 2-3 years. As reviewer #1 suggests, perhaps authors should have tried to analyze 13C of wood in a chronological way. Growth rates of tropical trees, as far as I know, can range from 0.6 mm per year (Kurokawa et al 2003) to 100 mm per year (fast-growing Falcata tree (Paraserianthes falcataria), for example). Which means radial growth of 5cm may represent growth increment from less than 1 year to 83 years. Over the past 83 years, influence of anthropogenic CO2 on wood d13C (Suess effect) can be as large as 4 permil (McCarrol & Loader 2004) and the Suess effect can have variable influence on wood d13C. Kurokawa et al. The age of tropical rain-forest canopy species, Borneo ironwood (Eusideroxylon zwageri), determined by 14C dating. Journal of Tropical Ecology 19(1) 1-7. McCarroll D., Loader NJ. (2004) Stable isotopes in tree rings. Quaternary Science Reviews 23 771-801."

Establishing quantitative growth rates for the trees studied was outside the scope of this preliminary study but would be very helpful for future studies attempting to use our methods. This assumption is based on the existing literature of analogous growth rates. We will clarify the text that this was not measured by us, and this is explicitly unknown in our study. Generally, the impacts on the trees other than elevated CO2 (e.g., Suess

effect, climate, etc.) have a relatively uniform distribution of exposure among the trees, with the primary difference being volcanic CO2 concentration exposure. As such, we are able to assess the effect of CO2 while maintaining relatively consistent control over other factors.

"2) Carbon isotope ratio of -26 peril is within the normal natural range and I still suspect that if there was significant contribution of volcanic CO2 to the wood. Even when large amount of 13CO2 (or 14CO2) is added to the crown, often it is blown away by wind and you do not see any trace of such carbon in the wood (for example, please read: Leavitt, S.W. and Long, A., 1989. Accelerator-measured 14C activity in tree rings from the vicinity of the first atomic bomb test. Radiocarbon 31:762-765.) If other environmental parameters such as radiation happen to have the same increasing patterns with Soil CO2 flux, then you may observe a pseudo-correlation between volcanic CO2 and wood d13C. To prove d13C increase is really caused by the volcanic CO2, authors should analyze 14C and 13C/14C ratio should be plotted against mean soil CO2 flux to prove the incorporation of volcanic CO2 into the plants. Volcanic CO2 is old and therefore 14C (half life of ca. 5300 years) concentration should be almost zero, I assume. Higher incorporation of volcanic CO2 means higher 13C concentration and lower 14C concentration, i.e. higher 13C/14C ratio. It is expensive to analyze 14C of wood (costs about 900 USD per sample in my country) compared to 13C (10 USD per sample). But there are many companies that offer such services. If you measure 14C concentrations of 12 data points in Fig.4, then it would be about 10800 USD. Is this possible?"

We agree with the reviewer that 14C is a valuable tracer for confident traceability of elevated volcanic CO2 exposure for the trees. Other studies have utilized this approach (e.g. Lewicki et al 2014, cited in manuscript). Unfortunately, as the reviewer notes, 14C analysis is significantly more expensive to analyze than 13C. This study did not have the budget that the reviewer suggests (e.g., $10,800USD) for this additional analysis. Future studies should expand the scope of this study to incorporate more measurements.

"Minor comments: Line 44. “including other gas species that accompany CO2 emissions at these springs” There are some studies that show effects of acidic deposition (SO2 and other pollutants) on leaf d13C. Santruckova et al. 2007 Carbon Isotopes in Tree Rings of Norway Spruce Exposed to Atmospheric Pollution. Environ. Sci. Technol., 2007, 41 (16), pp 5778–5782. Are effects of SO2 gas on leaves really absent? Acidic pollutants such as SO2 are known to affect stomata, hence, d13C of trees. Authors should analyze SO2 concentration in the air at the crowns/the leaf surfaces, then compare these concentrations with those of other literature so that they can be sure that effect of SO2 gas on d13C is absent."

This concern is certainly warranted, as many volcanic systems around the world do exhibit other emissions. Throughout Costa Rica’s volcanoes, however, almost none of them emit SO2 to any significant degree. Further, we note that in general SO2 is emitted only out of the craters; whereas, CO2 is emitted both from the craters and from the flank areas (Symonds et al 2001). It is the forested flank areas exposed to elevated CO2 that are the focus of interest to our study. As such, SO2 is very minimal in our study. Nonetheless, Turrialba is one of the only Costa Rican volcanoes with SO2 emissions (see Pieri et al 2013; Diaz et al 2015; Xi et al 2016), which is why we made sure to assess the distribution and impact on the surrounding forests. Fortunately, the prevailing winds tend to blow the crater emissions away from the forested areas.

Pieri, D., Diaz, J.A., Bland, G., Fladeland, M., Madrigal, Y., Corrales, E., Alegria, O., Alan, A., Realmuto, V., Miles, T. and Abtahi, A., 2013. In situ observations and sampling of volcanic emissions with NASA and UCR unmanned aircraft, including a case study at Turrialba Volcano, Costa Rica. Geological Society, London, Special Publications, 380(1), pp.321-352. Diaz, J.A., Pieri, D., Wright, K., Sorensen, P., Kline-Shoder, R., Arkin, C.R., Fladeland, M., Bland, G., Buongiorno, M.F., Ramirez, C. and Corrales, E., 2015. Unmanned aerial mass spectrometer systems for in-situ volcanic plume analysis. Journal of the American Society for Mass Spectrometry, 26(2), pp.292-304. Xi, X., Johnson, M.S., Jeong, S., Fladeland, M., Pieri, D., Diaz, J.A. and Bland, G.L., 2016.

Constraining the sulfur dioxide degassing flux from Turrialba volcano, Costa Rica using unmanned aerial system measurements. Journal of Volcanology and Geothermal Research, 325, pp.110-118. Symonds, R.B., Gerlach, T.M. and Reed, M.H., 2001. Magmatic gas scrubbing: implications for volcano monitoring. Journal of Volcanology and Geothermal Research, 108(1-4), pp.303-341.

"Lines 133-134 “It averages 4-15 m in height” Was there any difference in tree heights in the three species studied? It is important because it affects how strongly the tree crowns are affected by volcanic CO2, which comes up from the ground. I suspect it is related to the different slopes of the two species in Fig.4."

We agree that measurements of tree height are important to understanding CO2 exposure. We do not have precise canopy height measurements, though we do have DBH measurements, which are related to canopy height. Detailed canopy height measurements were outside the scope of our study, but future studies should measure canopy height.

"Line 186 “which we estimated to be representative of roughly the last 2-3 years” You may be able to prove this, for example, by analyzing oxygen isotope cycles at high resolution or finding 14C bomb spike peak around 1964."

14C and high-resolution oxygen isotopes would be useful tools to determine precise growth rates, but are unfortunately out of the budget and scope of this study. We thank the reviewer for this design suggestion for future studies.

"Line 199-222 Why you did not measure SO2 (and CO2) concentrations at the canopy? The model estimates may not reflect the concentrations of these gases surrounding the leaves."

We discuss this from lines 323-341. Longer-term studies could benefit from installing gas sensors in the canopy at various heights, but since we were measuring each site only once, each concentration measurement is more likely to reflect instantaneous

meteorological conditions than long-term CO2 exposure. Thus, for our preliminary study measuring the input of CO2 to the system (volcanic soil fluxes) made more sense.

"Line 263 Average d13C values of -26 permil are observed in trees unaffected by volcanic CO2. This statement is somewhat ambiguous, but we assume that the reviewer is referring to our reported average δ13C value of $\sim$-26 per mil. This average is independent of reported volcanic CO2 fluxes, and does not indicate that trees with values near -26 per mil are unaffected by volcanic CO2. "

"Lines 319 “Tree ring 14C content in volcanically active areas has been linked to variations in volcanic CO2 emissions, and comparing patterns of d13C to 14C measurements for the same wood samples provide additional confirmation of this finding” I can not understand why you did not measure 14C, especially after reading this sentence in your paper."

See response to major concern 2. We will edit this sentence to avoid confusion with an expectation of 14C measurements in our study.

"Line 352 “Additionally, none of the trees displayed obvious signs of stress” This part seems to contradict with the following part: Line 195 “during analysis we excluded all trees that were observed in the field to have significant stress. . .” By the way, how many trees were excluded?"

We will edit these lines for clarity in the revised manuscript. Of 51 total trees sampled, 17 were excluded.

"Fig 4, Why are the slopes of the two regression lines are different? Is it related to the difference in tree height between Oreopanax xalapensis and Buddeleja nitida?"

This is a great question. It is more likely due to species or trait differences in physiology than due to height or exposure, but could be both. This difference highlights the challenge with inferring ecosystem-level responses across measurements of only a few species. To do so would necessitate a much larger sampling across samples and

species - very clearly needed. In the discussion, we will add a section that mentions the value of a more thorough study, whereby more species are sampled, potentially by aircraft or satellite.

"Line388 “but 14C is relatively expensive and a limited number of labs are capable of making these measurements” Now there are lab services that offer 14C analysis and I don’t know if “limited number of labs are capable of making these measurements” is true now."

We apologize for the confusion, we meant that they are limited in comparison to 13C, which is comparatively more straightforward and inexpensive to analyze. We will edit this line for clarity in the revised manuscript.

"Line 426 “Confounding factors that are known to influence d13C values in wood appear not to have affected our measurements, indicating that the heavier wood isotope values are most likely caused by photosynthetic incorporation of volcanic excess CO2” I disagree with this statement and strongly feel that authors should measure 14C of the wood powder at least for the wood samples plotted in Fig.4."

We agree with the reviewer in that 14C would certainly help support our results, although it is not possible for us to include in this paper due to our limited budget. We will edit this sentence to incorporate the sentiments from the reviewer.

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