Interactive comment on "Laser vision: lidar as a transformative tool to advance critical zone science" *by* A. A. Harpold et al.

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We thank Anonymous Referee #1 for the thoughtful comments designed to improve our manuscript's impact and message. From these comments, it is clear that the original manuscript still needs sharpening due to the inherently difficult nature embedded in the review of an emergent transdisciplinary application rather than reviewing application of that tool to any single established field. As such, our paper is a hybrid that straddles the line between a review paper and a vision paper. As Referee #1 suggests, the challenge lies in providing (1) an analysis of what lidar has been used for, (2) how this is transforming CZ science beyond the state of the science, and (3) what opportunities lay ahead.

We agree that this is the central challenge, and indeed motivation for the study, and thank the referee for providing a great launching pad from which to improve the analysis, discussion, and overall manuscript! In the following responses, we address the referee's comments in a general discussion sense (and as rebuttal where appropriate) and leave the detailed response and manuscript edits to the final response.

AC: While the authors note in the abstract that lidar has led to "fundamental discoveries" in a variety of CZ fields, much of the paper merely reads like a laundry list of applications. It's a blur of citations and I'm left without an answer: what was truly gained here beyond what we'd have in the state of the practice without lidar?

RC: The referee's comment shows that we did a poor job in this critical part of the paper in differentiating between outlining fundamental discoveries in the individual fields (hydrology, geomorphology, and ecology) that are important for critical zone (CZ) science versus those made in the interdisciplinary field of critical zone science. The later inherently integrates knowledge from these other disciplines. We now realize that by failing to clearly state what we mean by transdisciplianry tools and science as compared to inter, multi or cross-disciplinary tools and science, we failed to provide the reader with a clear vision of what just such a tool or science can accomplish. To this end we will be modifying Section 1 of the paper with clear definitions of inter-, multi-, cross- and most importantly, transdisciplinary science and use this definition as a conditional metric to judge both existing and future lidar applications as discussed below. While we are still refining the definition among the Earth Science community, we are building off definitions from other fields, such as the following: "Large advances in CZ science dictate transdisciplinary research and tools that allows researchers to transcend their own disciplines to inform one another's work, capture complexity, and create new synergistic intellectual spaces and outcomes." (Adapted from: http://www.obesity-cancer.wustl.edu/en/About/What-Is-Transdisciplinary-Research)

We did not direct our efforts towards describing all the ways that lidar was used in these individual fields, which is well beyond the scope of a cross-disciplinary review paper.

Rather our intent was to provide a sense of fundamental lidar-based advances from individual disciplines with applications to CZ science. As a result, our description of the fundamental advances in each of these fields does perhaps read like a laundry list. An essential finding of this study is that while lidar has contributed substantially to individual CZ fields, its use as a transdisciplinary tool is lacking, thus providing limited (to-date) transformation of CZ science beyond multidisciplinary or interdisciplinary work. We will follow the referee's advice and provide clearer review about how these field-specific advances would not have been accomplished without lidar datasets thereby providing "an analysis of what lidar has been used for" in Section 1. In addition, we will focus our discussion of how lidar will advance the state of CZ science in terms of large-scale questions such as: What controls CZ properties? And processes? What will be the response of CZ structure, and its stores and fluxes, to climate change? And land use change? How can improved understanding of the CZ be used to enhance resilience and sustainability and restore function of the CZ?

Our intent was to focus on the limited number of studies that are using multiple, complimentary information from lidar to answer CZ-relevant questions (put another way, "how this is transforming CZ science beyond the state of the science") and thus to provide examples for the reader to consider for future applications. We focused on these exemplar studies in order to highlight how lidar offers tremendous potential to concurrently investigate feedbacks and interactions between the hydro, eco, and geosphere in a manner that has not been accomplished in the individual fields. We will re-write section 2.1 of the text to better explore what fundamental understanding of CZ processes was gained by using lidar in a transdisciplinary context based on our definition and using the following question as a guiding framework: How do CZ processes co-evolve over long-time scales and interact over shorter time scales to develop thresholds and shifts in states and fluxes of water, energy, and carbon? We believe that by providing a clear definition of transdisciplinary tools and science as well as a framework to evaluate and envision lidar's role in making the leap from intra-, multi- or cross discipline science, the manuscript will take a leap towards providing a vision for future CZ science

endeavors.

RC: What I'd prefer to have seen here is some analysis of the application of lidar–not just a count of what fields the method has been used in. The ecology section early on does a pretty good job of this, but it's lacking throughout the rest of the paper. Even the "three areas in which lidar can make a contribution" still feels like a laundry list of things done.

AC: We agree that sections 1.1-1.3 could have more detail to describe some of these disciplinary-focused lidar applications; however, we also feel that a full description of these applications would be beyond the scope of this paper. With regards to the application of lidar, section 2.2 lays out three applications of lidar data: change detection, scaling CZ processes, and model parameterization and verification. With that, we understand that the level of discussion across all parts of the text needs to improve to the level provided in the ecology section and are targeting this in revision.

RC: Perhaps the authors could insight on nesting lidar measurement scales? What about a few example datasets in figures, showing what could be done with a well-integrated field study using lidar?

AC: This is an extremely challenging request to show examples of how to integrate lidar into field studies, as none of the co-authors are currently working together at any single field site. Previously we too have considered the same idea and found that remote sensing alone was insufficient to robustly tackle integrated temporal and spatial scale questions. However we are hoping that this paper spurs researchers to do exactly as the referee suggests. To this end, we developed conceptual figures showing the range of scales captured with different lidar datasets (Figure 1) and what science questions could be asked to integrate lidar into a CZ science question (Figure 3). We absolutely agree with the referee's comment that showing 'what could be done with a well-integrated field study' is important. We show through highlighting exemplar papers that effectively integrate lidar into field campaigns allowing for nested observations

of interacting processes and have extended well beyond what typical field crews are capable of. We will better highlight these important examples in Section 2.

RC: I find figure 2 strange–it implies there are only 3 good interdisciplinary papers out there (I'm still not sure the word 'transdisciplinary' really holds for what is being described here)–but maybe those three have examples worth highlighting in figure form.

AC: To our understanding, transdisciplinary science transcends one single discipline to inform the work, capture complexity, and create new intellectual advances. We realize that Figure 2 did a poor job explaining this idea of transdisciplinary science. We will modify the figure to more clearly demonstrate the dearth of transdisciplinary studies and expand the discussion of exemplar works to demonstrate how they are expanding the state of the science and potentially adding more examples there.

RC: Lastly, if this manuscript is to reach to a broad CZ audience, simply explaining the methodology of the lidar methods out there (TLS, ALS, SLS, etc.) in detail would be really useful.

AC: The referee makes an excellent point. An additional paragraph will be added to the introduction to better define, and provide examples, for these methods.

RC: The last bit of the paper–the vision piece–could be particular useful, and is thoughtful but feels too short and not expanded on fully. That might be the real contribution of this paper, but as is feels like a last-minute add-on.

AC: We will expand on the five recommendations to given in the vision to discuss how these create opportunities and reduce impediments to the transdisciplinary vision of lidar in CZ science advocated in the paper. Specifically, we will frame the vision around opportunities to move past inter- and multi- disciplinary collaborations to transdisciplinary science that is needed for large, fundamental advances in CZ science. Many of the recommendations and roadblocks will remain the same (i.e. better tools, better communication, etc.), but we will provide more context of how/why they are needed for

transdisciplinary advances.

RC: As a last aside, the abstract is fairly weak, and reads more like an introduction than a true abstract. I realize this is a review paper, but there should be more content here. Maybe the issue is that the paper itself is a bit light on its content and conclusions, but perhaps the abstract is an opportunity to ask: "what specifically has been gained here?" It's the piece that would make this publishable.

AC: The referee makes an excellent point and we will rewrite the abstract to focus specifically on what has been gained, and, importantly the grand challenges for Critical Zones science in terms of quantifying the co-evolution of landscapes at multiple temporal and spatial scales. We will specifically draw on the advances made in the exemplar papers and what opportunities lay ahead to use lidar to build bridges for emerging transdisciplinary science.

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