Re: Submission of Replies to referee comments (MS No.: egusphere-2023-789) "Ideas and Perspectives: Sensing Energy and Matter fluxes in a biota dominated Patagonian landscape through environmental seismology – Introducing the Pumalín Critical Zone Observatory"

Dear Editorial Team of Biogeosciences,

Please find below our replies to the referee comments as requested. For your convenience, you'll find the replies in the corresponding lines below the respective comment. We thank you for considering our manuscript for publication in Biogeosciences. We particularly thank the Associate Editor Christoffer Still for handling our manuscript with so much care.

First of all, we want to express our thanks to the handling editor Christoffer Still, Susan Brantley and an anonymous referee for their time spent in providing constructive reviews and assessments. We highly appreciate all these efforts. In the following, we reply to the comments.

First, while both reviews are positive, both referees suggest some changes that we cannot meet all suggestions raised. For example, referee #1 suggested to include more information on 'framing our site within the CZOs' in our work, while Susan Brantley asked for a more condensed version. Nevertheless, we try to balance both reviews as good as possible of course.

Review #1: Anonymous

This paper describes a research plan to investigate a comparatively little-studied ecosystem, the coastal temperate evergreen rainforest of southern Chile, using a critical zone observatory framework. The stated aim of the research effort described in the paper is to gain 'quantitative understanding of carbon sinks, biota-driven landscape evolution, water, biogeological and energy fluxes, and disturbance regimes'. Their work focuses on roles of trees and forests in carbon cycling.

The study is entitled "Pumalin CZO" in reference to the Pumalin National Park, a 400,000-hectare area which was created and endowed by Doug Tompkins, founder of The North Face and Esprit outdoor clothing companies, and his wife, Kris Tompkins, former CEO of Patagonia, Inc. The Pumalin Park, which has been donated the government of Chile, encompasses land from the coastal fjords to the border with Argentina in the Andes. The geology and geomorphology of the park is dominated by past glaciation and volcanism. Glaciation created extremely steep, hard rock slopes and broad flat valleys buried in sediment from glacial retreat. Volcanism has overprinted some of the glacial sculpting, including the massive Michinmahuida volcano and Chaitén volcano, which erupted in 2008 with major effects on the landscape of most of the Pumalin Park.

The authors emphasize the need for work on understudied coastal temperate rainforests of the global south. They present results of pilot studies in a small (16 km^2) study watershed in which they (1) used lidar to census trees and estimate biomass, (2) used seismic sensors to detect winds, high rainfall intensity, and tree movement that may be related to landslide initiation, and (3) used seismic sensors to detect streamflow events and the possible signature of large wood moving in the stream. The reliance upon remote sensing and sensor arrays both builds on contemporary technological advances and also is necessary in this landscape, which is extremely difficult to access. The authors should be commended for their work in such a challenging setting.

A: We appreciate the reviewer's overall positive impression of our study. We want to add here that our perspective is largely driven from an ecogeomorphic approach. We also may emphasise that this Ideas and Perspectives paper aims at introducing a CZO, with an emphasis on the conceptual the instrumental approach at the current state, a state that is envisioned to grow through the course of the lifetime of the observatory. The scope of the paper is not to present results collected at the end of a CZO's lifetime. This scope is important to know in order to correctly anticipate and interpret the content of the manuscript. We will add that crucial information to the updated version of the text.

Major comments:

1) The authors could improve their explanation of the physical setting of the study basin and how it relates to the larger landscape. The study area for "Pumalin CZO" described in this paper represents a very small and particular fraction of the landscape. It is less than 0.5% of Pumalin Park, a 1630-ha catchment draining to the fjord just west of the ferry port of Caleta Gonzalo. Small, steep catchments draining directly to fjords represent a rather small portion of the landscape of Pumalin Park and this portion of southern Chile, which is dominated by much larger river basins (e.g. Amarillo, Rio Blanco Chaitén, Rio Rayas, Rio Michinmahuida) where steep glaciated slopes mantled with volcanic deposits drain to broad, flat valleys with meandering rivers and wetlands. It is unclear from the paper how the studies from this small catchment can be generalized to the larger landscape.

A: It is correct that the Caleta Gonzalo (CG) catchment covers only a small fraction of the entire Pumalin NP, a characteristic which places it in line with the scope of many other CZOs. Small catchments allow for both simplified assumptions and boundary conditions. Rather than the simple size of a studied area it is, as the referee carefully pointed out, the question of representativeness but also the degree to which one can get insight to the ecosystem functioning. We explain these essential points below and would also add a clarifying sentence to the manuscript to avoid confusion for the wider readership.

1) ***According to landslide and wind exposure modeling across the entire region, the CG site shows no exceptional status regarding landslide susceptibility or wind exposure, though notably steep gradients in both metrics. As we follow the disturbance exposure sampling design, CG provides therefore a prime preconditions for our research. CG is a pristine catchment that hosts some of the largest (and potentially oldest) forest stands within the entire Pumalin NP, showing typical characteristic forest structure and species composition (e.g., and is largely unaffected by large-scale landscape disturbances, such as earthquake and volcanic eruption-driven landsliding). Therefore, we consider CG one representative end-member of ecosystem functioning within the Pumalin NP. We will add this discussion to the manuscript.***
2) ***In the course of the project we have started to instrument a further site. The Michinmahuida catchment (MC), some 30 km to the S of CG, differs fundamentally from the CG settings, yet it stands for another ecosystem end-member on the Pumalin NP. MC is partially glaciated, has a longer drainage network and complexity, had been severely affected by the 2008-Chaiten volcanic eruption, and host floodplain forests that differ fundamentally in terms of species and age distributions. However, since that catchment has not been part of the initial manuscript, we see no reason to explicitly mention it (see also reply to first comment of the referee).***

3) The paper could provide more clarity on how the narrowly focused work is related to the ecological and geomorphic processes that govern carbon cycling. The actual work described in this paper is focused on three principal efforts: (1) lidar based estimates of forest structure and topography, (2) seismic sensors to measure rainfall intensity and tree movement, to address the role of wind in toppling trees and their effects on landslide generation, and (3) water stage information and characteristic frequency band from seismic sensors to identify large wood in motion in the stream channel, in order to determine rates of large wood movement in this “undisturbed” catchment. It is unclear how the results of these focused studies will contribute to the understanding of broader ecological and geomorphic processes.

A: Our work will contribute to the understanding of broader and general ecological and ecogeomorphic processes in this specific Biome. Among all processes studied, carbon fluxes are one member, but definitely not the sole one. We will clarify that in the manuscript. Once we get a proper process understanding and can attribute the relevant drivers (e.g., topographic, hydrometeorologic, volcanic proximity parameters among others), we can regionalize the activity based on easily available driver information (DEM derived metrics, weather data, reanalysis or projected data) together with transferable process-understanding via physics-based modeling, i.e. Landlab. For the aforementioned reasons on the study site selection, we thus argue that the processes that we observe in CG may be observed elsewhere in the broader study area where forest stands are not severely affected by the recent Chaiten eruption. We will add this scope to the manuscript to avoid the impression of pursuing a narrowly focused perspective.

Our seismic approach goes beyond the list of objectives identified by the referee. More important, it is not the metrics we are able to cover, but essentially the combination of temporal and spatial scale at which we can jointly assess those metrics. Of course, there are dedicated sensors for each of those variables. However, those either have a very small spatial footprint or long lapse times. For examples, tree mortality is a vital parameter in forest ecology that we may monitor using our geophones in the ground. Previous studies focus on either plot-scale (thus problematic in estimating tree mortality given its small spatial scale) and/or remote sensing. The latter, however, is often of too coarse spatial resolution and may also fail in capturing tree fall of smaller trees that are hidden by the canopy. Such information may be particularly valuable when exploring carbon cascades in the future. Hence, given our CZO and the equipment installed, we cover not only an understudied biome and the ecogeomorphic processes but also address an understudied spatial gap. Therefore, the seismic approach complements existing technologies but fills technological research gaps, which is of special relevance for the scope of Earth surface processes driven CZOs. As a result, methodologically we consider the combined approach of high-resolution multi-purpose lidar data collection, multi-proxy seismic sensing and on-site control data collection a fair bit from "narrowly focused", but instead and in junction with the representativeness of the CG site (see answer above) a generic and scalable tool set to explore the cascading and/or feedback roles of forests, disturbances, biomass and concomitant carbon fluxes.

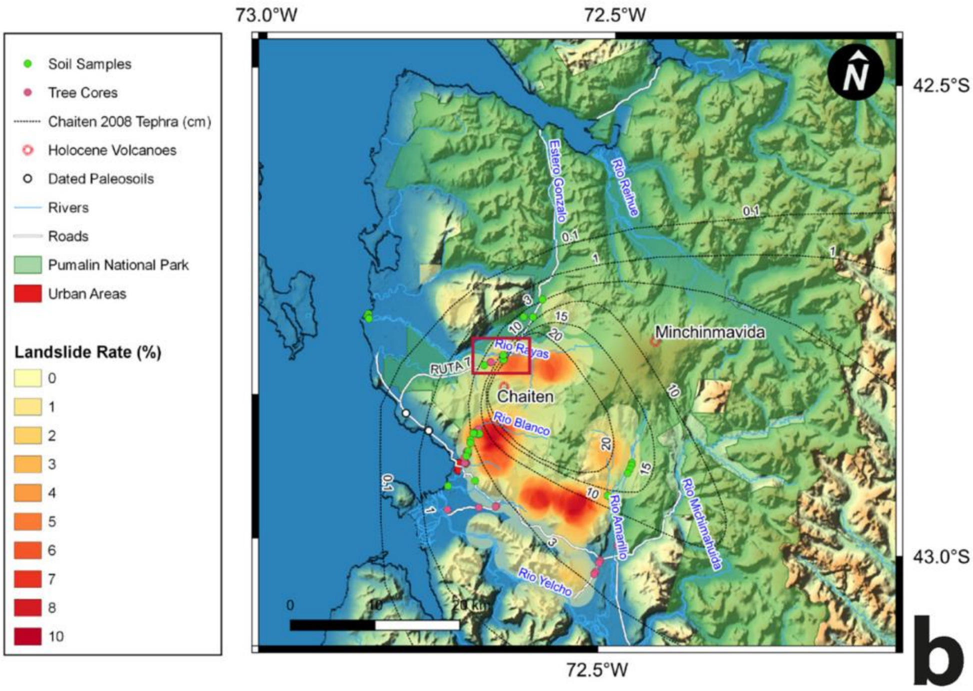
Regardless, we will make sure to better include aspects of carbon cycling into our manuscript.

1) The work lacks context within a broader conceptual framework for carbon cycling and disturbances.
    1. The authors could do a better job of placing their work within the context of how cascading disturbance effects influence carbon cycling.

       A: Thanks for this suggestion. We could of course expand our work here within the cascading context. However, this may open an entirely new story given that we would then talk about compounding processes that can be not only cascades but also of preconditioned, multivariate, spatially and temporally compounding nature. On the other hand, we already to explicitly address such cascading context as we explore carbon fluxes from the mobilization (landslide, tree mortality) into the drainage network via connectivity (discharge, large wood), while quantifying carbon stocks along disturbance gradients. Once more, we want to echo our previous reply that carbon fluxes are one scientific scope of our research but not the sole. We take the suggestion as a well-motivated driver of a future focus on that topic, once sufficient data and additional instrumental equipment can provide a base for that project.

       The authors state, "The local disturbance regime is comparably simple." But this does not seem accurate. The study area received substantial tephra deposits from the 2008 eruption of Chaitén volcano. Many studies have been conducted of the effects of this volcanic eruption on forests, landslides, and rivers, including several by the lead author of this paper. Published work has revealed how tephra deposition and other processes during the Chaitén eruption killed large areas of forest on hillslopes and in river valleys (Swanson et al., 2013), how this tree mortality combined with tephra deposition accelerated landslides, and how subsequent extraordinary elevated sediment export (Major et al. 2016) transported large wood in large rivers. This is not a simple disturbance regime.

A: Thanks for raising this and allowing us to clarify. Yes, the Chaiten eruption in 2008 caused massive forest dieback that led to a distinctly delayed hillslope response via biotically controlled landsliding. However, the Caleta Gonzalo catchment has remained unaffected from this specific eruption (see figure below). In fact, the absence of 2008-Chaiten-tephra in CG was one critical criteria for us to choose our study area. Yet, there is definitely evidence for Holocene tephra layers preserved along road cuts between CG and Chaiten township. Nevertheless, we did not find evidence for recent volcanic layers in the CG catchment. We neither find any evidence for wild fires in the Caleta Gonzalo catchment, i.e. charred coal embedded into soil layers. Hence, we are inclined to argue that the disturbance regime in this specific catchment is indeed rather simple and mostly controlled by landslides and wind disturbance. Both disturbances are largely constrained to topography and are, thus, relatively simple to predict. We would clarify this important aspect in the updated version of the manuscript.



The map of landslides in Figure 4 does not refer to the role of tephra deposits from the Chaitén eruption, although one of the authors of this paper has published work on post-eruption landslides in the area. Nor does the paper explain how tephra deposition from the Chaitén eruptions (or from other volcanic eruptions) may have contributed to the finding that “the highest denudation rates along the entire Chilean Andes [were found] under dense Patagonian CTRs [coastal temperate rainforests].”

A: The purpose of Fig. 4 is to show that Landlab is able to mechanistically predict the biotic controls of surface processes in disturbed landscapes, and not to illustrate a possible effect of tephra deposits. The notion of tephra and volcanic eruptions on high denudation rates is indeed intriguing. Yet, we have also high volcanic activity along other segments of the Andes. Hence, the volcanic activity within the Patagonian rainforest is not necessarily the sole and decisive ingredient needed to cause highest denudation under Patagonian forest cover. Our work presented here does not claim to explain the high denudation rates we observed.

This is another topic we are currently working on and definitely worth proceeding in the future potentially linked to our CZO. We would therefore hold back that suggested expansion of the manuscript to keep the focus sharp and clear.

This paper does not set the work on wind-triggered landslides in this broader context. The concept of disturbance cascades in space and time could be useful for their framing.

A: Our work presented here is not intended to link with other work on denudation rates. This contribution is largely conceptualized to explore the forcing of wind exerting geomorphic work – in a mechanistic way.

2. The authors could better explain the expected importance of the carbon transfer processes they are studying, which appear to have the effect of storing, rather than transporting carbon in the landscape. The authors note that extremely low concentrations of suspended sediment (<0.001 g/l) immediately after a rainfall-runoff event in March 2022 suggest "a high recycling rate of hillslope debris within the catchment and not necessarily high sediment and organic carbon export into the fjords." Does this mean that the authors believe that chronic processes such as small landslides produce low export of carbon, and that instead carbon export from this landscape is dominated by less frequent disturbance-mediated events, such as the combined effects of volcanic eruption, elevated landsliding, and sediment and wood-laden floods?

   A: This is one hypothesis we are thinking of. Using our experimental setup teamed up with Landlab modeling may be a promising way of testing this (and other) hypothesis. Yet, we are not in the stage of providing here a deep analysis of this basic geomorphic question that circles around magnitude-frequency relationships in the context of surface processes going back to the seminal works by Wolman and Miller (1960). As a consequence, this valuable idea is off scope for this manuscript with the data sets collected to date. We would therefore thank the referee for this concept but feel it is too speculative until rigorous data have been collected as part of the mid-term effort of the project.

   This paper does not make clear how the research they are conducting will be combined with prior work to understand the relative roles of chronic vs. disturbance-mediated carbon transport processes.

   A: We kindly ask you to refer to the reply above.

3. The authors could improve their explanations of the spatial and temporal scales of their studies. The authors state, "disturbances are predicted to change in this biome not only quantitatively but also qualitatively: The disturbance regime has likely already started to change." The landscape has been recently (in the past two

decades) changed by a volcanic eruption. What are the time scales and spatial scales of changes in disturbance that motivate the research described in this paper?

A: Thanks for raising this and giving us the opportunity to clarify. Following our reply on the selection criteria for the CG catchment (see above), we want to stress that exploring critical zone processes to volcanic eruptions and their concomitant ecological effects lie off the main scope of our research. Recurrence intervals of Chaiten-type eruptions, i.e. > 4 VEI, occur on centennial-to-millennial scale across the Northern Patagonian rainforest. Instead, we refer to changes on shorter time scales, particularly changes induced by ongoing global warming. Due to global warming, the disturbance regime is predicted to change qualitatively and much faster in such that, for example, wildfires will become more frequent. Up to date, wildfires are more restricted to the drier parts of the Patagonian Andes, e.g. around Coyhaique.

2) The paper is presented as an introduction to a CZO, but the work is not evaluated in the context of how CZOs are framed. There is no mention of soils, for example, which are a key part of many CZOs.

A: We appreciate the reviewer's comment here. In fact, there exists no general context of CZOs in general, and a catalogue which lists all the requirements needed to call a CZO a proper CZO in particular. We agree, however, that we will provide additional information on the framing of CZO, such as soils. We propose to combine this suggestion with the suggestion raised by Susan Brantley providing a table.

3) The paper is presented as an introduction to a place, rather than a set of findings about geomorphic and ecological processes.

A: Thank you very much for this comment that we use to underline that this paper is a potential 'ideas and perspective' contribution. Thus, we explicitly aim on introducing a CZO concept to the scientific community (as written in the title) but to not claim providing an 'into-depth' going research article. Instead, we regard this contribution as a base for future studies.

4) There are a lot speculative statements scattered through the paper, which are not phrased as hypotheses, nor are they tested.

A: Thank you very much for this comment. We will screen the text for possible occurrences and revise to be concise and mark hypotheses accordingly where needed.

5) The paper seems to describe a research plan, rather than research results. It seems more focused on the measurement technology than on findings. It does not provide clear

hypotheses or interpretations about what the results reveal about geomorphic and ecological processes.

A: Thank you very much for this comment. We kindly refer here to the reply above.

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