

# **Drought responses of a Norway spruce forest on drained peat soil: combining sap-flow sensors, eddy-covariance, soil and UAV data**

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## **Response to Review No. 1**

**We sincerely thank the Reviewer for the valuable insights and constructive recommendations on how to improve our work. Our responses will be highlighted with blue.**

### **General comments**

Overall, the paper is suitable for publication in Biogeosciences, as it provides an important overview of the efficacy of various methodological approaches for investigating the responses of boreal forests to drought. However, given the many concepts and datasets presented in this paper, the overall structure needs improvement to provide more clarity for the reader. Some of the ideas presented are not well connected, or require clarification to contextualize them within the paper's premise and the scale of the results. Moreover, because the figures can be very data-heavy, captions and/or legends need to be improved so they can stand alone without requiring embedded supporting text in the manuscript. Nonetheless, the conclusions are clearly drawn and can support further research on the usability of the proposed methods to understand the onset and effects of drought on boreal forest productivity. - **We are very pleased to receive such feedback on our work and once again thank the Reviewer for the positive and thorough assessment of this manuscript. We will clarify the text and improve the structure. Figure legends will be improved to make them stand alone.**

### **Specific comments**

The introduction needs some light reorganization to improve the flow of ideas. For example, in lines 51 to 56, the introduction of the Standardized Precipitation Evaporation Index (SPEI) feels disconnected from the ideas presented in the previous paragraph. I understand that this index is used later in the paper to explore regional drought characterization, but it is not well integrated here, nor does it support a strong segue to the next paragraph. A suggestion is to combine the

paragraphs from lines 45 to 56 into one and make the connection between Norway spruce responses to VPD clearer in preparation for the next paragraph. – These paragraphs will be reworked to improve the flow, as advised.

In the introduction, the paper's main goal is first presented: to investigate the drought responses of two adjacent stands in a boreal forest in Finland (lines 98 and 99). However, in line 104, the statement about the difficulty of detecting drought responses in boreal forests serves as the main premise. Given the importance of this premise in the introduction and abstract, I suggest reframing the goals to clarify the paper's main question. If the paper aims to identify the utility of different methodologies to characterize drought and then explain how two adjacent stands behaved differently under drought, a reframing could benefit the reader. – The aims and hypotheses will be reformulated. We understand that, in its present form, this part does not achieve the desired effect.

In the methodology section, specifically in “meteorological and soil environmental conditions” (Section 2.2.2), there is mention of datasets that were collected but not incorporated into the discussion. I suggest removing mention of any datasets that are not presented in the results and discussion. – Will be done

I suggest renaming section 2.2.3, “meteorological drought assessment”, to better represent both the atmospheric and soil drought definitions. Moreover, a clearer distinction between these two definitions is needed, as their use in the results and discussion sections was often confusing (see other comments below). Moreover, this section does not seem to belong in the “field setup” description and would be more appropriate in another section describing derived indices and drought characterization. The same would be more appropriate for Section 2.2.4 on drought proxies. In this section, acronyms need to be more clearly defined and used consistently throughout the paper, and providing more context on why these proxies were chosen would probably help the reader. – Thank you for this recommendation, we do believe it would indeed improve the structure. The sections 2.2.3 – 2.2.7 will be unified under a new subsection, “2.3 Proxies for drought assessment”. The acronyms definitions will be revised.

The novel approach to measuring tree stomatal conductance (section 2.2.7) also does not appear to be well suited to the “field setup” section. Moreover, this seems like a pivotal contribution of this paper to the literature. It may be best to include it in another section of the methods for physiological stress characterization, for example, or within section 2.2.6 (e.g., 2.2.6.1). – We agree, and this will be done, as per the previous comment,

In the results section, I am unclear what is the goal of the monthly SPEI distribution for the entire country (Figure 2c). It is tied to national rainfall patterns, but this is not investigated enough to provide sufficient contextualization for the study site-specific results. I suggest this be reframed for greater clarity or removed entirely. Moreover, Figure 2b needs more clarity: the soil drought points correspond to both atmospheric and soil drought conditions (line 395). The figure

should be comprehensible on its own, and the current caption and legend are not sufficiently self-explanatory. – The Fig. 2b legend will be improved. The geographical distribution of SPEI over Finland is intended to allow the reader to evaluate how strong the drought conditions were at the measurement site (marked with the red dot) compared with the rest of the country, and we consider this a useful insight. This will be better explained in the main text and caption.

Please include a legend for Figure 2a. I assumed that the colors and line patterns corresponded to different blocks and years, as in other figures, but that should be clearer here. – Will be added

Lastly, I understand that Figure 2b is representative of the harvest block, likely due to the placement of the eddy-covariance tower. That is not well described in section 2.2.2, nor in the caption or the text. Make this clearer to the reader in one of these places. – Thank you for this note, we will clarify that.

Results for the Bowen Ratio in lines 425-428 are unclear because there is no frame of reference for the Bowen Ratio in the methods section. Please include contextualization for what it means when the Bowen ratio increases or decreases. Contextualization may also be needed for the Canopy Water Stress Index, since the averaged CWSI during drought periods is not presented relative to other values. – Thank you, we will rethink the presentation of the Bowen ratio and the CSWI, and add the missing interpretations.

In Figure 6a-6d, it is unclear why and how the VPD values were binned. What was the criterion for binning the values? Could a line have displayed that with either shaded standard deviations or a shaded confidence interval? Moreover, the legend is small and hard to read. Please increase the point size of the legend. – the binning was done for every 0.25 kPa step in VPD – This will be clarified. The font sizes will be increased.

Please consider reorganizing section 3.2 for greater clarity. This is a very data-heavy section and can be confusing for the reader. It might be beneficial to discuss ecosystem-level data first, as currently presented in Figures 4 and 6, and then use the block distinctions in Figure 6 to discuss differences between blocks, including Figure 5. The main issue identified here is the discussion of NEE that opens and closes this section, which leads to some repetition; perhaps bringing the two together could facilitate the reader's comprehension of the data. Moreover, a reorganization may help with the weather contextualization of this section (e.g., drought is often associated with more sunlight, weather conditions for EC measurements, etc.). – Thank you for the recommendation. Section 3.2 will be rearranged as proposed.

Throughout the results section, please consider being clearer about the atmospheric and soil drought. Currently, the term “drought” is used in both contexts with much explanation, which has hindered easier comprehension of the results. Perhaps some context can be introduced in the relevant methods section and reinforced here. – Thanks for important observation. The current ambiguity is for two primary reasons: First, it arises from our approach, where we attempt to

address both types of drought and have not succeeded to be specific enough when atmospheric vs. soil drought are discussed. This will be revised in the next version of the manuscript for better clarity. Second, the concepts of atmospheric, soil and ecological drought are still not mature and clear overall. Currently, the research community has no effective or unified way to describe drought. We will highlight this problem further and clarify the definitions as much as possible.

Two previous studies discussing the complexity of drought definitions will be cited, Crausbay et al. (2017), “Defining Ecological Drought for the Twenty-First Century”, and Wilhite et al. (1985), “The Drought Phenomenon: The Role of Definitions.”

In Figure 7, similar to Figure 6a-6d, it is unclear how the VPD values were binned. Please provide context for the specific criteria used to bin these values. – It was done by dividing the VPD range of [0...3] into eight intervals. This will be clarified and explained in the text.

In lines 511-512, it is noted that the harvest-block trees show higher sap flow than the control trees. Is that the result on average? Is it per range of tree diameter? How are these values contextualized? – This part refers to Figure 7, where these relations may be observed visually. What is meant is the mean ratio of sapflow at  $VPD > 1$  for all trees in Harvest and Control. However, the text will benefit from a numerical expression of these relations, which we will provide.

In the UAV survey results (section 3.4), inconsistent use of abbreviations and symbols may hinder the reader’s ability to understand the results. Please consider using abbreviations and symbols more consistently, such as when discussing thermal stomatal resistance and stomatal conductance. Thank you for pointing this out - the quantity names will be harmonized, e.g.  $g_{sT}$

The paragraph in lines 585-595 compares the median of the distributions from the tree stomatal conduction to the eddy covariance values, which is not immediately clear from the figure. An indication of the tree medians could be included to facilitate comparison with the EC lines. Moreover, rewording this paragraph may benefit the reader; lines 593-595 were confusing. – These sentences will be reformulated for clarity. This is correct: the paragraph talks about the median values and widths of the plant index distributions.

In Figure 12, tree height and NDVI values were binned. As with previous figures showing binned VPD values, it is unclear here why or how these variables were binned. Please provide some context. – Will be done. As before, the binning was done by dividing the x-axis range into equal intervals.

Again, in the discussion section, there’s confusion about which type of drought the argument concerns (atmospheric or soil). In the first paragraph of this section, for example, it is not immediately clear that changes in vegetation functioning with drought refer to the atmospheric drought. Improving clarity would greatly benefit the dissemination of this paper. – As we

indicate in a response to another comment above, this lack of clarity in drought definitions is in fact one of the foci and premises for this work. We will try to present this conundrum in a clearer way.

The ideas in the paragraph on lines 654-657 should be distributed across the previous paragraph and the following paragraphs for greater clarity. – Will be done

In lines 661-665, it is unclear why bring up a previous study finding greater reductions in boreal forest productivity under low soil moisture contents if the last sentence is about the effects of atmospheric drought in the absence of soil drought. – Apologies for poor wording in this paragraph – the mentioned studies explored the conditions of drought, when high VPD were most often found to coincide with low soil water. These studies did not intend to explore the individual effects of air or soil drought, to my best understanding.

In the results section, it states that soil moisture was measured at 20 cm in addition to 5 cm. Why is that not shown in the paper, and why was it not used to explore additional stress from soil drought further? Moreover, how might the water table depth mediate the soil response to drought stress? How can the decoupling between soil moisture and water table depth help explain the effects of soil drought on boreal forest productivity? – The mention of the -20 cm measurement level will be removed, as it indeed is not used in the present study.

The -5 cm measurement level was chosen in order to highlight the short-term dynamics in topsoil moisture content. This level also has a closer link with the soil surface condition, which in turn directly affects the ground surface conductance and thus the site-average  $g_s$ , Bowen ratio and other drought proxies. Conversely, the -20 cm moisture time series are much smoother, concealing the short-term weather change effects. The trees in the site have shallow root systems so they too can be expected to be affected by topsoil (-5cm) moisture.

The discussion section follows a strong structure, from ecosystem-level responses to drought and block effects (thinning) to individual tree responses. It ends with a comparison of the EC data to the UAV approach, which is incredibly valuable to the community. - Thank you very much for this positive assessment!

### **Technical corrections**

Line 234: include BR abbreviation in parentheses or brackets (consistent with other abbreviations). – Will be done

Line 239: include symbol and units for aerodynamic resistance to water vapour transport in parentheses or brackets (consistent with other symbols). – Will be done

Line 253: include symbol and units for surface conductance in parentheses or brackets (consistent with other symbols). – Will be done

Line 254: include Canopy Water Stress Index abbreviation in parentheses or brackets (consistent with other abbreviations). – Will be done

Line 263: include WUE abbreviation in parentheses or brackets (consistent with other abbreviations). – Will be done

Line 268: include LUE abbreviation in parentheses or brackets (consistent with other abbreviations). – Will be done

Line 435: Figure 4 needs a title before the description of the specific panels. – Will be done

Line 467: add a comma after PAR for greater clarity. – Will be done

Line 474: unsure whether there's a typo or if the sentence needs more clarification. Unsure what "at no drought on the c shows" means. – Will be clarified

Line 481: Figure 6 needs a title before the description of the specific panels. – Will be added

Line 529: Figure 9 needs a title before the description of the specific panels. – Will be added

Line 578: Figure 10 needs a title before the description of the specific panels. – Will be added

Line 669: correct Mirabel et al. (2023) citation. – Will be done

Line 709: Is Figure 12 the correct figure here? Shouldn't it be figure 9? – Sorry, you are correct, it should be Figure 9.