Reply to comments of Reviewer 1

In ***"blue"*** we copied the comments of the reviewer, in **black** our reply, in **green** new additions that will be included in the manuscript, and in **red** the deletions to the manuscript. We also indicated within square brackets the line number when we refer to specific points or sections of the manuscript "[Line:]". The numbering of figures and tables of this reply are preceded by R aiming to differentiate them from the original figures and tables of the manuscript.

"Paper summary: In response to a growing body of research indicating that plants routinely use water from bedrock, these authors asked the question: what happens to modeled plant transpiration if, instead of relying exclusively on soil water, they are allowed to access a deeper bedrock bucket? They found that having access to more water improved the accuracy of transpiration in a widely used land surface model (when compared to actual sap flow data) in places with pronounced dry seasons. The authors suggest that this provides additional motivation for the better inclusion of plant-available bedrock water in land surface models. The manuscript is well written and easy to read."

1. Reply:

We would like to thank the reviewer's positive comments and the constructive feedback. Hereafter, we provide a separate response to each query.

"I am supportive of the goals of this manuscript and would like to see it published, but I would also appreciate the authors considering how they could address what I perceive are two shortcomings:

1. *The study illustrates transpiration dynamics using field data for sapflow at four sites, but no actual local field information about the storage dynamics of the bedrock underlying soil, local rooting profiles, etc. is provided. So, there is little meaningful context regarding the subsurface properties at the sites (properties that are the primary focus of the paper)."*

2. Reply:

Detailed physical features such as hydraulic conductivity, water holding capacity, or percentage of fractures are not available for the weathered bedrock beneath the experimental sites. There have been some regional assessments of the role played by the interaction between soil and groundwater systems close to Puechabon [FR-Pue] and Hesse [FR-Hes] (Kirchen et al. 2017, Ollivier et al. 2021) but detailed information of their physical properties is missing. However, each location has different degrees of data availability describing soil characteristics. The sites Puechabon [FR-Pue] (e.g., Hoff et al. . 2002), Hesse [FR-Hes] (e.g., Granier et al. . 2008), and Alto Tajo [ES-Alt] (e.g., Forner et al. 2018) have a good record, but the information available for Fyorodorovskoye [RU-Fyo] is limited (e.g., Vygodskaya et al. 2002). Table R1 summarizes the available information and provides a better context of the subsurface structure of each experimental site. Therefore, aiming to provide a better contextualization of the subsurface characteristics of each site, we proposed to add Table R1 and improve the characterization of each site as follows:

In [Line: 95]:

"... and lowlands (RU-Fyo). All the sites lack detailed information concerning the physical properties of the weathered bedrock, such as hydraulic conductivity, water holding capacity, or percentage of fractures. The sites are distributed across an environmental ..."

For ES-Alt [Line: 101]:

"... et al. 2017). The soils are formed from Cretaceous carbonate rocks settled on top of sandy sediments (Carcavilla et al. 2008), showing a poor development (Granda et al. 2012) with maximum soil thickness varying between 25 cm at the top of the slopes, and more than 1.0 m at the bottom (Martín-Moreno et al. 2014). The climate ..."

[Line: 108]:

"... et al. 2014). Quercus ilex trees at this site have the capacity to allocate structural and fine roots down to 8.0 m depth (Penuelas et al. 2003). The plant ..."

For FR-Pue [Line: 112]:

"... et al. 2002). The superficial soil layers have a high soil permeability thanks to the elevated stone fraction of 0.75. On the other hand, soil layers beneath 50 cm have a larger clay content (> 30%) and a stone fraction of more than 0.9 (Limousin et al. 2009, Pita et al. 2013). This location ..."

[Line: 115]:

"... 2008). This forest stand allocates most of the fine root biomass in the top 50 cm of the soil profile with a small fraction of roots reaching depths down to 4.5 m (Allard et al. 2008). Similarly, to ..."

For FR-Hes [Line: 112]:

"... 2007). It is a clear transition between the eluviated horizon and the horizon with high clay accumulation at 50 cm depth (Zapater et al. 2012), leading to a low clay content in the upper soil layers (Granier et al. 2000 a). It has ... "

[Line: 124]:

"... 2001). Fagus sylvatica trees allocate most of the fine roots in the upper 40 cm of soil with some fine roots reaching depths down to 1.5 m (Granier et al. 2000a, Granier et al. 2000b, Zapater et al. 2012, Bestch et al. 2011). The dominant ..."

For RU-Fyo [Line: 131]:

"… and still present. The peat layer at this site has an average depth of 50 cm (Schulze et al. 2002, Vygoskaya et al. 2002, Arneth et al. 2002, Kurbatova et al. 2002), and the glacial deposits result in a loamy texture of the soil beneath it (Novenko et al. 2010, Schulze et al. 2002). The water table at this site is shallow, forcing the trees to allocate most of the fine roots in the top 20 cm of the soil (Milyukova et al. Schulze et al. 2002, Vygodskaya et al. 2002). The climate …"

Also, adding Table R1 as an appendix:

Table R1. Summary of the main sub-surface characteristics of each experimental site.

Main Site Characteristics	**ES-Alt**	**FR-Pue**	**FR-Hes**	**RU-Fyo**
Rooting Depth (m)	8.0	4.5	> 1.5	0.2
Peat Layer Depth (cm)	None	None	None	50
Soil Depth (cm)	20-40 | 100	50	145	N.A.
Soil Texture: % Clay	25.9	39	25	N.A.
Soil Texture: % Sand	57.3	26	N.A.	N.A.
Soil Texture: % Silt	16.8	35	N.A.	N.A.
Soil Type	Sandy Clay Loam	Silty Clay Loam	Clay Loam	Loam
Soil Permeability	N.A.	High	N.A.	N.A.
Superficial Stone Fraction	N.A.	0.75 (0-50cm)	N.A.	N.A.
Deep Stone Fraction	N.A.	0.90 (>50 cm)	N.A.	N.A.
Bedrock Type	Cretaceous carbonate	Jurassic Limestone	Sandstone	Glacial deposits
Water Table Depth	Deep	Deep	Deep	Superficial
Plant Water	Soil Water, Weathered Bedrock, Groundwater	Soil Water, Weathered Bedrock, Groundwater	Soil Water	Non-Saturated Substratum
Hydraulic Lift	Present	N.A.	Present	N.A.
References	Grossiord et al. (2015) Penuelas et al. (2003) Forner et al. (2018) Martin-Duque et al. (2008)	Allard et al. (2008) Pita et al. (2013) Limousin et al. (2009)	Granier et al. (2007) Granier et al. (2000a) Granier et al. (2000b) Le Goff et al. (2001) Zapater et al. (2012) Betsch et al. (2011)	Schulze et al. (2002) Vigodskaya et al. (2002) Novenko et al. (2010) Arneth et al. (2002) Kurbatova et al. (2002) Milyukova et al. (2002)

"This means the study essentially looked at the effect of varying a model parameter (water storage bucket size) on T and found that the default model configuration could be improved upon. Other default model parameters could have also been varied (the PFT properties, for example), and modeled transpiration might have been improved as well."

3. Reply:

We agree with the reviewer's point that many environmental and physiological parameters of the model can be changed (e.g., Ψ_{p50}, K_{max}, soil texture, slope of the stomata conductance model, etc.) to improve the simulated transpiration response. However, the focus of this manuscript is not to tune the CLM model to each experimental site. Instead, we wanted to test the sensitivity of the simulated transpiration to the bedrock representation using novel sap flow data as a reference dataset. Consequently, we only focus on modifying the depth to bedrock using the default model to isolate its effect.

Moving the bedrock deeper implies solving the issue of how to parameterize this newly created water storage. "Section 3.2 Bedrock Configuration" [Line: 154] describes the selected approach which relies on two main assumptions: a fractured bedrock will have a high-water conductivity and low water holding capacity. This approach is based on the recent studies at regional and continental scales stressing the importance of the accumulated sediments in weathered bedrock fractures that enhances the water holding capacity beneath the soil (Jian et al. 2020), allowing the woody ecosystems to use the rock moisture at regional scales (McCormick et al. 2021). The widespread use of rock moisture by vegetation is supported by the vast number of studies carried out during the last two decades stressing the importance of adding the weathered bedrock as a small reservoir that serves as a buffer during dry conditions (Hubbert et al. 2001, Aranda et al. 2007, Baldocchi et al. 2010, David et al. 2013, Forner et al. 2018, Gil-Pelegrín et al. 2017, Nadezhdina et al. 2008, Penuelas & Filella 2003, Zapater et al. 2012).

Furthermore, numerous studies have shown that the increasing complexity of LSMs may also increase the number of model parameters with substantially uncertain values (e.g., Mu et al. 2021). This trend requires the implementation of statistically robust approaches to test model sensitivity and uncertainty. A prominent example along this line is the Parameter Perturbation Ensemble Project using CLM5 (Lawrence et al. 2020). We recognize that all these points should be clearer in the manuscript. Consequently, we propose to add:

In [Line 49]:

> "… and Koven, 2020). However, the recent developments in LSMs have increased the number of parameters exerting control over multiple fluxes, pointing out the need to provide a better way to constrain these parameters to improve the LSM simulations (Mu et al. 2021). These constraints are of high importance because they allow assessing the effect of the parameter selection on the model sensitivity and uncertainty (Lawrence et al. 2020). The representation of subsurface …"

In [Line: 76]:

> "… et al. 2016). Recent studies stressed the importance of the accumulated sediments in weathered bedrock fractures that enhances the water holding capacity beneath the soil (Jian et al. 2020). These sediments allow the woody ecosystems to use the rock moisture at the continental scale across different rock

> types (McCormick et al. 2021). The widespread use of rock moisture by vegetation is supported by the vast number of studies carried out during the last two decades stressing the importance of adding the weathered bedrock as an additional water reservoir that serves as a buffer water supply during dry conditions (Hubbert et al. 2001, Aranda et al. 2007, Baldocchi et al. 2010, David et al. 2013, Forner et al. 2018, Gil-Pelegrín et al. 2017, Nadezhdina et al. 2008, Penuelas & Filella 2003, Zapater et al. 2011). This reservoir is critical for properly representing transpiration fluxes during dry periods (e.g., summer, drought, heat waves) of vegetation growing in water-limited environments. Consequently, it is necessary to provide a preliminary evaluation of the impact that additional water storage may have on the simulated transpiration fluxes."

Also, aiming to clarify the decision of using the default configuration, we proposed to add the following:

In [Line 145]:

> "… et al. 2019). We use the default plant physiological parameterization (Lawrence et al. 2019) according to the PFT classification of each experimental site. Site-specific …"

In [Line 166]:

> "… clay (Table 1). This approach aims to mimic the hydrological behavior of a fractured bedrock based on two main assumptions: a fractured bedrock should have a high-water conductivity and low water holding capacity. The high sand percentage will mimic the fast water movement through the primary and secondary porosity of the fractured bedrock. At the same time, the low clay content allows having a low water holding capacity for plant water uptake."

Also, we will add the reference "(Jones & Graham 1993)" in Line 27 to support the sentence.

The soil parametrization used for the Default Model Configuration (DMC) and Deeper Bedrock Configuration (DBC) agreed with the published data for FR-Hes, FR-Pue, and FR-Hes (Figure R1). These configurations are located within the boundaries of the soil texture-classification of each site. In this regard, the agreement of soil water storage capacity, infiltration, and percolation rates will agree with the expected site conditions. Clay content in ES-Alt is similar among model configurations, providing a similar water holding capacity. However, the sand content in the model for the DMC and DBC configurations determines a reduced hydraulic conductivity than the one expected from the field data. This condition implies that the CLM 5 model tends to percolate less water than under actual conditions. In this regard, the subsurface parametrization doesn't need to be adjusted for the sites, while the infiltration and percolation rates of ES-Alt are expected to be larger than the modeled results.

Aiming to clarify the impacts of soil characteristics on the soil water reservoir, we proposed to add Figure R1 as an appendix and the following sentences:

In [Line: 265]:

"... configurations.

The soil parametrization used in DMC and DBC agreed with the published data for FR-Hes, FR-Pue, and FR-Hes (Figure R1). These configurations are located within the boundaries of the soil texture classification of each site. In this regard, the agreement of soil water storage capacity, infiltration, and percolation rates agreed with the expected site conditions. Clay content in ES-Alt is similar between model configurations and site conditions, providing a similar water holding capacity. However, the sand content of the model for DMC and DBC configurations represents a lower hydraulic conductivity than the one expected for this site."

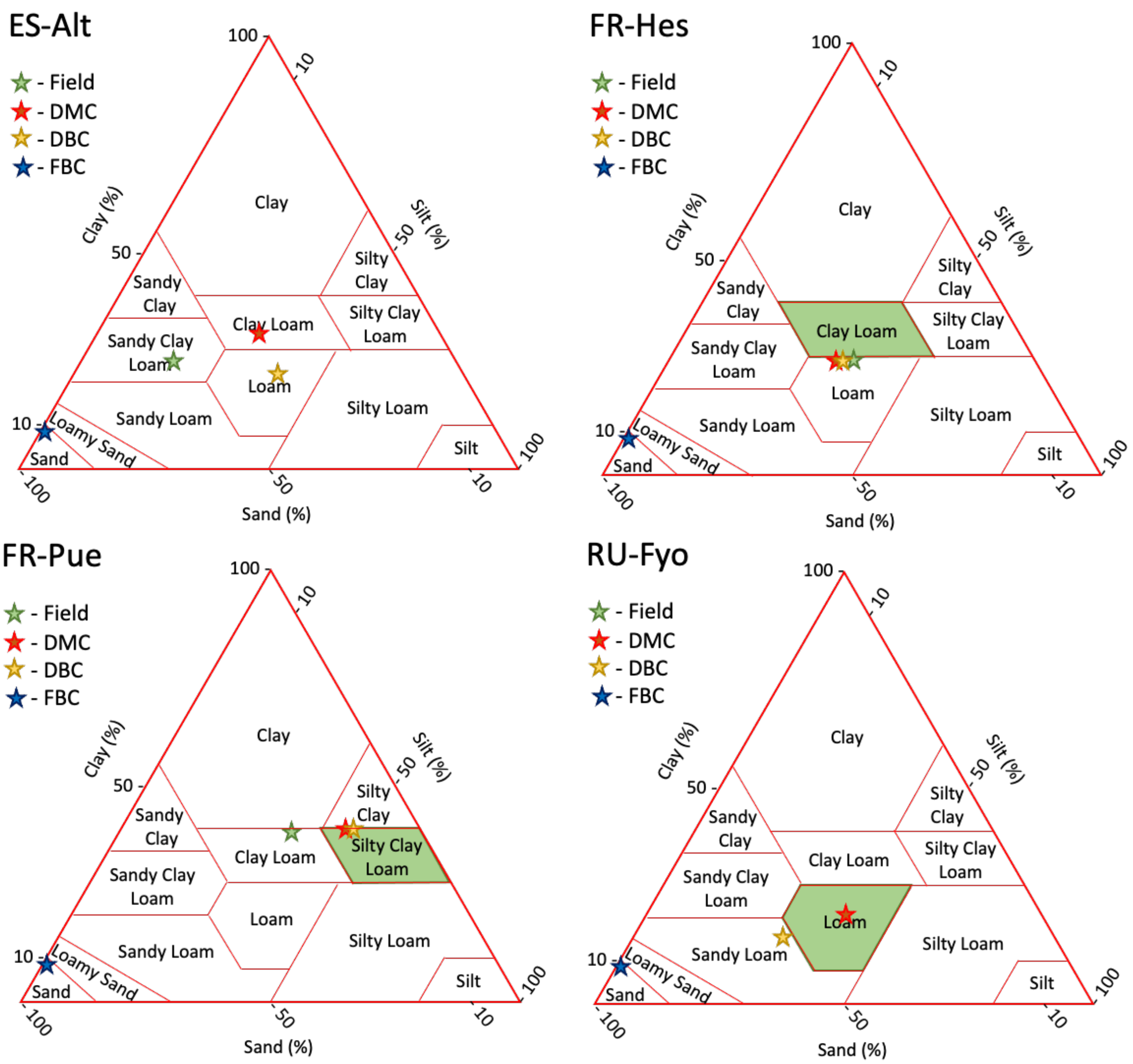

Figure R1. Soil texture classification of each experimental site and model configuration. The green star and polygons highlight the experimental site classification according to the literature (the classification may differ between authors). Red, yellow, and blue stars represent the substrata classification according to the default, deeper bedrock, and fracture bedrock configurations, respectively.

"So, while the authors have shown that changing a model parameter from the default can improve model performance (larger storage buckets can improve T representation [and I don't doubt that this is the likely reason]), without any actual data showing that plants use deeper water from bedrock at these sites it has not been demonstrated that this is mechanistically why T has improved for these particular sites. Is any of this context available at the four study sites, and could it be added to the paper?"

4. Reply:

The reviewer highlights the lack of evidence supporting the deep-water use by trees at the selected sites, especially at Puechabon [FR-Pue] and Alto Tajo [ES-Alt]. We agree with the reviewers that such evidence would be very valuable, but unfortunately, it is not available for all sites. However, there is extensive evidence at the species level, supporting the assumption that different oak species can access deep water storage (Aranda et al. 2007, Baldocchi et al. 2010, David et al. 2013, Forner et al. 2018, Gil-Pelegrín et al. 2017, Nadezhdina et al. 2008, Penuelas & Filella 2003, Zapater et al. 2011). Baldocchi et al. (2010) and Forner et al. (2018) show evidence of deep-water uptake by Quercus ilex trees growing at Puechabon and Alto Tajo, respectively.

Fagus sylvatica trees are believed to strongly rely on shallow soil water because of their superficial root system (Houston Durrant et al. 2016, Kirchen et al. 2017, Leuschner 2020), using in some cases more than 40 % of water allocated in the first 8 cm of soil (Lüttschwager & Jochheim 2020). Fagus sylvatica trees growing in Hesse (France) have shown a strong reliance on shallow soil water (Granier et al. 2000b, Zapater et al. 2012) because of the high accumulation of fine root biomass on the first 50 cm of soil (Le Goff & Ottorini 2001, Granier et al. 2008), and the stable water isotope evidence of no deep-water use (Zapater et al. 2012).

The rooting characteristics of Picea abies, Pinus sylvestris, and Betula pubescens (Gale & Grigal 1987, Špulák et al. 2021) might allow the trees at Fyodorovskoye to retrieve water from different depths. However, the transpiration rates at this site are reduced, likely because of the shallow water table and anoxic conditions in the root zone (Kurbatova et al. 2002, Launiainen et al. 2016). [Lines: 449-451].

Aiming to address this issue, we propose to add the following in the manuscript:

In [Line: 373]:

"… Dietricht, 2018). Oak tree species are known to access deep water storage because of their extensive rooting depths (Gil-Pelegrín et al. 2017). The Quercus ilex trees growing at ES-Alt and FR-Pue have shown this feature (Baldocchi et al. 2010, Forner et al. 2018) allowing the trees to transpire during the dry season despite the low soil water potentials. The transpiration signal …"

In [Line: 378]:

> "… transpired soil water. Fagus sylvatica trees strongly rely on shallow soil water because of their superficial root system (Lüttschwager & Jochheim 2020), a condition documented at FR-Hes by Granier et al. (2000b) and Zapater et al. (2012). Meanwhile, during drought periods, this tree species uses the water stored in the trunk and roots as a reservoir to maintain transpiration until the next rainfall event (Betsch, et al. 2011). However, the limited access of vegetation to …"

"Based on the findings of the paper, what should be done by the modeling community?"

5. Reply:

Previous studies have highlighted the importance of groundwater and lateral flow for an improved simulation of transpiration fluxes in LSMs. In contrast, other studies highlighted the importance of an extended rooting system with the same aim. However, the binary distinction between soil and bedrock and the neglect of any water storage below the soil layer may prevent the LSM from producing more accurate results in locations with shallow soils during dry periods. In this work, we show that allowing the root system to access water stored in the weathered bedrock improves the transpiration and plant water stress estimates during dry periods. We think that the modeling community should address these two issues in a unified approach, which will eventually improve the representation of water supply at sites with shallow soils and pronounced dry periods.

Consequently, the discussion will be improved adding the following in [Line: 152]:

> "5.3 Breaking the bedrock to release the roots
>
> The occurrence and severity of extreme weather conditions like droughts and heat waves (He et al. 2020) highlight the importance of representing the vegetation's mechanisms to avoid or cope with the adverse effects of this new reality. However, the inclusion of rock moisture stored in the weathered bedrock, which is neither soil water nor groundwater, is necessary to simulate plant transpiration under limited water conditions (Rempe and Dietrich, 2018). The challenge to quantify this rock moisture is linked with the large uncertainty in determining the physical characteristics of this weathered bedrock (Pelletier et al. 2016) and the lack of spatially distributed field information related to the water storage properties of the weathered bedrock. Previous studies have highlighted the importance of groundwater and lateral flow for an improved simulation of transpiration fluxes in LSMs (Maxwell and Condon, 2016, Zeng et al. 2018). In contrast, other studies highlighted the importance of an extended rooting system with the same aim (Fan et al. 2017, Ichii et al. 2009). However, the focus of LSMs on soil water neglects the interaction between these essential components and the weathered bedrock. In this work, we show that allowing the root system to access water stored in the weathered bedrock improves the transpiration and plant water stress estimates during dry periods. The modeling community should address these two issues in a unified approach, eventually improving the water supply at sites with shallow soils

and dry conditions. This unified approach, where we allow to break the bedrock and release the root profile, will create a new water reservoir that will refine the vulnerability assessment of forest ecosystems growing in regions with a tendency to experience drier conditions."

"Should the water storage bucket just be freely calibrated instead of prescribed?"

6. Reply:

We think that the free calibration process carries the general danger of getting "the right results for the wrong reasons". It could be a suitable solution for point-scale simulations if field data is available (e.g., electro resistivity measurements, well description logs) to provide physical constraints for the water holding capacity and vertical extent of the fractured bed rock. However, for an application of the land surface model at the regional or global scale, this bucket should be prescribed accordingly with the spatial distribution of the pedology, geology, and climate conditions driving the process of bedrock weathering.

"What exactly is the goal of changing this parameter? To improve accuracy of historically observed T, or to better predict T under non-stationary climate, etc?"

7. Reply:

Both. If the model is not capable of reproducing dry season transpiration in the past, it is likely not suitable to predict transpiration in future climate conditions. The main goal is to allow the model to better represent the plant water uptake of ecosystems relying on rock moisture by including this missing water storage (e.g., Mediterranean forests, dry lands). This is of high relevance for the non-stationary climate conditions expected under different climate change scenarios. Despite the scenario, the expected seasonal changes in intensity and frequency of precipitation and drought (Grillakis 2019, Hosseinzadehtalaei et al. 2020) will induce drier soil conditions. Consequently, it is of paramount importance to have a better representation of all the water storages that alleviate the soil water deficits. In this way, it will be possible to identify those areas/locations where the rock moisture will become more important for the established vegetation.

We propose to add the following in [Line: 33]:

"… et al. 2014). The inclusion of rock moisture stored in the weathered bedrock can better represent dry season vegetation water use at sites with shallow soils. Furthermore, this additional water reservoir may become even more significant under climate change, where seasonal changes in intensity and frequency of precipitation and drought (Hosseinzadehtalaei et al. 2020, Grillakis 2019) are expected to result in extended drought severity and duration. Consequently, it is paramount to better represent the entire water storage accessible to plants during dry periods. However, due to the …"

2. *“Other studies have already shown that increasing the size of the storage bucket accessible to plants can improve modeled T patterns in seasonally dry (e.g., Mediterranean) climates (e.g., Ichii, K., Wang, W., Hashimoto, H., Yang, F., Votava, P., Michaelis, A. R., & Nemani, R. R. [2009]. Refinement of rooting depths using satellite-based evapotranspiration seasonality for ecosystem modeling in California. Agricultural and Forest Meteorology, 149(11), 1907-1918.). Yes, these studies do this by changing rooting depths, or adding deeper soil (rather than calling it bedrock), but isn’t the fundamental result the same: more stored water accessible to plants? What exactly is the novel finding in this study in relation to what these other studies have done (which is to change a model parameter that ultimately allows for more water storage for plants, thereby resulting in a better T or ET estimate)?”*

8. Reply:

We agree with the reviewer that the different approaches have the same objective of increasing the amount of plant-accessible below-ground water storage in order to better reproduce observed transpiration patterns. The refinement of rooting depths (Ichii et al, 2009) and the increase of soil reservoir (de Rosnay and Polcher, 1998) are strategies developed to improve reproduction of observed transpiration rates by increasing the water reservoir. However, the novelty of this manuscript relies on the fact that no other work has addressed this problem with CLM 5 and using at the same time sap flow data to compare in detail the impact of different water reservoirs. Also, we use the plant water stress as an additional indicator of realistic conditions, so we could even detect odd patterns in the model response if we did not have sap flow measurements.

“Other items:

Table 1: Is the p50 correct for the Russian site? I am surprised it would be such a low water potential in such a cold climate.“

9. Reply:

We agreed with the reviewer that the default Ψ_{p50} value used for this temperate needle-leaf evergreen site is too low with respect to the values reported for the tree species of the site (from -1.5 Mpa to -3.5 Mpa) (Choat et al, 2012). This point is discussed in the manuscript [Lines: 442-448]. We use deliberately the default configuration for the plant hydraulic stress routine without adjusting the Ψ_{p50} values. This decision was taken to focus only on the impact of modifying the plant water uptake and plant water stress. Despite the low Ψ_{p50} values used for RU-Fyo, the large water availability under the three configurations allows the modeled vegetation to transpire at the potential rate [Lines: 467-468].

Aiming to clarify the decision of using the default configuration of root distribution and plant hydraulic traits, we proposed to add the following in Line 145:

"... et al. 2019). We use the default plant physiological parameterization for each experimental site according to their PFT classification. Site-specific ..."

- *"I understand the goal of Figure 4: compare modeled to actual sapflow patterns by time (note that nowhere in the figure or caption is this stated, however). This figure is extremely difficult to comprehend, even after quite a few minutes of study. It is also worth noting that a continuous variable is reported as an area (circle area) rather than a length, leading to potential interpretation ambiguities. Can these not be plotted as regular time series points, whose values vary along a continuous rather than categorical y-axis?"*

10. Reply:

Thanks for the recommendation, the simpler the better. Following your recommendation, Figure R2 will replace Figure 4 of the manuscript. This figure change will require to modify the manuscript as follows:

Deleting [Lines: 268-277]:

"... experimental sites. In the graphical scheme adopted in this figure ... proportionally to the α value (e.g., ES-Alt.DMC.March)."

Replacing Figure 4 with Figure R2 and updating the figure's caption as follows:

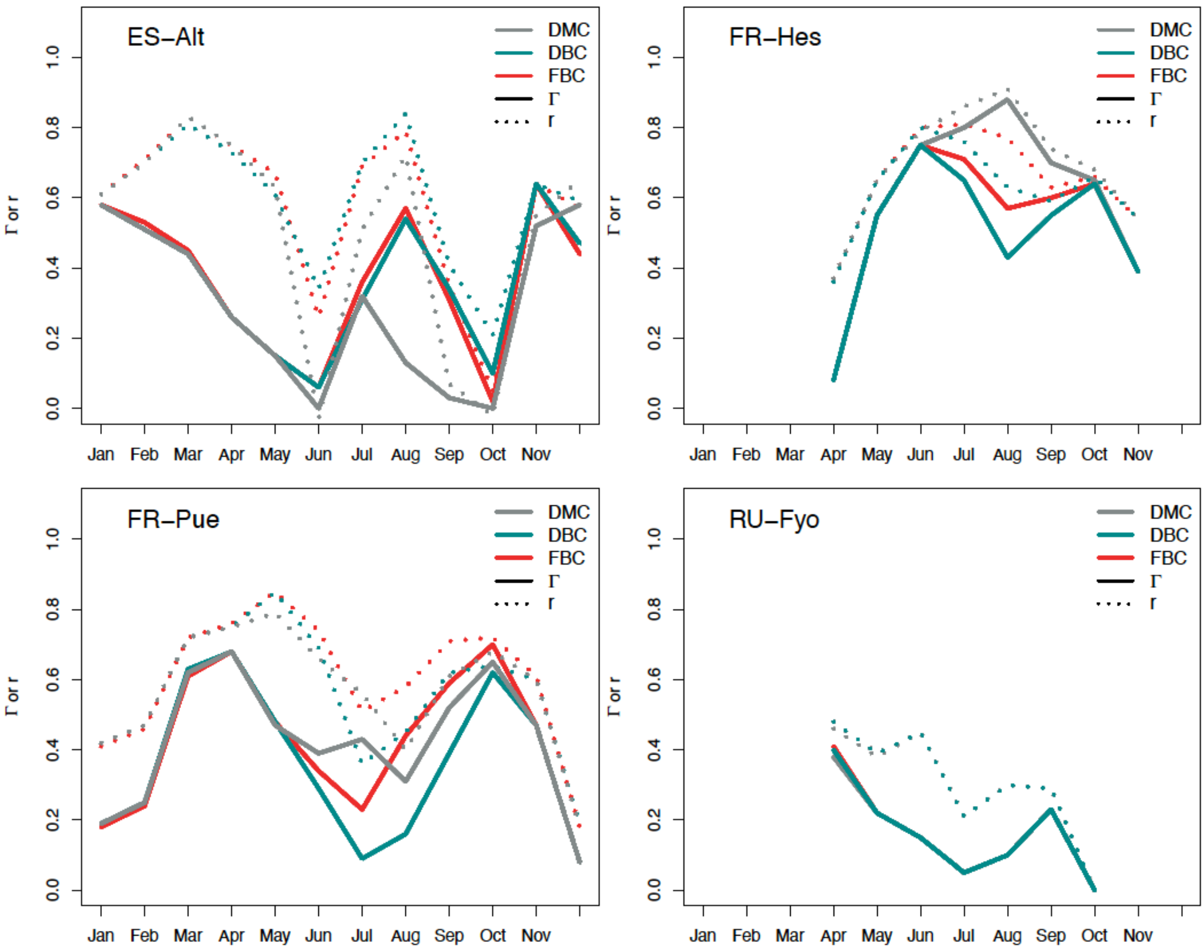

Figure R2. Multi-annual monthly variation of the Pearson correlation coefficient (r) and the index of agreement (Γ) for the default model configuration (DMC), deeper bedrock configuration (DBC), and fractured bedrock configuration (FBC).

"Figures 5 and A2-A5 are not legible when printed on standard paper and need to be reformatted so that they can be read."

11. Reply:

We will modify these figures to improve their readability.

"Line 165: It is reported that in order to mimic the hydraulic behaviour of fractured bedrock, it is modeled as a pile of sand (90% sand, 10% clay). This model choice is not supported by any reference to literature on bedrock hydraulic properties, and surprised me as it is not how I would conceive of bedrock hydraulic properties."

12. Reply:

We agree with the reviewer that this is not the way how fractured bedrock properties should be included in the model. We did not address the physical representation of the fractured bedrock, but we used the CLM 5 flexibility to provide the first attempt to understand the impact of increasing the water reservoir for plants. This aspect is mentioned shortly in methodology [Lines: 166-167], extended with Reply 3 with an addition in [Line: 166], and stressed as well in the conclusions [Lines: 477-480].

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