Future changes in water availability: Insights from a long-term monitoring of soil moisture under two tree species

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Author´s response to Reviewer#2

Comment#1

The title mentions future changes in water availability but the results refer to the past 22 years (2000-2021). I have no doubts that global warming is changing climate patterns in Central Europe. However, climate change can be detected only on very long time series by capturing decadal trends. In other words, climate change should be supported by data. The authors should state what is the baseline-historical climate regime in terms of rainfall and temperature observed in the past century. Climate change can be predicted by climate projections from 2020 up to 2100 which are based on scenarios depending on the carbon dioxide emissions (RCPs). There are many GCMs available in internet.

Response#1

Thank you for pointing out this discrepancy in the current manuscript's framing of the study. We agree that it will be helpful for the reader to see a baseline at the appropriate scale to assess longer-term climate-driven shifts. We also agree the text needs to be clarified on this point: our intention was not to make specific projections of future water availability; rather, we examine how ecosystem functioning modulates the hydrological impacts of climate change. As relevant vegetation processes play out on timescales shorter than the overall climatic drivers (incl. differences in seasonal and sub-seasonal vegetation functioning), their effects on local water flux partitioning are readily apparent in our data. We will make this clearer both by changing the title and in the text itself.

To provide a baseline for the reader to evaluate climate-driven shifts in flux partitioning, we will add potential and actual evapotranspiration (PET and AET) and precipitation values since the start of local measurements in the experimental watershed in 1975, using the Budyko framework suggested by the reviewer (see Comment#3 below). The expected broader climate-induced shift is well supported by these local data (Fig. R10), which evidence an accelerating shift in the balance between atmospheric water supply and demand at a decadal time-scale.

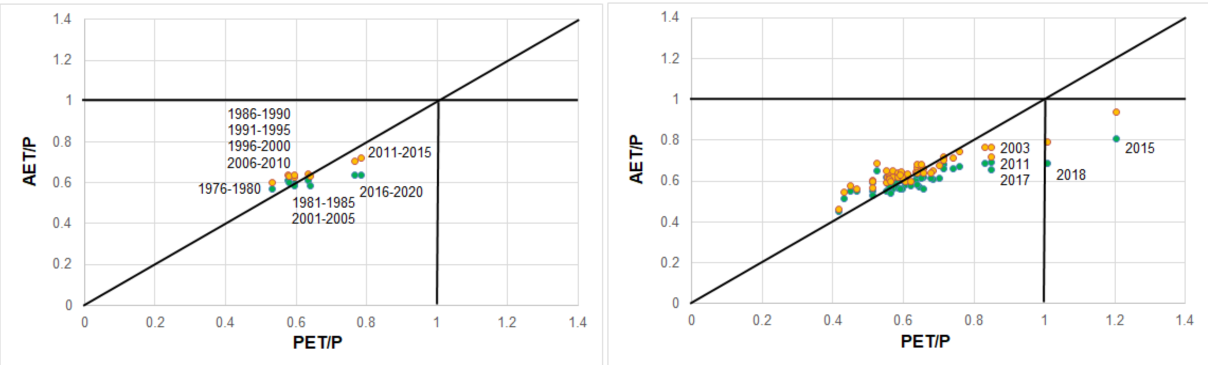

Fig. R10 Ratios of actual and potential evapotranspiration to precipitation from the experimental watershed covering the period 1976 to 2020 shown within the Budyko curve reference frame; left: 5y averages, right: annual values.

We believe that adding this local time-series (1976-2020) will be sufficient to situate our study within the broader climatically driven pattern. It shows our data cover a period (2000-2021) in which the climatic drivers are forcing a gradual shift from a fully energy-limited state (1976-2000) through more co-limited regimes, in which the most recent outlier years already show strict water-limitation. We do not feel our work needs to belabour the fact of climate change or its expected broader-scale, exogenous impacts on the hydrologic balance any further – there are plenty of studies demonstrating these, sufficiently referenced in the manuscript (lines 38-45).

Our work specifically poses questions about how climatic drivers interact with vegetation processes to produce hydrologic flux partitioning and ecosystem function. The processes we studied occur over sub-annual time-scales and their effects can be adequately evaluated in inter-annual differences in site/watershed hydrologic balance. The core 22-year dataset is thus entirely sufficient to evaluate their effects. It is also by far the longest available of its kind that we are aware of.

We see little added value from the use of GCMs to produce climate projections for our study. Mainly, this is because we are not aiming to make any projections. Instead, we analyse observable ongoing changes to advance process understanding of climate-vegetation interactions beyond what is currently represented in GCMs. Using GCMs that cannot adequately represent the feedbacks between climate, vegetation, and soil hydraulic properties to make projections of future water availability strikes us as a highly uncertain means of addressing our questions. Rather, we believe process understanding needs to be improved before GCM projections can meaningfully encompass such feedbacks. In response to this comment, we will make our aims clearer in the manuscript introduction (around lines 63-67).

Comment#2

The authors present a detailed and interesting analysis on the impact of climate forcings on the water balance components and profile-average pressure head under two different land uses. However, what is the novelty of this article? I appreciate the unique long-term data set, but what is new if compared to the state of the art? How can readers exploit the findings of this study?

Response#2

We appreciate these questions from the reviewer as they indicate that the manuscript still needs to state the novelty, significance, and usefulness of our work more clearly. The state of the art is currently a mosaic of short-term studies with mutually contradictory results (Manuscript lines 52-55, 388-392). Their unresolved contradictions stem mostly from the limited duration of each study, which makes each partial result context-dependent on the specific climatic conditions of the study period (lines 56-63).

The main novel advantage of our long-term dataset is the ability to make **robust interannual comparisons** over a range of climate conditions (Line 395). This enabled us to disentangle interactions of specific climatic (summer/winter precip, temperature) and vegetation (phenology, rooting, hydraulics) drivers of forest hydrologic response to dry vs wet years and seasons. A second advantage of the dataset is **depth coverage over the rooting zone** and high replication, allowing us to overcome site-scale heterogeneity and study limitations due to limited vertical extent of measurements (e.g., lines 390-392). Finally, the integration of this dataset within long-term observations from the experimental watershed enables us to impose **closure on the hydraulic balance** and estimate individual fluxes for both forest types.

Our main novel contribution, enabled by this unique combination of dataset advantages, lies in showing which climatic variables have driven water limitation so far (atmospheric water supply more so than demand), and which vegetation processes most exacerbate or dampen it in the studied forest types. We showed which vegetation traits or processes become important to the hydrological balance under which conditions, including during previously unobserved water-limited years. The revealed interactions produce feedbacks that will ultimately lead to differences in function and fate between these important forest types. Specific novel findings with broader significance include:

- whether beech or spruce forest soils end up drier in the growing season depends on intra-annual precipitation distribution due to seasonal differences in flux partitioning by the two forest types (lines 366-375); this helps to resolve previous contradictions in the literature as a majority of studies are limited to a single number of years.
- differences in winter drainage between the forest types increase with winter precipitation (lines 400-402); under expected summer to winter shifts in precipitation, this novel interaction should enhance beech forests' water limitation and affect their role in baseflow generation and intra-annual storage/discharge timing, with implications for forest and water management.
- beech hydraulic function capable of sustaining transpiration during drought interacts with summer atmospheric water balance (PET/P) to exacerbate recharge reductions in warmer or drier years (lines 374-382).
- by contrast, higher spruce contributions to summer drainage due to reduced transpiration initially persist as water limitation begins to affect the system, but eventually decline to zero under water *supply* limitation (lines 386-387).
- collectively, these findings demonstrate divergent patterns of forest hydraulic functioning under water limitation in summer/winter, due to atmospheric supply/demand, which advance process understanding in support of model development or direct application to ecosystem and water management.
- the difference in soil moisture between the forest types is dominated by depths > 30cm (lines 392-394); this is not entirely unexpected due to known rooting depth differences, but quantifying this dominance remains a finding valuable for scientific practice when the vast majority of soil moisture measurements are done at depths < 20cm.

A final point of novelty is the recent occurrence of annual-scale water limitation of AET, which is unprecedented over the 40+ year instrumented period and entirely unexpected in this montane system. The entire range, including our sites, is classically thought of as energy-limited, not just under "baseline" (1961-1990) climate but for past millennia. Our results include some of the first observations of differences in hydrologic functioning of these cold, humid montane forest types under water limitation. Anticipated climatic trends make the publication of these findings all the more timely.

We believe diverse readers will make use of our findings because cross-scale interactions in land-atmosphere feedbacks such as these are one of the key sources of uncertainty in predicting shifts in ecosystem function and composition driven by climate change. Our study contributes towards filling key gaps in the required process understanding by empirically resolving specific processes that contribute to differences in forest hydrologic functioning under shifting climate. For researchers, this understanding contributes towards the next generation of models and projections. Practitioners can use it to evaluate interactions between the ecosystem and water management. We will reorganise the discussion to improve the explanation of the novelty and significance of the results.

Comment#3

It comes to no surprise that the comparison of soil moisture regimes proves to be precipitation dependent. The results related to this site-specific study (area of 1 km2) cannot be representative for the impact of climate and land use change in Central Europe. The water balance depends on soil depth, layering, and soil hydraulic properties, on the terrain features, on vegetation patterns and characteristics, on climate regimes and many other factors. The last sentence is usually supported by visualizing the Budyko curve, which is used to understand the long-term balance between water availability and energy in a catchment (a region drained by a river or stream). It helps us analyze how much precipitation is evaporated versus how much becomes streamflow.

Response#3

Thank you for suggesting the Budyko conceptual framework. We agree this is a very productive framing for our work and we will add a figure to illustrate this statement. Fig. R10 (above) shows clearly that both study sites have slowly transitioned from energy-limitation towards co-limitation over recent decades and in the driest recent years, they indeed switch to a clearly water-limited regime.

Importantly, the plot also shows increasing divergence between the hydrologic functioning of the sites with increased water limitation. This further underlines the importance of not only the climate but also its interactions with vegetation to the hydrologic balance, placing the processes our study examines in context. We will **update the discussion** to make use of this framing in explaining the significance of our findings.

We agree with the reviewer that our study does not achieve representativeness at the landscape, let alone regional scale. We appreciate this comment as it gives us an opportunity to better clarify the significance of our work despite this lack of representativeness.

The landscape-scale implications of our work do not depend on the watershed's broad representativeness so much as its particular landscape position. Due to the region's geography, montane forests in headwater catchments represent the areas of high precipitation and low evapotranspiration. Through both locally higher inputs and intra-annual storage, forested montane headwater catchments play an outsize role in baseflow generation, supporting regional hydrological stability. The broader landscape's (i.e. downstream) water regimes will thus be particularly sensitive to their seasonal functioning under climate change.

Due to land use patterns, these montane forests also represent the majority of strictly protected areas (IUCN categories Ia, Ib, and II) in Central Europe, with a dominant proportion of our two tree species. This includes the twinned Bohemian/Bavarian Forest national parks directly adjacent to our sites. Understanding the ecohydrology of montane forests dominated by these species will be one of the keys to regional biodiversity and ecological conservation during the ongoing hydroclimatic shift.

In sum, understanding vegetation-mediated land-atmosphere feedbacks in montane, mid-slope beech and spruce forest such as these is particularly important to projections of future ecological and hydrological dynamics across the region.

In terms of direct generalisation, our study is most like a paired watershed study in hydrology or a common garden experiment in vegetation ecology. Our study design allows the key processes to be examined at the appropriate scale, without needing to represent the entire landscape. The resulting process understanding is always only transferable to an extent circumscribed by an adequate consideration of conditions in the study system. Scaling the effects of the processes we described to an entire landscape would require a separate exercise that would take into account the factors mentioned by the reviewer, but is beyond the scope of our study.

That said, some of our novel findings generalise directly. Our catchment lies close to the cold, humid end of the spectrum of Central European climate zones (e.g., unit C7 on the Quitta Climatic Classification, Vondrakova et al., 2013 https://doi.org/10.1080/17445647.2013.800827). Observation of an annual-scale flip to a water-limited regime here is not only entirely out of line with historical experience. It is also strongly indicative for large parts of the generally warmer, drier Central European landscape: if it has started to happen here, it will be happening at least episodically in most places.

We will improve the discussion section to clarify both the limits on generalisation of our conclusions and their broader landscape significance despite these.

Comment#4

Another concern is on the use of a bucket model. Bucket models are usually used at coarse spatial scales where data are poor or inaccurate (regional to continental to global scales). The rich data set at plot scale in this study could support a Richards-based model which is more complex than the bucket model and provides a better performance in terms of model simulations.

Response#4

Solving the Richards equation for soil flows was our choice in our previous study (Sipek et al., 2020) dealing with a 5y data set at the same site. We found that modelling the soil water regime this way at multiple depths continuously for 5 years introduces significant uncertainty. RMSE ranged from 99 to 176 cm for the column average pressure head (it was even larger when we assessed specific depths), parameters of the root water uptake function needed to be far from physically reasonable values, and parameters of the soil water retention curves also had to be adjusted from their measured values.

The reasons for the doubtful performance were namely:

- large amounts of rock fragments in the soil. If a certain percentage of the profile is formed by the rock fragments, then the vegetation will extract more water from the areas between those rock fragments to fulfil the water demand. This could result in a higher actual drop in observed pressure heads, which would not be represented in the model.
- the hydrophobicity of the soils may result in non-uniform drainage of water into deeper soil layers and formation of a shallow biomat flow. The percolation of water can then be limited only to certain locations (eventually bypassing the measurement probes).
- occurrence of preferential flow in the forested catchment can cause non-sequential reaction of soil moisture sensors at different depths
- soil hydraulic properties are described by the soil water retention curves, which strictly define properties of the porous media. However, if 21 years are modelled continuously, soil properties undergo gradual changes, which were not measured.

Hence, for this long-term study we have chosen simpler bucket type of the model as (1) it is sufficient to answer questions posed (soil column water balance) without adding more complexity, (2) it uses “Feddes” type of equation for the estimation of plant water use as Richards-based models, (3) it is more convenient for the simulation of longer periods, (4) the soil column is represented by one unified domain with column average soil hydraulic properties, which is beneficial especially when the soil encompasses a lot of rock fragments.

Comment#5

Model calibration is poorly described. The authors used a local or global optimization tool? What's the objective function? The RMSE of what? Of pressure heads? Or else?

Then in the results, close to line 270 (please add continuous line numbers!), the authors mention about the model calibration against observed snow cover equivalents. In Line 274 the authors state that the calibration was done against observed soil water content that pop out of the blue. In M&Ms I do not see the description of soil water content sensors. I rather see only the installation of tensiometers. Did I miss anything?

Response#5

Thank you for the valuable comment. We will clarify important information about model calibration in the manuscript. The type of line numbering is pre-described by the journal template for manuscript submission.

The model parameters were fit using the **genetic algorithm using the RMSE as an objective function**. The model was calibrated in two steps (lines 171-179). First, parameters of the degree-day snow accumulation/melt model were calibrated using measured snow water equivalents. Second, the remaining model parameters were calibrated using a measured soil water regime represented by pressure heads. For soil water balance modelling, the measured pressure heads were used to calculate the volumetric soil water content by means of the van Genuchten (1980) function. The function parameters were retrieved from the measured retention curves specific for each site and depth (lines 181-184).

Comment#6

The authors force the simulated annual cumulative drainage to be close to 360 mm year-1 because this value corresponds to the mean annual observed runoff. In this case, the study area should be described more in detail by adding hydrogeological information to support this hypothesis which is strong.

Response#6

Yes, this is a fundamental part of the modelling framework. It is based on the previous hydrogeological survey which documented crystalline bedrock in the catchment which only allows water circulation in the weathered zone and does not communicate with adjacent catchments. Therefore, the hydrological catchment corresponds well to the hydrogeological catchment (Hrkal et al., 2009). (lines 85-87) and the assumption, while strong, is also well supported.. We will make this clearer in the manuscript.

Comment#7

The M&Ms would benefit from the use of a schematic figure that presents the overall study (measurements, modeling calibration/validation, data analysis, etc.)

Response#7

Thank you for the comment, we will add the required figure into the manuscript or supplements.

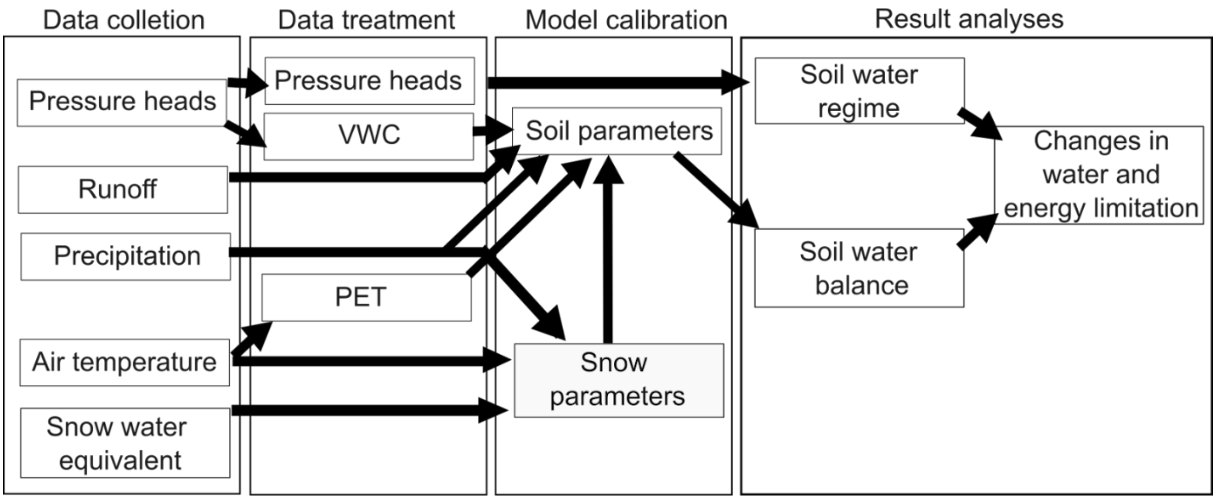

Fig. R11 Scheme representing the workflow of the study

References:

Šípek, V., Hnilica, J., Vlček, L., Hnilicová, S., and Tesař, M.: Influence of vegetation type and soil properties on soil water dynamics in the Šumava Mountains (Southern Bohemia), J. Hydrol., 582, 124285, doi:10.1016/j.jhydrol.2019.124285, 2020.