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

Nikol Zelikova et al.

<u>Author´s response to Reviewer#1</u>

Comment #1

A weak point of the study is the approach used to calculate evapotranspiration. It does not explicitly regard the differences between spruce and beech. In my opinion the Penman-Montheith equation is state of the art and it allows the differentiation via canopy and aerodynamic resistance. A method to reduce the uncertainty are direct measurements of evaporation and transpiration. The authors already named sapflow measurements within the paper. Here I would like to point out that scaling to the forest stand is critical and that an underestimation of transpiration usually occurs.

Please, explain (and discuss) the choice of your method for the **calculation of the evapotranspiration** ET. As far as I understood, you have all variables for the calculation of the actual ET available at your site. Why do you calculate the PET following a reduced approach (Oudin et al. 2005) and estimate the actual ET for the two sites from that? Which approach did you use Oudin et al. (2005), or the Penman-Montheith equation?

Response#1

- Thank you for pointing out the difference in aerodynamic resistance between the two species, which we address below. Importantly, the model we used does differentiate between spruce and beech on two important processes: (1) the interception is estimated differently for both sites and the estimation is based on the measured characteristics, (2) soil water balance model parameters (namely theta_S, theta_R and Ksat) used for the estimation of beech and spruce transpiration and drainage are different as they were obtained by the model calibration on the different soil water regimes. This results in higher transpiration of beech in dry summer periods than for spruce – which is proven by the observed soil water regime.
- As the hydrological models are usually based on the two-stage modelling scheme – potential (PET) and actual evapotranspiration (AET) we have chosen Oudins approach for the estimation of PET.
- The reasons for the Oudin´s approach were:
    - Oudin´s method represents a **robust approach** relying only on the air temperature, and therefore it can be used for the estimation of PET also in the periods with limited data availability without the loss of consistency in the input data series when they are replaced by the data from the neighbouring meteorological station
    - **Side-experiments** utilizing the values of the P-M reference evapotranspiration aside from Oudins approach (in the period of available data) documented the influence of selected approach only on the soil water balance model parameters and not on the resulting water fluxes.
        - acceptable differences among P-M and Oudin's values of PET, especially when e.g. monthly means are considered. The day-to-day fluctuations are more averaged by Oudin (Fig.R1).
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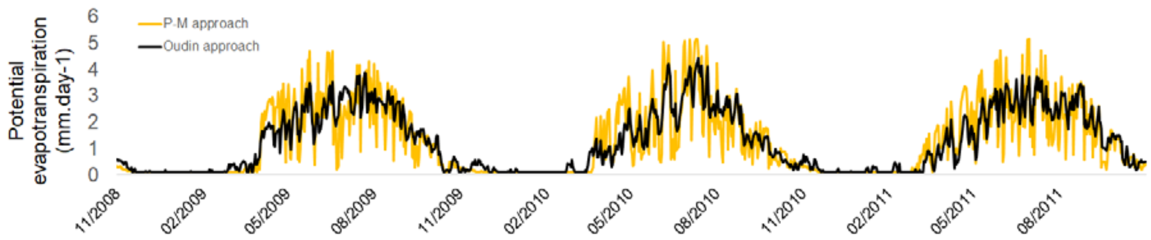

Fig. R1 Comparison of Penman-Monteith and Oudin PET

- the above-mentioned differences led to similar performance of the soil water balance model using both P-M and Oudin approach for the estimation of potential evapotranspiration (Fig. R2).

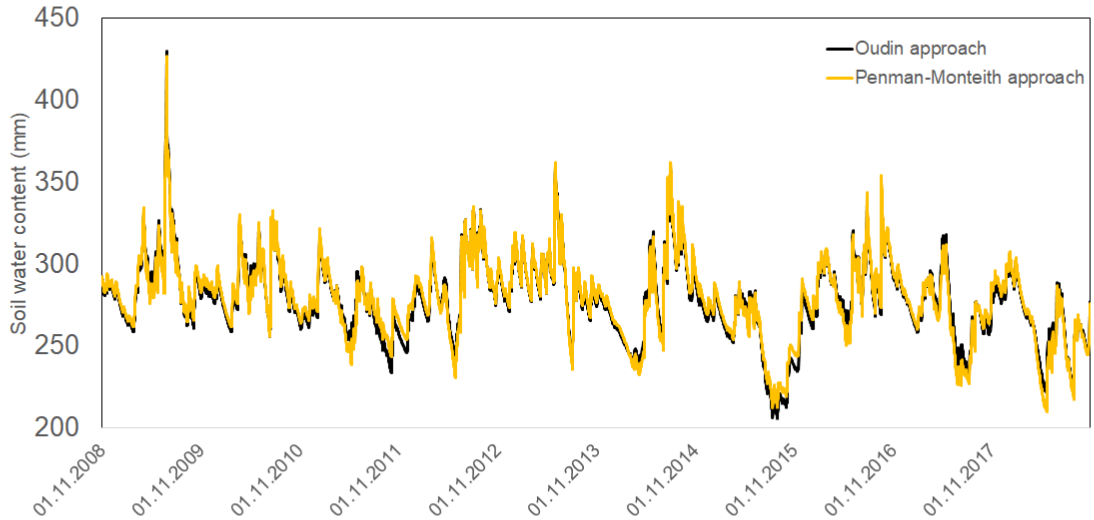

Fig. R2 Modelled soil moisture using Penman-Monteith and Oudin PET

- canopy specific parametrization of P-M approach by means of adjusted aerodynamic resistance (difference in canopy height was set to 5 m) resulted in the seasonal difference in PET of only 3.7 mm in 2010 and 1.5 mm in 2009. If the amount of soil water was changed by only 1%, it resulted in a change of AET by 9.4 mm in 2009 and 8.9 mm in 2010, respectively. This documents the limited influence of aerodynamic resistance compared to the influence of soil water availability (reflected in stomatal resistance) which is an inherent part of the model.

- **Literature review**: 1) Oudin et al (2005) paper showing reasonable results of hydrological models when using his approach compared to state-of-the art models in the conditions of limited data availability and 2) Touskova et al. (2025) paper showing a reasonable correspondence of Oudin's PET values and pan evaporation data in the Czech Republic and also with P-M reference evapotranspiration in terms of the seasonal sums
- The necessary **data for the Penman-Monteith (P-M) method are available only from 2008** and they originate from the nearby grass covered meteorological

station (300 m distance) at the forest opening. Hence, we do not have the opportunity to obtain site-specific information about wind profiles separately for beech and spruce forest.

Comment#2

What is the reason for calculating the Net longwave radiation (L155)? It seems not necessary, neither in your described model nor in the PET approach of Oudin et al. (2005). However, you cite Kofroňová et al. (2019), who used the Penman-Montheith equation to calculate the potential evapotranspiration (which is actually not correct, since the Penman-Montheith equation calculates the actual evapotranspiration).

Response#2

Yes, long-wave radiation was not necessary – it is a mistake in the manuscript text which will be deleted.

Comment#3

Another uncertainty is the high spatial heterogeneity of soil moisture due to canopy and soil structure. The authors mentioned up to five measurement profiles. A description of the variability between the profiles with respect to canopy cover would help to establish confidence in the representativeness of these measurements.

As mentioned above the question arises: **Are the measurements representative for the sites?** Did you compare other measurements on the same patches? On L119, you write "One to four tensiometers were available for each measuring depth at each site, and the single value for a particular depth was taken as their average." First, what is meant by "single value", second could you illustrate the positioning of the sensors with respect to canopy cover, and third could you show the variability of the soil moisture for both sites?

Response#3

We ensured the representativeness of our measurements for the sites in several ways.

- Our sites are even-aged, single species stands with closed canopies and no gaps; this relative homogeneity of vegetation makes representing bulk soil moisture/potential mostly a question of sufficient replication and avoiding placement of sensors at non-representative microsites.
- Locations of the plots in which the tensiometers were installed were carefully picked so that they will represent the **average slope** of the catchment and they will be located in **between trees**. Hence, they do not represent the places close to trees, which will be influenced by preferential water flow by stem flow, as well as they are not located in the forest openings. The measuring profiles are approximately 3.6 m from spruce trees and 2.7 m from beech trees. The average distance between two neighbouring trees is 5.4 m in spruce forest and 4.5 m in beech forest, indicating locating the measuring profiles approximately in between the trees.
- Both beech and spruce forests are of uniform age and the **spatial variability of canopy cover** represented by coefficient of variation of LAI is 12.8 % in spruce and 8.9 % in beech forest, respectively. The coefficient of **variation of soil moisture** ranged from 2.2-2.4 % for particular depths in beech and from 3.5 to 10.8 % in the spruce forest. The spatial variability of forest canopy and soil moisture measurements is of similar order as the error in precipitation measurement.
- In our previous work (Sipek et al., 2020), we have compared the average values of measured pressure heads for several depths in spruce site with another three profiles equipped with UMS T8 tensiometers located nearby (20 m from original profiles). The

comparison proved similar pressure head values demonstrating a **good correspondence with other measurements** (see Fig. R4).

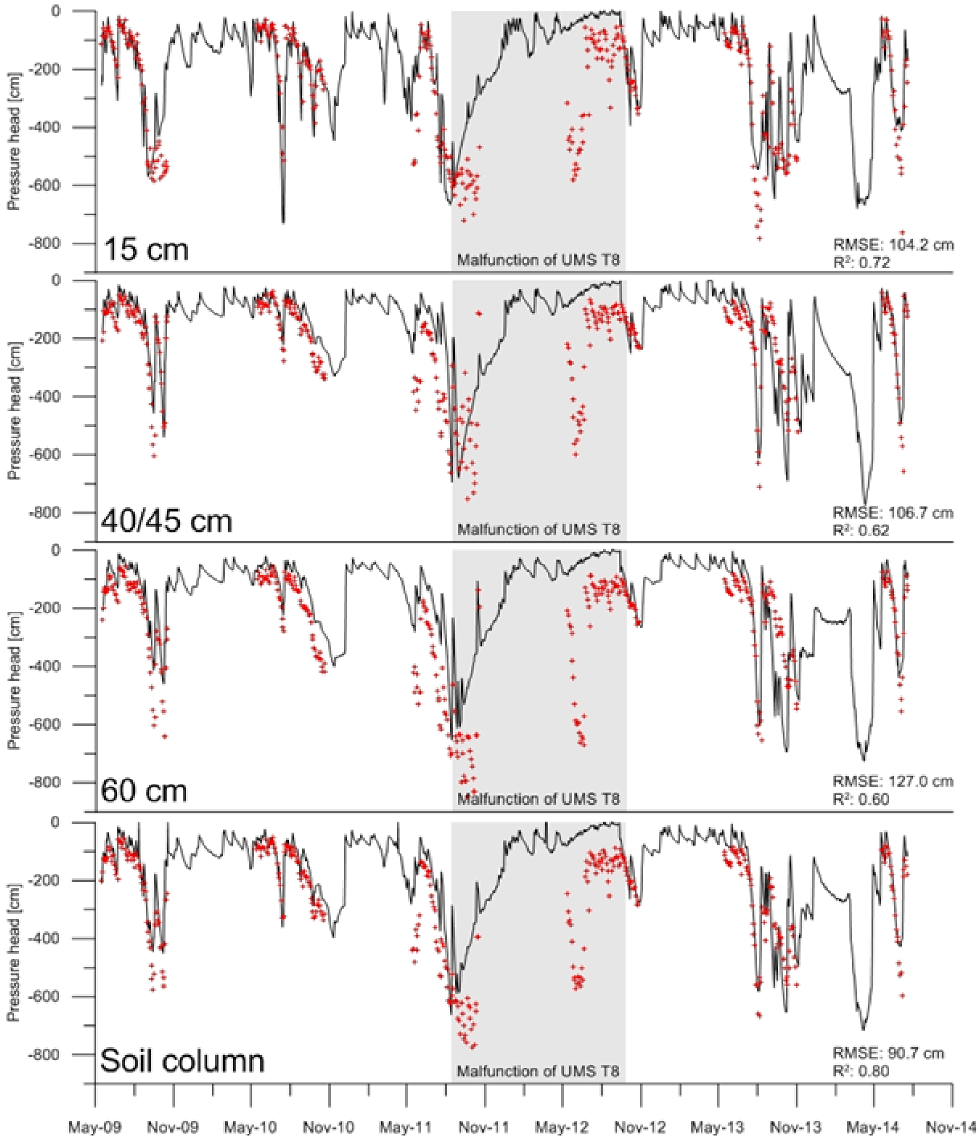

Fig. R4 Comparison of pressure heads measured by UMS T8 (black lines) and Thies (red crosses) tensiometers at the SPR site in the period of 2009–2014. The grey area represents the malfunction of UMS T8 tensiometer and was not included in the statistical assessment. Each plot represents a particular depth of measurements (bottom left corner). RMSE stands for a root mean square error and R2 for a coefficient of determination (Sipek et al., 2020).

Comment#4

As the authors stated, a big advantage of the long term measurements is the possibility to investigate trends in the time series (see line 63, henceforth the shorting L63 is used). However, I missed a discussion of whether or not changes can be observed over time. Subsection 3.1 shows the inter-annual variation of air temperature and precipitation but not of the soil water content and the other terms of the water balance. Also, "3.3 Climate-induced soil water regime and soil water fluxes" covers more seasonal changes at the site than changes induced by climate variability or change (long term changes).

As a distinct feature of the tree type specific water budget the authors discuss the inner-annual variation of the terms. It would be nice to have a visualisation of a typical annual cycle of soil moisture, evapotranspiration and drainage (something like a climograph).

Response#4

Thank you for the valuable comment. We have newly tested the existence of trends in soil moisture time series using a trend-free pre-whitening Mann-Kendall approach (Yue et al., 2002) and statistically significant negative trends were observed in both soil moisture time-series documenting gradual changes in soil water regime, which were also observed by the reported increasing occurrence of water limited seasons. This will be added to the manuscript.

A climograph is a thoughtful comment and the figure below (Fig. R5) documenting the differences between beech and spruce plots will be added to the manuscript.

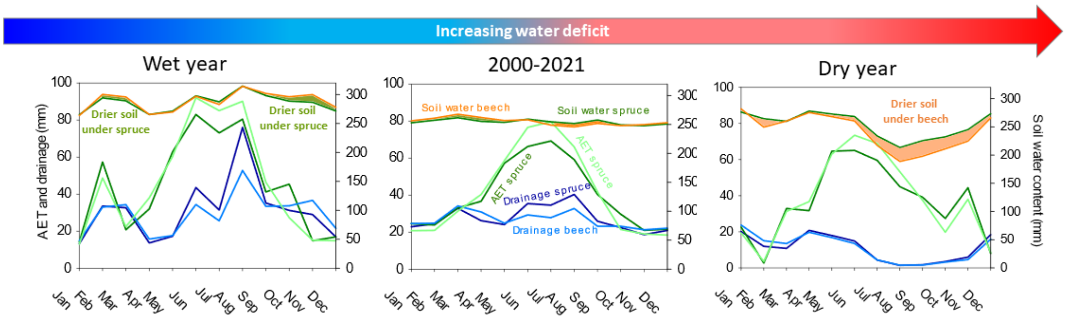

Fig. R5 Average monthly sums of soil water balance components in beech and spruce forest

Comment#5

Concerning the "**Vertical distribution of pressure heads**": Long term mean values over different seasons and conditions (Fig. 3) are difficult to interpret, as the differences between the measurement levels are small compared to the variability of the pressure head. I am wondering whether there is a significant deviation of the pressure head in a certain depth from the other levels, especially for beech. The categorisation according to precipitation is a good approach, however, Figure 4 shows that there is still a large degree of variation when considering a whole year. It would be interesting to see what the differences between levels and sites in the time domain look like (similar to flood statistics, i.e., what is the return interval of pressure heads below a certain value and how long do they persist).

Response#5

Thank you for suggesting a better way of documenting depth differences in soil water regime between beech and spruce site. We will remove figures 3 and 4 and we will add the pressure head exceedance probability plot instead (Fig. R6). The manuscript text will be modified accordingly.

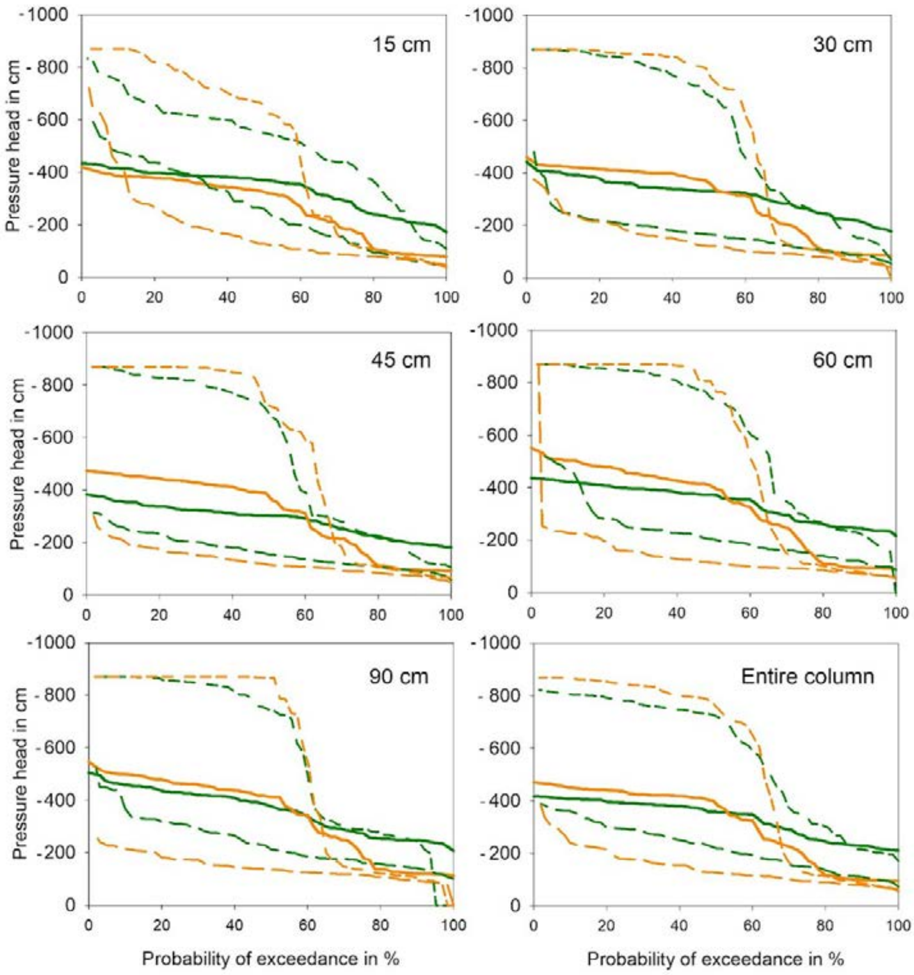

Figure R6. Exceedance probabilities of pressure head for particular depths for averaged the entire period (thick solid lines), dry year 2015 (short dashed lines) and wet year 2020 (long dashed lines). Green colour represents spruce and orange beech forest.

Comment#6

In Figure 5 and the text, you use four soil moisture categories. Unfortunately, I couldn't find a clear definition. L199: "Dry and wet years were identified by analysing the soil moisture regime in terms of the vertical distribution of pressure heads". Typical time series were given in Figure 5. Could you give a clear definition? Please explain the method or give a reference.

Response#6

The definition of the soil moisture is in the lines 245-254. It originates from the observed soil moisture regime:

- category A - spruce retained lower pressure heads throughout most of the season
- category B - only one single event when the beech site attained lower pressure heads than spruce
- category C - the pressure head decreased more pronouncedly at the beech site for a significant part of the summer season
- category D - refers to the seasons when the tensiometer measurement limit of –865 cm was reached (mostly at the beech site)

Comment#7

Model calibration: "The **entire period** of available data was used for model calibration".

Validation of the model is therefore only partially possible at best. The given RMSE of the pressure heads are just an assessments of the quality of the fitting procedure (Btw: What method was used to optimise the parameters?). Usually, one part of the data is used to calibrate the model, and the other part is used for validation.

Response#7

Thank you for the valuable comment. We will add following important information about model validation, which was done prior to the overall model calibration presented in the manuscript. Our previous omission of this information unnecessarily undermines confidence in the results.

At the very beginning, we started with the standard procedure as we calibrated the model using several 5y calibration periods. For this purpose, we **split the period of interest into 4 sub-periods** – each covering 5y (2000-2004,2005-2009,2010-2014,2015-2019) and calibrated the model separately for each of these periods, always carefully maintaining the fit of drainage to the measured runoff. The model parameters were fit using the **genetic algorithm using the RMSE of volumetric water contents as an objective function**.

As the model parameters and also the model performance did not change substantially (see Fig. R7 below) we have chosen to calibrate the model for the entire period so that the water balance (i.e. discharge) can be maintained as close as possible to the measured long-term mean. The amount of drainage estimated from the water balance is more precise, and we could utilize this approach with only minor deterioration of an objective function compared to the situation when parameters from each of the 5y periods were used.

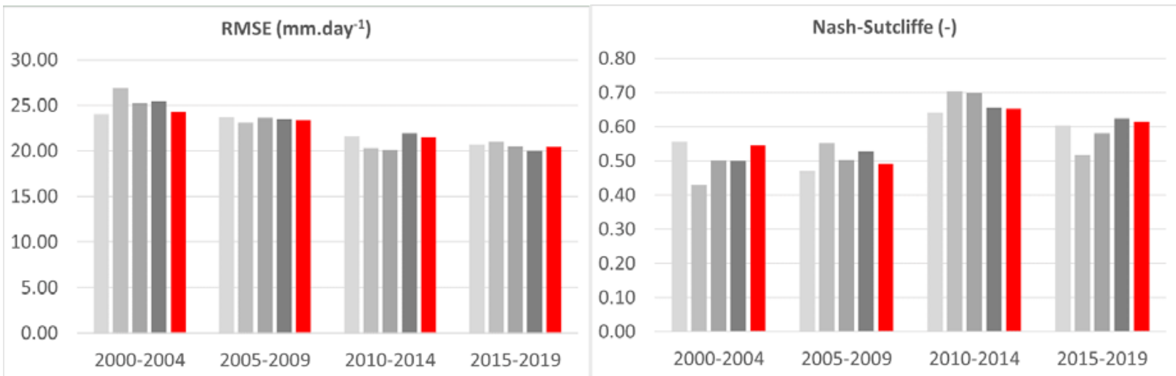

Fig. R7 Model performance when calibrated in particular periods. Values from first columns represent calibration from 2000 to 2004, the second and following columns represent the following calibration periods (2005-2009, 2010-2014, 2015-2019, and the last column is an overall calibration)

Comment#8

The model is calibrated with respect to the soil water content. The long-term means of the drainage fits well to the measured runoff. Although, it is assumed that beech and spruce stands experience the same drainage in the long term, that might not be realistic (see your discussion starting at L437). Could assess the error in S(t) and D(t)?

You write "However, the modelled high transpiration rates at the beech sites mostly follow from fitting to the high-resolution time series of measured local soil moisture data, which show lower values during the summer season compared to spruce, and simultaneous observations of no change in groundwater levels." (L440). However, this is no justification for the assumption that the ground water recharge below the beech is the same as below the spruce.

Response#8

Thank you for pointing out this lack of clarity in the manuscript, which gives the impression that we assumed that the beech plot experienced the same drainage as spruce. In fact, we assumed similar or lower values of drainage based on the fact that in summer periods when no changes in groundwater level were observed, we observed more pronounced declines in measured soil water content under beech. This assumption is supported by the literature (most relevant papers cited), as studies on the topic predominantly report higher transpiration rates of beech.

Moreover, we have started the measurements of sap flow in August 2024 at seven trees at each site using Trunk Heat Balance method with EMS-81 sensors (EMS, Czech Republic). The monthly sums (August) of transpiration of 60.2 mm in the case of spruce forest and 76.2 mm in the beech forest were observed. Further, the soil water model run was extended to August 2024 and modelled monthly transpiration sums of 61.2 and 81.5 mm for spruce and beech forest were modelled. This indicates that the modelled differences in transpiration are in an acceptable agreement with measurements - although we are aware that one-month period is very short for a proper analysis and hence, we will not add this analysis to the manuscript.

To sum up, it arose from the facts that (1) the soil moisture declined more pronouncedly, (2) reported transpiration of beech is higher and (3) no changes in groundwater level were observed during these declines.

Comment#9

Concerning S(t) (L160): How is the influence of tree type regarded?

Response#9

The influence of tree type is reflected through different parametrization of the effective wetness (theta_E) restricting the rate of PET. The parameters include theta_S and theta_R, which govern the linear relationship of S(t) representing the rate of actual evapotranspiration to potential one based on the available soil moisture similarly to the approach of (Feddes and Rijtema, 1972). The different parameter values are documented in Table 1. In most cases, this results in the effective wetness ranging from 0.29 to 0.60 in the case of spruce and from 0.40 to 0.80 in the case of beech. Hence, in the case of beech plot, the rate of actual ET is following PET more closely.

We are aware that the utilized modelling approach is not describing the physiological behaviour of plants entirely, especially in the drought stress periods as more complex reaction to the water deficiency stress was reported both in the case of beech (Walthert et al., 2021) and spruce (Zweifel et al., 2002), but is is current state-of-the-art approach in hydrological modelling.

Comment#10

Looking for a correlation between the terms of the water balance and environmental quantities (L326), why do you use the snow cover duration and not the precipitation during the winter season (water equivalent of the snow). I am not surprised by the weak correlation between snow cover duration and soil moisture, there can be long cold winters with snow cover but little precipitation and vice versa for warm winters. The usual argument, snow cover enhances infiltration, is not applicable at your site, as you wrote on L131: "surface runoff is not generated in the experimental catchment and all water directly infiltrates into the soil".

Response#10

The information about snow cover duration was used to demonstrate the limited role of winter characteristics on the summer soil moisture (correlation coeff = 0.08). The same is valid for the maximum snow water equivalent (correlation coeff = 0.15), winter precipitation (correlation coeff = 0.09; see Fig. R8 using winter precipitation in comparison with original Figure R9) and the length of continuous snow cover (correlation coeff = 0.01). Both figures show similar limited influence of winter meteorological characteristics.

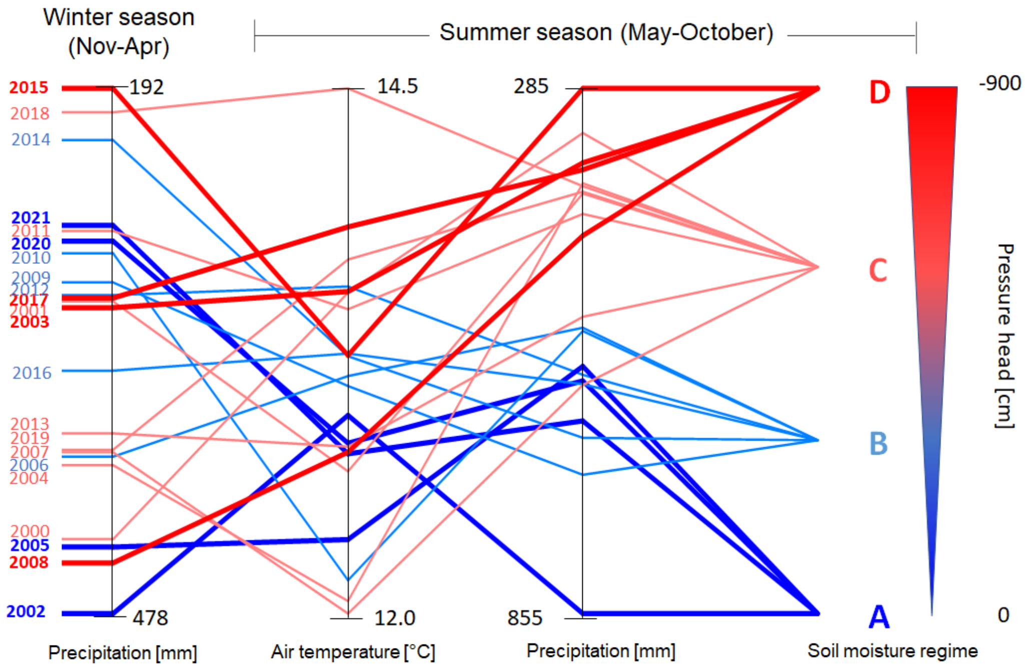

Fig. R8 Demonstration of winter precipitation (very left column) influence of summer soil moisture regime

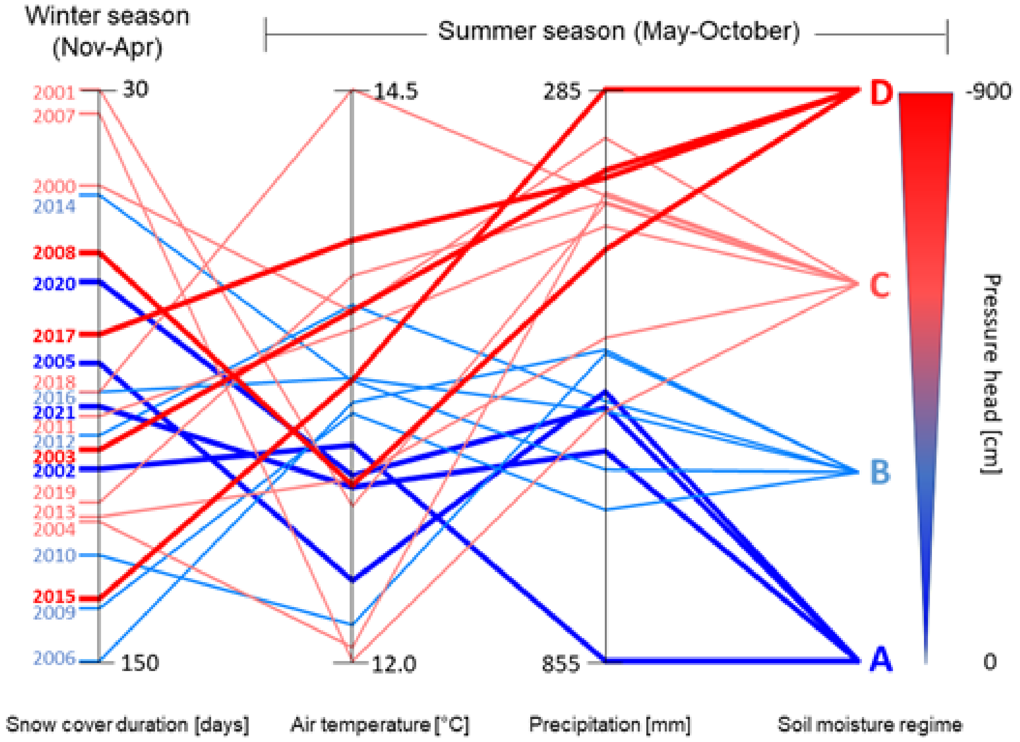

Fig. R9 Demonstration of snow cover duration (very left column) influence of summer soil moisture regime

Comment #11

Results from literature and own observations get sometimes mixed up in the argumentation (see L382 ff. and L442: "The comparatively high transpiration rates of beech during the summer season were separately validated by measured sap flow (Brinkmann et al., 2016; Gebhardt et al., 2023)"). Please make clear what is your observation and what can you conclude from that, and finally compare it to literature.

Response#11

Yes, thank you for the notice. We did not want to mix up our results with the results from the literature. We will polish the mentioned parts of the text so it can be clearly distinguished what is the result and what are the comparisons with other authors.

Comment#12

Technical corrections

Response#12

Thank you for mentioning several inaccuracies in the text. We will carefully correct all points that you have mentioned.

References:

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andréassian, V., Anctil, F., and Loumagne, C. : Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2 - Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling, J. Hydrol., 303, 290–306, doi:10.1016/j.jhydrol.2004.08.026, 2005.

Toušková, J., Falátková, K., and Šípek, V.: Estimating potential evapotranspiration in a temperate zone: The challenge of model selection, Water Res. Manag., 2024 (under review).

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.

Yue, S., Pilon, P., Phinney, B., Cavadias, G.,:. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol. Process., 16, 1807–1829.