Reply to the comments of reviewer 1

"This manuscript investigates the role of soil characteristics in the root zone and climate properties in determining the probability of occurence and characteristics of agricultural drought. The manuscript is well written albeit sometimes rather lengthy and repetitive. Analyses are systematic as is the presentation of the results. The main conclusion to my understanding is that root zone storage characteristics are important for agricultural drought assessment and people should not only look at meteorological metrics. Although I fully agree with that statement irrespective of the results in this study, I do not think that this statement is justified based on this study's findings. My main issues are:"

We would like to thank the reviewer for the critical remarks on our study and its assumptions, which will certainly help to improve the manuscript significantly. In summary, we fully agree that an overall evaluation with streamflow observations was missing and suggest adding such analyses carried out for 50 catchments with near-natural flow across the study region as supplementary material (see reply to major remark 3). In addition, we agree that (spatial) simulation analyses are prone to uncertainties related to assumptions made, in our case regarding the parameterization of the root zone and used drought definition and threshold. Therefore, we will include additional sensitivity analyses, comparing our approach with other approaches, although we believe that there are advantages of our approach in this regional assessment (see reply to major remark 1). Further, we realize that using the term "soil moisture drought stress" is not the most suitable. This because of the above stated uncertainties and because of the fact that we do not simulate specific plant species, which have specific (growth stage related) stress levels, but rather a more general agricultural land use class. We will refer to reduced soil moisture (SM) availability instead and emphasize that this is simulated. Nonetheless, we see some advantages of characterizing periods of reduced SM availability compared to periods with below normal soil moisture anomalies, which we will clearly outline in a new manuscript (see Reply to major remark 1). We will also weaken claims about controls on reaching a state of reduced SM availability and its development time and duration, emphasize that these are model based, and discuss how controls change under different modelling assumptions (related to major remark 2). In addition, we can remove „controls" from the title, as it is one of the conclusions, but not intended as the main one. Other conclusions relate to e.g. the characteristics of events with reduced SM availability and their development, including the drought of 2018.

Below, we will reply in blue to the comments of the reviewer (numbered for referencing purposes). However, before we do so, we would like to make two clarifying remarks related to specific comment #3.

- The available water holding capacity of the potential root zone soil (AWC) was derived from a soil dataset (Section 2.2). This dataset is based on extensive field investigations on soil profiles distributed over the whole of Germany, which led to a detailed soil map, including information about soil types, grain size distribution, sequence and depth of soil horizons as well as parameters describing water-holding capacity (field capacity, wilting point, air potential). In addition, it includes information about the potential depth of the root zone constraint by e.g. the occurrence of a root restrictive layer (broadly ranging between a few decimetres up to two meter). To make sure the reader is aware of this, we will provide the more accurate description above in Section 2.2 and Section 2.3. In addition, we will make sure to emphasize already in the method section that this is the potential root zone and that agricultural crops might not make full use of it as well as that the potential root zone of an individual grid cell might not be representative for plot scale observations.

- The focus of the current study is on agricultural grid cells, which are all (parameterized as) annual crops (see e.g. Section 2.3, Line 164-166). These annual crops are different from perennial ecosystems such as forests and grasslands, which can gradually develop and adapt over the years – possibly optimizing their root zone systems to deal with droughts of certain return periods (as presented in part of the references provided in specific comment #3).

Major comment #1

"The data used for the available water-holding capacity (AWC, i.e., the amount of plant available water in the root zone at field capacity), might not be representative for the actual amount of water available to vegetation at all and could be significantly biased as climate and land cover types are in reality the main controls on root zone storage capacity and not the soil type. This would be fine, however, if we would accept that AWC is simply a soil characteristic, but then the definition of soil moisture stress occuring at 30% AWC might be biased instead. "

On the made assumptions

We acknowledge that our soil-based definition of the potential root zone might not be representative of the actual root zone. However, regional assessments rely on certain assumptions, and we prefer a soil based root zone definition in this study, as it at least takes into account the variability in potential rooting depth and available water holding capacity (AWC). In addition, the occurrence of a root-restricting layer in the soil has shown to influence root development (Schneider and Don 2019), and is more often used as one of the boundary conditions in crop or hydrological models (Gayler et al. 2014; Eyshi Rezaei et al., 2015). The reviewer is right that climate also exerts a control on the root zone. An alternative assumption would be to derive a climate dependent root zone, following approaches presented in part of the papers in specific comment #3. However, the adaptation of root zone systems to deal with droughts of certain return period is expected to mainly occur for perennial ecosystems such as grasslands or forests, and lesser for planted annual crops (as also discussed in De Boer-Euser et al. 2016). We further agree with the reviewer about the influence of land cover (crop type) on rooting depth (see also e.g. Fan et al. 2016). We could assume crop specific rooting depth, but such plant specific rooting depths would not match with our more general land use parameterization. In our simulation, we do not consider a variety of different crops, since we carry out a long-term simulation over a spacious area, for which no information about crop rotation is available. We use a parameterization in the model, which takes into account average characteristics (e.g., planting dates, LAI development) derived from a selection of typical crops grown in the area investigated.

We further acknowledge issues regarding our drought definition not being representative. We agree that it is inaccurate to refer to soil moisture drought stress for events with AWC < 30%, because 1) we do not know whether crops will assess all water in the potential root zone, and 2) at which level SM drought stress occurs, as the latter depends on crop type, growth stage, soil type, climate, meteorological conditions etc. We will therefore refer to periods with reduced SM. Nonetheless, we see some advantages of our drought identification approach, which can be used (in combination with) traditional drought identification that would define soil moisture drought as an anomaly and characterize periods with below normal soil moisture levels (Fig. R1). Such an anomaly-based definition matches the traditional definition of the drought hazard. However, from a drought impact perspective, a below normal anomaly only becomes a drought when it has the potential to cause related impacts. In that sense, it could be argued whether an anomaly-based definition is most suitable, especially outside or at the beginning or end of the growing season. In any case, time series can be quite different.

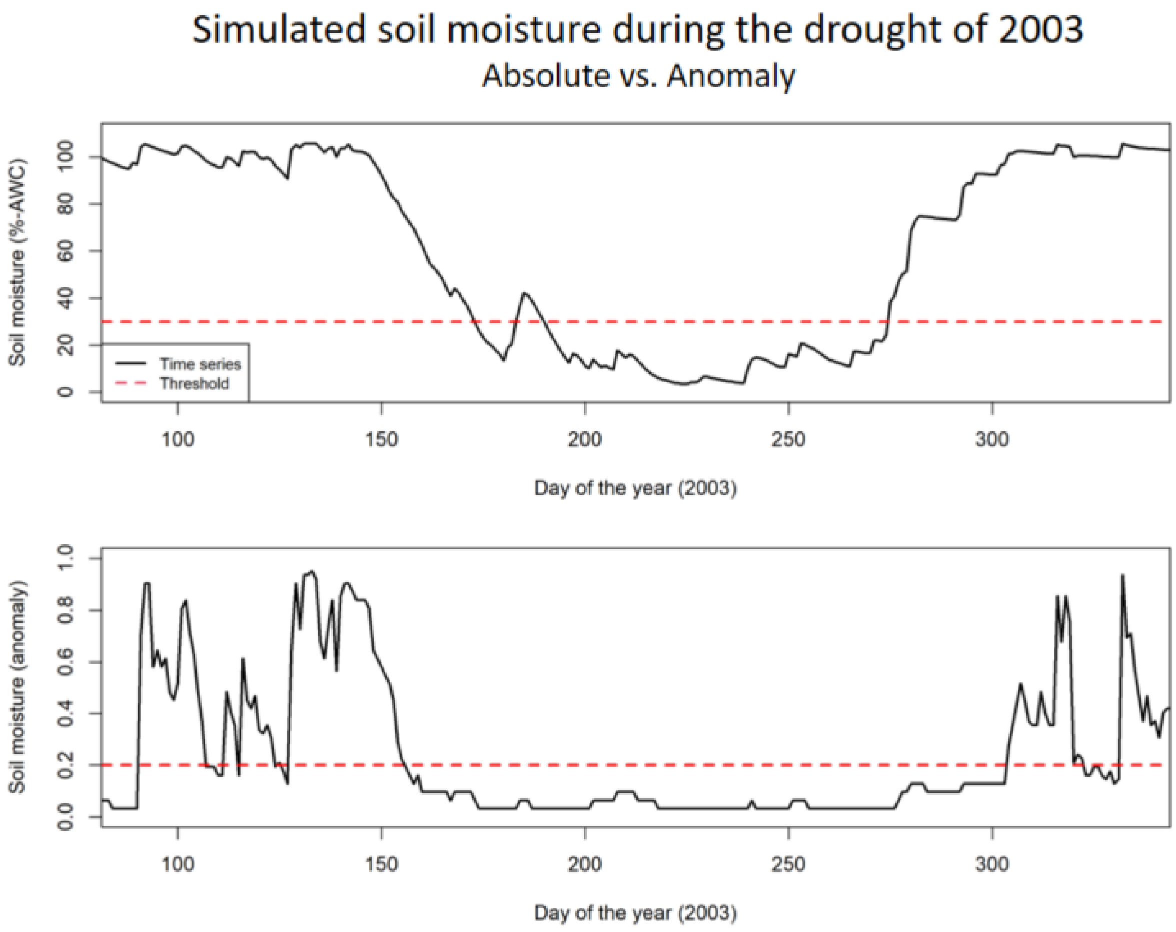

Figure R1. Simulated soil moisture for an exemplary grid cell. expressed as: percentage left in the potential root zone (upper row) and daily anomaly (lower row).

How to deal with the assumptions

Overall, we stress that we prefer the used root zone parameterization and drought identification method within the context of this study for reasons outlined above. However, we acknowledge that we should more carefully discuss the implications of our methods and assumptions, and therefore propose to include.

- A sensitivity analyses on how the parameterization of the root zone and definition of drought affect the derived drought characteristics and controls.
- A more careful discussion on how the derived results change under different assumptions and definitions as well as how derived results might be different from plot scale observations.

Finally, we do not think that we can validate / derive the depth of the root zone of the considered agricultural grid cell with a comparison against streamflow data, given the constraints presented in the reply to major comment #3.

Proposed sensitivity analyses

The analyses will be the same as those presented in the manuscript, only with different (1) parameterizations of the root zone and (2) drought definitions and thresholds. We suggest that most of these analyses can be presented in the supplementary material for discussion.

(1) Different parameterizations of the root zone soil

- Soil based AWC as used in the original manuscript.
- Climate based AWC to comply with specific comment #3, although we contemplate whether this should be included in a new version. Calculation procedure (for each grid cell):
    - Run the model under optimal conditions (no water stressed reduction in evapotranspiration).
    - Derive maximum soil moisture deficit for each year.
    - Calculate the maximum deficit that has an expected return period of 10 years.
    - Use the deficit with return period of 10 years as AWC for the final simulations
- Fixed AWC (100 mm & 200 mm). Included to completely remove the effect of the root zone soil characteristics. Two arbitrary values were used to represent both shallow and deep rooting crops.

(2) Different soil moisture drought definitions

- Absolute (%-AWC).
    - Different thresholds to comply with SC-2 (50%, 30%, 10%); emphasizing that 30% is most appropriate (10% is likely to extreme, 50% not really water stress)
- Anomaly based (daily percentiles: rank(SM_{DOY}) / (n+1). Threshold: 20th percentile.
    - Comparing SM in a certain day and year with SM for the same day in other years.

Results

In this reply, results are shown for a subset of 100 randomly selected grid cells due to high computational demands. For brevity reasons, only total time in drought is shown. In case of a revised version, these analyses will be carried out for all grid cells and considered characteristics.

Total time in drought for prominent drought years (1991, 2003, 2015, 2018)

The ordering of prominent drought years is similar, independent of the used root zone parameterization, drought identification method or threshold (Figs. R2, R3). This would mean that, independent of the used method, we would reach the same conclusion about which drought year was more severe according to total time in drought. However, absolute differences in total time in drought vary substantially, especially among methods. Anomaly based definitions generally result in higher total time below the threshold (Fig. R2). In addition, differences between root zone parameterizations are more obvious for anomaly-based definitions (e.g. Fig. R2g vs. R2h). Obviously, increasing the drought threshold increases the total time in drought (Fig. R3); However, the ordering of major drought years often does not change.

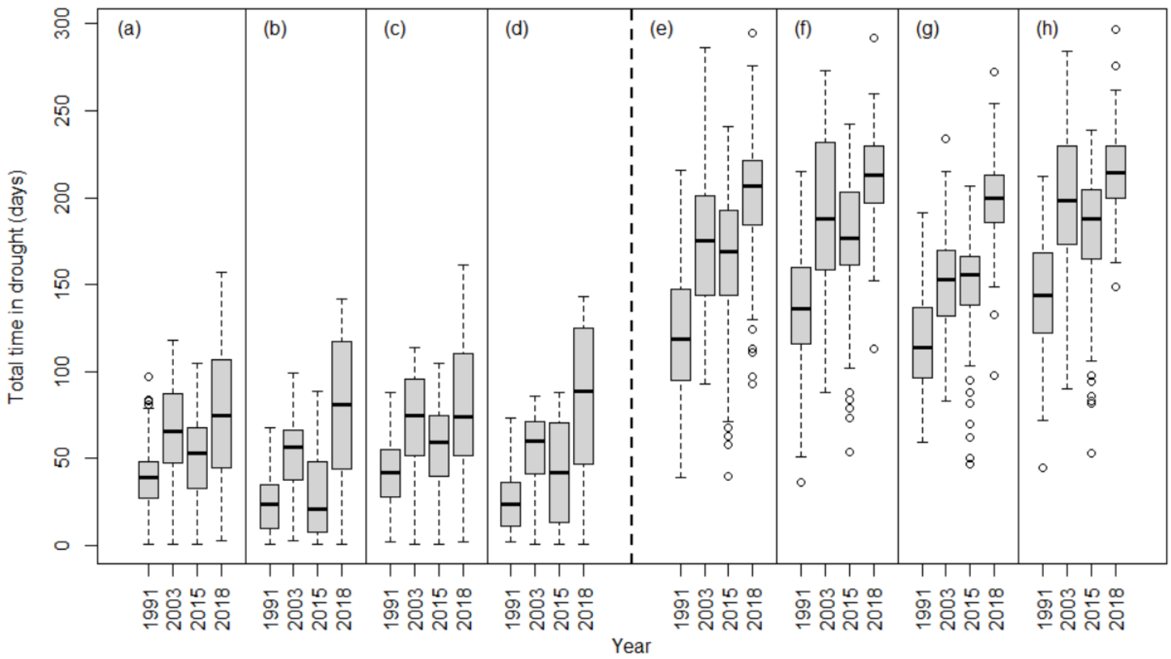

Figure R2. Total time in drought (days) according to different root zone parameterizations and different drought identification methods. Root zone parameterization: Soil based (a, e), climate based (b, f) fixed – 100 mm (c, g), fixed – 200 mm (d, h). Drought identification method: <30% AWC (a-d) <20th percentile (e-h).

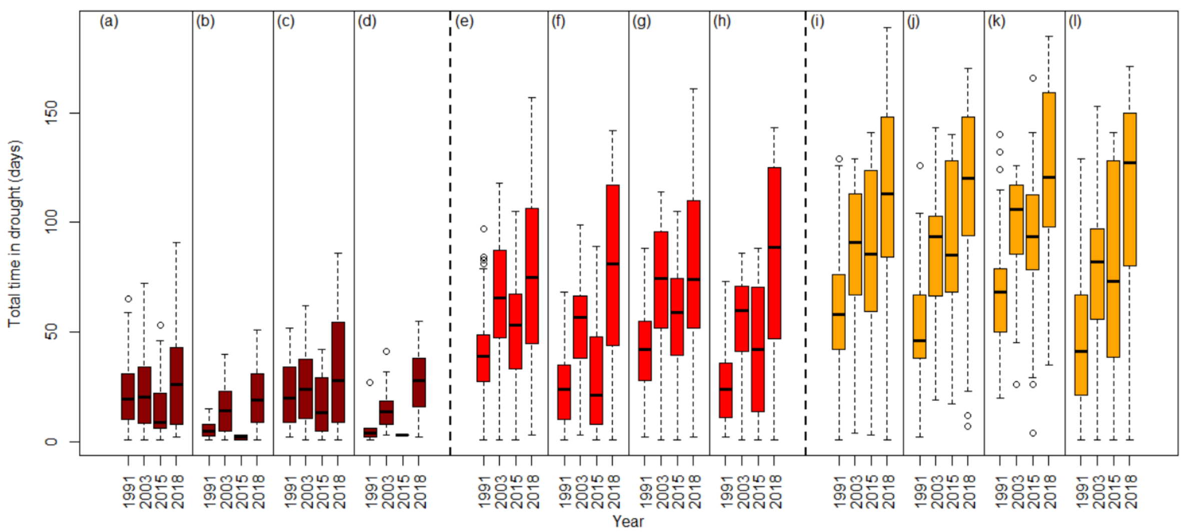

Figure R3. Total time with reduced SM availability (days) according to different root zone parameterizations and thresholds. Root zone parameterization: soil based (a, e, i), climate based (b, f, j) fixed – 100 mm (c, g, k), fixed– 200 mm (d, h, l). Threshold: 10% AWC (a-d), 30% AWC (e-h), 50% AWC (i-l).

Controls

Controls on the simulated total time in drought vary as well depending on the used drought definition and parameterization of the root zone (Table R1). Interesting is for example the contrasting relationship between AWC and time in drought: during drought years, thicker root zones are longer in anomalously low conditions, but not necessarily longer in a state of reduced SM availability.

Table R1. Spearman's rank correlation between total time in drought vs. AWC and annual average precipitation (mm year^{-1}) for prominent drought years (1991, 2003, 2015, 2018).

	Root zone parametrization	AWC (mm)				Annual average precipitation (mm year^{-1})			
		1991	2003	2015	2018	1991	2003	2015	2018
%-AWC	Soil based	-0.72	-0.52	-0.64	-0.29	-0.16	-0.16	-0.1	-0.28
%-AWC	Climate based	0.38	0.72	0.48	0.78	-0.48	-0.45	-0.45	-0.55
%-AWC	Fixed (100 mm)					-0.57	-0.47	-0.43	-0.52
%-AWC	Fixed (200 mm)					-0.55	-0.44	-0.46	-0.48
Anomaly	Soil based	0.45	0.67	0.63	0.70	-0.33	-0.25	-0.32	-0.32
Anomaly	Climate based	0.22	0.79	0.49	0.26	-0.51	-0.49	-0.63	-0.51
Anomaly	Fixed (100 mm)					-0.23	-0.30	-0.20	-0.41
Anomaly	Fixed (200 mm)					-0.41	-0.49	-0.66	-0.35

Additional discussion

We suggest carefully discussing the sensitivity of the results related to assumptions made in a separate section of the discussion. In addition, we will emphasize why we now talk about a state of reduced SM availability and not about drought stress anymore, i.e., specifically because we do not consider:

- Crop specific (temporally varying) rooting depths.
- Crop specific land use parameterization, taking into account differences in space and time due to e.g. crop specific differences, climatic differences, meteorological differences & modifications in crop genotype.
- Crop specific water stress thresholds; depending on e.g. the development stage.

A comprehensive analysis to the points above goes beyond the scope of the current manuscript. However, showing these will make the reader aware of differences between our simulations and the real world, which is always a caveat of regional simulation studies.

Second major comment

"Conclusions are drawn on AWC being a control of reaching 30% AWC. This is clearly circular reasoning and those findings can hardly be considered surprising."

We fully agree that these findings are obvious and will strongly emphasize this, as well as weaken conclusions with regard to the AWC being a dominant control – see also the comment above. However, one could argue what matters more for the depletion of the soil moisture store: its size or the magnitude of fluxes going in and out of it. In addition, besides being obvious and model based, we see value in showing this to, e.g., reflect upon the use of meteorological proxies in agricultural drought assessments that do not consider the potential buffering capacity of the soil. Further, the shift in likelihood functions in prominent drought years towards root zone soils with a higher AWC is worth showing. We think that showing this is justified when assumptions are; carefully discussed (major comment #1), when emphasized that AWC is not only a soil characteristic, and when more carefully related to previous findings e.g. describing the role of AWC on simulated drought stress and crop yield in crop models (Eyshi Rezaei et al., 2015).

Third major comment

For convenience, this comment is split up in different parts.

"This study evaluates the soil moisture within a hydrological model (TRAIN), however, there is no information shown on the setup of the model and whether this model performs well at all based on streamflow or other measurements. This might be shown in the papers that are referred to, but I would find it useful here as well."

We will present a flow chart of the model (draft in Fig. R4) and make sure to more accurately describe how the model was setup.

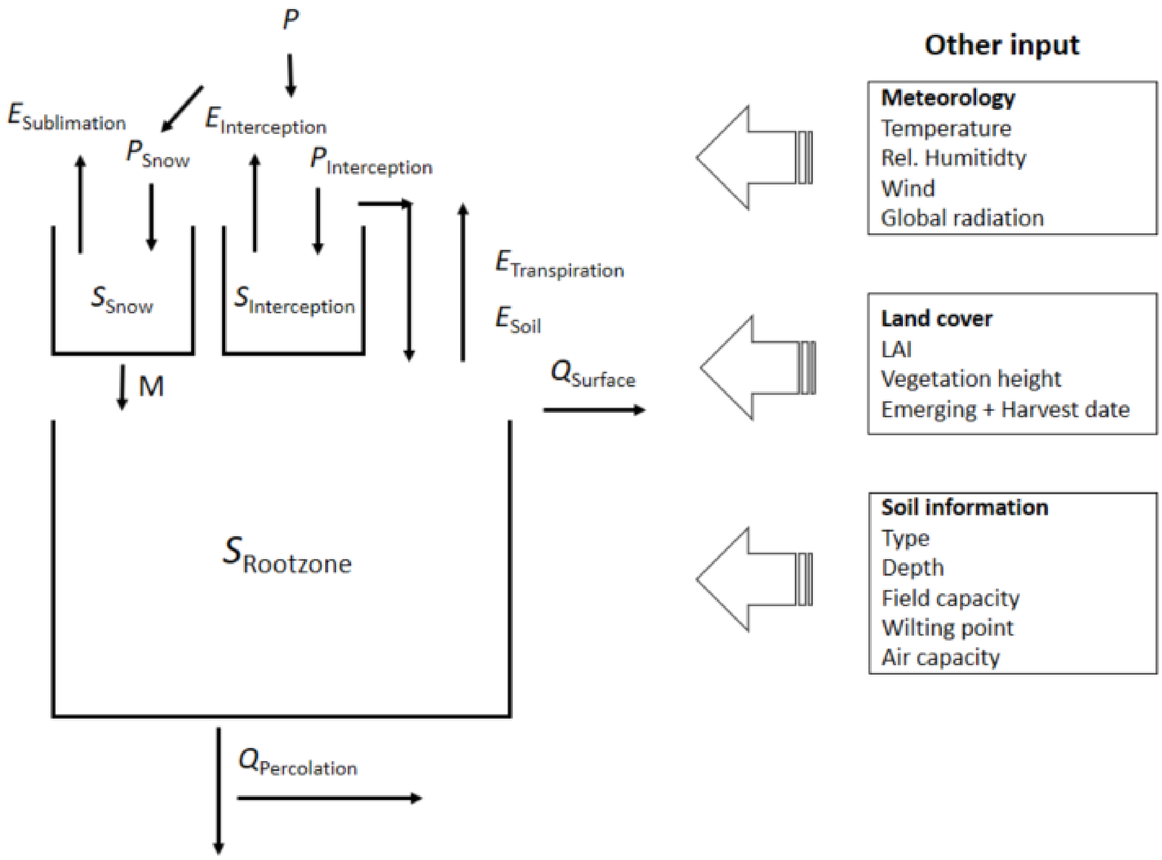

Figure R4. Flowchart describing the fluxes, stores and input variables of the TRAIN model.

With regard to model performance: TRAIN is a hydrological model / SVAT (Soil-Vegetation-Atmosphere Transfer scheme) that has been developed to illustrate the water fluxes between soil, vegetation and atmosphere and thus includes detailed, physically based descriptions of the processes that govern the water exchange. It is however not a rainfall-runoff model. Usually, the model performance is checked against measured soil moisture or evapotranspiration on the plot scale (e.g. studies section 2.3). However, the fact that TRAIN can perform well on the plot scale does not warrant an acceptable performance on the regional scale, especially given the assumptions needed to be made in order to scale up the model. Since soil moisture and evapotranspiration measurements are not available on the regional scale, measured and aggregated streamflow can be used as an approximate evaluation of the model. Therefore, we agree with the reviewer that an evaluation of the simulated fluxes and states vs. observed streamflow is helpful and suggest including the analyses below in the supplementary material. However, streamflow itself is controlled by a number of factors which are not accounted for in the model, such as geology (resp. groundwater conditions, for example the extent of groundwater storage or the velocity of underground flow).

Proposed analyses for the supplementary material

The performance of TRAIN was evaluated by comparing the sum of catchment average simulated percolation and surface runoff ($Q_{Surface}$ + $Q_{Percolation}$; the latter component comprising both deep percolation and lateral flow) vs. observed streamflow ($Q_{Observed}$) for 50 catchments located across the study area (Figure R5).

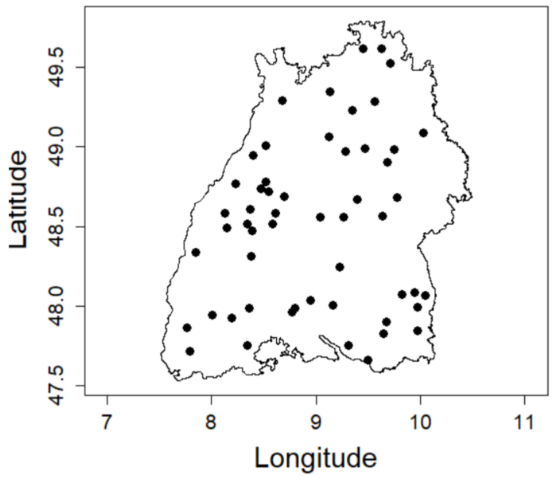

Figure R5. Location of streamflow gages used for evaluation.

The considered catchments have near-natural flow and continuous data for the considered period (1989-2018). The performance in TRAIN was evaluated by:

- Comparing the annual average of $Q_{Surface}$ + $Q_{Percolation}$ with the annual average of $Q_{Observed}$ (1989-2018).
- Assessing the correlation between simulated annual $Q_{Surface}$ + $Q_{Percolation}$ vs. annual $Q_{Observed}$.
- Assessing the correlation between simulated monthly average root zone storage ($S_{Rootzone}$) vs. $Q_{Observed}$ for all summer months.

Simulated annual average $Q_{Surface}$ + $Q_{Percolation}$ and annual average $Q_{Observed}$ reveal a good agreement (Fig. R6). Differences are mostly within the 100 mm range, with a few exceptional catchments showing larger differences, especially in the wetter domains (forested catchments).

Figure R7 reveals the distribution of Spearman's rank correlation coefficients of the relationship between simulated annual $Q_{Surface}$ + $Q_{Percolation}$ vs. annual $Q_{Observed}$ (averages over the hydrological year). The generally high correlation coefficients indicate that TRAIN gets the inter-annual variability more or less right, especially when considering that TRAIN does not have a base flow reservoir and therefore is not able to simulate long-term variability in e.g. groundwater stores.

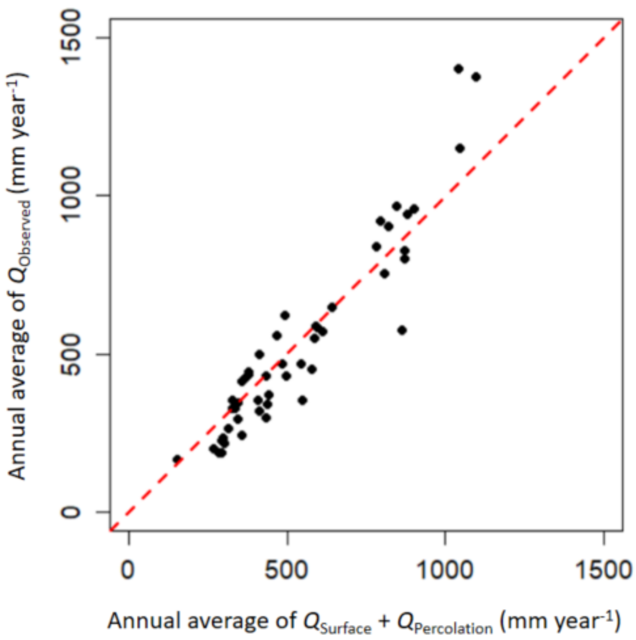

Figure R6. Simulated annual average $Q_{Surface}$ + $Q_{Percolation}$ vs. annual average $Q_{Observed}$ (each dot reflects one catchment). Dashed red line is the 1:1 line.

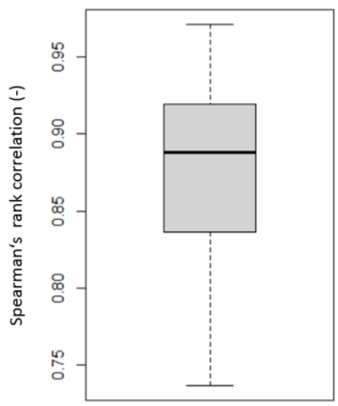

Figure R7. Distribution of Spearman's rank correlation between the simulated annual $Q_{Surface}$ + $Q_{Percolation}$ and annual $Q_{Observed}$ (October - September) for all considered catchments.

Figure R8 reveals Spearman's rank correlation between monthly catchment average $S_{Rootzone}$ and monthly average $Q_{Observed}$ for all summer months. These correlations are plotted against the base flow index (BFI), i.e., the fraction of flow stemming from base flow. In general, the correlation magnitude implies that low average root zone soil moisture conditions coincide with low river flows (not a causal relation). Further, a decrease in correlation is visible towards catchments with a higher BFI. For these catchments with a high BFI, groundwater stores are likely more important, and can sustain low flows, even though root zone soil moisture stores are depleted.

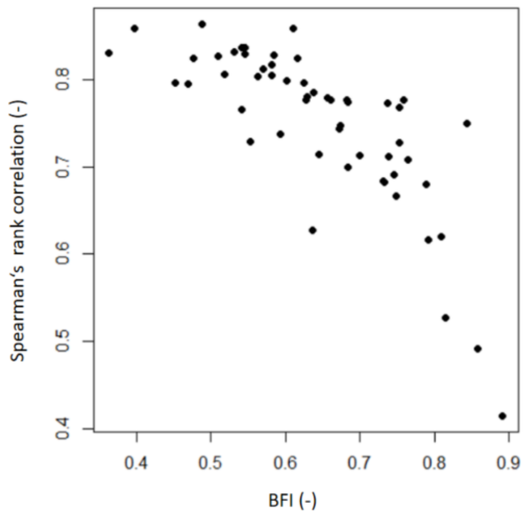

Figure R8. The correlation between monthly catchment average root zone soil moisture vs. monthly average $Q_{Observed}$ for all months between June and September plotted against the BFI. Each dot reflects the correlation for a single catchment.

Continuation of the comment:
"Neither is it evaluated how crucial information/parameterization affects the results. Does the in- or exclusion of the AWC data vs. a fixed value improve model performance?"

As outlined above, the aim of the TRAIN model was not to simulate daily river flow. In addition, we can modify our AWC parameter, e.g., fix the AWC, make the AWC climate dependent (as is done in the sensitivity analyses presented in the reply to major comment #1), or even calibrate the AWC. Overall, this might improve the simulations of $Q_{Observed}$; however, we argue that we will not know whether the improvement relates to a better representation of the AWC for the considered agricultural grid cells. Therefore, we propose not to include any additional calibration / evaluation exercise against observed streamflow, but rather a sensitivity analyses as described in the reply to major comment #1 as well as the model evaluation analyses against observed streamflow as outline above.

Continuation of the comment:
"Is the vegetation water stress formulation in TRAIN really the best and would other parameters lead to worse or better streamflow predictions?"

The vegetation water stress formulation in TRAIN has been developed through extensive field investigations, based on detailed observations of soil moisture, plant development stages, LAI etc. This has been done for a small number of agricultural crops (such as wheat or barley), and the findings are quite similar to ones reported in the literature. Is it really the best? No, as it depends on various factors, e.g., vegetation type and climate etc. However, it is suitable for the regional assessment as carried out in this study. Could another definition of water stress result in better streamflow predictions? Possibly. However, we argue that we cannot justify whether the possible improved streamflow predictions are because of a better representation of the feedback between evapotranspiration - vegetation water stress, as evapotranspiration can be increased or decreased by various processes, including a different formulation of water stress, a different parametrization of the root zone, a different parameterization of the LAI etc.

Concluding remark

Conclusion: although the research is systematic and well presented, and I do not have a lot of comments, I personally do not see how the authors would be able to address these comments without adding new analyses. Doing so, would make the revision deviate considerably from the original submission and, therefore, I would recommend a rejection with the encouragement to resubmit, rather than major revisions. I believe that although this is a harsh recommendation it would also be in the interest of the authors themselves to have a revised manuscript evaluated starting from the public discussion phase.

We thank the reviewer for the positive remark on the presentation of our research and appreciate the critical remarks on the scientific quality. We do not agree with the recommendation of rejection, despite appreciating the well-intended nature of it. We think that the presented additional analyses, i.e., a sensitivity analyses of the used method and an overall evaluation with streamflow data, as well as the additional discussion, are more complimentary and do not completely change the manuscript. They will help with the interpretation and discussion of the results, but will not result in new major findings.

Specific comments:

#1: "L38: "Droughts are often defined as a below normal water availability"
I would have expected some critical reflections on this directly in or directly after this paragraph and not by the end of the introduction."

We will provide a critical reflection regarding drought definition here (see also reply to Major comment #1).

#2: "L75: "which is indicative for low soil moisture levels causing drought stress for plant"
Given the fact that at this point in the introduction drought has only be described to be defined as an anomaly and not as an absolute measure, low soil moisture levels can occur without having a drought, so the plants in this example just experience water stress and not drought stress."

Will be changed

#3: "L109: "Vectorized soil property data (field capacity and wilting point of the root zone soil) were derived from the BK-50 (scale of 1:50,000) dataset provided by the Federal State Office for Geology Resources and Mining (LGRB, 2019)."
Is this the available water-holding capacity in the rootzone? Does it include thickness as well as soil type? This is not clear. More importantly: how do you know that plants' roots really access all this water? There have been many studies showing that the root zone storage capacity is not a characteristic of the soil, but mainly that of the climate and the plant (e.g., de Boer-Euser et al., 2016; Fan et al., 2017; Gao et al., 2014; Guswa, 2008; Kleidon, 2004; Nijzink et al., 2016; Speich et al., 2018). Therefore, it should be made clear in the manuscript that AWC is a soil property within a part of the rootzone, but not necessarily a characteristic of the rootzone itself, and may even be completely unrelated to root zone water storage capacity."

Will be clarified. See the first clarifying remark (page 1) and reply to major comment #1.

#4: "L145-146: "Thus, the root zone soil is not subdivided into different layers but understood as one uniform soil column."

Does it have a specific pre-defined thickness? Was it calibrated on something? This is a crucial parameter, so a more comprehensive description would be useful to the reader."

We will clarify that the soil column was derived from characteristics of the soil and can have a variable thickness and available water holding capacity (See the first clarifying remark on page 1). It was not calibrated (for reasons explained in reply to major comment #3).

#5: "L218-L220: "The latter suggests a stronger influence of root zone soil characteristics, over the influence of the climatological setting, on whether or not SM drought stress developed. SM drought stress was further found to be more likely to develop in soils that have a lower AWC (Fig. 5a), as the likelihood of Socc increases with decreasing AWC.""
Yes, obviously this is the case. The probability of occurrence of SM drought stress (defined as <30% of AWC!) is related to AWC. It's extremely obvious that these variables are related, so it's not surprising at all to find a strong relation, especially as this is an entirely model-determined results. This is clearly circular reasoning and can hardly be considered surprising.

See reply to major comment #2.

#6: "L302-L303: "SM drought stress was generally more likely to develop, and evolved faster and earlier in the year, in shallow root zones with a lower AWC."
Yes, obviously this is the case as SM drought stress is defined as <30% of AWC! This is again clearly circular reasoning and can hardly be considered surprising."

See reply to major comment #2.

#7: "L305-L306: "Results also confirm that AWC of the root zone is an important factor to determine the vulnerability to agricultural drought"
In your model that is and with a definition where agricultural drought is defined as a percentage of AWC. This conclusion is, therefore, overstated and should be withdrawn in case it cannot be backed up with any observations (crop yields, vegetation observations, etc.) or hard proof that the hydrological model is a reliable descriptor of true states and fluxes."

We will weaken this statement, and emphasize that these conclusions are drawn from a modelling result for agricultural grid cells. In addition, we will emphasize that plants might not make use of the entire rooting depth (see above), and that a soil based AWC might differ from the actual amount of water available for plants. Given the above, we will stress that a soil based AWC is not a suitable vulnerability factor. However, we could discuss that AWC can also be seen as a plant specific property – and that a shallow rooting species is much more likely to reach a state of reduced SM than deep rooting species (also specific remark #9). Finally, we believe that the model is a reliable descriptor of the observations (reply to major remark 3).

#8: "L352: "However, roots do not necessarily utilize the water in the entire soil column"
Exactly! Or they are able to access more water than what you think based on the soil map and model parameterization. There would likely be great differences between forests, grasses and crops and the roots would develop differently under different climates. Therefore, what you define as soil moisture drought stress could be far from reality."

We will emphasize that we focus on agricultural grid cells. We agree that our results might differ from reality, especially at the point scale. By referring to simulated reduced SM availability instead of SM drought stress, we remove the link with stressed crops. We will also acknowledge the subjectivity in our drought definition. However, we also stress that regional simulation studies often suffer from issues of being representative and that many drought definitions and (anomaly) thresholds are subjective as well - especially when applied in a regional setting (see reply to major comment #1).

#9: "L357: "However, by analyzing a large sample of grid cells, we cover most combinations of root zone
characteristics and climatological settings that occur within the study region"
Even if we accept that the rootzone characteristics and climate to be wrongly represented in individual grid cells, you have no basis to claim that the probability distribution function of root zone vs. climate is representative of reality."

We will emphasize that these finding are model based and carefully discuss the implications of modelling choices and assumptions as well as discuss how representative our results are of reality (see above). We do think that our root zone likelihood functions are more representative of reality, especially if we discuss that root zone is not a soil characteristic (see specific comment #7), given that climate it the more certain input variable. We agree that the climate functions are more uncertain, given the higher uncertainties in the root zone. This will be carefully discussed based on the newly proposed sensitivity analyses, i.e., how controls change if we keep the root zone storage fixed.

Technical corrections:

Thanks a lot for providing these technical corrections. They will be applied as suggested.

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