RC2

The manuscript presents an interesting topic and shows long-term measurements of soil moisture at a municipal landfill site in Germany. The data covers a relatively large period with quite distinct climatic conditions (wet, dry years) and measurements on soil moisture are available for several depths and various profiles at the site. Despite the rich data set I found it difficult to read, because of the uncomplete description of the experimental data and the used methods in this study. The unclear description of the lysimeter/field cover and drainage data of each filed makes it difficult to interpret the results. The authors should include at least information on the land surface cover and their change or development over time. The same should be done for the drainage data and interactions between climate, vegetation, and soil should be investigated and discussed. Hence I recommend the authors to include more data and consequently explore their data more in deep! In addition the authors should include a discussion of their results in the context of other study in the Results and Discussion section. Nevertheless it was an interesting read and I want to encourage the authors to carefully rewrite, revise and improve their manuscript.

We are thankful to Reviewer 2 for the valuable insights and the classification of the manuscript as an interesting read. We are also thankful for the more critical questions that helped to further improve the manuscript. Replies to the specific comments are given below. Description of the field site was expanded upon in the manuscript as well as additional data on precipitation and discharge added and discussed.

Specific comments:

L13: Soil moisture is not a flux. Please reformulate the sentence.

Reduced the sentence from “soil moisture fluxes” to only read “moisture fluxes”.

L28: Change evaporation to evapotranspiration.

changed

L31-36: Che authors may include also the discussion about soil moisture measured by different method see e.g. Jackisch et al. (2020).

A citation to the discussion in Jackisch et al. (2020) on the different sensor systems is now added to our introduction: “A comparison and discussion of several sensor systems using different measurements principles is given in Jackisch et al. (2020), highlighting also the need for thorough calibration before the use of such systems.”

L39-40: Change eg. to e.g.

changed

L49:High precision and high temporal resolved measurement with lysimeter are also able to exactly determine incoming water at the land surface due to precipitation and non-rainfall-events like dew or fog. I suggest to add this point here.

Added this important point and a corresponding reference to (Groh et al., 2018).

L53: Not clear if observations from one or two lysimeters are used in this study? Please clarify this point.

Measurements from both lysimeters were used in this study. Lysimeter Field 1 consists of one field, while Lysimeter 2 is subdivided into two separate fields that were built at the same time (see Fig. 2.). Changed this line in the manuscript to represent this fact more clearly.

L56-67: At this stage it is not clear to me why the authors need lysimeter in this study. Neither the introduction text nor the objectives are link to lysimeters. Please clarify this point! If not any soil profile with long term soil moisture measurements could be taken here instead of a more sophisticated measurement set-up with lysimeters.

We added discharge and precipitation data to make better use of the more complicated setup of the lysimeter compared to other soil moisture measurements. As the reviewer

points out, any long term soil moisture measurements could be taken here instead. We included modeled soil moisture data provided by the DWD (for a differing soil type to our measurements, thus making them not directly comparable).
Bayesian time series decomposition of further soil moisture time series from different sources (e.g. the ones published by ESA based on remote sensing) would most certainly yield interesting results, but are beyond the scope of this study.
L73-82: Please provide a table with detailed info on soil properties for all fields. This includes not only the basic info on soil texture but also other important information's, which are normally available at such municipal landfill experimental sites.
We agree that comprehensive information on used materials is important in interpreting results and added the available information to the manuscript. Unfortunately, detailed properties of the soil are not available. The major point of the monitoring program and reason for building of the lysimeters has been and still is the proper functioning of the landfill cover to stop water from percolating through the landfill itself. The material used as recultivation layer was only of minor importance during construction. Overall the soil is very heterogeneous, containing clay, sand and even larger rocks. Taking soil samples now would create cavities and change the overall behavior of the lysimeter, which is undesirable.
L85-86: The authors should explain the modification of the measurement devices in detail, if not study results might not be comparable to other studies.
The diameter of the probe was reduced to fit within the installed steel pipes. This does not influence the measurements. Both neutron probes were calibrated (Augenstein, 2015).
L93: How does this number fit with the mean inclination angle of 23.5 ◦ for each field reported in L75 & L79?
Final depth is not dependent on inclination angle. Exchanged "bottom" by "final depth" to alleviate the confusion. Depths given indicate distance from surface to bottom of the recultivation layer. The inclusion of a figure showing lysimeter cross sections should make this more clear.
L102: The authors should explain how the used uFC data were derived for this study. This includes the important assumption e.g. vegetation, model, boundary conditions and soil types/ properties.
The data are provided by the DWD as is. Added an explanation on their calculation and boundary conditions to the manuscript.
L102-107: Totally unclear why the authors want to use the model uFC? This should be explained in the section.
As noted by the reviewer in a previous comment, any soil moisture time series could be used. We used external data by the DWD to compare with measured soil moisture and validate our findings. Added this explanation to the manuscript.
L103: Which soil types are used for this uFC data? The authors should describe the soil properties to be able to compare it with the landfilled soil profiles.
Added a description.
L109-116: The authors should clarify why time series were transformed into a radial coordinate system. This was done only for soil moisture observations?
We added the reason given in the results section to the calculations section. Yes.
L117: Explain more in detail why the authors used linear regression and for what. Did the authors also check if the assumptions for using such a model are full filled?
Before experimenting with more sophisticated models that are often unnecessarily complex and hard to interpret, we tried to gain insights by using well known methods. Linear regressions are widely used and they are easy to formulate and calculate.

Decline in soil moisture does not follow a strictly linear trend over the complete observation period (as mentioned several times throughout the manuscript). Furthermore, a large seasonal component is superimposed on the overall trend. We still think our use of linear regressions is useful to gain insights and that our careful attempt at interpreting results (overall decline in soil moisture) is valid.

L121: What happens in leap years? Why using 365.2425 instead of just using the length of the corresponding year, which can be 365 or 366 days long!

No measurements were taken on 31. Dez. (day 366) during leap years, so no overlap between years occurs. The difference between the two calculations is only minor and does not affect overall interpretation. For calculation into the radial coordinate system, we changed calculation to be based on lengths of individual years.

As for the slope of the regression lines, these span over multiple years and thus an average length for a year was used.

L134-137: Please explain the used method i.e. “Bayesian change point detection” and “time series decomposition” used in this investigation more in detail! The used methods should also be included in the introduction section and it should be shown why this kind of methods are appropriate for such an investigation.

We added a short justification for the use of the Bayesian change point detection model and an explanation for the underlying methodology. A more detailed description is presented in the cited literature and does explain the intricacies of the model more thoroughly than we can present them in our manuscript.

L139: Please be precise: Figure 2 shows the monthly soil moisture profiles at the corresponding position, which were derived from the single measurements. I recommend also to add a) to the soil moisture and b) to the uFC subplot. I suggest in addition to use the same coloring scheme for both subplots. This makes it easier for the reader to compare between soil moisture and uFC.

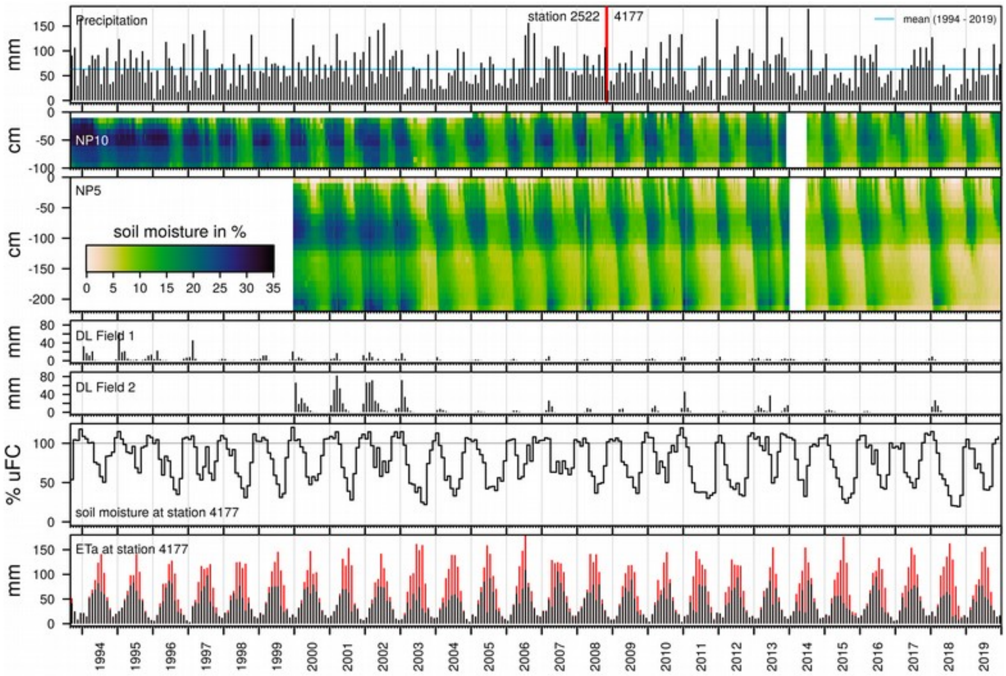
The plot shows all measured soil moisture data before monthly averages were calculated. We changed this sentence to be more precise. Furthermore, we moved the complete figure to the appendix and replaced it with a new one showing only a selection of the soil moisture data plus some additional precipitation and discharge data in an effort to increase comprehension.

L142: Please explain why only RL will be evaluated?

We did this because it reflects best the processes and moisture dynamics found in natural soils. The mineral clay liner, capillary barrier system and functioning of the sealing system as such are not representative of processes in natural soils.

L152: The authors should show this recharge data for each lysimeter in a separate figure! In addition to that the authors might show the precipitation data in the figure. Please discuss the different conditions during the observation period e.g. dry years, wet years and its implications for the observed soil moisture.

We added precipitation data provided by the DWD as well as measured discharge from both lysimeters. We further added information on especially wet and dry years.



L153: Re-wetting 2018. This might be related to the in general wetter conditions in 2017! The authors should explore their data more in depth!

It is true that precipitation in 2017 was above average as a whole, and especially during the second half of the year. At the time the year 2017 did not stand out as a particularly dry year and therefor the very low soil moisture in lower soil layers was surprising. Precipitation at the change of the years 2017/2018 percolated through the soil column in the lysimeter leading to measurable discharge re-wetting of the soil at the beginning of 2018.

L139-165: The general patterns of the soil moisture can be seen relatively well from the figure 2. However, other results discussed here are difficult to see from this figure. I suggest the authors to re-think what the main purpose for showing the figure here is and change it in a way that main findings are clearly visible.

We replaced the figure by one that is hopefully easier to read, and also contains additional data on precipitation and discharge, but reducing the number of soil moisture data shown.

L139-165: Please discuss results in the light of soil properties at each plot and the vegetation of these fields/lysimeters.

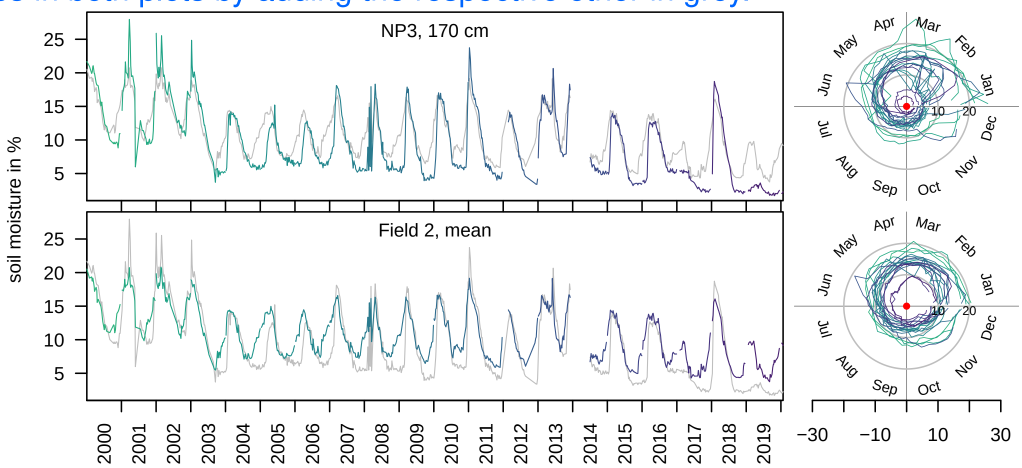
Both lysimeters share same soil and vegetation cover.

L168: Please report which model bottom boundary was by the DWD to simulate uFC and discuss this in the light of the presented uFC values.

The model used by the DWD uses constant water content as boundary condition at the bottom of the model. At the upper boundary, precipitation and evapotranspiration are used to calculate water content.

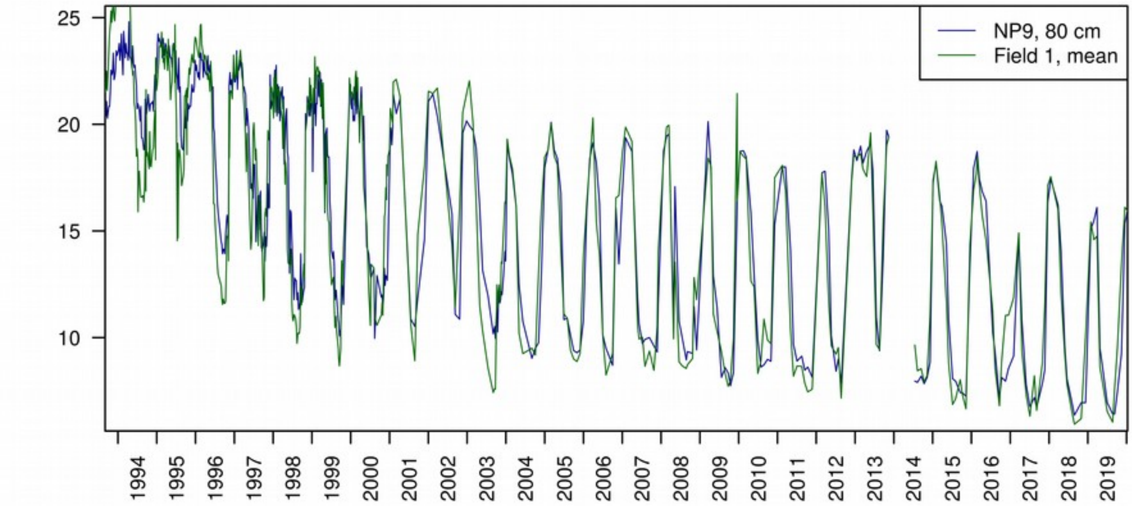
L171: Not sure from which observations I can see evaporation depths over 200cm from Figure 2? Please explain your findings more in detail! Augenstein et al. (2015) reports that the fields are covered by grass, so the authors should discuss also here the vegetation development of the lysimeters/fields and refer in the manuscript consequently to evaporation and transpiration. Was there any change in the vegetation over the observation period? From my perspective higher soil moisture values at the beginning of the period might be rather related to the establishment of vegetation on the fields i.e. change from bare soil with only evaporation to a field cover with grass including evaporation and transpiration. Please clarify this point!

Regarding your first comment raised on the visibility of evaporation depth. This can be seen from the measurements at the lysimeter and the seasonal pattern visible at these depth, not the modeled data.
Regarding your second comment on the vegetation cover. Both lysimeters are covered by grass. Further information on the development of the vegetation cover is not available. Nonetheless, the reviewer raises an interesting point here on the evapotranspiration being higher under dense vegetation cover compared to bare soil. This could indeed be the case here or at least a contributing factor. It has to be noted, however, that even the modeled data show this change in behavior at around the same time. If indeed the change in soil moisture is a result of a change in vegetation, this change must (at least in part) be driven by the factors included in the model, mainly meteorological parameters (precipitation, temperature, radiation). Changes in measured soil moisture at around the year 2003 could also be the result of the establishment of a vegetation cover after the construction of the lysimeter and over several consecutive years. The soil cover is important to prevention of erosion and lowering overall percolation by increasing evapotranspiration. The system is designed with a vegetation cover as an integral part to it's proper functioning. Furthermore, Field 1, which has been constructed several years prior to Field 2 shows a similar change. And, as mentioned, a similar change is visible in the modeled data. It is still possible that vegetation and evapotranspiration both drive this change, but then it has to be connected through the meteorologic parameters used in the model (e.g. longer vegetation periods).
L171: After looking at Augenstein et al. (2015) the authors should also clarify in the M&M section that the depths across the inclined field varied. In addition the authors should include the info that layers of the profiles e.g. in field 2B are not the same missing mineral clay liner (referring Fig. 1b in Augenstein et al. (2015))
This is true. We also added cross sections of the lysimeters to make this more clear.
L176: For a better comparison of the time series I recommend to put both in on plot. This makes it easier to compare.
The time series serves also as a reference for color in the radial plots. Having both in one plot would require different color scales for the two time series. To conserve this reference to color and at the same time improve comparability between the two, we now show both time series in both plots by adding the respective other in grey.



L177: Mean soil moisture of what depths or measurement profiles?
Mean soil moisture of the recultivation layer in Field 2 was calculated as average of NP3 at depth between 10 cm and 180 cm and NP5, NP6 and NP7 at depth between 10 cm and 220 cm. This is the same depth range that is used and presented in Fig. 5 and Fig. 7.
L175-181: It would be interesting to see this time series for the field 1 as the time series of this plot is much larger than for field 2.

The mentioned asymmetry is much more pronounced in time series from Field 2. As noted in section 3.1., measurements for Field 1 were only taken monthly after Field 2 was built. This reduced temporal resolution might be one factor affecting this. Additionally, the recultivation layer in Field 2 is much thicker than in Field 1 and downward propagation of the moisture front is spread out over a longer time frame. The time series for Field 1 is given below.



L175-181: First: I can see from the time series specific changes after the extremely dry year 2003. Please discuss here possible reasons! You might have a look at e.g. Robinson et al. (2016) or Groh et al. (2020), which showed within their investigations a change in the soil moisture level after drought events. Rahmati et al. (2020) showed for two grassland site a trend of decreasing seasonal minimal soil moisture after drought event in 2015. I guess there is much more literature on that point and I suggest the authors to include a more profound discussion/comparison of their findings.

We agree that discussion of the changes in soil moisture following the extremely dry year 2003 is important and want to thank the reviewer for the suggested literature that was a great help in this. We expanded on our interpretations given in the section on time series decomposition (4.4) and included some additional references (Robinson et al. 2016, D'Orico et al. 2007).

L139-187: I recommend the authors to use additional methods to analyze the soil moisture time series. It would be worth also to include time series of precipitation and potential evapotranspiration. The authors could also look at the relations between those variables and soil moisture observations e.g. by Wavelet-analysis (see e.g. Graf et al., 2014; Bravo et al., 2020; Rahmati et al., 2020).

We added information on precipitation and evapotranspiration to the manuscript. Relations between variables might indeed be very interesting to look at in a future study.

L-Figure 2: The authors should explain visible artefacts, i.e. strange lines between 2007 and 2008, white points, and strange lines in 2004 [. . ..].

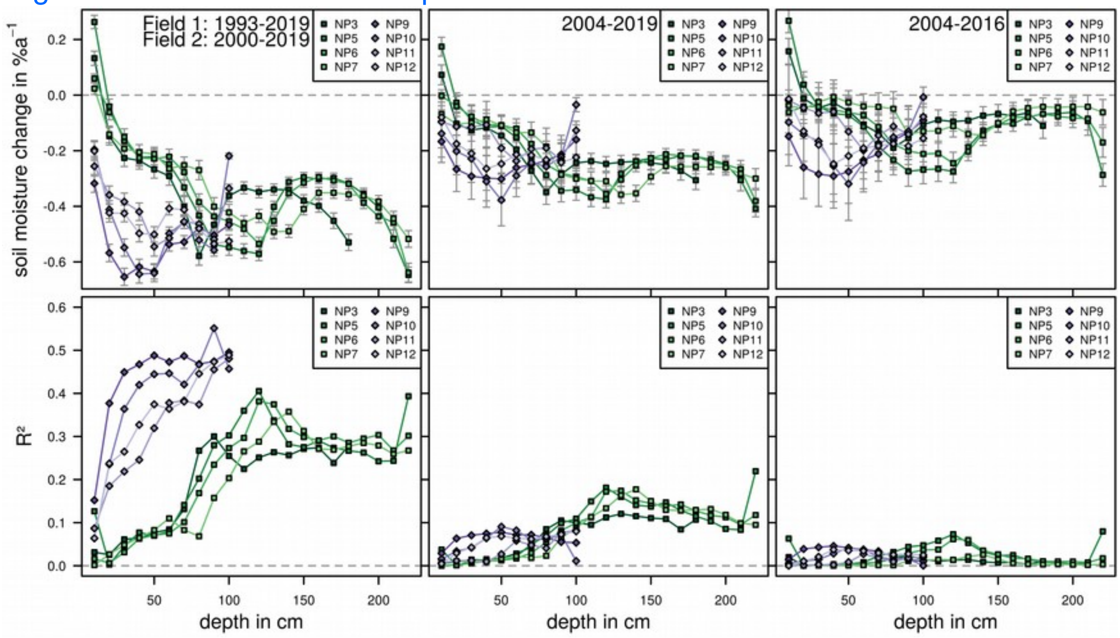
White points are missing data. Due to external circumstances it can sometimes happen that measurements in the field have to be aborted, leaving gaps in the data.

Strange lines are most likely artifacts caused by faulty data entry into the data base. It can also be seen in Augenstein et al. (2015) and was left as is.

L188 & 200: Did the authors check the important assumptions associated with a linear regression model? The questions arises as I can see a change in soil moisture level after drought event in 2003, which might affect the distribution of the data.

This change in soil moisture is mentioned many times in the manuscript as well as the influence that the length of time series has as a result. We are aware of the assumptions made in linear regressions and considered these during interpretation.

L198-199: Please reformulate the sentence.
Sentence reformulated
L201: Please show also the values for field 1 below 100 cm in figure 5.
Only results for the recultivation layer are shown. The recultivation layer in Field one only has a thickness of 100 cm.
L205-206: Please explain in detail why data for field 1 before 2003 where excluded here.
All data are included in the analysis discussed in this passage.
L207-208: Not sure why the inclusion of data before 2003 would bias the results of field 1?
Because soil moisture was significantly higher at the beginning of the measurement series. The graph below (also shown in Appendix of the discussion article) shows the influence that the length of the time series used has on resulting soil moisture change based on linear regression. Exclusion of data pre 2003 leads to reduction in R^2 values.



L215: The authors should show and discuss this percolation data.
Data added to the manuscript (see above)
L215-218: The authors should clarify to which field this results are related.
Results are related to both lysimeter fields. Added this information to the manuscript.
L219-229: The authors should as already mentioned provide the background info of this model simulation in the M&M section. This is important to better understand and especially discuss the results. So e.g. which vegetation was used in the simulation, which model, does this model provide a coupling of plant and soil dynamically or use of a fixed LAI and so on.
Added information on the model used by the DWD to the manuscript
L227: Unclear how the authors come to this conclusion. Please clarify this!
We opted to exclude this conclusion.
L230: I could not fully evaluate this section as there is very few information on the used methods in the M&M section.
Added more information on this method to the manuscript in the corresponding section
L235: The authors should explain why 2003 was that important for the soil moisture and actually discuss reason for this observations. Please do this in the whole manuscript.

2003 was exceptionally dry leading to lower soil moisture levels in the following years. Feedback mechanisms between soil moisture, temperature, precipitation and evapotranspiration are probably some of the reasons.

L238: Is this related to climatic conditions, evolution of the land surface cover or due to changes in the soil after packing the lysimeter? Please clarify this point! The authors also should be aware that landfill soils might behave different than natural developed soils.

This could be related to both, external factors like climate and internal factors regarding the lysimeter. But the temporal changes of soil properties in the lysimeter and vegetation cover have not been recorded. So we currently don't know.

L262: Yes indeed that might be a reason! This is actually the first line where discussion of the results starts! However I want to point out that current lysimeters might overcome such issues as those systems are able mimic not only a more dynamical recharge but also the capillary rise from shallow groundwater or deeper soil layers. For further details on this lysimeters see Unold and Fank (2008); Pütz et al. (2016); Herbrich et al. (2017); Groh et al. (2020); and the effect of shallow groundwater table on land surface water fluxes Kollet and Maxwell (2008); Groh et al. (2016).

The lysimeter was built in 1993 and does not provide this capability.

L263:

This is not truth as the model used by the DWD accounts also for capillary rise. See https://www.dwd.de/DE/fachnutzer/landwirtschaft/dokumentationen/allgemein/bf_erlaeuterungen.pdf;jsessionid=C44 at the chapter "Hintergründe zum Modell".

The DWD model assumes constant water content at the bottom boundary. Discussion was changed accordingly.

L271: I could not find any data in the manuscript that actual shows that hysteresis plays are role at this site. So please clarify the following sentence: "There are clearly hysteresis effects during drying and re-wetting of the soil".

Section 4.1 is dedicated to the asymmetry of drying and re-wetting. This asymmetry could also be called a hysteresis, as drying and re-wetting do not follow the same temporal paths.

Additionally, we added a citation to Augenstein et al. (2015). They investigated and found evidence for the hysteresis between soil moisture and discharge.

L278-280: Very vague statement! Please discuss this in a broader context and compare findings with other studies!

Expanded discussion and added references to further studies.

L300: Not sure if the observation provide the info if this processes are irreversible or reversible! Please discuss this before in the Results & Discussion section.

By use of the word "permanently" we did not necessarily mean "irreversible". We reformulated the sentence to avoid this word and leaving the question of reversibility open. Although other studies described similar phenomena as irreversible.

L301: I am confused about this statement as the authors used a simple linear model in this manuscript!

While it is true that we used a lot of simple linear models, (that are unable to detect changes in the overall dynamics of trend and especially seasonality) we also applied a Bayesian model to detect changepoints in trend and seasonality during time series decomposition.

L301-303: That's truth! Thus I recommend the authors to include also vegetation and drainage data to further explore their already rich data set and to include possible interactions between land surface cover, soil moisture and drainage.

We added available data on vegetation and drainage to the manuscript.

Augenstein, M., Goeppert, N., Goldscheider, N., 2015. Characterizing soil water dynamics on steep hillslopes from long-term lysimeter data. Journal of Hydrology, 529: 795-804, https://doi.org/10.1016/j.jhydrol.2015.08.053. Bravo, S., González-Chang, M., Dec, D., Valle, S., Wendroth, O., Zúñiga, F., Dörner, J., 2020. Using wavelet analyses to identify temporal coherence in soil physical properties in a volcanic ash-derived soil. Agricultural and Forest Meteorology, 285-286: 107909, https://doi.org/10.1016/j.agrformet.2020.107909. Graf, A., Bogena, H.R., Drüe, C., Hardelauf, H., Pütz, T., Heinemann, G., Vereecken, H., 2014. Spatiotemporal relations between water budget components and soil water content in a forested tributary catchment. Water Resources Research, 50(6): 4837-4857, 10.1002/2013WR014516. Groh, J., Vanderborght, J., Pütz, T., Vereecken, H., 2016. How to Control the Lysimeter Bottom Boundary to Investigate the Effect of Climate Change on Soil Processes? Vadose Zone Journal, 15(7): 1-25, 10.2136/vzj2015.08.0113. Groh, J., Vanderborght, J., Pütz, T., Vogel, H.J., Gründling, R., Rupp, H., Rahmati, M., Sommer, M., Vereecken, H., Gerke, H.H., 2020. Responses of soil water storage and crop water use efficiency to changing climatic conditions: a lysimeter-based space-for-time approach. Hydrol. Earth Syst. Sci., 24(3): 1211-1225, 10.5194/hess-24-1211-2020. Herbrich, M., Gerke, H.H., Bens, O., Sommer, M., 2017. Water balance and leaching of dissolved organic and inorganic carbon of eroded Luvisols using high precision weighing lysimeters. Soil and Tillage Research, 165: 144-160, 10.1016/j.still.2016.08.003. Jackisch, C., Germer, K., Graeff, T., Andrä, I., Schulz, K., Schiedung, M., Haller-Jans, J., Schneider, J., Jaquemotte, J., Helmer, P., Lotz, L., Bauer, A., Hahn, I., Šanda, M., Kumpan, M., Dorner, J., de Rooij, G., Wessel-Bothe, S., Kottmann, L., Schittenhelm, S., Durner, W., 2020. Soil moisture and matric potential – an open field comparison of sensor systems. Earth Syst. Sci. Data, 12(1): 683-697, 10.5194/essd-12-683-2020. Kollet, S.J., Maxwell, R.M., 2008. Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model. Water Resources Research, 44(2): W02402, 10.1029/2007WR006004. Pütz, T., Kiese, R., Wollschläger, U., Groh, J., Rupp, H., Zacharias, S., Priesack, E., Gerke, H.H., Gasche, R., Bens, O., Borg, E., Baessler, C., Kaiser, K., Herbrich, M., Munch, J.-C., Sommer, M., Vogel, H.-J., Vanderborght, J., Vereecken, H., 2016. TERENO-SOILCan: a lysimeter-network in Germany observing soil processes and plant diversity influenced by climate change. Environmental Earth Sciences, 75(18): 1-14, 10.1007/s12665-016-6031-5. Rahmati, M., Groh, J., Graf, A., Pütz, T., Vanderborght, J., Vereecken, H., 2020. On the impact of increasing drought on the relationship between soil water content and evapotranspiration of a grassland. Vadose Zone Journal, 19(1): e20029, C810.1002/vzj2.20029. Robinson, D.A., Jones, S.B., Lebron, I., Reinsch, S., Domínguez, M.T., Smith, A.R., Jones, D.L., Marshall, M.R., Emmett, B.A., 2016. Experimental evidence for drought induced alternative stable states of soil moisture. Scientific Reports, 6: 20018, 10.1038/srep20018. Unold, G., Fank, J., 2008. Modular Design of Field Lysimeters for Specific Application Needs. Water Air Soil Pollut: Focus, 8(2): 233-242, 10.1007/s11267-007-9172-4.