RC1

General comments The paper presents soil moisture data observations covering 20 years (and for some of the data even longer) measured at different soil depths and at a high temporal resolution. Soil moisture was measured at several locations in a large lysimeter on a landfill. The long and more or less continuous soil moisture observations with a high temporal resolution cover different climatic conditions and make the study valuable. This allows analyzing soil moisture development in the soil horizon under different climatic conditions over several years, including very dry conditions. The structure of the manuscript is clear and concise. Despite this wealth of data, I have severe concerns that the way the data are presented and discussed misses important aspects. The discussion and interpretaion remains rather vague and should go into more detail. The manuscript requires a major revision. My suggestions are listed below:

Specific comments

1. The manuscript does not provide basic information on factors that have substantial influence on soil water movement and evapotranspiration. Please provide these information in the study site description, and also use these additional data in the interpretation and discussion of your results (e.g. by applying an analysis of variance) a) The data stem from two large lysimeters installed at a landfill. This makes a very specific case study, since the soil layers have been build up artificially. This specific case is not discussed in the paper, but it seems as if the landfill cover can be compared to surrounding non-artificial soil or landscapes. Unfortunately, there is no presentation of the soil profile(s) of the two lysimeters and no description of soil properties, like texture, bulk density, pore volume, pF values and so on. I assume that the cover of the landfill has to meet specific requirements, and I would expect that information on soil properties therefore are available. I recommend including a table with information on soil properties (in different depths or discretized by the layer type, e.g. recultivation layer, drainage layer etc.) in the site description, and along with that, a figure of the soil profile with indications of compaction horizons or other information which are specific to that soil.

More Information on the lysimeters was added to the manuscript along with the available information on vegetation and soil properties. We added cross sections of both lysimeters. The cover was built as an alternative landfill cover not following or using any of the approved sealing systems at the time. Therefore the lysimeter was built to prove the proper functioning of the sealing system.

b) Along with missing information on soil properties, there is no description of the vegetation cover of the landfill (if there is a cover, or is it bare soil / something else?). If the two lysimeters have the same (vegetation) cover type, the effects on evaporation, transpiration and drainage are likely comparable. The second lysimeter was implemented later than the first one. Are there changes in the (vegetation) cover between the two? Please add this information in the study site description, and also consider it in the further discussion and interpretation of results.

We agree that comprehensive information on used materials is important in interpreting results. 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.
We added available information on vegetation to the manuscript. Both lysimeters have the same vegetation cover consisting of grass and weeds. Unfortunately, not much information on soil properties and the establishment and past development of a grass cover is available.
c) A photo might be helpful to give the reader an idea of the site
We agree, photo added:

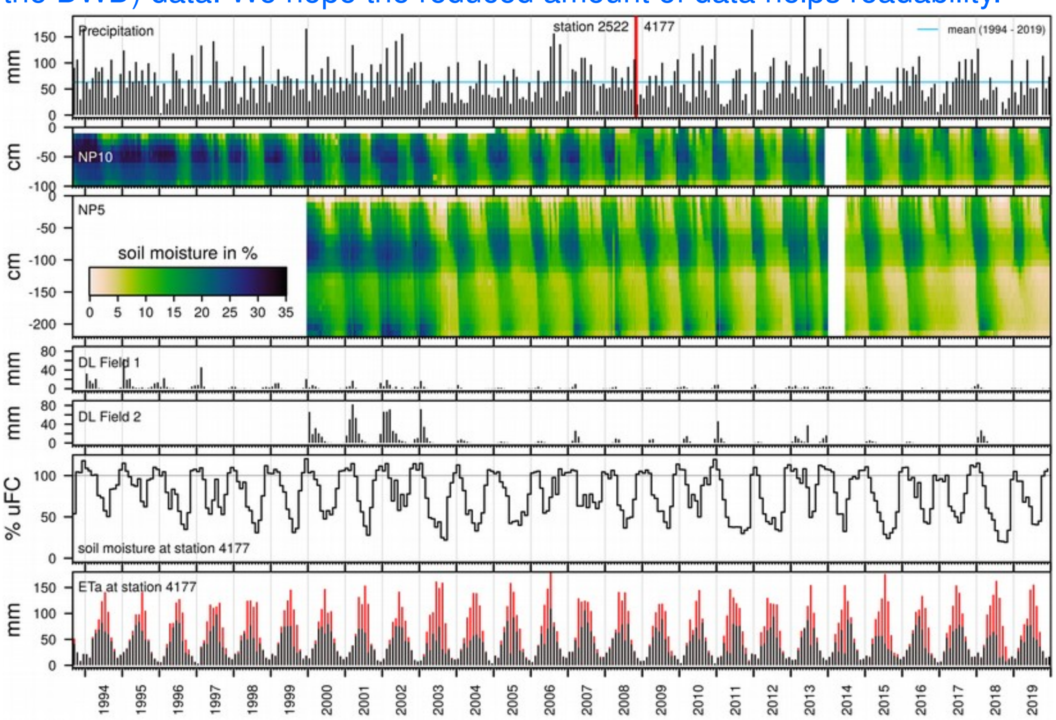
2. Information on mean annual and monthly precipitation and temperature at the study site or in its vicinity (e.g. from DWD station data) is missing. Since the authors discuss the effects of the very warm and dry summer 2003 on subsequent soil moisture, it would help the reader to see some information on average conditions and on the deviation from long-term averages during the observation period. Please add a table and/or figure with mean annual and mean monthly precipitation and temperature at least, and indicate the deviation from these average conditions during your observation period. You may also consider to highlight years with very strong deviations (e.g. very warm/cold, wet/dry).
We added a figure showing annual precipitation and mean annual temperatures to the manuscript. These data are sourced from the DWD.
3. The methods section (3.3. Theory and calculations) is very brief. Especially the Bayesian change point detection should be explained in more detail. Please also add a reference to the software you used for calculating the linear regression models.
We explained the Bayesian changepoint detection in more detail and added a reference to the lm-function (R Core Team, 2020) used to calculate the linear models.
4. Comparison of soil moisture measurements with modelled uFC: a) When using the (modelled) usable field capacity (uFC) provided by DWD I wonder why you did not try to make these data more comparable to the volumetric soil moisture measurements from the two lysimeters. This could either be done by converting the modelled uFC into volumetric soil moisture making use of the soil properties (in particular pF values, pore volume) these calculations are based on - as far as these information are provided along with the modelled uFC data. Or do it the other way round and calculate uFC at the soil moisture sampling points based on the volumetric soil moisture content and the soil properties (e.g. layer specific pF values) of the soil layers of the two lysimeters. This touches the above-mentioned missing information on soil properties. b) A discussion on how well modelled uFC can be compared with soil moisture measurements at the the lysimeters is missing. Presumably, the modelled uFC is based on non-artifical soils,

but soil moisture observations at the two lysimeters represent conditions in an ‘artificial’ soil layer. Please include a more detailed discussion here, or skip the modelled uFC data, if the soil properties on which the calculations are based are not comparable the conditions at the lysimeters.

The soil parameters used to model uFC data are different to the soil used in the lysimeter. Comparison of modeled and measured values is not possible quantitatively. However, as noted in the manuscript, they share similar temporal distribution patterns. We added information on the soil and boundary conditions used in the model to the manuscript.

5. Presentation of results: Figure 2 (discussed chapter 4) is hard to read and the information might therefore not reach the reader. Since there is many data ‘squeezed’ into this figure I find it hard to read or to really compare the different NP measurements. It is particularly difficult for the NP data of Field 1. Can think of another way of presenting the data, or (this goes more to the Editor) place this figure in landscape format? It might also be worth to plot it in a different way, e.g. calculate the difference from average for each depth increment over the entire observation period for each pixel/time step. I suggest to remove the map with modelled uFC at the bottom of Fig. 2 completely, or to move it to the appendix.

As suggested we moved the modeled uFC to the appendix. The Figure containing all measured soil moisture data was also moved to the Appendix and replaced by a figure showing selected soil moisture at two measurement points, along with the requested discharge (measured at lysimeter), precipitation and evapotranspiration (measured by the DWD) data. We hope the reduced amount of data helps readability.



L. 149: explain climatic conditions 2003 (dry and hot summer in the study region) – this can be accompanied or underlined by further general information on climate characteristics at the study site over the study period (see also #2 of my general comments above)

A figure showing annual precipitation and temperatures was added and a description of exceptional years given in section 2 “Study site” of the manuscript.

L. 161 – 165: give a more detailed description on soil properties, and discuss the effects of soil compaction. Could a compaction horizon result in a capillary barrier in the soil layer? How would that effect soil water movement?

Additional information added to section 2 of the manuscript.

Usually a capillary layer is formed by a fine material on top of a coarse material with a sharp contact. This sharp contact is not present within the compacted layer (porosity follows a gradient). The sharp contact with the layer on top is inverse to the one usually found within a capillary barrier (lower capillary forces in top layer due to higher porosity).

L. 193 – 199: please provide a more in-depth discussion in this paragraph on potential effects of soil compaction and why moisture patterns at some depths are more persistent than in other depth. E.g. continuously ‘wet’ conditions at approx. 100 cm in field 2 or at roughly 150 – 200 cm at field 1; why are there drier conditions in a small area above 150 cm at field 1).

added an explanation to this section regarding different compaction and soil material used during construction.

L. 203 – 206: In this paragraph you argue that the shorter observation period in field 2 is reason why the observed decrease in soil moisture is not significant. I wonder if this is the only way of interpreting this result. A) When looking at Fig. 5 there seems to be a change in the direction of soil moisture change at approx. 70 cm at field 2. This might also correspond to the rooting depth (in case vegetation is present), resulting in a quick recycling of precipitation via root water uptake / evapotranspiration which does not allow percolation to deeper soil layers. B) A compaction layer might further impede percolation. C) The different soil depths of field 1 and 2 and the different duration since the lysimeters have been installed, resulting effects on soil properties and (vegetation) cover should be discussed, too.

It certainly is not the only way of interpreting this result. There might be a correlation between rooting depth of plants with quick recycling of water in the upper soil and different trend in moisture change in deeper soil layers. However, both lysimeters have similar vegetation and thus should show similar results. It seems more likely that this effect is caused by the length of time series and differing compaction/differing material in both lysimeters.

L. 209 – 212: please provide a more detailed discussion on the reasons for the observed reductions in soil moisture (e.g. in the context of precipitation / temperature regimes). Why is the reduction in the lowest part of the soil profile most pronounced from January – May in field 2, and why is it not obvious in field 1?

We added a more detailed discussion and the precipitation data to the manuscript. Highest absolute moisture is observed during these month at the mentioned lower part in Field 2 at the beginning of the time series (largest seasonal amplitude). Maximum values of soil moisture are affected more by drying of the soil. Reduction is not obvious in Field 1 because depth of the soil in the lysimeter is less.

Figure 7, time series decomposition: this analysis is valuable to detect trend changes. As with Figure 2 I am concerned that, with the amount of data, the figure is still readable. As suggested before, it might be worthwhile to test different colour schemes, or highlight particularly relevant results.

We moved this figure to the appendix and replaced it with a figure showing only a selection of the results at two measurement points, greatly reducing the amount of data that is presented. Furthermore, to familiarize the reader with the results of the model, an example of model results is presented in an additional figure as a “more traditional” line graph and a discussion added.

L. 262: it is the first time in the manuscript that re-wetting from groundwater is mentioned. Are the lysimeters connected to the groundwater in this specific setting on a landfill? If so, please also describe this in the study site description

Lysimeters are not connected to the groundwater. Both lysimeters are constructed using plastic sealing liners at the sides and the bottom.

L. 270: which soil properties do you think of? Please include that in more detail in this paragraph

These could be any of the properties that are related to moisture transport and retention in the soil.

Added some examples for these soil properties to the manuscript: “(water retention, preferential flow paths, hydraulic conductivity, soil structure, etc.)”

Technical comments:

Chapter 1

L. 27-28: which were the effects of El Nino? Please explain the results of the cited studies (Solander, Kolusu) in more detail (1-2 sentences) or skip it

Added short explanation of main findings: “The 2015-2016 El Niño event is associated with extreme drought and groundwater storage declines in Southafrica while at the same time in east African countries south of the equator an increase in precipitation and groundwater recharge was recorded (Kolusu et al. 2019). Similarly, Solander et al. (2020) found evidence for both, increase (eastern Africa) and decrease (northern Amazon basin, the maritime regions of southeastern Asia, Indonesia, New Guinea) in soil moisture storage depending on location.”

Additionally updated reference Solander, 2019 from discussion article to published version Solander 2020.

L. 30-36: you could state which measurement type is used

Added measurement type used in this study to the introduction

L. 44-46: rearrange order of sentences (e.g. start with second sentence in this paragraph

Sentences rearranged

L. 55 ‘with regard’ instead of ‘in regard’ Please check and correct where necessary throughout the manuscript: - ‘depth’ and ‘depths’ - ‘In depht’ vs. ‘in-depth’ - ‘at depth of’ vs. ‘at a depth of’

Changed to “with regard”. Also checked throughout the manuscript and corrected several other instances.

Chapter 2

Include information on soil properties (at least those that are most relevant for soil moisture movement/storage), (vegetation) cover of the landfill, and climate characteristics

Added information on vegetation to the manuscript. Unfortunately not much information on soil properties and the establishment and past development of a grass cover is available.

Explain why the two lysimeters have different soil depths

Added an explanation for different soil depth in the two lysimeter fields to the manuscript. Results from the first lysimeter suggested a stronger recultivation layer better protects the mineral clay liner from drying out and thus improves long term stability of the system.
L. 78: add year '. . .being taken in December 2000' / '.. in December of that year'
added "of that year" to the manuscript
Chapter 3
Are there more neutron probe measurement points in the lysimeters (since NP numbers start with 3, and if so, why was that data not used
There are more measurement points in Field 2. As mentioned no measurements were taken at these points. Due to settling of the cover material after construction, some of the steel pipes were bent and are not usable for measurements.
L. 90: when was Field 2 constructed?
As mentioned in the section about the study site Field 2 was constructed in 2000. Added "(December 2000)" to the manuscript.
L. 122 – 127: could you please explain more clearly what you did here?
We added another figure to make this more clear.
L. 134 – 137: please describe in more detail the Bayesian change point detection and time series decomposition: how is it done and which information does it provide?
Added more information on Bayesian changepoint detection
Chapter 4
L. 141: please indicate the mentioned clay layer in Fig. 2
In accordance with a previous comment to reduce the amount of information we changed Fig. 2. It now only includes the recultivation layer.
L. 155 – 157: it is hard to see the discussed results in the Figure in its current form (see #5 in general comments)
changed figure
L. 157: change '. . .the missing occurrence. . .' into a less complicated sentence
changed
L. 160: delete 'or so'
deleted "or so"
L. 168: delete duplicate 'the bottom of'
deleted "of the bottom"
L. 170: depending on the DWD station, there is an annual cycle of uFC at 60 cm depth, so I would not call it 'minimal'
As suggested by reviewer 2, we added an indication to the boundary condition used at the bottom of the model defined as a constant water content. So annual cycle in soil moisture at the model bottom should not be very high.
L. 171: 'at a depth'
added "a", new sentence is "… is only minimal at a depth of 60 cm."
L. 172-173: Why is there a clear change in modelled uFC already after 2001, but for the soil moisture measurements this is only visible after 2003?
because we moved the time series of depth dependent usable field capacities to the appendix we removed these lines from the results and discussion section.
L. 177: add 'and a mean time series from all sampling points at field 2 are shown'
added to the manuscript according to suggestion.
L. 178 and 183: change 'in the individual time series' to 'in the time series of NP at 170

cm'
changed in both lines as suggested
L. 190: change 'could be observed' to 'soil moisture decreases by 0.34 % . . .'
Changed sentence accordingly
Figure 3: even with a good colour printer it is difficult to discern the colours representing the different years in the polar coordinate system. I suggest to try out other colour or gray scale palettes, or you just highlight very dry or very wet years.
The main reason to show data in a ploar coordinate system was to highlight the seasonal asymmetry (the opening of the nautilus representing fast re wetting). The offset from the center illustrates seasonal dynamics. Different years under dry and wet conditions can be discerned by looking at the traditional time series plot.
L. 202: change end of sentence to 'are indicated by a marker'
end of sentence changed accordingly
L. 208: I would not use 'bias' in this case, since the differences are not artefacts
bias replaced by "push" in the manuscript.
L. 215 – 218: please discuss in more detail why less water is percolating during winter in recent years
This is a direct consequence of the reduced soil moisture. We added percolation data to the manuscript.
L. 226: typo in the DWD station code?
2935 changed to correct code 3925
L. 228: 'increase' instead of 'increases'
changed

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.

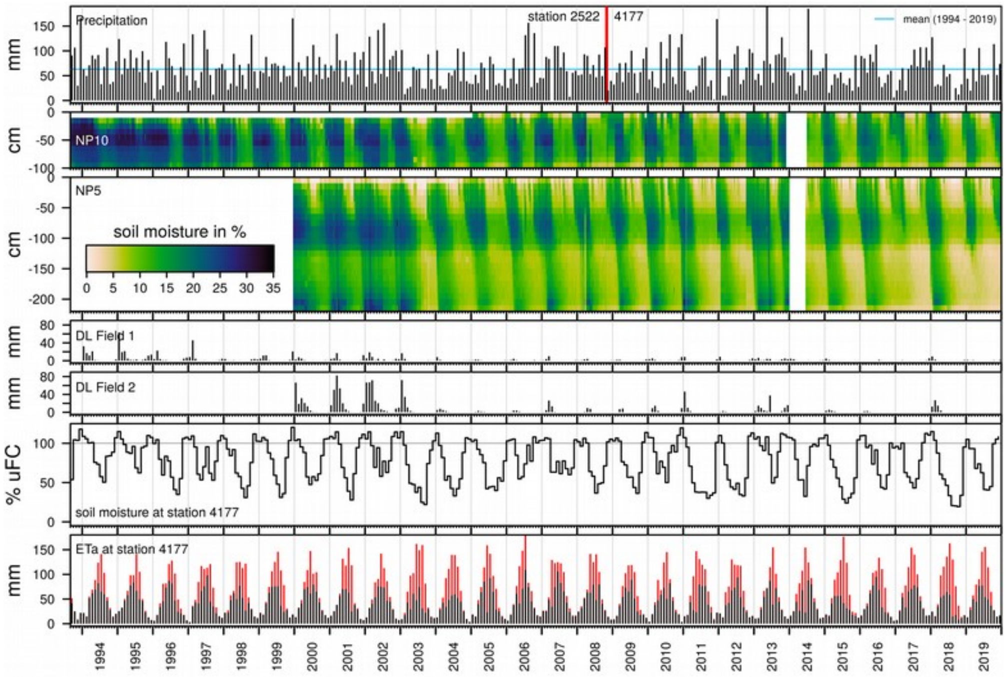
The plot shows all measured soil moisture data before monthly averages were calculated. We changed this sentence to be more precise. Furthermore, we moved the complete figure to the appendix and replaced it with a new one showing only a selection of the soil moisture data plus some additional precipitation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

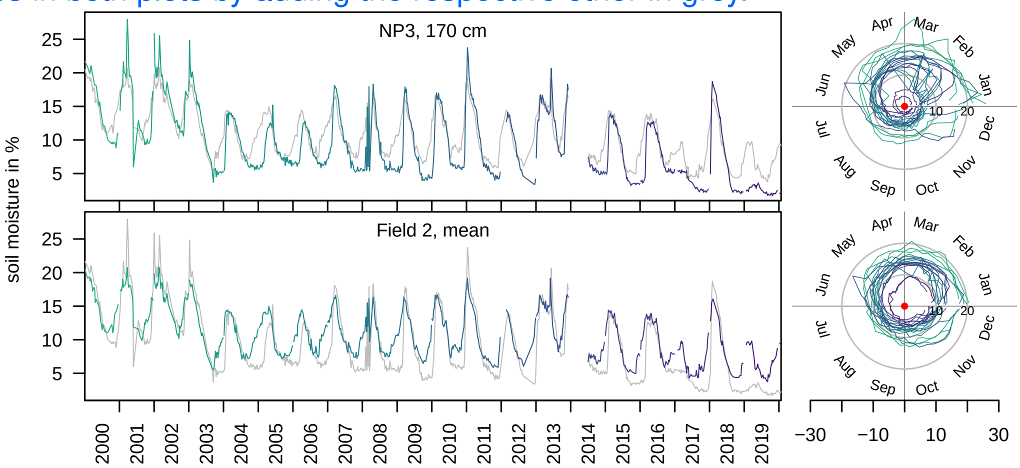
Both lysimeters share same soil and vegetation cover.

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.

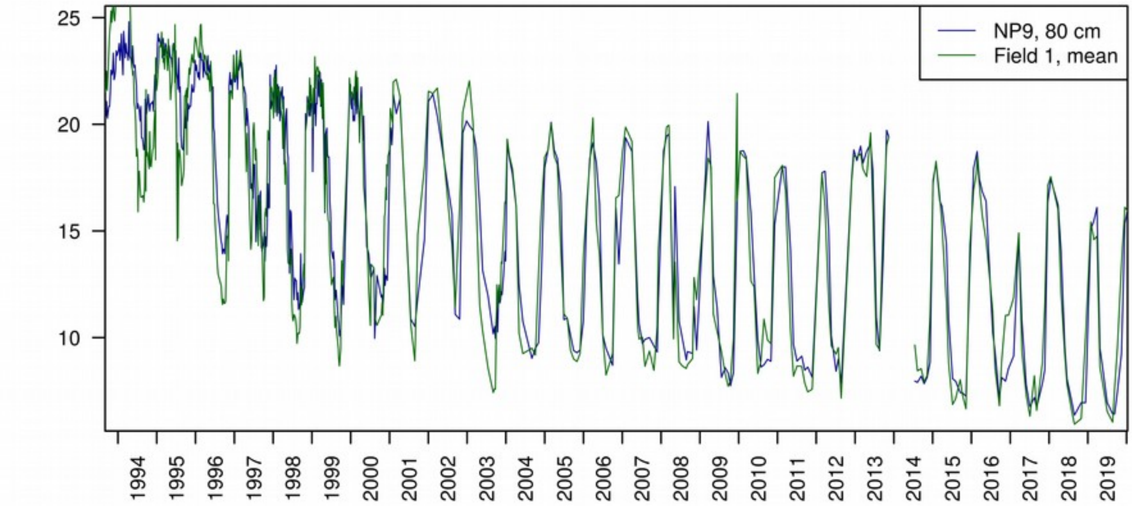
L171: Not sure from which observations I can see evaporation depths over 200cm from Figure 2? Please explain your findings more in detail! Augenstein et al. (2015) reports that the fields are covered by grass, so the authors should discuss also here the vegetation development of the lysimeters/fields 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 [. . ..].

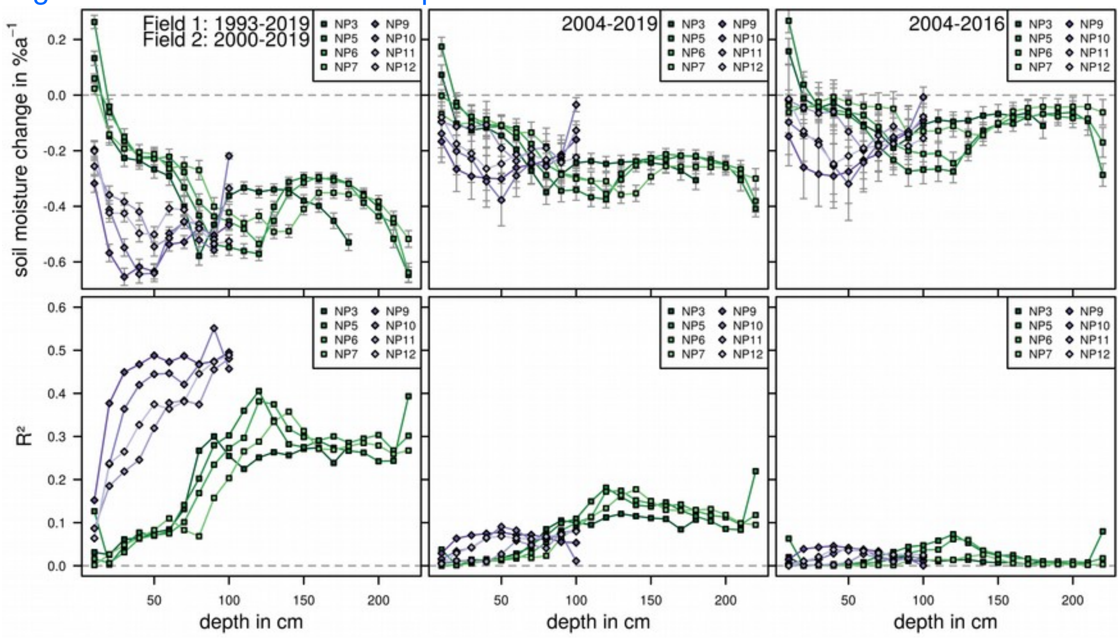
White points are missing data. Due to external circumstances it can sometimes happen that measurements in the field have to be aborted, leaving gaps in the data.

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.

Deep desiccation of soils observed by long-term high-resolution measurements on a large inclined lysimeter

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Abstract. Availability of long-term and high-resolution measurements of soil moisture is crucial when it comes to understanding all sorts of changes to past soil moisture variations and the prediction of future dynamics. This is particularly true in a world struggling against climate change and its impacts on ecology and economy. Feedback mechanisms between soil moisture dynamics and meteorological influences are key factors when it comes to understanding the occurrence of drought events. We used long-term high-resolution measurements of soil moisture on a large inclined lysimeter at a test site near Karlsruhe, Germany. The measurements indicate (i) a seasonal evaporation depth of over two meters. Statistical analysis and linear regressions indicate (ii) a significant decrease in soil moisture levels over the past two decades. This decrease is most pronounced at the start and the end of the vegetation period. Furthermore, Bayesian change point detection revealed (iii), that this decrease is not uniformly distributed over the complete observation period. Largest changes occur at tipping points during years of extreme drought, with significant changes to the subsequent soil moisture levels. This change affects not only the overall trend in soil moisture, but also the seasonal dynamics. A comparison to modeled data showed (iv) that the occurrence of deep desiccation is not merely dependent on the properties of the soil but is spatially heterogeneous. The study highlights the importance of soil moisture measurements for the understanding of ~~soil~~ moisture fluxes in the vadose zone.

1 Introduction

The understanding of soil moisture dynamics and its coupling to climate and climate change is crucial when it comes to predictions of future variability of soil moisture storage and exchange with the atmosphere and vegetation. Long term data sets of measured soil moisture are of critical importance to achieve a better understanding of how these systems interact and to identify the main drivers for seasonal and long term soil moisture variations. Drought and feedback mechanisms between soil moisture and extreme temperatures are documented in the literature (Lanen et al., 2016; Perkins, 2015; Samaniego et al., 2018). Mass and energy fluxes in soils are coupled processes (Zehe et al., 2019). Due to less evaporative cooling during drought periods, temperatures tend to be higher (Hirschi et al., 2011). A review of soil moisture and climate interactions is given in Seneviratne et al. (2010).

Main drivers of soil moisture dynamics are rainfall (wetting) and the vegetation period (radiation driven drying) (Mälicke et al., 2020). Vegetation can influence the soil water budget through an increase in transpiration, hydraulic lift of water from lower soil layers, reduced runoff on steep slopes and reduced soil evaporation due to shading (Liancourt et al., 2012). Other impact factors include soil type, local groundwater availability, inclination angle and direction of exposition (Schnellmann et al., 2010). Feedback mechanisms between soil moisture and groundwater resources with weather phenomena like El Niño are also described in the literature (Kolusu et al., 2019; Solander et al., 2020). The 2015-2016 El Niño event is associated with extreme drought and groundwater storage declines in Southafrica while at the same time in east African countries south of the equator an increase in precipitation and groundwater recharge was recorded (Kolusu et al., 2019). Similarly, Solander et al. (2020) found evidence for both, increase (eastern Africa) and decrease (northern Amazon basin, the maritime regions of southeastern Asia, Indonesia, New Guinea) in soil moisture storage depending on location. An increase in catchment evapotranspiration was observed during the past decades (Duethmann and Blöschl, 2018). As groundwater recharge is dependent on the availability of excess soil moisture, therefore aquifers respond to climatic periodicities (Liesch and Wunsch, 2019).

Traditionally, soil moisture was determined by taking representative soil samples for gravimetric determination, following oven drying. The main disadvantage of this method, despite being very precise, is its destruction of the sampling location and the sample itself. Achievement of long term data sets is challenging using this method. Non destructive measurement methods include cosmic ray neutrons (Rivera Villarreyes et al., 2011; Kędzior and Zawadzki, 2016), installation of TDR sensors (Li et al., 2019), thermal infrared sensors (Yang et al., 2015), resistivity measurements like the OhmMapper (Walker and Houser, 2002), capacitance measurements or neutron probes (Hodnett, 1986; Evett and Steiner, 1995). 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. During this study two calibrated neutron probes were used. Numeric approaches include modeling of depth-dependent soil moisture based on surface measurements (Qin et al., 2018) or modeling of soil moisture for specific locations based on available weather data (Menzel, 1999). Another modeling approach of soil moisture is based on remote sensing data. This has been done on catchment scale (e.g. Pellenq et al., 2003; Penna et al., 2009), regional scales (e.g. Mahmood et al., 2012; Otkin et al., 2016; Long et al., 2019) and the global scale (eg. Dorigo et al., 2017; Albergel et al., 2019) with various calculation grid sizes and temporal resolutions. Analysis of inherent parameter uncertainty in modeled soil moisture and implications for current discussions about soil moisture dynamics should be considered (Samaniego et al., 2012), as well as upscaling of measurements to different temporal and spatial scales (Mälicke et al., 2019).

Lysimeters are also suitable for gaining in-~~-~~depth knowledge about water balance and water movements in soil, which is the main reason the lysimeter in this study is operated. ~~They~~It provides a direct measurement of percolation rates through the soil, which makes ~~them~~ it suitable for monitoring and demonstration of equivalency of the ~~-~~earthen landfill cover~~s~~ (Abichou et al., 2006)~~, which is the main reason the lysimeter in this study is operated.~~ Application of lysimeters, however is not restricted to monitoring of legally acceptable percolation rates, but also allows for studies into water and solute transport in the vadose zone that would not be possible by other means (Singh et al., 2018). Their usage allows for precise determination of evapotranspiration (ET), if soil water storage is accounted for to well below the root zone (Evett et al., 2012)~~.~~ as well as determination of incoming water at the land surface due to precipitation and non-rainfall-events like dew or fog (Groh et al., 2018). Furthermore, they are used for determination of preferential flow (Schoen et al., 1999; Allaire et al., 2009), particle transport (Prédélus et al., 2015) and contaminant transport in the vadose zone Goss et al. (2010).

There are about 2500 lysimeters installed at around 200 sites across Europe, around half of them in Germany (Sołtysiak and Rakoczy, 2019). In the present study, we analyze long term soil moisture time series from ~~a~~two large inclined lysimeters located in southern Germany. Data from the monitoring of this test site has previously been evaluated and published concerning the proper function of the landfill cover (Zischak, 1997; Gerlach, 2007) and ~~in~~ with regard to flow processes on steep hillslopes (Augenstein et al., 2015) using only much shorter parts of the time series available.

However, a time series analysis of all available soil moisture measurements from this test site to gain insight into long term soil moisture variations has not been done previously and is the main focus of this study. The inclusion of previously unpublished data from the more recent soil moisture measurements allows for a more comprehensive analysis of the time series. Using the available data from this test site, it is possible to identify past events that led to significant changes in the long term dynamics of soil moisture. Main research questions are:

- How did the measured soil moisture levels change over the past decades?
- Can these changes be described by simple linear models, or does it require more sophisticated modeling approaches?
- Can exceptional hydro-meteorological events that had a lasting impact on soil moisture levels be identified as tipping points by statistical methods?
- Are there seasonal differences? During which time of the year did the greatest change in soil moisture level occur?
- Which part of the soil is affected the most?

2 Study site

The study site is located in southern Germany (8.337°N, 49.019°E) near the city of Karlsruhe (Fig. 2). The climate in the region is classified as warm temperate, fully humid with warm summers or as Cfb according to the Köppen-Geiger Classification scheme (Beck et al., 2018; Kottek et al., 2006). Mean annual precipitation is 760 mm (1990 – 2007, DWD station 2522, Karlsruhe). Annual precipitation and temperatures are shown in Fig. 1. Exceptionally dry years within the observation period between 1994 and 2019 are 2003 with 566.3 mm and 2018 with 566.7 mm of precipitation. Highest annual precipitation was recorded in 2002 with 981.6 mm, followed by 2013 with 972.4 mm of precipitation. Mean annual temperature was highest in 2018 (12.33 °C) and lowest in 1995 (9.69 °C).

Two large inclined lysimeters are embedded in the municipal landfill site Karlsruhe-West for mandatory monitoring purposes. Cross sections of both lysimters are shown in Fig. 3. The first lysimeter (Field 1) was built in 1993 and started operation at the end of that year. With a width of 10 m and a length of 40 m, it has a size of 400 m². The mean inclination angle is 23.5° (43.5 %) with a southern exposition. The recultivation layer (RL) in this field has a thickness of 100 cm, it is underlain by a drainage layer (DL) with a thickness of 15 cm followed by a mineral clay liner (MCL) and capillary barrier.

The second lysimeter (Field 2, pictured in Fig. 4) was built in 2000, with first measurements being taken in December of that year. It consists of two separate fields with a size of 10 m by 20 m each, resulting in a total size of 400 m². The mean inclination

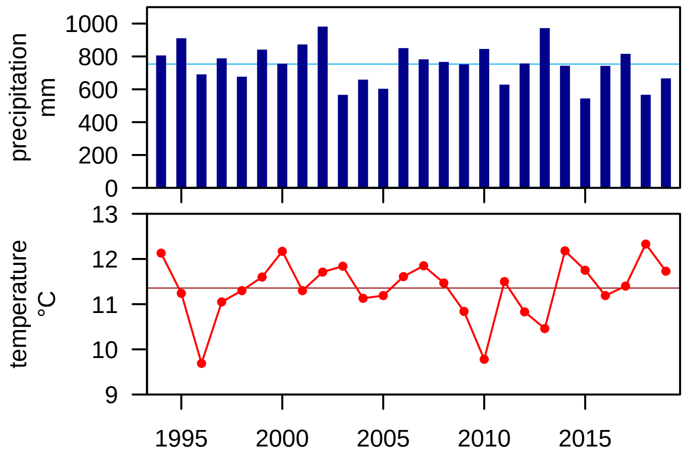

Figure 1. Precipitation and Temperature at stations 2522 (Jan 1994 – Oct 2008) and 4177 (Nov 2008 – Dec 2019) (DWD Climate Data Center (CDC), 2020)

angle is 23.5° (43.5 %) with southern exposition. Results from Field 1 showed, that a thicker RL is necessary in order to protect the MCL from drying out. This insight was considered during the construction of Field 2. The RL in Field 2A has a thickness of 200 cm, in Field 2B it has a thickness of 215 cm. It is underlain by a drainage layer (DL) with a thickness of 15 cm followed by a mineral clay liner and capillary barrier. Depth across the inclined field varies. Additionally, the mineral clay liner is not present in the lower half of Field 2B, reducing the final depth of the lysimeter by 50 cm, affecting measurements taken at NP5 and NP6 below the RL. The RL was constructed by adding layers of soil on top of the compacted surface of the previous layer. Use of different materials in the soil layers can not be ruled out. Further details on the construction of both fields is given in Augenstein et al. (2015). The soil properties of the RL relevant to this study have been modeled by Gerlach (2007) using HELP (Berger, 2015). For the year 2002, the porosity of the RL is 0.4, usable field capacity 0.25 and the wilting point at 0.14. The permeability was estimated as $k_f = 1.0 \cdot 10^{-6}$. Values were observed to be variable over time.

Both fields are covered by grass and weeds, depending on the current season. The growth of deeply rooted plants that would damage the sealing system is prevented and the grass is cut regularly on the complete landfill cover including both lysimeters. In recent years, sheep have been used to limit the growth of vegetation in a more natural way. Further records on the vegetation cover and plant maintenance are not available.

3 Material and Methods

3.1 Soil moisture measurements

Soil moisture measurements were carried out using two different neutron probes. A modified Wallingford IH2 neutron probe was used until 23 August 2012. From 30 November 2012 onward, a modified Troxler 4300 Depth Moisture Gauge was used.

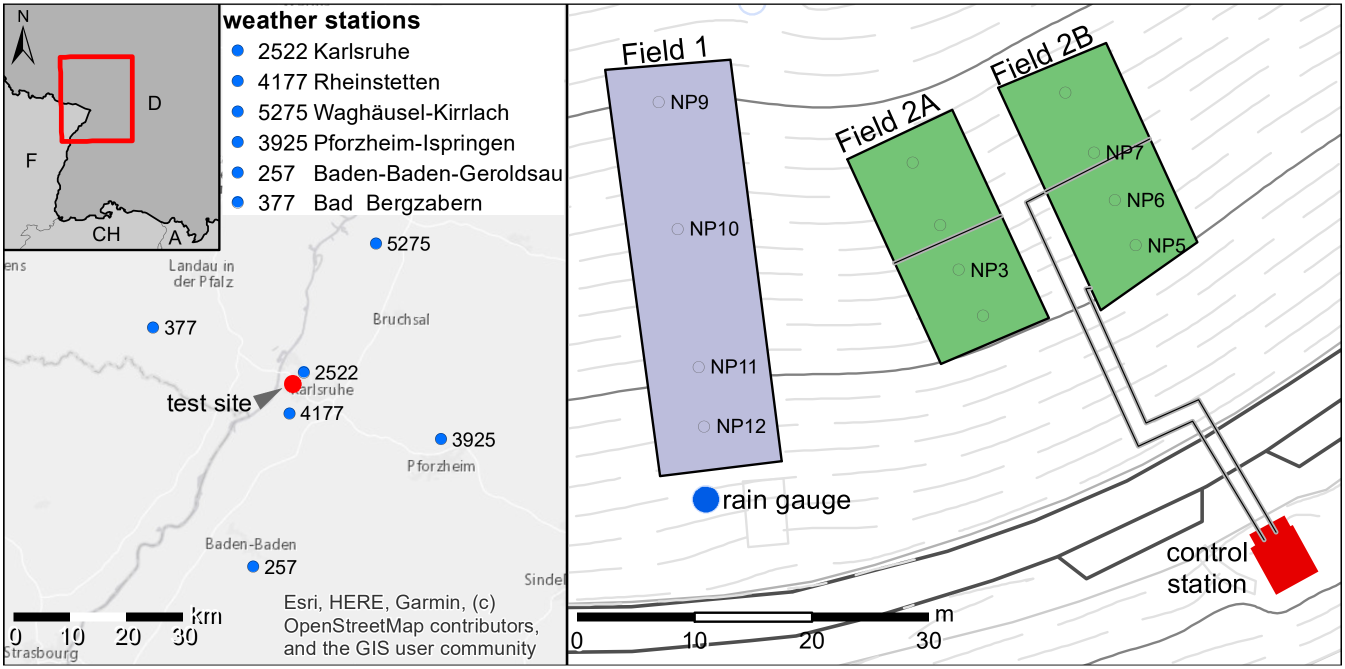

Figure 2. Location of the study site on a municipal landfill site in Karlsruhe, Germany, and locations of the weather stations used in this study. Lysimeter 2 consists of two separate fields (Field 2A, Field 2B).

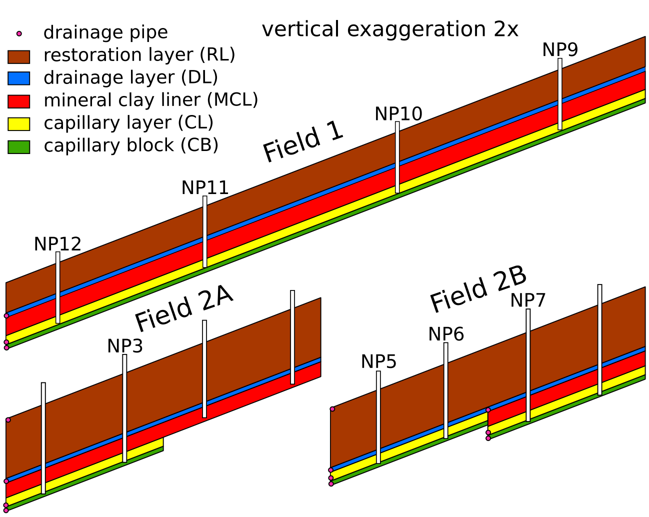

Figure 3. Cross sections of lysimeter Field 1 and Field 2 with the different layers and moisture measurement points.

Figure 4. Lysimeter Field 2 (visible in the upper part of the image between vertical beams)

Both models used an Am/Be source with activities of 1.85 GBq and 370 MBq respectively (Augenstein et al., 2015). They were modified to fit into the installed measurement tubes. Selected measurement points are shown in Fig. 2. Neutron probe measurement points (NP) are constructed from steel tubes (∅ 40.5 mm) installed vertically in the soil column. At neutron probe measurement point 9 through 12 (NP9, NP10, NP11, NP12) located in lysimeter Field 1, measurements were carried out on a weekly basis until Field 2 was constructed (December 2000). After construction of Field 2, measurements were taken monthly in Field 1. At the same time, weekly measurements in Field 2 at neutron probe measurement points NP3, NP5, NP6 and NP7 started. Measurements were taken in depth increments of 10 cm until the bottom of the lysimeter is reached (~~bottom~~final depth - Field 1: between 2.1 m –and 2.3 m; ~~bottom~~final depth - Field 2: between- 2.8 m – and 3.4 m). No measurements were taken at the remaining four points in Field 2. During the period of January 2014 to June 2014, no measurements were taken at neither of the two fields due to ongoing construction of new accessibility stairs for Field 2.

3.2 Additional data

Additional data used for this study include daily precipitation and modeled values of usable field capacity (uFC). Daily precipitation data at a station near Karlsruhe is published by the German weather service (DWD) (DWD Climate Data Center (CDC), 2020). Data for this station (Station ID: 2522) is available for the time range until October 2008. Another station, still in operation by the DWD, is located in Rheinstetten (Station ID: 4177), approximately five km south of the test site, providing data from November 2008 onward. Locations of both weather stations are shown in Fig 2.

The DWD also publishes derived model results for usable field capacity (uFC) (DWD Climate Data Center, 2020) that can be used for comparison of measured soil moisture time series. They are provided for two different soil types and as depth resolved values for the top 60 cm of the soil column. They are computed by the agrometeorological model AMBAV. For this study the depth resolved values for soil moisture under grass with sandy loam (wilting point 0.13, field capacity 0.37) were used. Additionally, soil moisture under grass and loamy sand (wilting point of 0.03, field capacity 0.17) up to 60 cm depth was used. A defined constant water content is used as boundary condition at the bottom of the model. Further model input parameters are hourly values of temperature, dew point, wind speed, precipitation, global radiation and reflected long-wave

Table 1. Location of weather stations, and distances to the test site and time range of data availability.

Station name	Station ID	Elevation	Latitude	Longitude	Distance
Karlsruhe	2522	112 m a.s.l.	49.0382°	8.3641°	2.9 km
Rheinstetten	4177	116 m a.s.l.	48.9726°	8.3301°	5.2 km
Bad Bergzabern	377	210 m a.s.l.	49.1070°	7.9967°	26.7 km
Pforzheim-Ispringen	3925	333 m a.s.l.	48.9329°	8.6973°	28.1 km
Waghäusel-Kirrlach	5275	105 m a.s.l.	49.2445°	8.5374°	29.0 km
Baden-Baden-Geroldsau	257	240 m a.s.l.	48.7270°	8.2457°	33.2 km

radiation. Data was used from five stations (Tab. 1: 4177, 377, 3925, 5275, 257, Fig. 2) and covers a time range from 1 January 1991 until 31 December 2019. Values at station 3925 are available from 2005 onwards. Measured soil moisture data is not directly comparable to uFC, because of a different scale being used. The uFC of 100 % is defined as the soil moisture content that can not be drained by gravity. Nonetheless, both measured soil moisture and usable field capacity have similar temporal distribution patterns.

3.3 Theory and calculations

Volumetric water content (θ) and uFC are expressed as %. Data analysis and visualization was done in the R system for statistical computing R Core Team (2020).

Time series were transformed into a radial coordinate system, to highlight the asymmetry of the seasonal cycle between gradual drying and fast re-wetting of the soil. New x- and y-coordinates for each measurement were calculated according to Eq. 1 and Eq. 2.

$$x = \cos\left(2 \cdot \pi \cdot \frac{d_{year}}{d/a}\right) \cdot \theta \tag{1}$$

$$y = \sin\left(2 \cdot \pi \cdot \frac{d_{year}}{d/a}\right) \cdot \theta \tag{2}$$

In these two equations, x and y are the new coordinates in a radially transformed coordinate system, θ is the volumetric water content in %. d_{year} is the day of the year. It is divided by the average length of one the respective year (d/a) in order for 2π to equal one year.

Mean soil moisture of the recultivation layer in Field 2 was calculated as average of NP3 at depths between 10 cm and 180 cm and at NP5, NP6 and NP7 at depths between 10 cm and 220 cm.

For each individual depth, a linear regression was calculated using all measurements for the years 2000 to 2019 (see 3.1). Calculations were done using the `lm()`-function in the R system for statistical computing (R Core Team, 2020). As linear regression can be dependent on the selected start and end times, additional regressions were calculated over the complete

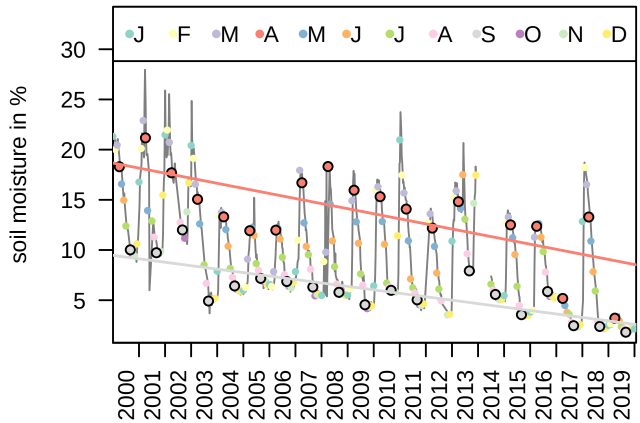

Figure 5. Example for the calculation of monthly linear regressions for April and September at NP 3 and at a depth of 170 cm.

available time span, based on time series cut off before 2004 and between 2004 and 2016. The resulting slope of these regression lines represent the mean change of soil moisture in $\%d^{-1}$. A conversion into $\%a^{-1}$ was calculated by using the average length of 365.2425 da^{-1}, according to the Gregorian calendar.

To overcome the limitations of linear regressions when used on data with large seasonal variation compared to a small overall trend, another set of linear trends was calculated based on monthly averages. The monthly values were calculated as averages based on the measured values within each month and depth. No weights were assigned to individual measurements. The time series for all depths were each subdivided into twelve time series, one for each month. For example, application of this subdivision on the time series at a depth of ~~10~~170 cm at NP3~~5~~ results in twelve time series (Fig. 5). Linear regressions were then calculated separately, based on all mean values for each month, giving the average slope for each measurement point, depth and month. An example for these calculations is shown in Fig. 5 for the months of April and September at NP3 and at a depth of 170 cm.

Measurements at Field 1 were taken weekly at the start of the time series, but the interval changed to monthly measurements later. Therefore, use of all values for regression would lead to an over emphasis of the early part of the time series, due to the higher number of samples during that time span. To avoid this bias and over emphasis, monthly averages were used. The regressions yielded individual values for the change in soil moisture by month and depth. Additionally, further information about the regressions were extracted from the results. These include standard deviations and p values for the slopes. The analysis was done with the time series of uFC in a similar fashion.

Time series analysis are sensitive to the selection of a suitable model. To overcome the paradigm of the single-best model approach in time series decomposition, Zhao et al. (2019b) implemented a Bayesian model averaging scheme to approximate complex relationships by the use of Markov Chain Monte Carlo stochastic sampling. The model space is explored by randomly traversing through combinations of coefficients. The number and location of individual changepoints in seasonality and trend are randomly sampled and all candidate models averaged based on how probable each of them is. Results of the model not only include best estimates for model parameters (e.g. location of changepoints), but also their probability distributions. Bayesian change point detection and time series decomposition was done using the `beast()`-function from the Rbeast package (Zhao et al., 2019a). This divides the time series into seasonal and trend components, along with change points in both. The period was set to 12 for monthly time series decomposition. The same monthly averaged time series were used as with the previous monthly linear regressions.

4 Results and Discussion

~~All m~~Measured soil moisture values in the RL at NP5 and NP10 are presented in Fig. 6 at the corresponding position on the respective soil moisture profiles and before monthly averages were calculated. There is a gap in measurements during the first half of 2014. Field 2 was built in 1999 and no data is available prior to the year 2000. In total, over 140 000 individual soil moisture measurements are shown. Due to grain size and soil properties, the mineral clay liner has a higher moisture content (> 25 %). It is overlain by the gravel drainage layer, which has a very low moisture content. For evaluation, only soil moisture content of the RL is used in this study (n = 91198)~~.~~, because it is thought to reflect best the processes and moisture dynamics found in natural soils.

From this figure, a seasonal pattern is clearly visible. Soil moisture increases relatively quickly in late autumn or winter, especially in the upper parts of the soil. After reaching a critical soil moisture level, discharge from these layers starts more or less instantaneous. This wetting period is followed by a more gradual drying period, starting in late spring and lasting until the consecutive wetting period. The years before 2003 appear to have higher soil moisture content and shorter drying seasons, especially at, but not restricted to, Field 2. This can be seen for example at NP3 in Field 2 where blue colors, indicating soil moisture of over 30 %, alternate with green colors (15 %) before 2003. After 2003, green colors alternate with yellow colors, indicating soil moisture below 10 %. In recent years, the re-wetting of the soil during the winter month repeatedly did not reach the lower parts of the soil, especially in Field 2. For example at NP3 in depths between 100 cm and 200 cm yellow colors indicate soil moisture levels below 5 % for the complete years 2017 and 2019. Measured discharge during these years was significantly lower compared to the prior years. Despite above average precipitation during the second half of 2017, re-wetting was only observed much later in early 2018. ~~Surprisingly, re-wetting took place in 2018, a year that is otherwise known to having been a very dry year.~~Precipitation in 2018 was well below average, again drying out the lower soil and no re-wetting occurring in the winter months.

Soil moisture in Field 1 is higher at the upper slope (NP9) compared to the lower slope (NP12), especially at the start of the measurement series. As with Field 2, soil moisture levels are lower after 2003. Because the RL is not as thick in Field 1 (100 cm) compared to Field 2 (~215 cm), ~~the missing occurrence of~~ re-wetting in the lower soil in depths below 100 cm is not observable~~ cannot be observed in recent years~~. However, in years with missing re-wetting (e.g. 2017, 2019), of lower soil in Field 2, a similar gap can be observed in Field 1 below the MCL (~200 cm). In data from Field 2, depth-dependence of soil moisture is clearly evident. Higher soil moisture at depths of around 100 cm sharply decreases over the next 20 cm~~ or so~~ and downward propagation of the moisture front is also delayed. This effect is caused by differences in soil compaction during construction of the lysimeter and possibly the use of different soil materials. The volume of the lysimeter was filled in several layers and soil consolidated in between each. Porosity and hydraulic conductivity is therefore not uniformly distributed over the complete depth of the lysimeter. Greatest differences are found at the interfaces of two consecutive stages of construction between strongly consolidated top of the underlying layer and the less densely packed bottom of the overlying layer. Settling down of the soil cover in the years after construction may additionally change soil properties over time.

Values of modeled uFC are also shown in Fig. 6 for DWD station 4177 under grass and loamy sand. ~~As with the measured soil moisture, propagation of high uFC with depth is almost instantaneous, followed by a more gradual drying period. This drying period appears to be more gradual in the modeled data and does not reach the bottom of the bottom of the model. It has to be noted that the final depth of the modeled data is much less than that of the measurements and the soil used for modeling is different to the one in the lysimeters. Looking at the model data only, it could be concluded that the final modeling depth is sufficiently large, as the annual cycle is only minimal at depth of 60 cm. However, measurements indicate evaporation depth of over 200 cm.~~

~~The period before 2001 in the uFC data at stations 5275 and 257 appears to have higher values compared to later years. This confirms that the soil moisture contents being lower after 2003 is not a measurement artifact.~~ 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 prevent erosion and to lower overall percolation by increasing evapotranspiration. The system is designed with a vegetation cover as an integral part to it's proper functioning. However, Field 1, which has been constructed several years prior to Field 2, shows a similar change at the same time. A similar change is likewise visible in the modeled data. It is still possible that vegetation and evapotranspiration both drive this changes, but then it has to be connected through the meteorologic parameters used in the model (e.g. longer vegetation periods).

4.1 Asymmetry of drying and re-wetting

To highlight the asymmetry of the seasonal cycle between gradual drying and fast re-wetting of the soil, two exemplary time series are shown in a polar coordinate system (Fig. 7). For comparison, the soil moisture time series of NP3 at a depth of 170 cm and a mean time series from all sampling points at Field 2 ~~-~~are shown. The overall trend of both time series is quite similar, however the asymmetry is much more pronounced in ~~individual depth time series~~ the time series of NP3 at 170 cm. The mean of all soil moisture time series in Field 2 was calculated over the complete depth of the recultivation layer (RL). Due to the time lag between two time series measured at different depths as a result of gradual downward propagation of the moisture front, the asymmetry of the seasonal cycle is evened out by calculation of the mean soil moisture over multiple depths and measurement points.

In the two time series shown in polar coordinates, the graph based on mean values describes a circle for each year of observation. In the ~~individual time series~~ time series of NP3 at 170 cm on the other hand, the graph describes spirals resembling nautiluses for each year of observation. The decreasing radius over time, apparent from both time series, indicates a decrease in soil moisture. White areas between lines indicate large and sudden changes in soil moisture levels during especially dry

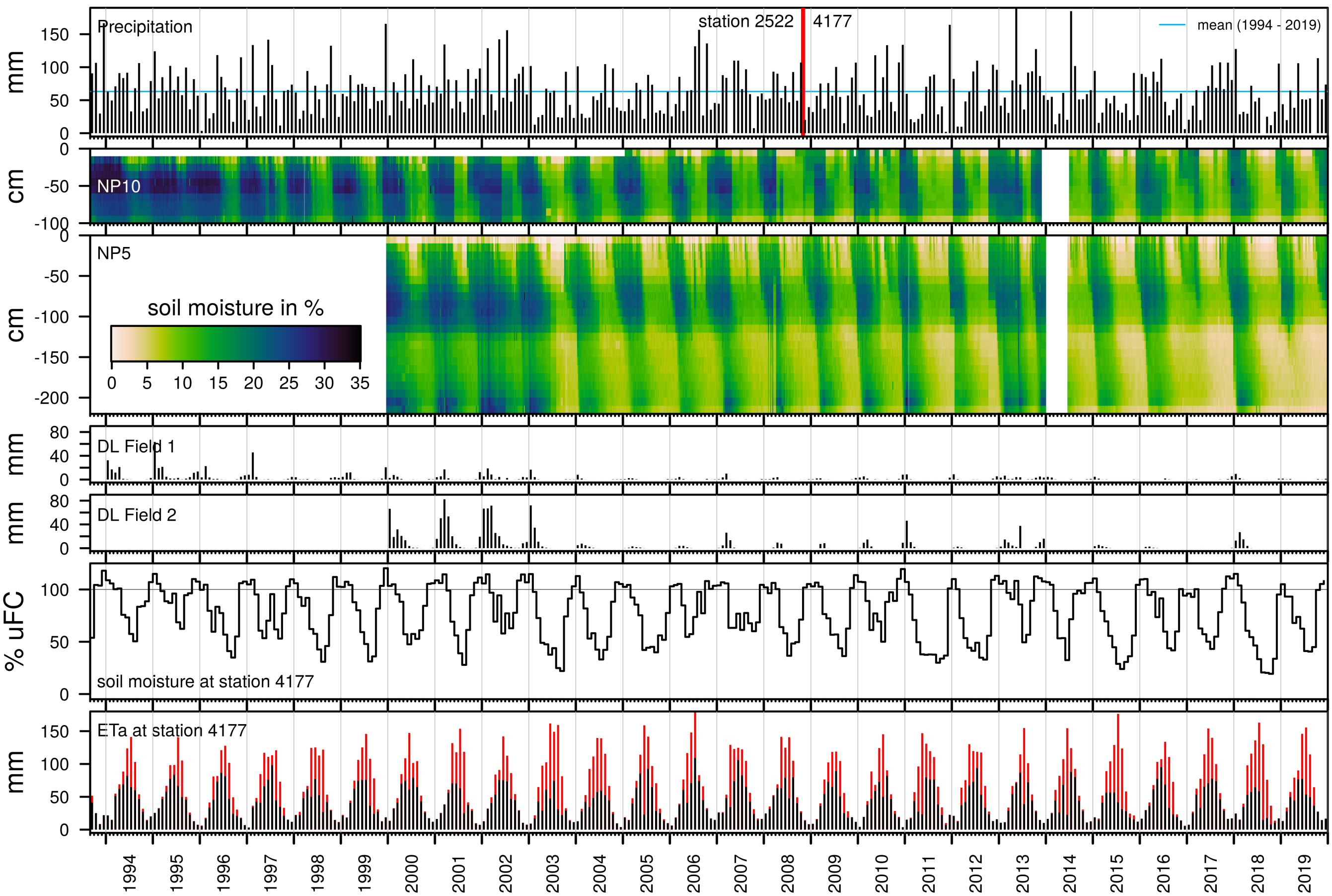

Figure 6. Precipitation at stations 2522 (Jan 1994 – Oct 2008) and 4177 (Nov 2008 – Dec 2019) (DWD Climate Data Center (CDC), 2020). Time series of selected soil moisture measurements (NP5, NP10) at the test site near Karlsruhe, Germany. Discharge of the drainage layer (DL) at both lysimeters.~~ and m~~Monthly averages of usable field capacity (loamy sand), potential evapotranspiration (red) and real evapotranspiration (black) (DWD Climate Data Center, 2020) at station 4177~~five selected weather stations~~. Measurements on Field 2 are available from 2000 onward. No measurements were taken during the first half of the year 2014.

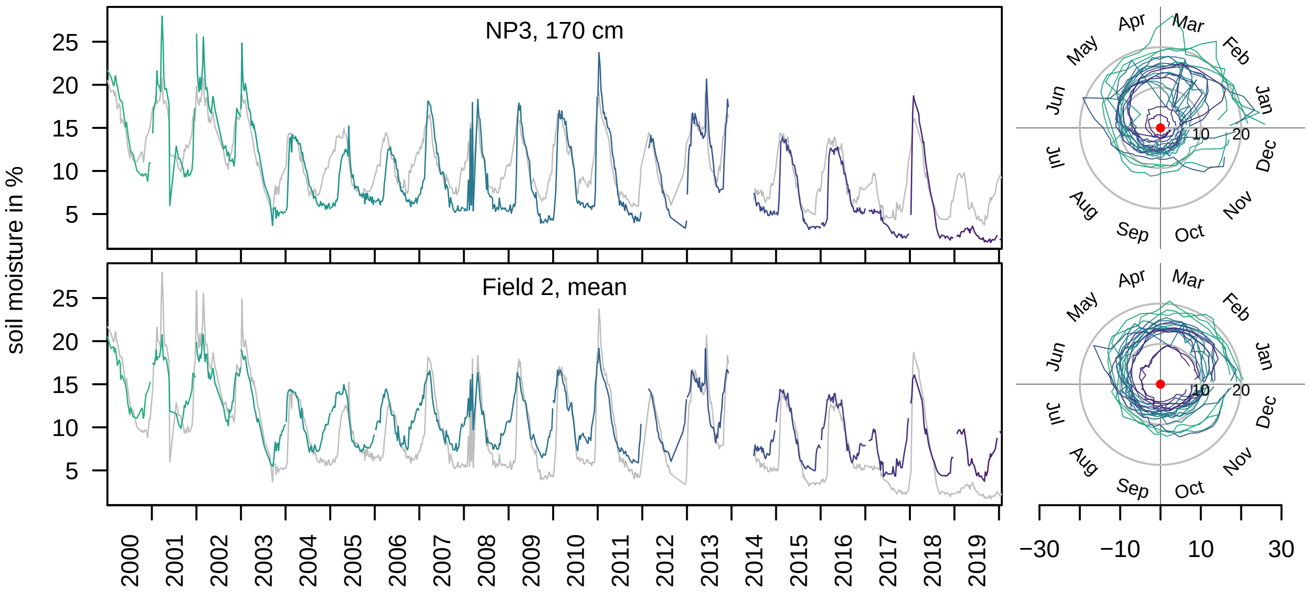

Figure 7. Time series of soil moisture at NP3 at 170 cm and mean soil moisture of Field 2 as well as the same data in a polar coordinate system to highlight seasonal asymmetry of gradual drying and fast re-wetting as well as the overall trend of declining soil moisture.

years. The opening of the nautilus corresponds to a rapid increase in soil moisture during winter. Depending on precipitation conditions, this increase may occur at the end of the year or the beginning of the consecutive year.

4.2 Overall linear regressions

In Fig 8, results of individual linear regressions of soil moisture measurements are shown for each depth and measurement point. Over the period between 2000 and 2019, ~~a mean decrease in~~ soil moisture decreases by ~~of~~ $0.34 \pm 0.14\ \% a^{-1}$ within the RL ~~could be observed~~. The observed decrease is lowest in the first 20 cm of the soil column at both lysimeter fields. At the depth of 10 cm there is even a small increase observable in Field 2.

Overall, the decrease in soil moisture is most pronounced at depths of 20 cm to 40 cm in Field 1 (NP9, NP10). Due to the thicker RL compared to Field 1, highest absolute decrease is found at a greater depth of around 100 cm in Field 2. Below 130 cm at Field 2, absolute rate of soil moisture change is slightly lower. Seasonal variations of soil moisture patterns larger than the overall trend lead to a relatively low coefficients of determination (0.20 ± 0.10). However, with exception of two points (NP5 20 cm, NP7 10 cm), all slopes of calculated regression lines are significant ($p < 0.05$, $n = 122$). Coefficients of determination are lowest at the top and increase until a depth of around 100 cm. ~~This is due to the influence of singular precipitation events being larger at the surface.~~ Precipitation events lead to short term variations in soil moisture. These variations are larger at the surface. Downward movement of the water in the soil column is being dampened with depth. At some depths, soil moisture patterns are more persistent. This might be due to different materials being used or differences in compaction during construction of the lysimeters and landfill cover. Differing soil properties like porosity, hydraulic conductivity and capillary forces determine the water retention capacity of the soil.

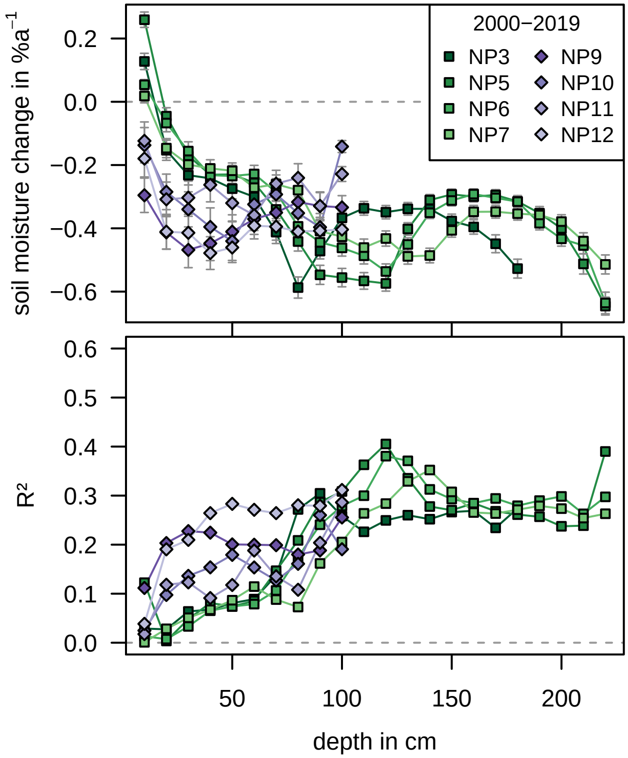

Figure 8. Results of individual linear regressions for soil moisture measurements in the recultivation layer, expressed as change in soil moisture content $\left[\%a^{-1}\right]$.

4.3 Monthly linear regressions

The results of linear regressions based on the monthly averages is shown in Fig. 9. Resulting slopes with p > 0.05 ~~are shown and an indication given by a marker~~are indicated by a marker.

A statistically significant increase in soil moisture can be observed in the top 10 cm of Field 2 (NP3, NP5, NP6, NP7) during the winter months only. Most other values show a significant decrease in soil moisture. The moisture change in the top 60 cm of the soil does show an increase during summer, but this increase is not statistically significant. The lack of statistical significance might be due to the shorter length of the time series at Field 2 compared to Field 1. As previously mentioned, overall soil moisture levels were higher before 2003. Inclusion of additional data before this point, as is the case with Field 1, would ~~bias~~push the resulting decrease in soil moisture towards higher absolute values. From depths of around 70 cm to 130 cm (70 cm to 90 cm at NP3), decrease in soil moisture has a semiannual distribution. Highest reductions in soil moisture occurred during November and December as well as during April and May. Below this, decrease in soil moisture is generally lower and

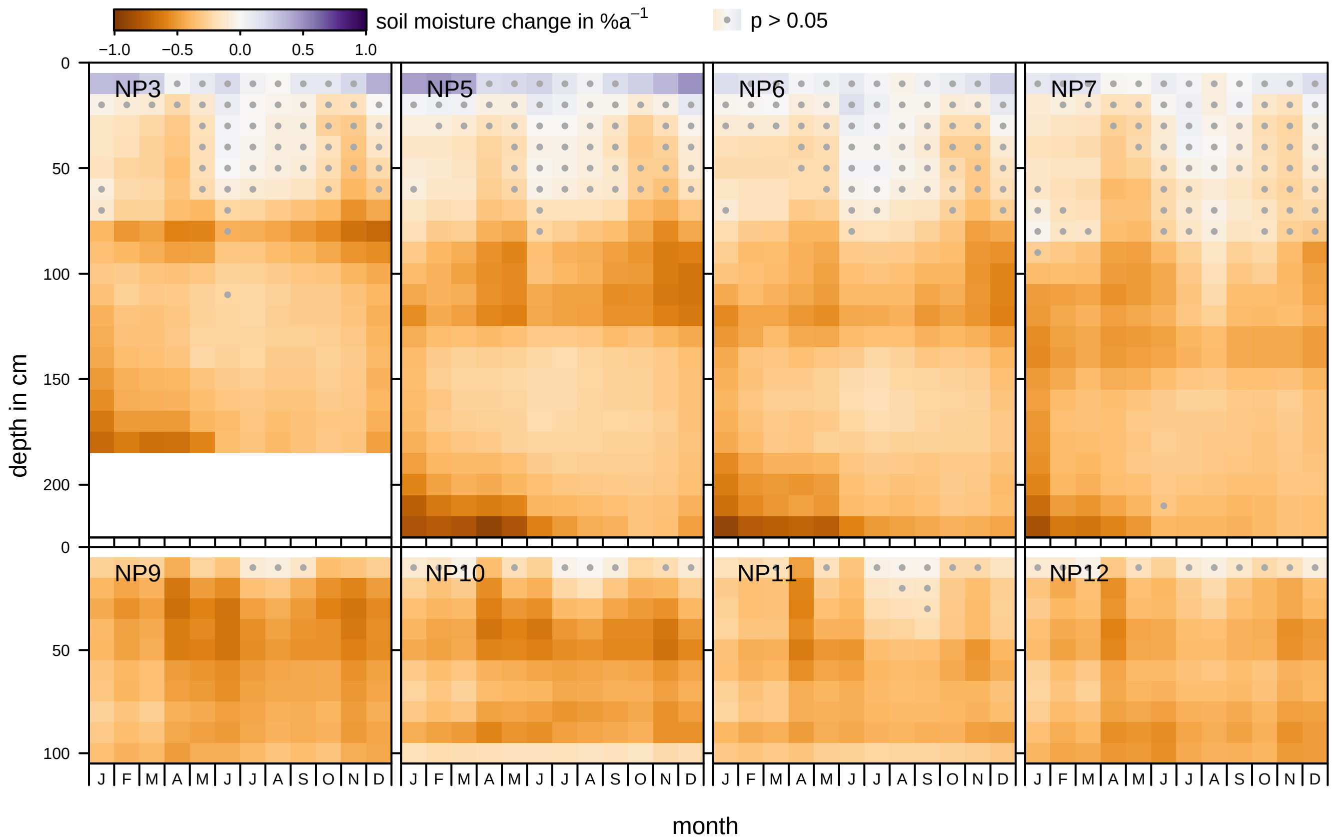

Figure 9. Results of individual linear regressions for soil moisture measurements in the recultivation layer, expressed as change in soil moisture content $\left[\%a^{-1}\right]$ calculated over the complete time series for each month based on monthly averages. Values for $p > 0.05$ are indicated by a marker.

does show a weak annual cycle with highest values in December and January and minima during June and July. Highest values are shown in the lowermost 30 cm of the RL directly above the DL between January and May.

In Field 1, a decrease in soil moisture can be observed at all depths. The semiannual distribution of soil moisture change is similar to that of Field 2. It is most pronounced during spring and autumn and less pronounced during winter and summer.

The winter months are usually times of largest groundwater recharge and highest soil moisture in the lower soil. In recent years however, less water percolated through the upper parts of the soil at both lysimeter fields, affecting especially the soil moisture levels in the lower soil. This drying effect is amplified by the DL. It drains excess water and inhibits capillary rise. This means the depth of evaporation in the lysimeter is greater than two meters and includes the complete RL.

Results of linear regressions based on monthly averages of uFC are shown in Fig. 10. Most values indicate a decrease of soil moisture, but at the same time, most linear regressions are not statistically significant ($p > 0.05$). However, results for station 5275 indicate a clear and significant decrease in soil moisture during most of the year. The decrease in the lower soil layers appears to happen later in the year. Compared to Fig. 9, the semiannual pattern is not as visible, but some month (August at station 4177, 377, 5275, 257) do show lower annual changes or even an increase in uFC (January at station 3925).

Compared to largest decrease in measured soil moisture at the beginning of the vegetation period in April and at the end of the vegetation period in November, the decline of uFC at the end of the vegetation period appears to happen much earlier (~~2935~~3925, 5275).

~~Again, results of modeled uFC suggest that the model depth is sufficiently large, having lowest trends at the final depth of 60 cm. For measured data however, absolute values of soil moisture change increases even beyond this depth, making real world measurements indispensable in interpreting these model results.~~

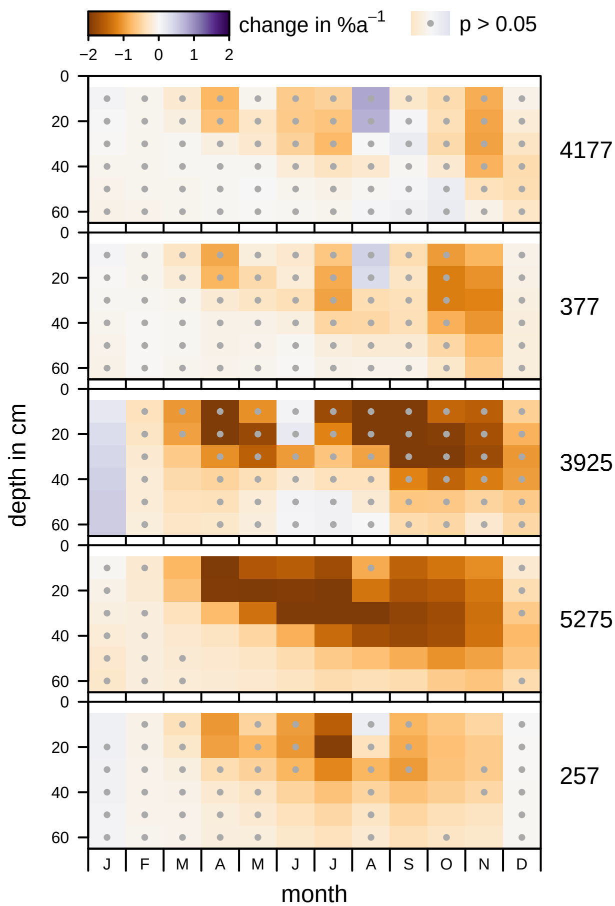

Figure 10. Results of individual linear regressions for usable field capacity (uFC) for the top 60 cm (at stations 4177, 377, 3925, 5275, 257), expressed as change in usable field capacity $\left[\%a^{-1}\right]$ calculated over the complete time series for each month based on monthly averages. Statistically non-significant values (p > 0.05) are indicated by a marker.

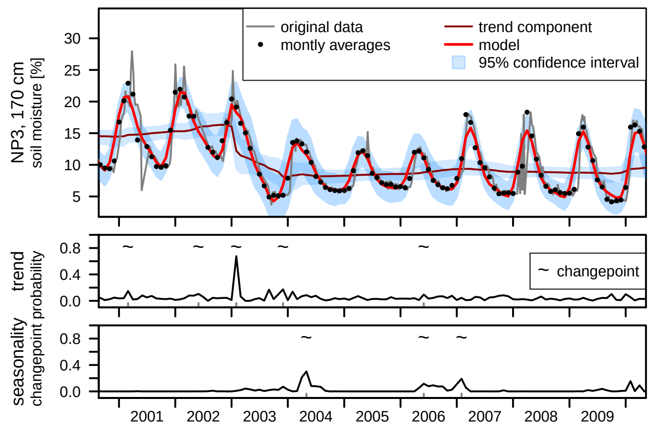

Figure 11. Results of time series decomposition for NP3 at a depth of 170 cm. Changepoints and their respective probability distributions are shown also.

4.4 Time series decomposition

During modeling with Rbeast, the time series are decomposed into a trend component and a seasonal component, along with change points in both, seasonality and trend. Individual calculations are done for each depth increment at all measurement points. An example for NP3 at a depth of 170 cm is given in Fig. 11. The trend component shows a positive slope before 2003. A changepoint in trend with a probability of 68% was discovered in February of 2003. After another changepoint with a lower probability in December 2003 (17%) the soil moisture trend stabilized at a lower level after a significant decrease in soil moisture levels between February and December. Changes in seasonality were detected in 2004 and 2006/2007. In between these, the amplitude of the seasonal variations was lower.

In Fig. 12 the main results of this model are shown for a measurement point in Field 1 (NP5) and Field 2 (NP10). This kind of decomposition allows for easier visual analysis of the underlying trend component (Fig. 12a). Probabilities of change point occurrence indicate times of significant changes in trend and seasonality. Overall, higher soil moisture contents are apparent before 2003 and during a shorter time period in 2013/2014. In the past few years, soil moisture is noticeably lower, especially in depths below 100 cm.

The decomposed time series of NP10 in Field 1 (NP9 - NP12 in Supplement A5) reveal higher initial soil moisture contents, followed by a gradual decrease over time. The decrease is most pronounced at the beginning of the measurement series, until around 1998 a more or less stable level of soil moisture is reached. The amplitude of seasonality at the top of the slope (NP9 and NP10) during this time of high initial soil moisture is lower. This is probably due to the maximum saturation of the soil being reached, leading to an increase in discharge from the soil instead of further increase in soil moisture content and storage. In 2003, a change point in trend is visible. Modeling resulted in high probabilities for this change point. In the following years, the soil moisture is at a lower level. Apart from the elevated soil moisture before 2003, higher soil moisture is also evident in 2013. The distribution of probabilities for a change point in trend does not show a clear cut during this event. Probabilities are

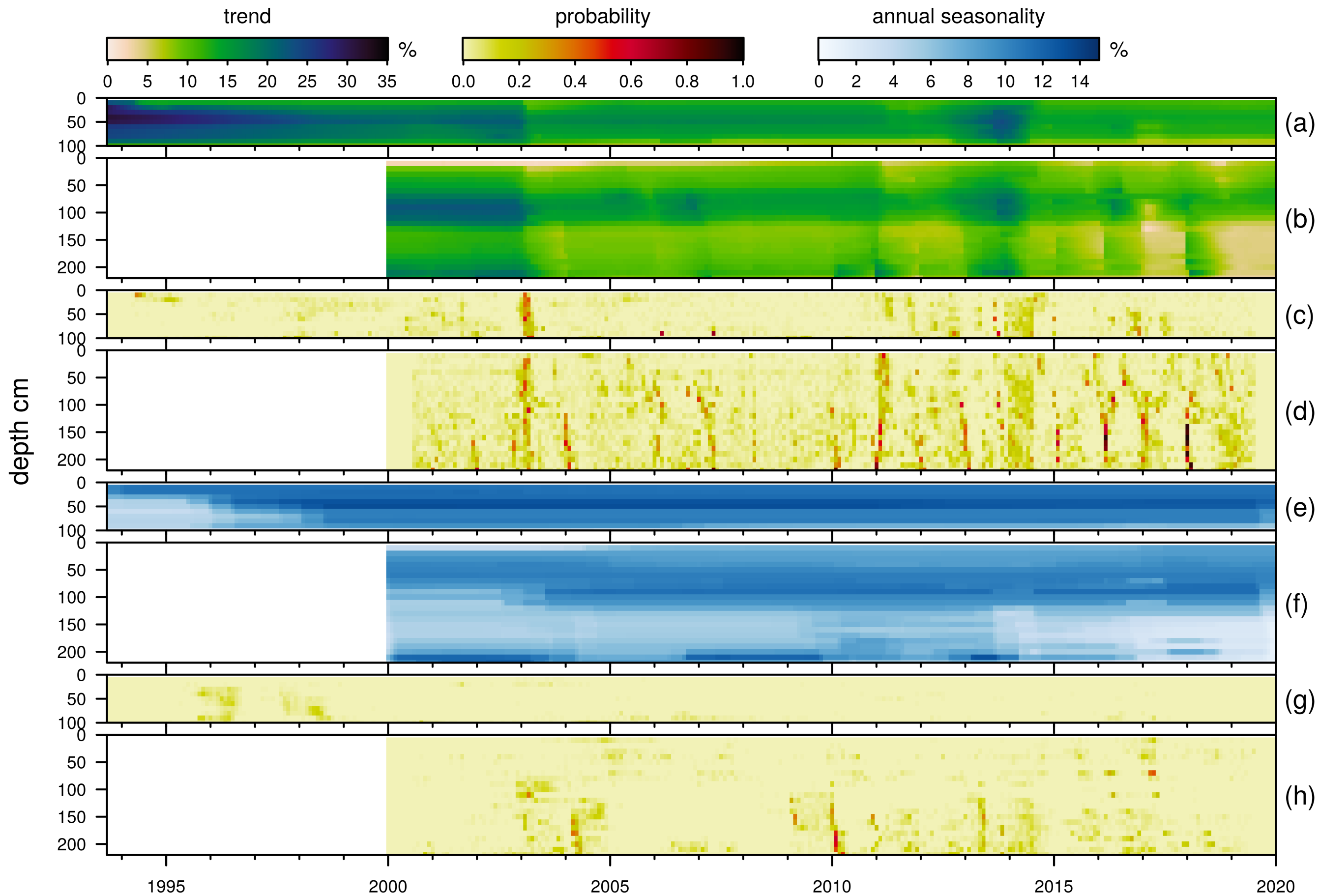

Figure 12. Results of modeling soil moisture at NP5 and NP10 with Rbeast. (a) Trend component of soil moisture time series at NP10 in Field 1. (b) Trend component of soil moisture time series at NP5 in Field 2. (c) Probability of change point in trend component at NP10 in Field 1. (d) Probability of change point in trend component at NP5 in Field 2. (e) Amplitude of annual seasonality derived from seasonal component at NP10 in Field 1. (f) Amplitude of annual seasonality derived from seasonal component at NP5 in Field 2. (g) Probability of change point in seasonality component at NP10 in Field 1. (h) Probability of change point in seasonality component at NP5 in Field 2.

elevated over a wider range of time. The amplitude of soil moisture seasonality is more or less stable for the remainder of the time series and does not show high probabilities.

Measurements at Field 2 (NP 3, NP5, NP6, NP7) have started later compared to Field 1. They also show higher initial soil moisture contents. As previously mentioned, depth dependence of soil moisture due to lysimeter construction is also visible in the deconstructed time series. No apparent trend is observable until the year 2003. A change point in trend and the corresponding probabilities is then visible around the same time as in Field 1. In the following year (2004) a change point in seasonality with elevated probabilities in the lower half of the RL at Field 2 occurred. Slightly elevated probabilities for this change point were already calculated for the year 2003 itself. In general, amplitudes of seasonal variations are higher towards the top of the RL. After the 2003 change point, higher amplitudes of seasonal variation are found lower in the RL than before (NP3, NP5, NP6). At NP7 (Supplement A5), the amplitude of seasonal variations ~~in~~ at a depth of 80 cm increased after this point, but amplitudes in the soil below are significantly lower.

Another visible change point in trend with elevated probabilities is visible at the end of 2011. This change point cannot be seen in Field 1. After 2015, change points with elevated probabilities appear to occur almost every year. At the same time, reduction of soil moisture to a low level not observed previously occurs, mainly in the lower half of the RL. Because of a thinner RL, this effect cannot be observed in Field 1. In recent years from 2015 onward, amplitude of seasonal variation in the lower half of the RL is greatly reduced, because dry soil without the reoccurring annual re-wetting does not show significant seasonality.

Interruption of capillary rise due to lysimeter construction inhibits re-wetting of the lower soil from groundwater. Thus, results of this study might not be applicable to soils with a shallow depth to the groundwater surface or modeled values of usable field capacity. ~~The same holds true~~Boundary conditions are different ~~-~~for the modeled usable field capacities analyzed in this study. ~~Because t~~They are ~~solely~~ calculated from weather data and standardized soil properties~~,~~. ~~they also neglect the possibility of a~~An additional source of soil moisture is provided by capillary rise due to a constant moisture boundary condition at the bottom of the model. The fact that some stations did show the same patterns as measured soil moisture, while other stations with same soil properties did not, could mean, that there are feedback mechanisms between soil moisture and the input parameters of the uFC model. Future studies should concentrate on these interconnections between soil moisture, groundwater recharge and groundwater level to determine if they amplify or dampen the temporal dynamics of soil moisture.

One possible explanation for the rapid change in soil moisture levels could be a change in soil properties (water retention, preferential flow paths, hydraulic conductivity, soil structure, etc.) as a result of singular extreme events like the exceptionally dry year 2003. There are ~~clearly~~ hysteresis effects during drying and re-wetting of the soil (Augenstein et al., 2015). Hydraulic conductivity in the vadose zone is dependent on the moisture content. This feedback mechanism might amplify or dampen the hysteresis, depending on the proportions of bound soil moisture in different states (available pore water, pore water in enclosed cavities). Furthermore, extreme drying of the soil might lead to non-reversible desiccation of clay minerals or formation drying cracks as preferential flow paths, both leading to significant changes regarding the overall hydraulic functioning of the whole system. However, though these likely phenomena may occur, changes in soil water dynamics are also visible from the modeled uFC. These are not based on physical measurements which are dependent on time-constant soil properties, but rather use time constant properties of a model soil. The fact that these modeled values also show changes in their temporal soil moisture patterns gives ample evidence that the change points found are not merely a function of soil properties but of the local climate as well, which the modeled values are solely based on.

Robinson et al. (2016) found evidence for the existence of drought induced alternative stable soil moisture states. They observed a step change that occurred at the beginning of 2004 with an apparent transition to a new stable state in which soil moisture levels never reached saturation again. They found water retention characteristics to change due to a loss of organic material by increased organic matter mineralization under moderate drought conditions. According to their findings, the bottom boundary behavior was modified from a seepage face behavior before 2004, to free drainage after. For arid regions, strong positive feedback between vegetation and soil moisture has been described by D'Odorico et al. (2007). Small changes in environmental variables can lead to rapid and irreversible shifts between two alternate stable states (D'Odorico et al., 2007).

5 Summary and conclusions

Aim of this study was to identify long term variations of soil moisture patterns and to identify the occurrence of particular events that led to tipping points in soil moisture levels. To achieve this, we analyzed high resolution soil moisture measurements from a test site near Karlsruhe, Germany. The data consists of depth-resolved, weekly soil moisture measurements in increments of 10 cm to a final depth of around 200 cm. Additionally, modeled data was used for comparison and interpretation of the results.

Over the investigation period, there is a significant decrease in soil moisture. This decrease is most pronounced ~~in~~ at greater depths up to around 200 cm. Comparison of the measured soil moisture with modeled data of uFC for different stations indicates spatial heterogeneity, meaning future changes in soil moisture will vary in severity based on location.

The model depth of 60 cm is sufficient only when looking at the overall dynamics of uFC. Measurements of soil moisture at depths of up to two meters show significant seasonal variations well below the depth of the model. This large seasonal evaporation depth means, change in soil moisture storage at these depths are an important component in future climate change models that can not be neglected and further real world measurements are needed in order to calibrate these models.

Times of largest changes to the soil moisture levels are the beginning of the vegetation period in April and the the end of the vegetation period in November.

Bayesian modeling of the soil moisture data revealed change points in both trend and seasonality that had high probabilities. It seems reasonable to suggest that specific events of extreme drought had a lasting impact on soil moisture storage and led to deep desiccation of the soil. The most pronounced tipping point being the one during the exceptionally hot drought year 2003. After this point, soil moisture levels were on a lower level. In recent years, soil moisture levels declined even further, accompanied by a decline in the amplitude of seasonal variations. Thus, the impact of a decline in soil moisture is not limited to absolute level of the overall trend, but includes a decrease in seasonality. The overall dynamics are ~~permanently~~ changed without any sign of a return to the previous state. This change in seasonality can not easily be described by simple linear models. Further application of the data and conclusions presented in this study can potentially be used in a much wider context when a applied to numeric modeling of soil moisture, vegetation and climate as well as their interactions.

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Data availability

The data that support the findings of this study are available from the authors upon reasonable request.

Competing interests

The authors declare that they have no conflict of interest.

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Appendix A: Supplemental figures

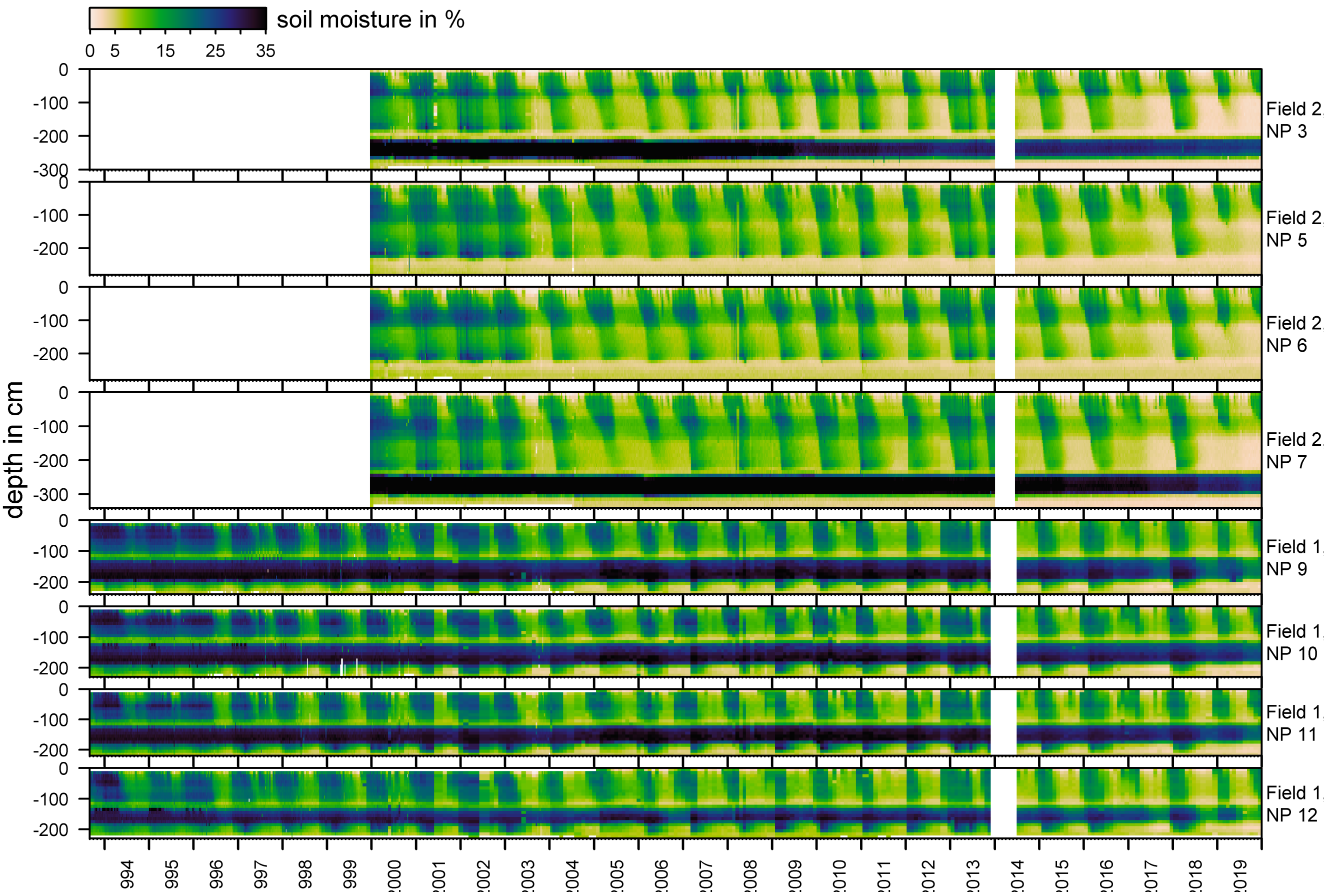

Figure A1. Time series of soil moisture measurements at the test site near Karlsruhe, Germany. Measurements on Field 2 are available from 2000 onward. No measurements were taken during the first half of the year 2014.

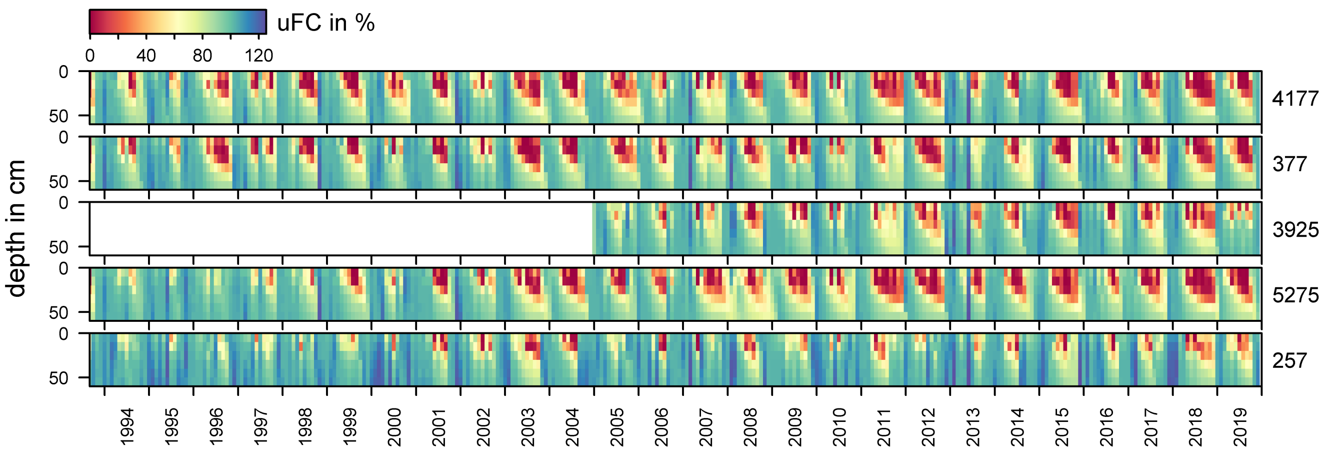

Figure A2. Monthly averages of usable field capacity calculated at five selected weather stations (DWD Climate Data Center, 2020). Values were computed by the agrometeorological model AMBAV. The model calculates soil moisture under grass with sandy loam. The soil sandy loam has a wilting point of 13 volumic% and a field capacity of 37 volumic%. Further model input parameters are hourly values of temperature, dew point, wind speed, precipitation, global radiation and reflected long-wave radiation.

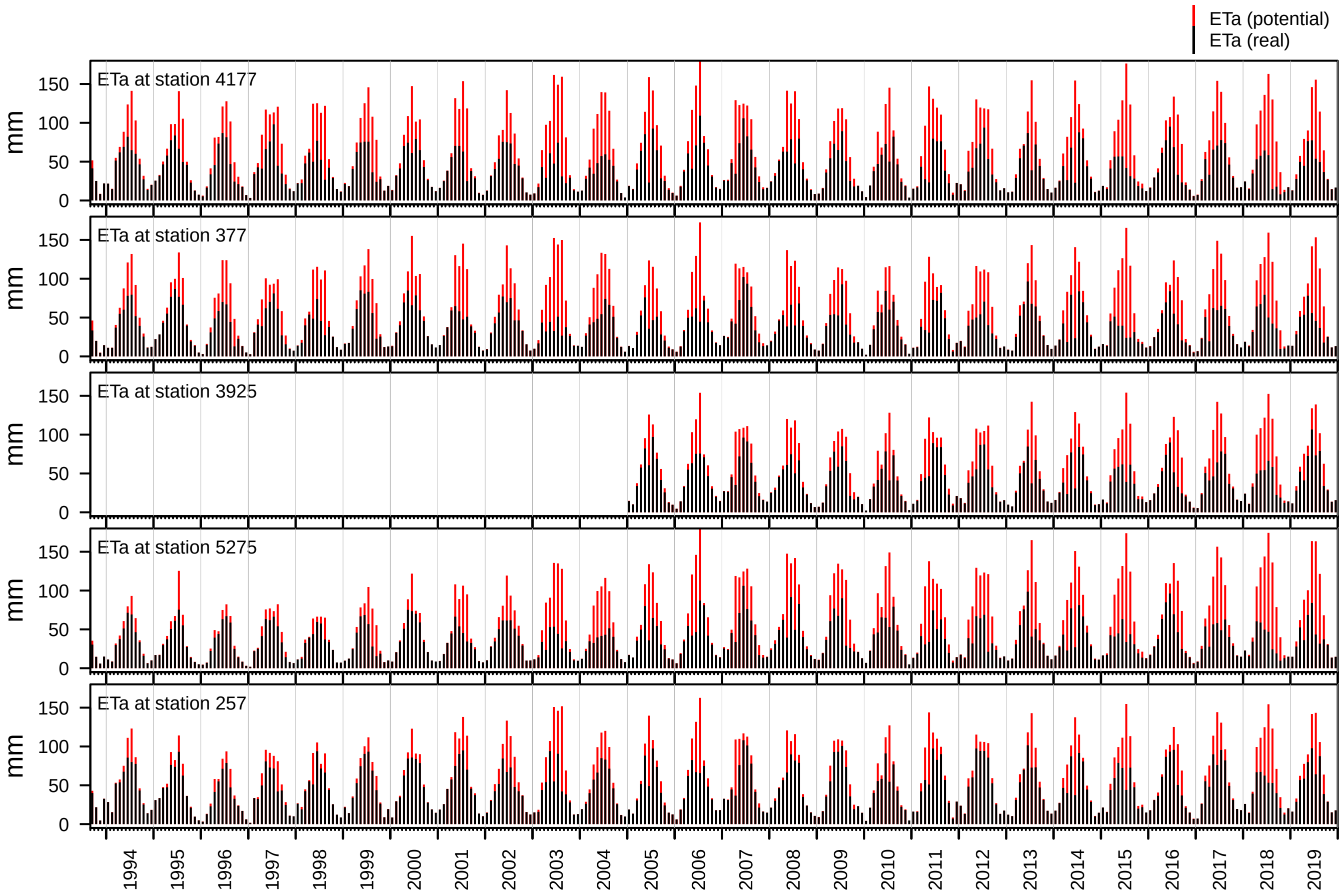

Figure A3. Potential and real evapotranspiration at five selected weather stations (DWD Climate Data Center, 2020).

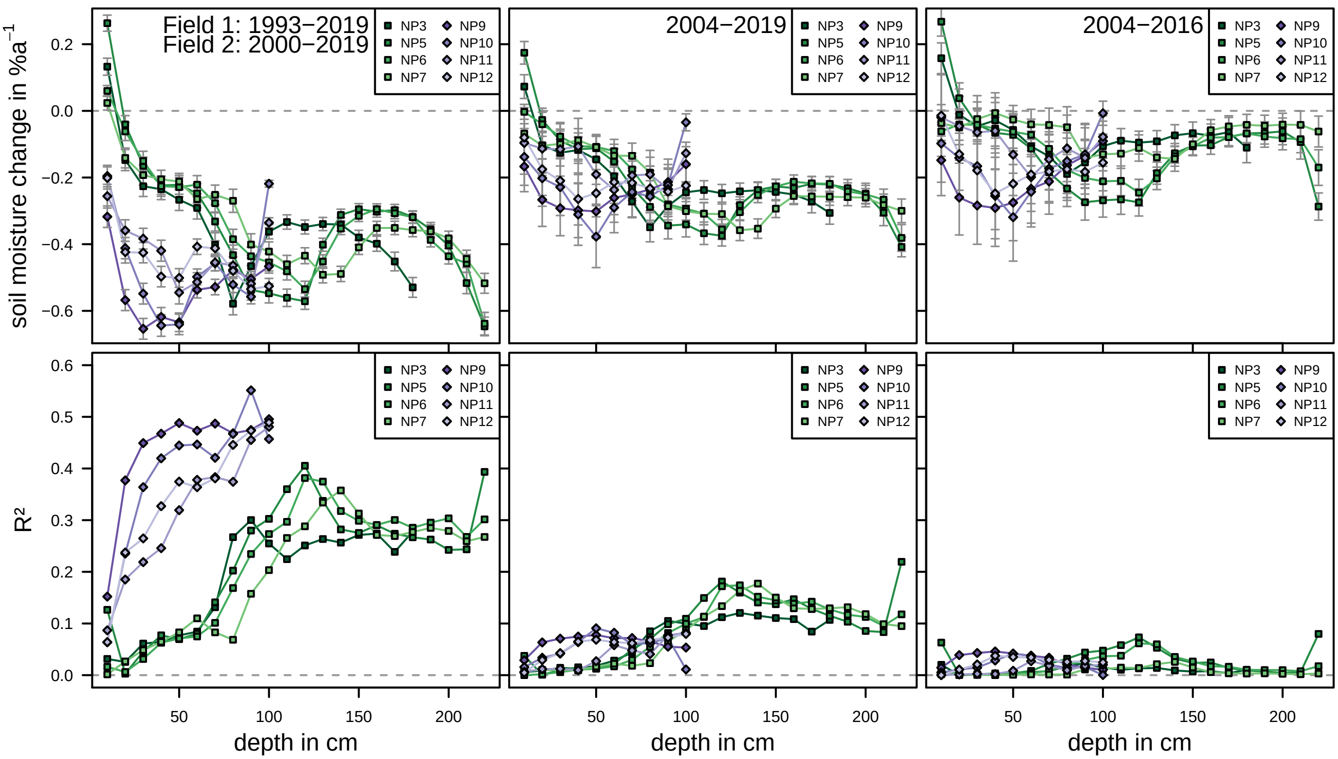

Figure A4. Results of individual linear regressions for soil moisture measurements in the recultivation layer, expressed as change in soil moisture content $[\%a^{-1}]$.

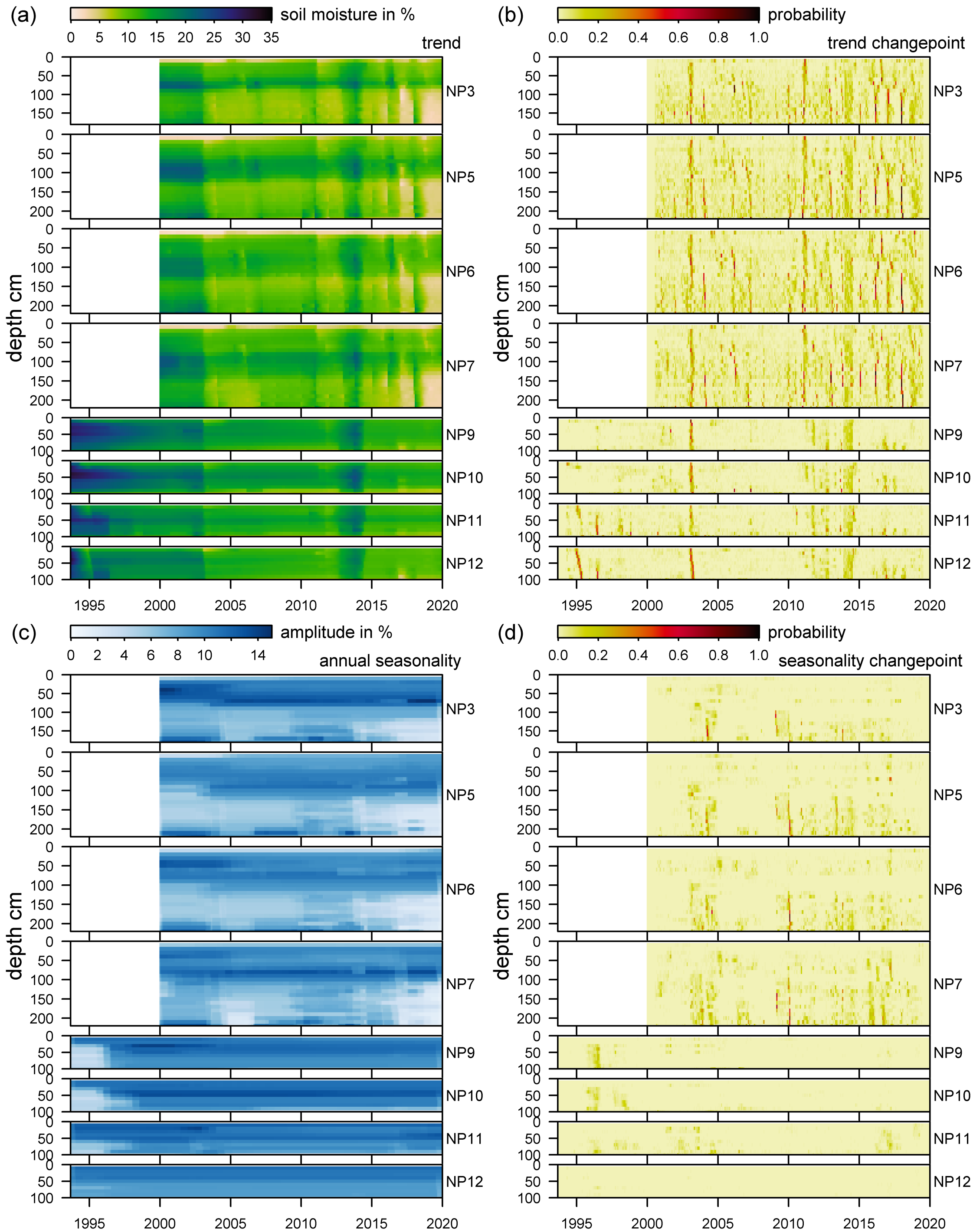

Figure A5. Results of modeling soil moisture with Rbeast. a) Trend component of soil moisture time series. b) Probability of change point in trend component c) Amplitude of annual seasonality derived from seasonal component. d) Probability of change point in seasonality component.

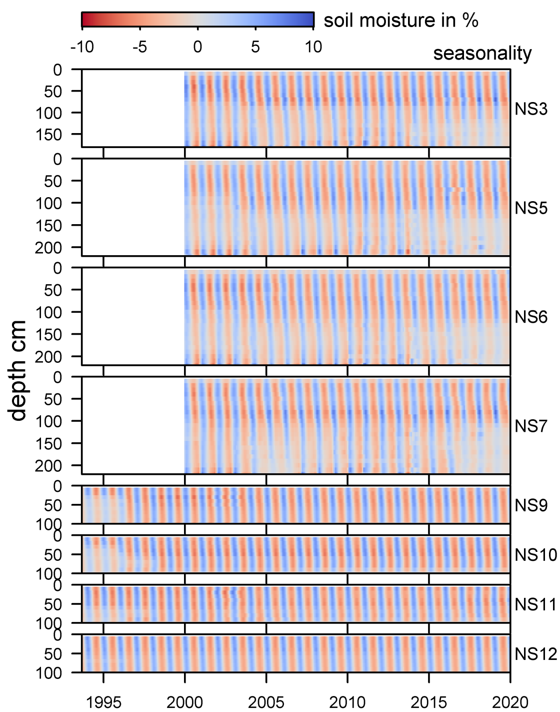

Figure A6. Seasonal component of soil moisture time series.