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Discussions

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

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Preprint. Discussion started: 2 July 2020

Hydrology and Earth System Sciences
Open Access
EGU
Discussions

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 (Solander et al., 2019; Kolusu et al., 2019). An increase in catchment evaporation 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). 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 (eg. 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. They provide a direct measurement of percolation rates through the soil, which makes them suitable for monitoring and demonstration of equivalency of earthen landfill covers (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). 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 large inclined lysimeter 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 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

https://doi.org/10.5194/hess-2020-274
Preprint. Discussion started: 2 July 2020

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. 1). 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).

Two large inclined lysimeters are embedded in the municipal landfill site Karlsruhe-West for mandatory monitoring purposes. 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 (CL) and capillary barrier.

The second lysimeter (Field 2) was built in 2000, with first measurements being taken in December. 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 angle is 23.5° (43.5 %) with southern exposition. 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. Further details on the construction of both fields is given in Augenstein et al. (2015).

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. Both models used an Am/Be source with activities of 1.85 GBq and 370 MBq respectively (Augenstein et al., 2015). Selected measurement points are shown in Fig. 1. Neutron probe measurement points (NP) are constructed from steel tubes (∅ 40.5

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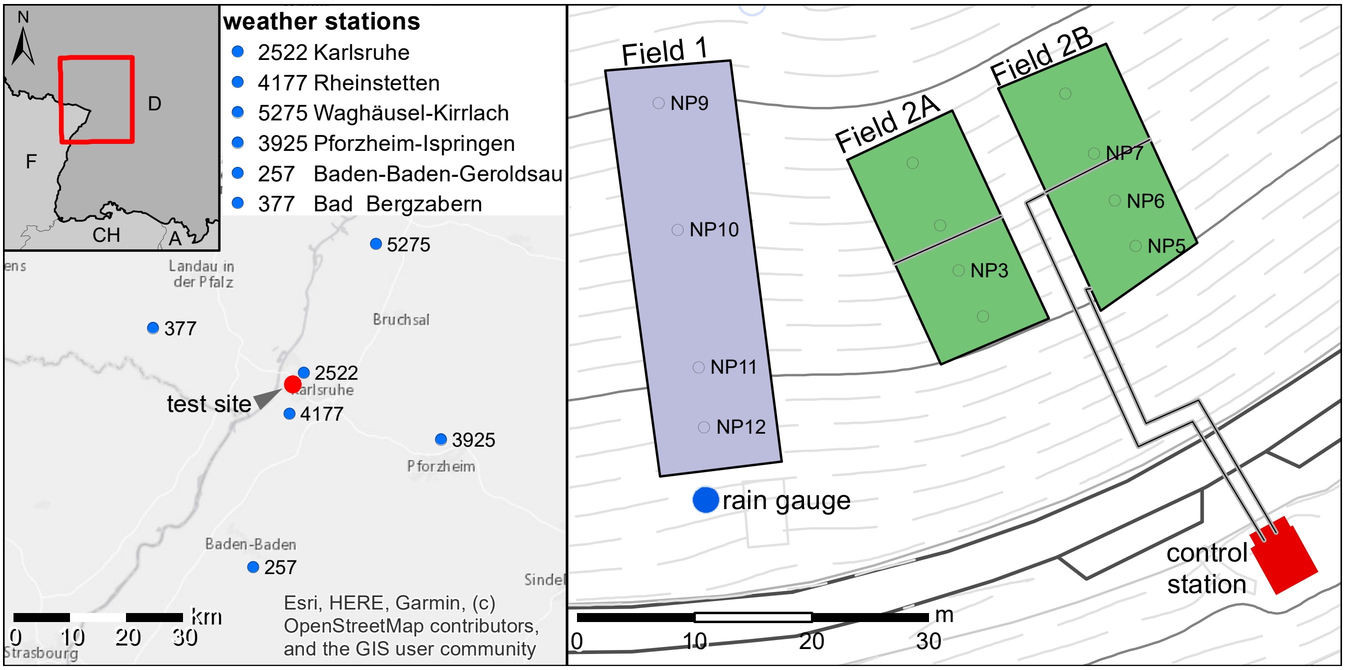

Figure 1. Location of the study site on a municipal landfill site in Karlsruhe, Germany, and locations of the weather stations used in this study. Lysimeter 2 consists of two separate fields (Field 2A, Field 2B).

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. 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 Field 1: 2.1 m – 2.3 m; bottom Field 2: 2.8 m – 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 1.

The DWD also publishes derived model results for usable field capacity (uFC) (DWD Climate Data Center, 2020). They are provided for two different soil types and as depth resolved values for the top 60 cm of the soil column. Data was used from

https://doi.org/10.5194/hess-2020-274
Preprint. Discussion started: 2 July 2020

Hydrology and Earth System Sciences
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Discussions

Table 1. Location of weather stations, 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

five stations (Tab. 1: 4177, 377, 3925, 5275, 257, Fig. 1) 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. New x- and y-coordinates for each measurement were calculated according to Eq. 1 and Eq. 2.

$$x = \cos\left(2 \cdot \pi \cdot \frac{d_{year}}{365.2425}\right) \cdot \theta \tag{1}$$

$$y = \sin\left(2 \cdot \pi \cdot \frac{d_{year}}{365.2425}\right) \cdot \theta \tag{2}$$

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 year in order for 2π to equal one year.

For each individual depth, a linear regression was calculated using all measurements for the years 2000 to 2019 (see 3.1). As linear regression can be dependent on the selected start and end times, additional regressions were calculated over the complete 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. 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 cm at NP5 results in twelve time series. 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.

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.

Bayesian change point detection and time series decomposition was done using the `beast()`-function from the Rbeast package (Zhao et al., 2019a, b). 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 measured soil moisture values are presented in Fig. 2. 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).

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 depth 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. Surprisingly, re-wetting took place in 2018, a year that is otherwise known to having been a very dry year.

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 cannot be observed in recent

https://doi.org/10.5194/hess-2020-274
Preprint. Discussion started: 2 July 2020

Hydrology and Earth System Sciences
Discussions

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 CL (~200 cm). In data from Field 2, depth-dependence of soil moisture is clearly evident. Higher soil moisture at depth 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. 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.

Values of modeled uFC are also shown in Fig. 2. 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.

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. 3). For comparison, the soil moisture time series of NP3 at depth 170 cm and a mean time series 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 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 depth 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 depth 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 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 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 4, 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 of $0.34 \pm 0.14\ \%a^{-1}$ within the RL could be

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Preprint. Discussion started: 2 July 2020

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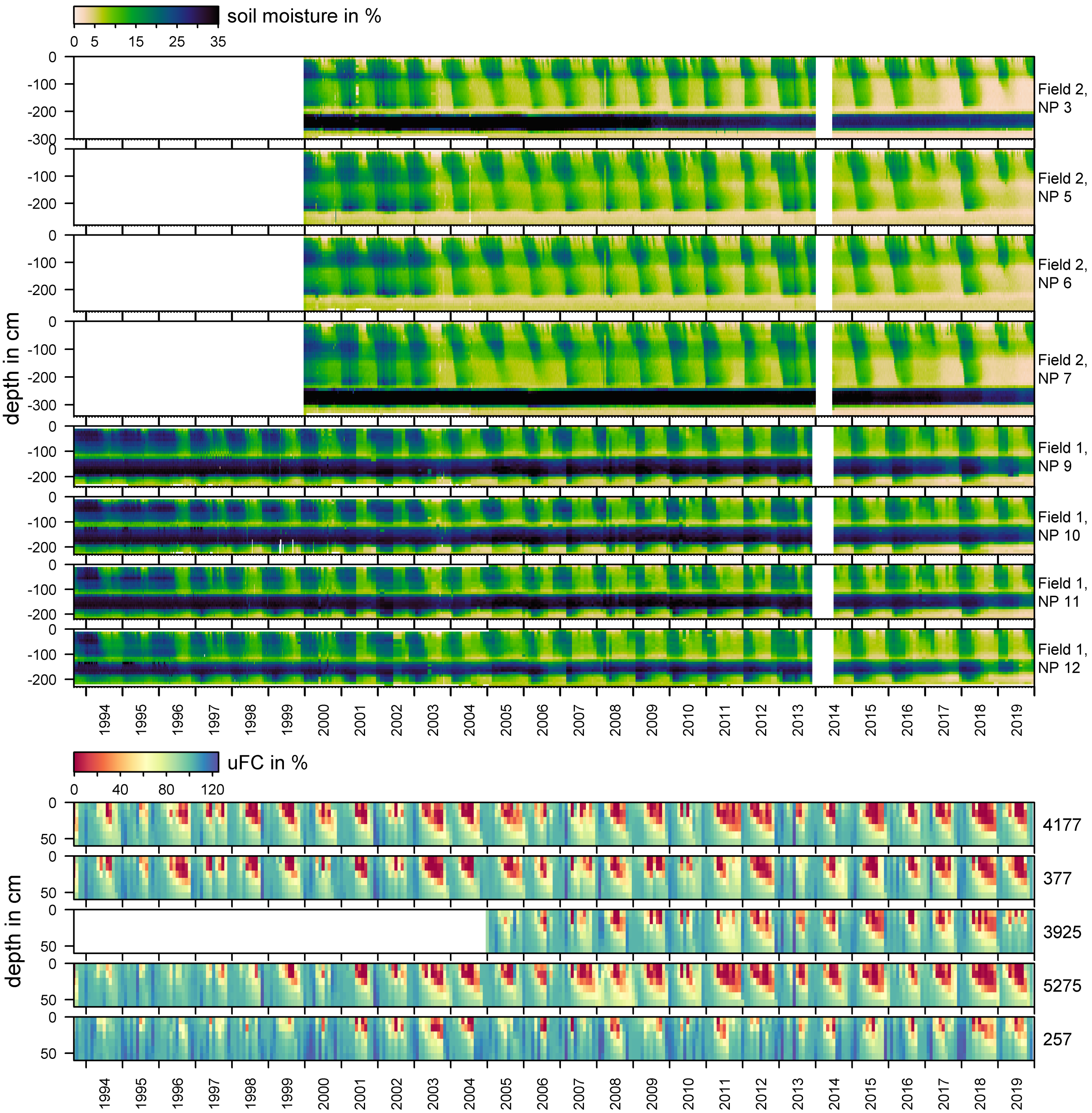

Figure 2. Time series of soil moisture measurements at the test site near Karlsruhe, Germany and monthly averages of usable field capacity (DWD Climate Data Center, 2020) at five selected weather stations. Measurements on Field 2 are available from 2000 onward. No measurements were taken during the first half of the year 2014.

https://doi.org/10.5194/hess-2020-274
Preprint. Discussion started: 2 July 2020

Hydrology and Earth System Sciences
Discussions

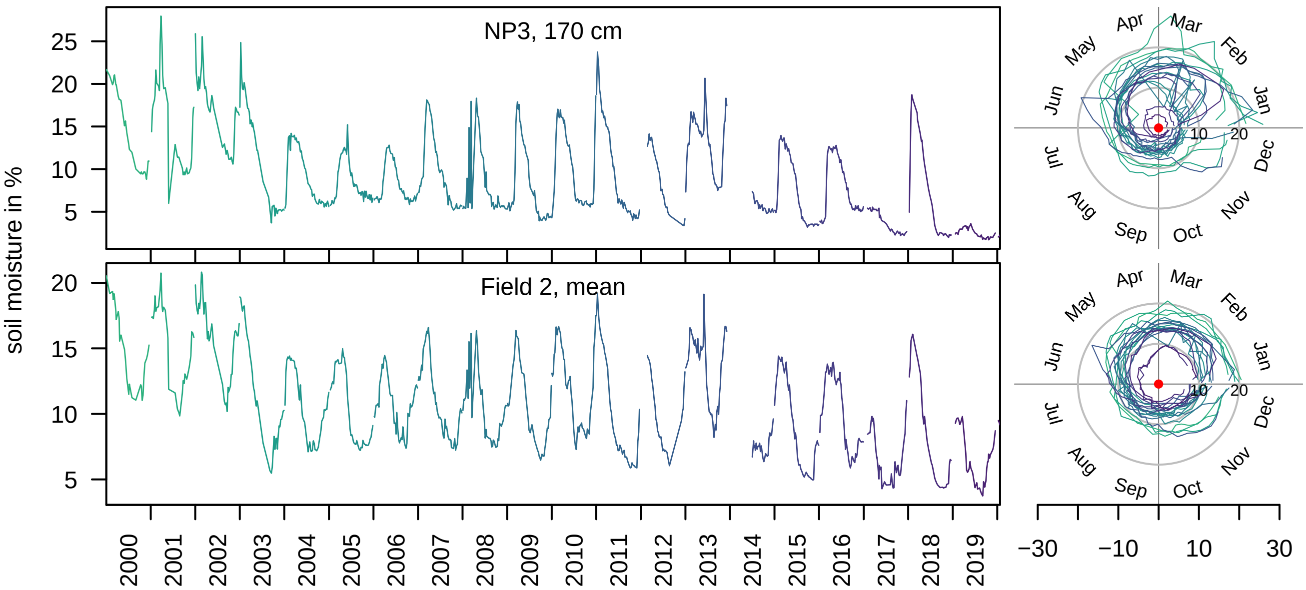

Figure 3. Time series of soil moisture at NP3 at 170 cm and mean soil moisture of Field 2 as well as the same data in a polar coordinate system to highlight seasonal asymmetry of gradual drying and fast re-wetting as well as the overall trend of declining soil moisture.

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 depth 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 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. Downward movement of the water in the soil column is being dampened with depth.

4.3 Monthly linear regressions

The results of linear regressions based on the monthly averages is shown in Fig. 5. Resulting slopes with $p > 0.05$ are shown and an indication given 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,

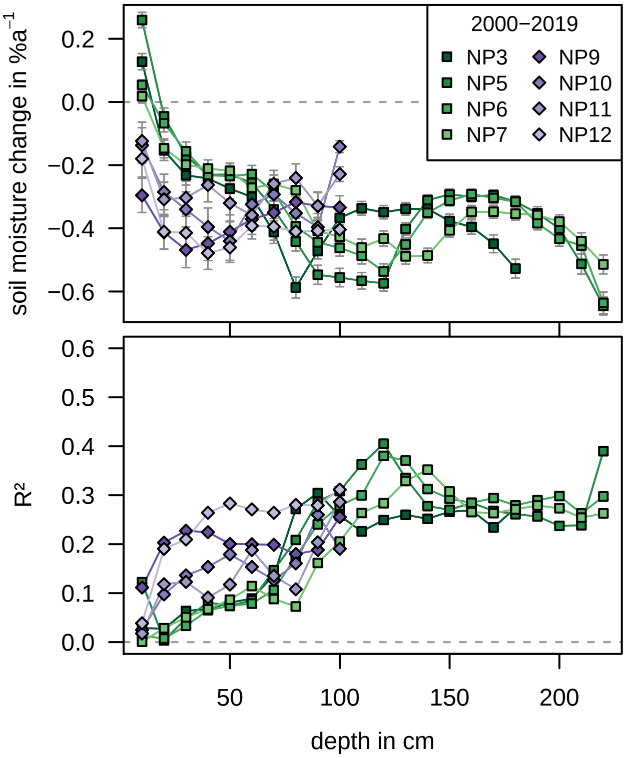

Figure 4. Results of individual linear regressions for soil moisture measurements in the recultivation layer, expressed as change in soil moisture content $\left[\%a^{-1}\right]$.

overall soil moisture levels were higher before 2003. Inclusion of additional data before this point, as is the case with Field 1, would bias 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 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 depth. 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, 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. 6. 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

https://doi.org/10.5194/hess-2020-274
Preprint. Discussion started: 2 July 2020

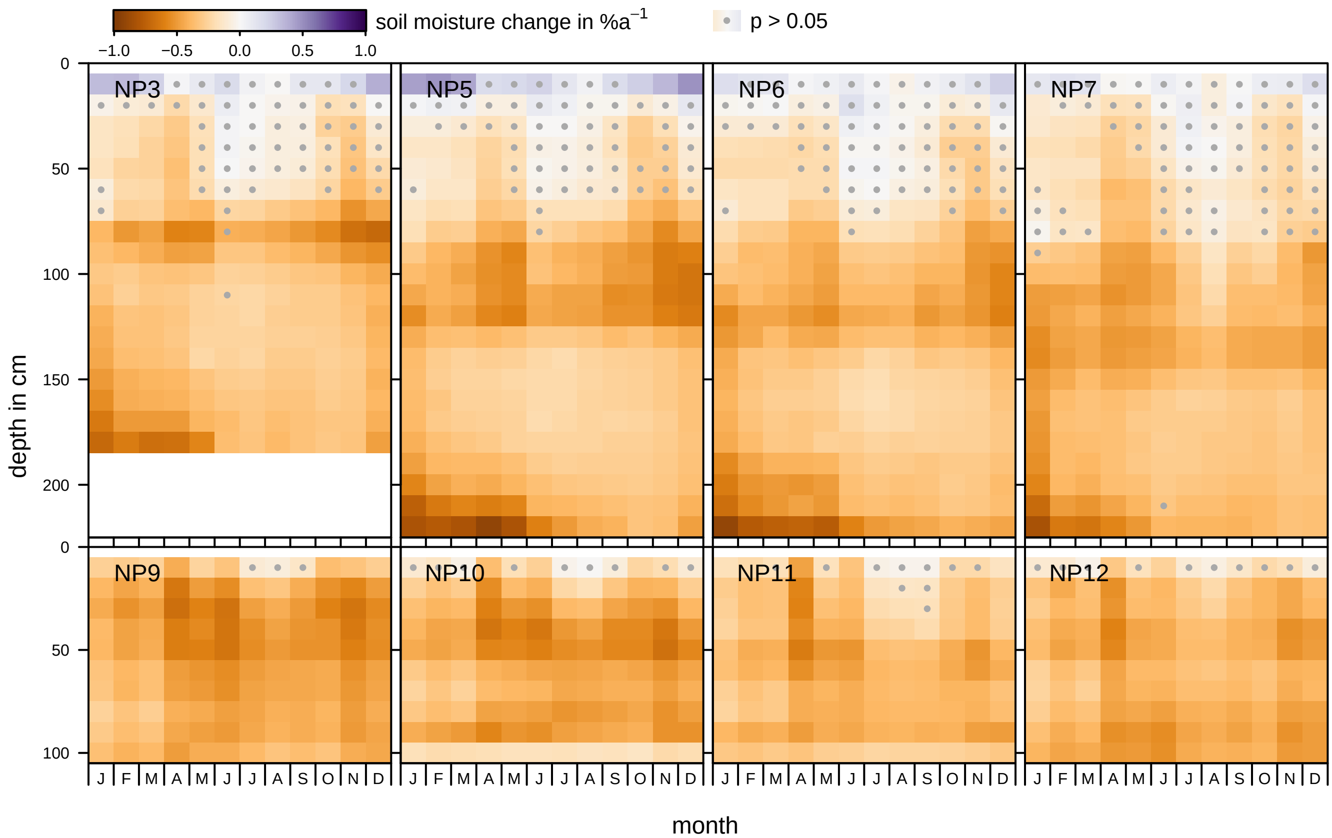

Figure 5. Results of individual linear regressions for soil moisture measurements in the recultivation layer, expressed as change in soil moisture content $\left[\%a^{-1}\right]$ calculated over the complete time series for each month based on monthly averages. Values for $p > 0.05$ are indicated by a marker.

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. 5, 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, 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.

https://doi.org/10.5194/hess-2020-274
Preprint. Discussion started: 2 July 2020

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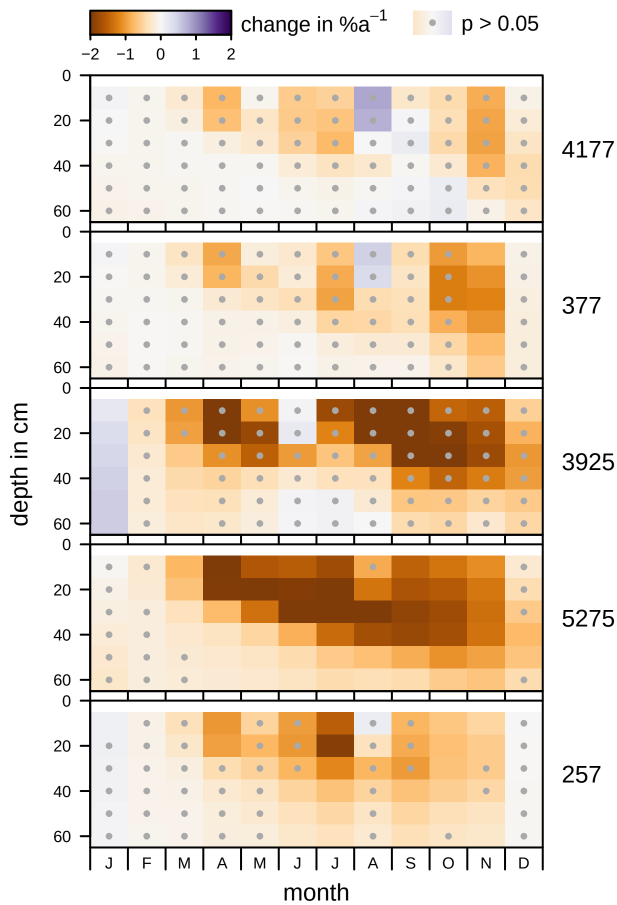

Figure 6. Results of individual linear regressions for usable field capacity (uFC) for the top 60 cm (at stations 4177, 377, 3925, 5275, 257), expressed as change in usable field capacity $[\%a^{-1}]$ calculated over the complete time series for each month based on monthly averages. Statistically non-significant values (p > 0.05) are indicated by a marker.

230 ## 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. In Fig. 7 the main results of this model are shown. This kind of decomposition allows for easier visual analysis of the underlying trend component (Fig. 7a). 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 depth below 100 cm.

The decomposed time series of Field 1 (NP9 - NP12) 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

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Preprint. Discussion started: 2 July 2020

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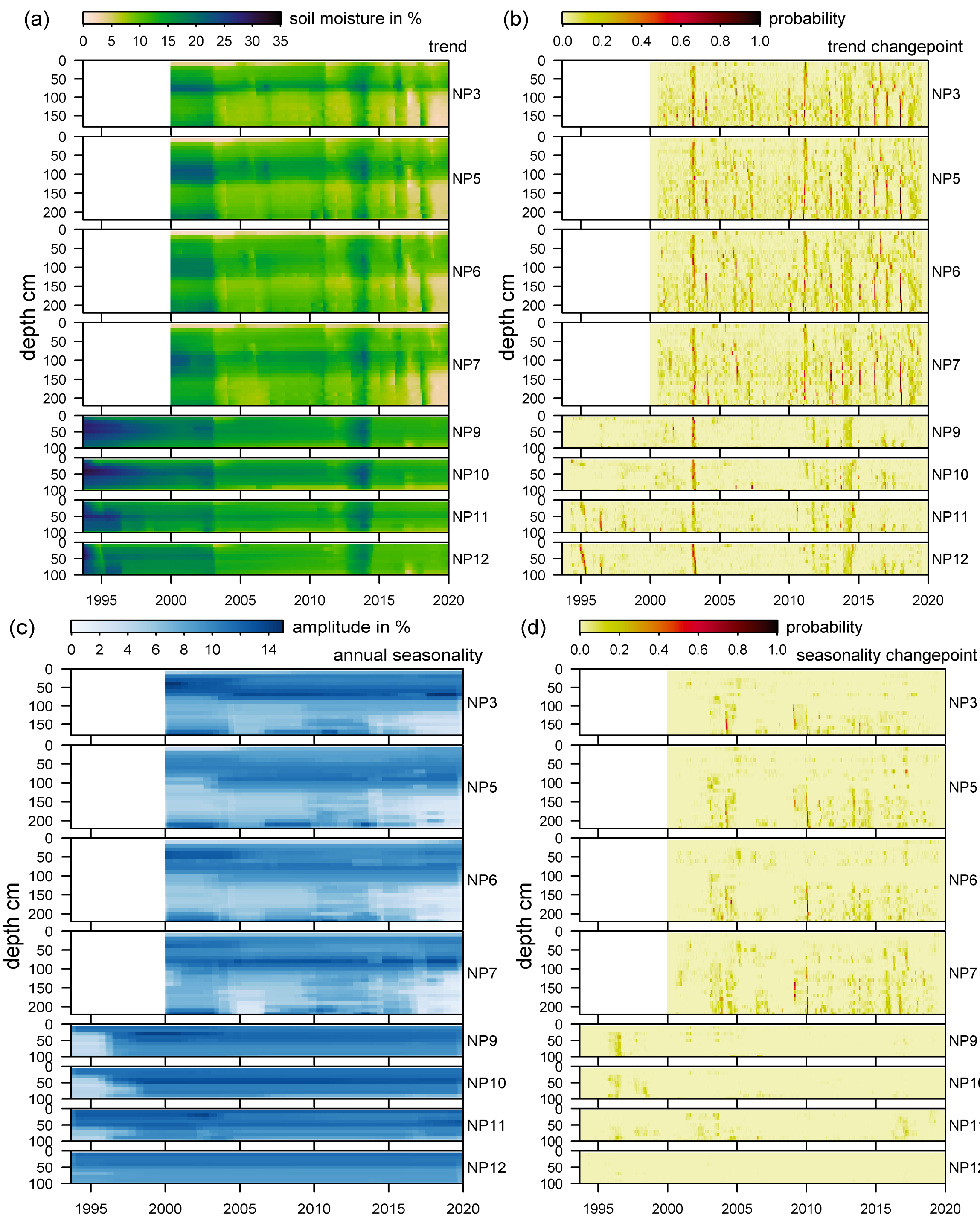

Figure 7. Results of modeling soil moisture with Rbeast. a) Trend component of soil moisture time series. b) Probability of change point in trend component c) Amplitude of annual seasonality derived from seasonal component. d) Probability of change point in seasonality component.

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 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, the amplitude of seasonal variations in 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. The same holds true for the modeled usable field capacities analyzed in this study. Because they are solely calculated from weather data and standardized soil properties, they also neglect the possibility of an additional source of soil moisture provided by capillary rise. 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 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. 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.

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 greater depth 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 depth 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 depth 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. This change 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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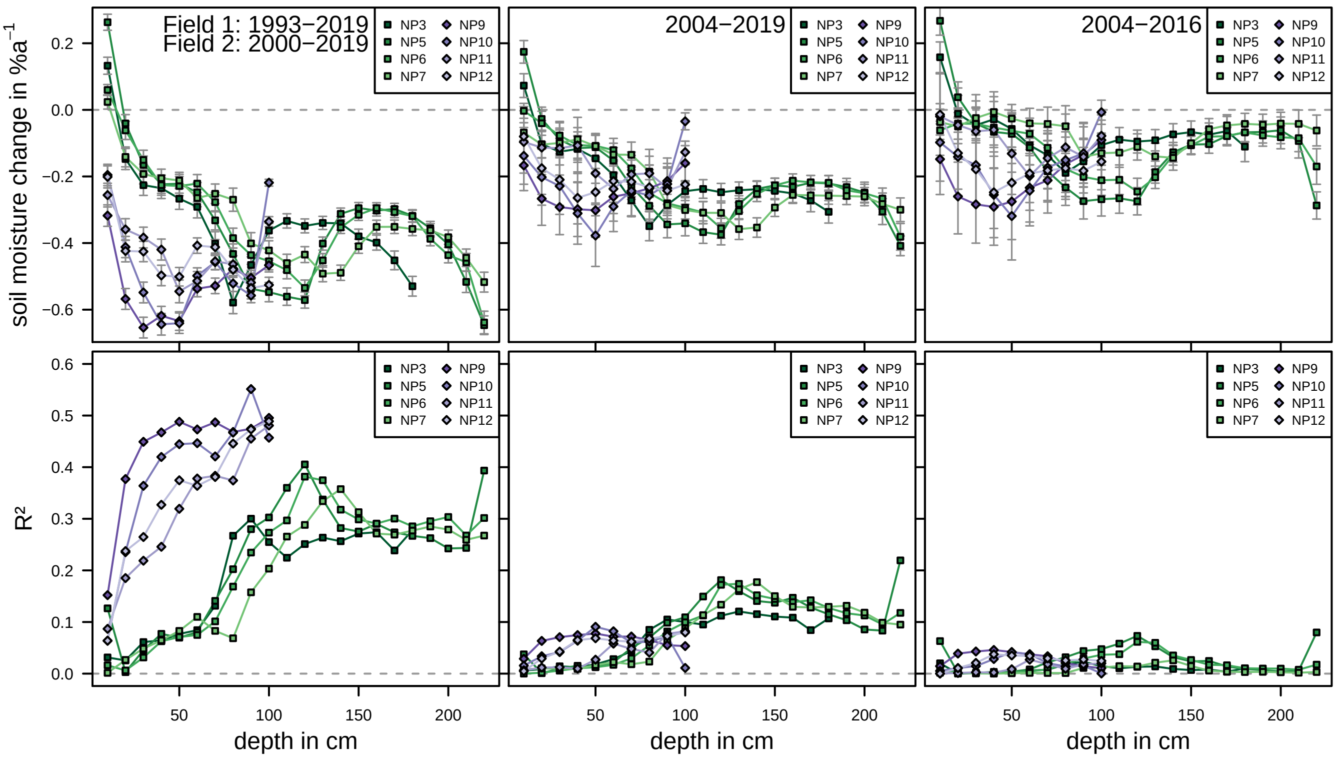

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Appendix B: Seasonal component of soil moisture time series.