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Detecting the resilience of soil moisture dynamics to drought periods as a function of soil type and climatic region

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Contents

In Figure S1 the model performance and soil water characteristics curve of the lysimeter used for model training is shown (soil material from Dedelow transported to Bad Lauchstädt). Figure S2 shows an illustrative example of a lysimeter adapting the response function to the drier climatic conditions. Figure S3 depicts an example of good general model performance deflecting from a systematic trend of error metrics and shift in the soil moisture response function. Text S1, Table S1, and Figures S4 to S7 present the model results using soil moisture classification (wet’, moderate’, dry’) based on the water content statistics calculated for each lysimeter (in the main text the classification was deduced from data of the lysimeter used for training).

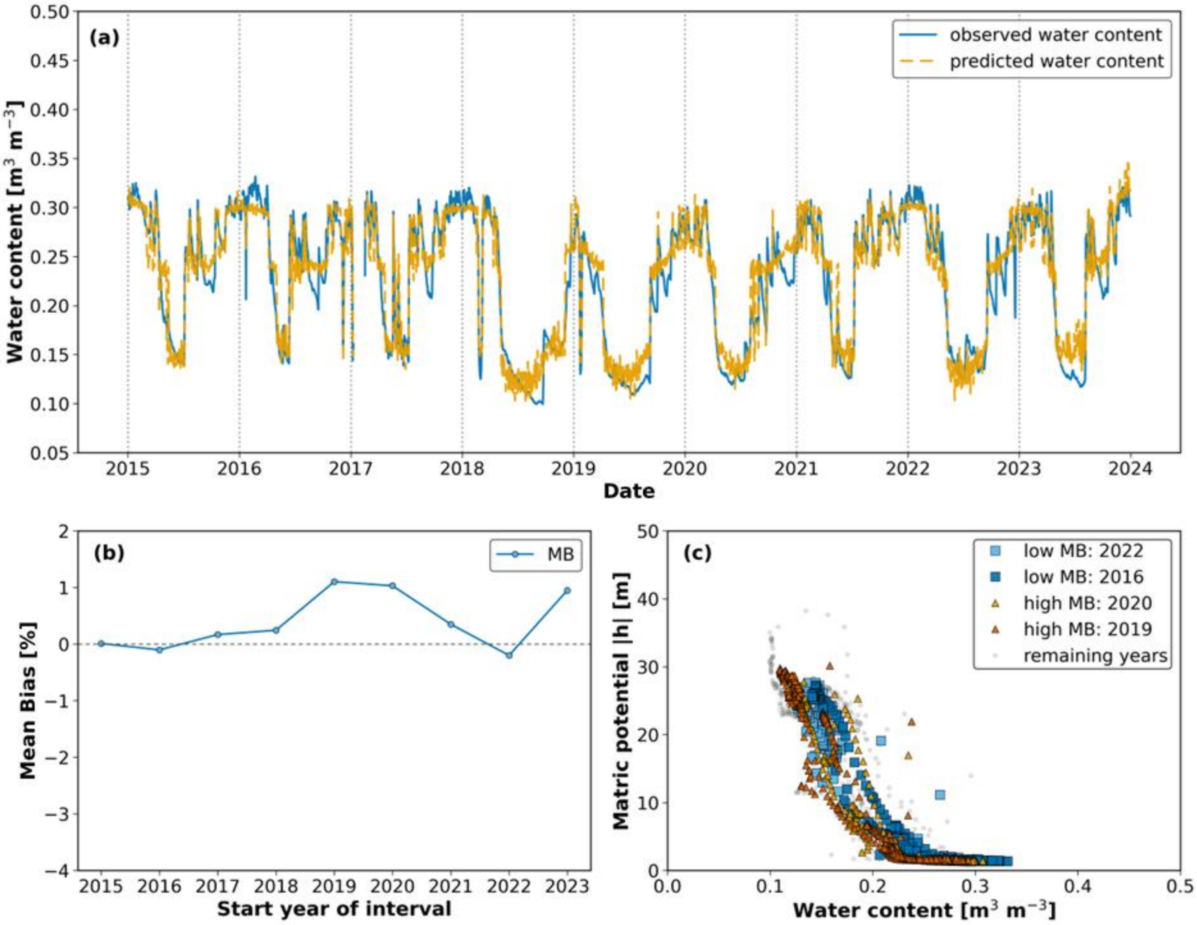

Figure S1. *The Dedelow-origin lysimeter relocated to Bad Lauchstädt was used as the reference site to calibrate the soil moisture response function. Data from January 2015–December 2023 were split into training (70%) and validation (30%)(a) Observed and predicted water content show close agreement during calibration and validation (b) Yearly mean bias (MB) remains close to zero with minor fluctuations. (c) Soil water retention data demonstrate that the difference between years with low MB (e.g., 2016, 2022) and high MB (e.g., 2019, 2020) is minimal, indicating that the response function at the training site remained stable over time*.

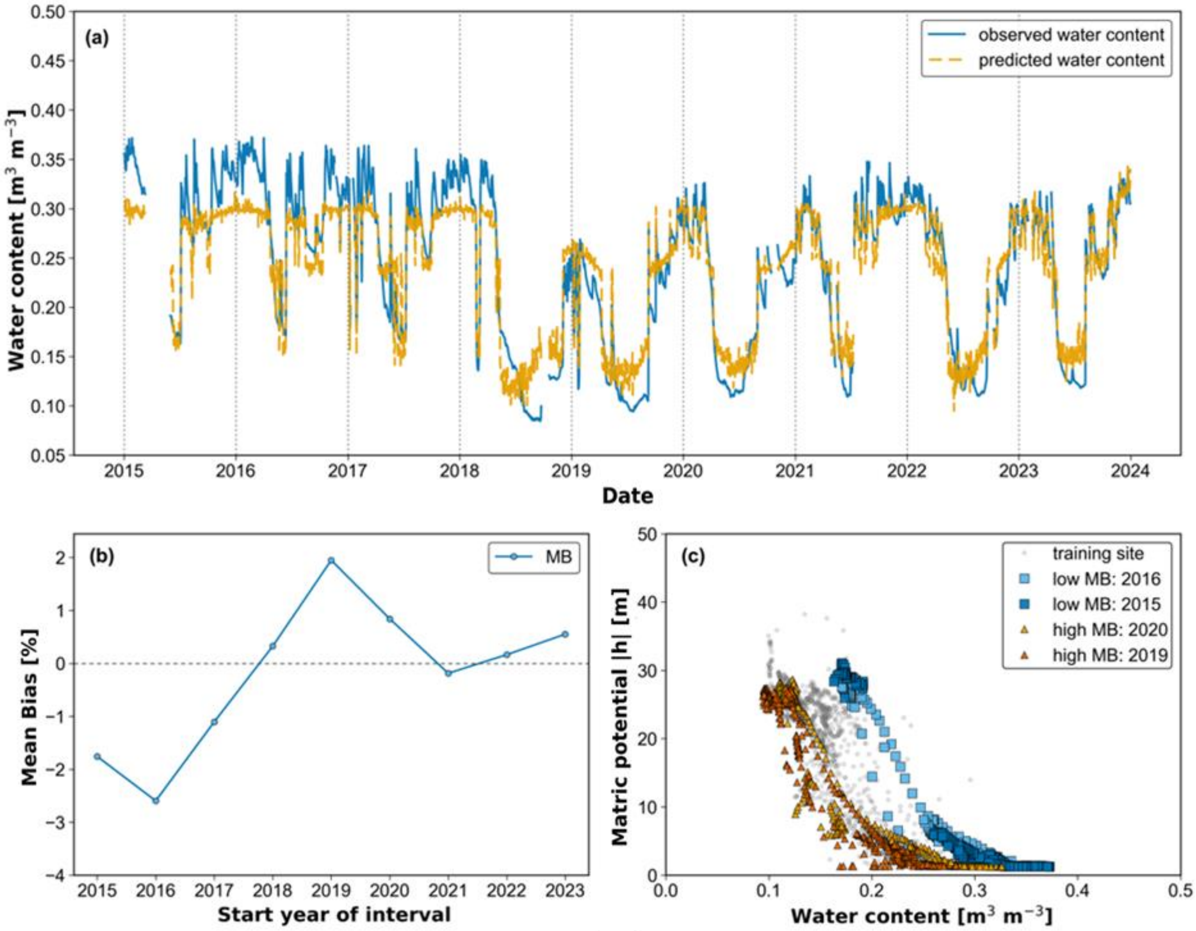

Figure S2. *Selhausen-origin soil relocated from the humid climate in Selhausen to the drier continental climate at Bad Lauchstädt. After 2018, predictions and observations (a) converged more strongly, with mean bias (MB) stabilizing near zero (b), indicating that the soil response functions shifted toward adjustment to the drier climate. (c) The soil water retention data show the shift from high water contents to lower water contents that are similar to the observations at the training site.*

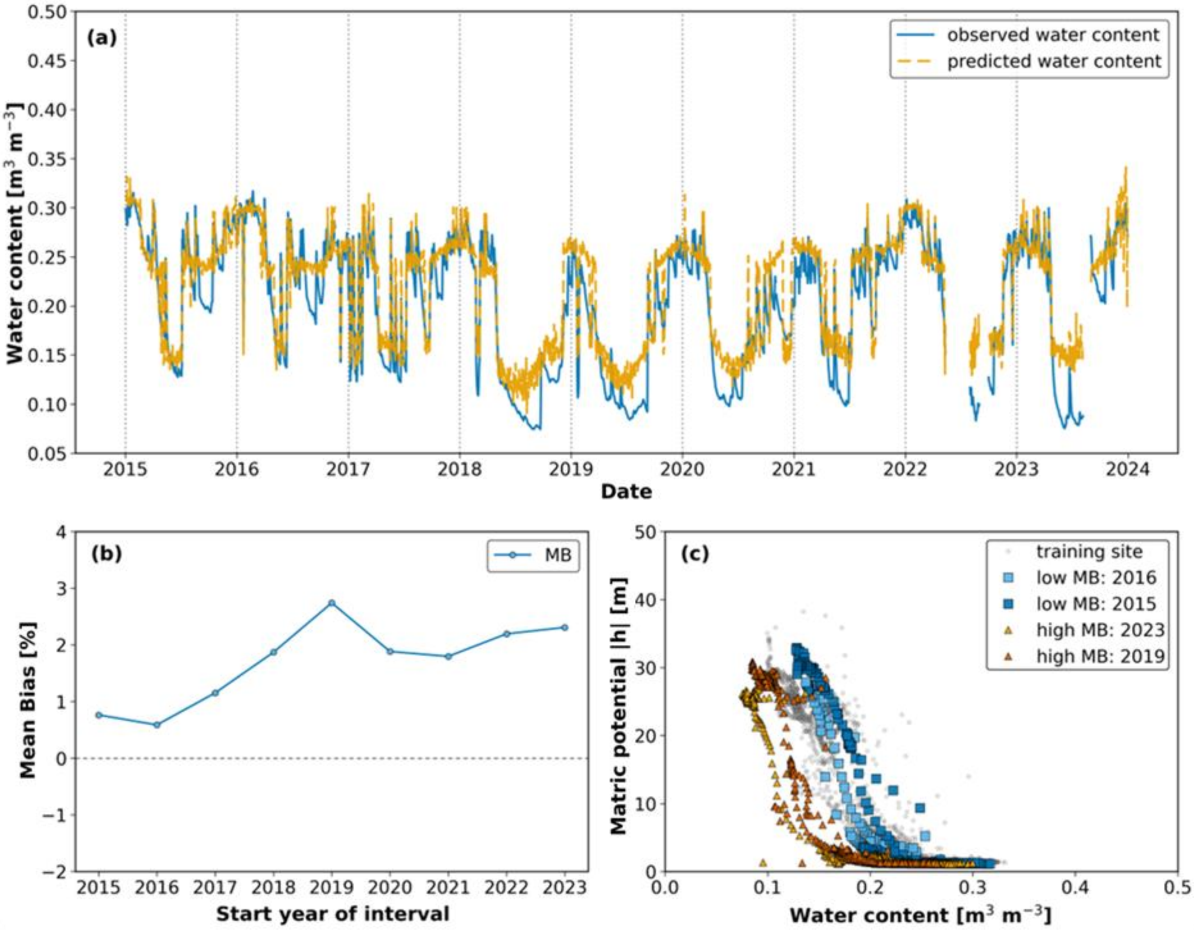

Figure S3. *Dedelow-origin soils relocated to Bad Lauchstädt. The predictions (a) maintained high NSE values (0.79) but the mean bias (MB) increased over time (b), with soil water retention data from the selected years reflecting this progressive change to lower water contents (c).*

Text S1: Model predictions based on soil specific soil moisture classification

In the main manuscript, percentile thresholds to classify daily water content into the three classes (‘wet’, ‘moderate’, ‘dry’) were derived from the Dedelow training site and applied uniformly across all prediction sites. With this choice, no information on the soil moisture statistics for the other lysimeters were required and shifts in the soil moisture response function could be compared relative to the training reference. However, because the range of water contents vary with soil texture (and structure), a value assigned as ‘wet’ in the sandy loam from Dedelow may be relatively dry for the silt loam at the other sites. To account for soil specific differences, the measured water content values θ of each lysimeter were normalized by $(\theta-\theta_{min})/(\theta_{max}-\theta_{min})$ with minimum θ_{min} and maximum θ_{max} value of the time series for each lysimeter. The 30%- and 70%-quantiles of the normalized values were then used to define a measured water content as ‘dry’, ‘moderate’ and ‘wet’. The overall classification of the soil moisture response function (‘stable’, ‘resilient’, ‘changed’) based on the normalized water contents remained nearly identical, with only three out of 24 lysimeters differing (Table S1), confirming that our conclusions are independent of the classification scheme. However, with such site-specific scaling we cannot define the location of the SWRC relative to the training site, since the training reference is no longer preserved, which is another reason that the individual scaling was not used in the main text.

Table S1: Resilience of soil moisture response function for the four soil materials transported to Bad Lauchstädt and Selhausen. In contrast to Table 1 in the main text, the classification of soil water content in three classes (wet, moderate, dry) was done individually for each lysimeter (and not based on the lysimeter from Dedelow used in the training). The 'type' describes the class of response function of the individual lysimeters (S for 'stable', R for 'resilient' and C for 'changed'). Only three out of 24 lysimeters obtained a different classification (highlighted by asterisk*). The 'drift' is the average value $|MB_{2023}\text{-}MB_{2015}|$ of the three lysimeters with the difference in Mean Bias (MB) between years 2023 and 2015. The 'amplitude' is the maximum difference of the MBs between the first year (2015) and the years between 2018 and 2022 (denoted as year 20xx).

	Located at Bad Lauchstädt			Located at Selhausen		
	Type	Drift	Amplitude	Type	Drift	Amplitude
Dedelow	**S, R, C**	0.89	1.63	**R, C, C**	1.10	1.96
Bad Lauchstädt	**S, S, R**	0.63	1.14	**R, C, C**	1.47	2.23
Sauerbach	**S*, R*, C**	0.87	2.28	**C, C, C**	2.45	3.58
Selhausen	**R* ,R ,C**	1.08	2.15	**S, S, R**	0.71	1.18

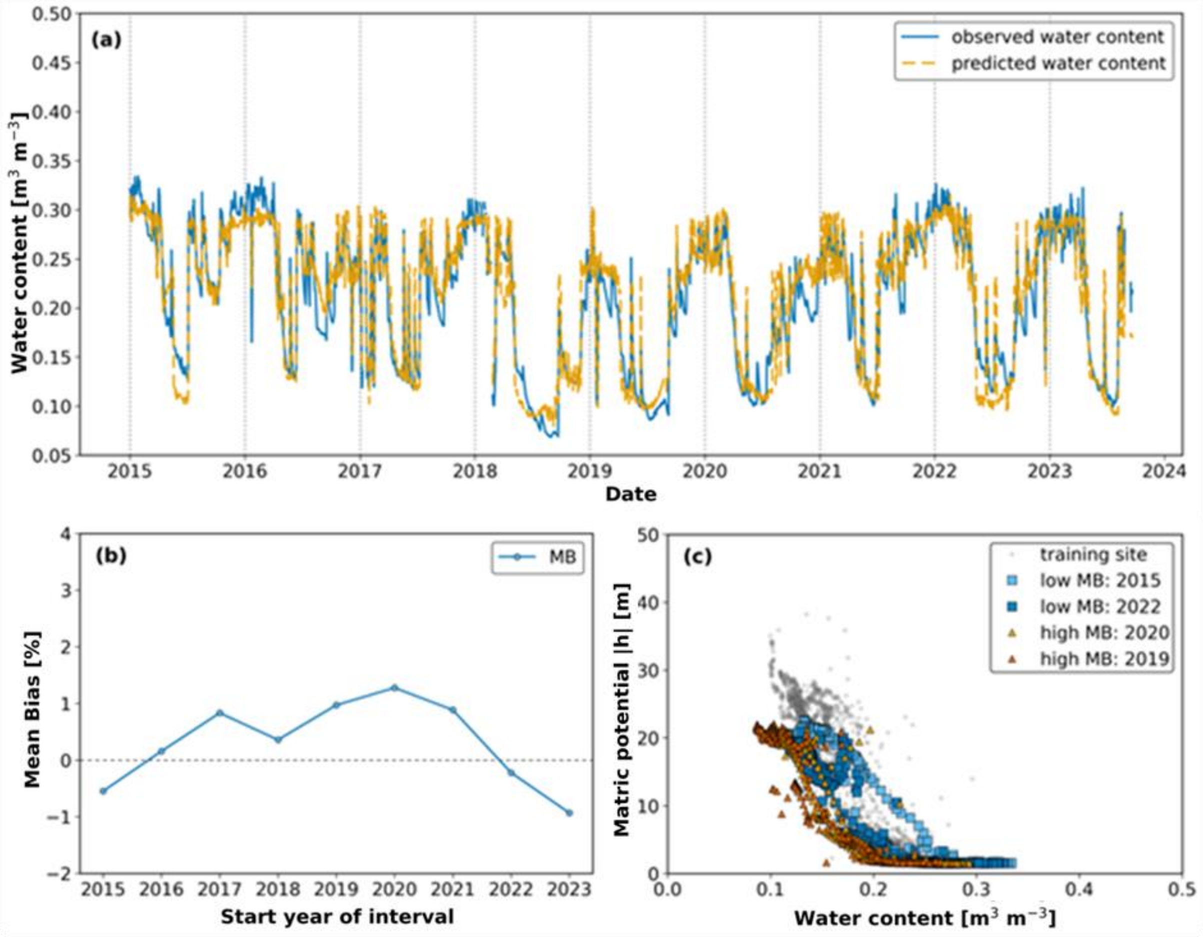

Figure S4. *Analysis of soil moisture dynamics (2015–2023) for a Dedelow-origin lysimeter tested at Bad Lauchstädt. Panel (a) shows the time series of observed (blue) and predicted (orange) water content. Compared to the figure in the main text (Fig. 5a), the fit during the dry years is better. The NSE value increased from 0.84 in Figure 5a to 0.87. (b) The mean bias (MB) curve still shows a rising trend around 2019–2020 followed by a return towards the initial 2015 value, consistent with a 'resilient' response function. Panel (c) displays soil water retention data from the training site (grey) and from selected years representing different MB conditions and is identical to Figure 5c in the main text.*

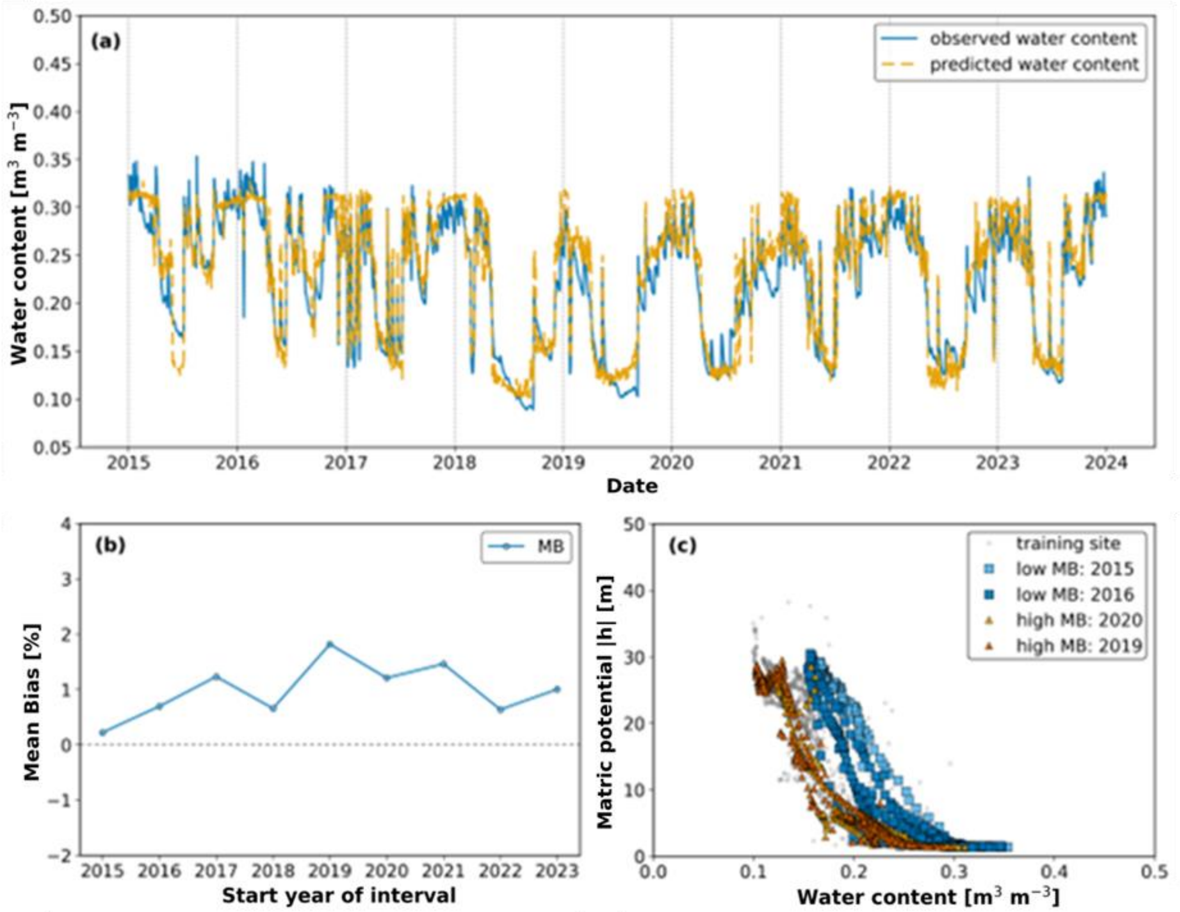

Figure S5. *Analysis of soil moisture dynamics (2015–2023) for a Bad Lauchstädt-origin soil lysimeter tested at Bad Lauchstädt. Comparison of measured (blue) and simulated (orange) daily water content values in (a) and mean bias (MB) in panel (b). Both figures are similar to Figure 6 in the main text, but with MB values that are consistently positive (predicted values slightly higher than measured values). The NSE value dropped from 0.88 in Figure 6a to 0.85. Panel (c) displays soil water retention data from the training site (grey) and from selected years representing different MB conditions and is identical to Figure 6c in the main text.*

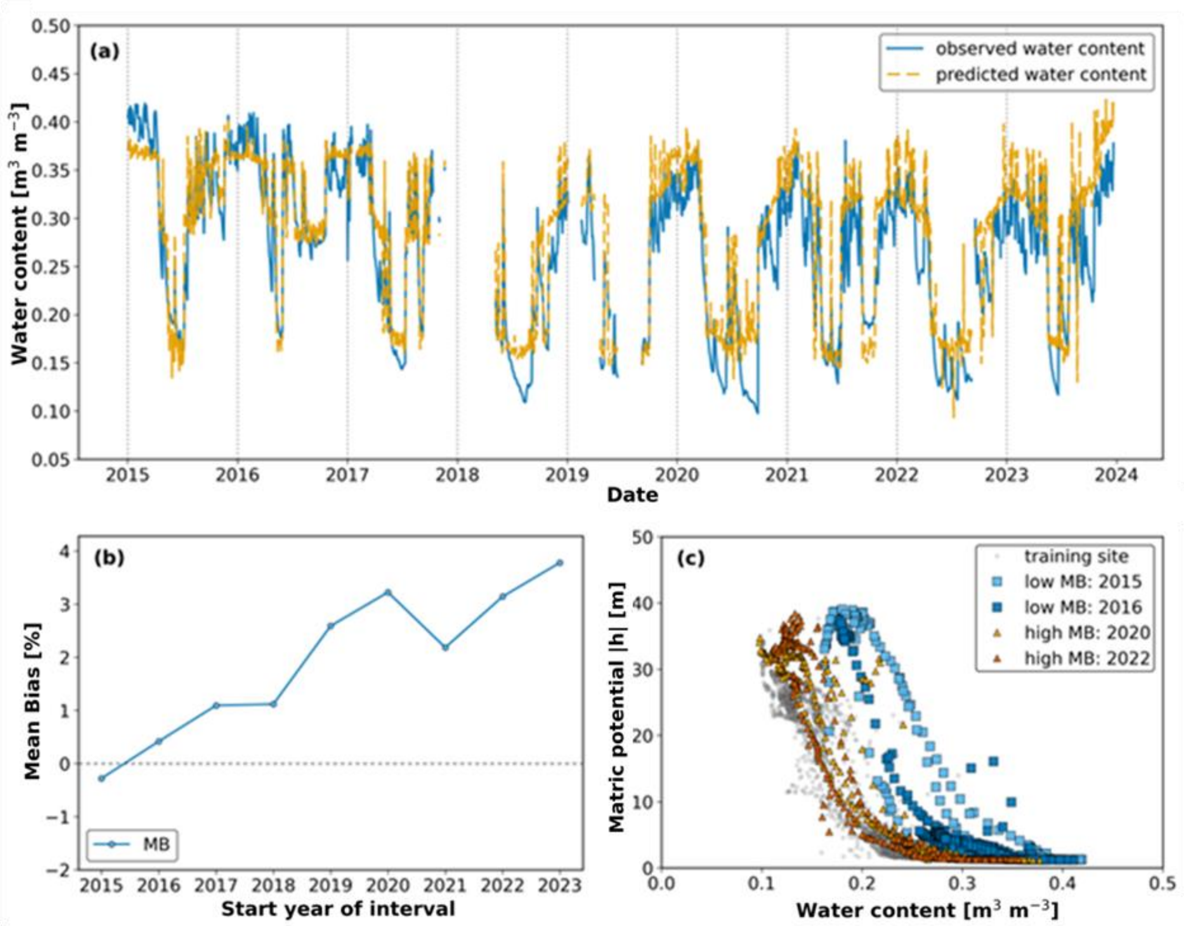

Figure S6. *Analysis of soil moisture dynamics (2015–2023) for Sauerbach-origin lysimeter relocated to Selhausen (a) Comparison of observed and predicted daily volumetric water content with better model agreement at the beginning of the observation period compared to Figure 7 in the main text. The NSE value increased from 0.74 in Figure 7a to 0.78 (b) The mean bias (MB) curve shows a steady rise from near zero in 2015 to strongly positive values by 2023, consistent with a 'changed' response function as in figure 7. Panel (c) displays soil water retention data from the training site (grey) and from selected years representing different MB conditions and is identical to Figure 7c in the main text.*

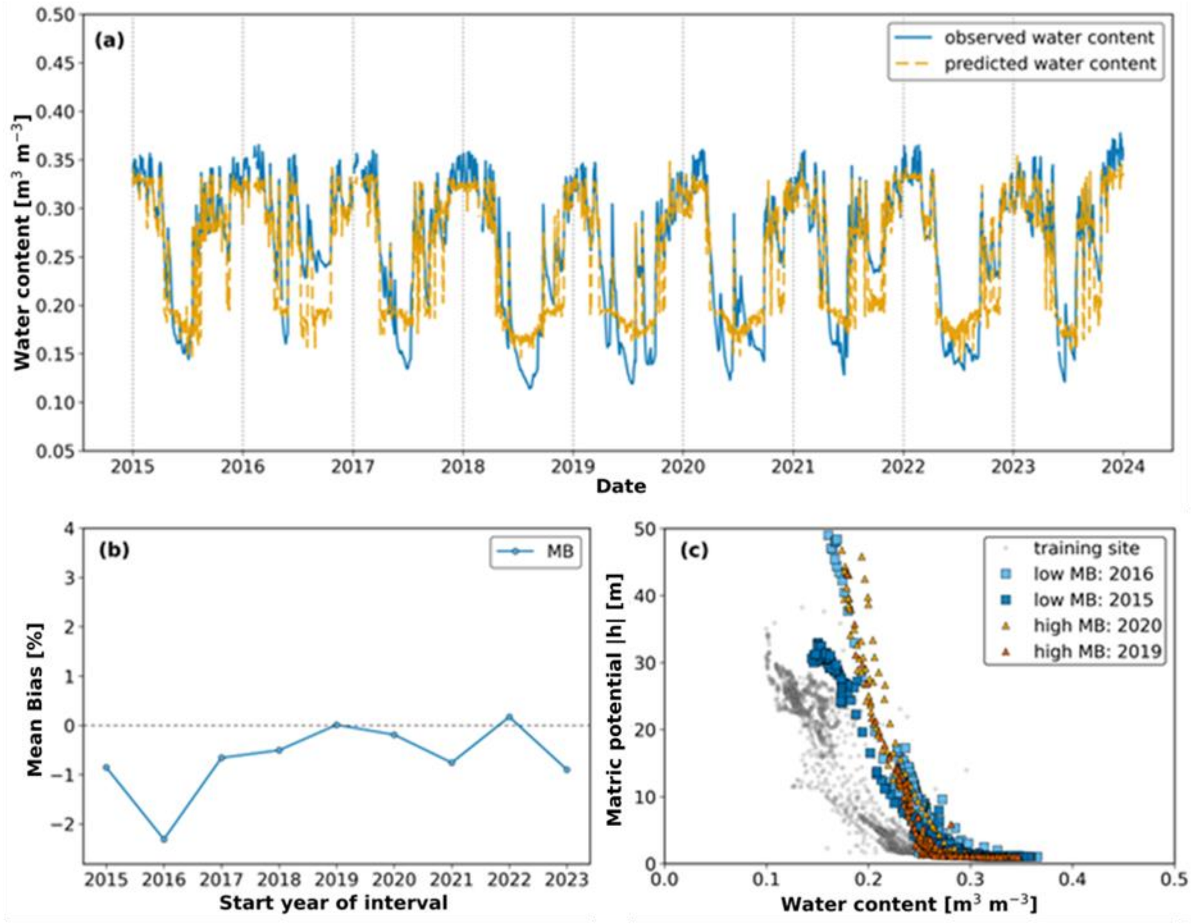

Figure S7. *Soil moisture dynamics (2015–2023) for a Selhausen-origin lysimeter tested at Selhausen. (a) In comparison to the main-text (figure 8a), the fit between observed (blue) and predicted (orange) water content improves in the saturated range but shows larger deviations at low water contents. The NSE value dropped from 0.86 in Figure 8a to 0.83. (b) The mean bias (MB) shows a similar trend as in 8b but with a more pronounced drop in 2nd half of year 2016 (underestimating the water content). Panel (c) displays soil water retention data from the training site (grey) and from selected years representing different MB conditions and is identical to Figure 8c in the main text.*

Text S2: Quantification of changes in soil water retention curve

In the main text we detected changes in the response function between soil moisture dynamics and climatic condition based on the analysis of water content data. Such changes in the response function are ultimately related to modified soil hydraulic properties like the soil water retention curve (SWRC). To compare SWRC between soil types, climatic regions (continental climate in Bad Lauchstädt and more humid climate in Selhausen), and different years, we computed the integral mean water content (*IMWC*) as defined in Romano et al. (2025), integrating the soil water content over a certain range of matric potential values (here expressed as absolute head value in m). In this study, we used a head value of 50 m as upper bound (more negative values were not measured) and 3.0 m as lower bound (to be above the lower range limit of the matric potential sensor that is 1.0 m). To integrate the soil water content in this pressure range, we fitted for each year the van Genuchten model to the daily values of matric potential and water content measured in 0.1 m depth and obtained for the *IMWC* [m^3 m^{-3}]:

$$IMWC = \frac{1}{\log_{10}(3.0) - \log_{10}(50)} \int_{\log_{10}(3.0)}^{\log_{10}(50)} \left[\theta_{res} + \frac{(\theta_{sat} - \theta_{res})}{\left(1 + \left(\alpha \cdot 10^{\lambda}\right)^{n}\right)^{(1-1/n)}} \right] d\lambda \tag{S1}$$

with residual θ_{res} [m^3 m^{-3}] and saturated volumetric water content θ_{sat} [m^3 m^{-3}], shape parameters α [1/m] and n [-], and where λ [-] is the logarithm of the absolute value of the matric potential head expressed in meters, and 3.0 m and 50 m are the lower and upper bound of the absolute values of the matric potential head, respectively. In figure S8 the *IMWC* is shown for each year from 2015 to 2023, with one panel for each soil material. As discussed in the figure captions, it can be seen that the categories of the response function (‘stable’, ‘resilient’, and ‘changed’) are in fair agreement with the trends of the IMWC values except for two lysimeters in Selhausen, that showed an increase in the IMWC in the last two years. Considering that the soil water content dynamics (without matric potential data) were similar in the last two years but high water content values were assigned to more negative potential values than in the previous years, we hypothesize that this deviation is related to problems with the matric potential sensor in the two lysimeters.

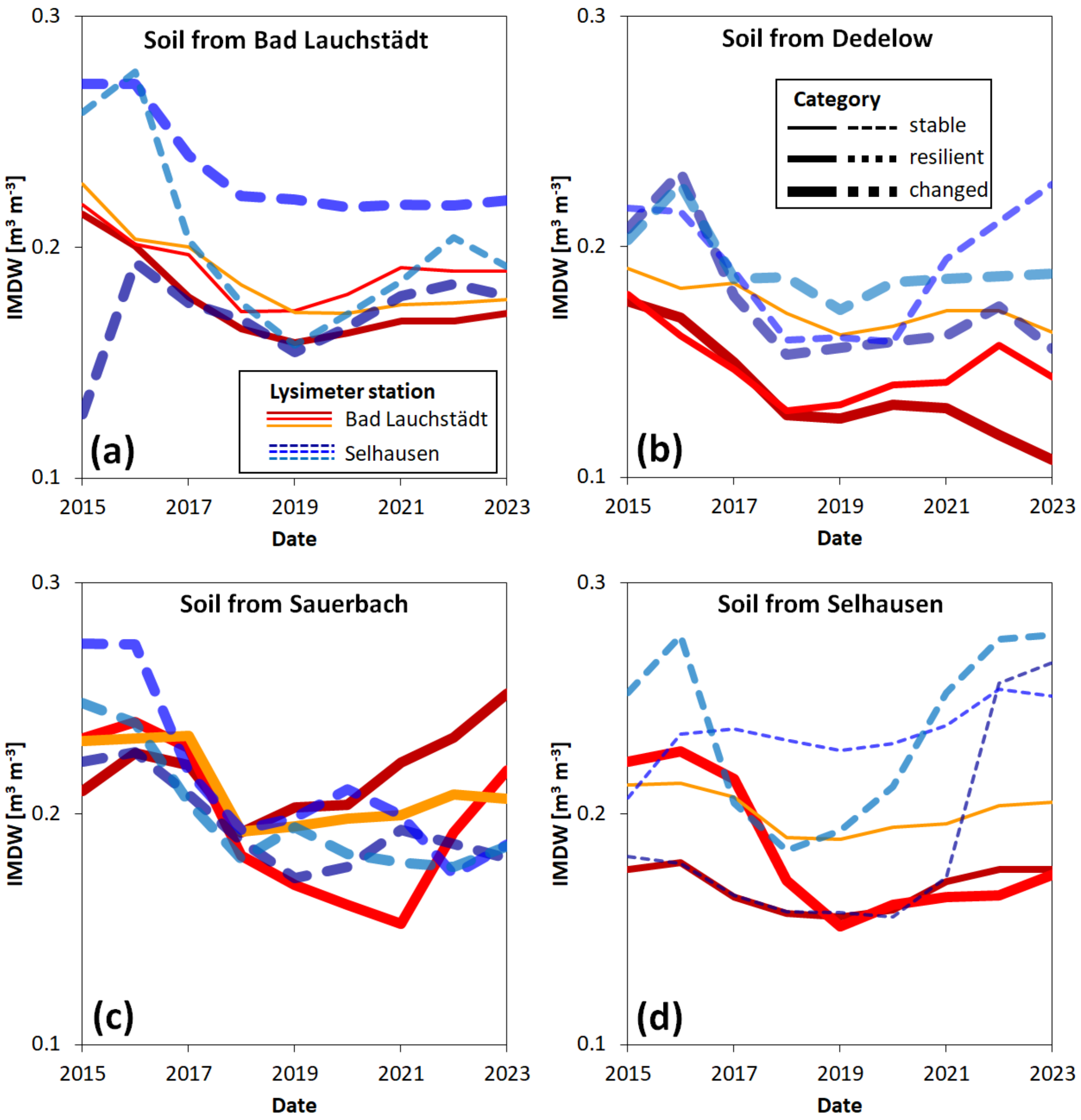

Figure S8. *Integrated mean water content (IMDW) for the four soil materials computed for each year of the observation period based on equation S1. Reddish bold lines are for the lysimeters at the Bad Lauchstädt site with continental climate and blueish dashed lines for the lysimeters at Selhausen (more humid climate). The line thickness shows the stability category as defined in the main text. (a) For the soil from Bad Lauchstädt, there is a big contrast between the lysimeters in their original climate zone (all three specimen show similar values and trends) and those in the more humid climate (different trends and values), supporting the results of Table 1 in the main text with more 'stable' response function at Bad Lauchstädt compared to Selhausen. (b) For the sandy loam from Dedelow, the only lysimeter classified as 'changed' at the Bad Lauchstädt station is manifested in a gradually decline of the IMDW value (dark thick red line). (c) For lysimeters with soil material from Sauerbach (a climate similar to Bad Lauchstädt), the soil water retention dynamics is never 'stable' but seems resilient in the climate of Bad Lauchstädt, with IMDW recovering to values found at the beginning of the observation period. (d) For soil material from Selhausen, the categories based on the main text match to the IMDW values for the climate in Bad Lauchstädt (one lysimeter with 'changed' response shown with dark red line), but are different for the lysimeters at their original climate: two curves that were classified as 'stable' based on the categories of the main text, show an abrupt 'change' of the IMDW values in the last two years. This is probably related to the matric potential sensor that were much more negative for high water contents compared to the seven previous years.*