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Does drought alter hydrological functions in forest soils? An infiltration experiment

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Abstract

The water cycle is expected to change in future and severely affect precipitation patterns across central Europe and in other parts of the world, leading to more frequent and severe droughts. Usually, it is assumed that system properties, like soil properties, remain stable and will not be affected by drought events. To study if this assumption is appropriate, we address the effects of drought on the infiltration behavior of forest soils using dye tracer experiments on six sites in three regions across Germany, which were forced into drought conditions. The sites cover clayey, loamy and sandy textured soils. In each region, we compared a deciduous and a coniferous forest stand to address differences between the main tree species. The results of the dye tracer experiments show clear evidence for changes in infiltration behavior at the sites. The infiltration changed at the clayey plots from regular and homogeneous flow to fast preferential flow. Similar behavior was observed at the loamy plots, where large areas in the upper layers remained dry, displaying signs of strong water repellency. This was confirmed by WDPT tests, which revealed, in all except one plot, moderate to severe water repellency. Water repellency was also accountable for the change of regular infiltration to fingered flow in the sandy soils. The results of this study suggest that the "drought-history" or generally the climatic conditions in the past of a soil are more important than the actual antecedent soil moisture status regarding hydrophobicity and infiltration behavior; and also, that drought effects on infiltration need to be considered in hydrological models to obtain realistic predictions concerning water quality and quantity in runoff and groundwater recharge.

1 Introduction

Soils moderate how water moves through the vadose zone and govern the percolation of water to groundwater and stream flow. Soils not only store water for plant growth, function as a habitat for different biota and as transition zone to groundwater, but are also important – especially the top layers – for sorption and degradation of contaminants and (agri-)chemicals (Hendrickx and Flury, 2001). The efficiency of this important ecosystem service for groundwater and surface water protection depends on the behavior of pollutants in the soil and the hydrological transport processes (Keesstra et al., 2012). How fast water passes the vadose zone depends on its hydraulic soil properties and distribution such as pore volume distribution, soil aggregation, water repellency and rooting pattern.

Due to climate change and increasing human intervention, the global water cycle is expected to change with probably increasing summer dryness and winter wetness in many regions across the world including Western and Central Europe (IPCC, 2012; Prudhomme et al., 2014). In addition, droughts are expected to be more frequent and severe in the future (Prudhomme et al., 2014; Seneviratne et al., 2006). Drought conditions can alter the hydrological functions of soils, and soil structure is responding to drought by shrinkage and fracturing of soil aggregates. These shrinkage cracks foster bypassing of the soil matrix (Hendrickx and Flury, 2001; Ritsema et al., 1997) and therefore alter the infiltration patterns in soil. Thus, the infiltration and redistribution of water within the soil changes and hence also the proportion of water reaching the groundwater (Hendrickx and Flury, 2001).

Soils under drought conditions are prone to become water repellent, depending on soil properties and organic matter content (DeBano, 1981, 2000). Due to modifications of the three-dimensional distribution and dynamics of soil moisture, water repellency has far reaching consequences for infiltration processes (Doerr and Ritsema, 2006). Water repellency hinders infiltration and thus either increases overland flow (Doerr and Ritsema, 2006) or redirects the water into preferential flow paths and creates instable wetting fronts (fingered preferential flow; Ritsema et al., 1993, 2000; Dekker and Ritsema, 2000).

To assess the impacts of drought and climate change, rainfall exclusion experiments are valuable and often applied tools (e.g. English et al., 2005; Phillips et al., 2009; Da Costa et al., 2010; Kopittke et al., 2014), often in addition to elevated CO_2

concentrations (e.g. Dermody et al., 2007) and night-time warming (e.g. Albert et al., 2011; Selsted et al., 2012). Many studies focus on single aspects of drought effects like plant growth and seedling activity (Meijer et al., 2011; Wu and Chen, 2013) or explore particular ecosystems like grassland (Suttle and Thomson, 2007; Bütof et al., 2012) and heather ecosystems (Albert et al., 2011; Selsted et al., 2012). Only a few studies focus on forest ecosystems or take a closer look at drought impacts on soils where often only soil moisture is observed (Ozolinčius et al., 2009; Albert et al., 2011; Glaser et al., 2013).

To achieve drought effects, extreme short-time drought events up to occurrence equivalents of 100-year or even 1000-year droughts are often introduced to the examined soils (e.g. Glaser et al., 2013). By introducing these extreme events, the question of transferability of the results to natural systems in respect to the expectable behavior under predicted future drought conditions arises. Therefore, this study employs a moderate rainfall reduction equivalent to an annual drought with a 40-year return period, in accordance to climate predictions, thereby avoiding tentativeness due to an overreaction to an unnatural extreme drought (Gimbel et al., 2015).

To monitor changes in soil hydraulic properties, the changes in infiltration patterns in the soil after two years of prolonged drought were observed in three regions across Germany. Infiltration patterns were chosen because they reflect integrally the changes of soil hydrological functions and directly show how water moves in the soil under altered conditions. In this paper, we present results of several dye tracer infiltration experiments before and after two years of prolonged artificial drought. The objectives of this study were: first, to investigate, whether droughts predicted by climate projections affect the infiltration behavior of forest soils, and second, whether changes in infiltration patterns can be attributed to changes in the hydrologic properties of the soils. Three hypotheses will be tested: (1) induced drought alters infiltration patterns due to changes in soil hydraulic properties; e.g. soil water repellency and forming of shrinkage cracks, leading to preferential flow paths and faster infiltration. (2) The main tree species have an effect on the magnitude of the observed response. (3) The drought will increase water repellency depending on tree species and soil properties.

2 Material and methods

2.1 Study sites

To identify the influence of drought on infiltration patterns of forest soils, six plots in three different regions across Germany were selected. The plots were located in Schwäbische Alb (South-West Germany), Hainich-Dün (Central Germany) and Schorfheide-Chorin (North-East Germany) (Fig. 1). All plots are part of the Biodiversity Exploratories framework that incorporates, in total, 150 sites on grassland and 150 sites in forest (for more information on the Biodiversity Exploratories, refer to Fischer et al., 2010). In each of the Exploratories, two forest plots were selected, which are – within each Exploratory – similar with respect to topography and soil type (Fig. 2) but differ in tree species composition. In each site, one plot with a coniferous and one with a deciduous main tree species was selected. At the Schwäbische Alb and Hainich-Dün sites, beech (*Fagus sylvatica*) and spruce (*Picea abies*) were chosen, in Schorfheide-Chorin beech and pine (*Pinus sylvestris*).

The Schwäbische Alb soils are shallow (25–35 cm) Leptosols on Jurassic shell limestone with a high stone content (Fig. 2, top). The mean annual temperature at this site is 6.5 °C and the mean annual precipitation amounts to 940 mm. The underlying geology of the Hainich-Dün is Triassic limestone. The soils are loamy Stagnosols with depths between 45 and 65 cm. The mean annual temperature is 7.2 °C and the mean annual precipitation is 533 mm. The Schorfheide-Chorin plots are located in a young glacial landscape where the dominant geological substrate is glacial till covered by glacio-fluvial and aeolian sands. The soils are deep, sandy Cambisols. At the Schorfheide-Chorin site, mean annual temperature is 8.5 °C and the mean annual precipitation amounts to 589 mm. All climate data are taken from nearby stations of the German weather service (DWD, years 1950–2010).

The experiments of this study are part of the interdisciplinary project "Global Change Effects on Forest Understorey: interactions between Drought and Land-use Intensity" (Gimbel et al., 2015). The artificial imposed drought was created by a 10 m × 10 m roofed subplot, covered with transparent panels. The incoming precipitation was reduced between March and November to the level equivalent to an annual drought with a return period of 40 years. In addition, a control plot with the same technical equipment, but without the roofing was installed. For a more detailed description of the whole experimental drought setting and of the study plots see Gimbel et al. (2015).

2.2 Dye tracer experiments

The dye tracer experiments were conducted in August 2011 before installation of the roofs and in August 2013 after two years of drought. For each experiment, an area of 80 cm × 120 cm was prepared by cutting smaller vegetation (grasses, herbaceous plants, and small tree offshoots), covering the surroundings with a thin plastic sheet and dividing the area into three sub-areas with a size of 80 cm × 40 cm each (Fig. 3a). The experimental area was kept shaded and sheltered in all weather conditions to minimize evaporation and uncontrolled water input during the experiments. Brilliant Blue FCF was diluted in water of local origin to a concentration of 4 $\mathrm{g\,L^{-1}}$ and was sprayed with a backpack nozzle sprayer for even distribution (Bachmair et al., 2009). For an overall application amount of 20, 40 and 60 mm, each sub-area was sprinkled with an intensity of 20 $\mathrm{mm\,h^{-1}}$. The applied rainfall intensity of 20 $\mathrm{mm\,h^{-1}}$ reflects a heavy rainfall event in all regions. After sprinkling, the experimental area was covered with plastic sheets to prevent evaporation and further water input through eventual rain.

The next day (after waiting at least 12 h), three vertical soil profiles per sub-area were prepared. Keeping a 10 cm buffer stripe at the beginning and between the individual sub-areas, every sub-area was divided in three sections, spaced 10 cm from each other (Fig. 3a). To obtain the dye pattern, the surface of the excavated soil profiles was smoothed with a spatula and loose particles were removed with a brush, avoiding smearing. Stones were left in place and shaped into relief when needed. Roots were trimmed. Pictures were taken from each profile with a standard digital compact camera with a resolution of 10 megapixels (3648 × 2736 pixel). The single profiles were photographed with a ruler frame and a grey scale under even illumination and different illumination settings (Weiler and Flühler, 2004). The picture with the best image quality from each profile was used for further processing.

2.3 Image processing and data analysis

To objectively compare the flow pattern of the different profiles, we used the image analysis procedure developed by Weiler and Flühler (2004). We provide a short description of the process here, for more detailed information, refer to Weiler (2001) and Weiler and Flühler (2004). The image processing consists of three main steps. In the first step, geometric distortion of the image is corrected by establishing a relationship between the image pixel location and the true location on the soil profile. During this step, the image is also scaled such that, one pixel corresponds to a square of 1 mm × 1 mm. In the second step, the spectral composition changes in daylight are balanced to ensure inter-picture comparability. This is done by a color adjustment of the image using the photographed grey scale. In the third step, the images are classified into stained and unstained areas. Applying a semi-supervised classification technique, a binary image of stained vs. unstained areas is obtained. In contrast to the work of Weiler and Flühler (2004), we did not use the information of different dye tracer concentrations, due to the high heterogeneity of the background color. In this step, objects like stones and vegetation are manually digitized, too. All calculations were done with IDL.

2.4 Dye pattern analysis

For objective measures to compare the dye patterns of the different profiles and sites, we derived three depth related variables of the binary images: (1) volume density, (2) surface density and (3) stained path width as basis for further delineation of flow processes. The volume density (vd) is similar to the frequently used dye coverage. It is defined as stained volume divided by the reference space and is originating from the methods of stereology, which relates a three-dimensional parameter to two-dimensional measurements (Weibel, 1979). Surface density (sd) is defined as surface area of an object divided by the volume of the reference space. Surface density provides information on the size and number of features: a high sd is caused by a large number of small objects, whereas a low sd indicates less but larger objects (Weiler, 2001). As third variable, the stained path width (SPW) was calculated. The stained path width is derived by measuring the width of every stained object at a certain depth. Using the frequency distribution of the SPW of every depth, the dye pattern can be related to distinct flow processes. The classification introduced by Weiler and Flühler (2004) was used to distinguish five flow processes: two types of matrix flow – (1) homogeneous and (2) heterogeneous, and three types of macropore flow – (3) low, (4) mixed and (5) high interaction with matrix, where interaction is understood as the lateral water flow from macropores into the surrounding soil matrix (Weiler and Naef, 2003).

2.5 Soil water repellency

Hydrophobicity in soil was measured with the water drop penetration time (WDPT) test (e.g., Bisdom et al., 1993). This test determines how long water repellency persists on a porous surface. The tests were performed immediately before the dye tracer experiments in 2013, in the drought and control profiles of the deciduous plots and in the drought profiles of the coniferous plots. For the WDPT tests, a water droplet is placed on a planar soil surface with a pipette and the time is taken until the complete intake of the water drop into the soil. The observation was stopped after exceeding a time of 3600 s. Depending on the profile depths, WDPT tests were performed in several depths of the profile. In each depth, five sampling locations were used to traverse the profile, and the tests were repeated three times per location, resulting in 15 WDPTs per depth (Fig. 3b). The mean and maximum values of the WDPT test were classified after Bisdom et al. (1993) (Table 2).

2.6 Soil moisture model – LWF-BROOK90

To evaluate the soil moisture conditions before and during the infiltration experiment, we used the forest hydrological LWF-Brook90 model of Hammel and Kennel (2001). LWF-Brook90 is a one-dimensional, process-oriented model (Federer et al., 2003). The daily soil water budget is simulated as the result of infiltrating precipitation, water flow through the soil and water loss by evapotranspiration. For the climate input data, daily time series of nearby weather stations (station-IDs 03402, 00487, and 00164) of the German Weather Service (DWD) were used. Additional soil and site parameters were obtained from soil profile and on-location analyses (soil genetic horizons and their soil texture, bulk density, stone content). The water retention curve and the hydraulic conductivity of the soil horizons were estimated using a pedotransfer function (Puhlmann and von Wilpert, 2011). Additional model parameter, used for the description of vegetation effects on the local water budget, were either obtained from field observations (depth distribution of roots), the BExIS database (id17687 forestEP stand structure and composition, stand density and tree age), approximated from literature (e.g. annual course of leaf area index). If a certain vegetation parameter was not available, the values were set following the suggestions of the model developers.

3 Results

3.1 Soil moisture changes

Figure 4 shows the results of the LWF-Brook90 simulations. All soils show a drop in soil moisture during the summer months (2011 and 2013). Before the experiment in 2013 (orange line marks the date), the soil moisture status of the drought treated plots and the control plots are very similar, except for the coniferous plot in Schorfheide-Chorin. Rainfall was reduced between March and November. Therefore, the highest soil moisture contents are observed during winter and early spring (December – April). However, the largest differences in soil moisture between drought and control plots are observed generally in fall and early winter (October – December). Compared to deciduous plots, all coniferous plots (drought and control) show pronounced low water contents in the 15 cm layers. Additional soil moisture measurements on the plots support the modeling results (not shown). Hence, the observed infiltration patterns and changes among the sites are mainly a result of changes in soil properties and not due to differences in soil moisture conditions prior and during the experiment.

3.2 Soil water repellency

Figure 5 shows the results of the WDPT test in 2013. All drought treated plots at all sites – coniferous and deciduous – exhibit water repellency (WDPT data from control plot under coniferous not available). All control plot soils are wettable (WDPT class 1) or feature at least lower water repellency than the drought treated plots. In general, coniferous plots under drought had higher WDPTs than deciduous plots. This is valid for both mean and maximum values, with the exception of the Schorfheide-Chorin deciduous plot, which showed higher water repellency than the coniferous plot. In all soil profiles, water repellency is highest in the topsoil and diminishes at a depth of about 20 cm. However, in the Schorfheide-Chorin deciduous plot, water repellency is present up to a depth of 50–60 cm. When present, strong to severe water repellency is dominant in the measured drought treated plots. Only the Hainich-Dün deciduous plot soil is classified as wettable in average and the Schorfheide-Chorin coniferous plot as slightly water repellent. Highest values in mean and maximum water repellency were found in the coniferous plots Hainich-Dün (mean 941 s; max 3600 s) in about 10–15 cm depth and in the Schwäbische Alb (mean 990 s; max 2340 s) in the topsoil (Fig. 5).

3.3 Dye tracer experiments and dye pattern analysis

3.3.1 Comparison between pre-drought pattern and control pattern

Differences between pre-drought and control plots (without drought treatment) reflect differences in soil structure, texture and moisture due to a distance of 20–40 m between the drought and reference plot, but may also include time dependent changes of the soil characteristics, which are independent from the drought treatment. To ensure validity of the dye pattern analyses, it is necessary to assure comparability among the plots. By comparing the pre-drought pattern and the pattern for the control plots time dependent changes as reason for differences in pre-drought and drought treated dye pattern can be excluded. Figure 6 compares the pre-drought pattern and the control pattern of the deciduous plots.

The Schwäbische Alb pre-drought plot (Fig. 6, top left) shows high vd in the top 10 cm in all profiles. The 40 and 60 mm sprinkling volume profiles show a high SPW in the top 5–10 cm. On the control plot (Fig. 6, top right) also large areas of the profiles top 10 cm are stained, but the vd and SPW are not as high as the pre-drought profiles. All Schwäbische Alb profiles have high stone content, in some cases exceeding 50 % of the profile width. Below 10 cm depth, the control plot profiles are almost completely stained. This pattern is very similar to the pre-drought profiles. In general, the patterns of the control profiles are similar in vd, SPW values, and distribution to the 20 mm pre-drought profile. The 60 mm control profile is reflecting the high vd and SPW values in top layers, which are characteristic of the 40 and 60 mm pre-drought profiles.

The Hainich-Dün pre-drought profiles (Fig. 6, center left) show low to medium SPW in all depths. Vd values are high in the top 5 cm in all profiles and between 10–30 cm in the 40 and 60 mm sprinkling amount profiles. The 20 mm profile displays only small vd values below 10 cm depth. All profiles have a medium to high stone content below 30 cm depth. The control plot profiles (Fig. 6, center right) are very similar in vd and SPW to the pre-drought profile pattern, but with generally lower vd in the top 5 cm of the 60 mm sprinkling amount profile. Except for the 20 mm profile, which displays no stones, the control plot profiles have a medium to high stone content below 25 cm depth. In all profiles, large areas of the profile stayed unstained. However, although having a low vd in top layer, the 60 mm control plot profile is not following the pronounced drop in vd between 5 and 10 cm depths and the subsequent rise between 15 and 25 cm, which is characteristic for all other profiles (pre-drought and control).

In the Schorfheide-Chorin pre-drought profiles (Fig. 6, bottom left), high vd and SPW values are present. The highest vd and SPW values can be found in the 60 mm sprinkling amount profile. Below 10 cm depth, the 20 mm pre-drought profile displays only small to medium SPW and – in comparison to the 40 and 60 mm profiles – small vd values. The control plot profiles (Fig. 6, bottom right), show in general high vd and SPW values, but have lower values in the top 10 cm than the pre-drought profiles. In the pre-drought and control plot, infiltration reached down to depths over 70 cm and no stones are present.

To summarize, the comparison between the pre-drought and control plots showed only small differences. In the Hainich-Dün, the drop and rise of vd in all profiles points to a soil layer boundary effect on infiltration. This is not time dependent and present in both pre-drought and control profiles, therefore the comparability between the pre-drought and drought pattern is not affected.

3.3.2 Comparison between pre-drought pattern and drought pattern

As can be seen in Fig. 7, all plots show marked differences between pre- and after-drought infiltration patterns. All clayey and loamy sites (Schwäbische Alb and

Hainich-Dün) develop unstained (= unwetted) areas in the topsoil layers. This is more pronounced in the coniferous plots, where unstained areas are already visible in the pre-drought infiltration pattern.

At Schwäbische Alb, the pre-drought deciduous plot showed medium to high vd in all depths; high vd in top 15 cm of 40 and 60 mm sprinkling volume profile. This is corresponding with small to medium stained path ways (SPW), found in pre-drought coniferous plots and large SPW in the top layer of the 40 and 60 mm sprinkling volume profiles of pre-drought deciduous plots (Fig. 7, top). Medium to low volume densities (vd) were found on the pre-drought coniferous plot throughout the whole profile for the 20 and 40 mm sprinkling depth and high vd for 60 mm sprinkling depth (Fig. 7, top). The dominating flow types in the pre-drought profiles are identified as macropore flow with low, mixed and high interaction depending on soil layer and infiltration volume. The flow processes identified as matrix flow are caused by local saturation due to low K_s (Fig. 7, top).

The Schwäbische Alb drought coniferous plot shows small to no (40 mm profile) vd in the top 10 cm followed by a rise of vd culminating around 20 cm depth (Fig. 7, top) for all sprinkling amounts (20, 40 and 60 mm). This is also the case for all deciduous profiles under drought. SPW as well coniferous as deciduous profiles is small to medium, except the 40 mm coniferous profile with large SPW between 20 and 35 cm. Dominating flow types are macropore flow with low, medium and high interaction. Heterogeneous matrix flow is identified at the coniferous plot with 40 mm sprinkling amount between 20 and 35 cm (Fig. 7, top).

The Hainich-Dün coniferous pre-drought plot show low vd for all sprinkling amounts especially in the topsoil between 4 and 22 cm (Fig. 7, center). Vd in the deciduous pre-drought plot is very low for the 20 mm sprinkling amount and medium for 40 and 60 mm. In both profiles, high vd in the topsoil alternates with low vd around 10 cm depths followed by a rise around 15 to 20 cm depth and a drop around 30 cm depth. In all pre-drought profiles, no large SPW occur and flow types are classified as macropore flow with low, mixed and high interaction. The coniferous pre-drought plot is dominated by macropore flow with low interaction, while this is only the case for the 20 mm profile in the deciduous pre-drought plot (Fig. 7, center).

The Hainich-Dün coniferous drought plot shows, for all sprinkling amounts, unstained areas in the top layers between 2 and 15 cm and low vd in all other depths (Fig. 7, center). Unstained areas and low vd is also found in the top 5–10 cm of the deciduous drought plot. They are followed in the profiles of all sprinkling volumes by a sharp rise in vd, with highest values between 15 and 30 cm. Despite the small overall vd values of the coniferous plots, the 40 mm profile shows large SPW around 20 cm depth, which can also be found for the 40 and 60 mm sprinkling depths of the deciduous plot. However, large SPW at 60 mm profile occur between 15 and 40 cm and therefore flow types are identified as matrix flow at these high SPW areas (Fig. 7, center).

All pre-drought profiles at Schorfheide-Chorin show high vd in the topsoil, declining with increasing depth (Fig. 7, bottom). While vd of the 20 and 40 mm coniferous pre-drought plots decline fast reaching unstained areas at 45 and 30 cm, respectively, the 60 mm coniferous and all deciduous pre-drought profiles keep a moderate vd until the end of profile. SPW is large in all profiles under pre-drought coniferous and deciduous plots, especially in top layers. An exception is the deciduous 20 mm profile, which has no large SPW. Flow types are dominated by matrix flow in the topsoil, however, except for the deciduous 60 mm profile, all profiles in both pre-drought plots have, a proportion of macropore flow (Fig. 7, bottom).

Whereas the Schorfheide-Chorin deciduous drought profiles show not much change in vd compared to the pre-drought profiles, vd in the coniferous plots differ substantially between the pre-drought and drought profiles (Fig. 7, bottom). Vd in the topsoil is small in the drought coniferous profiles and very low vd and even unstained areas occur (at the 20 mm sprinkling amount in 5 cm depth and at the 40 mm sprinkling amount in 5 cm depth, respectively). For the drought profiles with 40 and 60 mm sprinkling amount, vd rises again between 10 and 35 cm depth, where a large SPW can also be observed. In contrast to the low changes in vd in the deciduous profiles between drought and pre-drought conditions, the SPW pattern are different: pre-drought profiles show large

SPW values in the top half of the profile, in the drought profiles, large SPWs occur in the bottom half. This is reflected by the flow type classification. Matrix flow is occurring in bottom half of all drought deciduous profiles. In the drought coniferous profiles, matrix flow is occurring between 10 and 25 cm in the 40 and 60 mm profiles (Fig. 7, bottom).

To summarize, compared with pre-drought infiltration pattern, the drought pattern of all plots reveal differences in infiltration processes. Clayey and loamy soils behave similarly, developing unwetted soil layers. High SPW values in 20–30 cm depth of the drought pattern indicate local saturation. In sandy soils, the change from high SPW values of the pre-drought pattern to medium and low in the drought pattern exhibit a change from front-like to a more scattered infiltration. In general, the effects were more pronounced at the coniferous plots. These findings correspond well with the results of the WDPT tests: in the clayey and loamy soils (except Hainich-Dün deciduous plot), the unstained topsoil layers are coinciding with the high WDPTs (Fig. 5). Coniferous plot Hainich-Dün stays unwetted up to a depth of about 15–20 cm and Schwäbische Alb plots to a depth of about 10 cm, which is corresponding to the depths where the highest WDPT values were observed (Hainich-Dün: WDPT class 4; Schwäbische Alb: WDPT classes 4 and 3, respectively). In the sandy soils of the Schorfheide-Chorin profiles, low SPW values correspond to high WDPTs (classes 2 and 3). Below the water repellent zone, SPW values are increasing again (Fig. 5, bottom).

4 Discussion

4.1 Infiltration patterns and influence of main tree species

The comparison of pre-drought infiltration patterns of the drought plots with patterns of the control plots (without drought treatment) showed no differences which can be addressed to other reasons than small scale heterogeneities of soil properties. All control plot profiles can be assumed to be comparable to the pre-drought plot profiles. Therefore, it can also be assumed that no substantial difference between the drought (treatment) plots and the pre-drought plots exist; no relevant time dependent changes happened between the pre-drought experiment in 2011 and the experiments on the control and drought plots in 2013. Therefore, we can directly compare the dye experiments at all sites before and during drought conditions.

In this study, it was hypothesized that the induced drought alters infiltration patterns due to changes in soil hydraulic properties (e.g., soil water repellency and forming of shrinkage cracks) and the tree main species is having an effect on the magnitude of the response. The results of the infiltration experiment show a clear evidence for changes in infiltration pattern as well as the importance of tree species on infiltration pattern: Schwäbische Alb plots have clayey soils with a high stone content, and show, in pre-drought and control plots, a slow and even infiltration. The drought-treated plots developed large areas with small volume densities and SPWs in the topsoil, while for deeper layers, broad stains (large SPW) were observed which cover the profiles for the most part (high vd). This is typical for preferential flow that follows the shrinkage cracks of clayey soils or biopores of roots or soil fauna (Dekker and Ritsema, 2000; Hendrickx and Flury, 2001; Hardie et al., 2011). Water infiltrates quickly to deeper layers, bypassing a large proportion of the soil matrix. In deeper soil layers where the cracks or biopores end, local saturation occurs, and lateral redistribution into the soil matrix due to the now lower infiltration capacity and velocity can be observed. This also explains the similar pattern in the loamy Hainich-Dün soils.

A trend to more preferential flow was also observed in the Hainich-Dün plots, where the dense and loamy soils are also prone to shrinkage. Furthermore, in the Hainich-Dün drought profiles unstained (i.e., unwetted) areas in the topsoil layers were observed. This is more pronounced in the coniferous plot, where unstained areas were already visible in the pre-drought experiment. Preferential flow does not only originate from cracks and biopores, but also from textual boundaries and instable wetting fronts (Doerr and Ritsema. 2006; Hendrickx and Flury, 2001). Unstable wetting fronts can occur due to air entrapment or hydrophobicity, which effectively hinders infiltration and redirects the water to structural and textural preferential flow paths (Doerr and Ritsema, 2006). The unwetted topsoil layers of the Hainich-Dün coniferous plots can be explained by the combination of severe water repellency and shrinkage cracks acting as effective bypasses.

In contrast to the other sites, Schorfheide-Chorin soils are sandy and highly permeable with low stone content. In both Schorfheide-Chorin plots, the infiltration patterns changed from a regular front-like stable infiltration to unstable, more scattered and fingered infiltration patterns. Following the conceptualization of unstable flow in water repellent soils by Ritsema et al. (1993, 2000), water flows, after entering the soil, through preferential pathways through the water repellent layer and distributes laterally in the divergence layer underneath. In fact, such flow patterns were pronounced in the Schorfheide-Chorin deciduous drought plot: medium vd and SPW up to a depth of 50–60 cm and larger SPW in the layer beneath. This fits with the results of the WDPT tests, which show a slight to strong water repellency in the top 50–60 cm of the profile.

In general, drought induced major changes on the infiltration behavior of the examined soils. Clayey and loamy soils developed preferential flow. In these soils, the bypassing of the top 10–20 cm is fostered by water repellency, leading to unwetted topsoil layers. Sandy soils developed fingered infiltration patterns, due to the forming of a water repellent layer. In all three sites, the effects of the drought treatment were more pronounced in soils with coniferous main tree species than with deciduous main tree species.

4.2 Water repellency

In this study, it was hypothesized that the artificial induced drought will increase soil water repellency depending on the main tree species and soil properties. The highest water repellency was found in the coniferous plots of Schwäbische Alb and Hainich-Dün. Soils under coniferous trees often feature acidic soil conditions, which promote water repellency (Orfánus et al., 2014). In a study by Orfánus et al. (2014) liming practices and associated rise of pH-values significantly reduced water repellency of former pine forest soils. Jost et al. (2004) explained the difference in recharge under a beech and a spruce forest stand, with the higher hydrophobicity, and therefore the hindering of infiltration, combined with higher surface runoff of the spruce stand. This is in contrast to the findings of Buczko et al. (2006), who found the highest proportion of water repellent soils in pure beech stands compared to pure pine and mixed stands on sandy soils. However, in our study the sandy Schorfheide-Chorin plots showed higher mean WDPTs in the deciduous (beech) plot, than on the coniferous (pine) plot.

The soil texture can also influence the water repellency: a study of Gonzalez-Penaloza et al. (2013) suggests that water repellency is related to soil particle size. They induced water repellency by using different concentrations of stearic acid on samples of fine, medium, and coarse sand. Water repellency was extreme in coarse textured samples. The authors explained that by the lower specific surface compared to fine textured samples and therefore smaller area that has to be covered by water repellent agents. We could not observe this effect in our sandy soils. The coarser textured coniferous plot was less water repellent than the finer textured deciduous Schorfheide-Chorin plot. However, water repellency can originate from a broad range of factors. The degree of water repellency of a soil also depends on the amount and type of organic matter that is incorporated in it (DeBano, 1981; Bisdom et al., 1993; Buczko et al., 2006; Vogelmann et al., 2013), the age and type of forest and litter type (Neris et al., 2013).

Several studies detected a significant impact of spruce litter on infiltration processes, either by hydrophobicity (Schume et al., 2004) or interception (Neris et al., 2013). Schume et al. (2004) found that spruce litter can intercept up to 5 mm of precipitation and Neris et al. (2013) found infiltration rates of 20 $\mathrm{mm\,h^{-1}}$ compared to that of 50 $\mathrm{mm\,h^{-1}}$ of deciduous stands, doubling the runoff of the sites. In this study, we did not record the interception of the litter layer, which may have altered the total amount of water infiltrating into the soil. However, a natural litter layer is always present and intercepts precipitation (e.g. Gerrits et al., 2010). By keeping the natural litter layer in our experimental setup, our test results include the two influencing factors of the systems natural response in the infiltration pattern: the redistribution of incoming precipitation by the litter layer, leading to more spatial heterogeneous water input in the soil, compared to a soil with removed or hydrophilic litter layer. The measured infiltration pattern is a result of both factors, giving a more natural representation than a separate observation of litter layer and soil response.

Furthermore, the plants of the forest understory can also influence hydrophobicity of the soil; plants are covered with a cuticle composed of hydrophobic liquids, embedded in a polyester matrix and wax crystalloids (Holloway, 1994; Barthlott and Neinhus, 1997). Water repellent plant coatings can be found in all plant life forms with a clear dominance in among herbs (Neinhus and Barthlott, 1997; Dekker and Ritsema, 2000). It is even discussed that hydrophobic exudates might be a strategy for plants, microorganisms and fungi, to suppress germination and growth of competing vegetation by reducing evaporation and nutrient leaching (Doerr et al., 2007).

Hydrophobicity is dependent on the moisture status of the soil, which is defined by Doerr and Thomas (2003) as critical moisture or transition zone. Vogelmann et al. (2013) found a critical water threshold of 0.36–0.57 $\text{cm}^3\,\text{cm}^{-3}$ beyond which hydrophobic soils become hydrophilic, varying as a function of soil organic matter content. In contrast to the findings of Doerr and Thomas (2003), we found very similar water contents in drought treated and control soils, but very different hydrophobicity conditions. This indicates that the "drought-history" or generally the climatic condition in the past of a soil is more important than the actual antecedent soil moisture status regarding hydrophobicity and infiltration behavior.

In our rainfall exclusion experiment drought stress was not intense enough to induce mortality or strong changes in above-ground biomass of a particular species (Gimbel et al., 2015). Nevertheless, drought and water repellency may promote the die-off of fine roots, which thereupon contribute to the total organic matter in the soil. The amount of soil organic matter and its composition has a strong influence on the strength of water repellency (e.g. Vogelmann et al., 2013; Bisdom et al., 1993; DeBano, 1981). Therefore, the die-off of fine roots may lead to a self-reinforcing circle of water repellency.

Soil organic matter can form micro- and macro-aggregates by acting as binding agent between soil components (e.g. Tisdall and Oades, 1982; Annabi et al., 2011) or by covering soil particles (e.g., Vogelmann et al., 2013a). Vogelmann et al. (2013b) concluded in their study, that water repellency leads to slower wetting of soil aggregates. Therefore, cohesive forces hold up longer, which increases the resistance to disaggregation and thus, indirectly aiding in maintaining soil structure. Terrestrial fungi are also in the focus of research concerning soil water repellency and aggregation (e.g. Tisdall and Oades, 1982; Rillig and Mummey, 2006; Chau et al., 2012). Zheng et al. (2014) found in three of nine species of ectomycorrhizal fungi associated with *Pinus sylvestris* seedlings increased soil water repellency and in six of nine species an increase of water stable aggregation. In our study, only the coniferous plot in Schorfheide-Chorin has *Pinus sylvestris* as main tree species. In fact, the plot showed slight (mean values) to strong (maximum values) water repellency in the top 20 cm. Nevertheless, the WDPT values of the deciduous plot in this area indicated stronger water repellency (in mean and maximum values).

All of our experimental plots showed clear response to the drought treatment, irrespective of their soil type and vegetation cover. Especially the fast bypassing of the topsoil layer and the developing of unstained and hence not wetted areas may bear consequences in the upcoming climate change. Sorption and degradation of contaminants is strongest in the topsoil and decrease with soil depth (Hendrickx and Flury, 2001). Thus, bypassing of the topsoil soil matrix foster early arrival times and high concentrations of contaminants in the groundwater, which was shown by several tracer field studies (e.g. Hendrickx and Flury, 2001; Ritsema et al., 1997; Hardie et al., 2011). Once formed, dry zones persist further wetting and additional water infiltrates through already existing preferential pathways, further stabilizing established flow paths (Dekker and Ritsema, 2000; Hagedorn and Bundt, 2002). Under present climate conditions, soil water repellency is already a widespread phenomenon (Buczko et al., 2006). For the predicted climate conditions, where droughts will be more common, an even higher level of hydrophobicity is to be expected, according to the findings of our rainfall reduction experiments.

5 Conclusions

Two years of rainfall reduction equivalent to an annual drought with a 40 year return interval was sufficient to change the soil properties and hence the infiltration pathways of six forest soils independent of soil type and tree species. All drought treated soils, except one, developed slight to severe water repellency. Main tree species had a particular effect on hydrophobicity, but is only accounting for minor differences in infiltration pattern. The "drought-history" or generally the climatic condition in the past had more effect on the observed hydrophobicity and infiltration behavior than the actual antecedent soil moisture conditions of the soils. The results of this study suggest that drought effects on infiltration processes need to be considered in hydrological models to obtain realistic predictions regarding water quality and quantity in runoff and groundwater recharge.

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Table 1. Classification of water repellency by WDPT time, after Bisdom et al. (1993).

WDPT in seconds	Classification	Class
< 5	wettable	1
5–60	slightly water repellent	2
60–600	strongly water repellent	3
600–3600	severely water repellent	4
> 3600	extremely water repellent	5

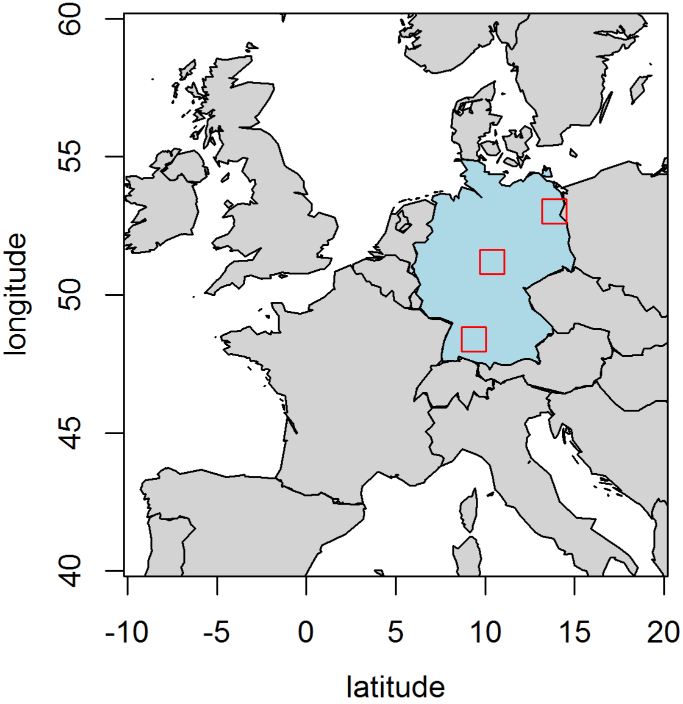

Figure 1. Location of the study sites (red squares) within Germany (light blue); South-West: Schwäbische Alb; center: Hainich-Dün; North-East: Schorfheide-Chorin.

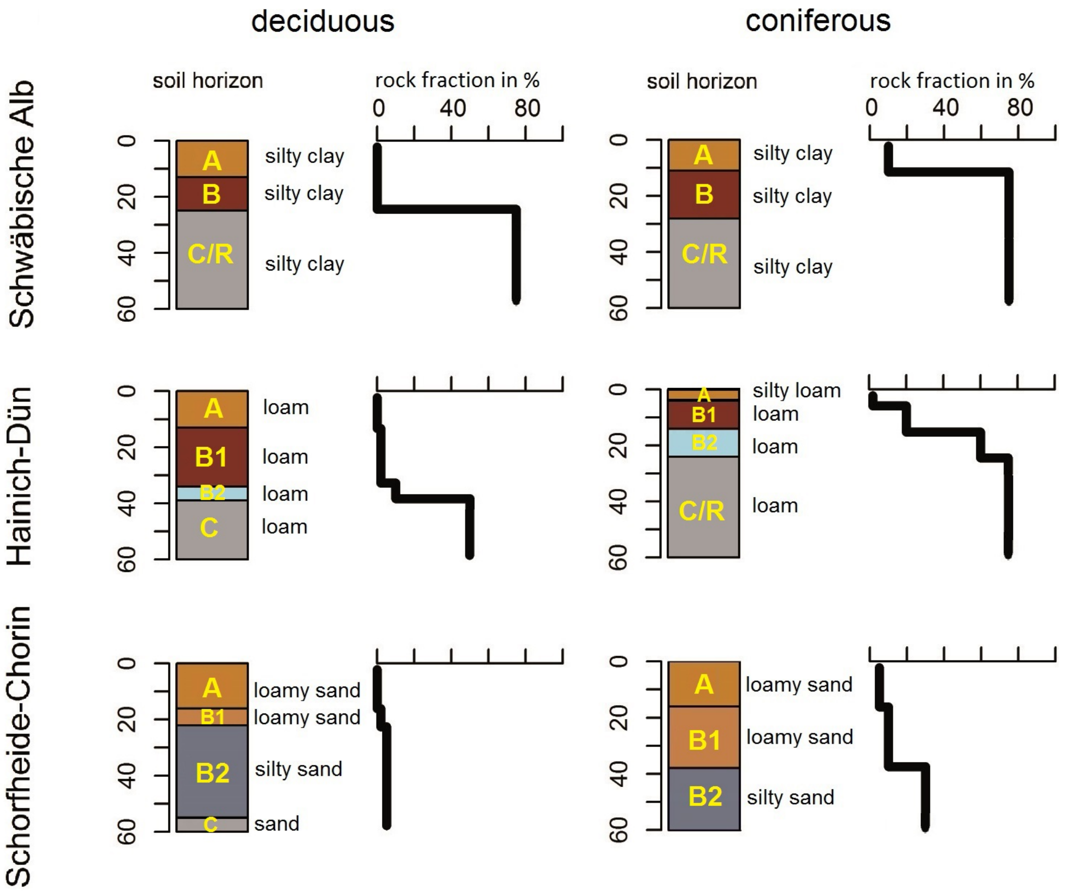

Figure 2. Soil horizons, texture, and rock fractions of the six experimental plots. Soil type classification according to the World reference base for soil (FAO, 2006a, b).

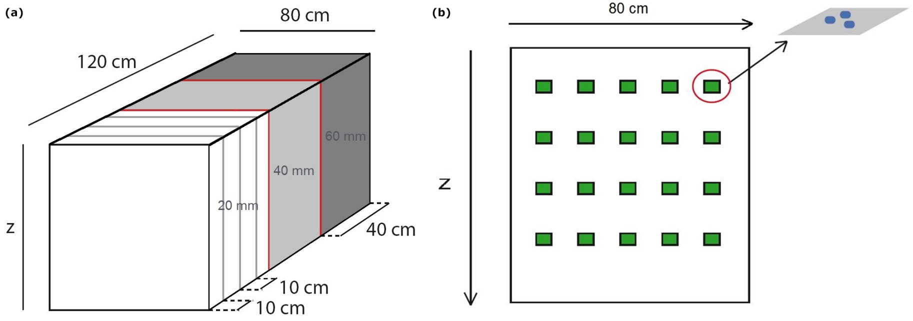

Figure 3. Scheme for profile excavation **(a)** and WDPT experiment **(b)**.

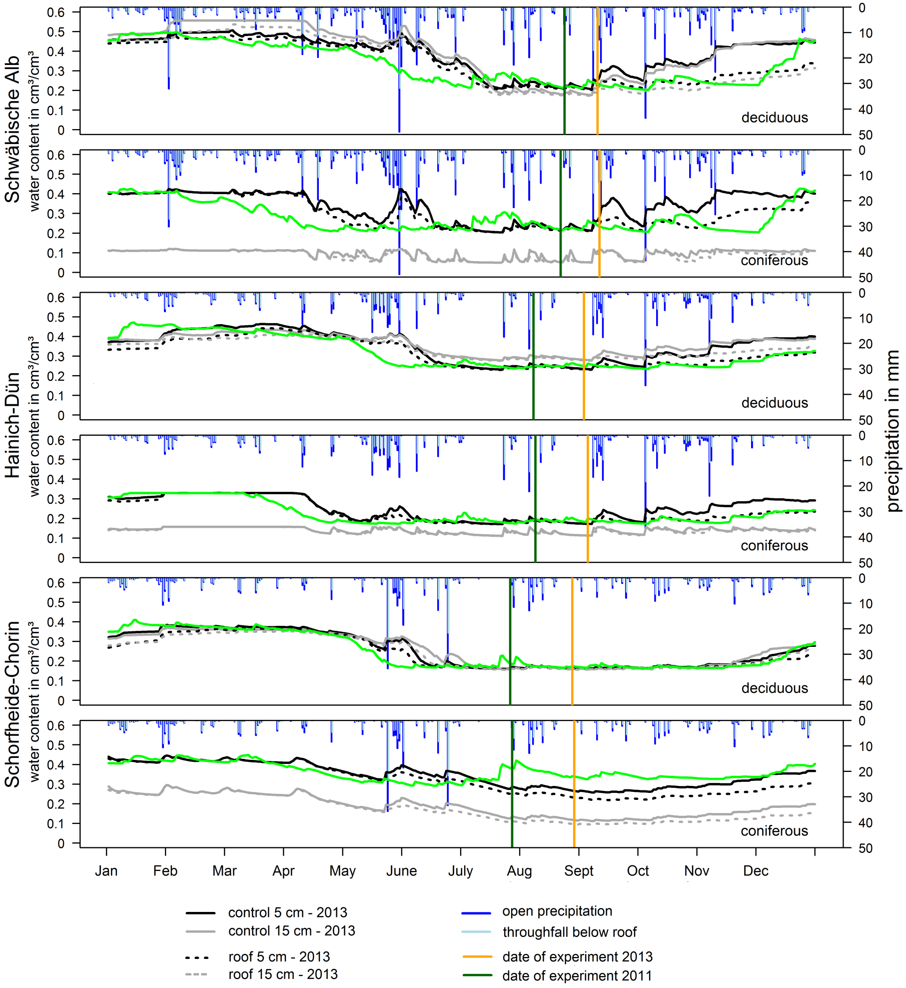
Schwäbische Alb
Hainich-Dün
Schorfheide-Chorin
water content in cm³/cm³
precipitation in mm
deciduous
coniferous
deciduous
coniferous
deciduous
coniferous
0
0.1
0.2
0.3
0.4
0.5
0.6
0
10
20
30
40
50
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
control 5 cm - 2013
control 15 cm - 2013
roof 5 cm - 2013
roof 15 cm - 2013
open precipitation
throughfall below roof
date of experiment 2013
date of experiment 2011

Figure 4. Results of the LWF-BROOK90 model runs for the six plots and comparison between the open precipitation and incoming precipitation under the roofs.

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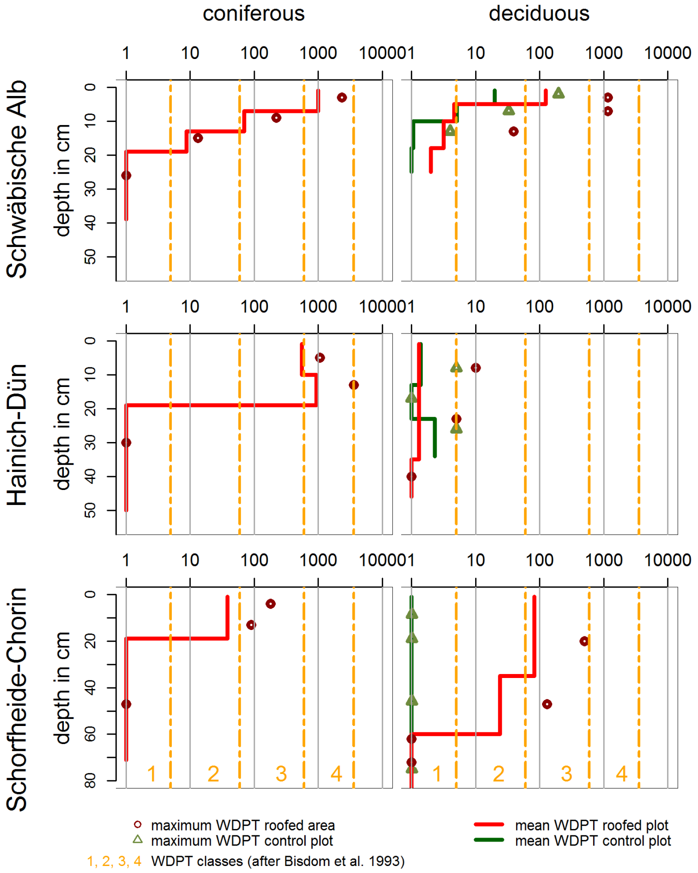

Figure 5. Mean and maximum water drop penetration times (WDPTs) of the control (green) and drought (red) plots. Orange lines and numbers refer to the WDPT classes after Bisdom et al. (1993) (see Table 2).

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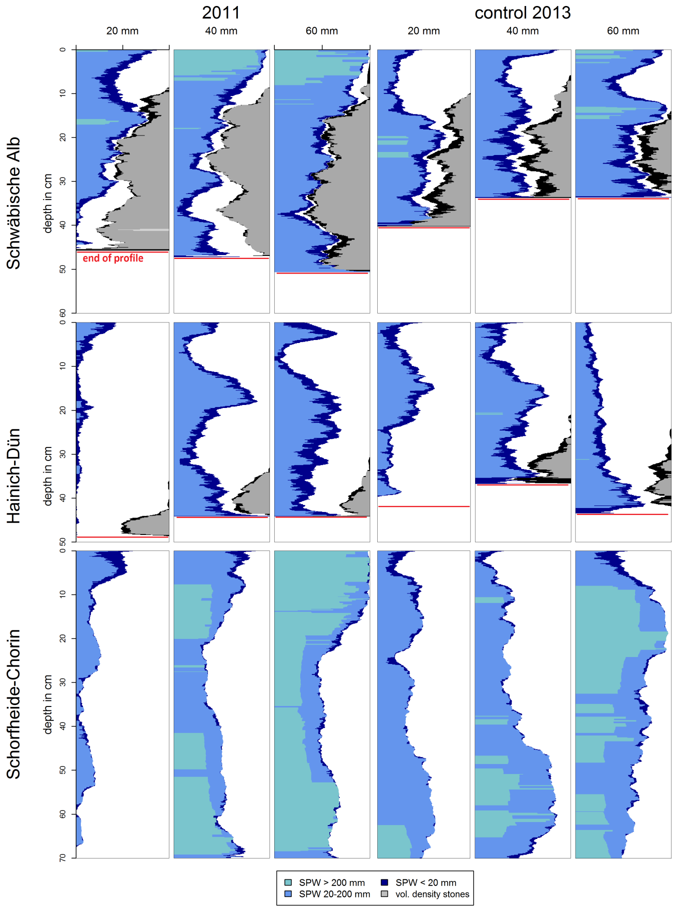

Figure 6. Comparison between stained path width (SPW) of pre-drought (2011) and control (2013) plot. Blue shades indicate the SPW classes. The sum of SPW is the volume density (vd) per depth. Grey and black indicate the vd of stones.

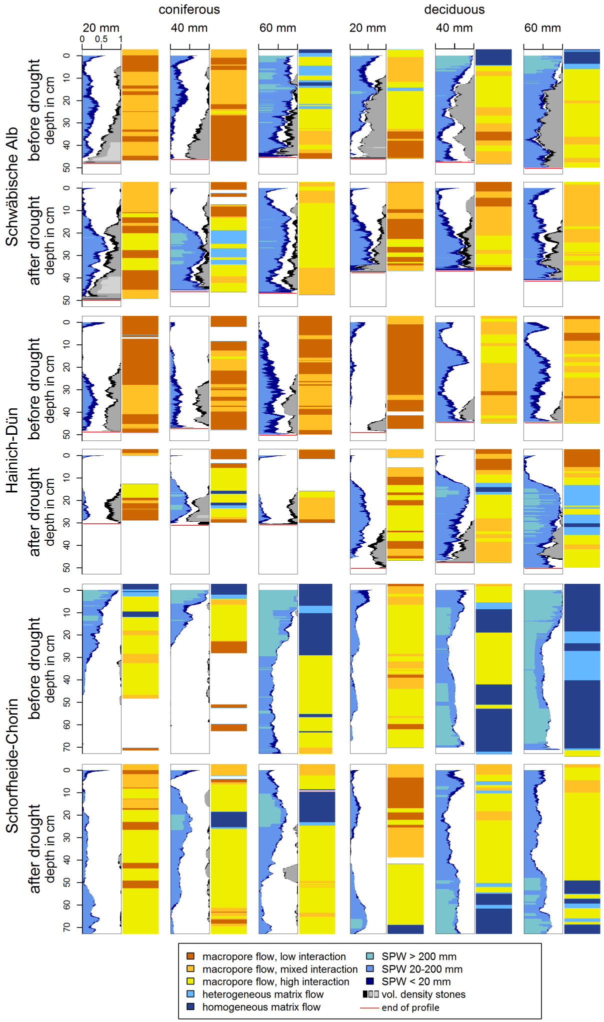
coniferous
deciduous
20 mm
40 mm
60 mm
20 mm
40 mm
60 mm
0
0.5
1
Schwäbische Alb
Hainich-Dün
Schorfheide-Chorin
before drought
after drought
depth in cm
0
10
20
30
40
50
60
70
macropore flow, low interaction
macropore flow, mixed interaction
macropore flow, high interaction
heterogeneous matrix flow
homogeneous matrix flow
SPW > 200 mm
SPW 20-200 mm
SPW < 20 mm
vol. density stones
end of profile

Figure 7. Comparison between before drought (2011) and after drought (2013) stained path widths (SPW) and flow processes for coniferous and deciduous stand plots. The sum of SPW is the volume density (vd) per depth. Grey and black indicate the vd of stones.

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