

1 Drought in forest understory ecosystems – a novel rainfall 2 reduction experiment

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19

20 **Abstract**

21 Precipitation pattern across Central Europe are expected to change over the 21st century due
22 to climate change. This may reduce water availability during the plant-growing season and
23 hence affect the performance and vitality of forest ecosystems. We established a novel rainfall
24 reduction experiment on nine sites in Germany to investigate drought effects on soil-forest-
25 understory-ecosystems. A realistic, but extreme annual drought with a return period of 40
26 years, which corresponds to the 2.5 %-percentile of the annual precipitation, was imposed. At
27 all sites, we were able to reach the target values of rainfall reduction, while other important
28 ecosystem variables like air temperature, humidity and soil temperature remained unaffected
29 due to the novel design of a flexible roof. The first year of drought showed considerable

1 changes in the soil moisture dynamics relative to the control sites, which affected leaf
2 stomatal conductance of understory species as well as evapotranspiration rates of the forest
3 understory.

4

5 **1 Introduction**

6 Temperature and precipitation are two of the key drivers of ecosystem processes. Climate
7 change alters global meteorological processes such as atmospheric circulation and
8 precipitation (Seneviratne et al. 2006; IPCC 2012). In central Europe, climate change is
9 predicted to severely affect precipitation patterns, which will result in reduced precipitation
10 input during the vegetation periods (Prudhomme et al. 2014, IPCC 2012, Christensen and
11 Christensen 2007). Field experiments are a valuable tool to examine the consequences of
12 changing climate on ecosystem processes, as demonstrated in numerous studies, and thus, a
13 number of climate change experiments have been established around the world in various
14 ecosystems: e.g. dry heathland ecosystems in Denmark (Albert et al. 2011, Selsted et al.
15 2012), Amazonian rainforest Brazilia (da Costa et al. 2011), temperate mixed broad-leaved
16 forest (Schraml and Rennenberg 2002) and sub-Mediterranean forest (Rodriguez-Calcerrada
17 et al. 2009).

18 Forests in central Europe are different from most other terrestrial ecosystems in the world;
19 while forest trees and the canopy are managed, the forest understory is a relatively natural
20 system, which however is influenced by the overstory (Ampoorter et al. 2014). The forest
21 understory contains a great variety of biodiversity in forests (Gillam 2007), especially in
22 central Europe with its comparably low tree diversity. Whereas the effects of drought on
23 grasslands has been addressed intensively there are only few studies examining the effect of
24 climate change on the understory of forests (Ozolincus et al. 2009). It remains unclear, how
25 the forest understory will respond to continuously reduced precipitation, as it might be the
26 case in a future Europe under climate change (Kreuzwieser & Gessler 2010). In general, we
27 can expect both direct and indirect impacts of continuously reduced precipitation on the forest
28 understory system. Decreased transpiration and water potentials are short-term responses of
29 plants to drought (Tschaplinski et al. 1998). As a result of the drop in water potential, stomatal
30 closure will occur, limiting water fluxes at the cost of reduced CO₂ uptake and assimilation.
31 At the level of plant communities and long-term response, the stress induced by drought may

1 modify competition and facilitation, or it may tip the balance towards a state where only stress
2 resistant plant species are able to survive (McDowell et al. 2008).

3 Since plants are closely linked to soil physical properties and interacting with soil microbiota,
4 the response of plants to drought should be coordinated with detailed characterization of soil
5 and hydrological properties. Soil characteristics are closely linked to the activity of soil
6 microbiota and plant roots, which modify water flow pathways along roots, organic matter
7 and water repellence of soils (Birkhofer et al. 2012; Carminati et al. 2011, Gregory 2006,
8 Schaumann et al. 2007, Spohn & Rillig 2012, Tang et al. 2011, Tisdall & Oades 1982).
9 Through shrinkage and fracturing of soil aggregates, soil structure is also responding to
10 changing environmental conditions (in particular drought). Hence, the understory vegetation
11 will be also be affected by indirect drought effects driven by soil processes. Since plants are
12 closely linked to soil physical properties and interacting with soil microbiota, the response of
13 plants to drought should not be studied isolated.

14 Our current understanding of drought effects on the forest understory is ambiguous and
15 insufficient for predicting responses of the forest ecosystem: On one hand, the understory
16 remains largely unmanaged, while the overstory structure of trees and canopy is a
17 consequence of forest management practices. But on the other, the understory also harbors the
18 tree seedlings, which will form the next tree generation und thus we need a better mechanistic
19 comprehension of this system. The knowledge of such mechanisms related to the understory
20 response to drought need to be included in current forest growth models in order to
21 understand all aspects of the system – including natural regeneration – under climate change.

22 We thus propose to experimentally manipulate precipitation and investigate in detail the
23 consequences for soil moisture, soil hydrological functions, and water uptake as well as
24 vegetation structure but also allowing to include more in-depth studies such as assessments of
25 the microbial community structure. The aim of this study was to apply a realistic reduction of
26 precipitation whilst avoiding any associated effects on air temperature or humidity and to
27 observe the initial drought effects on the forest-understory-soil-system. Many other
28 precipitation manipulation experiments introduce extreme short-time drought events (e.g.
29 Glaser et al. 2013), which often eliminate precipitation completely, generating unrealistic
30 drought effects (Beier et al., 2012). In addition, the constructions used in previous studies
31 often need electrical supply or intensive technical installation, supervision, and maintenance
32 (e.g. Beier et al. 2004, Albert et al. 2011, Parra et al. 2012, Kopittke et al. 2014). Our

1 approach employs a moderate, adaptive, and continuous rainfall reduction, equivalent to a
2 drought with 40-year return period. To achieve our goal, nine investigation sites at three
3 different geographical locations in Germany were established. Here, we describe and explain
4 the set up and monitoring of the rainfall exclusion experiment and present first results of
5 rainfall reduction with soil physical and biological evidence in effectiveness of drought set up.

1 **2 Material and methods**

2 **2.1 Investigation sites**

3 Our study sites are part of the German Biodiversity Exploratories, which are located in three
4 different sites in Germany (Schwäbische Alb, Hainich-Dün, Schorfheide-Chorin) (Figure 1).
5 The German Biodiversity Exploratories comprise a research platform for biodiversity and
6 ecosystem research (DFG Priority Programm 1374). The research focus of the Biodiversity
7 Exploratories is on understanding the inter-relationship between land use, biodiversity and
8 multiple ecosystem processes, as well as biodiversity change and biogeochemical cycles in
9 real-world ecosystems (Fischer et al. 2010). In each of the Exploratories, we selected three
10 forest plots, which cover different forest types, management intensities and understory
11 vegetation communities (Table 1), but are similar with respect to topography and soil type
12 within each exploratory.

13 The site of the Biodiversity Exploratory Schwäbische Alb is located in the low mountain
14 ranges of south-western Germany; the underlying geology consists of Jurassic shell limestone.
15 The soils at the investigation sites are extremely rich in clay, are very shallow (25 cm to
16 35 cm) and have a very high stone content. The soils of the Hainich-Dün site (situated in
17 central Germany) generally have a loamy to clayey texture with soil depths between 45 and
18 65 cm and low water conductivity. Here, the underlying geology consists of Triassic
19 limestone.

20 The site of the Biodiversity Exploratory Schorfheide-Chorin is located in a young glacial
21 landscape in the lowlands of north-eastern Germany. The dominant geological substrate is
22 glacial till covered by glacio-fluvial or aeolian sands. Therefore, soils have textures in the
23 range of sandy loam to pure sand. Due to their sandy texture, the soil depth in this area is
24 identified by rooting depths.

25 More information on general plot properties is prepared in Table 2. All weather data is taken
26 from stations of the German weather service (DWD, actual and annual data years 1950-2010)
27 nearby (station-IDs 03402, 00487, and 00164).

28 **2.2 Roof construction for a flexible rainfall reduction**

29 At each of the nine selected plots, five roof subplots and five control subplots were
30 instrumented. One of the five roof subplots and one of the five control subplots has a size of
31 10 x 10 m (“main subplot”, Figure 2); the other four pairs of subplots (“satellite subplots”)

1 have a size of 3 x 3 m. Roof and control subplots are in close vicinity to each other (distance
2 between roof and control ranges between 15 m and 30 m for the main roofs, and between 6 m
3 and 15 m for the satellite subplots), in order to ensure similar subplot properties with respect
4 to topography, soil and vegetation. A central overstory tree (Figure 2 and 3) is included in
5 each of the central subplots, whereas the satellite subplots do not contain any large trees. The
6 selected central trees are similar in age, size and canopy structure.

7 The roofs have a height of around 2 m and are supported by an unpainted timber construction
8 leveled on a foundation of bricks or wooden support (Figure 3a, b). All four sides of the
9 timber construction are open in order to provide sufficient circulation and exchange with
10 ambient air and to avoid heat-up and changes in air humidity. Due to the roof dimensions, it
11 was not possible to circumvent supporting constructions in the center of the roofed area, but
12 they were kept at a minimum to reduce shading.

13 The roofs are covered with transparent POLYLUX© trapezoidal corrugated panels (Figure
14 3c). To allow a flexible reduction of precipitation, we decided to adjust the number of roof
15 panels on a pre-defined time interval. In order to avoid any spatial persistent reduction of
16 precipitation, we manually changed the position of the roof panels randomly in space. The
17 roof panels of the large roofs have a size of 1.16 m x 1.33 m = 1.543 m² and those on the
18 small satellite roofs 0.9 m x 0.58 m = 0.522 m². The main roof allows for 48 x 7 = 336
19 possible positions for the roof panels. Complete coverage – without overlapping of panels – is
20 realized with 56 units (covering 100 %). The satellite roofs hold 22 x 4 = 66 possible
21 positions and are at maximum covered with 12 small roofing units (covering: 100 %). The
22 coverage of the roofs is adjusted every month by manually adding/removing and repositioning
23 the roof panels. The timber construction and gutters itself already intercepts 11 % (main
24 roofs) and 15.5 % (satellite roofs) of precipitation.

25 Rainwater from the roof panels and the timber construction is collected by rain gutters
26 mounted along the roof frame and is drained into rain barrels. Stemflow (of all roofed beech
27 trees) is also collected and drained to the rain barrels by a stem rim (Figure 3d). The water
28 level in the rain barrels is continuously logged with a pressure transducer to quantify the total
29 amount of water removed by the roof. Above a certain water level the barrel is emptied
30 through an electromagnetic valve and the water is conveyed through a hose away from the
31 roof. Eight of the nine plots are situated at very flat angled-slopes, therefore re-entering of the
32 water is prevented. Only plot AEW8 is situated on a steeper slope, which made compromises
33 at the construction necessary; to balance the differences in height of the central roof, one side

1 of the roof is placed directly on the ground without wooden support, the other is at 3.2 m
2 above ground. Nevertheless, the roof has the same dimensions, rain gutters and
3 instrumentation as the other eight plots. No adjustment had to be made at the smaller satellite
4 roofs at this plot.

5 To avoid shading and uncontrolled overflow of rainwater, all roofing units, as well as rain
6 gutter, downpipes and barrels were cleaned periodically. This roof system can reduce rainfall
7 between 11 % and 100 % and due to its design, rainfall exclusion is variable and not
8 persistent in space. It holds the advantage not only to have the same temporal and spatial
9 variability of water input distribution (where no covering takes place) as the surrounding
10 forest, but also to preserve the hydrochemical composition. This would not be the case, if
11 precipitation was completely intercepted and tap or river water was used for monthly
12 irrigation.

13

14 **2.3 Rainfall reduction for realistic drought conditions**

15 Our target rainfall reduction level was a total annual precipitation input equivalent to a
16 drought with a 40 year return interval. However, any other target value can be defined with
17 the above described roof construction. We assume that the relative reduction in measured
18 gross precipitation is equal to the relative reduction in throughfall under the forest canopy.
19 The target value of the precipitation reduction was calculated from long-term precipitation
20 data (1950 to 2010) using climate stations of the German Weather Service (DWD) in the
21 vicinity of the investigation sites (Schorfheide-Chorin: DWD station Angermünde (ID
22 00164), Hainich-Dün: Erfurt-Bindersleben (ID 00487), Schwäbische Alb:
23 Münsingen/Apfelstetten (ID 03402)). Annual precipitation varies in the observation period
24 between 322 mm and 714 mm in Angermünde, between 295 mm and 767 mm in Erfurt-
25 Bindersleben and between 618 mm and 1228 mm in Münsingen/Apfelstätten.

26 The 2.5 percentile of the annual precipitation, corresponding to a drought with a 40 year
27 interval, was derived for each climate stations, the result of which was used as the target value
28 for the reduction of the precipitation on the roofed plots. The target value for the reduced
29 annual precipitation sum at the Schorfheide-Chorin sites is 392 mm, which corresponds to an
30 average reduction of the incoming precipitation by 27 %. The target values for Hainich-Dün
31 and Schwäbische Alb are 355 mm and 700 mm corresponding to a reduction of 33 % and
32 26 %, respectively (Figure 4).

1 The practical implementation of the precipitation reduction on the plots involves a monthly
 2 adjustment of the percentage of reduction (i.e. the number of roof panels) and their spatial
 3 distribution (i.e. the position of the panels on the roof). Therefore, the target values for the
 4 reduced annual precipitation sum were transferred to monthly target sums. To preserve the
 5 inter-annual variability, we calculated the monthly target sum by weighting the average
 6 monthly sum (i.e., one twelfth of the annual target sum) by the ratio between the long-term
 7 mean precipitation sum of each calendar month and the mean annual precipitation sum
 8 (equation 1).

9

$$10 \quad a_{m_i} = a_a \cdot \frac{P_{mean\ m_i}}{P_{mean\ a}} \quad (1)$$

11

12 Where a_m = monthly target sum of a given month i ;

13 a_a = annual target sum (2.5 %-Percentile of annual precipitation);

14 $P_{mean\ m_i}$ = long term mean precipitation of given month i ;

15 $P_{mean\ a}$ = annual mean precipitation

16

17

18 To calculate the actually required reduction, the reduced precipitation input under the roofs of
 19 the current month is compared with the target values. If the antecedent input fits the target
 20 value, the reduction is set to the theoretical reduction obtained from the long-term series for
 21 the month to achieve the target value. If the antecedent input under the roof is above or below
 22 the target value, the reduction is set higher or lower according to the magnitude of deviation.

23 Though reduction is calculated for the entire year, the roof remains uncovered from first
 24 snowfall until the end of the snow season, to avoid roof damage from a heavy snowpack.

25 During this period precipitation was only reduced by 11 % (for main roof and 15.5 % for
 26 satellite subplot roof, for construction reasons) from mid-November/early December until
 27 January/February. To account for the absent reduction in winter months, the reduction in
 28 spring balances winter-month excess or deficit. Similarly, November reduction can be
 29 increased to create a reserve for wet winter month.

30

1 **2.4 Monitoring and sampling**

2 The effects of the imposed precipitation reduction on the atmosphere and soil were
3 continuously monitored under the central roof subplots and compared with parallel
4 measurements and sampling campaigns at the central control subplots. The central subplots
5 are divided into four sectors: one for field experiments and soil sampling, one for vegetation
6 surveys and experiments, one for long-term soil-hydrological monitoring, and one remains
7 untouched and is reserved for possible future investigations (Figure 2). The satellite control
8 and roof subplots are used exclusively for vegetation surveys and soil sampling for microbial
9 analyses.

10 *Meteorology and soil hydrology*

11 Monitoring at the main subplots includes measurements of soil moisture and soil temperature
12 (5TM, Decagon Devices Inc.), soil electrical conductivity (5TE, Decagon Devices Inc.) and
13 only under the roofs matric potential (MPS-2, Decagon Devices Inc.) at 2 m, 3 m and 4 m
14 distance from the central tree, and in four soil depths (5, 15, 30 and 60 cm). At the shallow
15 sites (HEW3, HEW12, HEW47, AEW8, AEW13, AEW29), the 60 cm depth probes were
16 omitted in at least one distance from the central tree. The measuring accuracy according to the
17 technical data sheets of the 5TE and 5TM probes is ± 1 °C for temperature, ± 10 % of the
18 measured value for electrical conductivity (5TE only), and ± 15 % of the measured value for
19 the volumetric water content. The MPS-2 probes have an accuracy of ± 25 % of the reading
20 (as per technical data sheet) within the measuring range of -5 kPa to -100 kPa. To observe
21 possible roof effects on the microclimate, air temperature and humidity sensors (HMP45C
22 with HUMICAP® 180 sensor, Campbell Scientific Inc.) were installed at one location under
23 the central roof and one at the central control subplot at the same height (2 m) above the
24 ground. The HMP45C temperature and humidity probes have an error in temperature
25 measurement of ± 0.2 °C to ± 0.3 °C and of 2 % to 3 % for air humidity. Sapflow in the central
26 trees is monitored using the three needle heat pulse sensor by 30 EAST Inc. with an accuracy
27 of around 5 % of the reading (Cohen et al. 1981). All data (soil, climate, and sap flow) are
28 logged at 15-minute intervals, except the water level in the rain barrels, which are logged at 1-
29 minute intervals. In addition, measurements of photosynthetic active radiation were carried
30 out periodically

31 *Botanical parameters and evapotranspiration*

32 To address the influence of the imposed drought on forest understory, we established at each
33 plot, ten vegetation recording sub-subplots, each with an area of 1 x 1 m. These sub-subplots

1 were marked and were not entered during the rain exclusion experiment. For each sub-
2 subplot, we determined plant species to identify the understory vegetation community and its
3 cover. The baseline survey for all plots took place between June 2011 and July 2011.

4 At each subplot the specific leaf area index (*LAI*) was determined from randomly selected
5 field-fresh leaves from all species with a coverage of more than 5 % (fresh weight per leaf
6 sample >1 g, which equals 2-12 leaves per species). Measurements were made 3 times in
7 2012 (spring – April, early summer – June/July, late summer – August/September) at all nine
8 plots. Digital photos, which were taken of these leaves in the field, were used to determine the
9 average area of a leaf ($LA_{species}$; defined as the area of an average leaf of a given species) using
10 the image analysis software imageJ 1.45s (Abramoff et al. 2004). For understory analysis we
11 took digital photos of four randomly chosen quadratic areas per control and roof sub-subplots
12 ($n = 4$; $A_{total} = 2.45 \text{ m}^2$) and counted the total number of leaves (N_{leaves}) of each species within
13 the known ground-surface area (A_{total}). *LAI* was calculated by the following equation:

14

$$15 \quad LAI = \frac{\sum_i^{N_{species}} N_{leaves} \cdot LA_{species}}{A_{total}} \quad (2)$$

16

17 where $N_{species}$ is the total number of species found on the quadratic area of 2.45 m^2 . For
18 subplot plant species richness we counted the total species number on the digital photos of the
19 2.45 m^2 areas for each treatment.

20 For further insight on the effect of drought on growth, we planted phytometers (proxy-plants
21 used as a measure of plant physical response) of *Fagus sylvatica* L. on all 90 subplots. We
22 used one-year old *F. sylvatica* saplings (Schlegel & Co. Gartenprodukte GmbH, Riedlingen,
23 Germany) in October 2011 from three different provenances corresponding to the three
24 different experimental sites. The saplings had an initial height of 30–50 cm (with a mean and
25 sd of $34.74 \text{ cm} \pm 8.15 \text{ cm}$, respectively) and a tap root length approximately of 10 cm. At the
26 time of planting, roots of all saplings were pruned to 10 cm to avoid crooked roots in shallow
27 soils, as they occur at the Hainich and Schwäbische Alb site. In October and November 2011,
28 we either planted the beech saplings into the resident plants or once removed the total
29 aboveground biomass of all herbaceous plants in a radius of 20 cm around the phytometer to
30 exclude herb layer competition. In total we planted 1080 beech phytometers (90 subplots x 12
31 individuals). For further information on the experimental design of the phytometer experiment
32 see Baudis et al. 2014.

1 Growth of all planted beeches was recorded by measuring different growth response variables
2 such as leaf number, plant height, leaf length and crown expansion and compared with the
3 phytometer data of the control plots. The phytometers were monitored three times in 2012
4 (spring, early summer, late summer). Relative growth rates (*RGR*) were calculated from April
5 2012 to July 2012. Leaf stomatal conductance (g_s) was measured on all monitoring dates with
6 a SC-1 leaf porometer (Decagon Devices Inc.).

7 In the field, gas-exchange chambers (transparent Perspex, size: 52 x 77.5 x 78.5cm,
8 $A = 0.61 \text{ m}^2$) comparable to the ones described in Yepez et al. (2005) were used for
9 measuring understory evapotranspiration (*ET*) rates. The chambers were open to the soil,
10 sealed with rubber foam gaskets to the ground and were use as closed systems to assess the
11 build up of water vapour from soil evaporation and plant transpiration. Measurements were
12 made three times in 2012 (spring, early summer, late summer) at all nine plots. *ET* rates were
13 determined on the control subplots and on the roof subplots. The increase in water vapor in
14 the closed chambers was measured with a cavity ringdown laser spectrometer (PICARRO
15 L1102-I, Picarro Inc.) directly in the field, with four replicates per control subplot and per
16 roof subplot between 10:00 a.m. and 15:00 p.m. (CEST). The chamber air was circulated
17 through the isotope water analyzer via a low absorption tube using the Picarro pump (flow
18 rate $<0.4 \text{ l min}^{-1}$) and fed back again in the chamber headspace. For each chamber, a
19 measurement lasted 10-12 minutes, and a fan provided mixing of the air in the gas exchange
20 headspace. Temperature, air humidity (VP-3 humidity temperature and vapor pressure sensor;
21 Decagon Devices Inc.) and photosynthetic photon fluency rate (*PPFR*) were continuously
22 logged (Par Photon Flux Sensor, Decagon Devices Inc.). *ET* rates were calculated from the
23 linear increase in water vapor concentration determined by the laser spectrometer in the
24 chamber over time and based on the ground area.

25 **2.5 Statistical analyses**

26 We applied t- tests to assess the differences in the *LAI* and for species richness between the
27 roof and control treatment using R (R-3.0.2, The R Foundation for Statistical Computing
28 2013).

29 Response variables for growth and stomatal conductance of the understory beech phytometers
30 were evaluated with linear mixed effects models with site (three different experimental sites),
31 drought (sheltered or not), competition (with and without competition) and provenance
32 (Schorfheide-Chorin, Hainich-Dün and Schwäbische Alb) as fixed factors and plot, subplot

1 nested in plot and sub-subplot nested in plot as random factors. The statistical analyses were
2 carried out with the R-Studio software (version 0.97.248; R version 3.0.0) using the “nmle”
3 package. Air temperature and humidity were tested with the Wilcoxon-Mann-Whitney rank
4 sum test R-Studio software (version 0.97.248; R version 2.15.2) using the “stats” package.
5

1 **3 Results**

2 **3.1 Precipitation reduction**

3 All roofs were installed during fall/winter 2011 (mid-September in Schorfheide-Chorin, mid-
4 October in Hainich-Dün, early December in Schwäbische Alb). On all plots the rain exclusion
5 started on all plots on March 1st 2012 and ended on November 30th 2013. Continuous
6 monitoring of meteorological and soil hydrological data started in Schwäbische Alb in mid
7 April 2012 and in Schorfheide-Chorin and Hainich-Dün at the end of August 2012.

8 With respect to precipitation, the year 2012 was an average year with a total precipitation of
9 940 mm (100.4 % of long term mean) in the Schwäbische Alb, 508 mm (95.5 %) in Hainich-
10 Dün and 543 mm (101.5 %) in Schorfheide-Chorin (Figure 4, blue lines). At all sites in 2012
11 winter rain and snowfall was greater than average. In contrast, the year 2013 was wetter than
12 the long term mean in Schwäbische Alb (976 mm, 104.3 %) and Hainich-Dün (596.5 mm,
13 112.1 %), and drier in Schorfheide-Chorin (483.2 mm, 90.4 %). To compensate the high
14 precipitation input, we had to raise the exclusion (Figure 4, blue bars) from 30 % (mean
15 value) to 50 %, which resulted in a reduction below the target (699 mm) of 11 %. Generally,
16 the reduced precipitation input on all plots satisfyingly reached the target values, both in 2012
17 and in 2013. The reduced input (dashed red and orange lines in Figure 4) hovers around the
18 target value (solid red line), depending on the monthly adaption of the roof cover. The
19 maximum applied roof coverage in 2012 and 2013 was 55 %.

20 In total, 221 mm were excluded in the Schwäbische Alb sites in 2012 which resulted in an
21 incoming precipitation under the roofs of 719 mm. In Hainich-Dün and Schorfheide-Chorin,
22 178 mm and 176 mm respectively were reduced (input under roof: 331 mm and 366 mm). In
23 2013, incoming precipitation under the roof were 619 mm, 366 mm and 346 mm for
24 Schwäbische Alb, Hainich-Dün and Schorfheide-Chorin respectively, which hit the target
25 values satisfyingly, even more, Schwäbische Alb and Schorfheide-Chorin had a reduction
26 below the target (11 % for both sites) (Figure 4).

27

28 **3.2 Roof effect on air temperature, air humidity and soil temperature**

29 In general, roofing on experimental plots can promote changes of air temperature and
30 humidity, due to alterations of radiation and ventilation (greenhouse effect). In fact, some
31 authors actually used roofing setups in order to achieve higher mean temperatures, mainly as

1 an effect of preventing the nocturnal emission of long wave radiation (e.g., Selsted et al.
2 2012). Because elevation of air temperature and humidity has significant effects on growth,
3 germination, transpiration and water uptake of plants, on microbial activity and on soil
4 evaporation, we aimed at avoiding any alteration of air temperature and humidity as well as
5 radiation. Based on the monitored air temperature, air humidity and soil temperature at the
6 main roof and the neighboring main control subplot, we tested whether the roofing had a
7 measureable effect on these variables. Air temperature and humidity were not affected by the
8 roofing on none of the experimental sites (Figure 5). The 15 min readings on control plot and
9 under the roof are not significantly different (except plot HEW3) according to the Wilcoxon-
10 Mann-Whitney rank sum test.

11 Similar to air temperature, mean values of soil temperature show no difference between main
12 control and main roofed subplot regarding to the measuring accuracy of the 5TM/5TE-probes
13 in all depths (data not shown).

14

15 **3.3 Roof effect on soil moisture**

16 As expected, the roof coverage had an immediate effect on the soil water content. However,
17 the respond to the reduced precipitation input varied between the sites. Figure 6 shows the soil
18 water deficit on the main roofed subplots when compared with the neighboring main control
19 subplots for the different measuring depths and distances from the central trees at the subplots
20 for the example month May 2013 (similar results were obtained for the other months).
21 Schorfheide-Chorin (Figure 6, bottom) showed the lowest reduction of all sites with little
22 differences between soil moisture of roofed and control subplot. The top soil layer of beech
23 plots SEW48 (4 m distance) and SEW49 (2 m and 3 m distance) even exhibited a small
24 increase in soil moisture. The difference between roofed subplot and control subplot are more
25 pronounced in Schwäbische Alb and Hainich-Dün than in Schorfheide-Chorin plots for this
26 time period. In Hainich-Dün (Figure 6, middle), the highest soil moisture reduction appeared
27 in spruce plot HEW3, especially in top layer (5 cm depth), where all distances to the central
28 tree showed high deficits compared to the control subplot. In contrast, HEW12 and HEW47
29 (both beech) did not show such high reduction rates in top layer. In HEW47, no difference
30 (15 cm depth in 3 m and 4 m distance and 30 cm depth in 4 m distance), and in both plots
31 (HEW12: 30 cm depth, 4 m distance; HEW47: 60 cm depth, 2 m distance) even a small
32 increase of soil moisture on roofed subplots compared to control subplots appeared. In

1 general, Schwäbische Alb plots (Figure 6, top) exhibit the highest soil moisture reduction of
2 all sites. The reduction was strongest in in the top soil layer (5 cm) of all plots at a distance of
3 3 m and 4 m from the center tree. In addition, the 2 m distance (5 cm depth) of AEW8 and
4 AEW13 and the 3 m distance (15cm depth) of AEW8 are showing high soil moisture deficits.
5 On AEW8 and AEW29 (both beech), 15 cm (AEW8 and AEW29) and 30 cm (AEW8)
6 sensors did not detect soil moisture differences between roofed and control subplot.

7

8 **3.4 Plant community and phytometer**

9 There were no significant differences between the total vegetation coverage of the sites
10 (27.9 %, 40.3 % and 38.9 % – average of the three plots per site of Schorfheide-Chorin,
11 Hainich-Dün and Schwäbische Alb, respectively). The type of the understory plant
12 community as assessed in the vegetation surveys is given in Table 1. A detailed overview of
13 the different functional groups (grass, herb, shrub and tree recruits) and the mean coverage on
14 the nine plots can be found in Table 3. Most plots are dominated by grasses and herbs;
15 subplots differ in total coverage between 2.26 % and 57.1 %. (Table 2).

16 In late summer 2012, i.e. at the end of the first growing season with the drought treatment,
17 there were significant differences in *LAI* between the roof and control subplots at the managed
18 beech plot at the Schwäbische Alb (AEW29; $p= 0.001$) and at the intensive managed conifer
19 plot at the Hainich exploratory (HEW03; $p = 0.01$) (Table 4). The species richness of the
20 understory plant community were significantly higher at the managed roof subplot of the
21 Hainich exploratory compared to the control subplot (HEW47, $p = 0.004$). Table 5
22 summarizes the drought effects on leaf stomatal conductance (g_s) of the planted phytometer as
23 a short-term response to drought. Leaf stomatal conductance was reduced under the roofs,
24 with a more significant reduction in July 2012 ($p = 0.0009$) than in September 2012
25 (marginally significant $p = 0.0602$) (Table 5).

26 Additionally, there was an interaction of drought and site (Table 4; Figure 7). While drought
27 had no effect at the wettest site (Schwäbische Alb), stomatal conductance was reduced under
28 the roof at the Schorfheide-Chorin and the Hainich-Dün sites. In contrast to g_s , growth
29 parameter did not show significant drought effects in this early stage of the experiment.

30 At the beginning of the 2012 growing season when the drought treatment had started, the
31 understory evapotranspiration rates between the roof and control subplots as determined with

1 chambers were not significantly different, indicating the initial comparability of the subplots
2 (Figure 8). In the late summer 2012 we detected no significantly lower *ET* rates with the
3 chamber measurements as response to reduced precipitation with one exception at SEW16
4 (pine) (Figure 8).

1 **4 Discussion**

2 **4.1 Precipitation reduction**

3 The aimed reduction of precipitation to a 40-year annual drought equivalent (2.5 %-
4 percentile) was met. The annual precipitation of the years 2012 and 2013 were in all regions
5 close to the long term annual mean. Possible problems may occur, using our technique in very
6 extraordinary dry or wet years, although we did not detect such meteorological circumstances
7 in the 1950 - 2010 records in all our regions when we tested our design in terms of figures.

8 In contrast to other constructions used in rainfall reduction experiments (see reviews of Beier
9 et al., 2012 and Wu et al., 2011), it was possible to reduce the precipitation to a certain level
10 over the year, instead of excluding the total precipitation input during a time period (e.g.
11 Kopittke et al. 2014, Glaser et al. 2013). Though untested, our construction is flexible enough,
12 to realize a wide range of reduction experiment designs, e.g. total reduction during distinct
13 growing season periods (manipulation of inter annual variability), shorter adjustment intervals
14 of roofing panels (daily, weekly) and combination with irrigation equipment (e.g. Glaser et al.
15 2013, Fay et al. 2000). The roofing design can be enlarged or reduced in size to meet the
16 requirements of a site or experimental design. Experimental drought or rainfall exclusion
17 experiments are often extended over 1 - 2 years (Parra et al. 2012, Dermody et al. 2007), but
18 our construction can be used to study long-term drought effects for several years due to the
19 stability of the timber construction.

20 **4.2 Roof effect on air temperature, air humidity and soil moisture**

21 As mentioned above, roofing on experimental plots can have a significant effect on air
22 temperature and humidity. Temperature controls – as a main effect – the duration of growth
23 period, but is also influencing processes like photosynthesis, respiration and transpiration
24 (Maracchi et al. 2005). The shielding can raise mean air temperature by 1.2 to 1.4 °C as
25 reported by Glaser et al. (2013) and can reach as much as 3.2 °C (Selsted et al. 2012). In
26 contrast to other studies (Selsted et al. 2012, Parra et al. 2012, Dermody et al. 2007), we
27 aimed in avoiding these “greenhouse” effects, to separate the effect of prolonged drought
28 from effects due to changes in air temperature and air humidity conditions. Our measurements
29 show no difference in humidity and air temperature between roofed and control plots, which
30 clearly indicates a comparable coupling of the airspace close to the ground to the atmosphere
31 on both subplots. In addition, the design of the roofs with an incomplete coverage (2 m high,

1 four sides open, maximum roof coverage 55 %, complete roof area only 100 m²) definitely
2 not represent a closed roof. Given that and the findings that air humidity and temperature stay
3 totally unaffected, it is very unlikely, that CO₂ concentrations increased under the roofs and
4 thus also no CO₂ fertilization effects are to be expected.

5 The drought treatment clearly reduced soil moisture content in all depths in all plots
6 (exceptions are the 5 cm depths of SEW48 and SEW49, the 60 cm depths of HEW47 and
7 SEW49). In Hainich-Dün and especially in Schorfheide-Chorin plots, soil moisture deficit
8 decreased with depth. This is in line with the findings of English et al. (2005), who found a
9 decrease of soil moisture deficit with depth. The reason for the difference in behavior of
10 Schwäbische Alb plots in soil moisture drought response is twofold: The reduction is always
11 relative, not absolute, which leads to more pronounced deficits in areas with higher
12 precipitation. Secondly, the Schorfheide plots, which showed the lowest deficits, are all sandy
13 soils. This type of soil is having already comparable low soil moisture when untreated.

14 We acknowledge that the water relations in the soil under the roof might have been influenced
15 by adult trees rooting partially outside and partially inside the sheltered area mainly due to
16 redistribution of water via the roots. As a consequence the intensity of the reduction of soil
17 water content might not only be affected by rain-fall reduction and soil properties but also
18 influenced by the intensity of such redistribution.

19 **4.3 Roof effects on evapotranspiration, leaf stomatal conductance and growth**

20 Only a small number of plots have shown a significant change in *LAI* and species richness as
21 a consequence of the treatment. This is in agreement with the findings from the phytometer
22 experiments, where leaf stomatal conductance was reduced as effect of the precipitation
23 manipulation, while growth variables were not affected at that stage of the experiment. Our
24 results show that reduced growth of understory plants and changes in community structure
25 does not occur as an early response to drought in the first year that under the precipitation
26 reduction regime applied. Drought stress was not that intensive to induce mortality or strong
27 changes in biomass of particular species on the short term. This seems to be partially in
28 contrast to conclusion drawn by Leuzinger et al. (2011) that initial responses of ecosystems to
29 drought (or other parameters related to Global Change) are highest and decline over longer
30 time periods. The ecosystem's response time to changes in environmental conditions will,
31 however, also depend on the treatment intensity. Changes in ecosystem functioning occur
32 after stress conditions exceed a certain level of climate severity threshold, which cannot

1 predicted until now (Bahn et al. 2014, Vicca et al. 2012). The achieved 40-year return interval
2 drought was in our experiment not enough to push the system beyond this physiological and
3 biochemical threshold.

4 Conversely, the quick response of leaf stomatal conductance (g_s) confirms that control of the
5 transpiration is a very sensitive and short-term response of plants to reduced water supply (c.f.
6 Gessler et al. 2004). The finding that g_s was mainly reduced in July and only marginally
7 significantly in September clearly reflects the fact that our rain reduction was not absolute but
8 proportional. As the amount of rainfall in September was much higher than in July, a
9 proportional reduction had a smaller effect on the plants than in July. For the same reasons,
10 we did not encounter a significant response to the drought treatment at the Schwäbische Alb,
11 which was the wettest site. Recently Hommel et al. (2014) provided evidence that various
12 forest understory species can respond to mild drought by reducing assimilation rates
13 simultaneously with g_s or even before it. As a consequence we need to expect effects of our
14 treatment on carbon assimilation and biomass production thus supporting our assumption that
15 over the longer-term changes in coverage and vegetation structure are likely to occur. When
16 scaling our results from leaf g_s to the understory ecosystem (evapotranspiration), the *ET*
17 response to the drought treatment was only observed in the pine plot in the Schorfheide site
18 during this initial phase. This points to the fact that the stomatal response observed on the leaf
19 level in the phytometer plants does not scale on the ecosystem water use, yet.

20

21 **5 Conclusion**

22 We conclude that our innovative roofing construction is a valid, and more realistic alternative
23 to the common drought simulation practice of total rainfall reduction. Due to the flexible
24 construction it is possible to preserve the temporal and spatial variability of rainfall pattern, in
25 particular under the forest canopy, while reducing precipitation input and soil moisture
26 without changing the air temperature and humidity on site. During the first two years of
27 treatment, the reduction of precipitation to a 40-year annual drought event did not introduce
28 artificial vegetation responses as an effect of unrealistically high rainfall reduction.

29

30

1

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14

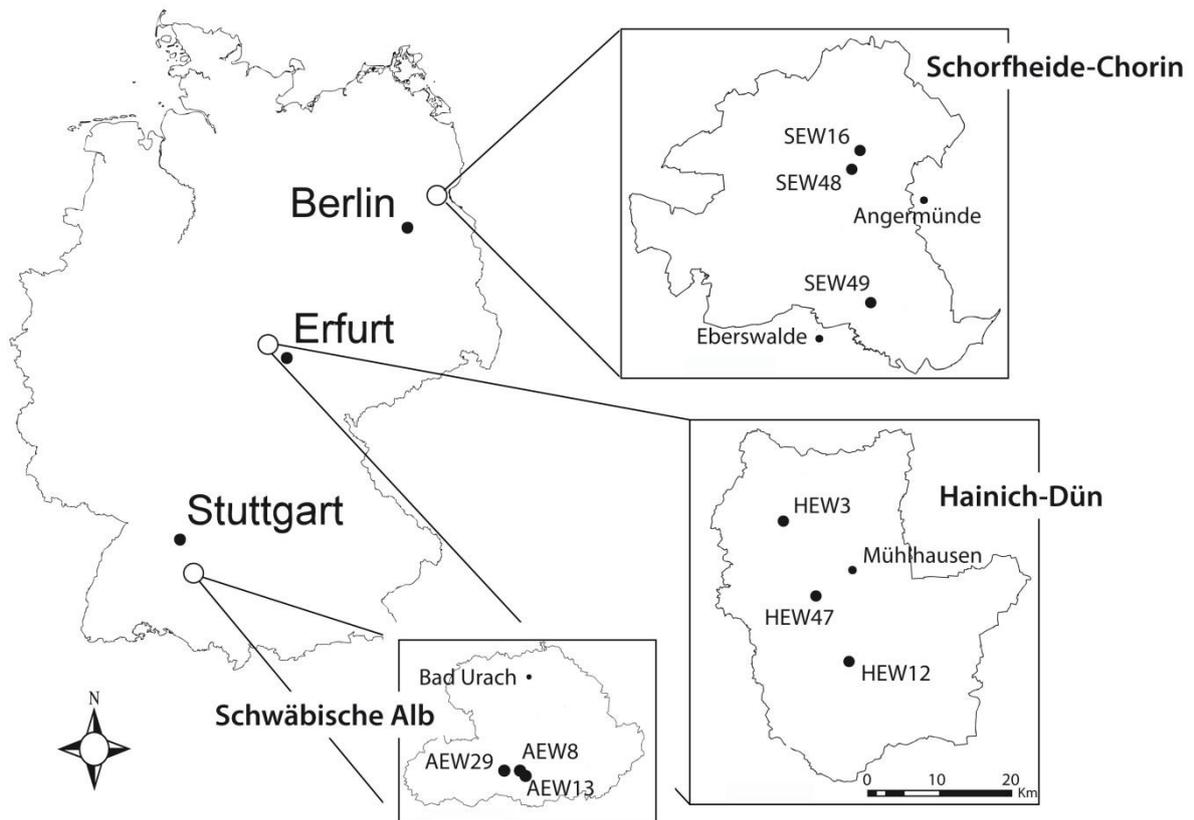
1 References

- 2 Abramoff M., Magelhaes P.J., Ram S.J.: Image processing with Image. *J. Biophotonics Int.*
3 11, 36–42, 2004.
- 4 Albert, K. R., Ro-Poulsen, H., Mikkelsen, T.N., Michelsen, A., Van Der Linden, L., and
5 Beier, C.: Effects of elevated CO₂, warming and drought episodes on plant carbon
6 uptake in a temperate heath ecosystem are controlled by soil water status, *Plant, Cell
7 & Environment*, 34, 1207-1222, doi:10.1111/j.1365-3040.2011.02320.x, 2011.
- 8 Ampoorter E., Baeten L., Koricheva J., Vanhellefont M., and Verheyen K.: Do diverse
9 overstoreys induce diverse understoreys? Lessons learnt from an experimental–
10 observational platform in Finland. *Forest Ecology and Management* 318, 206-215,
11 doi:10.1016/j.foreco.2014.01.030, 2014.
- 12 Bahn, M., Reichstein, M., Dukes, J.S., Smith, M.D., and McDowell, N.G.: Climate-biosphere
13 interactions in a more extreme world. *New Phytologist*, 2002, 356 – 359, 2014
- 14 Baudis, M., Ellerbrock, R. H., Felsmann, K., Gessler, A., Gimbel, K., Kayler, Z., Puhmann,
15 H., Ulrich, A., Weiler, M., Welk, E. and Bruelheide, H.: Intraspecific differences in
16 responses to rainshelter-induced drought and competition of *Fagus sylvatica* L. across
17 Germany, *Forest Ecology and Management*, 330, 283–293,
18 doi:10.1016/j.foreco.2014.07.012, 2014
- 19 Beier, C., Beierkuhnlein, C., Wohlgemuth, T., Penuelas, J., Emmett, B., Körner, C., de Boeck,
20 H., Christensen, J. H., Leuzinger, S., Janssens, I. A., Hansen, K.: Precipitation
21 manipulation experiments – challenges and recommendations for the future. *Ecology
22 Letters*, 15: 899–911. doi: 10.1111/j.1461-0248.2012.01793.x, 2012.
- 23 Birkhofer, K., Schoening, I., Alt, F., Herold, N., Klarner, B., Maraun, M., Marhan, S.,
24 Oelmann, Y., Wubet, T., Yurkov, A., Begerow, D., Berner, D., Buscot, F., Daniel, R.,
25 Diekoetter, T., Ehnes, R. B., Erdmann, G., Fischer, C., Foessel, B., Groh, J., Gutknecht,
26 J., Kandeler, E., Lang, C., Lohaus, G., Meyer, A., Nacke, H., Naether, A., Overmann,
27 J., Polle, A., Pollierer, M. M., Scheu, S., Schloter, M., Schulze, E.-D., Schulze, W.,
28 Weinert, J., Weisser, W. W., Wolters, V., and Schrumpf, M.: General Relationships
29 between Abiotic Soil Properties and Soil Biota across Spatial Scales and Different
30 Land-Use Types, *PLoS ONE*, 7, doi:e43292.10.1371/journal.pone.0043292, 2012.
- 31 Carminati, A., Schneider, C.L., Moradi, A.B., Zarebanadkouki, M., Vetterlein, D., Vogel, H.-
32 J., Hildebrandt, A., Weller, U., Schüler, L., and Oswald, S.E.: How the Rhizosphere
33 May Favor Water Availability to Roots, *Vadose Zone Journal*, 10, doi:988,
34 10.2136/vzj2010.0113, 2011.
- 35 Christensen, J.H., and Christensen, O.B.: A summary of the PRUDENCE model projections
36 of changes in European climate by the end of this century, *Climatic Change*, 81, 7-30,
37 doi:10.1007/s10584-006-9210-7, 2007.
- 38 Cohen, Y., Fuchs, M., and Green, G.C.: Improvement of the heat pulse method for
39 determining sap flow in trees, *Plant, Cell and Environment* 4391–397, doi:
40 10.1111/j.1365-3040.1981.tb02117.x, 1981
- 41 da Costa, A.C.L., Galbraith, D., Almeida, S., Portela, B.T.T., da Costa, M., de Athaydes
42 Silva, J. jun., Phillips, O.L., Metcalfe, D.B., Levy, P., and Meir, P.: Effect of 7 yr of
43 experimental drought on vegetation dynamics and biomass storage of an eastern
44 Amazonian rainforest. *New Phytologist* 187, 579–591, doi:10.1111/j.1469-
45 8137.2010.03309.x, 2010.

- 1 Dermody, O., Weltzin, J.F., Engel, E.C., Allen, P., and Norby, R.J: How elevated [CO₂],
2 warming, and reduced precipitation interact to affect soil moisture and LAI in an old
3 field ecosystem? *Plant Soil* 301(1-2), 255-266, doi:10.1007/s11104-007-9443-x, 2007
- 4 English, N.B., Weltzin, J.F., Fravolini, A., Thomas, L., and Williams, D.G.: The influence of
5 soil texture and vegetation on soil moisture under rainout shelters in a semi-desert
6 grassland. *Journal of arid environments*, 63(1), 324-343, doi:10.1016/j.jaridenv.
7 2005.03.013, 2005.
- 8 Fay, P.A. Carlisle, J.D., Knapp, A.K., Blair, J.M. and Collins, S.L.: Altering Rainfall Timing
9 and Quantity in a Mesic Grassland Ecosystem: Design and Performance of Rainfall
10 Manipulation Shelters. *Ecosystems*, 3, 308–319, doi: 10.1007/s100210000028. 2000.
- 11 Fischer, M., Kalko, E.K.V., Linsenmair, K.E., Pfeiffer, S., Prati, D., Schulze, E.-D., and
12 Weisser, W.W.: Exploratories for Large-Scale and Long-Term Functional Biodiversity
13 Research, Long-Term Ecological Research: Between Theory and Application, edited
14 by: Muller, F., Baessler, C., Schubert, H., and Klotz, S., Springer, 233 Spring Street,
15 New York, Ny 10013, United States, 429-443 pp., 2010.
- 16 Gessler, A., Keitel, C., Nahm, M., and Rennenberg, H.: Water shortage affects the water and
17 nitrogen balance in central European beech forests. *Plant Biology*, 6(3), 289–298.
18 doi:10.1055/s-2004-820878, 2004.
- 19 Gilliam, F.S.: The ecological significance of the herbaceous layer in temperate forest
20 ecosystems. *Bioscience*, 57(10), 845-858, doi:10.1641/B571007, 2007
- 21 Glaser, B., Jentsch, A., Kreyling, J., and Beierkuhnlein, C.: Soil-moisture change caused by
22 experimental extreme summer drought is similar to natural inter-annual variation in a
23 loamy sand in Central Europe. *Journal of Plant Nutrition Soil Science* 176, 27-34,
24 doi:10.1002/jpln.201200188, 2013.
- 25 Gregory, P.J.: Roots, rhizosphere and soil: the route to a better understanding of soil science?
26 *European Journal of Soil Science*, 57, 2-12, doi:10.1111/j.1365-2389.2005.00778.x,
27 2006.
- 28 Hommel, R., Siegwolf, R., Saurer, M., Farquhar, G. D., Kayler, Z., Ferrio, J. P., and Gessler,
29 A.: Drought response of mesophyll conductance in forest understory species – Impacts
30 on water-use efficiency and interactions with leaf water movement. *Physiologia*
31 *Plantarum*, online, doi:10.1111/ppl.12160, 2014.
- 32 Kopittke, G.R., Tietema, A., van Loon, E.E., and Asscheman, D.: Fourteen annually repeated
33 droughts suppressed autotrophic soil respiration and resulted in an ecosystem change.
34 *Ecosystems* 17, 242–257, doi:10.1007/s10021-013-9720-x, 2014.
- 35 Kreuzwieser, J. and Gessler, A.: Global climate change and tree nutrition: influence of water
36 availability. *Tree Physiology* 30, 1221–1234, *Tree Physiology* 30, 1221–1234, doi:
37 10.1093/treephys/tpq055, 2010.
- 38 Leuzinger, S., Luo, Y., Beier, C., Dieleman, W., Vicca, S., and Körner, C.: Do global change
39 experiments overestimate impacts on terrestrial ecosystems? *Trends in Ecology &*
40 *Evolution*, 26(5), 236–241. doi:10.1016/j.tree.2011.02.011, 2011.
- 41 Maracchi, G., Sirotenko, O., Bindi, M.: Impacts of present and future climate variability on
42 agriculture and forestry in the temperate regions: Europe. *Climatic Change* 70, 117-
43 135, doi:10.1007/s10584-005-5939-7, 2005.
- 44 McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D. Cobb, N., Kolb, T., Plaut, J.,
45 Sperry, J., West, A., Williams, D.G., Yezpez, E.A.: Mechanisms of plant survival and

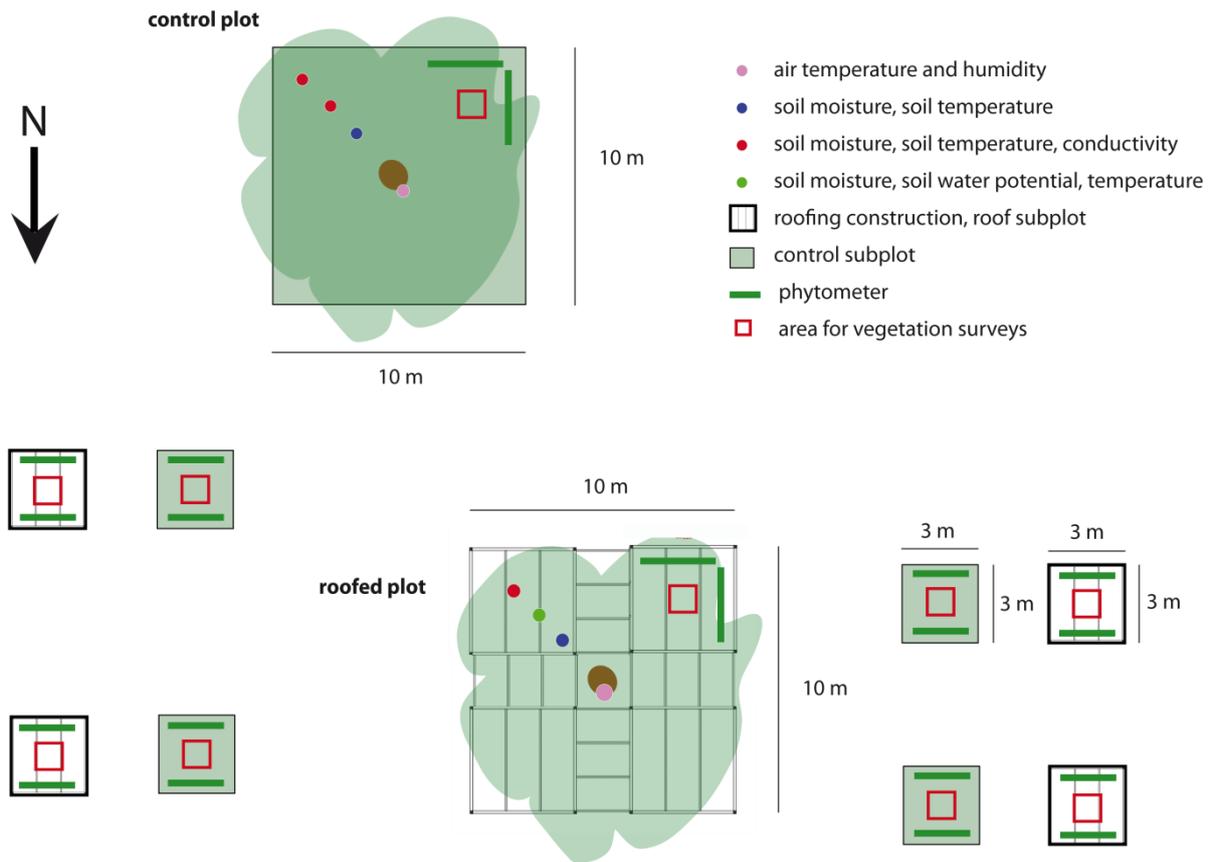
- 1 mortality during drought: why do some plants survive while others succumb to
2 drought? *New Phytologist* 178, 719-739, doi: 10.1111/j.1469-8137.2008.02436.x,
3 2008.
- 4 Ozolincius, R., Stakenas, V., Varnagiryte-Kabasinskiene, I., and Buozyte, R.: Artificial
5 drought in Scots pine stands: effects on soil, ground vegetation and tree
6 condition. *Annales Botanici Fennici* 46(4), 299-307, 2009.
- 7 Parra, A., Ramirez, D.A., Resco, V., Velasco, A., and Moreno, J.M.: Modifying rainfall
8 patterns in a mediterranean shrubland: system design, plant responses, and
9 experimental burning. *Int J Biometeorol* 56, 1033–1043, doi:10.1007/s00484-011-
10 0517-3, 2012.
- 11 Prudhomme, C., Giuntoli, I., Robinson, E.L., Clark, D.B., Arnell, N.W., Dankers, R., Fekete,
12 B.M., Franssen, W., Gerten, D., Gosling, S.N., Hagemann, S., Hannah, D. M., Kim,
13 H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D.: Hydrological drought
14 in the 21st century, hotspots and uncertainties from a global multimodel experiment,
15 *Proceedings of the National Academy of Sciences of the United States of America*,
16 111(9), 3262-7, doi:10.1073/pnas.1222473110, 2014
- 17 Rodriguez-Calcerra, J., Atkin, O.K., Robson, T.M., Zaragoza-Castells, J., Gil, L., and Aranda,
18 I.: Thermal acclimation of leaf dark respiration of beech seedlings experiencing
19 summer drought in high and low light environments. *Tree Physiology* 30, 214–224,
20 doi:10.1093/treephys/tpp104, 2009.
- 21 Schaumann, G. E., Braun, B., Kirchner, D., Rotard, W., Szewzyk, U., and Grohmann, E.:
22 Influence of biofilms on the water repellency of urban soil samples, *Hydrological*
23 *Processes*, 21, 2276-2284, doi:10.1002/hyp.6746, 2007.
- 24 Schraml, C., and Rennenberg, H.: The different reactions of beech tree (*Fagus sylvatica* L.)
25 ecotypes to drought stress. *Forstw. Cbl.* 121, 59-72, doi:10.1046/j.1439-
26 0337.2002.00059.x, 2002.
- 27 Selsted, M.B., Linden, L., Ibrom, A., Michelsen, A., Larsen, K.S., Pedersen, J.K., Mikkelsen,
28 T.N., Pilegaard, K., Beier, C., and Ambus, P.: Soil respiration is stimulated by
29 elevated CO₂ and reduced by summer drought: three years of measurements in a
30 multifactor ecosystem manipulation experiment in a temperate heathland
31 (CLIMAITÉ), *Global Change Biology*, 18, 1216-1230, doi:10.1111/j.1365-
32 2486.2011.02634.x, 2012.
- 33 Seneviratne, S.I., Luethi, D., Litschi, M., and Schaer, C.: Land-atmosphere coupling and
34 climate change in Europe, *Nature*, 443, 205-209, doi:10.1038/nature05095, 2006.
- 35 Spohn, M., and Rillig, M.C.: Temperature- and moisture-dependent soil water repellency
36 induced by the basidiomycete *Agaricus bisporus*, *Pedobiologia*, 55, 59-61,
37 doi:10.1016/j.pedobi.2011.10.006, 2012.
- 38 Tang, J., Mo, Y., Zhang, J., and Zhang, R.: Influence of biological aggregating agents
39 associated with microbial population on soil aggregate stability, *Applied Soil Ecology*,
40 47, 153-159, doi:10.1016/j.apsoil.2011.01.001, 2011.
- 41 Tschaplinski, T.J., Gebre, G.M., Shirshac, T.L.: Osmotic potential of several hardwood
42 species as affected by manipulation of throughfall precipitation in an upland oak forest
43 during a dry year. *Tree Physiology* 18, 291-298, 1998.
- 44 Tisdall, J.M., and Oades, J.M.: Organic matter and water-stable aggregates in soils, *Journal of*
45 *Soil Science*, 33, 141-163, 1982.

- 1 Vicca, S. Gilgen, A.K., Camino serrano, M., Dreesen, F.E., Dukes, J.S., Estiarte, M., Grey,
2 S.B., Guidolotti, G., Hoepfner, S.S., Leakey, A.D.B., Ogaya, R., Ort, D.R.,
3 Ostrogovic, M.Z., Rambal, S., Sardans, J., Schmitt, M., Siebers, M., van der Linden,
4 L., van Straatten, O., and Granier, A.: Urgand need for a common metric to make
5 precipitation manipulation experiments comperable. *New Phytologist*, 195, 518 – 522,
6 doi:10.1111/j.1469-8137.2012.04224.x, 2012
- 7 Wu, Z., Dijkstra, P., Koch, G. W., Peñuelas, J. and Hungate, B. A.: Responses of terrestrial
8 ecosystems to temperature and precipitation change: a meta-analysis of experimental
9 manipulation. *Global Change Biology*, 17: 927–942. doi: 10.1111/j.1365-
10 2486.2010.02302.x, 2011.
- 11 Yepez, E., Huxman, T., Ignace, D., English, N., Weltzin, J., Castellanos, A., and Williams,
12 D.: Dynamics of transpiration and evaporation following a moisture pulse in semiarid
13 grassland: A chamber-based isotope method for partitioning flux components.
14 *Agricultural And Forest Meteorology* 132, 359–376, doi:10.1016/
15 j.agrformet.2005.09.006, 2005.
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Figure 1: Location of the three Biodiversity Exploratories and the experimental plots.

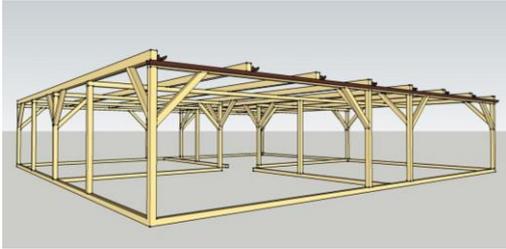


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2 Figure 2: Schematic sketch of roofed and control subplots with roof construction indicated.

3

a



b



c

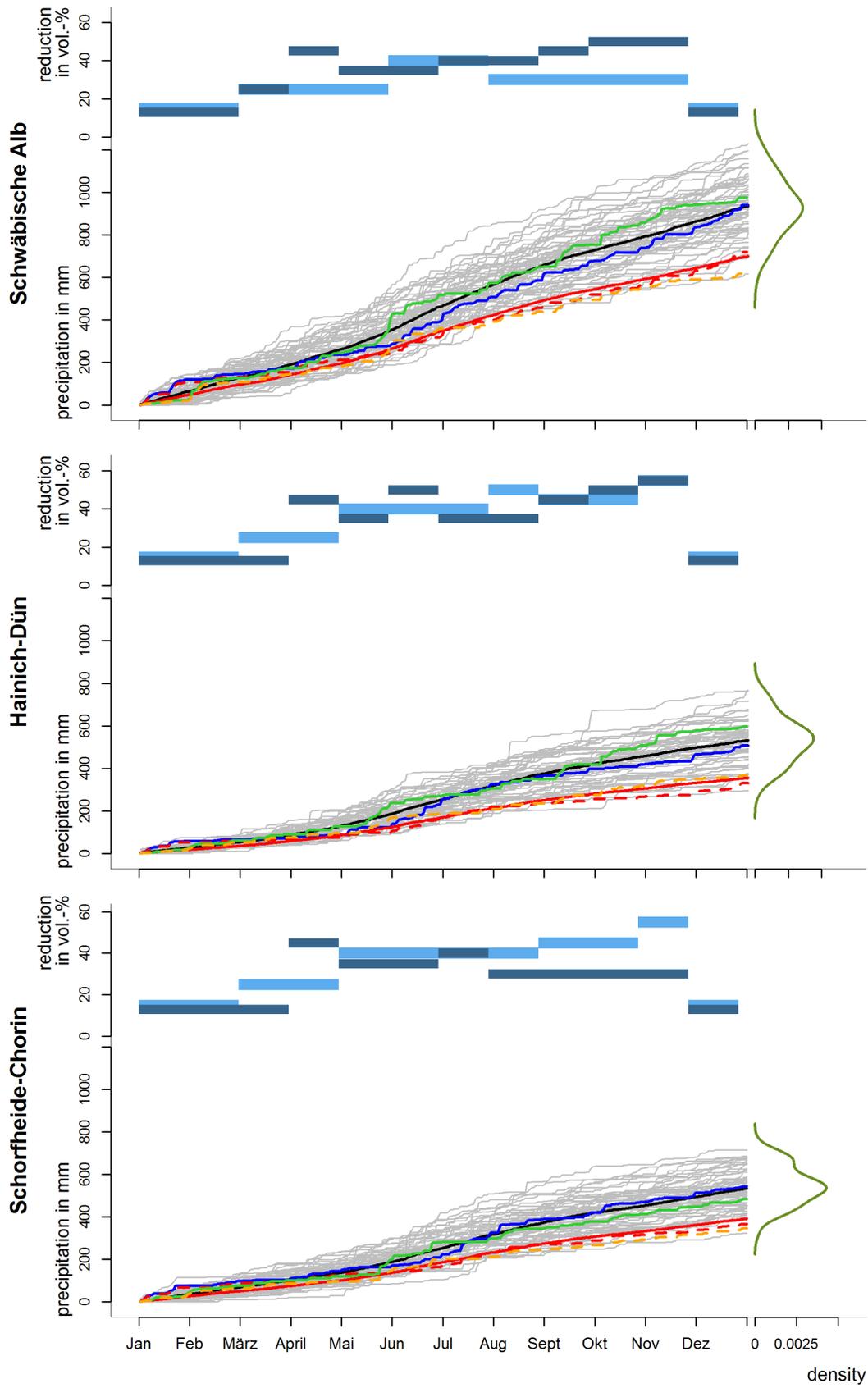


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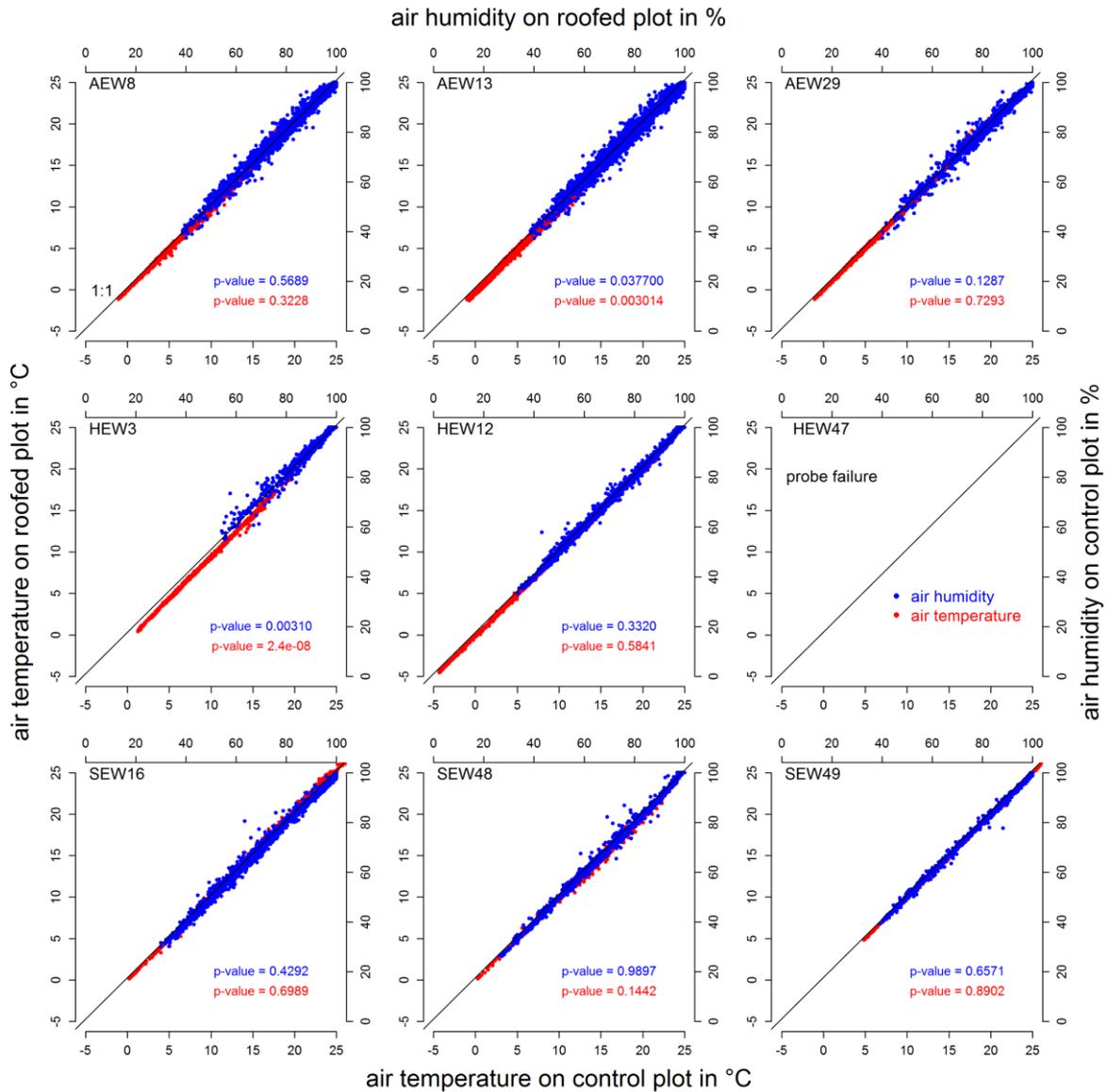
1 Fig. 3: Roof construction sketch of the main roof (10x10m) (a). Roof with panels, rain gutters
2 and water barrel and main tree (b, c). Roof detail with main tree and stem rim to collect stem
3 flow (d). All pictures were taken at plot SEW48.

4

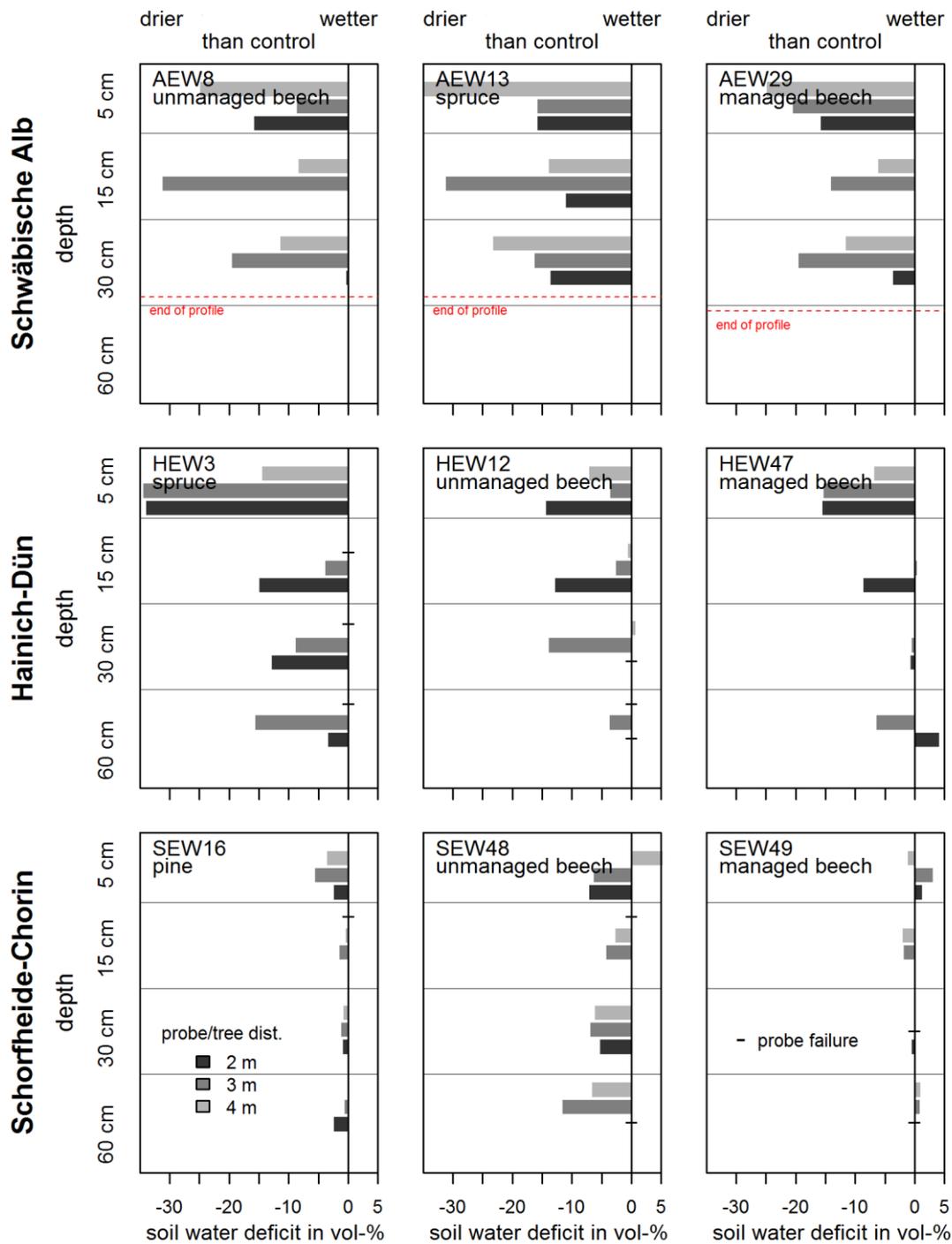


- prec. 1950-2010
- mean 1950-2010
- prec. 2012
- prec. 2013
- target value
- prec. input 2012 under roof
- prec. input 2013 under roof
- density
- ▬ prec. reduction 2012
- ▬ prec. reduction 2013

1 Figure 4: Cumulated sums of precipitation. Grey lines: individual years 1950 – 2010. Black
2 line: cumulated mean of 1950 – 2010. Dark green line: appearance distribution of
3 precipitation 1950 – 2010 (density). Light blue bars: reduction of precipitation 2012 in vol-%.
4 Dark blue bars: reduction of precipitation 2013 in vol-%. Blue line: cumulated precipitation of
5 year 2012. Green line: cumulated precipitation of year 2013. Solid red line: cumulated 2.5 %-
6 percentile (target value). Dashed red line: cumulated precipitation under roofs in 2012.
7 Dashed orange line: cumulated precipitation under roofs in 2013.
8

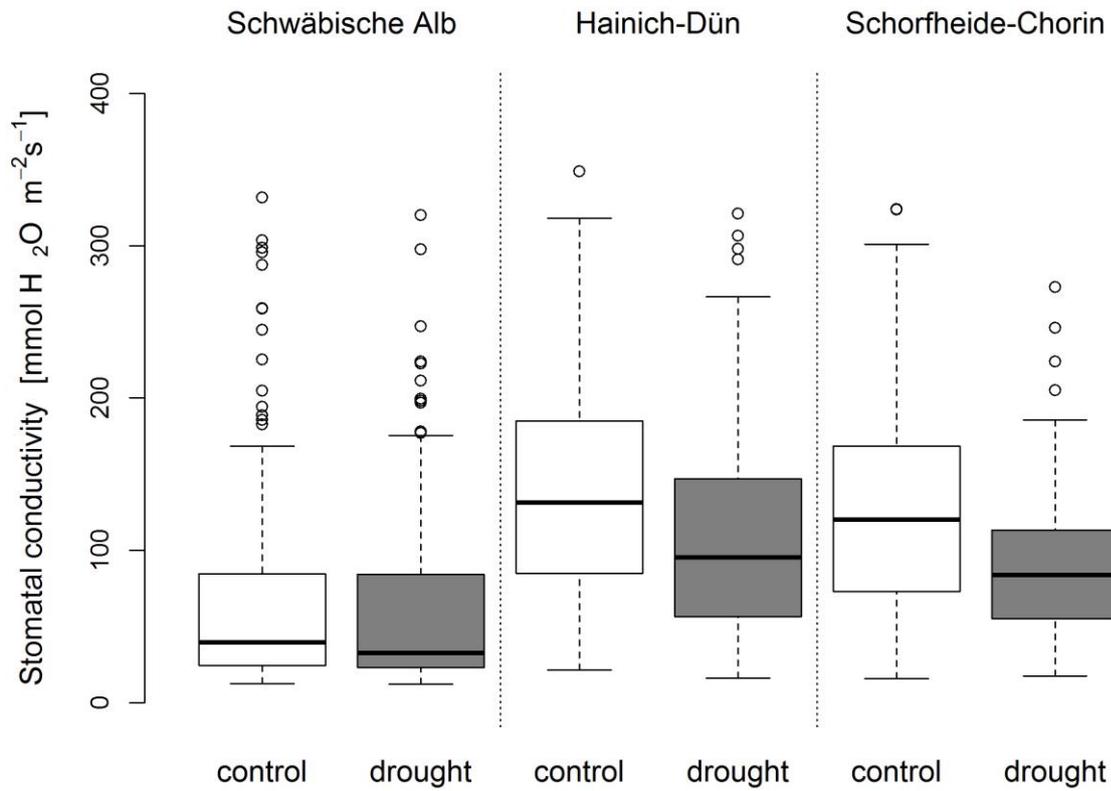


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 2 Figure 5: Air temperature control plots vs. air temperature roofed plots (red dots) and air
 3 humidity on control plots vs. air humidity on roofed plots (blue dots) for all experimental sites
 4 in May 2013. No data for HEW47 are shown due to probe failure.
 5



1
 2 Figure 6: Soil water deficit (soil water content of control minus roofed subplot) of the main
 3 subplots. All values originate from May 2013, except the values from HEW47 (April 2013),
 4 due to probe failure. “-“ marks missing values.
 5

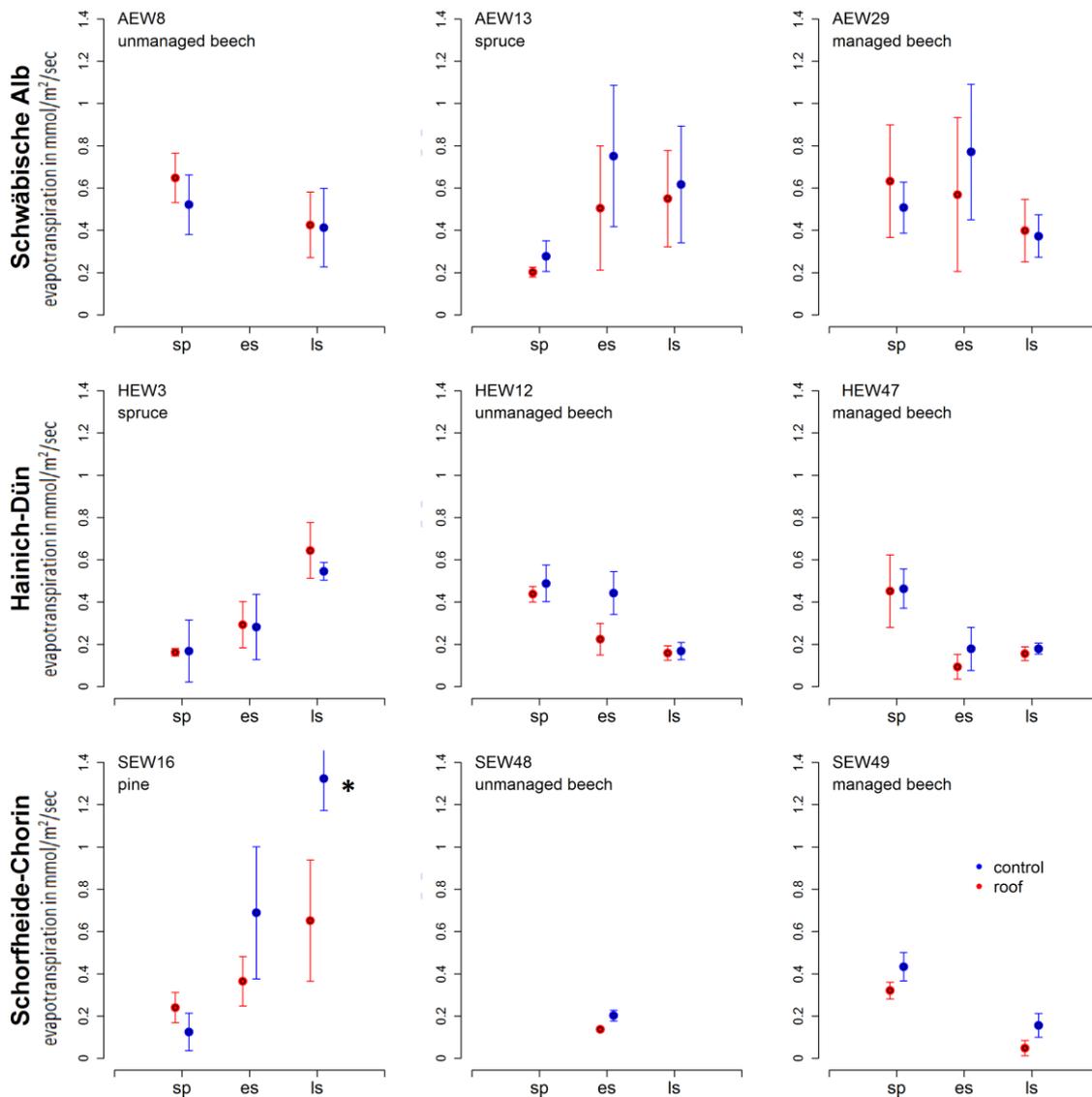
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3 Figure 7: Leaf stomatal conductance at the three experimental sites in July 2012. The boxes
4 show medians and quartiles, the whiskers show 1.5 times the interquartile range of the data.
5 For statistical analyses see Table 4.

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 2 Figure 8: Mean evapotranspiration rates (\pm SD) for control and drought treatments ($n = 4$) at
 3 different times during the growing season (sp: spring; es: early summer; ls: late summer).
 4 Data are shown for the different management intensities (managed/unmanaged beech and
 5 pine/spruce) in the three exploratories. The asterisk marks significant differences (p-
 6 value < 0.05).

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2 Table 1: Forest type, main tree species, tree stand density and understory community at the
 3 various experimental plots.

Exploratory	plot name	forest type	main tree species	tree basal area m ² /ha	Plant community
Schwäbische Alb	AEW8	unmanaged	beech	39.04	Hordelymo-Fagetum
	AEW13	intensively managed	spruce	38.08	<i>Picea abies</i> plantation
	AEW29	managed	beech	31.59	Hordelymo-Fagetum
Hainich-Dün	HEW3	intensively managed	spruce	27.77	<i>Picea abies</i> plantation
	HEW12	unmanaged	beech	32.15	Hordelymo-Fagetum
	HEW47	managed	beech	34.55	Hordelymo-Fagetum
Schorfheide-Chorin	SEW16	intensively managed	pine	37.92	<i>Deschampsia flexuosa-Pinus sylvestris</i> community
	SEW48	unmanaged	beech	25.95	Galio-Fagetum
	SEW49	managed	beech	36.11	Galio-Fagetum

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1 Table 2: General properties of the nine experimental plots.

Exploratory	Plotname	Mean annual precipitation	Mean annual temperature	Elevation m asl	Soil class
Schwäbische Alb	AEW8			766 m	Cambisol
	AEW13	940 mm	6.5 °C	714 m	Cambisol
	AEW29			760 m	Leptosol
Hainich-Dün	HEW3			410 m	Luvisol
	HEW12	533 mm	7.2 °C	332 m	Luvisol
	HEW47			333 m	Stagnosol
Schorfheide-Chorin	SEW16			69 m	Cambisol
	SEW48	589 mm	8.5 °C	74 m	Cambisol
	SEW49			65 m	Cambisol

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3 Table 3: Results of the vegetation monitoring of the understory vegetation for various
4 functional groups at all three sites shown as mean coverage per plot in percent; calculated as
5 mean from ten vegetation recordings of 1x1m per subplot

Exploratory	plot name	understory	mean cover in functional group (%)			
		vegetation cover (%)	grass	herb	shrub	tree recruits
Schwäbische Alb	AEW8	22.87	0.73	19.90	0.00	2.30
	AEW13	57.10	0.65	50.10	3.90	3.20
	AEW29	36.77	5.60	20.80	0.00	10.50
Hainich-Dün	HEW3	48.95	19.70	26.60	1.15	0.20
	HEW12	44.67	0.00	34.0	0.00	10.70
	HEW47	27.30	8.00	9.20	0.00	10.40
Schorfheide-Chorin	SEW16	33.60	28.60	5.00	0.00	0.00
	SEW48	2.26	1.80	0.43	0.00	0.10
	SEW49	47.90	0.03	39.40	7.50	1.30

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1 Table 4. *LAI* (mean \pm SD, n = 4) and species richness ($A_{\text{total}} = 2.45 \text{ m}^2$) for control and roof
 2 subplots in late summer (August/September) 2012 for the different exploratories and
 3 management types. no veg. assings no vegetation on plot; t- tests were applied to assess the
 4 differences in the *LAI* and for species richness between the roof and control treatment * p <
 5 0.05, ** p < 0.01

plot	manage- ment type	<i>LAI</i>			species richness		
		control	roof	roof vs. control	control	roof	roof vs. control
AEW13	spruce	1.74 \pm 0.41	1.63 \pm 0.50	-	9	8	-
AEW8	beech unmanaged	0.75 \pm 0.21	0.44 \pm 0.24	-	5	4	-
AEW29	beech managed	0.97 \pm 0.05	0.71 \pm 0.06	**	9	8	-
HEW3	spruce	0.92 \pm 0.15	0.53 \pm 0.09	**	5	5	-
HEW12	beech unmanaged	0.40 \pm 0.08	0.24 \pm 0.09	-	3	3	-
HEW47	beech managed	0.37 \pm 0.04	0.42 \pm 0.04	-	6	8	**
SEW16	pine	0.62 \pm 0.10	0.44 \pm 0.13	-	5	3	-
SEW48	beech unmanaged	no veg.	no veg.	-	no veg.	no veg.	-
SEW49	beech managed	0.63 \pm 0.18	0.88 \pm 0.20	-	8	7	-

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1 Table 5: Results of the linear mixed model for the leaf stomatal conductance (g_s) as a function
 2 of site, drought and competition of the *Fagus sylvatica* phytometers in July and September
 3 2012 (spring data not shown). Values are p-values. Significant probabilities ($p < 0.05$) are
 4 shown on bold; den df = degrees of freedom.

Factor	Leaf Stomatal Conductance			
	den df	g_s (July)	den df	g_s (September)
(intercept)	752	<.0001	690	<.0001
site	6	0.0254	6	0.3133
drought	78	0.0009	70	0.0602
competition	84	0.7268	76	0.9837
site:drought	78	0.0473	70	0.1547
site:competition	84	0.4376	76	0.8865
drought:competition	84	0.1939	76	0.6987
site:drought:competition	84	0.6997	76	0.0219

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