Anonymous referee #1

General comments

1. **Referee:** … how their rainfall manipulation experiments can prevent the soil water flow from the surrounding to the plots, especially for the subplots with only 3m*3m? As they admitted, the adult trees could extract water through root systems from outside. This issue needs to be addressed.

Answer: Adult trees are not incorporated under the small roofs; therefore water extraction from the surrounding of the plot is not an issue for the small roofs. Parts of the phytometer experiments were performed under the small roofs; the main experiments were realized exclusively under the large roofs, where a distance to the borders was kept. Anyway, the focus of our study was on understory vegetation, which is not prone to extract water from outside the plots. (Please see also the answers to comment no. 10 and 11 of refree#1, comment no. 1 of referee#2, and comment no. 3 of referee#3). To address the soil water flow issue, the selected plots are all situated on flat angled slopes to avoid water input through overland and subsurface flow. We might assume that some hydraulic redistribution via the rooting system of the adult trees might occur and that the understory vegetation might also benefit from such redistribution. We can, however, show that the roofs cause a clear reduction of soil water content and we did not see any diurnal rhythms in soil moisture that would be an indication of hydraulic redistribution. We thus have good reasons to assume this effect to be negligible.

2. **Referee:** … in the manuscript, they presented both the experiment design and the drought effects on forest understory ecosystems in the first year. Generally, after the disturbance, the ecosystem response to drought in the first year is not good information. Hence, it's not a good idea to address the point of drought effects at this stage. It's better to focus on the novelty and unique of their experiment design.

Answer: We do not fully understand this point raised by the referee: We agree with the referee, that freshly disturbed (after roof and probe installation etc.) plots may give unsteady data. Therefore, (as stated in 14332 L14 – 18) the installation of the roofing construction took place between September and early December in the year before the described experiment. All work was performed with maximal care to avoid unnecessary stepping and disturbing on the experimental area.

If the referee assumes that one year of drought is not sufficient to address ecosystem responses we disagree: Our aim was to induce an extreme drought with a return period of 40 years. We certainly need to assume that such extreme drought events will occur more often when we refer to the climate scenarios for the future but we still cannot assume that we will have many of such extreme years in sequence. As a consequence we consider it fully justified to study ecosystem reactions after one year and strongly believe that it is necessary to study realistic drought effects and responses in the time frame as we did. We certainly agree that also long-term precipitation manipulation experiments are needed to study trajectories of ecosystem reactions and developments but we think the assessments of long- and short-term responses are highly complementary.

3. **Referee**: … the drought conditions in the natural settings are generally characterized by a long dry period and some intense rainfall before or after the drought. From their Figure 4,

the removal of rainfall is quite uniformly distributed over the growing season. Can this design represent the natural drought events?

Answer: Here, we simulated not a short drought spell, but an overall reduced precipitation input, similar to the ones forecasted for Central Europe (increased summer dryness, Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA).
But, as stated in 14336 L18 – 24 the construction is flexible enough to realize a (total) reduction over longer periods (weeks, months) and can be combined with irrigation equipment.

Specific comments:

Abstract

4. **Referee**: The first sentence is not clear. In my opinion, changes in precipitation patterns is part of climate change, rather not climate change affecting it. Also, they need one sentence which stated how novel is their experiment.

Answer: We changed the sentences; the Abstract reads now as follows:

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

Introduction

5. **Referee**: They need provide more information about previous studies in which how they make their rainfall manipulation experiments and the drawback.

Answer: We agree with the referee and inserted following sentence:

"In addition, the constructions used in previous studies often need electrical supply or intensive technical installation, supervision, and maintenance (e.g. Beier et al. 2004, Albert et al. 2011, Parra et al. 2012, Kopittke et al. 2014)."

Material and methods

6. **Referee**: 2.1 This part about the sites could be simplified. A table could be more clear.

Answer: We agree with the referee, shortened the section, and inserted a table. The section now reads as follows:

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

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

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

7. **Referee**: 2.4 Specific leaf area has special definition as the ratio of leaf area to dry mass. Need another term for LAI_{sp}.

Answer: We now don't refer to specific leaf area index any longer but just to leaf area index (LAI), a term which is generally used to indicate the leaf area per ground area. We now also do not refer any longer to specific leaf area when we refer to the area of an average leaf of a species.

Discussion

8. **Referee**: There are many conclusions which are not support by the experimental results, at least at this stage, but from other references or 'expect'. This should be avoided. As suggested in the general comments, the discussion of drought effects is not appropriate from only one-year data. They should focus on the experiment design.

Answer: We have now considerably shortened the discussion section 4.3 the referee refers to. We have omitted the sections where we describe our expectations for longer term reactions of the ecosystem to keep the paper more focused on the experimental design.

9. **Referee**: P14337, L16-19: why not measure CO2 flux?

Answer: We fully agree that measurements of CO_2 concentrations and fluxes would be an important complement to the assessments shown here and such approaches need to be included in future studies using such a roof design.

10. **Referee**: P14337, L20-28: for soil moisture, I would say that there are some effects from soil water flow between outside and inside the plots.

Answer: We do only partially agree with the referee here. We did not detect any (nocturnal) replenishment of soil moisture at our soil moisture probes and we kept our experiments at an adequate distance to the borders of the roofed area. We agree, that in close vicinity of the borders exchange effects might occur.

(Please see also the answers to comment no. 1 and 11 of refree#1, comment no. 1 of referee#2, and comment no. 3 of referee#3).

11. **Referee**: P14338, L1-5: We knew this problem for long time. How did you address this issue?

Answer: The referee is referring to the problem of adult trees rooting inside and outside of the roofed area, and therefore possible extract water outside the roofed area and release it via hydraulic redistribution inside. We did not detect any rise in our soil moisture data, which can be associated with hydraulic redistribution. We focused in our study on understory vegetation and not on adult trees. Any water that is extracted from adult trees outside the roofed area (and is not redistributed) is consumed by the tree itself and therefore not changing the soil moisture budget. (Please see also the answers to comment no. 1 and 10 of refree#1, comment no. 1 of referee#2, and comment no. 3 of referee#3).

12. **Referee**: P14338, L15-28: These conclusions are not support by the results at this stage.

Answer: As written above we have now focused on the short-term effects and avoided speculations about potential reactions of the ecosystem under longer drought periods. We do think that we have now better focused on these short-term responses but still relate them to effects observed in other studies and to the general mechanisms of drought responses of ecosystems.

Conclusion

13. **Referee**: P14340, L1-4: The conclusion cannot be ‘expected’.

Answer: We have now focused on the effects supported by our results and have omitted the expectations.

Anonymous referee #2

General comments

1. **Referee**: "…although this is important, the paper is now written to understand ecosystem consequences, while the experimental design was only one year without having any statistically differences. They finally conclude that the roof structure itself also has the problem that adult trees can extract water from the surrounding, which is already the problem for decades by these manipulation experiments. So I do not see why the system is that innovative. In the whole paper I can not find any interesting point that increases our understanding of the system."

Answer: We do not agree with the referee – a misapprehension might have occurred here: in this paper, we present the construction of an innovative flexible roof for rainfall exclusion/reduction experiments. The focus lies on the construction and operation of this roof which allows flexible reduction of the precipitation and not only a fixed amount of reduction. It is well suited to reach predefined target values and can be operated at many sites and also in remote areas since for operation neither electricity nor intensive technical supervision is necessary; moreover as stated repeatedly in the manuscript the roofs are meant to manipulate the water relations of the understory. The results of the plant experiments are an illustrative "add-on" to show how initial understory reactions look like. The general focus is NOT on the adult trees and thus their extraction of water from the surrounding soil is not a problem. This is, because the trees consume the additional water and don´t change the water budget for understory plants under the roofs. Only hydraulic redistribution could change the budget, which we didn´t observe. Hydraulic redistribution to drier soil areas should occur during night and thus a night-time in increase in soil moisture should be observed when we assume that such mechanism should play a role. Since we did not observe such night-time response we can be confident that hydraulic redistribution is negligible and thus does not compromise our design at all.

If our roofs were to be applied for assessing the effects of drought for adult trees the problem of their roots taking up water from outside the roofed area can be easily avoided by enlarging the roof over the perimeter of the roots (Please see also the answers to comment no. 1, 10, and 11 of refree#1, and comment no. 3 of referee#3).

To conclude, our system is indeed innovative: we`ve overcome the problem of complete reduction of precipitation; our roof offers the possibility to use an adaptive reduction level between 11 - 100 %; it does not need any electrical components; it can be adjusted in size to the experimental and local requirements; it is easy to build, to handle, and to maintain; it is not promoting any greenhouse effect; and, with extra handling, litter build up is least disturbed (not described in this paper).

Specific comments:

2. **Referee**: Pg 14322, L19-20: How will ecosystem response depend on ecosystem stability? This is a very important question from ecology. But what is ecosystem stability, can you measure this? It is unclear why the authors have stated this. Do they refer to the stability-diversity debate, as the have included in their introduction microbial community structure?

Answer: Since the paper is mainly meant to demonstrate the design of the rainfall reduction system and referee # 1 also suggested to focus on this part we have now omitted this sentence. We agree with the referee that this is an important question but discussing this point here would be beyond the scope of our manuscript.

3. **Referee**: Pg 14330 L3-5: The specific LAI was measured, but unclear what this is. It seemed to be the total LAI assuming that the leafs are horizontal. Interesting from an ecohydrological point of view is the real LAI, so including the angle of the leaf. Why didn't you measure this?

Answer: We agree that the LAI as determined here is a proxy for the real LAI. However, especially when assessing a not very intensively structured canopy with most of the species having their leaves very close to the ground classical LAI measurements (e.g. with ceptometers) are difficult and error prone. We think that our approach is a good compromise and it also allows an estimate of the effect of drought on leaf area.

4. **Referee**: Pg 14330 L19: Interesting are the experiments with phytometers, but it is unclear to me how this will work.

Answer: For clarification, we changed the sentence 14331 L1 to: "Growth of all planted beeches was recorded by measuring different growth response variables such as leaf number, plant height, leaf length and crown expansion and compared with the phytometer data of the control plots." (Please see also answer to comment no. 8 of refree#2 below)

5. **Referee**: Pg 14331 L9: You measure evapotranspiration in the gas chambers. I do not understand this, I assume that you measure the transpiration and not the evaporative fluxes, right?

Answer: We indeed measured evapotranspiration. To make that point more clear we have now added the following explanation to the Materials and Methods section: "The chambers were open to the soil, sealed with rubber foam gaskets to the ground and were use as closed systems to assess the build up of water vapour from soil evaporation and plant transpiration."

6. **Referee**: Pg 14333 L20: Interesting would be how CO2 will change under the canopies as I would expect higher values. This would be a nice research, however, the authors didn't look to that.

Answer: We agree that CO_2 concentration measurements would have been a nice complementary assessment. We think, however, that we have very good arguments not to assume a CO_2 build up under the roofs. We normally need to assume that total evaporation fluxes from the whole understorey system should be up to three orders of magnitude higher than net CO2 emission (mmol/m2/s for water vs µmol/m/s for CO2). If the roofs would prevent air mass mixing this should be then also visible in the RH under the roofs. Our measurements show no difference in RH and air temperature between roofed and control plots, which clearly points to a comparable coupling of airspace on both subplots. In addition, the design of the roofs with an incomplete coverage (2 m high, four sides open, maximum roof coverage 55 %, complete roof area only 10 m^2) definitely not represent a closed roof. Given that, it is very unlikely, that RH and temperature stay totally unaffected and CO2 would be affected.

We have stated this point as follows in our manuscript (section 4.2):

"Our measurements show no difference in humidity and air temperature between roofed and control plots, which clearly indicates a comparable coupling of airspace on both subplots. In addition, the design of the roofs with an incomplete coverage (2 m high, four sides open, maximum roof coverage 55 %, complete roof area only 100 m^2) definitely not represent a closed roof. Given that and the findings that air humidity and temperature stay totally unaffected, it is very unlikely, that CO_2

concentrations increased under the roofs and thus also no CO_2 fertilization effects are to be expected."

7. **Referee**: Pg 14333 L25: Now I am lost. What kind of significant effects? We are now discussing your results while you came up with references

Answer: We agree, the sentence might be capable of being misunderstood. We changed the sentence to:

"Because elevation of air temperature and humidity has significant effects on growth, germination, transpiration and water uptake of plants, on microbial activity and on soil evaporation, we aimed at avoiding any alteration of air temperature and humidity as well as radiation."

8. **Referee**: Pg 14335 paragraph 3.4: Plant community and phytometer: More information is needed for the phytometer, what are the rooting depths, are they different. How well are they performing.

Answer: We agree with the referee and inserted following explanation and a reference in section 2.4:

"The saplings had an initial height of 30–50 cm (with a mean and sd of 34.74 cm ±8.15 cm, respectively) and a tap root length approximately of 10 cm. At the time of planting, roots of all saplings were pruned to 10 cm to avoid crooked roots in shallow soils, as they occur at the Hainich and Schwäbische Alb site."

"…For further information on the experimental design of the phytometer experiment see Baudis et al. 2014."

9. **Referee**: Pg 14335, L 14: If there is no significant difference then a tendency is not interesting. It is not significant so.

Answer: The description of the non-significant tendencies has been omitted.

10. **Referee**: Pg 14335, L23: "Interesting that there is an interaction effect between drought and site, however, why? Do you have a hypotheses on this, e.g. due to higher storage capacities? The authors doesn't give any information about this."

Answer: The interaction effect between drought and site corresponds to the soil moisture results (Figure 6) and caused by soil texture and total precipitation input: the amount of plant available water is (in general) highest in the Schwäbische Alb region, caused by the interaction of water storage capacity and absolute water input.

11. **Referee**: Pg 1433, L4-6: This is the only interesting result I would say, and it would be great to understand this. Apparently the ecosystem can adapt in such a way that the functioning remains the same. Interesting would be to find the shift, but for that the system needs to be run for more years with probably more extreme drought and fixing the problem that the roofs are too small.

Answer: We agree that for the understanding the general reaction of an ecosystem with threshold values and tipping points towards extreme drought long-term experiments would be necessary. We are however, also of the strong opinion that we additionally need to assess responses of ecosystems to realistic drought conditions most probably occurring in future. The roofing system presented here allows both, realistic rather short drought periods and more intensive long-term treatments and is also flexible enough to adapt the precipitation regime.

12. **Referee**: Pg14337, L20: The work of Dermody et al (2007) is work on CO2?

Answer: The citation has been omitted. The sentence reads now as follows: "This is in line with the findings of English et al. (2005), who found a decrease of soil moisture deficit with depth."

13. **Referee**: Pg14338, L1: The problem that the soil under the roof is influenced by trees rooting outside the roof is always the problem. This is why the roofs should be made bigger and I hoped that this was the case with this study. It means that still all interpretations should be made with care.

Answer: We agree with the referee, and therefore used and propose the use of roofs with the size of 100 m^2. The referee is also referring to the problem of adult trees rooting inside and outside of the roofed area, and therefore possible extract water outside the roofed area and release it via hydraulic redistribution inside. We did not detect any nocturnal rise in our soil moisture data, which can be associated with hydraulic redistribution. We focused in our study on understory vegetation and not on adult trees. Any water that is extracted from adult trees outside the roofed area (and is not redistributed) is consumed by the tree itself and therefore not changing the soil moisture budget. (Please see also the answers to comment no. 1, 10, and 11 of refree#1, comment no. 1 of referee#2, and comment no. 3 of referee#3).

14. **Referee**: Pg 14338, L12: Of course stress induced by drought may alleviate competitive exclusion, but indeed I would expect that shifts in species will take more time. So this paragraph is a bit confusing, as later on you only talk about effects in fluxes by (e.g. Leuzinger et al. 2011) and not in species shifts. As your experiment is not long enough and not strong enough (L26, p 14338), your experimental design can not say anything on these processes

Answer: We have now omitted this speculative part of the discussion also in agreement with comment of referee # 1.

15. **Referee**: Pg 14339 L22: We conclude that our innovative roofing … etc: But you have not tested anything. Why innovative, as you still have the problem of adult tree extracting water outside the roof.

Answer: We do not fully understand this point raised by the referee: As stated above (comment #1). Our roof allows for a flexible rainfall reduction and therefore overcomes the problem of fixed amounts of former roofing designs. Furthermore, our roof offers the possibility to use an adaptive reduction level between 11 - 100 %; it does not need any electrical components; it can be adjusted in size to the experimental and local requirements; it is easy to build, to handle, and to maintain; and it is not promoting any greenhouse effect. As also stated above and repeatedly in the manuscript, the roof was designed to manipulate the water relations of the understory. Nevertheless, if the roof sized is enlarged over the perimeter of the adult tree roots, the addressed problem of external extraction of water can be easily avoided (Please see also the answers to comment no. 1, 10, and 11 of refree#1, and comment no. 3 of referee#3)

Anonymous referee #3

General comments

1. **Referee**: The Results section, in places, fails to present statistical justification for the claims made and I had considerable difficulty in understanding two of the figures (Figures 4 and 6). We are told only that drought conditions had no effect, in this initial period, on growth parameters. I would, nevertheless, have liked to see some of the supporting data - perhaps in an appendix.

Answer: In agreement with referee 1 we have now focused the discussion as well as the conclusion to the ecosystem responses on the short-term avoiding speculation on the system behavior under longer-drought exposure. (see also comments 2 and 23).

Concerning the Figures 4 and 6, please see the answers to comments 13 and 15.

Further data on growth parameters is already published in a paper by Baudis et al. 2014 (Baudis, M., Ellerbrock, R. H., Felsmann, K., Gessler, A., Gimbel, K., Kayler, Z., Puhlmann, H., Ulrich, A., Weiler, M., Welk, E. and Bruelheide, H.: Intraspecific differences in responses to rainshelter-induced drought and competition of Fagus sylvatica L. across Germany, Forest Ecology and Management, 330, 283–293, doi:10.1016/j.foreco.2014.07.012, 2014). We now inserted a reference to this paper in the text (section 2.4).

2. **Referee**: The Discussion again makes a number of claims that appear unsupported by the results as presented here. The question of whether the authors expect drought effects to be more pronounced over short or long periods is rather vague here – in contrast with the final sentence in the Conclusion.

Answer: We have now focused the discussion as well as the conclusion to the ecosystem responses on the short-term avoiding speculation on the system behavior under longer-drought exposure.

3. **Referee**: In my opinion, the detailed aims of this pilot study could be made more explicit at the start (e.g. reduction of rainfall whilst avoiding any associated effects on air temperature or humidity). Those same points could then be summarised in the Conclusion.

Answer: We agree with the referee and integrated the following sentence in the Introduction section and tied the conclusion back to these aims:

"The aim of this study was to apply a realistic reduction of precipitation whilst avoiding any associated effects on air temperature or humidity and to observe the initial drought effects on the forest-understory-soil-system."

Specific comments

Introduction

4. **Referee**: 14321-15 The opening sentence is perhaps too bold – what about soil structure, biota, nutrient availability?

Answer: We agree with the referee and changed the sentence to:

"Temperature and precipitation are two of the key drivers of ecosystem processes."

5. **Referee**: 14322-15 I had to read the phrase 'alleviate competitive exclusion of subdominant species' several times – the idea is that difficult conditions could increase biodiversity. Try to rephrase in positive language.

Answer: We agree with the referee and changed the sentence to:

„At the level of plant communities and long-term response, the stress induced by drought may modify competition and facilitation, or it may tip the balance towards a state where only stress resistant plant species are able to survive (McDowell et al., 2008).

Material and methods

6. **Referee**: The second, third and fourth paragraphs of 2.1 are repetitive. Could all this be summarized in a table?

Answer: We agree with the referee, shortened the section, and inserted a table. See comment #6 of referee 1.

7. **Referee**: 14326-17 Is re-entry of water not also a problem (or more of a problem) at flat sites?

Answer: Steep angled slopes are prone to overland flow. Therefore, at steep slopes, water transfer from outside under the roofs can be a problem, which we wanted to avoid. We choose flat angled plots, where water (from the barrels) is following gravity away from the plots, but are not too steep to be prone to overland flow. (Please see also the answers to comment no. 1, 10, and 11 of refree#1, and comment no. 1 of referee#2).

8. **Referee**: 14327-26 I found this adjustment calculation hard to follow in text. Could you include a formula to show the working?

Answer: We agree with the referee here and added following formula:

$$a_{m_i} = a_a \cdot \frac{P_{mean\ m_i}}{P_{mean\ a}}$$

Where a_m = monthly target sum of a given month i;
a_a = annual target sum (2.5 %-Percentile of annual precipitation);
$P_{mean\ mi}$ = long term mean precipitation of given month i;
$P_{mean\ a}$ = annual mean precipitation

9. **Referee**: 14329-4 What is matric potential?

Answer: Matric potential is part of the soil water potential; some use the terms as interchangeables.

10. **Referee**: LAIsp – describe this as species-level leaf area index. See next point about SLA.
11. **Referee**: Specific leaf area (SLA) has a widely accepted definition in the literature (mm2 mg-1) which is not what you want here. Need to find another term for LAsp.

Answer: We now don't refer to specific leaf area index any longer but just to leaf area index (LAI), a term which is generally used to indicate the leaf area per ground area. We now also do not refer any longer to specific leaf area when we refer to the area of an average leaf of a species.

12. **Referee**: Useful to explain what a phytometer is. I take it as a group of plants used as a measure of physiological responses, but it sounds like a piece of equipment.

Answer: The term "phytometer" is a commonly used term for a plant planted into an existing community and used as a standardized measure of the abiotic and biotic growth conditions. But we agree with the referee and changed the sentence 14330 L19 to:

"For further insight on the effect of drought on growth, we planted phytometers (proxy-plants used as a measure of plant physical response) of Fagus sylvatica L. on all 90 subplots."

Results

13. **Referee**: The second paragraph of 3.1 dealing with the rainfall patterns by site and season is difficult to read and follow – lots of repetition. And I found Figure 4 difficult to interpret – especially the panels at the top.

Answer: We agree with the referee and shortened the section.

For Figure 4 we choose to present our (precipitation) input data as cumulated sums – an illustration often used for hydrological purposes. Since the legend and figure description state it as cumulated sums, we do not fully understand the point raised by the referee.

14. **Referee**: Section 3.2 – much of this (up to the sentence starting 'Air temperature ..') doesn't look like it belongs in the Results section.

Answer: We changed the section in agreement with the referee #1. The section (parts) reads now as follows:

"…Because elevation of air temperature and humidity has significant effects on growth, germination, transpiration and water uptake of plants, on microbial activity and on soil evaporation, we aimed at avoiding any alteration of air temperature and humidity as well as radiation. Based on the monitored air temperature, air humidity and soil temperature at the main roof and the neighboring main control subplot, we tested whether the roofing had a measureable effect on these variables. Air temperature and humidity were not affected by the roofing on none of the experimental sites (Figure 5). The 15 min readings on control plot and under the roof are not significantly different (except plot HEW3) according to the Wilcoxon-Mann-Whitney rank sum test. …"

15. **Referee**: Section 3.3. I had great difficulty understanding Figure 6. No statistical analysis is offered to underline the effects at Site/Plot/Depth/Distance – not all of these classes are different from the control plots.

Answer: We provided Figure 6 to give an overview of the soil moisture state on the roofed subplots compared to the control subplots. We agree with the referee and explained the term soil water deficit in the caption of the Figure. The capitation now read as follows:

"Soil water deficit (soil water content of control minus roofed subplot) of the main subplots. All values originate from May 2013, except the values from HEW47 (April 2013), due to probe failure. "–" marks missing values."

16. **Referee**: "The reduction was strongest in (in) the top soil layer (5cm) of all plots at a distance of 3 and 4 m from the centre tree." But is that true? 2 m bars look just as strong in AEW8 and AEW13. And reductions in AEW8 are most pronounced at a depth of 15 cm (3 m distance).

Answer: We agree with the referee and changed the sentence to: "The reduction was strongest in the top soil layer (5 cm) of all plots at a distance of 3 and 4m from the center tree. In addition, the 2 m distance (5 cm depths) of AEW8 and AEW13 and the 3 m distance (15 cm depths) of AEW8 are showing high soil moisture deficits."

17. **Referee**: Section 3.4 No statistical justification is given for the assertion that "There were no significant differences between the total coverage of the sites". I would argue that 40.3% is much greater than 27.9%.

Answer: We agree with the referee that the values indicated a significant difference. However we used a linear mixed effects model (lme) with plot and subplot as random factors. Because of the high variance of the cover per plot (land-use) and subplot, we found no significant difference between the sites ($p = 0.6715$). The high variance resulted from the three different land-use types at the three sites which was all over very similar at the three sites. With relatively low coverage at the unmanaged beech forest and very high coverage at the managed coniferous plots.

18. **Referee**: Table 3 – again we are shown no results of the Kruskal-Wallis test. For example at AEW8, at first glance 0.796 Control looks much higher than 0.462 Roofed.

Answer: We have now changed several text passages associated to the raised issue.

section 2.5: "We applied t- tests to assess the differences in the LAIsp and for species richness between the roof and control treatment using R (R-3.0.2, The R Foundation for Statistical Computing 2013)."

section 3.4: "In late summer 2012, i.e. at the end of the first growing season with the drought treatment, there were significant differences in LAI between the roof and control subplots at the managed beech plot at the Schwäbische Alb (AEW29; $p= 0.001$) and at the intensive managed conifer plot at the Hainich exploratory (HEW03; $p = 0.01$) (Table 3). The species richness of the understorey plant community were significantly higher at the managed roof subplot of the Hainich exploratory compared to the control subplot (HEW47, $p = 0.004$)."

section 4.3: "Only a small number of plots have shown a significant change in specific LAI and species richness as a consequence of the treatment."

table 3. : We include in the table legends: t- tests were applied to assess the differences in the LAIsp and for species richness between the roof and control treatment * $p < 0.05$, ** $p < 0.01$. Furthermore we include two more rows in the table (roof vs. control) to show the results of the t-tests.

19. **Referee**: Table 4 – I was confused by the values (p-values? Values are error probabilities?) What does the (intercept) line refer to?

Answer: We agree with the referees and changed the caption of the Table. The intercept indicates that the overall mean is different from zero. The capitation of the Table reads now as follows:

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

20. **Referee**: Figure 7 – The boxes are squashed because of the single high outlier at SEW. Could this be excluded from the analysis? The y-axis then would be much shorter and comparisons among the boxes much easier. Lettering could be applied to the boxes to indicate those that are significantly different, one from the other.

Answer: We agree with the referee and changed Figure 7 accordingly.

Discussion

21. **Referee**: Section 4.2: I don't understand the meaning of " …points to a comparable coupling of airspace on both subplots."

Answer: We agree with the referee and changed the sentence to: "…indicates a comparable coupling of the airspace close to the ground to the atmosphere on both subplots."

22. **Referee**: I don't agree with the statement "The drought treatment clearly reduced soil moisture content in all depths in all plots."

Answer: We agree with the referee and changed the sentence to: "The drought treatment clearly reduced soil moisture content in all depths in all plots (exceptions are the 5 cm depth of SEW48 and SEW49, the 60 cm depths of HEW47 and SEW49)."

23. **Referee**: Conclusions – tie these back to explicit aims laid out in the Introduction.

Answer: We have now focused on the aims we stated in the introduction.

Technical corrections

Watch the spelling of understory (instances of understorey also).

Answer: We checked spelling and changed where needed.

Exploratories is not a word I know. Explorations?

Answer: "Biodiversity Exploratories" is a fixed term, introduced for a large scale and long term functional biodiversity research platform. Refer to Markus Fischer et al. 2010, Basic and Applied Ecology, 473 – 485. (See also http://www.biodiversity-exploratories.de/1/home/). We used the facilities for our research.

Can you find another term for sub-subplot? Minor-plot?

Answer: We do not agree with the referee here; the change of the word sub-subplot to minor plot would not increase the readability or understandability.

14322-9 Rephrase e.g. "…as might be the case in a future Europe.

Answer: We agree with the referee and changed the sentence to: "It remains unclear, how the forest understory will respond to continuously reduced precipitation, as it might be in the case in a future Europe under climate change (Kreuzwieser and Gessler, 2010)."

14323-8 Omit 'to be able'.

Answer: We agree with the referee and changed the sentence to: "The knowledge of such mechanisms related to the understory response to drought need to be included in current forest growth models in order to understand all aspects of the system – including natural regeneration – under climate change."

14323-10 Omit 'above the forest floor'.

Answer: We agree with the referee and changed the sentence to: "We thus propose to experimentally manipulate precipitation and investigate in detail the consequences for soil moisture, soil hydrological functions, and water uptake as well as vegetation structure but also allowing to include more in-depth studies such as assessments of the microbial community structure."

14323-20:23 Really belongs in the Methods

Answer: We do think that this manuscript focuses on the description of a roof system allowing flexible reductions of precipitation in forest understory ecosystems. Therefore we are of the strong opinion that the section the referee refers to fits well to the end of the introduction.

14326-27 Replace 'random' with variable.

Answer: We agree with the referee and replaced 'random' with 'variable'. The sentence is now as follows: "This roof system can reduce rainfall between 11 and 100% and due to its design, rainfall exclusion is variable and not persistent in space."

14330-16 Replace 'per' with of.

Answer: We agree with the referee and replaced 'per' with 'of'. The sentence is now as follows: "…where $N_{species}$ is the total number of species found on the quadratic area of 2.45 m^2."

14331-8 Briefly describe the chambers rather than asking us to look up Yepez et al.

Answer: We agree with the referee have now added additional information to the respective section. The paragraph now reads as follows:

"In the field, gas-exchange chambers (transparent Perspex, size: 52 x 77.5 x 78.5cm, A = 0.61 m^2) comparable to the ones described in Yepez et al. (2005) were used for measuring understory evapotranspiration (*ET*) rates. The chambers were open to the soil, sealed with rubber foam gaskets to the ground and were use as closed systems to assess the build up of water vapour from soil evaporation and plant transpiration. Measurements were made three times in 2012 (spring, early summer, late summer) at all nine plots. ET rates were determined on the control subplots and on the roof subplots. The increase in water vapor in the closed chambers was measured with a cavity ringdown laser spectrometer (PICARRO L1102-I, Picarro Inc.) directly in the field, with four replicates per control subplot and per roof subplot between 10:00 a.m. and 15:00 p.m. (CEST). The chamber air was circulated through the isotope water analyzer via a low absorption tube using the Picarro pump (flow rate <0.4 l min^{-1}) and fed back again in the chamber headspace. For each chamber, a measurement lasted 10-12 minutes, and a fan provided mixing of the air in the gas exchange headspace."

14331-14 What is (MESZ)?

Answer: We agree with the referee and changed 'MESZ' to 'CEST'. The sentence is now as follows: "The increase in water vapor in the closed chambers was measured …. between 10:00 a.m. and 15:00 p.m. (CEST)."

14333-3 '…we had to increase the reduction..' needs to be rephrased

Answer: We agree with the referee and changed the sentence to:
"To compensate the high precipitation input, we had to raise the exclusion (Fig. 4, blue bars) from 30 % (mean value) to 50 %, which resulted in a reduction below the target (699 mm) of 11 %."

14333-13 'excluded' is better here than 'reduced'

Answer: We agree with the referee and changed the sentence to:
"In total, 221mm were excluded in the Schwäbische Alb sites in 2012 which resulted in an incoming precipitation under the roofs of 719 mm."

14335-6 coverage here refers to vegetation, but elsewhere you talk about roof coverage. Important to be explicit and make these distinctions clear for the reader.

Answer: We agree with the referee and cleared the sentence to:
"There were no significant differences between the total vegetation coverage of the sites…"

14335-23 should refer to Table 4 not Table 3.

Answer: We agree with the referee and changed the reference to Table 4.

14336-14 Replace 'calculative' with 'calculation'

Answer: We agree with the referee and changed the sentence to: "Possible problems may occur, using our technique in very extraordinary dry or wet years, although we did not detect such meteorological circumstances in the 1950–2010 records in all our regions when we tested our design in terms of figures."

14336-17 Replace 'reducing' with 'excluding'

Answer: We agree with the referee and changed the sentence to: "In contrast to…, it was possible to reduce the precipitation to a certain level over the year, instead of excluding the total precipitation input during a time period…."

14337-8 Replace '..can reach a maximum of..' with '..by as much as..'.

Answer: We agree with the referee and changed the sentence to: "The shielding can raise mean air temperature … and can reach as much as 3.2 °C… ."

14338-23 Rephrase e.g. "Changes in ecosystem functioning occur after stress conditions exceed…"

Answer: We agree with the referee and changed the sentence to: "Changes in ecosystem functioning occur after stress conditions exceed a certain level of climate severity threshold, which cannot predicted until now (Bahn et al., 2014; Vicca et al., 2012)."

14339-22 Rephrase e.g. " … a valid, and more realistic, alternative to the common…"

Answer: We agree with the referee and changed the sentence to: "We conclude that our innovative roofing construction is a valid, and more realistic, alternative to the common drought simulation practice of total rainfall reduction."

Drought in forest understory ecosystems – a novel rainfall reduction experiment

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Feldfunktion geändert

Abstract

Precipitation pattern across Central Europe are expected to change over the 21st century due to climate change. ~~Climate change is predicted to severely affect precipitation patterns across central Europe.~~ This may reduce water availability during the plant-growing season and hence affect the performance and vitality of forest ecosystems. We established a novel rainfall reduction experiment on nine sites in Germany to investigate drought effects on soil-forest-understory-ecosystems. A realistic, but extreme annual drought with a return period of 40 years, which corresponds to the 2.5 %-percentile of the annual precipitation, was imposed. At all sites, we were able to reach the target values of rainfall reduction, while other important ecosystem variables like air temperature, humidity and soil temperature remained unaffected

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due to the novel design of a flexible roof. The first year of drought showed considerable changes in the soil moisture dynamics relative to the control sites, which affected leaf stomatal conductance of understory species as well as evapotranspiration rates of the forest understory.

1 Introduction

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

Forests in central Europe are different from most other terrestrial ecosystems in the world; while forest trees and the canopy are managed, the forest understory is a relatively natural system, which however is influenced by the overstory (Ampoorter et al. 2014). The forest understorey contains a great variety of biodiversity in forests (Gillam 2007), especially in central Europe with its comparably low tree diversity. Whereas the effects of drought on grasslands has been addressed intensively there are only few studies examining the effect of climate change on the understory of forests (Ozolincus et al. 2009). It remains unclear, how the forest understory will respond to continuously reduced precipitation, as it might be ~~in~~ the case in a future Europe under ~~changing~~ climate change ~~in the future~~ (Kreuzwieser & Gessler 2010). In general, we can expect both direct and indirect impacts of continuously reduced precipitation on the forest understory system. Decreased transpiration and water potentials are short-term responses of plants to drought (Tschaplinski et al. 1998). As a result of the drop in water potential, stomatal closure will occur, limiting water fluxes at the cost of reduced CO_2 uptake and assimilation. At the level of plant communities and long-term response, the stress induced by drought may alleviate modify competition and facilitationmoderate competitive exclusion of subdominant species, or it may tip the balance towards a state where only stress resistant plant species are able to survive (McDowell et al. 2008). The whole ecosystem response to reduced water supply will depend on ecosystem stability.

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

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

We thus propose to experimentally manipulate precipitation above the forest floor and investigate in detail the consequences for soil moisture, soil hydrological functions, and water uptake as well as vegetation structure but also allowing to include more in-depth studies such as assessments of the microbial community structure. The aim of this study was to apply a realistic reduction of precipitation whilst avoiding any associated effects on air temperature or humidity and to observe the initial drought effects on the forest-understory-soil-system. Many other precipitation manipulation experiments introduce extreme short-time drought events (e.g. Glaser et al. 2013), which often eliminate precipitation completely, generating unrealistic drought effects (Beier et al., 2012). In addition, the constructions used in previous studies

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often need electrical supply or intensive technical installation, supervision, and maintenance (e.g. Beier et al. 2004, Albert et al. 2011, Parra et al. 2012, Kopittke et al. 2014). Our approach employs a moderate, adaptive, and continuous rainfall reduction, equivalent to a drought with 40-year return period. To achieve our goal, nine investigation sites at three different geographical locations in Germany were established. Here, we describe and explain the set up and monitoring of the rainfall exclusion experiment and present first results of rainfall reduction with soil physical and biological evidence in effectiveness of drought set up.

2 Material and methods

2.1 Investigation sites

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

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

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

More information on general plot properties is prepared in Table 2. All weather data is taken from stations of the German weather service (DWD, actual and annual data years 1950-2010) nearby (station-IDs 03402, 00487, and 00164).The site of the Biodiversity Exploratory Schwäbische Alb is located in the low mountain ranges of south-western Germany. The altitude of the three investigation sites ranges between 714 m and 766 m a.s.l. Mean annual precipitation is about 940 mm and mean annual temperature is about 6.5 °C (data from German Weather Service, DWD, station-ID 03402, years 1950-2010). The underlying geology consists of Jurassic shell limestone. The soils at the investigation sites are extremely

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rich in clay, are very shallow (25 cm to 35 cm) and have a very high stone content. Soils are classified as Cambisol (AEW8, AEW13) and Leptosol (AEW29).

The site of the Biodiversity Exploratory Hainich-Dün is located in central Germany. The altitude of the plots ranges between 330 m and 410 m a.s.l. Mean annual precipitation is about 533 mm and mean annual temperature is 7.2 °C (data from German Weather Service, station-ID00487, years 1950-2010). The underlying geology consists of Triassic limestone. The soils generally have a loamy to clayey texture and have low water conductivity. Soils are classified as Luvisols (HEW3 and HEW12) and Stagnosols (HEW47) with soil depths between 45 and 65 cm.

The site of the Biodiversity Exploratory Schorfheide-Chorin is located in a young glacial landscape in the lowlands of north-eastern Germany. The plots range in altitude between 65 m and 74 m a.s.l. Mean annual precipitation is about 589 mm and mean annual temperature is 8.5 °C (data from German Weather Service, station-ID 00164, years 1950-2010). The dominant geological substrate is glacial till covered by glacio-fluvial or aeolian sands. The soils have textures in the range of sandy loam to pure sand. Soils are classified as Cambisols and have a mean depth of 115 cm (SEW49) and 125 cm (SEW48 and SEW16). Due to their sandy texture, the soil depth in this area is identified by rooting depths.

2.2 Roof construction for a flexible rainfall reduction

At each of the nine selected plots, five roof subplots and five control subplots were instrumented. One of the five roof subplots and one of the five control subplots has a size of 10 x 10 m ("main subplot", Figure 2); the other four pairs of subplots ("satellite subplots") have a size of 3 x 3 m. Roof and control subplots are in close vicinity to each other (distance between roof and control ranges between 15 m and 30 m for the main roofs, and between 6 m and 15 m for the satellite subplots), in order to ensure similar subplot properties with respect to topography, soil and vegetation. A central overstory tree (Figure 2 and 3) is included in each of the central subplots, whereas the satellite subplots do not contain any large trees. The selected central trees are similar in age, size and canopy structure.

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

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

Rainwater from the roof panels and the timber construction is collected by rain gutters mounted along the roof frame and is drained into rain barrels. Stemflow (of all roofed beech trees) is also collected and drained to the rain barrels by a stem rim (Figure 3d). The water level in the rain barrels is continuously logged with a pressure transducer to quantify the total amount of water removed by the roof. Above a certain water level the barrel is emptied through an electromagnetic valve and the water is conveyed through a hose away from the roof. Eight of the nine plots are situated at very flat angled-slopes, therefore re-entering of the water is prevented. Only plot AEW8 is situated on a steeper slope, which made compromises at the construction necessary; to balance the differences in height of the central roof, one side of the roof is placed directly on the ground without wooden support, the other is at 3.2 m above ground. Nevertheless, the roof has the same dimensions, rain gutters and instrumentation as the other eight plots. No adjustment had to be made at the smaller satellite roofs at this plot.

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

2.3 Rainfall reduction for realistic drought conditions

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

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

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

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

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

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

$P_{mean\, mi}$ = long term mean precipitation of given month i;

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

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

Though reduction is calculated for the entire year, the roof remains uncovered from first snowfall until the end of the snow season, to avoid roof damage from a heavy snowpack. During this period precipitation was only reduced by 11 % (for main roof and 15.5 % for satellite subplot roof, for construction reasons) from mid-November/early December until January/February. To account for the absent reduction in winter months, the reduction in spring balances winter-month excess or deficit. Similarly, November reduction can be increased to create a reserve for wet winter month.

2.4 Monitoring and sampling

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

Meteorology and soil hydrology

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

Botanical parameters and evapotranspiration

To address the influence of the imposed drought on forest understory, we established at each plot, ten vegetation recording sub-subplots, each with an area of 1 x 1 m. These sub-subplots were marked and were not entered during the rain exclusion experiment. For each sub-subplot, we determined plant species to identify the understory vegetation community and its cover. The baseline survey for all plots took place between June 2011 and July 2011.

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

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

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

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

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

In the field, gas-exchange chambers (transparent Perspex, size: 52 x 77.5 x 78.5cm, A = 0.61 m^2) comparable to the ones described in Yepez et al. (2005) were used for

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measuring understory evapotranspiration (*ET*) rates. The chambers were open to the soil, sealed with rubber foam gaskets to the ground and were use as closed systems to assess the build up of water vapour from soil evaporation and plant transpiration. Measurements were made three times in 2012 (spring, early summer, late summer) at all nine plots. ET rates were determined on the control subplots and on the roof subplots. The increase in water vapor in the closed chambers was measured with a cavity ringdown laser spectrometer (PICARRO L1102-I, Picarro Inc.) directly in the field, with four replicates per control subplot and per roof subplot between 10:00 a.m. and 15:00 p.m. (CEST) ~~h~~. The chamber air was circulated through the isotope water analyzer via a low absorption tube using the Picarro pump (flow rate <0.4 l min^{-1}) and fed back again in the chamber headspace. For each chamber, a measurement lasted 10-12 minutes, and a fan provided mixing of the air in the gas exchange headspace. Temperature, air humidity (VP-3 humidity temperature and vapor pressure sensor; Decagon Devices Inc.) and photosynthetic photon fluency rate (*PPFR*) were continuously logged (Par Photon Flux Sensor, Decagon Devices Inc.). *ET* rates were calculated from the linear increase in water vapor concentration determined by the laser spectrometer in the chamber over time and based on the ground area.

2.5 Statistical analyses

We applied t- tests to assess the differences in the LAI_{sp} and for species richness between the roof and control treatment using R (R-3.0.2, The R Foundation for Statistical Computing 2013).~~All statistical analyses for the LAI_{sp} and for species richness were done with the software sigma plot 12.3. The differences in LAI_{sp} and species richness between the roof and control subplots were tested with the Kruskal-Wallis One Way Analysis of Variance on Ranks. To isolate the groups that differ from the others, a multiple comparison procedure (Tukey Test) was performed.~~

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Response variables for growth and stomatal conductance of the understory beech phytometers were evaluated with linear mixed effects models with site (three different experimental sites), drought (sheltered or not), competition (with and without competition) and provenance (Schorfheide-Chorin, Hainich-Dün and Schwäbische Alb) as fixed factors and plot, subplot nested in plot and sub-subplot nested in plot as random factors. The statistical analyses were carried out with the R-Studio software (version 0.97.248; R version 3.0.0) using the “nmle” package. Air temperature and humidity were tested with the Wilcoxon-Mann-Whitney rank sum test R-Studio software (version 0.97.248; R version 2.15.2) using the “stats” package.

3 Results

3.1 Precipitation reduction

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

With respect to precipitation, the year 2012 was an average year with a total precipitation of 940 mm (100.4 % of long term mean) in the Schwäbische Alb, 508 mm (95.5 %) in Hainich-Dün and 543 mm (101.5 %) in Schorfheide-Chorin (Figure 4, blue lines). At all sites in 2012 winter rain and snowfall was greater than average. ~~In the Schwäbische Alb this wet winter was followed by a dry summer and fall, in Hainich-Dün the winter was followed by a dry spring, wet summer and a below-average fall, while in Schorfheide-Chorin the winter was followed by a dry summer.~~ In contrast, the year 2013 was wetter than the long term mean in Schwäbische Alb (976 mm, 104.3 %) and Hainich-Dün (596.5 mm, 112.1 %), and drier in Schorfheide-Chorin (483.2 mm, 90.4 %). ~~2013 started in Schwäbische Alb with a dry winter, which was followed by a wet summer and fall.~~ To compensate the high precipitation input, we had to ~~increase~~ raise the ~~reduction~~ exclusion (Figure 4, blue bars) from 30 % (mean value) to 50 %, which resulted in a reduction below the target (699 mm) of 11 %. ~~In Hainich-Dün 2013, spring/early summer and late fall/winter were wet, but summer/early fall were dry. Spring was dry in Schorfheide-Chorin, followed by a wet early summer and a dry late summer, which led to an under average year in respect to precipitation.~~ Generally, the reduced precipitation input on all plots satisfyingly reached the target values, both in 2012 and in 2013. The reduced input (dashed red and orange lines in Figure 4) hovers around the target value (solid red line), depending on the monthly adaption of the roof cover. The maximum applied roof coverage in 2012 and 2013 was 55 %.

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

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

In general, roofing on experimental plots can promote changes of air temperature and humidity, due to alterations of radiation and ventilation (greenhouse effect). In fact, some authors actually used roofing setups in order to achieve higher mean temperatures, mainly as an effect of preventing the nocturnal emission of long wave radiation (e.g., Selsted et al. 2012). Because elevation of air temperature and humidity has significant effects on growth, germination, transpiration and water uptake of plants, on microbial activity and on soil evaporation, we aimed at avoiding any alteration of air temperature and humidity as well as radiation~~Because of the significant effects on growth, germination, transpiration and water uptake of plants, on microbial activity and on soil evaporation, we aimed at avoiding any alteration of air temperature and humidity as well as radiation~~. Based on the monitored air temperature, air humidity and soil temperature at the main roof and the neighboring main control subplot, we tested whether the roofing had a measureable effect on these variables. Air temperature and humidity were not affected by the roofing on none of the experimental sites (Figure 5). The 15 min readings on control plot and under the roof are not significantly different (except plot HEW3) according to the Wilcoxon-Mann-Whitney rank sum test.

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

3.3 Roof effect on soil moisture

As expected, the roof coverage had an immediate effect on the soil water content. However, the respond to the reduced precipitation input varied between the sites. Figure 6 shows the soil water deficit on the main roofed subplots when compared with the neighboring main control subplots for the different measuring depths and distances from the central trees at the subplots for the example month May 2013 (similar results were obtained for the other months). Schorfheide-Chorin (Figure 6, bottom) showed the lowest reduction of all sites with little differences between soil moisture of roofed and control subplot. The top soil layer of beech plots SEW48 (4 m distance) and SEW49 (2 m and 3 m distance) even exhibited a small increase in soil moisture. The difference between roofed subplot and control subplot are more pronounced in Schwäbische Alb and Hainich-Dün than in Schorfheide-Chorin plots for this time period. In Hainich-Dün (Figure 6, middle), the highest soil moisture reduction appeared in spruce plot HEW3, especially in top layer (5 cm depth), where all distances to the central tree showed high deficits compared to the control subplot. In contrast, HEW12 and HEW47 (both beech) did not show such high reduction rates in top layer. In HEW47, no difference (15 cm depth in 3 m and 4 m distance and 30 cm depth in 4 m distance), and in both plots (HEW12: 30 cm depth, 4 m distance; HEW47: 60 cm depth, 2 m distance) even a small increase of soil moisture on roofed subplots compared to control subplots appeared. In general, Schwäbische Alb plots (Figure 6, top) exhibit the highest soil moisture reduction of all sites. The reduction was strongest in in the top soil layer (5 cm) of all plots at a distance of 3 m and 4 m from the center tree. In addition, the 2 m distance (5 cm depth) of AEW8 and AEW13 and the 3 m distance (15cm depth) of AEW8 are showing high soil moisture deficits. On AEW8 and AEW29 (both beech), 15 cm (AEW8 and AEW29) and 30 cm (AEW8) sensors did not detect soil moisture differences between roofed and control subplot.

3.4 Plant community and phytometer

There were no significant differences between the total vegetation coverage of the sites (27.9 %, 40.3 % and 38.9 % – average of the three plots per site of Schorfheide-Chorin, Hainich-Dün and Schwäbische Alb, respectively). The type of the understory plant community as assessed in the vegetation surveys is given in Table 1. A detailed overview of the different functional groups (grass, herb, shrub and tree recruits) and the mean coverage on the nine plots can be found in Table 32. Most plots are dominated by grasses and herbs; subplots differ in total coverage between 2.26 % and 57.1 %. (Table 2).

In late summer 2012, i.e. at the end of the first growing season with the drought treatment, there were no significant differences in LAI_{sp} between the roof and control subplots (Table 3).at the managed beech plot at the Schwäbische Alb (AEW29; p= 0.001) and at the intensive managed conifer plot at the Hainich exploratory (HEW03; p = 0.01) (Table 43). The species richness of the understorey plant community were significantly higher at the managed roof subplot of the Hainich exploratory compared to the control subplot (HEW47, p = 0.004). There was, however a tendency to lower LAI_{sp} in the roofed subplots for the conifer

~~management sites in all exploratories. Moreover, such a tendency was also observed for the unmanaged and managed beech sites in the Schwäbische Alb exploratory and for the unmanaged beech site at Hainich-Dün.~~ Table 5~~4~~ summarizes the drought effects on leaf stomatal conductance (g_s) of the planted phytometer as a short-term response to drought. Leaf stomatal conductance was reduced under the roofs, with a more significant reduction in July 2012 (p = 0.0009) than in September 2012 (marginally significant p = 0.0602) (Table 5~~4~~).

Additionally, there was an interaction of drought and site (Table 4~~3~~; Figure 7). While drought had no effect at the wettest site (Schwäbische Alb), stomatal conductance was reduced under the roof at the Schorfheide-Chorin and the Hainich-Dün sites. In contrast to g_s, growth parameter did not show significant drought effects in this early stage of the experiment.

At the beginning of the 2012 growing season when the drought treatment had started, the understorey evapotranspiration rates between the roof and control subplots as determined with chambers were not significantly different, indicating the initial comparability of the subplots (Figure 8). In the late summer 2012 we detected no significantly lower *ET* rates with the chamber measurements as response to reduced precipitation with one exception at SEW16 (pine) (Figure 8).

4 Discussion

4.1 Precipitation reduction

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

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

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

As mentioned above, roofing on experimental plots can have a significant effect on air temperature and humidity. Temperature controls – as a main effect – the duration of growth period, but is also influencing processes like photosynthesis, respiration and transpiration (Maracchi et al. 2005). The shielding can raise mean air temperature by 1.2 to 1.4 °C as reported by Glaser et al. (2013) and can reach ~~a maximum of~~ as much as 3.2 °C (Selsted et al. 2012). In contrast to other studies (Selsted et al. 2012, Parra et al. 2012, Dermody et al. 2007), we aimed in avoiding these "greenhouse" effects, to separate the effect of prolonged drought from effects due to changes in air temperature and air humidity conditions. Our measurements show no difference in humidity and air temperature between roofed and control plots, which clearly ~~points to~~ indicates a comparable coupling of the airspace close to the ground to the atmosphere on both subplots. In addition, the design of the roofs with an incomplete coverage (2 m high, four sides open, maximum roof coverage 55 %, complete roof area only 100 m^2) definitely not represent a closed roof. Given that and the findings that air humidity and temperature stay totally unaffected, it is very unlikely, that CO_2 concentrations increased under the roofs and thus also no CO_2 fertilization effects are to be expected.

The drought treatment clearly reduced soil moisture content in all depths in all plots (exceptions are the 5 cm depths of SEW48 and SEW49, the 60 cm depths of HEW47 and SEW49). In Hainich-Dün and especially in Schorfheide-Chorin plots, soil moisture deficit decreased with depth. This is in line with the findings of ~~Dermody et al. (2007) and~~ English et al. (2005), who found a decrease of soil moisture deficit with depth. The reason for the difference in behavior of Schwäbische Alb plots in soil moisture drought response is twofold: The reduction is always relative, not absolute, which leads to more pronounced deficits in areas with higher precipitation. Secondly, the Schorfheide plots, which showed the lowest deficits, are all sandy soils. This type of soil is having already comparable low soil moisture when untreated.

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

4.3 Roof effects on evapotranspiration, leaf stomatal conductance and growth

Only a small number of plots have shown a ~~We did not detect any~~ significant change~~s~~ in ~~specific~~ *LAI* and species richness as a consequence of the treatment. This is in agreement with the findings from the phytometer experiments, where leaf stomatal conductance was reduced as effect of the precipitation manipulation, while growth variables were not affected at that stage of the experiment. ~~At the level of the plant community and as a long-term response, the stress induced by drought may alleviate competitive exclusion of subdominant species, or it may tip the balance towards a state where only stress-resistant plant species are able to survive (McDowell, 2008). As a consequence, species turnover is to be expected (Maracchi et al. 2005).~~ Our results show that reduced growth of understory plants and changes in community structure does not occur as an early response to drought in the first year that under the precipitation reduction regime applied. ~~drought~~ Drought stress was not that intensive to induce mortality or strong changes in biomass of particular species on the short term. This seems to be partially in contrast to conclusion drawn by Leuzinger et al. (2011) that initial responses of ecosystems to drought (or other parameters related to Global Change) are highest and decline over longer time periods. The ecosystem's response time to changes in environmental conditions will, however, also depend on the treatment intensity. Changes in ecosystem functioning occur after stress conditions exceed ~~exceeding~~ a certain level of climate severity threshold, which cannot predicted until now (Bahn et al. 2014, Vicca et al. 2012). The achieved 40-year return interval drought was in our experiment not enough to push the system beyond this physiological and biochemical threshold. ~~We assume that the cumulative effect of our precipitation reduction over time periods of two or three years will cause stronger effects than in this early stage of the experiment (Martin-StPaul et al. 2013; Breda et al. 2006; Jongen et al. 2013) but the effect size also might be dampened again after a longer period.~~

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

5 Conclusion

We conclude that our innovative roofing construction is a valid, and more realistic alternative ~~and probably much more reasonable~~ to the common drought simulation practice of total rainfall reduction. Due to the flexible construction it is possible to preserve the temporal and spatial variability of rainfall pattern, in particular under the forest canopy, while reducing precipitation input and soil moisture without changing the air temperature and humidity on site. During the first two years of treatment, the reduction of precipitation to a 40-year annual drought event did not introduce artificial vegetation responses as an effect of unrealistically high rainfall reduction. For prolonged drought, we expect more pronounced effects on plants, e.g. drop in biomass production and carbon assimilation, as well as effects on soil structure e.g. change in soil hydrological functions, aggregation and hydrophobicity.

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References

Abramoff M., Magelhaes P.J., Ram S.J.: Image processing with Image. J. Biophotonics Int. 11, 36–42, 2004.

Albert, K. R., Ro-Poulsen, H., Mikkelsen, T.N., Michelsen, A., Van Der Linden, L., and Beier, C.: Effects of elevated CO2, warming and drought episodes on plant carbon uptake in a temperate heath ecosystem are controlled by soil water status, Plant, Cell & Environment, 34, 1207-1222, doi:10.1111/j.1365-3040.2011.02320.x, 2011.

Ampoorter E., Baeten L., Koricheva J., Vanhellemont M., and Verheyen K.: Do diverse overstoreys induce diverse understoreys? Lessons learnt from an experimental–observational platform in Finland. Forest Ecology and Management 318, 206-215, doi:10.1016/j.foreco.2014.01.030, 2014.

Bahn, M., Reichstein, M., Dukes, J.S., Smith, M.D., and McDowell, N.G.: Climate-biosphere interactions in a more extreme world. New Phytologist, 2002, 356 – 359, 2014

Baudis, M., Ellerbrock, R. H., Felsmann, K., Gessler, A., Gimbel, K., Kayler, Z., Puhlmann, H., Ulrich, A., Weiler, M., Welk, E. and Bruelheide, H.: Intraspecific differences in responses to rainshelter-induced drought and competition of Fagus sylvatica L. across Germany, Forest Ecology and Management, 330, 283–293, doi:10.1016/j.foreco.2014.07.012, 2014

Beier, C., Beierkuhnlein, C., Wohlgemuth, T., Penuelas, J., Emmett, B., Körner, C., de Boeck, H., Christensen, J. H., Leuzinger, S., Janssens, I. A., Hansen, K.: Precipitation manipulation experiments – challenges and recommendations for the future. Ecology Letters, 15: 899–911. doi: 10.1111/j.1461-0248.2012.01793.x, 2012.

Birkhofer, K., Schoening, I., Alt, F., Herold, N., Klarner, B., Maraun, M., Marhan, S., Oelmann, Y., Wubet, T., Yurkov, A., Begerow, D., Berner, D., Buscot, F., Daniel, R., Diekoetter, T., Ehnes, R. B., Erdmann, G., Fischer, C., Foesel, B., Groh, J., Gutknecht, J., Kandeler, E., Lang, C., Lohaus, G., Meyer, A., Nacke, H., Naether, A., Overmann, J., Polle, A., Pollierer, M. M., Scheu, S., Schloter, M., Schulze, E.-D., Schulze, W., Weinert, J., Weisser, W. W., Wolters, V., and Schrumpf, M.: General Relationships between Abiotic Soil Properties and Soil Biota across Spatial Scales and Different Land-Use Types, PLoS ONE, 7, doi:e43292.10.1371/journal.pone.0043292, 2012.

Bréda, N., Huc, R., Granier, A. and Dreyer, E.: Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences, Annals of Forest Science, 63(6), 625–644, doi:10.1051/forest:2006042, 2006.

Carminati, A., Schneider, C.L., Moradi, A.B., Zarebanadkouki, M., Vetterlein, D., Vogel, H.-J., Hildebrandt, A., Weller, U., Schüler, L., and Oswald, S.E.: How the Rhizosphere May Favor Water Availability to Roots, Vadose Zone Journal, 10, doi:988, 10.2136/vzj2010.0113, 2011.

Christensen, J.H., and Christensen, O.B.: A summary of the PRUDENCE model projections of changes in European climate by the end of this century, Climatic Change, 81, 7-30, doi:10.1007/s10584-006-9210-7, 2007.

Cohen, Y., Fuchs, M., and Green, G.C.: Improvement of the heat pulse method for determining sap flow in trees, Plant, Cell and Environment 4391–397, doi: 10.1111/j.1365-3040.1981.tb02117.x, 1981

Formatiert: Englisch (USA)

da Costa, A.C.L., Galbraith, D., Almeida, S., Portela, B.T.T., da Costa, M., de Athaydes Silva, J. jun., Phillips, O.L., Metcalfe, D.B., Levy, P., and Meir, P.: Effct of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. New Phytologist 187, 579–591, doi:10.1111/j.1469-8137.2010.03309.x, 2010.

Dermody, O., Weltzin, J.F., Engel, E.C., Allen, P., and Norby, R.J: How elevated [CO_2], warming, and reduced precipitation interact to affect soil moisture and LAI in an old field ecosystem? Plant Soil 301(1-2), 255-266, doi:10.1007/s11104-007-9443-x, 2007

English, N.B., Weltzin, J.F., Fravolini, A., Thomas, L., and Williams, D.G.,: The influence of soil texture and vegetation on soil moisture under rainout shelters in a semi-desert grassland. Journal of arid environments, 63(1), 324-343, doi:10.1016/j.jaridenv.2005.03.013, 2005.

Fay, P.A. Carlisle, J.D., Knapp, A.K., Blair, J.M. and Collins, S.L.: Altering Rainfall Timing and Quantity in a Mesic Grassland Ecosystem: Design and Performance of Rainfall Manipulation Shelters. Ecosystems, 3, 308–319, doi: 10.1007/s100210000028. 2000.

Fischer, M., Kalko, E.K.V., Linsenmair, K.E., Pfeiffer, S., Prati, D., Schulze, E.-D., and Weisser, W.W.: Exploratories for Large-Scale and Long-Term Functional Biodiversity Research, Long-Term Ecological Research: Between Theory and Application, edited by: Muller, F., Baessler, C., Schubert, H., and Klotz, S., Springer, 233 Spring Street, New York, Ny 10013, United States, 429-443 pp., 2010.

Gessler, A., Keitel, C., Nahm, M., and Rennenberg, H.: Water shortage affects the water and nitrogen balance in central European beech forests. Plant Biology, 6(3), 289–298. doi:10.1055/s-2004-820878, 2004.

Gilliam, F.S.: The ecological significance of the herbaceous layer in temperate forest ecosystems. Bioscience, 57(10), 845-858, doi:10.1641/B571007, 2007

Glaser, B., Jentsch, A., Kreyling, J., and Beierkuhnlein, C.: Soil-moisture change caused by experimental extreme summer drought is similar to natural inter-annual variation in a loamy sand in Central Europe. Journal of Plant Nutrition Soil Science 176, 27-34, doi:10.1002/jpln.201200188, 2013.

Gregory, P.J.: Roots, rhizosphere and soil: the route to a better understanding of soil science? European Journal of Soil Science, 57, 2-12, doi:10.1111/j.1365-2389.2005.00778.x, 2006.

Hommel, R., Siegwolf, R., Saurer, M., Farquhar, G. D., Kayler, Z., Ferrio, J. P., and Gessler, A.: Drought response of mesophyll conductance in forest understory species – Impacts on water-use efficiency and interactions with leaf water movement. Physiologia Plantarum, online, doi:10.1111/ppl.12160, 2014.

~~Jongen M., Lecomte X., Unger S., Pintó-Marijuan M. and Pereira J.S.: The impact of changes in the timing of precipitation on the herbaceous understorey of Mediterranean evergreen oak woodlands. Agricultural and Forest Meteorology 171-172, 163-173, doi: 10.1016/j.agrformet.2012.11.020, 2013.~~

Kopittke, G.R., Tietema, A., van Loon, E.E., and Asscheman, D.: Fourteen annually repeated droughts surpressed autotrophic soil respiration and resulted in an ecosystem change. Ecosystems 17, 242–257, doi:10.1007/s10021-013-9720-x, 2014.

Kreuzwieser, J. and Gessler, A.: Global climate change and tree nutrition: influence of water availiability. Tree Physiology 30, 1221–1234, Tree Physiology 30, 1221–1234, doi: 10.1093/treephys/tpq055, 2010.

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Leuzinger, S., Luo, Y., Beier, C., Dieleman, W., Vicca, S., and Körner, C.: Do global change experiments overestimate impacts on terrestrial ecosystems? Trends in Ecology & Evolution, 26(5), 236–241. doi:10.1016/j.tree.2011.02.011, 2011.

Maracchi, G., Sirotenko, O., Bindi, M.: Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe. Climatic Change 70, 117-135, doi:10.1007/s10584-005-5939-7, 2005.

~~Martin-StPaul, N.K., Limousin, J.-M., Vogt-Schilb, H., Rodríguez-Calcerrada, J., Rambal, S., Longepierre, D. and Misson, L.: The temporal response to drought in a Mediterranean evergreen tree: comparing a regional precipitation gradient and a throughfall exclusion experiment, Global Change Biology, 19(8), 2413–2426, doi:10.1111/gcb.12215, 2013.~~

McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D. Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D.G., Yepez, E.A.: Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New Phytologist 178, 719-739, doi: 10.1111/j.1469-8137.2008.02436.x, 2008.

Ozolincius, R., Stakenas, V., Varnagiryte-Kabasinskiene, I., and Buozyte, R.: Artificial drought in Scots pine stands: effects on soil, ground vegetation and tree condition.Annales Botanici Fennici 46(4), 299-307, 2009.

Parra, A., Ramirez, D.A., Resco, V., Velasco, A., and Moreno, J.M.: Modifying rainfall patterns in a mediterranean shrubland: system design, plant responses, and experimental burning. Int J Biometeorol 56, 1033–1043, doi:10.1007/s00484-011-0517-3, 2012.

Prudhomme, C., Giuntoli, I., Robinson, E.L., Clark, D.B., Arnell, N.W., Dankers, R., Fekete, B.M., Franssen, W., Gerten, D., Gosling, S.N., Hagemann, S., Hannah, D. M., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., and Wisser, D.: Hydrological drought in the 21st century, hotspots and uncertainties from a global multimodel experiment, Proceedings of the National Academy of Sciences of the United States of America, 111(9), 3262-7, doi:10.1073/pnas.1222473110, 2014

Rodriguez-Calcerra, J., Atkin, O.K., Robson, T.M., Zaragoza-Castells, J., Gil, L., and Aranda, I.: Thermal acclimation of leaf dark respiration of beech seedlings experiencing summer drought in high and low light environments. Tree Physiology 30, 214–224, doi:10.1093/treephys/tpp104, 2009.

Schaumann, G. E., Braun, B., Kirchner, D., Rotard, W., Szewzyk, U., and Grohmann, E.: Influence of biofilms on the water repellency of urban soil samples, Hydrological Processes, 21, 2276-2284, doi:10.1002/hyp.6746, 2007.

Schraml, C., and Rennenberg, H.: The different reactions of beech tree (Fagus sylvatica L.) ecotypes to drought stress. Forstw. Cbl. 121, 59-72, doi:10.1046/j.1439-0337.2002.00059.x, 2002.

Selsted, M.B., Linden, L., Ibrom, A., Michelsen, A., Larsen, K.S., Pedersen, J.K., Mikkelsen, T.N., Pilegaard, K., Beier, C., and Ambus, P.: Soil respiration is stimulated by elevated CO2 and reduced by summer drought: three years of measurements in a multifactor ecosystem manipulation experiment in a temperate heathland (CLIMAITE), Global Change Biology, 18, 1216-1230, doi:10.1111/j.1365-2486.2011.02634.x, 2012.

Seneviratne, S.I., Luethi, D., Litschi, M., and Schaer, C.: Land-atmosphere coupling and climate change in Europe, Nature, 443, 205-209, doi:10.1038/nature05095, 2006.

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Spohn, M., and Rillig, M.C.: Temperature- and moisture-dependent soil water repellency induced by the basidiomycete Agaricus bisporus, Pedobiologia, 55, 59-61, doi:10.1016/j.pedobi.2011.10.006, 2012.

Tang, J., Mo, Y., Zhang, J., and Zhang, R.: Influence of biological aggregating agents associated with microbial population on soil aggregate stability, Applied Soil Ecology, 47, 153-159, doi:10.1016/j.apsoil.2011.01.001, 2011.

Tschaplinski, T.J., Gebre, G.M., Shirshac, T.L.: Osmotic potential of several hardwood species as affected by manipulation of throughfall precipitation in an upland oak forest during a dry year. Tree Physiology 18, 291-298, 1998.

Tisdall, J.M., and Oades, J.M.: Organic matter and water-stable aggregates in soils, Journal of Soil Science, 33, 141-163, 1982.

Vicca, S. Gilgen, A.K., Camino serrano, M., Dreesen, F.E., Dukes, J.S., Estiarte, M., Grey, S.B., Guidolotti, G., Hoeppner, S.S., Leakey, A.D.B., Ogaya, R., Ort, D.R., Ostrogovic, M.Z., Rambal, S., Sardans, J., Schmitt, M., Siebers, M., van der Linden, L., van Straatten, O., and Granier, A.: Urgand need for a common metric to make precipitation manipulation experiments comperable. New Phytologist, 195, 518 – 522, doi:10.1111/j.1469-8137.2012.04224.x, 2012

Wu, Z., Dijkstra, P., Koch, G. W., Peñuelas, J. and Hungate, B. A.: Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation. Global Change Biology, 17: 927–942. doi: 10.1111/j.1365-2486.2010.02302.x, 2011.

Yepez, E., Huxman, T., Ignace, D., English, N., Weltzin, J., Castellanos, A., and Williams, D.: Dynamics of transpiration and evaporation following a moisture pulse in semiarid grassland: A chamber-based isotope method for partitioning flux components. Agricultural And Forest Meteorology 132, 359–376, doi:10.1016/ j.agrformet.2005.09.006, 2005.

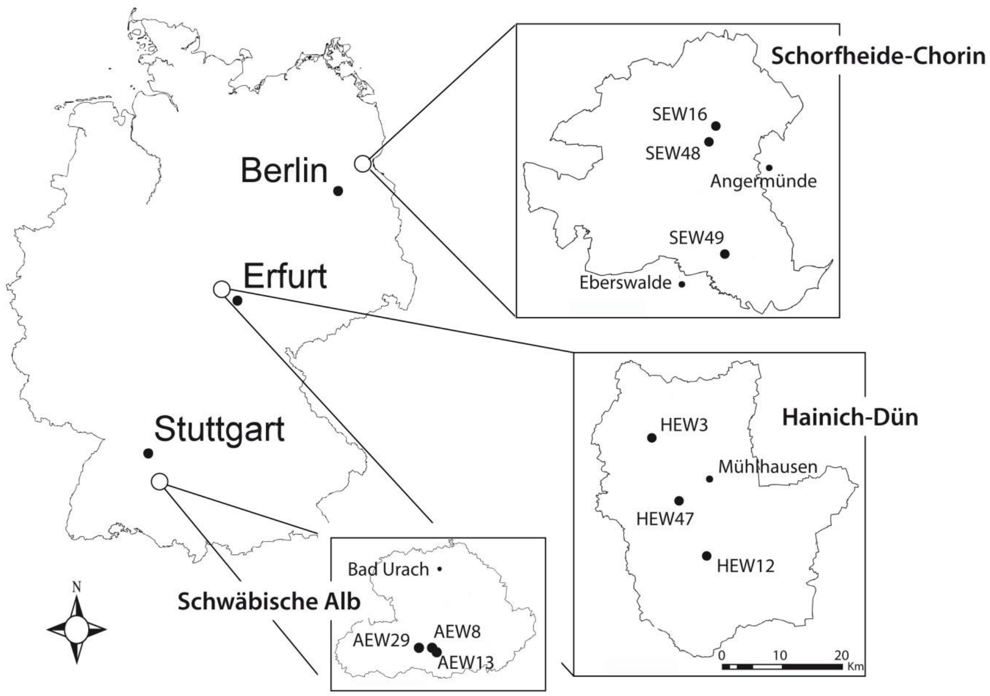


Figure 1: Location of the three Biodiversity Exploratories and the experimental plots.

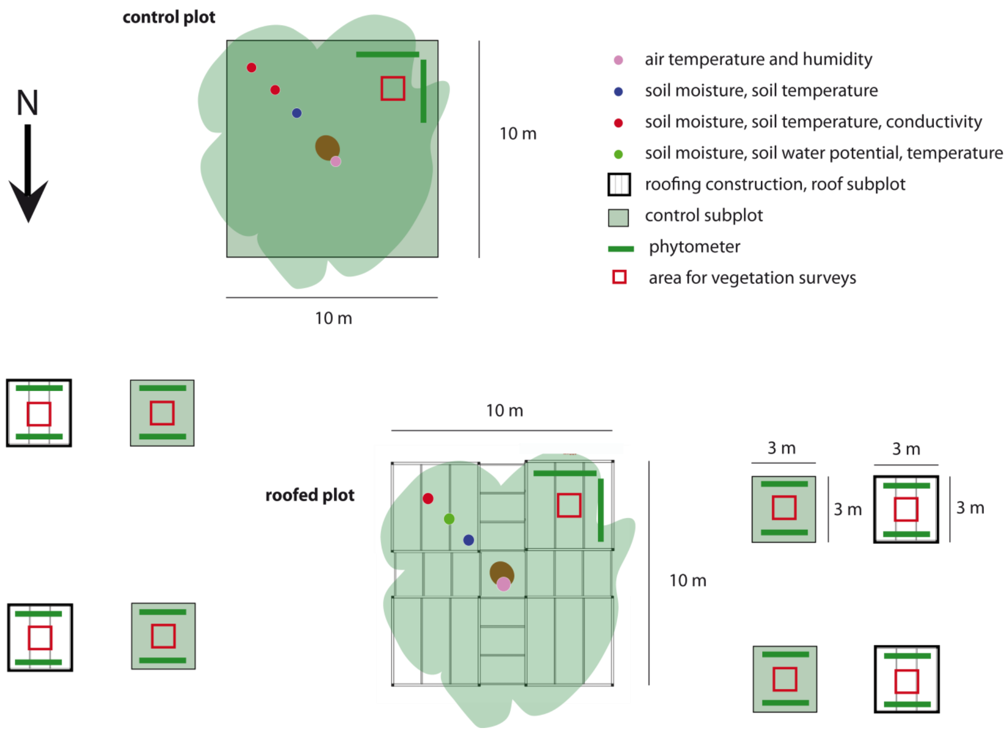


Figure 2: Schematic sketch of roofed and control subplots with roof construction indicated.

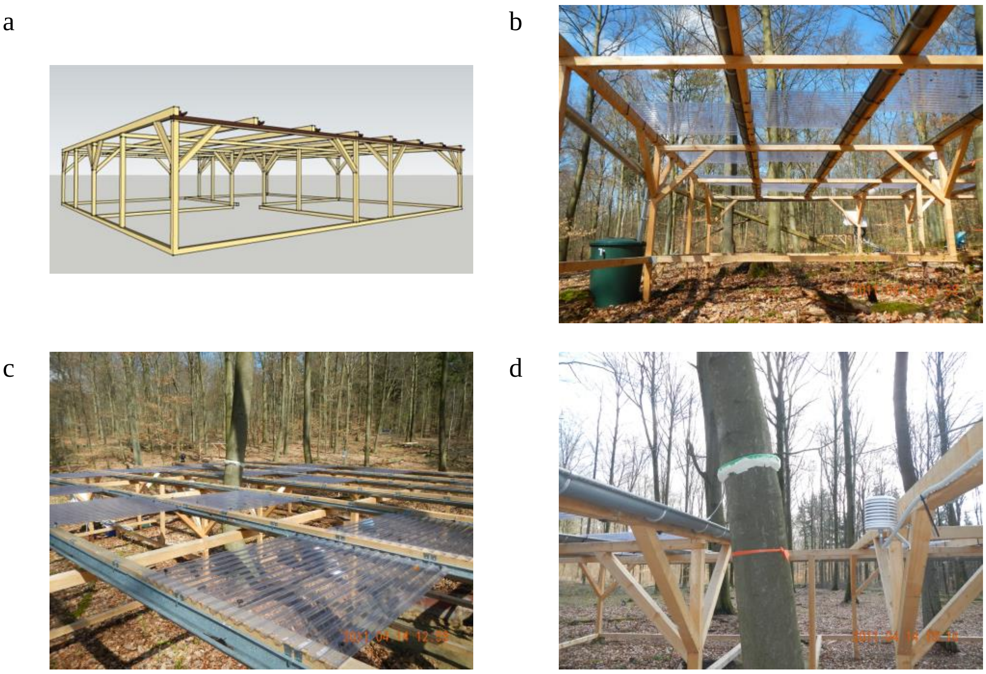
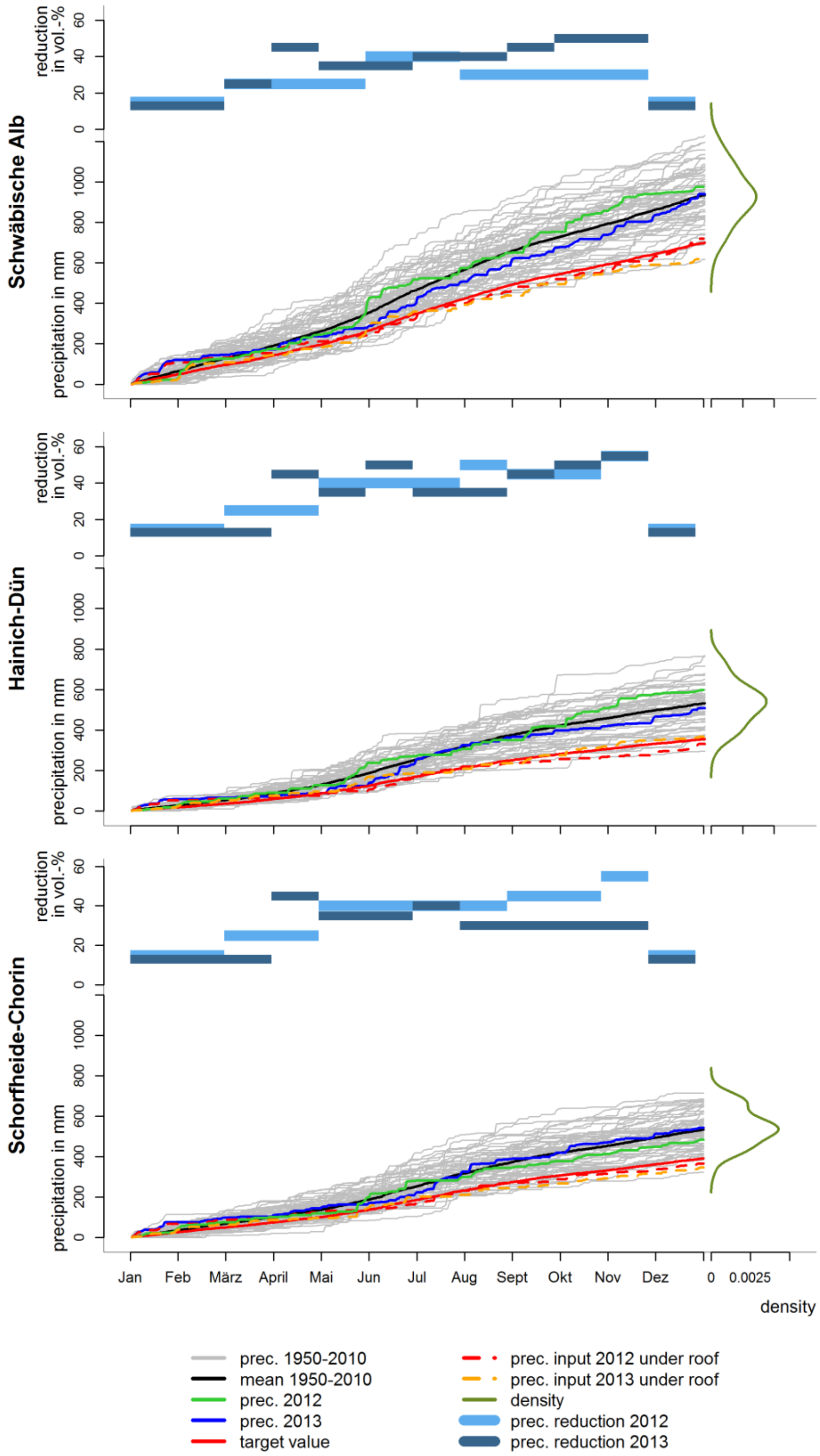


Fig. 3: Roof construction sketch of the main roof (10x10m) (a). Roof with panels, rain gutters and water barrel and main tree (b, c). Roof detail with main tree and stem rim to collect stem flow (d). All pictures were taken at plot SEW48.


Schwäbische Alb
Hainich-Dün
Schorfheide-Chorin
reduction in vol.-%
precipitation in mm
Jan
Feb
März
April
Mai
Jun
Jul
Aug
Sept
Okt
Nov
Dez
0
0.0025
density
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 line: cumulated mean of 1950 – 2010. Dark green line: appearance distribution of precipitation 1950 – 2010 (density). Light blue bars: reduction of precipitation 2012 in vol-%. Dark blue bars: reduction of precipitation 2013 in vol-%. Blue line: cumulated precipitation of year 2012. Green line: cumulated precipitation of year 2013. Solid red line: cumulated 2.5 %-percentile (target value). Dashed red line: cumulated precipitation under roofs in 2012. Dashed orange line: cumulated precipitation under roofs in 2013.

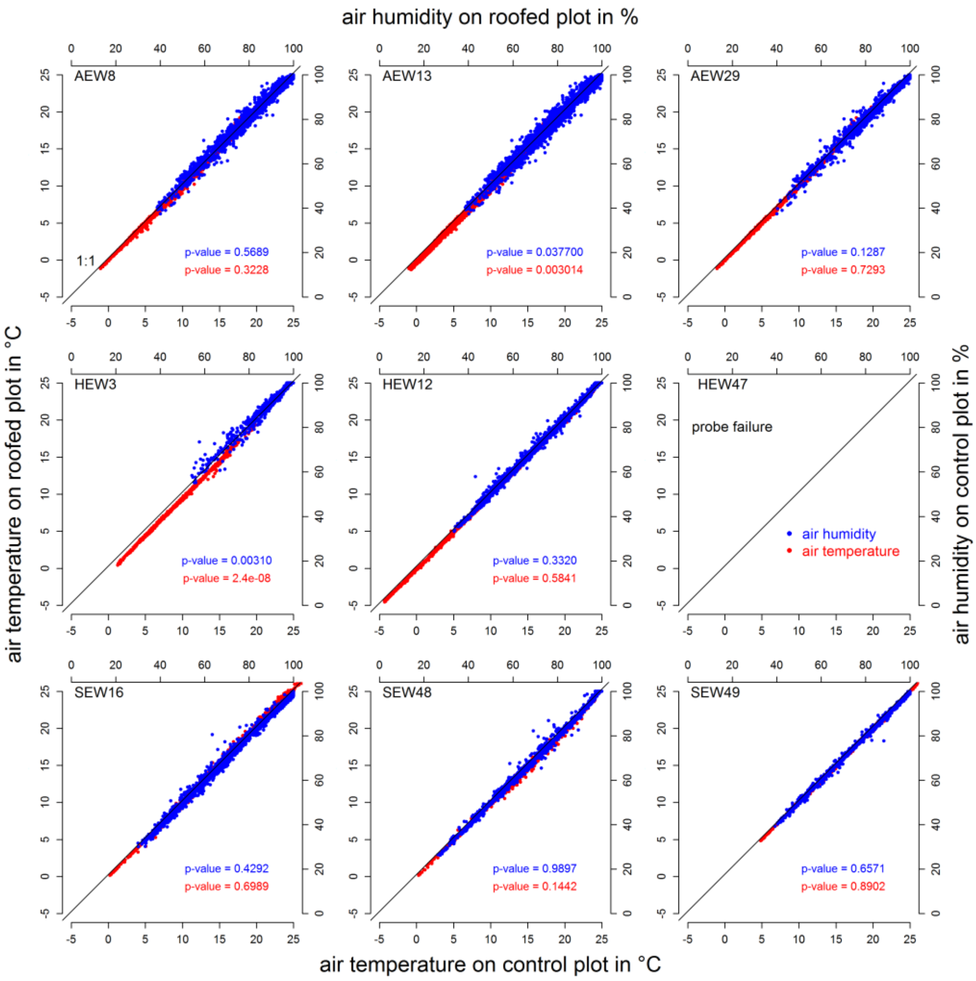


Figure 5: Air temperature control plots vs. air temperature roofed plots (red dots) and air humidity on control plots vs. air humidity on roofed plots (blue dots) for all experimental sites in May 2013. No data for HEW47 are shown due to probe failure.

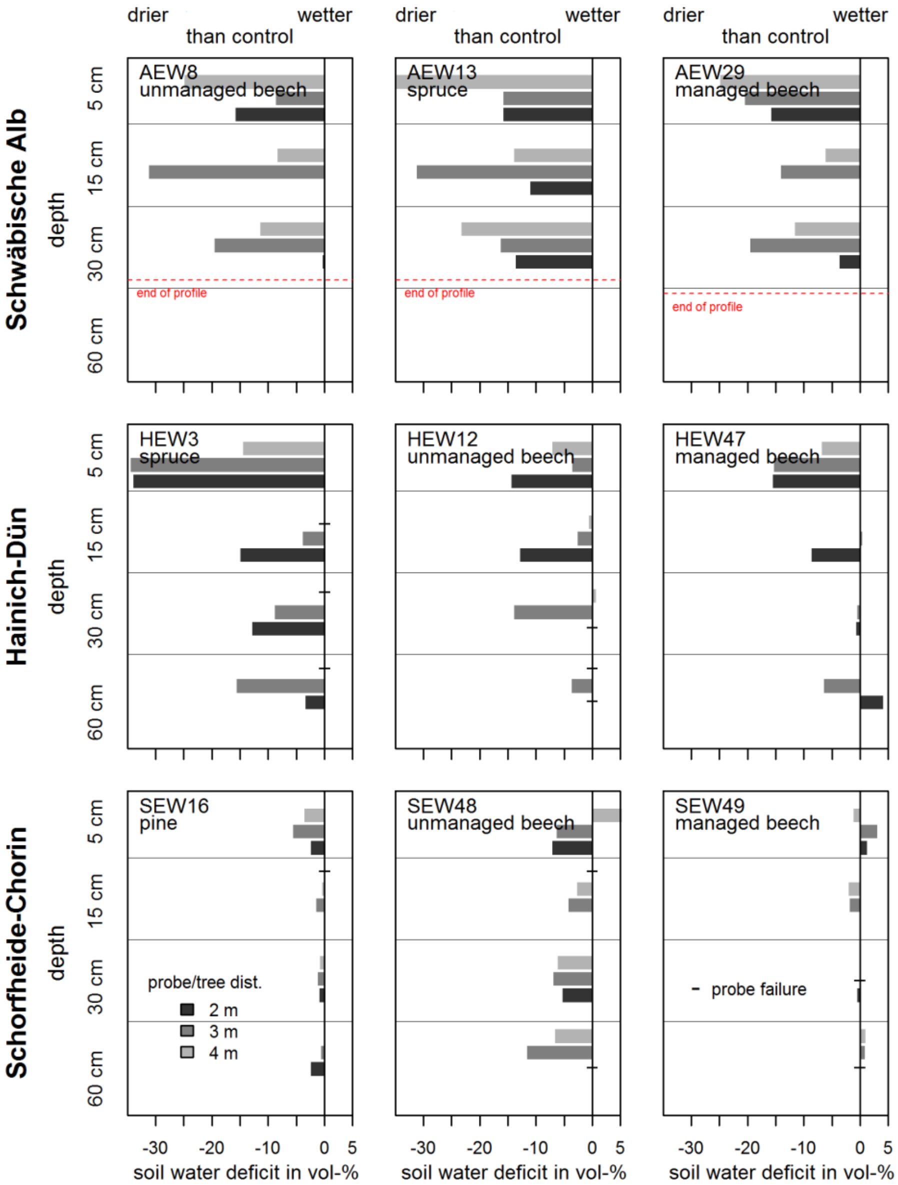
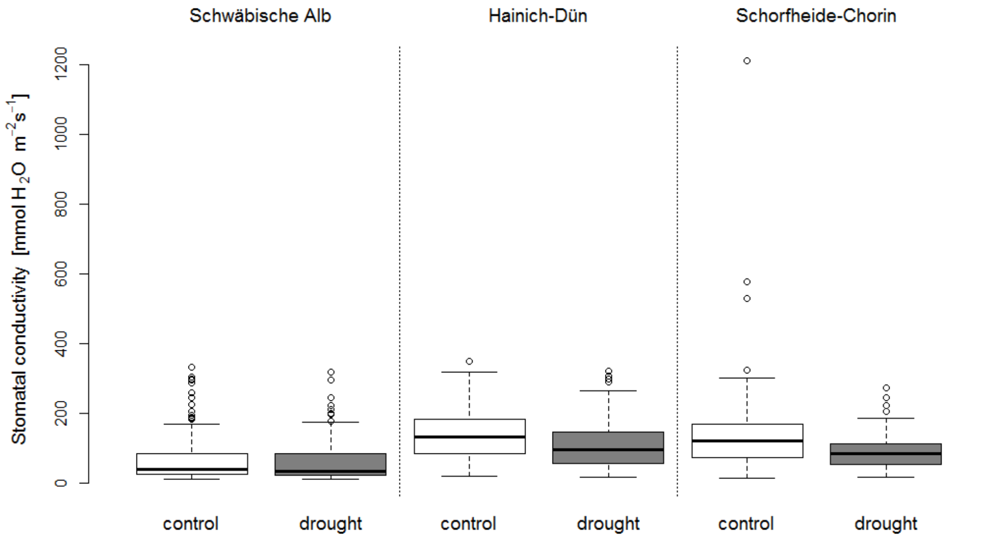


Figure 6: Soil water deficit (soil water content of control minus roofed subplot) of ~~main roofed subplots compared to~~ the main ~~control~~ subplots. All values originate from May 2013, except the values from HEW47 (April 2013), due to probe failure. "–" marks missing values.



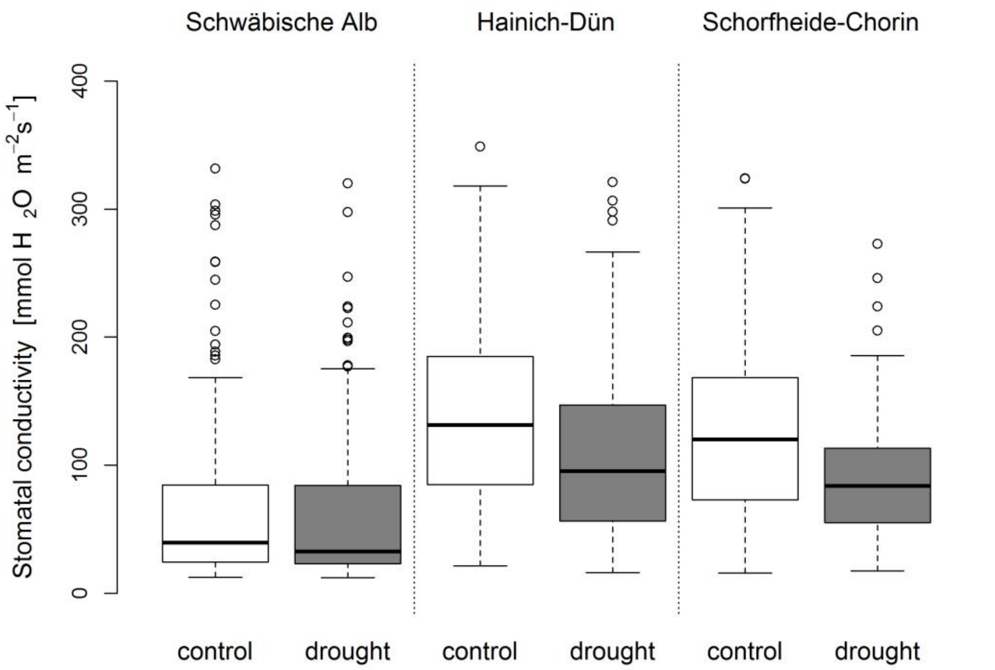


Figure 7: Leaf stomatal conductance at the three experimental sites in July 2012. The boxes show medians and quartiles, the whiskers show 1.5 times the interquartile range of the data. For statistical analyses see Table 4.

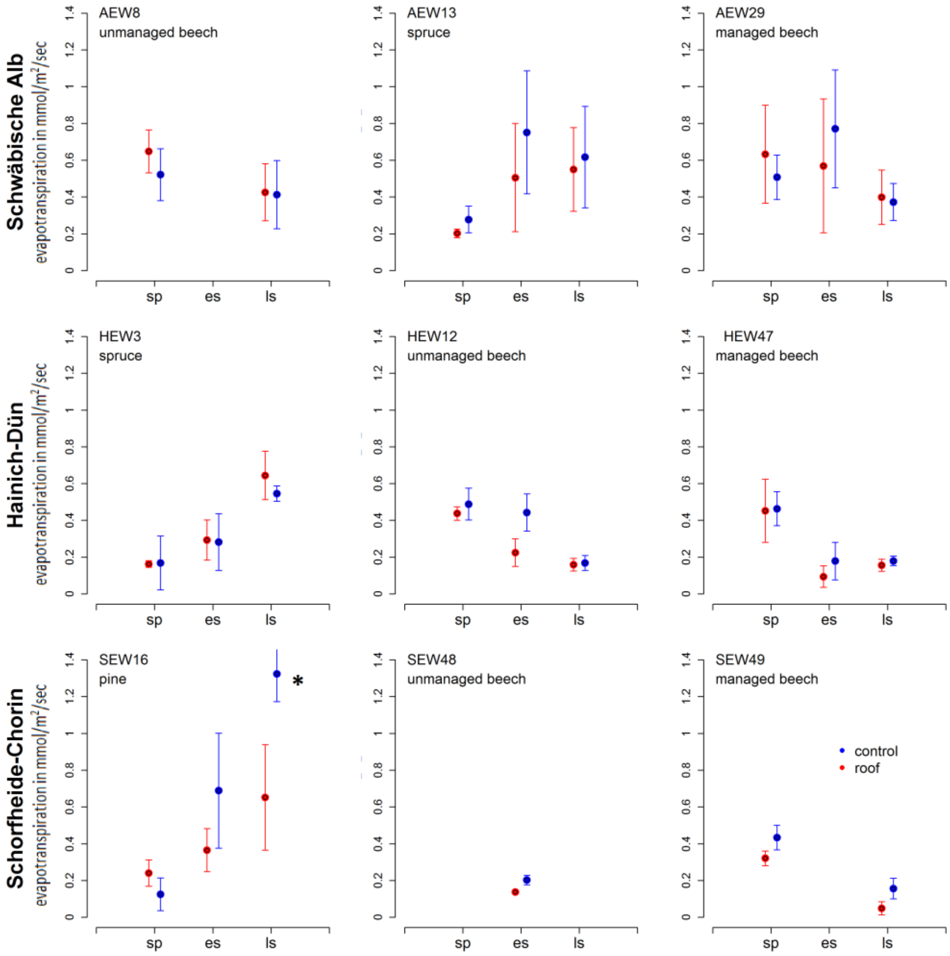


Figure 8: Mean evapotranspiration rates (± SD) for control and drought treamtents (n = 4) at different times during the growing season (sp: spring; es: early summer; ls: late summer). Data are shown for the different management intensities (managed/unmanaged beech and pine/spruce) in the three exploratories.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

Table 1: Forest type, main tree species, tree stand density and understory community at the 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	*Picea abies* plantation
	AEW29	managed	beech	31.59	Hordelymo-Fagetum
Hainich-Dün	HEW3	intensively managed	spruce	27.77	*Picea abies* plantation
	HEW12	unmanaged	beech	32.15	Hordelymo-Fagetum
	HEW47	managed	beech	34.55	Hordelymo-Fagetum
Schorfheide-Chorin	SEW16	intensively managed	pine	37.92	*Deschampsia flexuosa-Pinus sylvestris* community
	SEW48	unmanaged	beech	25.95	Galio-Fagetum
	SEW49	managed	beech	36.11	Galio-Fagetum

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

Table 32: Results of the vegetation monitoring of the understory vegetation for various functional groups at all three sites shown as mean coverage per plot in percent; calculated as mean from ten vegetation recordings of 1x1m per subplot

Exploratory	plot name	understory vegetation cover (%)	mean cover in functional group (%)			
			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

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

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

Table 5~~4~~: Results of the linear mixed model for the leaf stomatal conductance (g_s) as a function of site, drought and competition of the *Fagus sylvatica* phytometers in July and September 2012 (spring data not shown). Values are ~~error probabilities~~ p-values. Significant probabilities ($p < 0.05$) are 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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