

Final author response to Anonymous Referee # 1 (RC1)

Referee comments – Author response

General Comments:

The manuscript presents a nice H₂¹⁸O-labelling study in a Mediterranean oak forest. Authors traced the fate of recent precipitation water in soil and understory vegetation and inferred from the respective partitions of this water for evaporation and transpiration on the use of recent precipitation for understory plants including the effects of tree shading on infiltration and water use. The study is generally well written and methods used seem generally sound. However, the discussion section at the moment is in parts confusing and gives room for improvement, as authors discuss many theories on e.g. hydraulic lift, competition for water between trees and understory, facilitation of infiltration through tree shade etc., but presently do not relate their results very well to these theories, which at the moment hampers the conclusion that they indeed disentangled all these processes. In addition, I believe that the study would benefit from a literature evaluation on the role of tree interception on infiltration and water use, a topic that has so far been disregarded in the study. The conclusions section and the abstract at the moment include deductions that either cannot be directly seen from the results, or are not well enough discussed yet. I am confident that after revision of these issues this topical field study will be acceptable for publication and appeal to the BGS readership.

The authors are thankful for the general appreciation of the submitted manuscript and the recommendation for publication in *Biogeosciences* by Anonymous referee # 1. The authors highly appreciate the thorough review of the manuscript and the very constructive comments. The authors have reviewed the manuscript with special focus on the discussion and conclusion section and include the mentioned literature evaluation on the role of interception.

Specific Comments:

Abstract

The abstract is well written, but would benefit from a revision of the conclusions.

The authors are thankful for the appreciation of the referee and incorporated the revised conclusions in the abstract.

Page 1 Line 26: “unproductive water loss” odd wording

Changed to unproductive evaporation.

Page 1 Line 27: this sentence should be removed, as no information on biomass production, carbon sequestration or nitrogen fixation is given in this paper

The sentence was removed.

Page 1 Line 28: “Light to medium precipitation events” Only one precipitation event was studied with 20 mm. I would not consider this light or medium, also this sentence sounds as if you would compare between precipitation events of different magnitudes, which was not the case in this study.

The authors agree that 20 mm of rain during one hour of watering can be considered as high precipitation intensity compared to the natural precipitation regime of the study site. We can

consequently be very certain about the fact, that naturally occurring light to medium precipitation events during drought periods have no effect on root water uptake, since the high precipitation intensity of the experiment had little impact either. We omitted the latter part of the sentence.

Page 1 Line 28: "This forces plants..." Too general: In this context this sounds, as if plants were generally forced to compete for water with trees in this system. You observed only a short period of the year, for which this is probably true. Reformulate to a more differentiated conclusion considering results of this study.

The statement was related to the drought period of the experiment and the onset of summer.

Page 1 Line 33ff: a bit too thick, see comments to conclusion section

The sentence was shortened.

Introduction

Generally nicely written, the introduction would benefit from some hypotheses on tree and open side effects on water infiltration, E and T.

The authors are thankful for the appreciation of the referee. The authors agree that working hypotheses will enhance the structure of the manuscript and incorporated the following hypotheses in the introduction, discussion and conclusions:

- I. Presence of understory vegetation increases evapotranspirative water loss compared to bare soil, but foster infiltration due to shading.
- II. Preferential root water uptake depth of understory plants is unaffected by changes in soil water availability after rain pulses during drought.
- III. Tree shading fosters infiltration of event water and reduces evapotranspiration generating favourable soil moisture conditions for understory plants.

Page 2 Line 7: context: the use of "thus" is not indicated, I suggest removal of this term

The term was removed.

Page 2 Line 17: context: the use of "for example" is not indicated, I suggest removal of this term

The term was removed.

Page 2 Line 20: wording: consider rewording "stable water isotopes"

The authors consider "stable water isotopes" as a common term for D_2O^{16} and H_2O^{18} isotopes in literature (c.f. *Sturm et al.* An introduction to stable water isotopes in climate models: benefits of forward proxy modelling for paleoclimatology, *Climate of the Past*, 2010) and insist of using it consistently with existing scientific publications.

Page 2 Line 26ff: "most data sets were limited..." Some references for limited data sets would be adequate

We now cite the works of Kurz-Besson et al., 2006 and Asbjörnsen et al., 2008

Page 2 Line 33: "evaporative water use" Consider rewording, water that evaporates is not really used

The term was changed to soil evaporation.

Material and methods

With small exceptions this part seems sound and methods and calculations are described adequately. However, a section on statistical analysis should be added, as the estimation of frequently mentioned significant effects in the results and discussion section cannot be inferred from the M&M part.

The authors are thankful for the appreciation of the referee. Section 2.8 was added, reporting the error propagation to the results as follows: All results are reported as replicate mean with associated standard error to achieve comparability between different sample sizes. All model calculations were applied to single replica and averaged afterwards. Observed effects were considered statistically different when no overlap of standard errors was observed.

Page 3 Line 16: Please expand on possible effects of meshes used for bare soil plots on water infiltration

The requested information was added: meshes were installed vertically, circumventing the undisturbed soil. The sites were kept vegetation free just by regular weeding. We expect no influence of the mesh on infiltration, since the plots were installed one year before the experiment and processes like preferential flow along the mesh is unlikely.

Page 3 Line 19: Irrigation was conducted how and over what time span?

The requested information was added: After a base line observation, all plots were watered with 20 mm water within one hour using watering cans. The water showed an oxygen isotopic signature of -139.5‰ to trace the influence of different vegetation components on water infiltration. All plots and the surrounding soil were watered equally to avoid lateral gradients and possible differences between trenched and control plots.

Page 3 Line 28, 30 and Page 4 Line 3: replace “in a logger” by “by a logger”

The term was corrected.

Page 4 Line 6: fresh material was harvested, what was the proportion of already dry material, particularly in comparison to previous study of Dubbert et al. during a non-drought year, and the different effects of plant cover on infiltration reported in the discussion. This may have also reflected on the event water use in transpiration.

In this particular year the proportion of dry material was minimal owing to the fact that due to the additional severe dry period between January and March 2012 the biomass development in general was very low and developed only following the start of the drought release in March. Dead biomass from the previous season was removed from the plots at the end of summer 2011.

Page 4 Line 8 and 11: Presenting Fig. A1 is ok to characterize biomass and species composition differences of the sites. However, it could be redundant, as this information is only presented in the two lines here and 1 line in the discussion. Biomass and species composition effects on event water use are not discussed much later. However, the tree site being dominated by grasses and the open site being dominated by forbs and potential effects on water use may be worth discussing, which would give presentation of this figure some more impact.

We agree and now discuss this effect in the discussion section (see page 12 line 32 to page 13 line 9)

Page 4 Line 17: Calculating g_t is presented as a method, but there is no data on this in the paper. I suggest removal.

The sentence was shortened by removing total conductance.

Page 5 Line 5: Leaf sampling did not affect ET in the vegetation plots? How big was the reduction of leaf area through sampling? Could this have affected the temporal progress of T from event water? Please elaborate on this here.

This is a very important issue indeed. Our leaf sampling protocol did ensure that leaf biomass sampling for isotope analysis was affecting the overall living biomass to an extent less than 5%, as we did not sample species specifically but took representative samples of the vegetation. Accordingly, we argue that the effects of destructive sampling were minimal in particular regarding the effect of event water use.

Page 7 Line 8: depths used showed negligible root density, please add information on estimating root density in different depths to “Environmental and plant parameters”

Below ground biomass was sampled with soil cores in -5, -15, -30, and -60 cm depth. Oven dried soil was sieved and root biomass was determined gravimetrically. 80 % of root biomass was distributed between -5 to -15 cm depth. Only 5% was distributed above -5 cm and 15% between -20 to -35 cm depth.

Results

This section is nicely written!

The authors are thankful for the appreciation of the referee.

Page 8 Line 14: Consider exchanging figure numbers 3 and 4 to achieve ascending order of figures mentioned in the text.

The authors ordered the figures 2 and 3 (we assume that the referee was not referring to 3 and 4, since they are not mentioned in the particular position of the manuscript) from measured to modelled data in order to show results in a logical order of retrieval. We therefore keep the current ordering.

Page 9 Line 12: correct “along with the lines of evaporation”

The term was corrected.

Page 9 Line 15: “Root water uptake allocation” sounds odd, Fig. 7 shows root water uptake from different depths over time but no allocation. Consider rephrasing.

The term was rephrased in the entire manuscript to “preferential root water uptake depth”.

Discussion

The discussion could still be improved by further increasing the implementation of own results in the theories discussed and enhancing the clarity of some statements made.

We appreciate the constructive suggestions and revised the discussion section in accordance with the suggestions.

Page 9 Line 28: remove “was”

The term was removed.

Page 9 Line 29: add comma after “Mediterranean soils”

The sentence was corrected.

Page 9 Line 31: remove “significantly”

The sentence was corrected.

Page 10 Line 3: add “This is” before “in contrast”

The sentence was corrected.

Page 10 Line 4ff: Dubbert et al. 2014 “reported beneficial effects of vegetation cover on soil water infiltration year-round” Fig. 2 in this paper shows indeed vegetation plots showing mostly higher infiltration than soil plots. However, it would be good to compare data specifically for the transition period between the wet and the dry year here. From Fig. 2 by Dubbert et al. 2014 one can infer that vegetation enhanced infiltration as compared to bare soil, particularly with large water pulses. The only data point comparable to your data shows a rain pulse of 10mm as compared to the 20mm you gave, with only little benefit of vegetation cover. Does that enhance or reduce the significance of your reversed results? In addition, how did you apply water? On the spot irrigation can hardly be expected to yield same infiltration results as a rainfall event over a certain amount of time? This may be good to discuss here.

The precipitation data displayed in Dubbert et al. 2014 (Fig. 2) represents daily sums of precipitation. Even though the daily sum of precipitation at the comparable data point end of May shows 10 mm of rain, the precipitation intensity could have been very different to the experiment conducted in this study. A low intensity of, e.g. 1mm per hour, would change soil moisture conditions and air moisture conditions in the boundary layer in the very beginning, fostering different processes during infiltration for the last 9 hours of the event. The results shown here are only valid for short term rain events with high intensities and thus not contradictory to the results of Dubbert et al. 2014. However, the authors agree with the referee that the topic of intensities need to be discussed. The authors changed the respective discussion section to: This is in contrast to previous studies, which reported beneficial effects of plant cover on daily sum of infiltration during the same period at the onset of drought in 2011 (Dubbert et al., 2014c). However, (Dubbert et al., 2014c) only observed precipitation events of light intensity during the period of interest. The present study reports on high intensity precipitation events. This unexpected turn in effect direction with increasing precipitation intensity, which depends on plant cover and atmospheric evapotranspirative demand, potentially plays a strong role for the water balance of the ecosystem in the course of ongoing climate change scenarios since the occurrence of extreme precipitation events is expected to increase (IPCC, 2013).

Page 10 Line 13: “anyway” reword

The sentence was corrected.

Page 10 Line 14: add “by” after “unaffected”

The sentence was corrected.

Page 10 Line 16: “effects of soil hydraulic properties beneath tree crowns” In what way were properties affected? Did that also apply to your study? Please elaborate further on the potential importance of this.

The respective discussion section was changed to: Previous studies reported similar, positive feedbacks of tree cover for the hydrological cycle in savannah-type ecosystems related to shading effects (Eldridge and Freudenberger, 2005). Effects of altered soil hydraulic properties beneath tree crowns, like the amount of preferential flow fostering infiltration (Bargués Tobella et al., 2014) could not be identified in this study.

Page 10 Line 17: remove brackets before reference to Bhark and Small, 2003

The sentence was corrected.

Page 10 Line 19ff: The positive effects of tree crown cover on infiltration may be lost by interception, as the authors state. Could you try to infer the role of interception for cork oak trees from literature values to better describe the significance of the climatic advantages in the shade for infiltration?

The amount of interception loss by the tree canopy and stem bark of cork-oaks (or trees in general) is highly variable, depending on meteorological variables like precipitation intensity, wind speed, relative air moisture and stand properties like tree density, branch geometry, leaf angle and shape. The authors included results from David et al. 2006 in the discussion, which were derived in an ecosystem with comparable stand and climatic conditions in order to give the reader a feeling for the magnitudes of the interception loss and infiltration enhancement. However, directly relating tree interception loss results from other studies to the infiltration effect results of this study is highly prone to misleading conclusions due to different boundary conditions and settings of the experiments. The authors therefore desist from direct deductions by comparisons with previous studies.

Page 10 Line 24: consider deleting “close to trees”

The term was deleted.

Page 10 Line 28: correct “overall”

The sentence was corrected.

Page 10 Line 29: reword “shortcoming”, odd in this context

The term was replaced by negative effect.

Page 11 Line 10: odd “productive water”, consider rewording

The term was replaced by transpiration water.

Page 11 Line 11: rephrase to “... from the longer time response lag of T., on the other hand from only little event water reaching deeper soil layers, where...”

The sentence was reformulated.

Page 11 Line 12: remove “prior to the precipitation pulse”

The term was removed.

Page 11 Line 13: “Event water use of the understory vegetation was overall low” Again the question, of how much living biomass was there? Is it possible that understory plants were on the verge of senescence and therefore did not use the water or readjust water uptake depths?

At both sites the understory vegetation was indeed already past the peak of biomass development. There were, however, differences between the two regarding the productivity evolving during the experimental period. At the open site, the understory still showed a significant net uptake of carbon throughout the entire experiment, while decreasing NEE and even a net release of carbon at the final day of the experiment could be observed at the tree site. Since we agree, that this information is rather important for the interpretation of the site specific difference and also explains the overall differences in ET and T throughout the experiment rather well, we added an additional graph A2, informing on the development of NEE over the experimental course. See also page 12 line 32 to page 13 line 9.

11 18: 180 signals of soil
water being more depleted in the tree site but this depletion not being visible in transpiration? Higher infiltration at the tree site must thus have been of no use for understory plants, because of competition with trees. Could you elaborate on this more?

It is indeed true that leaf and transpirative isotopic signatures did not show a such significant depletion at the tree site compared to the open site as could be observed for the soil isotopic values. This is mostly due to the lesser general uptake of water (i.e. lower T rate) below the trees compared to the open site. Whether this is due to competition with trees is not provable with the current data set, mostly because we are missing isotopic data on tree root water uptake (tree xylem). Moreover, the current approach of spacially explicit labelling of the discrete plots did not allow for estimation of tree reaction to the irrigation pulse.

What can be clearly seen is, that the vegetation below the trees was already at the verge of senescence (see above). Previous data by Dubbert et al. (2014) however suggests, that the phenological shift and earlier senescence might very well be strongly related to tree understory competition.

Page 11 Line 22ff: “Hydraulic lift” This point is contrary to the previously discussed competition for water. If water from hydraulic lift was up in the layer of understory roots you would expect 1) a dilution of the event water signature, and 2) a higher soil moisture. You do not find any of this. Thus, I think from your data you can infer that hydraulic lift was not a major factor here. Roots preferentially taking up water in this depths may be due to hydraulic lift, but you find the same in the open site, so I would take out this argumentation here.

The authors agree with the opinion of the referee and removed this discussion section.

Page 12 Line 2: context: the use of “therefore” is not indicated, I suggest removal of this term

The term was removed.

Page 12 Line 8: remove “the” before “type”

The sentence was corrected.

Conclusions

The conclusions at the moment seem overstated considering the results presented, and should be rewritten. The study itself is nice enough and does not need this thick laid conclusion.

The authors incorporated the recommendations of the referee into the conclusions section to a large degree in order to make it more adequate for results presented in the study.

Page 12 Line 13: I do not really agree that your study disentangled and quantified tree and understory interactions. As such you compared sites with and without trees, but do not go into much depth regarding tree understory interactions. For this statement to stand this topic should be more thoroughly discussed on base of the results presented. Either adapt the discussion to really try and disentangle the role of hydraulic lift vs. competition vs. enhanced interception, or be more modest here.

The authors reformulated the sentence: In this study, the various interactions between understory vegetation and trees of a Mediterranean cork – oak woodland affecting the ecosystem water flows could be quantified.

Page 12 Line 18: Consider removing “or just bare soil”

The term was removed.

Page 12 Line 19: The sentence “Thus, the amount of unproductive water loss....” is a large overstatement and should be removed. This study did not show any data on nitrogen fixation, carbon sequestration or biomass production, for this statement to hold true.

The sentence was modified to: Thus, the amount of unproductive evaporation is largely reduced, in favour of transpiration.

Page 12 Line 21: I would not consider a 20mm precipitation pulse as light or medium.

The sentence was changed accordingly.

Page 12 Line 22ff.: “Therefore, these understory plants were forced into competition....However, the understory plants could profit from tree root induced soil water redistribution.” Both statements do not hold true, the first point I can agree upon, but it should be included in more detail in the discussion with better implementation of own results. The second statement, I don’t believe that this was shown!

The statement was removed.

Page 12 Line 23: “Cork oak trees foster infiltration....” I would not make this statement without considering interception of rainfall.

The sentence states that the study could show a strong increase of infiltration due to favourable climatic conditions under tree crowns. That is true independent of a possible negative effect of interception losses on throughfall. However, the authors agree with the referee that the effect of

throughfall interception was not investigated in this study and plays a major role in the overall ecosystem water balance. Therefore the authors keep this important statement, but reworded the sentence by removing the emphasis of the infiltration part in the revised version.

Page 12 Line 26: that is too laid on thick, given the study's outcome. I would not use this sentence.

The sentence was removed.

Final author response to Anonymous Referee # 2 (RC2)

Referee comments – Author response

General Comments:

This very interesting work deals with an important and hard to assess ecohydrological problem, where once more stable isotopes prove to be useful. The manuscript presents a NICELY WELL done experiment. With very interesting results which suggests that vegetation keeps withdrawing water from the same depths after simulated rain events. Event size showed that short to medium precipitation were not very important under a dry scenario; that vegetation below trees are fierce competitors and that these lead to senescence at the beginning of the drought, and last that Trees also ameliorate the micrometeorological conditions and soil water infiltration rates. This is, in my opinion, the most relevant finding of this study.

However, some issues need to be address first: The authors made the experiment in a Cork-Oak forested area. However, they refer to it as Cork - Oak, cork-oak and cork oak. Please, select one and be consistent throughout the document. Please, pay attention to the use of hyphenated words.

The manuscript have been revised for consistent naming and use of hyphenation.

Citations also need to be checked. For example on material and methods, the authors cite: “(Piayda et al., 2015)”. However, later the authors start using parenthesis enclosing the year. I understand is possible to it like that, but for example on line 10, just before equation 4 (page 6) the citation is: “(Moreira et al., (1997); Yakir and Sternberg (2000))”. However, it should read “(Moreira et al., 1997; Yakir and Sternberg, 2000)”. Please, check this throughout the document. Also, pay attention to repeated parenthesis that are not needed.

We checked the citations list and citations within the text and corrected the errors. We apologize for the inconvenience.

Equation 2, is referenced to Craig and Gordon (1965). However, that equation does not appear in that document.

$$\delta_E = \frac{1}{(1-h) + \Delta\epsilon} \left(\frac{\delta_S}{\alpha_{v-w}^*} - (h\delta_A) - \Delta\epsilon + \epsilon^* \right)$$

*Where δ_E , stands for isotopic composition of the water vapour coming from the evaporating surface (δ_S) and δ_A stands for the atmospheric isotope composition. Also, the fractionation factor α , is referred as $\alpha +$, for condensation; and $\alpha *$ for evaporation. It is important to note that in this case, and according to nomenclature introduced by Craig and Gordon, (1965), and followed by others (e.g. Gat, 1996; Gibson and Reid, 2010):*

$$\alpha_{w-v}^+ = \frac{1}{\alpha_{v-w}^+}$$

$$\frac{1}{\alpha_{v-w}^+} = \alpha_{v-w}^*$$

Please note that W and v stand for water and vapour. And that the reactant (i.e. source) is noted in last place. Hence, w-v should read as vapour to water (i.e. condensation). While, v-w should read as

water to vapour (i.e. evaporation). Hence, α^* is used for evaporation process. I have checked also Mathieu and Bariac (1996); Dubbert et al. (2014) and couldn't find it either. Please, could you provide the right cite?; If this equation was derived by the authors, then please add include it in the appendix.

Craig H, Gordon L. 1965. Deuterium and oxygen 18 variations in the ocean and the marine atmosphere. In *Stable Isotopes in Oceanographic Studies and Paleotemperatures*, Tongiorgi E (ed.).Spoleto; 9–130. which can be downloaded from <http://climate.colorado.edu/research/CG/>

Dubbert M, Piayda A, Cuntz M, Werner C. 2014. Oxygen isotope signatures of transpired water vapor – the role of isotopic non-steady-state transpiration of Mediterranean cork-oaks (*Quercus suber* L.) under natural conditions. *New Phytologist* 16: 2014

Gat J. 1996. Oxygen and Hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Sciences* 24: 225–262. DOI: 10.1007/s13398-014-0173-7.2

Gibson J, Reid R. 2010. Stable isotope fingerprint of open-water evaporation losses and effective drainage area fluctuations in a subarctic shield watershed. *Journal of Hydrology* 381 (1–2): 142–150 DOI:10.1016/j.jhydrol.2009.11.036

Mathieu R, Bariac T. 1996. A numerical model for the simulation of stable isotope profiles in drying soils. *Journal of Geophysical Research* 101 (D7): 12685–12696 DOI: 10.1029/96JD00223

In the reference list, please check all of them. Some of them are in full capital letters; other don't have volume and/or page number

We apologize for the errors in the citation list, they are checked and corrected. The Craig and Gordon formula was written however not in delta notation but isotope ratios following previous publication of the authors. We now cite Dubbert et al., 2013 and Harverd and Cuntz, 2010 to refer to it. In addition we added a sentence on the transformation of R_E to δ_E (page 6 line 7).

Specific Comments:

Abstract

Check hyphenation.

The hyphenation errors have been corrected.

Line 24 (page 1): consider using “soil evaporation and transpiration were quantified.”; instead of “evapotranspiration were quantified.”. I think it would add the right value to your work, since you actually separate both evapotranspiration components.

The sentence was changed accordingly.

Line 26 (page 1): it is not clear to me, who “use water”...soils or vegetation. If it refers to soils, I would change “use” for “evaporates”

The term refers to transpiration by plants and was changed accordingly.

Line 30 (page 1): Consider adding a comma after Thus.

The sentence was corrected.

Line 30 (page 1): consider rephrasing "...faster subject" to "...subjected faster"

The sentence was changed accordingly.

Introduction

Please, consider adding the hypothesis already tested in this great work. This will only add more value to your research and again, great work.

The authors are thankful for the appreciation of the referee. The authors agree that working hypotheses will enhance the structure of the manuscript and incorporated the following hypotheses in the introduction, discussion and conclusions:

- I. Presence of understory vegetation increases evapotranspirative water loss compared to bare soil, but foster infiltration due to shading.
- II. Preferential root water uptake depth of understory plants is unaffected by changes in soil water availability after rain pulses during drought.
- III. Tree shading fosters infiltration of event water and reduces evapotranspiration generating favourable soil moisture conditions for understory plants.

Material and Methods

Line 12 (page 3): Please, consider adding the standard deviation in the temperature and precipitation.

The authors do not have access to data about the standard deviation of the long term temperature and precipitation distribution and therefore apologize for the missing information.

Line 28-29 (page 3): Please, consider rephrasing this sentence. "...was measured at 5 cm depth", instead of "...in -5 cm depth was measured".

The sentence was changed accordingly.

Line 1-2 (page 4): please consider rephrasing "Volumetric soil water"

The sentence was changed accordingly.

Line 14 (page 4): Add WS to CRDS...Picarro is a Wavelength Scanned-Cavity Ring Down Spectrometer (WS-CRDS).

The sentence was changed accordingly.

Line 19 (page 4): Please, remove parenthesis enclosing the publication years, since they are not needed. Please consider separating both equations Equation 1.1 and 1.2.. For example.

The parenthesis were removed and the equation was split in two.

Line 6 (page 5): Please, add a cite after cryogenic distillation...This will clarify which kind of system did you use...West et al., 2006 and Orlowski et al., 2013 both use cryo-distillation, but the systems are very different. Could you add also information on your water recoveries (if measured), extraction temperature and time it took the whole process of water extraction from soils and leaves. I think this will add robustness to your work.

We used a cryogenic system of our own design, which are in long term use in the labs in the PSI and Freiburg. The system is similar to that of Orlowski et al., which we cite now respectively.

Line 4 (Page 6): I really don't think that the mesophyll in a leaf measures 5 cm. please check the unit and correct.

This was misleading. The 0.05 m refers to the effective path length. We corrected the sentences.

Line 10 (page 6): please, remove the parenthesis from the publication years on Moreira et al. and Yakir and Sternberg.

The sentence was corrected.

Line 4 (page 7): please, consider "three-source linear model" instead of "three-source model".

The term was changed accordingly.

Line 7 (page 7): please, consider removing the "s" in "depths"

The term was corrected.

Line 21 (page 7): please, consider rephrasing "(bare: 14.9 °C, veg: 11.3 °C, Fig 1)" to "(14.9° and 11.3° C for bare and vegetated soils, respectively, Fig 1)"

The term was changed accordingly.

Results

Line 24 (page 7): please, consider adding a comma after "Systematically..."

The sentence was corrected.

Line 8 (page 8): please, change "Lowest..." for "Depleted...", I think it is more adequate.

The term was changed accordingly.

Line 11 (page 8): please, consider removing "only", is not needed.

The term was removed.

Line 28 (page 8): please consider removing "here much" and adding after "than", "that of". Please, remember that water evaporates, water is not used by evaporation or soil. (Line 10 (page 9)).

The sentence was changed accordingly.

Discussion

Line 23 (page 9): please check the double space you have before "Different".

The space was removed.

Line 28 (page 9): please remove "was", not necessary.

The term was removed.

Line 17 (page 10): please remove the parenthesis before “Bhark and Small”, is not needed.

The parenthesis was removed.

Line 6 (page 12): please add “et al” after Orlowski and remove the parenthesis from the year.

The citation was corrected.

Line 8 (page 11): please remove the word “the”. The word is not needed. It would be interesting that you could add more literature to this paragraph.

Craig H, Gordon L. 1965. Deuterium and oxygen 18 variations in the ocean and the marine atmosphere. In Stable Isotopes in Oceanographic Studies and Paleotemperatures, Tongiorgi E (ed.).Spoleto; 9–130.

Dubbert M, Piayda A, Cuntz M, Werner C. 2014. Oxygen isotope signatures of transpired water vapor – the role of isotopic non-steady-state transpiration of Mediterranean cork-oaks (Quercus suber L .) under natural conditions. New Phytologist 16: 2014

Gat J. 1996. Oxygen and Hydrogen isotopes in the hydrologic cycle. Annual Review of Earth and Planetary Sciences 24: 225–262. DOI: 10.1007/s13398-014-0173-7.2

Gibson J, Reid R. 2010. Stable isotope fingerprint of open-water evaporation losses and effective drainage area fluctuations in a subarctic shield watershed. Journal of Hydrology 381 (1–2): 142–150 DOI: 10.1016/j.jhydrol.2009.11.036

Mathieu R, Bariac T. 1996. A numerical model for the simulation of stable isotope profiles in drying soils. Journal of Geophysical Research 101 (D7): 12685–12696 DOI: 10.1029/96JD00223

The term was removed. Regarding the literature no specific action was taken. However, in response to the suggestions of both reviewers, the paragraph was restructured and more literature was added in response to the other specific comments.

Conclusion

Line 18 (page 12): please consider changing “Irrespective” by “Regardless”.

The term was changed accordingly.

Line 22 (page 12): please consider changing “Therefore” by “Hence”.

The term was changed accordingly.

Line 23 (page 12): Do you have any proof of root water redistribution in your study area...if you have it and are planning to publish it maybe, you could briefly comment.

Unfortunately we do not have data on root water redistribution at our study sites. Hence, the authors removed the aspect of root water redistribution from the discussion in compliance with important comments of referee RC1.

Quantification of dynamic soil—vegetation feedbacks following an isotopically labelled precipitation pulse

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15 **Abstract.** The presence of vegetation alters hydrological cycles of ecosystems. Complex plant—soil interactions govern the fate of precipitation input and water transitions through ecosystem compartments. Disentangling these interactions is a major challenge in the field of ecohydrology and pivotal foundation for understanding the carbon cycle of semi—arid ecosystems. Stable water isotopes can be used in this context as tracer to quantify water movement through soil—vegetation—

20 atmosphere interfaces.
The aim of this study is to disentangle vegetation effects on soil water infiltration and distribution as well as dynamics of soil evaporation and grassland water —use in a Mediterranean cork— oak woodland during dry conditions. An irrigation experiment using $\delta^{18}O$ labeled water was carried out in order to quantify distinct effects of tree and herbaceous vegetation on infiltration and distribution of event water in the soil profile. Dynamic responses of soil and herbaceous vegetation fluxes to precipitation regarding event water —use, water uptake depth plasticity and contribution to ecosystem evapotranspirationsoil
25 evaporation and transpiration were quantified.

Total water loss to the atmosphere from bare soil was as high as from vegetated soil, utilizing large amounts of unproductive water—losseevaporation for biomass—production, carbon—sequestration and nitrogen—fixation. During the experiment
notranspiration, but infiltration rates decreased. No adjustments of main root water uptake depth to changes of water availability could be observed, rendering light to medium precipitation events under dry conditions useless during the
30 experiment. This forces understory plants to compete with adjacent trees for soil—water in deeper soil layers, at the onset of summer. Thus, understory plants are subjected faster subject to chronic droughtwater deficits, leading to premature senescence at the onset of drought. Despite this water competition, the presence of Corkcork oak trees fosters infiltration to
large—degrees. That—and reduces drought—stress, caused by—evapotranspiration, evapotranspirative water losses from
understory and soil, both due to favourablealtered micro climatic conditions under tree crown shading. This study highlights

complex soil—plant—atmosphere and inter—species interactions ~~in both space and time~~ controlling ~~the fate of~~ rain pulse transitions through a typical Mediterranean savannah ecosystem, disentangled by the use of stable water isotopes.

1 Introduction

Vegetation influences ecosystem water cycling in many ways. Rainfall is intercepted while at the same time infiltration, redistribution and translatory flow might be altered depending on rooting depths and soil structure (Bhark and Small, 2003; Dawson, 1993; Devitt and Smith, 2002; Dubbert et al., 2014c; Schwinning and Ehleringer, 2001; Tromble, 1988). E.g., a dense vegetation layer can strongly reduce soil evaporation (Dubbert et al., 2014c; Wang et al., 2012). In turn, plant transpiration is controlled by soil water availability and distribution and plant species have different abilities to use different soil water pools (i.e. surface vs. deep or ground water). ~~Thus, large~~Large parts of ecosystem water losses by transpiration strongly depend on plant functional types, stomatal regulation and leaf area index (*LAI*). Although studies within the last decades emphasized the pivotal role of plant roots for soil water redistribution or the role of plant transpiration on ecosystem water losses (Caldwell, 1987), it remains a major challenge to quantify dynamic soil—vegetation—atmosphere feedbacks within the water cycle.

Stable water isotopes are widely used to trace water transfers in soils, through plants and at the soil—vegetation—atmosphere interface (Werner and Dubbert, 2016; Yakir and Sternberg, 2000). Fractionation between the heavier and lighter isotopes occurs during phase changes (from liquid to gaseous, equilibrium fractionation) and movement (kinetic fractionation). This leads to different stable isotope compositions (δ^2H and $\delta^{18}O$) in various water pools (i.e. rain, groundwater), along soil profiles, in different plant species and between water ~~vapor~~vapour evaporated from soil compared to water transpired by plants. These differences provide the basis for tracing water through an ecosystem. ~~For example,~~utilizationUtilization of different water pools within the soil by different plant individuals may be possible (Dawson, 1993; Volkmann et al., 2016a). Isotopes can further help to separate transpiration from soil evaporative fluxes (Dubbert et al., 2013; Yepez et al., 2003) or to study infiltration or distribution of precipitation in soils (Garvelmann et al., 2012; Rothfuss et al., 2015). Stable water isotopes have also been used to study water movement at the soil—vegetation interface (Caldwell et al., 1998). The isotopic composition of plant water uptake can be determined by sampling the ‘output’ of the root system, for example the plant xylem, because the water isotopic signatures are usually not altered by plant water uptake (Dawson, 1993). Compared with values observed in the soil water profile, the preferential plant extraction depth or the proportional use of “event water” (i.e. singular precipitation events) can be determined. Although this method has been successfully used to identify processes such as hydraulic lift and soil water redistribution (Caldwell et al., 1998), most datasets were limited in temporal and spatial resolution: ~~(Asbjornsen et al., 2008; Kurz-Besson et al., 2006)~~. Over the last decade, the development of field—deployable laser spectroscopy has enabled continuous measurements of water vapour and its isotopic signatures in ecosystem fluxes and atmospheric concentrations. This opens the door for large-scale assessment of the soil-vegetation-atmosphere interactions in the water cycle. In particular, these developments have enhanced the spatial and temporal

resolution tremendously, furthering the understanding in the fields of plant ecophysiology (Cernusak et al., 2016) and ecosystem physiology (Dubbart et al., 2014a; Dubbart et al., 2014c).

In the present study, we focus on disentangling the vegetation effects on soil water infiltration and distribution as well as dynamics of soil ~~evaporative~~evaporation and grassland water-use in a Mediterranean cork-oak woodland. An irrigation experiment with $\delta^{18}O$ labeled water was carried out to quantify the distinct effects of tree and herbaceous vegetation on 1) infiltration and distribution of “event water” (freshly introduced water) in the soil profile and 2) to quantify the dynamic responses of soil and herbaceous vegetation fluxes to precipitation regarding event water-use, plasticity of water uptake depth and contribution to ecosystem *ET*. The following hypotheses were tested:

I. Presence of understory vegetation increases evapotranspirative water loss compared to bare soil, but foster infiltration due to shading.

II. Preferential root water uptake depth of understory plants is unaffected by changes in soil water availability after rain pulses during drought.

III. Tree shading fosters infiltration of event water and reduces evapotranspiration generating favourable soil moisture conditions for understory plants.

2 Material and methods

2.1 Study site and experimental design

Measurements were conducted between May 26 and June 6 2012 in an open cork-oak woodland (*Quercus suber* L.) in central Portugal, approximately 100 km north-east of Lisbon (N39°8'17.84'' W8°20'3.76''; Herdade de Machoqueira do Grou). The trees are widely spaced (209 individuals ha⁻¹) with a leaf area index of 1.1 and a gap probability of 0.7 (Piayda et al., 2015).

The herbaceous layer is dominated by native annual forbs and grasses. The site is characterized by Mediterranean climate, with a 30 year long-term mean annual temperature of approximately 15.9 °C and annual precipitation of 680 mm (Instituto de Meteorologia, Lisbon). We established two sites: one directly under the oak crown projected area (tree site, ts) and another one in an adjacent open area (open site, os). Two types of plots (sized 40 × 80 cm) were installed in each site: bare soil plots with total exclusion of above and below-ground biomass (~~lateral~~ root ~~in~~—~~growth~~growth was prevented by ~~inserting~~vertically inserted trenching meshes around the plots, mesh diameter < 1 μm, Plastok, Birkenhead, UK), and understory plots with herbaceous vegetation (four plots per site and treatment). All plots were established 1 year before measurements to minimize effects of disturbance (For further details see Dubbart et al. (2013)).

After a base line observation, all plots were watered with 20 mm water ~~of~~within one hour using watering cans. The water showed an oxygen isotopic signature of -139.5‰ to trace the influence of different vegetation components on water infiltration. All plots and the surrounding soil were watered equally to avoid lateral gradients and possible differences between trenched and control plots. Thereafter, all measurements were conducted in 7 diurnal cycles over the following 10-

12 days. The open and tree sites were watered independently, as the measurement setup did not allow highly resolved observations of all treatment plots at the same time. Environmental variables (PPFD; soil water content; vpd) were not significantly different between the first and second half of the observation period.

2.2 Environmental variables and plant parameters

5 Photosynthetic photon flux density (PPFD) was measured at both sites at approximately 1.5 m height (PPFD, LI-190SB, LI-COR, Lincoln, USA). Rainfall (ARG100 Rain gauge, Campbell Scientific, Logan, UT, USA), air temperature, and relative humidity (rH, CS-215 Temperature and Relative Humidity Probe, Campbell Scientific, Logan, UT, USA) were measured and 30 min averages were stored ~~in~~^{by} a data logger (CR10x, Campbell Scientific, Logan, UT, USA). Soil temperature (custom built pt-100 elements) ~~in -5 cm depth~~^{at -5 cm depth on} vegetation and bare soil plots at both sites
10 and 60 min averages were stored in a data logger (CR1000, Campbell Scientific, Logan, UT, USA; 4 sensors per depth and treatment). Temperature at the soil surface was manually measured on each measurement day in diurnal cycles corresponding with the gas exchange measurements using temperature probes (GMH 2000, Greisinger electronic, Regenstauf, Germany). Volumetric soil water content (θ_v , 10hs, Decagon, Washington, USA) was measured in -5, -15, -30,
15 and -60 cm depth ~~was measured~~ on vegetation and bare soil plots at both sites and 60 min averages were stored in a data logger (CR1000, Campbell Scientific, Logan, UT, USA; 4 sensors per depth and treatment).

Living aboveground biomass of herbaceous plants was determined destructively on five randomly selected, 40 × 40 cm plots at the beginning and end of the experiment in the open and under the trees. All green fresh aboveground plant biomass was collected, divided by species, dried (60 °C, 48 hours) and weighed. Below ground biomass was sampled with soil cores in -5, -15, -30, and -60 cm depth. Oven dried soil was sieved and root biomass was determined gravimetrically. 80 % of root biomass was distributed between -5 to -15 cm depth. Only 5% was distributed above -5 cm and 15% between -20 to -35 cm depth. Total aboveground biomass was relatively low compared to previous years between 42 and 78 g m⁻² (see Fig. A1),
20 due to the considerable winter/spring drought in the hydrological year 2012 (Costa e Silva et al., 2015; Dubbert et al., 2014b; Piayda et al., 2014). While total aboveground biomass was similar between plots, species composition and relative dominance differed with the open sites being dominated by *Tuberaria guttata* and the tree sites by grass and legume species
25 (Dubbert et al., 2014b).

2.3 Cavity Ring-Down Spectrometer based gas-exchange flux and $\delta^{18}\text{O}$ measurements

Water fluxes and isotopic composition were measured with a Wavelength Scanned Cavity Ring-Down Spectrometer (WS-CRDS, Picarro, Santa Clara, USA) in combination with custom built soil chambers (following the design of Pape et al. (2009)) in an open gas exchange system (n=3 per treatment and experimental site). Background and sampling air were
30 measured alternately after stable values were reached. A five minutes interval average was used for the calculation of evapotranspiration (*ET*) and evaporation (*E*). ~~*ET*, *E* as well as total conductance (*g*)~~^{*ET* and *E*} were calculated according to von Caemmerer and Farquhar (1981). Oxygen isotope compositions of soil evaporation (bare soil plots) as well as

evapotranspiration of the understory (vegetation plots) were estimated using a mass balance approach (Dubbett et al., 2013; Dubbert et al., 2014c; Dubbert et al. (2014c)):

$$\delta_E = \frac{u_{out}w_{out}\delta_{out} - u_{in}w_{in}\delta_{in}}{u_{out}w_{out} - u_{in}w_{in}} \quad (1),$$

$$\delta_E = \frac{w_{out}\delta_{out} - w_{in}\delta_{in}}{w_{out} - w_{in}} - \frac{w_{in}w_{out}(\delta_{out} - \delta_{in})}{w_{out} - w_{in}} \quad (2),$$

where u is the flow rate [$\text{mol}(\text{air}) \text{ s}^{-1}$], w is the mole fraction [$\text{mol}(\text{H}_2\text{O}) \text{ mol}(\text{air})^{-1}$] and δ is isotope value of the incoming (in) and outgoing (out) air stream of the chamber. Flow rates are measured with humid air so that conservation of dry air gives $u_{in}(1-w_{in}) = u_{out}(1-w_{out})$, which leads to the second line of Eq. (2). The second term in Eq. (2) corrects for the increased gas flow in the chamber due to addition of water by transpiration. In addition to isotopic signatures of soil evaporation and understory evapotranspiration, the oxygen isotope signatures of ambient water vapor (in 9 m height) were measured with the CRDS. All measurements were conducted as diurnal courses with 5-6 measurement points between 7 a.m. and 7 p.m. For more details about the chamber design and measurement setup see Dubbert et al. (2013).

2.4 Sampling and measurement of $\delta^{18}\text{O}$ of soil and leaf water

Soil samples for water extraction and $\delta^{18}\text{O}$ analysis were taken on vegetated and bare soil plots using a soil corer. Samples were collected from the soil surface (0-0.5 cm depth), -2, -5, -10, -15, -20, and -40 cm soil depths ($n=4$ per depth and treatment) usually during midday, but on the day of irrigation directly proceeding the irrigation pulse and additionally at 18:00. Mixed leaf samples of the herbaceous vegetation for water extraction were obtained in daily cycles in 2-hourly steps from 8:00 to 18:00. Soil and leaf water samples were extracted on a custom build vacuum line by cryogenic distillation. Water $\delta^{18}\text{O}$ analysis was performed by headspace equilibration on an Isoprime IRMS (Elementar, Hanau, Germany) coupled via open split connection to a μ gas autosampler (Elementar, Hanau, Germany). Equilibration with 5% He gas was done for 24 hours at 20 °C. For every batch of 44 samples 3 different laboratory standards were analyzed. Laboratory standards were regularly calibrated against VSMOW, SLAP, and GISP water standards (IAEA, Vienna). Analytical precision was 0.1‰.

2.5 Partitioning of evapotranspiration

Oxygen isotope signatures of soil evaporation were calculated using the Craig and Gordon equation (Craig and Gordon, 1965; Dubbert et al., 2013; Haverd and Cuntz, 2010):

$$R_E = \frac{1}{\alpha_k \alpha^+ (1-h)} (R_e - \alpha^+ h R_a) \quad (23),$$

where R_E is the isotope ratio ($^{18}O/^{16}O$) of evaporated water vapor and R_e is the isotope ratio of bulk soil water at the evaporating sites. The evaporating site is the vapor-liquid interface below which liquid transport and above which vapor transport is dominant (Braud et al., 2005). It has been shown for unsaturated soils that this site is related to a strong enrichment in soil water isotopic composition relative to the rest of the soil column and an exponential depletion in isotopic signature within few cm of the underlying soil due to evaporative enrichment of the remaining liquid water (Dubbert et al., 2013; Haverd and Cuntz, 2010). Thus, for R_e and temperature at the evaporating sites (T_e), temperature and oxygen isotope signatures of bulk soil water were measured along the soil profile and those values along the soil profile were used where the strongest enrichment in bulk soil $\delta^{18}O$ could be detected (residual soil water volumetric content was only 1% and therefore neglected). R_a is the isotope ratio of ambient water vapor, α_k is the kinetic fractionation factor, α^+ is the water vapor equilibrium fractionation factor (α_k and $\alpha^+ > 1$; [see Majoube \(1971\); Merlivat \(1978\); for the formulation of \$\alpha_k = \alpha_{diff}^{nk}\$ \[see \\(Mathieu and Bariac, \\(1996\\)\\)\]\(#\), and \$h\$ is the relative humidity normalized to \$T_e\$. \$R_E\$ can then be transferred to delta notation as \$\delta = R_E - 1 * 1000\$.](#)

Although direct estimates of E and $\delta^{18}O_E$ were available for bare soil plots, vegetation depresses E and also influences $\delta^{18}O_E$, for example due to different isotopic signatures of soil water and also temperature at bare soil and vegetated soil patches (Dubbert et al., 2013). Therefore, bare soil plots only served to validate the Craig and Gordon equation, because on bare soil plots E contributes entirely to the evaporative flux and could be tested against modeling results. Finally, the Craig and Gordon equation was used to calculate $\delta^{18}O_E$ of vegetation plots.

The oxygen isotope signature of transpired water vapor $\delta^{18}O_T$ was calculated based on the isotopic signature of bulk leaf water $\delta^{18}O_L$ using the Craig and Gordon equation (Eq. 23) instead of measuring xylem/source water isotopic signatures and modeling $\delta^{18}O_L$ of leaf water at the evaporating sites due to the lack of suberized/lignified plant parts in the herbaceous vegetation. The isotopic signature on the evaporating site $\delta^{18}O_e$ was thus estimated by:

$$\delta^{18}O_e = \frac{\delta^{18}O_L \wp}{1 - e^{-\wp}} \text{ with the Péclet number } \wp = \frac{TL_{eff}}{CD} \quad (34),$$

where L_{eff} is the effective path length of water movement in the leaf mesophyll ($\delta^{18}O_L$ which we assumed to be 0.05 m), C is the molar water concentration ($55.6 \times 10^3 \text{ mol m}^{-3}$) and D is the tracer diffusivity in liquid water ($2.66 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$). T was estimated iteratively with equation (Eq. 45) using ET as initial value. Convergence was generally reached after five iterations. Small differences in isotopic compositions were found compared to a direct use of $\delta^{18}O_L$ in equation (Eq. 23), which were not significant for results shown throughout this work.

Finally, the contribution of T to ET , $ft = T/ET$, can be estimated based on measured understory $\delta^{18}O_{ET}$ and modeled soil $\delta^{18}O_E$ and herbaceous $\delta^{18}O_T$ ([Moreira et al. \(1997\); Yakir and Sternberg, 2000; Yakir and Sternberg \(2000\)](#)):

$$ft = \frac{\delta^{18}O_{ET} - \delta^{18}O_E}{\delta^{18}O_T - \delta^{18}O_E} \quad (45).$$

This approach is based on the assumption that the isotopic signature of evapotranspiration is a mixing ratio of not more than the two sources (evaporation and transpiration) and that no water vapor is lost other than by the mixing of the two sources with the atmospheric pool (i.e. no condensation).

2.6 Event water partitioning

- 5 Event water describes the amount of water in ecosystem pools or fluxes that originates from a certain rain event. To calculate the amount of event water in volumetric soil water content θ that originates from the isotopically labeled watering event, the following linear two-source mixing model was used:

$$f_{\theta, eve} = \frac{\delta^{18}O_{\theta} - \delta^{18}O_{\theta, pre}}{\delta^{18}O_{eve} - \delta^{18}O_{\theta, pre}} \quad (56),$$

- where $f_{\theta, eve}$ is the fraction of rain event water in θ at a certain time after the event, $\delta^{18}O_{\theta}$ is the stable isotope ratio in θ at a certain time after the event, $\delta^{18}O_{\theta, pre}$ is the stable isotope ratio of soil water before the rain event and $\delta^{18}O_{eve}$ is the stable isotope ratio of the precipitation event water. The model assumes no fractionation of rain event water during infiltration and was solved separately for each depth. Contributions of infiltrated event water to evaporation fluxes from soil and transpiration fluxes from plant surfaces were calculated analogously:

$$f_{E, eve} = \frac{\delta^{18}O_E - \delta^{18}O_{E, pre}}{\delta^{18}O_{E, eve} - \delta^{18}O_{E, pre}} \quad (67),$$

$$15 \quad f_{T, eve} = \frac{\delta^{18}O_T - \delta^{18}O_{T, pre}}{\delta^{18}O_{T, eve} - \delta^{18}O_{T, pre}} \quad (78),$$

- where $f_{E, eve}$ and $f_{T, eve}$ are the fractions of rain event water in evaporation E and transpiration T . $\delta^{18}O_{E, pre}$ and $\delta^{18}O_{E, eve}$ are the isotopic compositions of evaporation calculated with equation (Eq. 23) assuming that the source water isotopic composition equals either $\delta^{18}O_{\theta, pre}$ at the evaporative site or $\delta^{18}O_{eve}$, respectively. $\delta^{18}O_{T, pre}$ and $\delta^{18}O_{T, eve}$ are the isotopic compositions of transpiration calculated with equation (Eq. 23) and (Eq. 34) assuming that the source water isotopic composition equals either bulk leaf composition before watering $\delta^{18}O_{L, pre}$ or $\delta^{18}O_{eve}$, respectively.

2.7 Root water uptake

- The allocation preferential depth of root water uptake by plants along the soil depth was estimated via a linear three-source model. Therefore, the isotopic composition of transpiration $\delta^{18}O_T$ calculated with equation (Eq. 23 and 34) from three independent observations of leaf water compositions $\delta^{18}O_L$ were compared with three independent solutions for isotopic transpiration composition $\delta^{18}O_T$ of equation (Eq. 23), each assuming the current water source for transpiration originating only from an observed depth ($d1 = -5$ cm, $d2 = -15$ cm, $d3 = -30$ cm). Soil depths above and below $d1$ to $d3$ showed negligible root density in the profile and could therefore be excluded from the model. The three possible source fluxes are related to the resulting transpiration flux mixture via the following system of equations (compare e.g Philips et al. (2005)):

$$\delta^{18}O_{T1} = f_{T, d1} \cdot \delta^{18}O_{T1, d1} + f_{T, d2} \cdot \delta^{18}O_{T1, d2} + f_{T, d3} \cdot \delta^{18}O_{T1, d3} + \epsilon_1 \quad (89),$$

$$\delta^{18}O_{T2} = f_{T,d1} \cdot \delta^{18}O_{T2,d1} + f_{T,d2} \cdot \delta^{18}O_{T2,d2} + f_{T,d3} \cdot \delta^{18}O_{T2,d3} + \varepsilon_2$$

$$\delta^{18}O_{T3} = f_{T,d1} \cdot \delta^{18}O_{T3,d1} + f_{T,d2} \cdot \delta^{18}O_{T3,d2} + f_{T,d3} \cdot \delta^{18}O_{T3,d3} + \varepsilon_3$$

$$1 = f_{T,d1} + f_{T,d2} + f_{T,d3}$$

where $f_{T,d}$ denotes the fraction of source water contribution from depths $d1$ to $d3$ to the transpiration flux. The system was solved for $f_{T,d1}$ to $f_{T,d3}$ using a shuffled complex evolution algorithm (Duan et al., 1992) minimizing a multi-objective cost function (Duckstein, 1981) combining the error terms ε_1 to ε_3 for each time step.

2.8 Error propagation

All results are reported as replicate mean with associated standard error to achieve comparability between different sample sizes. All model calculations were applied to single replica and averaged afterwards. Observed effects were considered statistically different when no overlap of standard errors was observed.

3 Results

3.1 Environmental and soil conditions

Tree cover significantly influenced diurnal courses of incoming global radiation R_g during daytime on the sites. Strong reductions of R_g between 09:00 and 18:00 o'clock reduced daily sum of energy input $\sum R_g$ by 17.1 MJ m⁻²d⁻¹ on the open sites (os) compared to the tree sites (ts) (Fig. 1). However, air temperature and relative humidity was very similar in the open area and below trees with mean values around 66% and 19°C throughout the experiment. Similar to R_g , the amplitude of daily mean soil temperatures T_s in the upper soil layer were smaller on tree sites (bare: 7.4 °C, veg: 5.5 °C) than in the open area (bare: 14.9 °C, veg: and 11.3 °C for bare and vegetated soils, respectively, Fig. 1). In contrast, understory vegetation cover reduced the soil temperature only by 2-3.6 °C on both sites.

Soil moisture θ prior to the irrigation pulse ranged from 5 ~~to~~ 10% (Fig. 3), which is low compared to the annual average, but typical for the observation period at the end of May and the beginning of the dry season. Systematically, lower soil moisture θ at depths below 20 cm could be observed at the tree sites located close to trees compared to open sites, whereas the upper soil layers showed comparable values for all sites prior to the experiment.

3.2 Oxygen isotope signatures of ecosystem water pools

Stable oxygen isotope composition of soil water $\delta^{18}O_s$ for all plots and all depths ranged between -7.3‰ and 10.1‰ before the irrigation. Compared to the very depleted irrigation water signature of -139.5‰, only small enrichment in $\delta^{18}O_s$ of on average 0.4‰ in the open sites compared to the tree sites were found and 2.9‰ enrichment of bare soil compared to

vegetation plots preliminary to the watering (Fig. 2). Irrigation caused a strong depletion of $\delta^{18}O_S$ with a peak only 1 h after irrigation in the upper soil layer. ~~Lowest~~**Strongest depletion of** $\delta^{18}O_S$ values were found at tree sites on bare soil plots with $\delta^{18}O_S = -106.06\text{‰}$ and tree sites with vegetation cover with $\delta^{18}O_S = -85.1\text{‰}$ whereas the open sites showed weaker maximum depletions of $\delta^{18}O_S = -79.9\text{‰}$ and $\delta^{18}O_S = -49.4\text{‰}$ on bare soil and vegetation plots, respectively. The nine days following the irrigation event were characterized by a steady increase of $\delta^{18}O_S$, which was ~~only~~ slightly depleted compared to pre-event $\delta^{18}O_S$ nine days after irrigation. In addition to the absolute differences in peak $\delta^{18}O_S$ between sites, the depletion in $\delta^{18}O_S$ was maintained for a longer period at tree sites (Fig. 2).

Oxygen isotope signatures of soil evaporation and leaf water as well as transpired water vapour (Fig. 4) showed an immediate response to the irrigation pulse with peak depletion only 1 hour after labelling for soil evaporation and 3 hours for leaf water and transpired vapour. Subsequently, an exponential rise to pre-event isotope values could be observed in all pools. Depletion in $\delta^{18}O_E$ of soil evaporation was much stronger compared to $\delta^{18}O_T$ of plant transpiration (and leaf water $\delta^{18}O_L$). $\delta^{18}O_E$ of soil evaporation and evapotranspiration $\delta^{18}O_{ET}$ were both ~~significantly~~ more reduced on the tree sites compared to the open sites. A similarly strong vegetation effect could be seen between $\delta^{18}O_E$ on bare soil plots in comparison to understory vegetation plots.

3.3 Infiltration and distribution of event water

Daily mean soil moistures θ throughout the experiment were characterized by the ongoing drought at all sites (Fig. 3). Watering the plots with 20 mm increased mean daily soil moisture θ in the upper layers only by 2%_{vol.} to 6%_{vol.} and had no effect on deeper soil layers. However, partitioning event water fractions revealed an extensive replacement of old, pre-event water with new event water up to 4%_{vol.} and even down to depths below -30 cm (Fig. 3), in particular on bare soil plots. Systematically increased infiltration and deepened distribution of event water was observed on tree sites compared to open sites. In the course of the experiment, soil moistures returned to pre-event values and below. The decrease of event water was ~~here much~~ stronger than that of pre-event water, leaving nearly no trace nine days after the watering.

3.4 Event water use by ~~soil evaporation and~~ plant transpiration

While pre-event E on bare soil plots was lower than ET on vegetation plots on both the open and tree sites, E and ET equally peaked with roughly $3.3 \text{ mmol m}^{-2} \text{ d}^{-1}$ on the open sites. However, on the tree sites post-event peak of E at bare soil plots ($2.1 \pm 0.1 \text{ mmol m}^{-2} \text{ d}^{-1}$) was higher than ET at vegetation plots ($1.5 \pm 0.2 \text{ mmol m}^{-2} \text{ d}^{-1}$). Moreover, the peak of ET on both sites was shifted by 24 h compared to E and occurred only 2 days after irrigation (Fig. 5). Following peaks in E and ET , evapotranspiration losses declined exponentially to pre-event values 3 days after irrigation on all sites.

Partitioning ET on vegetation plots on both sites into soil E and plant transpiration T revealed that the time shift of the response of the ET flux compared to bare soil plots E was caused solely by a slower reaction of T to the irrigation pulse. Throughout the experiment the proportion of T to ET ranged from 9% to 59% on open sites and 17% to 66% on shaded sites.

Event water fraction in soil evaporation $f_{E, eve}$ and plant transpiration $f_{T, eve}$ differed considerably with T utilizing only a peak of 12% of the event water while E is fed up to 62% by event water following irrigation (Fig. 6). Nine days after the irrigation pulse event water contribution of T and E converged on average to 10% of the respective flux and differences between $f_{E, eve}$ and $f_{T, eve}$ faded. Event water ~~use of~~ lost by soil evaporation $f_{E, eve}$ showed no significant differences between open and tree sites nor between bare soil plots and vegetated plots except on the day of watering on the open vegetation plot. Here, $f_{E, eve}$ reached only about 25%, corresponding to the limited availability of event water in the soil (Fig. 2). ~~Along the lines of evaporation,~~ No significant differences could be observed between $f_{T, eve}$ on open and vegetation plots.

3.5 ~~Root~~ Preferential root water uptake ~~allocation~~ depth

Prior to the irrigation pulse we refrained from calculations of preferential root water uptake ~~allocation~~ depth, since the differences in $\delta^{18}O_S$ along soil depth were too small (see above) for a sufficiently accurate prediction power solving equation system (Eq. 89) and derive significant $f_{T, d}$. Following the label pulse, soil water uptake by plants was located solely at soil depths around -30 cm with no change in time or between open and tree sites despite a small uptake of water for transpiration from soil layers around -15 cm on day 0 and 1 after watering (Fig. 7).

4 Discussion

4.1 Infiltration and distribution of event water

Mosaic patterns of vegetation cover by understory plants and trees are characteristic for savannah-type ecosystems (Belsky, 1994; Greig-Smith, 1979). ~~–~~ Different vegetation cover is known to alter soil hydrological conditions and micro climate (Scholes and Archer, 1997) which in turn have effects on vegetation cover and ecosystem sustainability in future climate change scenarios (Breman and Kessler, 1999; Pueyo et al., 2012). Infiltration of event water into soil in this ecosystem is strongly altered by understory cover and tree shading. Vegetation cover of understory plants reduced infiltration on average by 24% compared to bare soil (Fig. 3). ~~3), which clearly contradicts part two of hypothesis I.~~ The reason can be found in interception, subject to instantaneous plant and litter surface evaporation before the first flux observations, which ~~was~~ took place one hour after watering. This water uptake limitation could neither be compensated by plant roots, breaking the crust formations which can be observed in the field and are common for Mediterranean soils, limiting hydraulic conductivity of top soils (Eldridge et al., 2010; Goldshleger et al., 2002; Maestre et al., 2002) nor by beneficial shading effects by the above ground biomass, which did not significantly reduce the soil surface temperatures ~~significantly~~ (Fig. 1) and thus, the evaporative demand of boundary layers. The observed infiltration on the day of watering can further be regarded as ~~unaffected~~ insignificantly affected by understory root water uptake confirmed by low transpiration fluxes on the day of watering (Fig. 5). ~~In~~ This is in contrast to previous studies, which ~~report~~ reported beneficial effects of plant cover on daily sums of infiltration ~~conducted year round in during~~ the ~~wet years~~ same period at the onset of drought in 2011 (Dubbert et al., 2014c). ~~This study is focused on the transition period between spring and the onset of summer drought, during the~~

~~exceptionally dry year 2012 with high atmospheric evapotranspirative demands intensifying interception losses. This unexpected turn in effect direction, which depends on plant cover and atmospheric evapotranspirative demand potentially plays a strong role for the water balance of the ecosystem in the course of the ongoing climate change scenarios (compare Fig. A1 and. However, (Dubbert et al. (2014b., 2014c), max. biomass $70 \pm 21 \text{ g m}^{-2}$ and 89 % cover in 2011 and 55 g m^{-2} biomass and 38 % cover in 2012), only observed precipitation events of light intensity during the period of interest. The present study reports on high intensity precipitation events. Furthermore, aboveground vegetation cover and biomass were reduced by 55 and 30 %, respectively, owing to the additional severe winter/spring drought in 2012. It is thus likely that such a drastic reduction in understory canopy cover eliminates much of the beneficial understory effects on the ecosystem water balance. This unexpected turn in effect direction with increasing precipitation intensity, which depends on vegetation cover and atmospheric evapotranspirative demand, potentially plays a strong role for the water balance of the ecosystem in the course of ongoing climate change scenarios since the occurrence of extreme precipitation events is expected to increase (IPCC, 2013).~~

Tree shading had a tremendous impact on the microclimate above understory plant and soil surfaces, but effects on infiltration amount could only be observed on vegetated plots. Reductions of the daily sum of global radiation $\sum R_g$ by 72% and daily peak soil temperatures $T_{S,5cm}$ up to 22% (Fig. 1) generated favorable conditions. Limited instantaneous evaporation from plant surfaces as described above led to 71% higher infiltration amounts (Fig. 3), whereas the ~~anyway~~-high infiltration amounts on bare soil plots were unaffected ~~by~~ tree shading. ~~This confirms part one of hypothesis III on vegetated plots.~~ Previous studies reported similar, positive feedbacks of tree cover for the hydrological cycle in savannah-type ecosystems, ~~which were not only~~ related to shading effects (Eldridge and Freudenberger, 2005) ~~but to the actual change of. Effects of altered~~ soil hydraulic properties beneath tree crowns, ~~like the amount of preferential flow fostering infiltration~~ (Bargués Tobella et al., 2014). ~~could not be identified in this study.~~ Supporting findings are given by (Bhark and Small, (2003) ~~and;~~ D'Odorico and Porporato, (2006). Considering the projected shading by crown cover of the tree layer (minimum of 30% at noon, increasing during the rest of the day, (Piayda et al. (., 2015)), ~~the infiltration enhancement has potentially large benefits on the ecosystem level. However, the impact of canopy interception losses in this ecosystem, potentially exceeding the infiltration), the infiltration enhancement has potentially large benefits on the ecosystem level. A former study of David et al. (2006) under comparable climatic and stand density conditions estimated only minor interception losses of 8% with respect to total canopy throughfall, due to low canopy cover typical for cork oak systems. However, the integral balance of canopy interception losses, increased infiltration and other~~ benefits of tree cover (compare Joffre and Rambal (1993) and Dubbert et al. (2014c)), ~~in this ecosystem~~ could not be analyzed in this study and needs further investigations with regard to tree density and age.

Subsurface distribution of soil water θ was systematically lower at depths below -20 cm at tree sites compared to open sites (Fig. 3). This clearly indicates the enhanced water extraction by tree roots ~~close to trees~~, similar to results of Dubbert et al. (2014b). The observed pattern could not be changed by the event water pulse of 20 mm per hour, equal to a rain event of ~~moderate~~high intensity on this site. That explains the intense drought stress understory plants suffer during the transition

period from moist spring to dry summer, leading to earlier dieback under tree cover (Dubbert et al., 2014b; Moreno, 2008); ~~and contradict part two of hypothesis III.~~ The depth distribution of event water is very similar on bare soil plots that show an ~~over-all~~ deeper infiltration of more water than the vegetated plots, caused by the higher infiltration amounts shown before. This ~~shortcoming~~ ~~negative effect~~ could partially be compensated by higher infiltration amounts below tree shading, but was consumed by tree water uptake from deeper depths within one day. During these dry conditions, pre-event water is located in small pores under high matrix potentials. Infiltrating event water partially displaced pre-event water downwards (Fig. 3) and additionally filled larger pores in the top soil. Thus, event water is more subject to evaporation due to lower matrix potentials in bigger pores than pre-event water. This observation is supported by a rapid decrease of event water content throughout the experiment.

4.2 Dynamic responses of event water-use and plasticity of water uptake depth

Successful biomass production of herbaceous vegetation highly depends on soil water availability in upper soil layers hosting the root system. Occasional precipitation events control the soil water regime (Porporato et al., 2004) which are prone to substantial changes in future climate change scenarios by stronger short term fluctuations of drought events (IPCC, 2013). Thus, a rapid adaptation of preferential root water uptake depth is crucial. This is particularly important for herbaceous vegetation in order to maximize the utilization of different soil water pools for a successful seed production, longevity and inter species competition (Ehleringer and Dawson, 1992; Rodriguez-Iturbe, 2000). It could be clearly shown that understory transpiration T responded slower to an incoming precipitation pulse than soil evaporation E , with a time lag of about 24h. ~~ET on vegetated plots and E on bare soil plots showed equally high peaks and a comparable decline until the end of the experiment, providing no evidence for higher water losses due to the presence of understory and contradicting part one of hypothesis I.~~ During the entire experiment, E was the dominant flux on both, tree and open sites, with a comparable contribution of transpiration T to evapotranspiration ET of 36% and 41% (Fig. 5), respectively. This small loss of ~~productivetranspiration~~ water originates on one hand from the longer time response lag of T . ~~On, on~~ the other hand ~~thatfrom~~ only little event water ~~reachesreaching~~ deeper soil layers, where understory plants have their main root water uptake depth ~~prior to the precipitation pulse~~. Event water use of the understory vegetation was overall low, since no shift of root water uptake depth could be observed within the nine days of the experiments (Fig. 7) leading to comparably small isotopic depletion of bulk leaf water and transpiration (Fig. ~~4)-4~~), ~~which supports hypothesis II.~~ This is in agreement with previous findings where annual savannah species were not fast enough readjusting their water extraction depth in order to exploit precipitation water more efficiently (Asbjornsen et al., 2008; Kulmatiski and Beard, 2013). More importantly, during that period of the year the dry conditions in the upper soil layers forces understory plants in the direct vicinity of trees to compete for soil water at lower depths where the trees have their roots (i.e. tree sites). This observation clearly opposes the widely discussed two-layer hypothesis, proposing independent ecological niches for root water uptake of trees and understory plants in savannahs in order to avoid competition (Hipondoka et al., 2003; Holdo and Planque, 2013; Kulmatiski et al., 2010; Walter et al., 1971). ~~Quite the contrary, previous findings of, e.g. Pryardarshini et al. (2015), suggest that tree-based soil~~

~~water redistribution by hydraulic lift (Dawson, 1993) is an important contribution in water limited ecosystems like savannahs. This is a possible explanation for understory root water uptake at the depth of the first tree roots, as we found it in our study.~~ Moreover, exponential soil profiles of plant available nitrogen causes a coupled water and nutrient competition between herbs and trees in this ecosystem during spring (Dubbert et al., ~~2014~~, 2014b). Modeling studies of e.g. Nippert et al. (2015) already suggested that understory plants do not exploit all accessible soil layers (including the top layers with high drought risk) in order to maximize water availability. Lower, but more resilient production is achieved instead by limiting root growth and water uptake to deeper depths, which could be confirmed by this study. It has to be additionally considered that the herbaceous vegetation already reached its growth peak when the experiment was conducted and thus maximizing root water uptake might not be a priority for the understory community past the growth peak and during seed production. Dubbert et al. (2014b) showed that the understory community is strongly adapted on a small spatial scale to the presence of oak trees regarding its species composition and overall vegetation period length. This is also observed in this study, with grasses dominating the understory community below the trees and forbs dominating in open areas. Effectively this leads to an earlier seed production and senescence of less drought tolerant grasses in water competition with trees and a longer vegetation period of drought tolerant native forbs (i.e. *Tuberaria guttata* or *Tolpis barbata*) in open areas. Consequently, while understory species in the open area remained a net sink for carbon during the entire experiment, the understory community below the trees was at the verge of senescence and turned into a net source for carbon at the last experimental date (Fig. A2), adding explanation to the site-specific differences of transpiration rate in response to event water (Fig. 5).

Recently, Volkmann et al. (2016a) used a similar flux / isotope approach to test the widespread dogma that plant water uptake depth is primarily controlled by root density distribution. While grassland species did not strongly alter their uptake pattern during the measurement campaign their water uptake depth profile was not in accordance with their root density distribution, with 85 % in the upper 10 cm of the soil profile. This clearly indicates that adapting the water uptake to soil water availability plays a role, but probably on longer time scales than what we observed during the 10 day's lasting experiment. ~~Therefore, the~~ The development of membrane-based *in-situ* methods of soil water (Gaj et al., 2015; Rothfuss et al., 2015; Volkmann et al., 2016a) ~~and~~ xylem sap sampling (Volkmann et al., 2016b) ~~will advance the studies of dynamic changes in eco-hydrological soil—and transpiration (Dubbert et al., 2014a; Dubbert et al., 2017) will advance the studies of dynamic changes in ecohydrological soil-~~vegetation feedbacks in the future. Furthermore, the coupling of isotope laser spectroscopes to gas-exchange chambers and soil or xylem equilibration probes overcomes the cost and time consuming classical destructive sampling methods. Recent studies (~~i.e.~~ (Orlowski et al., 2013)) showed significant isotopic deviations between actual soil water that is available for the plants and water that is cryogenically extracted from soil samples depending on soil ~~the~~ type. While we did not observe this in ~~the~~ sandy soils at our study site, these effects might severely hamper the usefulness of destructive soil sampling techniques in clay or loam soils. The newly developed in ~~—~~situ techniques will thus facilitate cost ~~—~~effective measurements of soil or xylem isotopic signatures with highest resolution,

enhancing our capacity to study the dynamics in soil water infiltration, in the uptake of water by plants and in the partitioning of evapotranspiration.

5 Conclusion

In this study, the various interactions between understory vegetation and trees of a Mediterranean cork —oak woodland affecting the ecosystem water flows could be ~~disentangled and~~ quantified. The immediate on-site determination (with CRDS) of the isotope ratios from different soil and ecosystem compartments in combination with in —situ sampling methods enhanced the resolution, precision and reliability of our results. This facilitated the tracing of the fate of rain pulse transitions through a typical Mediterranean savannah ecosystem using stable water isotopes.

~~Irrespective~~Regardless of the presence of vegetation ~~or just bare soil~~, the total evapotranspirative water loss of soil and understory remains unchanged. ~~Thus, but infiltration rates decreased by 24% (hypothesis I rejected). Still,~~ the amount of unproductive ~~water loss~~evaporation is largely reduced, in ~~favor~~favour of ~~biomass production, carbon sequestration and nitrogen fixation~~transpiration. Adjustments of main root water uptake depth to changing soil water availability after rain pulses could not be observed. ~~(hypothesis II supported)~~. Consequently the understory plants could not utilize ~~light to medium~~the applied precipitation. ~~Therefore of 20 mm. Hence,~~ these understory plants were forced into water competition with trees, rooting at deeper soil layers. ~~However, the understory plants could profit from tree root induced soil water redistribution. Cork~~Crown shading of cork oak trees ~~foster~~altered micro climatic conditions, thus fostering infiltration ~~to large degrees~~ and considerably ~~reduced~~reducing understory and soil evapotranspiration ~~by altered micro climatic conditions under tree crown shading (hypothesis III, part one supported)~~. Despite these benefits, understory plants in immediate vicinity of trees suffer from systematically lower soil moistures in deeper layers leading to premature senescence at the onset of drought. ~~Complex soil — plant — atmosphere and inter — species interactions could be successfully disentangled in both space and time. (hypothesis III, part two rejected).~~

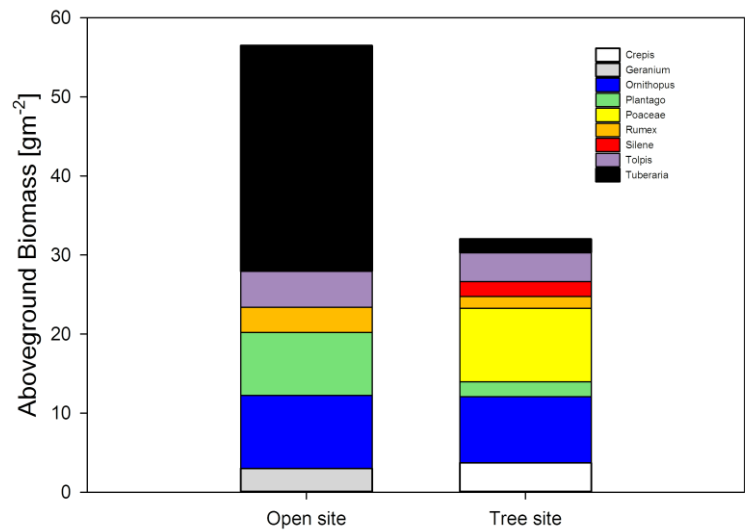


Figure A1: Aboveground biomass on vegetated plots during the experiment time given for each genus. Standard errors are not given for the sake of clarity, but amount on average 30% of displayed genus biomass.

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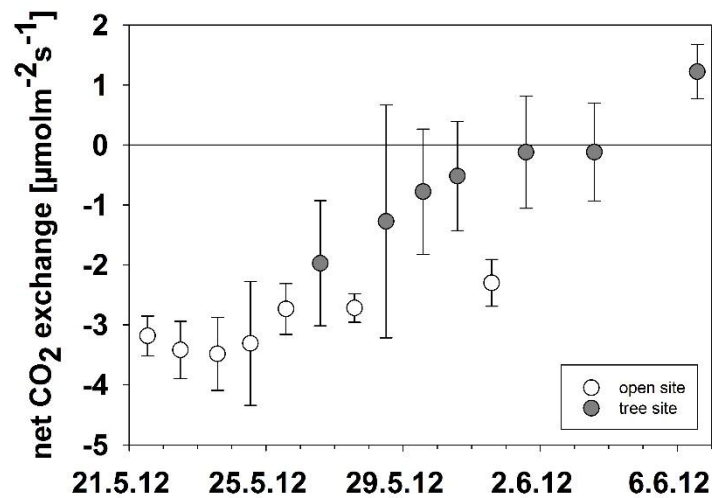


Figure A2: Mean midday net ecosystem exchange (NEE) of the understory vegetation at the open site (white circles) and the tree site (dark grey circles).

Author contribution

Arndt Piayda and Maren Dubbert contributed equally to experimental work, data analysis and writing the manuscript. Rolf Siegwolf proofread the manuscript. Matthias Cuntz contributed to data analysis and proofread the manuscript. Christiane Werner ~~contributed to field work and~~ proofread the manuscript.

5 Competing interests

The authors declare that they have no conflict of interest.

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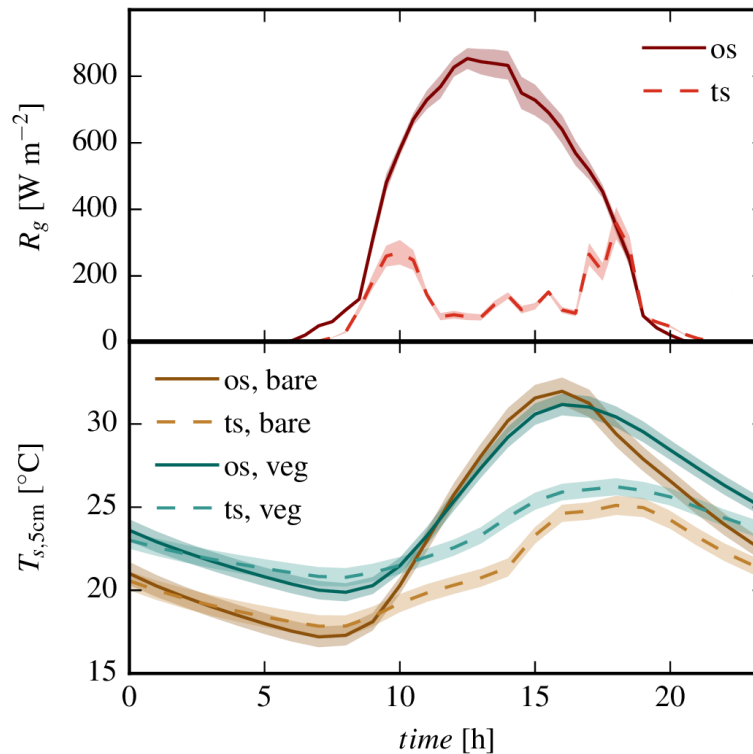
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15 **Figure 1: Daily cycles, averaged over the experiment period, of a) global radiation R_g in 1.5 m height and b) soil temperature $T_{s,5cm}$ in -5 cm depth under bare soil (bare) or vegetation cover (veg). Observations at open sites between tree crowns (os) and shaded sites beneath tree crowns (ts) are shown. Uncertainty bands display standard error.**

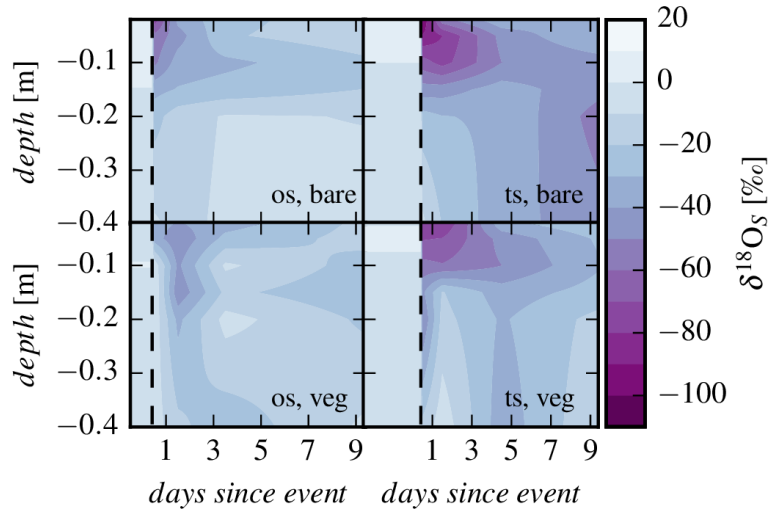


Figure 2: Mean daily isotopic composition of soil water $\delta^{18}O_s$ during experiment under bare soil (bare) or vegetation cover (veg) at open sites between tree crowns (os) and shaded sites beneath tree crowns (ts). Dashed lines mark time of watering event. Interpolation method: linear. The standard error for soil isotopic composition during the experiment amounts on average 1.4‰ in natural abundance.

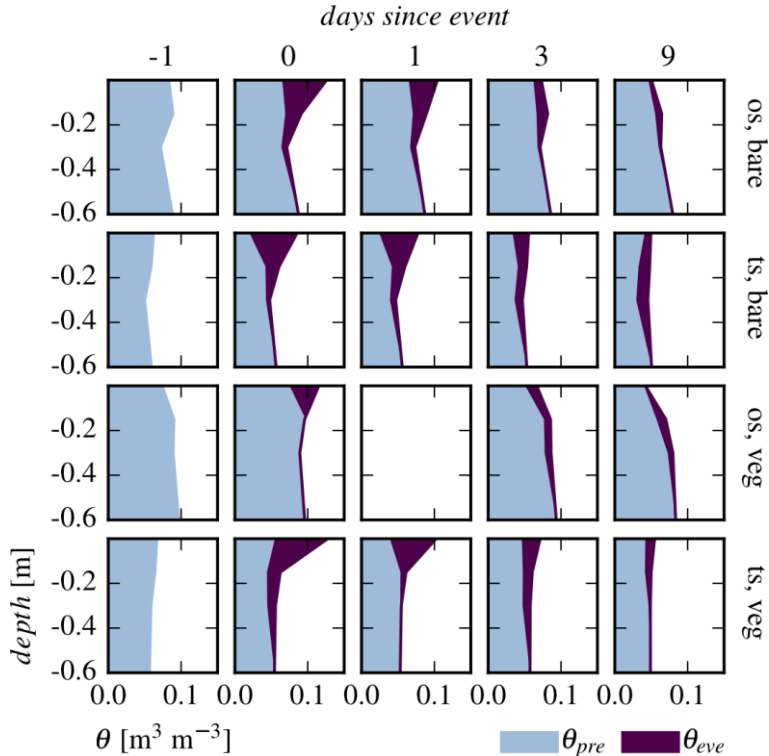


Figure 3: Mean daily soil water content θ along soil depth separated in pre-event soil water content θ_{pre} and infiltrated event soil water content θ_{eve} . Observations are displayed for plots under bare soil (bare) or vegetation cover (veg) at open sites between tree crowns (os) and shaded sites beneath tree crowns (ts). Numbers on top mark days since the watering event. Uncertainties for soil moisture observations during the experiment amount on average 2.3%_{vol.} propagated from the observations. Event water partitioning for day 1 on open, vegetated plots needed to be omitted due to insufficient field data quality.

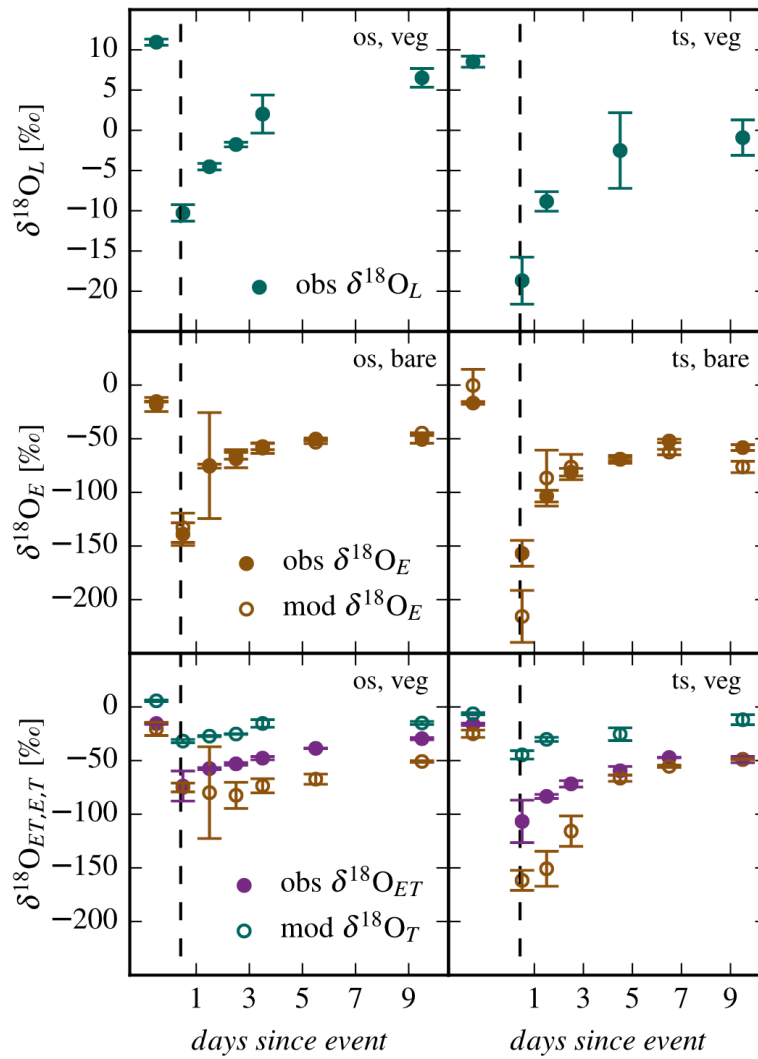


Figure 4: Mean daily isotopic composition of bulk leaf water $\delta^{18}\text{O}_L$, soil evaporation $\delta^{18}\text{O}_E$, plant transpiration $\delta^{18}\text{O}_T$ and combined evapotranspiration $\delta^{18}\text{O}_{ET}$ from bare soil (bare) or vegetation plots (veg) at open sites between tree crowns (os) and shaded sites beneath tree crowns (ts). Full dots represent observed values (obs), hollow dots represent modelled values (mod). Dashed lines mark time of watering event. Uncertainty bars display standard error.

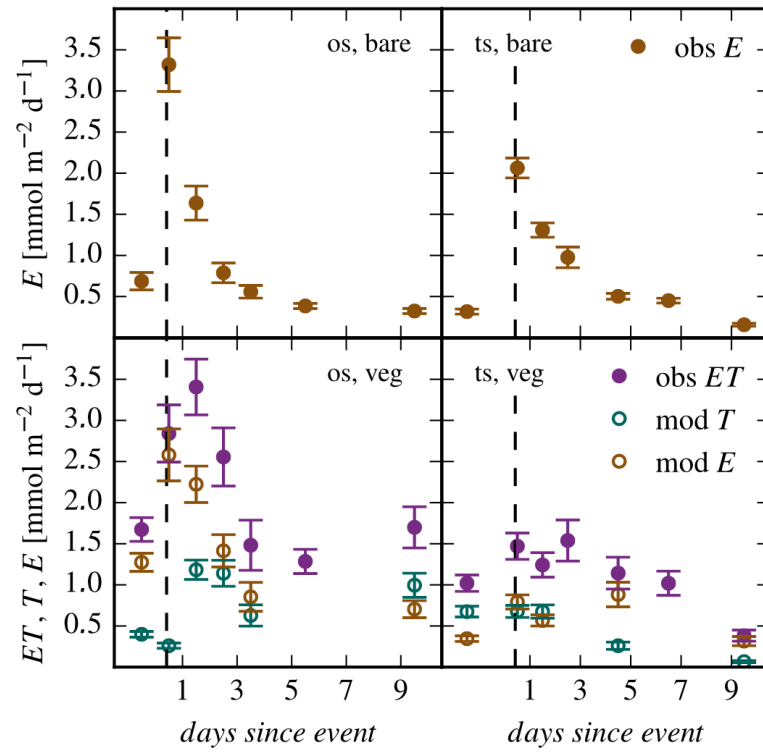


Figure 5: Mean daily flux rates of soil evaporation E , plant transpiration T and combined evapotranspiration ET from bare soil (bare) or vegetation plots (veg) at open sites between tree crowns (os) and shaded sites beneath tree crowns (ts). Full dots represent observed values (obs), hollow dots represent modelled values (mod). Dashed lines mark time of watering event. Uncertainty bars display standard error.

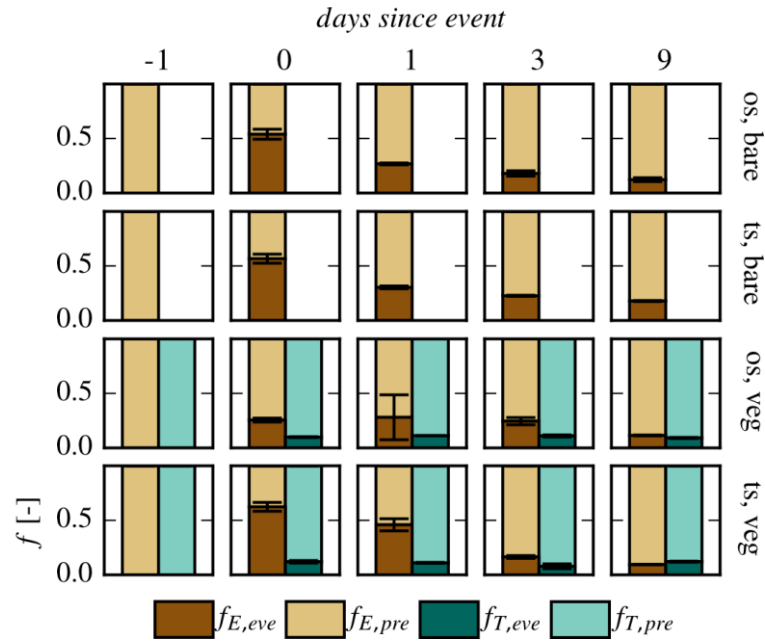


Figure 6: Mean daily fractions f of event water (*eve*) and pre-event water (*pre*) in soil evaporation E and plant transpiration T from bare soil (*bare*) or vegetation plots (*veg*) at open sites between tree crowns (*os*) and shaded sites beneath tree crowns (*ts*). Numbers on top mark days after watering event. Uncertainty bars display standard error.

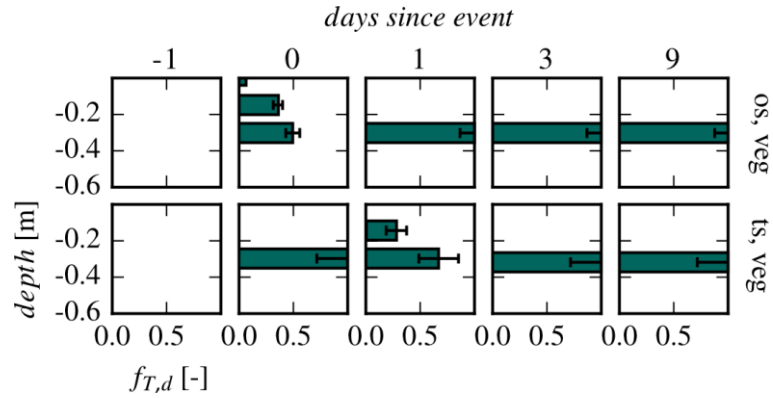


Figure 7: Mean daily fractions of root water uptake $f_{T,d}$ of understory plants for modelled soil depths. Numbers on top mark days after watering event. Uncertainty bars display standard error.