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Biogeosciences
Discussions

Interactive comment on "Spatially variable soil water repellency enhances soil respiration rates (CO_2 efflux)" *by* Emilia Urbanek and Stefan H. Doerr

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We are grateful to both reviewers for their detailed and constructive suggestions, which will allow us to further improve the manuscript. We are pleased to note that the reviewers share our view that the study is novel, interesting and timely. The questions raised on the relationship and respective roles of water repellency and soil moisture suggest that we have not made it sufficiently clear which effects we have directly determined and which are implied from the results and established knowledge about soil water repellency. This is an issue that we will clarify more specifically in the revised manuscript. We agree with most of the specific comments provided and will implement the suggested changes. The main issues raised are listed below marked with (R#1 or

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R#2) and our responses on how they will be addressed in the revised manuscript are marked with (#A). There are a couple of suggestions that we do not fully agree with and hope we have given a sufficiently thorough explanation for our reasons.

Referee #1 (R#1) (R#1) The most important concern I have with the manuscript is that due to the strong co-correlation between soil temperature, soil water content and SWR it is not clearly distinguishable whether the observed effects on CO2 efflux were due to temperature/soil moisture or SWR.

(#A) The referee's concern about a strong co-correlation between soil temperature, soil water content and SWR and the difficulty to distinguish between the individual effects on soil respiration is fully justified. Indeed we therefore do not claim that water repellency itself controls soil CO2 fluxes. Instead, we suggest that SWR, by controlling soil moisture distribution, will affect soil respiration mainly in relation to heterotrophic respiration. The appearance and nature of soil water repellency is influenced by moisture and temperature, but once present, water repellency will strongly influence infiltration patters and resulting soil water distribution, which in turn affects respiration. It is this effect that is investigated in this study for the first time under field conditions. The finding that respiration is highest for patchy water repellency (within a confined temperature class) is clearly an important outcome that might not have been expected based on previous insights from laboratory studies.

(#R1) (. . .) SWR was determined only for the topsoil while soil respiration arises from the whole soil

(#A) Soil CO2 flux indeed results from the respiration over the full depth profile, however, previous studies (e.g. Fang and Moncrieff, 2005) have shown that the majority of soil respiration, especially heterotrophic respiration, originates from the top soil where the organic matter content is higher and consequently the carbon sources for microorganisms are high. Given that at both sites organic carbon contend below 10cm depth is very low it is reasonable to expect that the majority of soil respiration comes from the top soil. Therefore focusing on soil moisture and SWR measurements within the top soil is sufficient for the purpose of this comparative study. We did measure soil water repellency at depth and on many occasions SWR was present up to 25cm depth, however, given their limited relevance for the study aims the results from the SWR depth distribution were not shown. Fang C, Moncrieff JB. 2005. The variation of soil microbial respiration with depth in relation to soil carbon composition. Plant and Soil, 268: 243-253. DOI: 10.1007/s11104-004-0278-4.

(#R1) There are several assumptions that are not justified based on the experimental findings of the study as well as inconsistencies in the discussion. It would certainly help to improve the manuscript if the results are treated and presented as being the outcome of a case study, meaning that a generalization of the observed effects is not necessarily possible.

(#A) We will go through the manuscript to improve consistency and make it clearer which findings are specific to this case study only and which can be reasonably expected to influence respiration in principle in soils affected water repellency elsewhere. Given that this is the first field study that examines the combined roles of water repellency, moisture and temperature in soil respiration, we feel it is important to the reader to highlight the potential wider implications of this case study. There is a substantial body of literature on water repellency and its effects on hydrology in soils from many regions around the world. From that it can be expected that the effect of water repellency on hydrological behaviour of most soils is fundamentally similar, but with the timing, duration and spatial extent of the effects being variable between different sites. In the revised manuscript we will make this clearer when discussing the results. This will include a statement that the magnitude of the hydrological effects on soil respiration will be site dependent therefore we suggest more studies to be done in the future to confirm the effect at other study sites.

(#R1) the title Title: The title states that spatially variable water repellency enhances soil respiration. This is not correct because it is not SWR itself but rather the (SWR-

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affected) soil water content (and temperature) that actually controls soil respiration. Replacing ‘enhances’ by ‘is associated with high’ would therefore be more appropriate. Moreover, using the term ‘spatially’ in the title is somewhat misleading as it suggests that the study was focused on the spatial distribution of SWR at the study sites. However, deriving conclusions about the spatial distribution of SWR is simply not possible based on the investigation of only six soil cores per site.

(#A) As highlighted already above, we agree that water repellency does not DIRECTLY enhance water repellency, but respectfully disagree that it is incorrect to state that water repellency enhances respiration. A key outcome of the study is the evidence it provides for the ability of water repellency to enhance respiration through its effects on moisture distribution in the soil. In a similar vein, many studies have shown that e.g. obesity reduces life expectancy even so it is its indirect effects on blood pressure and diabetes (and their own first order effects) that reduce life expectancy.

We have indeed not determined the specific spatial distribution of water repellency. This could have only been done by destructive sampling, which is not possible in the context of repeated efflux measurements. We do, however, feel we have provided sufficient evidence for the presence of spatially variable water repellency and its influence on soil water distribution based on repeated water repellency and soil moisture measurements at the study site as a whole and an understanding of the effects of water repellency on soil water distribution from previous studies.

We therefore feel the title is justified and hope the hypotheses and supporting evidence provided in this study will be sufficient to trigger studies by other teams that will test the validity of our findings for other environments in future studies

P1L7: Here, hydrophobicity is used as a synonym of soil water repellency. This is not correct because SWR covers the entire range of states where soil repels water, while hydrophobicity explicitly denotes a state where water is not able to penetrate the soil (often defined as having a soil-water contact angle above 90 degrees)

(#A) The term hydrophobicity it often used synonymous with water repellency in the soil literature depending on the specific definition used. We agree, however, that it simplifies the text and will use water repellency throughout the body text.

P1L18: The authors discuss preferential flow as a possible mechanism to explain their results. This is fine in the main text, however, as this was not proved in the study it is conjecture and should not be in the abstract.

(#A) We will amend the abstract to emphasise the effect of water distribution patchiness rather than preferential flow being responsible for the higher respiration effect.

P4L6: What is meant by 20-m transect here? Is 20 m the distance between the plots on the left and the plots on the right? If yes, then including a scale would certainly help the reader because it is not immediately intelligible from Fig. 1 that the plots are arranged along a transect.

(#A) Thank you for pointing this out. The figure will be amended with a scale to make this clear.

P7L18-20: Given the total number of measurement events (n = 16) I was wondering whether the removal of soil material approx. 10 cm away from the flux collars would not influence the moisture distribution and hence CO_2 efflux. Could you please comment on that?

(#A) We would not expect that the removal of soil samples has affected the soil moisture condition, as the holes after soil removal were filled out with a similar material from the site to avoid such effects.

P8L7-8: The determination of WDPT frequency distribution and the SWR distribution parameter was based on measurements carried out on material from 4 depths at 6 plots. While SWR distribution with depth could be reasonably described, this is clearly not possible for the horizontal distribution as the plots were located several meters away from each other, not allowing to draw meaningful conclusions regarding the spatial dependence and spatial structure of SWR. Moreover, considering that the material for the SWR determination was extracted at some distance from the flux collars, it seems very difficult to directly relate the measured CO2 fluxes to the measured SWR distribution

(#A) As mentioned before, we intended to determine the specific spatial distribution of water repellency at each measurement event and correlate it with the soil CO2 fluxes. This would ideally be done by destructive sampling, but this is not possible in the context of repeated efflux measurements. We therefore used the most viable alternative: repeated water repellency and soil moisture measurements at the study site as a whole. With these, and the established understanding of the effects of water repellency on soil water distribution from previous studies, we feel we have provided sufficient evidence for the presence of spatially variable water repellency and its influence on soil water distribution. The insights into SWR distribution are been based on 120 measurements per event and per site, which gives sufficient representation for SWR condition at the site.

P12L18: What is meant by ‘surrounding’? As the plots are several meters away from each other, it is not possible to draw any conclusion about the conditions of the surrounding soil (i.e. in close proximity)

(#A) We agree that using the term ‘surrounding’ is not sufficiently specific and will change it to ‘in close proximity’

P13, Figure 4: What is the rationale for using the standard error here (and in Figures 6, 7, 8 and Table 2)? Using the standard deviation (as in Table 1) is more appropriate to get an idea about the variation of the water content.

(#A) Standard error will be replaced by standard deviation in the Figures.

20L5: The authors assume that the SWR distribution parameter can be used as a proxy of heterogeneity in soil moisture distribution in the flux collars, however, the validity of this assumption was not proved in this study and seems highly questionable considering the points mentioned above.

(#A) SWR distribution presented in Fig 8 is a different presentation of results from Fig 4, which shows how variable the SWR was at each measurement event. SWR distribution was calculated from the percentage of the highest SWR persistence (>3600s) which represents the 'most extreme scenario' for SWR with expected lowest localised water contents and the thinnest water film on soil particles (according to Bachmann et al. 2008 and Derjaguin And Churaev, 1986, the more hydrophobic the soil, the thinner and more discontinued is the water film on soil particles). Soil with highest SWR distribution represents soils with similar SWR persistence for all investigated samples, while lower SWR distribution will represent soil of variable SWR persistence with patches of less and more water repellent and wettable soil. Based on the notion that higher SWR persistence will represent thinner and more discontinued water films we feel it is correct to use the SWR distribution as a proxy of heterogeneity of soil moisture distribution. We recognise that due to experimental constraints we can't refer the SWR distribution from adjacent soil sample directly with the soil flux collar therefore the combined results from all samples from each measurement event vs. mean CO_2 flux from all samples have been used to show how variable soil water contents can affect soil CO_2 fluxes in water repellent soils. We agree that the explanation given in this section of the manuscript were not sufficient and will therefore will amend the section to clarify better the rationale for calculating the SWR distribution and the meaning of it.

P20L8: The assumption that uniformly water repellent soil (SWR distribution = 1) is necessarily associated with homogeneously distributed low moisture content is not valid. This becomes immediately evident when considering that the calculation of this parameter is based on core material extracted from plots that were located several meters away from each other. Considering the dimension of the soil cores (5 cm diameter, 9 cm length) it becomes clear that the SWR distribution parameter is not representative of the site and not even representative of the individual plot. In other words, it is easily conceivable that the wetting properties and thus the moisture distribution of the surrounding soil is different from that measured for the soil cores

(#A) This issue is already addressed in the previous comment. We reiterate that we feel that SWR distribution is the most effective way of giving a reasonable representation of the overall heterogeneity of water repellency for each sampling event (see explanation for 20L5). Given that it was based on 120 measurements for each event (6 sites, 4 depths and 5 measurements) we are confident it provided a sufficiently representative and statistically robust sample set to provide a reasonable overall estimate of heterogeneity of water repellency at of the sampling dates.

P22L21-22: Such detailed statements regarding SWR distribution at the sites are not justified (see comments above).

(#A) See comment above. Events where soil was exposed to long dry spells had indeed resulted in very consistent results with all showing high (WDPT>1hr) water repellency, in contrast to other events where the results where more variable. We will, however, remove the statement ‘in the entire soil’ as, indeed, we haven’t measured the entire soil.

P23L3-5: Apart from the fact that spatial heterogeneity was actually not investigated in the present study (this is simply not possible by investigating only six soil cores per site) this statement is difficult to understand and in contrast to the assumption that SWR is the cause of preferential flow and a heterogeneous water distribution as stated, for instance, at P26L9-11. What is the authors’ opinion? Is spatial variability of SWR caused by a spatially uneven infiltration into the soil which, in turn, is affected by preferential flow, or is SWR itself the cause of an uneven water infiltration and preferential flow phenomena?

(#A) As explained before we intended to measure the spatial heterogeneity of SWR at each site and relate that to soil CO_2 fluxes. As it has been shown in many different studies, SWR causes the uneven infiltration after dry spells, enhanced preferential flow

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and can cause very patchy soil water distribution. We will clarify the message in the revised manuscript to avoid any confusion.

P23L10-12: The statement in this sentence is not clear (see comment above). It is not proper to state that the preferential flow paths caused by SWR resulted in a high spatial variability of SWR.

(#A) The work done previously on water repellent soil with presence of roots and stones (cited in the manuscript) has shown that water infiltrates into the macropores created by the 'obstacles' to move downwards leaving majority of the soil water repellent and only near the 'obstacles' switching of wettability takes place in a progressive way. Soil water distribution expands towards the soil matrix away from the preferential flow paths and wetting of more soil takes place. This could indeed not be monitored directly in the current study. However, based on previous work, this can reasonably be expected to take place in water repellent soils under field conditions. There is no reason to assume that our field sites would be exceptions from this behaviour.

P24L18-20: The statement in this sentence (high CO2 flux at high water content) is in contrast to the findings presented in Figure 7 and the conclusions and are not consistent with the 'model' resented.

(#A) Thank you for spotting this. That was a mistake indeed and it will be corrected accordingly.

P24L25: What is meant by 'severity of SWR'? Is it different from 'persistence of SWR'?

(#A) In this sentence we refer to the work of Goebel et al and Lemparter et al. who have measured soil water repellency by determining the contact angle of the soil. The measurement of contact angle between the soil and the liquid gives an indication of severity of SWR rather than water infiltration persistence. Several studies showed relatively good correlation between the severity and the persistence of SWR in different soils, but it is important to refer to the work methodology using the correct terminology.

P25L8-10: The use of ‘response’ is not justified in this context because it is not SWR itself but rather the SWC (influenced by SWR) that actually influences soil respiration. Using ‘associated’ would be more appropriate (‘... different CO_2 fluxes were associated with different patterns of SWR ...’).

(#A) We agree. The sentence will be corrected as suggested.

P25L11: Please check this sentence. What is meant by ‘... the more realistic effect of SWR ...’? (more realistic than ... ?).

(#A) The sentence will be corrected. Instead of ‘realistic effect’ we will use ‘representative’

P25L12: I have some issues with the ‘conceptual model’ presented in Figure 9. According to the model, wettable soil (Figure 9a) represents a condition where soil moisture is too high or soil temperature is too low for SWR to develop. The CO_2 efflux associated with this particular state was found to be low. However, it was not SWR that caused the low CO_2 efflux but rather the high water contents or the low temperatures (as was correctly stated by the authors). Hence, it is not justified to state that the model is accounting for the complex effect of SWR as both SWR and CO_2 efflux are simply co-correlated and controlled by soil moisture and soil temperature. In addition, Figure 9c, which represents the ‘water repellent state’ with uniformly water repellent soil suggests extremely low water contents (near zero) as compared to the other states. Apart from the general problem of relating the measured parameters in the present study (please see comment to P20L8), the results presented in Figure 4 show that this is not necessarily the case. As shown in Figure 4a, there was a transition from a uniformly water repellent soil (on 19/7/13) to a variably water repellent soil (on 29/8/13 and 8/10/13), while the corresponding water content remained fairly constant around 10 vol-%, which is far from being completely dry (as suggested in Figure 9c). There is also some ambiguity about the intermediate (variably water repellent) state illustrated in Fig. 9b. What do the authors really think? Is SWR the cause of an uneven water infiltration and causes preferential flow phenomena, or is it the spatially uneven infiltration into the soil which, in turn, is affected by preferential flow that causes the high spatial variability of SWR (as stated at P23L3-5)? Generally, the proposed 'model' would only be valid for the specific conditions of the sites investigated. For instance, it is well conceivable that a wettable soil is characterized by an intermediate water content (particularly in case of sandy soils). And the occurrence of such a situation is also possible in summer as shown in a study by Buczko et al. (2007, Ecological Engineering 31: 154–164). Under such conditions (i.e. intermediate water contents and high temperature) microbial activity and CO2 efflux can be expected to be high (and might be even higher than for variably water repellent soil). Overall, given the lack in general validity and explanatory power, using the term 'model' seems not appropriate, although the given explanations and the illustrations in Fig. 9 are valuable for understanding the observed effects on CO2 efflux at the investigated sites.

(#A) We have attempted to explain the concept of different hydrological conditions caused by presence of SWR and how this can affect soil respiration. In this concept (model) we are not representing the soils that are continuously wettable independent of the temperature and the moisture status, but soil which will turn water repellent when exposed to low soil moisture contents, usually also related to higher soil temperatures. In the model we show that soils prone to development of SWR will be wettable only when soil moisture is high and the temperatures are low and therefore it will be associated with low respiration rates, resulting from the temperature and high soil moisture effect. It is indeed the temperature and moisture effect on soil respiration rather than soil wettability on its own. We will clarify this paragraph to show the message more clearly. We will also amend the text and the Fig 9c graph to show that some residual water content can be present although it will be low and the connectivity between the pores will be severely disrupted which will result in low respiration rates. We agree with the reviewer that after frequent rainfall soils can become wettable during the summer at high temperatures (similar to Buczko at al. study). At the site it was observed especially during the 2014 summer where majority of soil was wettable, but despite high temperatures soil respiration was low see Fig5 & Fig4 for grassland. We understand that the findings of Buczko may suggest the respiration under hot and not moist conditions can be expected to be high, but the respiration rates have not been measured in that study, so it is the referee's speculations rather than demonstrated behaviour that the respiration rates were high in that case.

P26L16-19: Again, it is not reasonable to state that the intermediate state of SWR enhances soil respiration. It is indeed conceivable that CO2 efflux of a wettable soil, which is characterized by an intermediate and homogeneously distributed water content, is even higher than of a variable water repellent soil, provided that the temperature is high enough (see comment above and comments to P25L8-10 and the title)

(#A) We would like to stress again that we were studying soil prone to development of soil water repellency, which below a certain soil moisture content & above a certain temperature will become water repellent. We don't claim that variably water repellent soils will have higher respiration rates than wettable soil at the same moisture level, this is indeed not possible to examine with the current research design. We will amend the text to clarify the issue raised by the referee.

P29L10-19: The conclusions presented here are not justified (see comments above). (#A)The text will be amended accordingly with changes in the discussion.

(#A) All minor issues listed by the reviewer below will be addressed as suggested.

Other minor points: P1L12: SWR is introduced at P1L7 and should subsequently be used instead of 'soil water repellency' throughout the text. This should be checked carefully as there are many instances where 'soil water repellency' or 'water repellency' is used. P2L5-7: The statement that soil moisture controls pore-water connectivity is self-evident and should be removed. P3L4: SOC is introduced at P2L6 and should subsequently be used instead of 'soil organic C' throughout the text. P3L18: Please check the style of the sentence (..., which ....., which). P4L8: Please replace 'for' by 'at' (At each study site ..., and at each ...) P6, Table 1: Please replace 'for' by 'of' (Selected

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soil properties of samples ...) P7L6: Please replace 'for' by 'at' (At each study plot ...) and 'was' by 'were' (... soil collar were temporarily removed ...). P7L12: I would suggest to replace the sentence by: '... was determined by fitting an exponential function to the evolution of CO2 concentration over time ...'. P7L13-14: Please check the style of this sentence. In addition, could you please add information about the overall percentage of fittings with R2<0.95. P7L19: Can you please specify what is meant by 'further soil measurements'. P8L3: Was bulk density really determined after each field visit? P8L7-8: Could you please state how many replicate measurements per plot and depth were carried out. P8L18: Please check this sentence ('... to reduce oxides of N, CO2 and N2 were determined...') P8L20: 'distilled' or rather 'deionized' water? P8L22-23: Please use SWC instead of 'soil water content'. This should be checked carefully throughout the text. P9L2-3: Could you please state the post-hoc test used in conjunction with the ANOVA. P10, Figure 2: Please replace 'Air Temp' by 'Air temperature'. P11, Figure 3: Consistent labeling should be used ('Soil temperature', 'vol-%'). Please use either 'Sampling event' or 'Soil sampling' in the legend. Is it correct that Fig. 3a begins with June 2013 while Fig. 3b begins with July 2013? P12L6-7: Please use the same rank order for text and numbers (from low to high), i.e., '... slight to moderate (WDPT 6 to 600 s) ...' and '... slight to extreme SWR (WDPT 6 to >3600 s). P13, Figure 4: Please be consistent with the labeling used in Figure 3 (vol-%) and use the same labeling for a and b (either 'Soil sample collection date' or 'Sample collection date'). Please use site designations consistently throughout the text and figures. Cur- rently there are several variants, e.g., forest (T-f), forest site (T-f), Thetford-forest (T-f), etc. P14L10: Is 14âŮę C correct? Figure 6 shows the highest fluxes at the forest site to be around 16âŮę C. Is there any explanation for the large difference in temperature where the maximum CO2 fluxes were found? P17, Figure 7: Please insert '(âŮęC)' after 'Soil temp.'. 'temperature ranges' -> 'tempera- ture bands'. Please replace '... for SWC's grouped into 10% SWC ...' by '... for SWC grouped into classes of 10 vol-% ...'. P18, Table 2: The case '**p<0.01' does not appear in the table and should be removed. P19, Table 3: Using * for referring to the footnote is not appropriate here as * is also

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used in the interaction term 'SWC * Temp'. P19L18-21: This paragraph is not adequate in the Results section and should be moved to the Discussion. P21, Figure 8: Please insert '(âŮęC)' after 'Soil temp.'. Please use a consistent description of the temperature bands in Figure 8 and Figure 7 (P17). P22L6 and L15: These statements here are inconsistent ('SWR was present for most of spring, summer and autumn' vs. 'SWR was observed from early summer until late autumn'). P22L23: Please delete 'and' in this sentence to read: '... frequent change between sufficiently dry and wet periods, ...'. P22L24: Please change to '... which allows development ...'. P23L3: Please replace the comma by 'and' to read: '... higher than 2013 and 20% higher than 2015.'. P23L19: What is meant by C fluxes here? Referring to soil respiration would be suf- ficient here as no other C fluxes (e.g. transport of dissolved organic matter) were investigated in the present study. P24L13: The reference is lacking: what is meant by 'this forest type'? This needs to be specified. P24L16: Using 'but' in the context of this sentence is not appropriate. P25L5-7: Please check the style of this sentence ('... wettability conditions with uni- formly low (wettable) and high (extreme) water repellency ...' as well as '... when soil is dominated either by wettable soil ...'). P25L12: Please check this sentence ('Wettable soil ... represents a condition observed when a soil water repellency is absent...'). P29L6: Please add an 's' to read '... becomes severely ...'. P29L10: Please change to '... were indeed associated ...'.

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