Spatially variable soil water repellency enhances soil respiration rates (CO2 efflux)

Response to Referee comments.

5   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

10   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 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. _We include the marked up version of the revised manuscript at the end of response to referee comments.

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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
20   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,
25   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.

30   (#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

35   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

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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-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)

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(#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 CO_2 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 CO_2 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 CO2 flux from all samples have been used to show how variable soil water contents can affect soil CO2 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 CO2 fluxes. As it has been shown in many different studies, SWR causes the uneven infiltration after dry spells, enhanced preferential flow 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 CO2 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 CO2 efflux associated with this particular state was found to be low. However, it was not SWR that caused the low CO2 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 CO2 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

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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.

5 (#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,
10 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
15 (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.
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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)
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(#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.
30 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.

35 (#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
40 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).
45 P4L8: Please replace 'for' by 'at' (At each study site ..., and at each ...)
P6, Table 1: Please replace 'for' by 'of' (Selected 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
50 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 $R^2 < 0.95$.

P7L19: Can you please specify what is meant by 'further soil measurements'.

P8L3: Was bulk density really determined after each field visit?

5 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, CO_2 and N_2 were determined...')

P8L20: 'distilled' or rather 'deionized' water?

10 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

15 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).

20 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. Currently there are several variants, e.g., forest (T-f), forest site (T-f), Thetford-forest (T-f), etc.

25 P14L10: Is 14°

C correct? Figure 6 shows the highest fluxes at the forest site to be around 16°

C. Is there any explanation for the large difference in temperature where the maximum CO_2 fluxes were found?

30 P17, Figure 7: Please insert '(°C)' after 'Soil temp.'. 'temperature ranges' -> 'temperature 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

35 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 '(°C)' after 'Soil temp.'. Please use a consistent description of the temperature bands in Figure 8 and Figure 7 (P17).

40 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, ...'.

45 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 sufficient here as no other C fluxes (e.g. transport of dissolved organic matter) were

50 investigated in the present study.

Response to Referee #2

The authors present a lot of data, which I find overwhelming. In my opinion, the manuscript would benefit from focusing, especially of the results section. Data that are not crucial for the explanation could go into supplementary information. This would guaranty that it is not an information overflow.

(#A) The changes suggested by Referee 1 already go some to focus the manuscript and we will revise the text to ensure further tightening. We do, however, feel that the figures included in the manuscript are necessary to understand the complexity of the phenomenon. It is already clear from Reviewer 1's comments that we have not made it sufficiently clear what is demonstrated by the data and what is inferred. The figures assist in making this clearer. Given that Referee 1 appears happy with the number of figures and has suggested some alterations to them, indicates the value of maintaining the figures in the main text. We have only moved 1 figure to the supplement section.

The experimental setup as described in Figure 1 and Table 1: I have a hard time following why bracken and vegetated soil was measured, and also what the information on bare soil and vegetation soil was used for. E.g. Figure 4 presents data from which plots exactly? And Figure 5 displays forest and grassland plots in vegetated and bare plots but where are the bracken? Or is bracken vegetated? Please clarify which data were used when and why in a concise way.

(#A) We appreciate that the plot vegetation and surface bareness could be slightly confusing. First of all we have 2 sites: grassland and forest. Both sites have variable vegetation type cover (bracken and grass) which was thought important to be included in the study design given that the vegetation type may affect development of soil water repellency as well as soil respiration differently. As it can be seen on Figure1, 6 study plots have been established at each study site, plots with bracken and grass vegetation cover. To differentiate the CO_2 flux origin from accumulated litter and soil only, vegetation has been removed from one collar of each plot. The differences in SWR between bracken and grass were insignificant, therefore the results from all plots were analyzed jointly. After CO_2 flux measurement for bare soil, the soil cover has been put back on the soil surface to allow litter leaching into the soil and reduce enhanced drying of the soil. Given that the soil samples were collected from vegetated part of the plot we were able to correlate CO_2 flux and SWR distribution only from vegetated plots. We will clarify the text and the figures to better explain why soil under different vegetation were used for the study and which results represent joint and which the separate results from study plots.

- I think I miss an explanation why you chose to use temperature and soil moisture classes. It seems somewhat arbitrary at the moment.

(#A) Given that the measurements were conducted under field conditions the results of soil moisture and temperature had similar, but not exactly the same values it was necessary to group the results into the moisture and temperature classes. As with most classifications of environmental values, they are indeed essentially arbitrary, but facilitate comparison and interpretation of complex datasets. We will clarify this point in the revised manuscript.

- Figure 9: I understand the information in the figure and it seems a good explanation for the observed soil respiration patterns. Though, I assume the basis for this figure is the information on WTPT (Figure 4). But I don't understand how this information, which is based on WDPT tells you about flow paths. Please clarify

(#A) We like your suggestion to entitle the figure 'Theoretical framework of soil water distribution due to SWR and its effects on soil CO2 fluxes'. Referee#1 has also raised some questions about the conceptual model therefore we plan to amend this section and the figure to explain our understanding of effects of variable SWR and soil moisture distribution on soil CO2 flux. As pointed out by the Ref#1 we will refer to soil water distribution rather than preferential flow in the 9b figure and we aim to amend the figure accordingly. We will also make some corrections to 9c figure and description to better visualize the water films and soil moisture content in soil pores.

Figure 2 - This figure is really busy and the shadings in different directions and colours are overwhelming. Consider putting the rainfall data in a table. Or/and present the temperature curves as mean +/- standard deviation as they are following each other closely anyway.

(#A) We decided to follow your advise and move the figure to the supplementary section and provide the table with the full data.

Figure 3 - Suggest to move this graph to a supplement. I don't see a direct connection to the study other than that it presents the expected variation in soil moisture and soil temperature during the years.

(#A) We feel this figure is important and should remain in the main text as it shows important information for the reader about the measurement dates and puts them into a context with the moisture and temperature data. We will clarify this point in the text.

Figure 4 - Where are your error bars on the barplots? I assume it is the means of replicated samples?

(#A) Figure 4 represents the frequency distribution of all individual samples and replicates (not only averages) and therefore the use of the error bars is not applicable. The variability of the results between the samples is represented by different colors of the bar. This will be clarified in the caption.

Figure 5 - The presentation of soil respiration is challenging for the eye. Why not present boxplots? Picking out the means is very difficult in this way. Some sampling dates seem to miss the mean altogether. Same as with Figure 3, I think this information could go into a supplement.

(#A) We also feel this figure is important in and should remain, however, we would be happy to make the suggested changes to the graph and to present the mean values more clearly and clarify its relevance more specifically in the main text.

Figures 6 following - You could combine figures 6, 7 and 8 to one figure with 3 panels. For figure 6, did you use data from bare and vegetated plots? How did you combine the soil respiration data? For figure 7, did you pool the forest and grassland data? Figure

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8: how do you calculate the SWR distribution and what exactly does it mean? You
mention it on page 8 line 8 but it is not clear to me how you calculate the distribution.
(#A) Thank you for the suggestion to combine the 3 figures into one graph panel. We agree that this it is a good idea and will combine it in the revised manuscript. We will also clarify which data have been combined and how the SWR distribution was
5 calculated in the methodology section.

Figures 7 and 8: - Figure 7 shows soil moisture, Figure 8 shows SWR. To me, the information gained from both plots looks similar. What is the new information in Figure 8? I
think I don't understand why you recommend the measurement of SWR (which is much
10 more effort than SWC) if the same information can be gained from the measurement
of SWC.
(#A) Soil moisture is expected to be very variable in soils with variable soil water repellency and that could cause a different heterotrophic respiration due to the patchiness of soil moisture distribution. Moisture content is clearly a key driver, but given that trends associated with climatic changes may lead to increased severity of soil water repellency, it is necessary to
15 understand more fully what effect it will have on soil respiration. We feel this study makes an important first step in that direction, however, more studies in which water repellency is measured are needed to determine to what degree the patterns and implications highlighted in this study are applicable elsewhere.

(#A) The remaining and more specific suggested edits below will be addressed as recommended by the referee
20 Specific comments: - Page2 line2: the reference to Karhu et al is wrong. Karhu et al themselves cite the reference that you need here.
Page 20 line17: where do you document the significant results mentioned?
Page 22 lines 18-20: what could the biological controls be?
Page 23 lines 12-14: reference to Figure 4: I can't relate the information in this sentence to any information presented in
25 Figure 4, please clarify.
Figure 9: the title of the Figure is misleading: The figure does not show soil CO2 efflux responses. It rather shows a theoretical framework of soil water distribution due to SWR.

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~~Spatially variable soil water repellency enhances soil respiration rates (CO_2 efflux)~~

35 # CO_2 efflux from soils with seasonal water repellency

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Abstract. Soil CO_2 emissions are strongly dependent on pore water distribution ~~in soil pores~~, which in turn can be modified ~~; which in turn can be affected~~ by reduced wettability. ~~soil water repellency (SWR; hydrophobicity).~~ Many soils around the world are affected by soil water repellency (SWR), which causes ~~SWR restricts~~reduced infiltration and ~~movement~~results in

5 diverse moisture distribution. SWR is temporally variable and ~~the same~~ soils can change from wettable to ~~water repellent~~water-repellent and *vice versa* throughout the year ~~depending on water content.~~ ~~of water, affecting soil hydrology as well as biological and chemical processes.~~ Effects of SWR on soil carbon (C) dynamics and specifically on ~~soil respiration (~~CO_2 efflux~~)~~ have only been studied in a few laboratory experiments and~~,~~ hence ~~but they~~ remain poorly understood. Existing studies suggest ~~reduced~~ that ~~soil~~ soil respiration is reduced ~~is~~with increasing severity of SWR ~~reduced in water repellent soils~~, but the

10 responses of soil CO_2 efflux to varying water distribution created by SWR are not yet known.

Here we report on the first field-based study that tests whether SWR ~~soil water repellency~~ indeed reduces ~~s~~soil CO_2 efflux~~respiration~~, based on *in situ* field measurements carried out over three consecutive years at a grassland and pine forest site under the humid temperate climate of the UK.

Soil CO_2 efflux was indeed very low ~~reduced~~ on occasions when soil exhibited consistently high SWR and low soil moisture

15 following long dry spells. Low CO_2 efflux was also observed when SWR was absent, in early spring and late autumn when soil temperatures were low, but also in summer when SWR was diminished ~~disappeared~~~~SWC was high due to~~by frequent rainfall events. The highest CO_2 efflux~~es~~ occurred~~,~~ not when soil was wettable, but when SWR, and thus soil moisture, was spatially patchy, a pattern observed for the majority of the measurement period. ~~We expect suggest that p~~Patchiness of ~~y~~ SWR is likely to have created ~~represents~~ zones with two different ~~stinguished~~ functions related to CO_2 production and transport. ~~:~~

20 ~~z~~Zones with wettable soil or low persistence of SWR with higher proportion of water filled pores are expected to provide ~~have a concentrated supply of~~ water with higher ~~and~~ nutrient concentration~~s~~ for microbial activity resulting in ~~utrients and therefore~~ high CO_2 production. Soil ~~by microbial activity, adjacent~~ zones with high SWR persistence, on the other hand, a~~are~~ dominated by air filled pores with ~~with~~ low microbial activity, but facilitating ~~providing respiration which act~~optimal for ~~as a path for~~ O_2 supply and CO_2 exchange between the soil and the atmosphere.

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The ~~Despite Our study shows S~~strong co-correlation ~~exist~~ between the ~~e~~effects of soil moisture and SWR on soil CO_2 efflux

exhibit strong co-correlation, but the results of this study support the notion that ~~shown in our study we claim that~~ SWR

indirectly affects soil CO_2 efflux by affecting soil moisture distribution~~, proving therefore it is difficult to distinguish between~~

~~the individual effects governing soil respiration. Given that.~~ T~~-~~he ~~nature and~~ appearance of SWR is influenced by moisture

5   and temperature, but once ~~therefore once SWR is~~ present, SWR ~~it does~~ influences subsequent infiltration patterns and resulting

soil water distribution, which in turn affects respiration~~However, the highest respiration rates occurred not when SWR was~~

~~absent, but when SWR, and thus soil moisture, was spatially patchy, a pattern observed for the majority of the measurement~~

~~period. This somewhat surprising phenomenon can be explained by SWR.~~ ~~-induced preferential flow, directing water and~~

~~nutrients to microorganisms decomposing organic matter concentrated in 'hot spots' near preferential flow paths. Water~~

10   ~~repellent zones provide air filled pathways through the soil, which facilitate soil atmosphere O_2 and CO_2 exchanges.~~ This

study demonstrates that SWR can have ~~have~~ contrasting effects on CO_2 efflux. It can reduce it in dry soil zones by preventing

their re-wetting, but, at the field soil scale and ~~es and, ww~~when spatially-variable, it ~~,~~ can also enhance overall CO_2 efflux.

Spatial variability in SWR and associated soil moisture distribution therefore need~~s~~ to be considered when evaluating the

effects of SWR on soil C~~carbon~~ dynamics under current and predicted future climatic conditions.

15

1 Introduction

Soil is the most important reservoir of terrestrial carbon (C), storing four times more C than plant biomass (Stocker ~~Karhu~~ et

al., 201~~3~~4), but large amounts of C are released back to atmosphere mainly as carbon dioxide (CO_2) formed by microbial

20   decomposition of organic matter as well as biological activity of roots and microfauna (Bond-Lamberty and Thomson, 2010;

Rey, 2015). Soil moisture is one of the most important environmental factors regulating the production and transport of CO_2

in terrestrial ecosystems (Maier et al., 2011; Moyano et al., 2012). It influences not only soil organic C~~carbon~~ (SOC)

bioavailability and regulates access to oxygen (O_2) (Moyano et al., 2012; Yan et al., 2016)~~,~~ but also C ~~controls pore water~~

~~connectivity and therefore SOC~~ mass transport (Davidson et al., 2012).

25   Soil C models consider changes in soil moisture conditions, but they use functions that represent a~~n average~~ response of soil

respiration to average soil water content (SWC)~~moisture content~~ and do not account for within-soil moisture variability, which

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is a characteristic of most soils (Yan et al., 2016; Rodrigo et al., 1997; Moyano et al., 2013). Soils are typically very heterogeneous, with moisture distribution and water movement being variable and dependent on a number of factors (e.g. texture, structure, organic matter content) that determine soil hydrological properties. Soils prone to development of soil water repellency (SWR) are particularly susceptible to spatially highly variable soil moisture distribution and irregular wetting (Dekker and Ritsema, 1995; Doerr et al., 2000; Ritsema and Dekker, 2000~~:~~). SWR is a common feature of many soils worldwide, and is expected to become even more widespread and severe under a warming climate (Goebel et al., 2011). SWR affects soil-water relations by restricting infiltration, which results in large areas of soil remaining dry for long periods even after substantial rainfall events (Keizer et al., 2007). It often leads to enhanced preferential flow where water moves along pathways offered ~~not only~~ by cracks, root channels ~~and other types of macropores, but also~~ and zones of less repellent soil, leaving other areas completely dry for long periods (Urbanek et al., 2015). Irregular water infiltration

~~Preferential flow~~ in ~~water repellent~~water-repellent soil, ~~is~~ often ~~described as fingered flow where~~ creates a distinct zones with water filled pores, concentrated dissolved organic carbon and nutrients adjacent to ~~of vertical flow can be observed next to~~ dry regions with air-filled pores (Müller et al., 2014~~;Muller, reaching down to subsurface soil areas (Dekker and Ritsema, 2000;~~ Wallach and Jortzick, 2008; Urbanek and Shakesby, 2009). ~~Such a division of soil compartments into regions of preferential water flow can create zones of elevated biological activity and organisation into so-called 'hot spots' around the water flow channels where it is easier for microorganisms to access O₂, water and nutrients (Jasinska et al., 2006; Or et al., 2007; Morales et al., 2010).~~

Several studies have investigated microbial activity in water-repellent soils, mainly to determine whether the microbial exudates and proteins can cause the development of hydrophobic particle surfaces in soils (White et al., 2000; Feeney et al., 2006; Lozano et al., 2014). SWR has also been reported as an important factor in reducing soil microbial activity and it has been considered as one of the factors protecting soil organic C from microbial decomposition by separation of the microorganisms from their food and water source (Piccolo and Mbagwu, 1999; Piccolo et al., 1999; Bachmann et al., 2008). Goebel et al. (2007) demonstrated that SWR affects the distribution and continuity of the liquid phase in the soil matrix and therefore restricts the accessibility of SOM and the availability of water, O_2 and nutrients to the microorganisms. Using laboratory-based studies, they observed lower respiration rates from soils in a ~~water repellent~~water-repellent state and

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decreasing CO_2 ~~flux~~efflux with increasing severity of ~~water repellency~~SWR (Goebel et al., 2005; Goebel et al., 2007). In a review of this topic Goebel et al. (2011) highlighted the importance of SWR in organic matter decomposition especially during extreme climatic events such as drought, suggesting that it reduces the total soil CO_2 ~~flux~~efflux. ~~After inducing experimental droughts, Muhr et al. (2010, 2008) speculated that a slow regeneration of CO_2 fluxes observed following wetting could have~~

5   ~~been caused by SWR, however, they did not actually test for water repellencySWR.~~ The small number of existing laboratory-based studies suggest reduced soil respiration (i.e. CO_2 efflux) when soil is ~~water repellent~~water-repellent, but a thorough field study investigating ~~spatio~~-temporal changes in ~~water repellency~~SWR and their effect on soil CO_2 efflux, however, is still lacking.

The aim of the current study is, therefore, to investigate, for the first time, soil CO_2 ~~flux~~efflux response to SWR under

10   undisturbed *in-situ* conditions in the field. We test the hypothesis that the presence of ~~water repellency~~SWR reduces soil respiration also under 'real world' field conditions. The study sites selected were humid-temperate grassland and pine forest in the UK, which were anticipated to exhibit substantial temporal and spatial variability in SWR (Doerr et al., 2006), ~~which is~~ a common feature of ~~water repellent~~water-repellent soils in general (Doerr et al., 2000).

15   **2 Materials and methods**

2.1 Experimental design

A forest and a grassland site, both subject to humid-temperate conditions, were chosen because of their likely high susceptibility to develop seasonal SWR in view of their sandy texture and permanent vegetation cover, which are characteristics known to be conducive to SWR development (Doerr et al., 2000). Both study sites consisted of six plots with

20   adjacent grass and bracken cover, arranged along a 20-m transect (Fig. 1). The sites were monitored during the growing seasons in three consecutive years (2013-2015), involving continuous measurement of SWC~~soil moisture~~ and soil temperature, and recording of CO_2 ~~flux~~effluxes and persistence of SWR during site visits at approximately monthly intervals. At~~For~~ each study site twelve PVC collars for CO_2 measurements were installed, and at~~for~~ each vegetation plot the vegetation inside of one collar

was left intact and other had vegetation and litter layer temporarily removed for the duration of the CO_2 ~~flux~~efflux measurement to assess the contribution of different layers to total soil respiration.

Given the near-impossibility of finding wettable and water-repellent soils for comparison that otherwise display identical properties (e.g. texture, organic matter content, pH, litter type), we examined sites that displayed temporally variable behaviour, switching between water-repellent and wettable states of soil. This facilitated examining the impact of SWR~~water-repellency~~ on CO_2 ~~flux~~effluxes, bearing in mind that temperature and moisture themselves are known to affect SWR and CO_2 ~~flux~~effluxes. C and N contents as well as pH were determined on soil samples in the laboratory to be considered as potential factors for CO_2 efflux variability between plots and study sites.
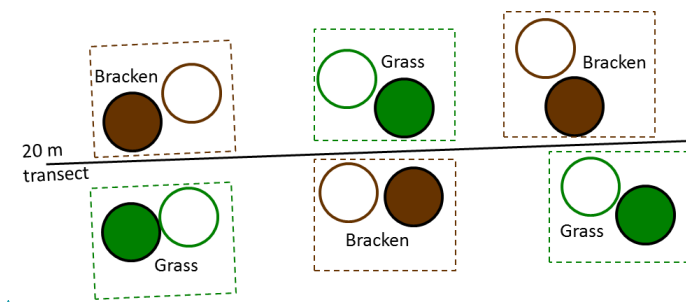

Figure 1: Schematic presentation of plots and CO_2 ~~flux~~efflux measurement collars at both, the forest (T-f) and grassland (T-g) study site arranged along a 20 m long transect. The dashed squares identify study plots (6) and circles - soil collars for CO_2 ~~flux~~efflux measurements (12), green coloured shapes represent soil surface vegetated with grass and brown – with bracken; closed circles represent vegetated area, open circles – bare soil with vegetation temporarily removed.

2.2 Study sites

The study sites are located in eastern England, approximately 8 km north-west (grassland site (T-g); 52°24'56.42"N 0°52'31.19"E) and 8 km east (forest site (T-f); 52°27'30.82"N 0°40'50.31"E) of Thetford. The sites are subject to humid-temperate conditions with an annual mean rainfall of 665 mm spread relatively uniformly throughout the year and an annual mean temperature of 14.5°C, with monthly mean maxima of 23°C in July and August and minima of 9°C in December and January (UK Met Office, 2017a). The site T-f is part of a long-term forest monitoring network established since 1995 aimed to assess the impact of the changing environment on forest and soil health (Vanguelova et al., 2010; Waldner et al., 2014; Jonard et al., 2015). Both sites have been planted with similar tree species, which were Scots Pine (88%), beech (6%) and oak (6%) (T-g in 1928 and T-f in 1967), but all trees at T-g were felled in 1999 and the site converted to a managed grassland. The dominant soil cover species at both sites are essentially the same with large areas covered by either grasses (*Holcus lanatus, Agrostis canina*) or bracken (*Pteridium aquilinum, Dryopteris dilatata*). At the site T-f, however, some moss (*Eurhynchium praelongum, Rhytidiadelphus sp.*) is also present at the soil surface (UK Forest Research, 2017a). The site T-f is subject to minimal management, a few trees having been removed during the winter/spring of 2014 near the monitoring site. At the site T-g, grass mowing is conducted twice a year to control tree seedling growth. The soil type at both study sites is Ferralic Arenosol with an approximately 3-cm thick litter layer at the T-f site, and 0-13 cm thick Ah horizon of organic rich sand with woody roots and occasional flints (UK Forest Research, 2017b). More information about the basic properties of the soils at the study sites is given in Table 1.

Table 1: Selected ~~soil~~ properties <u>of</u>~~for~~ <u>soil</u> samples (n=12) retrieved from the CO$_2$ efflux monitoring collars after the field campaign had been completed. See main text for further details.

Site	Soil depth (cm)	C content (%, mean (st.dev))		C:N (mean (st.dev))		pH (-)		Bulk density (g cm^{-3})	
		Bracken	Grass	Bracken	Grass	Bracken	Grass	Bracken	Grass
T-f	0-2.2	26.9 (12.1)	7.2 (6.1)	23.5 (2.0)	13.2 (6.3)	3.6	4.6	0.3	0.9
	2.2-4.5	8.3 (4.7)	2.4 (1.5)	16.3 (9.3)	9.7 (6.1)	3.7	5.2	0.7	1.2
	4.5-6.7	3.0 (2.4)	1.5 (0.8)	10.3 (2.7)	7.0 (3.4)	4.0	5.1	1.1	1.1
	6.7-9.2	1.2 (0.7)	1.6 (0.7)	6.6 (4.6)	7.2 (2.6)	4.1	5.2	1.3	1.3
T-g	0-2.2	24.3 (6.1)	20.0 (5.3)	23.1 (6.6)	20.4 (8.6)	2.9	3.1	0.5	0.7
	2.2-4.5	8.7 (4.4)	7.4 (5.2)	13.2 (8.3)	12.2 (6.0)	3.0	3.0	1.1	1.2
	4.5-6.7	3.3 (1.3)	3.0 (2.1)	10.5 (4.5)	7.9 (8.0)	3.0	3.1	1.2	1.3
	6.7-9.2	0.8 (0.1)	1.2 (0.2)	4.9 (1.7)	5.7 (2.8)	3.2	3.1	1.5	1.8

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2.3 *In situ* monitoring of soil CO_2 ~~flux~~effluxes, soil moisture and temperature

PVC collars (twelve per study site; Fig. 1) were inserted into the soil to enable CO_2 ~~flux~~efflux measurements to be made. The collars (20 cm diameter, 6 cm height) were inserted to a depth of 4 cm leaving the remaining 2 cm protruding above the surface. This minimal insertion depth (Heinemeyer et al., 2011) ensured that the collars remained in place allowing a sealed contact

5   with the chamber during the measurement, but minimised the ~~unnatural~~ isolation of soil and plant roots inside the collars from areas outside. ~~At~~For each study plot, the vegetation and the litter layers within one soil collar w~~as~~ere temporarily removed for the duration of the CO_2 ~~flux~~efflux measurements and carefully put back after to avoid increased soil evaporation, while vegetation in the other collar was left undisturbed.

CO_2 efflux~~fluxes~~ were measured using a Li 8100A Infrared Gas Analyser (IRGA) system with a 20-cm diameter dark chamber

10   (LiCor Inc, Lincoln, NE, USA) placed over the installed PVC collars for the time of the measurement. The change in CO_2 concentration in the chamber was monitored over 2 minutes starting at the ambient CO_2 concentration and repeated twice for each collar at 2-minute intervals. The CO_2 ~~flux~~efflux was determined by fitting an exponential function to the evolution of CO_2 concentration over time~~calculated based on the exponential fit of change in dry CO_2 concentration through time~~, excluding a 30-s initial phase at the start of the measurement. ~~The~~ CO_2 ~~flux~~efflux data where the function fitting R^2 was below value of

15   0.95 ~~results with exponential fit R^2<0.95~~ were excluded (less than 5% of overall measurements)~~not included~~.

During each CO_2 ~~flux~~efflux measurement, volumetric ~~soil water content (~~SWC~~)~~ was recorded with a Theta-Probe (ML3, Delta-T Devices) inserted at the soil surface up to 5cm depth next to PVC collar. Continuous monitoring of soil moisture and temperature at 5 and 10 cm depths at study plots was also conducted using soil sensors (5TM, Decagon Devices, Inc.) connected to a datalogger. During each field visit, intact soil samples were collected from each plot approx. 10 cm from the

20   CO_2 ~~flux~~efflux collars using PVC tubes (5 cm diameter, 9 cm height) to allow detailed measurements of SWC and wettability at each 2 cm depth interval ~~further soil measurements~~ under controlled laboratory conditions. In addition to this regular soil sampling, intact soil samples from within collars were also collected at the end of the measuring campaign to determine soil properties within the collar.

Meteorological data were obtained from the Santon Downham meteorological station located 500 m from the site T-g, while

25   a dedicated rain gauge for monitoring of precipitation was installed at the T-f site.

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2.4 Soil sample analysis

Soil samples collected during each field visit were kept sealed in a constant temperature room for 24 hrs, then split into 4 depths (0-2.2, 2.2-4.5, 4.5-6.7, 6-7-9.2 cm) to determine their SWR and SWC~~bulk density (dB), SWR and SWC~~. Wettability of soil was determined under field moist conditions using the WDPT test by applying 5 water drops (15 µl each) of tap water

5   to the soil surface of each sample and recording the time until their full infiltration (Doerr, 1998). 20 WDPT readings were~~have been~~ recorded for each sample, giving a total of 120 WDPT readings per measurement event. Based on the readings, WDPT frequency distribution per event were ~~have been~~ determined by separating WDPT data into ~~The median value of 5 drops for each sample was used to determine the wettability~~ "persistence" classes ~~-~~(Doerr, 1998), wettable (<5 s), slight- (6-60 s), moderate- (61-600 s), strong- (601-3600 s) and extreme- (>3600 s) ~~water repellency~~SWR. ~~The results were calculated and~~

10 ~~presented as WDPT frequency distribution (based on results from 6 plots & 4 depths).~~ In addition, for determining the response of CO_2 fluxes to SWR conditions, the results were grouped into the SWR distribution based on the proportion of samples falling into the extreme ~~water repellency~~SWR class per measuring event. WDPT class divisions are essentially arbitrary, but the division chosen here is based on the reasoning that presence of soil with the highest level of ~~water repellency~~SWR (i.e. extreme) has the most severe effect in terms of inhibiting water infiltration and resulting in ~~inducing preferential flow and thus~~

15 most diverse soil water distribution.

Water content of soil samples was determined gravimetrically by drying them at 105°C for 24 hrs and converting the weights into volumetric equivalents by incorporating soil bulk density values.

Total C and nitrogen (N) contents in the soil samples were determined using a PDZ Europa ANCA GSL Elemental Analyser coupled with a 20/20 isotope ratio mass spectrometer. Samples of dried, homogenised soil were weighed in ~~tin~~ tin foil~~foil~~

20 capsules and combusted over chromium oxide in helium with excess O_2 at 1000°C. The resulting gases were reacted over hot copper (600°C) and ~~to reduce oxides of N, CO₂ and N₂ were~~ quantified ~~determined~~ using the gas chromatography. Elemental composition and C:N ratios were calculated based upon peak areas relative to the standard reference materials acetanilide and atropine. Soil pH was determined after 1:5 dilutions in deionised~~distilled~~ water and measured with the pH electrode.

2.5 Data analysis

Statistical analyses of data were performed using SPSS 22. For purpose of some data analyses the results of SWC and ~~soil water content,~~ soil temperature ~~and soil water repellency~~SWR ~~distribution~~ have been grouped into bands representing a narrow range values (e.g. ~~of~~ ± 2°C temp or ±10% SWC each) in order to facilitate comparison and interpretation of the dataset (e.g. soil temperature within the 8°C band included values of 6.1-10 °C). Data were tested for normal distribution and homogeneity of variance, and data with non-normal distribution and/or unequal variances were transformed (square root, log) in order to carry out parametric analyses. A general linear model (linear mixed model) was used to identify key factors analysed that might be affecting soil CO_2 fluxes using a grouped results approach. For multiple comparisons, the ANOVA test and Tukey's post-hoc test was used to analyse significant differences. Significance of all test outcomes was accepted at p levels <0.05.

3 Results

3.1 Meteorological and soil conditions

The average annual temperatures and precipitation during the three years of the field monitoring campaign were very close to 30-year average (1961 to 1990; UK Met Office, 2017b). The average air temperatures between three years of monitoring were also similar but the precipitation patterns showed important variations (supplementary Table S1, ~~Fi~~Fig. S1~~2~~, S2). Contrasting rainfall patterns occurred during summer of 2013 and 2014 with the former showing exceptionally low and scarce rainfall, the latter high total precipitation with rainfall events occurring frequently throughout the season.

The temporal and seasonal changes in meteorological conditions directly influenced soil conditions. Soil temperatures responded closely to air temperature but, as would be expected, changes were buffered by the insulating effect of the soil especially in the forest environment where it was less cold in the winter and less warm in the summer in comparison to the air temperature (1/24°C; 4/19 °C minimum/maximum soil temperature at 5 cm depth at grassland and forest, respectively) (Fig. 2~~3~~). Weather conditions also resulted in drying and wetting of soil with the highest, relatively uniform water contents persisting from late autumn until early spring, contrasting with very variable water contents in spring and summer. At the forest site (T-f), especially in winter, the water content in top soil layer was distinctly higher than lower down, while at the grassland site (T-g) the differences between SWC at different depths were less pronounced. In summer, the responses to precipitation at

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different soil depths were variable: typically rainfall caused an immediate increase in SWC both in the upper and lower soil. On some occasions (e.g. T-g 8/2013, 5/2014), however, the response of SWC to rainfall at 10 cm depth was more pronounced than at 5 cm depth.
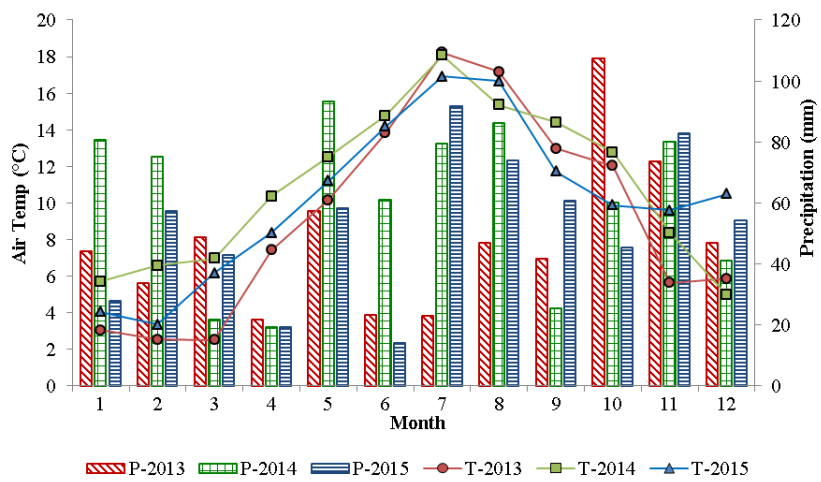
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Figure 2: Meteorological conditions at the study sites during 3 years of measurements (2013-2015) including average monthly air temperature (T) and total monthly precipitation (P). Differently coloured bars and symbols identify each year of the measurement.

a)

a)
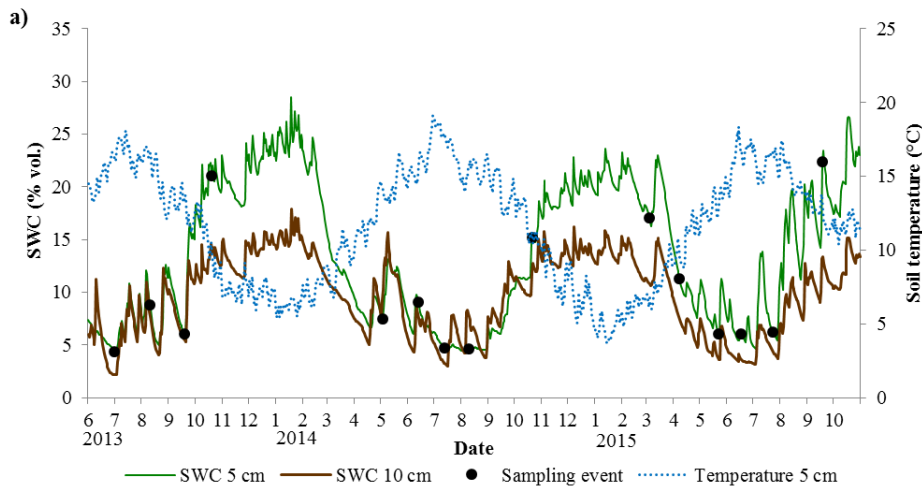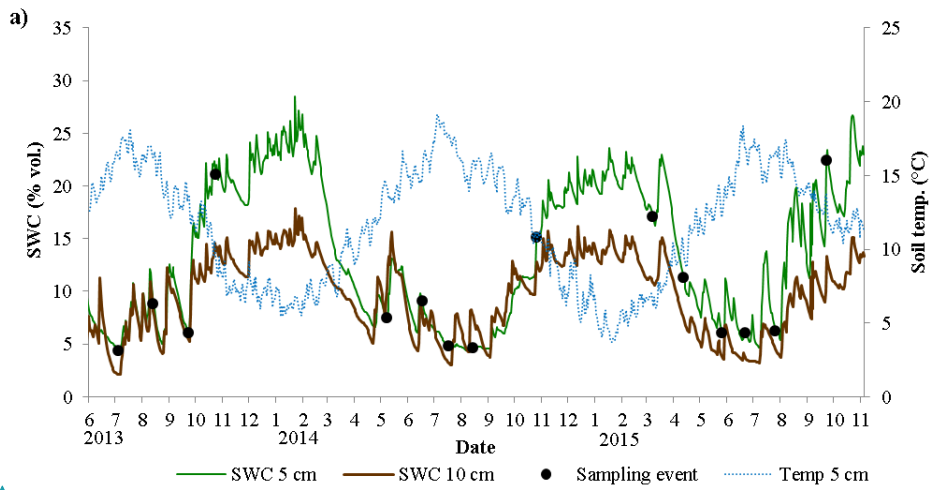
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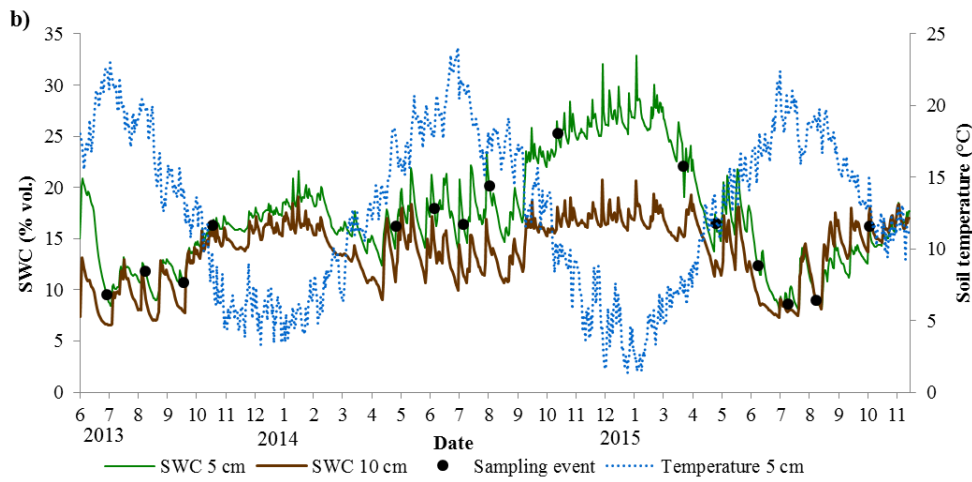
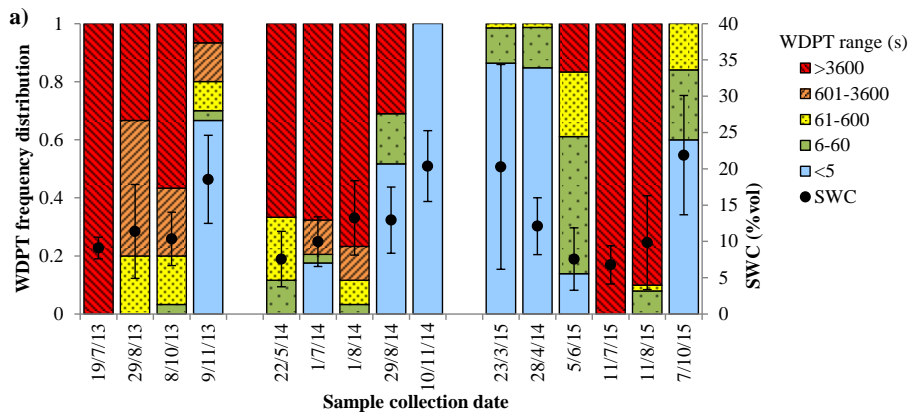Formatted: Left, Line spacing: single

b)

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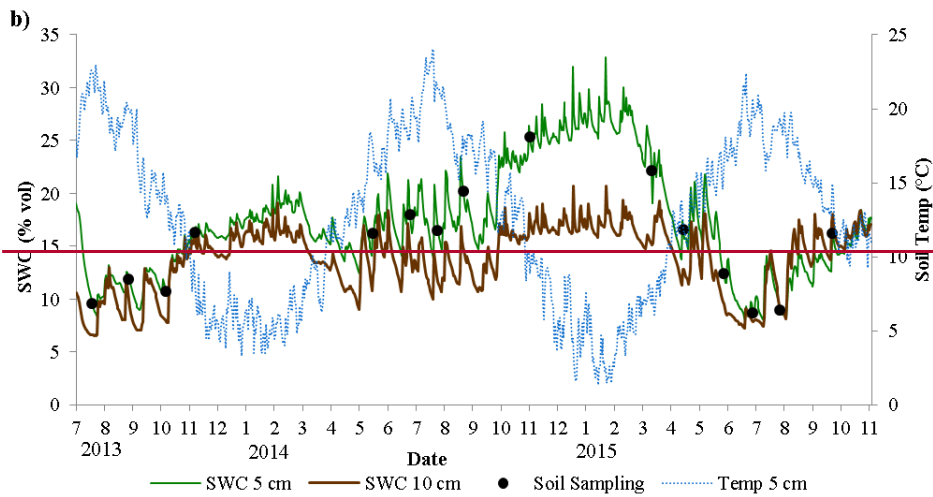
Figure 23: Temporal changes in soil temperature at 5 cm depth (—blue line) and soil moisture (—green line – SWC at 5 cm depth; —brown line – SWC at 10 cm depth) at both study sites over 3 years; a) Thetford-forest (T-f); and b) Thetford-grassland (T-g). Field measurements and sampling events are marked with black circles (•).
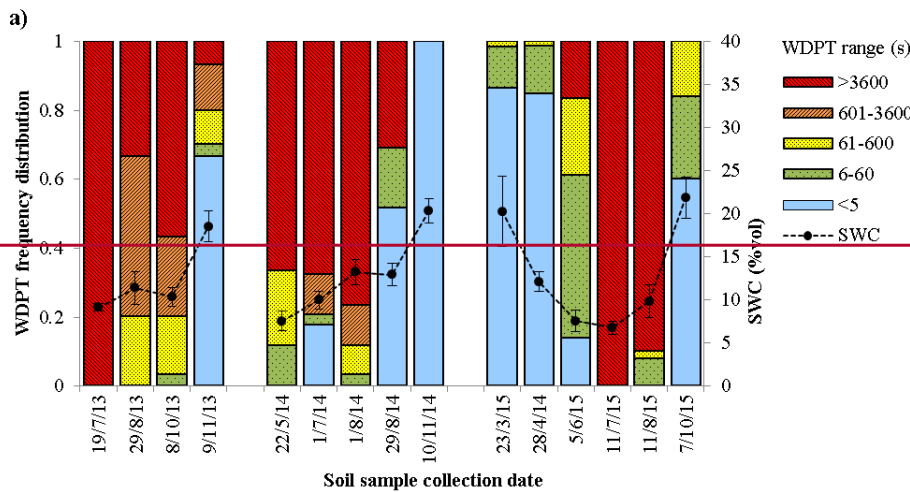
3.2 Seasonal changes in SWR

SWR occurred to some degree for the majority of the warmer months (May-October) followed by a change to wettable soil

conditions in the colder half of the year (November - April) (Fig. 34), however, this varied from year to year depending on

specific temperature and soil moisture conditions. During the warmer months of 2013 and 2015 when the total precipitation

5   was low, the majority of soil was water-repellent (WDPT >60 -s; moderate to extreme). In 2014, during a wetter and warmer

summer season, SWR was very spatially variable with parts of the soil remaining wettable (e.g. T-g 1/7/14), while the others

showed slight to moderate SWRto slight water repellency (WDPT 6-600 s) at site T-g and slight to extreme SWRto slight

water repellency (WDPT 6 - >3600s —6 s) at site T-f. Only on a few occasions during the whole measurement period (e.g.

19/7/13 for T-g and e.g. 1/8/14 for T-f) was soil uniformly extremely water- repellent (WDPT > 3600 s), which coincided with

10 long dry spells lasting at least two weeks prior to the measurements. For most sampling events, soils showed very high spatial

variability in wettability with samples exhibiting a full range of different WDPT values (0 - >3600 s) at each plot on at a given

sampling event.

The WDPT values corresponded well with SWC. Thus, for the majority of cases at lower SWCwater contents, higher WDPT

15 values were observed, but it was also notable that highly variable SWC values were measured when soils exhibited a range of
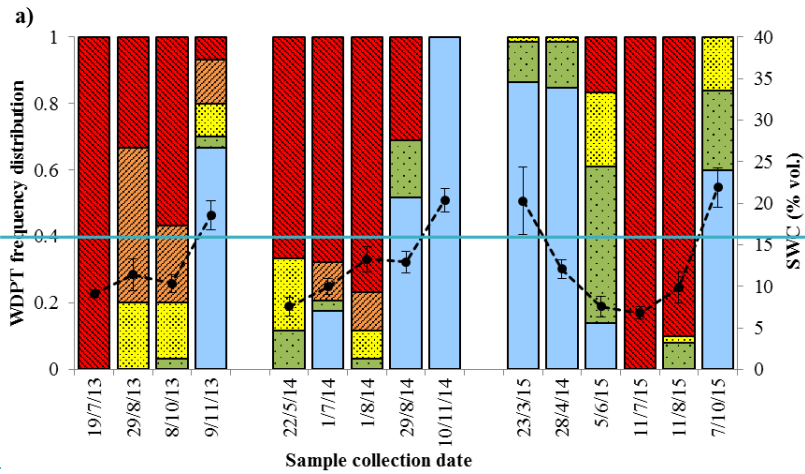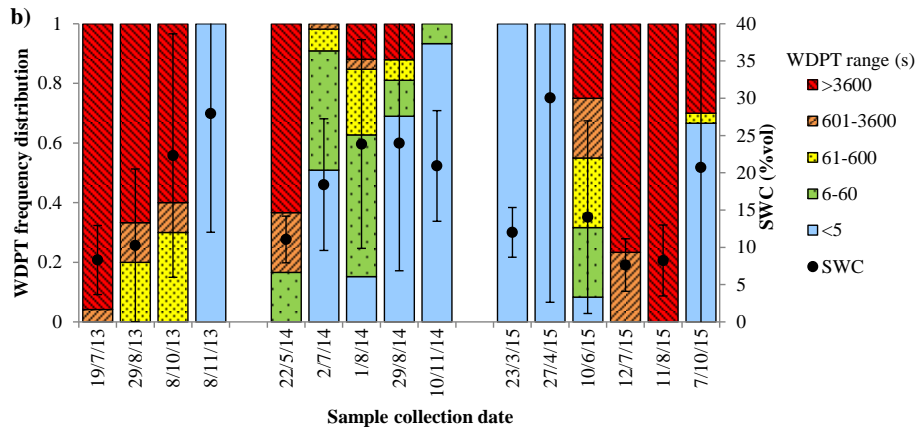
different WDPT levels.

Although the general pattern of SWR occurrence at both sites was relatively similar, soil at the forest site (T-f) showed overall

higher and spatially less variable WDPT values than at the grassland (T-g) site. Thus, soil at the former site showed more

frequent occurrence of extreme SWR (especially during 2014) and also a higher proportion of soil samples remaining water-

20 repellent when other samples on the surrounding soil waswere already wettable on the same sampling event (e.g. 9/11/13,

23/3/15, 28/4/15) (Fig. 34).

a)

a)

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b)

WDPT range (s)
- >3600
- 601-3600
- 61-600
- 6-60
- <5
- SWC

Sample collection date
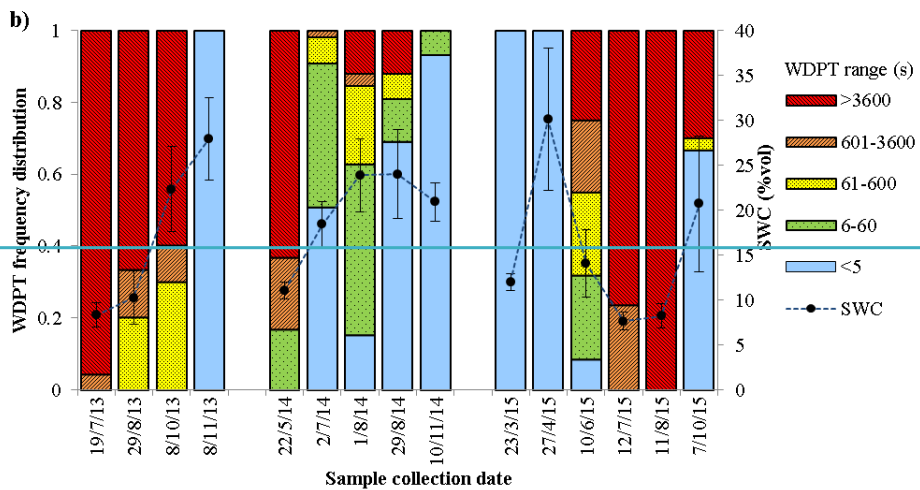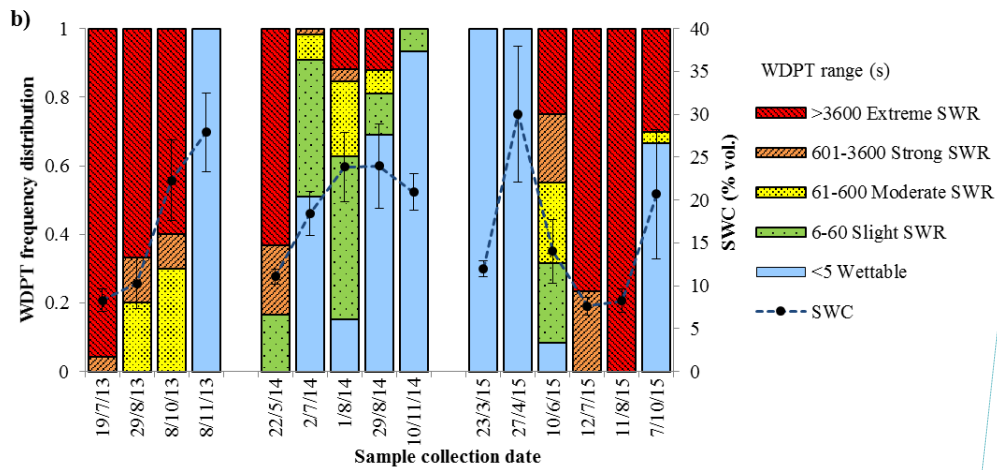
a)

Sample collection date

b)

Figure 43: Frequency distribution of SWR persistence (measured by WDPT) and soil water content (SWC) for both study sites at 0-9 cm depth at all sampling dates (a) forest (T-f) and (b) for grassland (T-g). Different colours reflect WDPT classes, black circles represent mean SWC and error bars the standard deviation error of the mean (n=24).
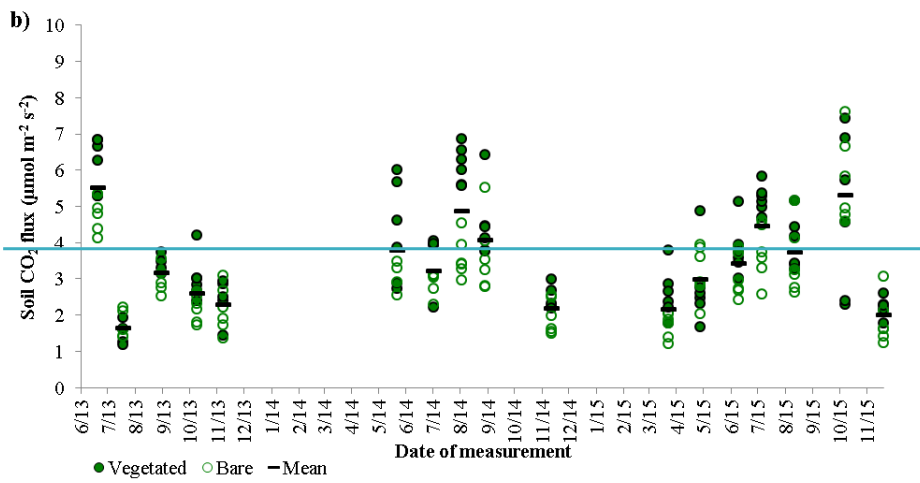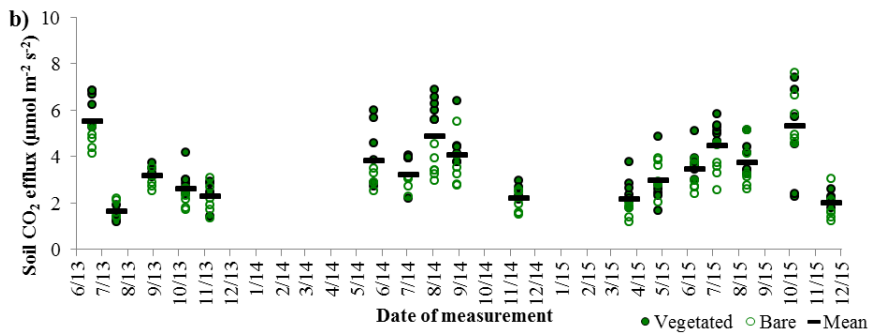
28

3.3 Seasonal variations in CO$_2$ fluxes

Measurements of CO$_2$ ~~flux~~effluxes showed high variability between sampling events, and between the warmer and cooler periods of each year. The lowest CO$_2$ efflux~~es~~ w~~as~~ere observed in early spring (e.g. 4/15, 5/15) and late autumn (11/14), but also on a few occasions during the summer (e.g. 7/13) (Fig. 45). The highest CO$_2$ efflux~~es~~ w~~as~~ere observed during spring and summer, which also corresponded with the highest spatial variability in efflux~~es~~ values between samples. Bare soil plots showed significantly lower CO$_2$ efflux than plots with vegetation and litter covers at the T-f site, but not at the T-g site (Table 2).

A clear division in soil CO$_2$ ~~flux~~effluxes between warmer and cooler periods was observed at both study sites, highlighting soil temperature as a major factor influencing soil CO$_2$ efflux~~es~~ (Fig. 5a6). CO$_2$ efflux values ~~fluxes~~ remained low up to 10 or 12 °C and increased with rising temperature above these. Beyond a maximum around 164 °C at the forest (T-f) site and 20 °C at the grassland (T-g), however, a reduction in CO$_2$ ~~flux~~efflux was observed, with the maximum efflux being higher at the former.

The other important factor affecting soil CO$_2$ efflux~~es~~ was soil moisture (Fig. 5b7) which, together with soil temperature, can explain overall 61% of total variations in soil CO$_2$ ~~flux~~efflux. By considering these two factors (soil temperature and soil moisture) together it was clear that especially at higher temperatures (16-20 °C), low soil moisture (SWC <20 %) can be the limiting factor and lead to reduced soil respiration. When SWC increased, soil CO$_2$ ~~flux~~efflux was also higher, but reduced again at high SWC values. At low soil temperatures (i.e. the 8 °C temperature band), soil moisture showed a very limited effect and soil CO$_2$ ~~flux~~effluxes remained low irrespective of SWC.

A high variability of CO$_2$ ~~flux~~efflux responses was observed even for similar mean ~~soil water content~~SWCs and the addition of other factors in the general model (e.g. study site, type of vegetation; Table 3) only slightly improved explanation of the overall variability in CO$_2$ ~~flux~~efflux~~es~~ (R^2=0.68).

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a)

Soil CO_2 flux ($\mu mol\ m^{-2} s^{-2}$)

Date of measurement

● Vegetated   ○ Bare   ─ Mean

Soil CO_2 efflux ($\mu mol\ m^{-2} s^{-2}$)

Date of measurement

● Vegetated   ○ Bare   ─ Mean

b)

b)

Figure 54: Variations in soil CO_2 effluxfluxes for each measurement event for vegetated (● filled circles) and bare (○ open circles) plots at
both study sites; (a) forest T-f and (b) grassland T-g with both bracken and grass plots.
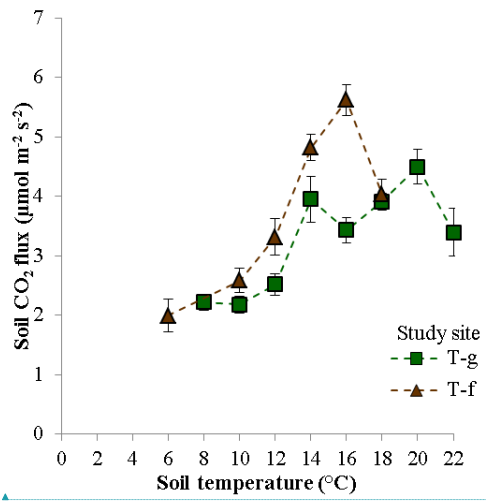
Figure 6: Relationship between soil CO_2 flux and soil temperature for the forest (T-f) and grassland (T-g) sites. Soil CO_2 fluxes are represented as means (with standard errors) for soil temperature grouped into 2 °C classes (±1 °C).

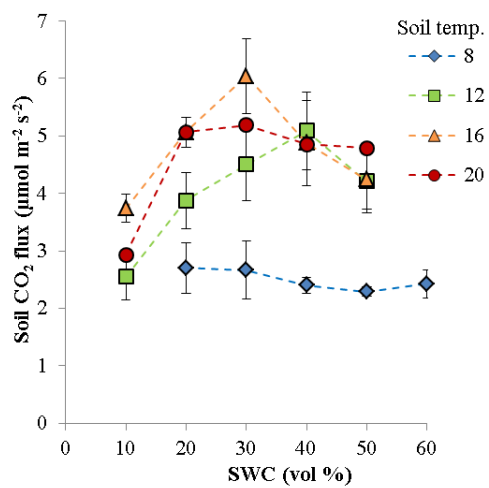**Figure 7:** Relationship between soil CO$_2$ flux and soil water content (SWC) for the forest (T-f) and grassland (T-g) sites for different soil temperature ranges. Soil CO$_2$ fluxes are represented as means (with standard errors) for SWC's grouped into 10 % SWC. Different colours and symbols represent results grouped into 4 soil temperatures bands 8: 6.1-10 °C; 12: 10.1-14 °C, 16:14.1-18 °C and 20: 18.1-22 °C.
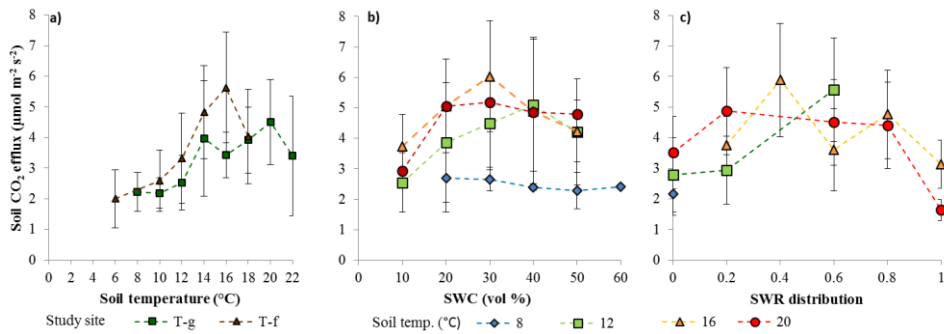
Figure 65: Relationship between soil CO_2 efflux and a) soil temperature, b) SWC and c) SWR distribution. In ~At figure 5a results are separated for the forest (T-f) and grassland (T-g) sites. Soil CO_2 fluxes are represented as means (with standard deviationerrors) for soil temperature grouped into 2 °C classes (±1 °C). b) soil water content (SWC) for the forest (T-f) and grassland (T-g) sites combined for different soil temperature ranges. Soil CO_2 fluxes are represented as means (with standard deviations) for SWC's grouped into classes of 10 vol.-%. Different colours and symbols represent results grouped into 4 soil temperatures classes of 2 °C. c) SWR distribution (0=wettable, 1=uniformly extreme SWR) for different soil temperature classes the same as in fig 5b. Soil CO_2 fluxes are represented as means (with standard deviation) for SWR distribution grouped within ±0.2.

Table 2: Total average CO_2 fluxes ($\mu mol/m^2/s^2$) from plots under bracken and grass understorey with vegetated and bare plots at the forest (T-f) and grassland (T-g) study sites. The asterisks indicate the statistically significant differences between groups of vegetated and bare plots (*$p<0.05$, **$p<0.01$, ***$p<0.001$).

Study site	Vegetation type	Vegetated plots mean(st.err)	Bare plots mean(st.err)
	Bracken	4.57(0.28)	3.02(0.18) *
T-f	Grass	5.14(0.28)	3.93(0.27) *
	all	4.86(0.20)***	3.57(0.16) ***
	Bracken	3.61(0.23)	3.12(0.15)
T-g	Grass	4.04(0.22)	2.96(0.21)
	all	3.82(0.16)***	3.04(0.13) ***

5

Table 3: Factors affecting soil CO_2 fluxes including the statistical significance level.

Source	Type III sum of Squares	df	Mean square	F	Significance level
Corrected model for sqrt CO_2 flux	23.11[a]	64	0.36	3.96	0.000
Intercept	24.43	1	24.43	267.72	0.000
SWC * Temp	19.85	62	0.35	3.51	0.000
Study Site	1.56	1	1.56	17.09	0.000
Vegetation type	0.84	1	0.84	9.15	0.003
Error	10.86	119	0.09		
Total	788.60	184			
Corrected total	33.96	183			

[a] $R^2 = 0.68$

Source	Type III sum of Squares	df	mean square	F	Sig.
Corrected model for sqrt CO_2 flux	23.11*	64	0.36	3.96	0.000
Intercept	24.43	1	24.43	267.72	0.000
SWC * Temp	19.85	62	0.35	3.51	0.000
Study Site	1.56	1	1.56	17.09	0.000
Vegetation type	0.84	1	0.84	9.15	0.003
Error	10.86	119	0.09		
Total	788.60	184			
Corrected total	33.96	183			

* $R^2 = 0.68$

3.4 Soil water repellency and CO$_2$ fluxes

Given that SWR ~~soil wettability was~~is strongly affected by both temperature and moisture and at the site ~~was~~ it was observed at higher soil temperatures and lower SWC, the relationship between ~~,~~ SWR and ~~effect on~~ CO$_2$ efflux ~~fluxes~~ was ~~therefore~~ considered separately from the above described model (Table 3). To consider the effect of SWR variability on CO$_2$ efflux,

5 SWR data (Fig. 3) was converted into a ~~A more hydrologically meaningful analysis~~ relative fraction of extremely water-repellent soil (WDPT >3600 s) ~~of the potential role of SWR was carried out by separating the results into groups representing the relative fraction of extremely water repellent~~water-repellent soil (WDPT >3600 s) for each sampling event (Fig. 5c~~8~~) described as SWR distribution. ~~This grouping of SWR results was used as a proxy of heterogeneity of soil moisture distribution in soils affected by water repellency~~SWR. The zero value represented ~~completely wettable~~ soil where extreme SWR was not

10 detected, while ~~water distribution was not affected by water repellency~~SWR, ~~and~~ a value of 1 denoted uniform extreme SWR~~ly water repellent~~water-repellent ~~soil where similarly low moisture content was expected throughout the soil~~. Values between zero and 1 represented increasing levels of extreme SWR presence; lower values indicated wettable soil with low percentage of ~~isolated patches of~~ extremely ~~water repellent~~water-repellent soil, while the values closer to 1 represented soils dominated by extreme ~~water repellency~~SWR with low percentage of ~~isolated zones of~~ wettable soil or at low SWR.

15 Soil CO$_2$ efflux showed a very clear response to SWR distribution. When SWR distribution had a value of zero (i.e. the ~~entire~~ soil was wettable) soil CO$_2$ flux was low, but it increased when a small fraction of soil became extremely ~~water repellent~~water-repellent. The maximum soil CO$_2$ efflux was reached for a SWR distribution around 0.4 – 0.6. SWR distribution values >0.6 were associated with a decreased CO$_2$ efflux, which reached its lowest values when all soil became uniformly ~~water repellent~~water-repellent (value of 1). The differences between soil CO$_2$ efflux~~es~~ for wettable/extremely SWR distribution

20 values (0 and 1) and intermediate values (0.2-0.8) were observed mainly for events with higher soil temperatures ~~and in many cases they were statistically significant. Considering the whole soil volume examined here, we can therefore reject the hypothesis that presence of water repellency~~SWR ~~unequivocally reduces soil respiration also under 'real world' field conditions. The response of soil respiration to the presence of soil water repellency~~SWR ~~is more complex than it has been originally anticipated and its effects are clearly more complex as discussed below.~~
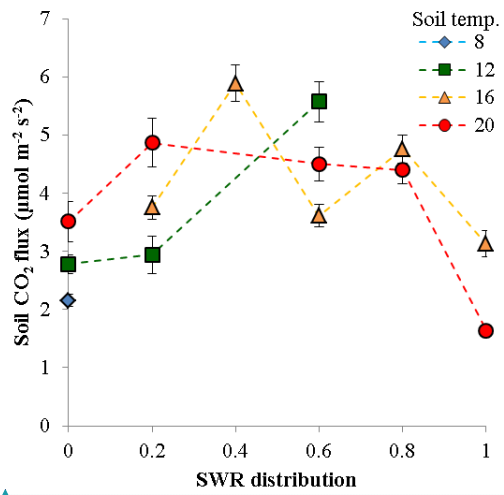
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Figure 8: Soil CO_2 flux response to SWR distribution (0=wettable, 1=uniformly extreme SWR) for different soil temperature bands (8 – 6.1-10 °C; 12 – 10.1-14 °C, 16 -14.1-18 °C, 20 – 18.1-22 °C). Soil CO_2 fluxes are represented as means (with standard errors) for SWR distribution grouped within ±0.1.

5

4 Discussion

4.1 Temporal variations in SWR

This study investigated, for the first time, the seasonal variability of ~~water repellency~~SWR persistence in UK soils and, for the first time globally, the potential impact of reduced soil wettability ~~of associated soil moisture distribution~~ on CO_2 efflux~~es~~ in

5 the field. Three years of monitoring of soils under humid temperate pine forest and grassland ~~in England~~, revealed that SWR was present for most of the ~~spring,~~ summer and early autumn. The presence of SWR at these locations was consistent with previous studies that also reported severe SWR for UK grassland, forest and heath (Doerr et al., 2006), arable land (Robinson, 1999; Hallett et al., 2001) and on golf greens (York and Canaway, 2000), and in The Netherlands on grass-covered sand dunes under a similar climate (Dekker and Ritsema, 1996a; Ritsema and Dekker, 2000). Both investigated sites were under permanent

10 vegetation, which is generally considered to be situation most susceptible to SWR development (Doerr et al., 2000; Woche et al., 2005) due to the continuous input of hydrophobic substances from the vegetation and soil microbes (Doerr et al., 2000), and a low level of soil disturbance.

SWR has long been known to be temporally variable and has commonly been observed when soil is ~~during~~ warm and dry ~~conditions~~, while disappearing during prolonged cold and wet conditions (Doerr et al., 2000; Leighton-Boyce et al., 2005;

15 Buczko et al., 2006; Stoof et al., 2011). At the sites investigated here, SWR was observed from early summer (May/June) until late autumn (November). The exact timing of ~~water repellency~~SWR development and also of its complete disappearance could not be precisely pinpointed in this study within each year due to the monthly timings of the sampling visits, but it was clearly associated with low soil moisture contents and higher soil temperatures. SWR was not observed at soil temperatures lower than 10 °C despite low ~~soil water content~~SWCs, suggesting not only soil moisture but also the temperature is important in

20 SWR development. SWR remained spatially and temporally variable throughout the entire warmer periods. Only long dry spells resulted in high persistence of ~~water repellency~~SWR in all investigated soil samples, suggesting that the majority of the soil at the site was water-repellent at that time~~being uniformly distributed in the entire soil~~. For the majority of the warmer season, SWR was present, but of variable severity and often spatially interspersed with a small proportion of wettable zones. The high variability of SWR can be attributed to frequent change between ~~and~~ sufficiently dry and wet periods, characteristic

25 of the UK climate, which allows development and partial disappearance of SWR. During the warmer dry periods in 2013 and

2015, the data suggest that soil became ~~water repellent~~water-repellent throughout (WDPT >5 s), but its persistence in different soil areas varied from minutes to hours. In contrast, during summer 2014, the proportion of wettable to~~soil patches near~~ water-repellent samples ~~zones~~ was very high (up to 65 % in T-g, up to 50 % in T-f), which can be attributed to the particularly rainy summer (total rainfall for summer 2014 was 50 % higher than 2013~~,~~ and ~~-~~20 % higher than 2015). The high spatial variability of ~~water repellency~~SWR and that partial change to a wettable state during the summer 2014 wa~~is~~ likely to be a consequence of spatially uneven infiltration into the soil~~, and~~ further enhanced by preferential flow, both caused by presence of hydrophobic particles surfaces. The flat topography and surface cover of litter (at the forest site) or vegetation (at the grassland site) probably restricted surface runoff and resulted mainly in spatially variable infiltration and preferential water flow (Bughici and Wallach, 2016). We anticipate that substantial amount of ~~Most~~ rainfall was ~~likely~~ transferred below the near-surface repellent layer ~~via preferential flow zones formed~~via by ~~by~~ faunal burrows (Shakesby et al., 2007), roots and soil cracks (Dekker and Ritsema, 1996b; Kobayashi and Shimizu, 2007; Urbanek et al., 2015) leaving zones with high persistence of SWR near wettable soil zones.

Patchy SWR distribution was associated with variable SWC, soil zones with high SWR persistence had lower soil moisture content while wettable and lower SWR soil were moist, which is consistent with the typically observed relationship between soil moisture and SWR reported in many other studies (Doerr and Thomas, 2000; Dekker et al., 2001). ~~The preferential flow paths induced by SWR have most likely resulted in the high spatial variability of water repellency~~SWR ~~and water content of the soil, as it is known that the soil adjacent to preferential flow paths is the first zone of the soil to switch into a wettable state (Urbanek et al., 2015). SWR induced preferential flow caused creation of dry, isolated~~ ~~water repellent~~water-repellent ~~soil patches that were frequently detected on occasions when the majority of soil was wettable (Fig. 4).~~ The~~se isolated~~ dry, water-repellent soil patches would have been not only been deficient in water, but would also have had a restricted supply of nutrients, due to the lack of their transfer by water (de Jonge et al., 2009; Goebel et al., 2011), while higher nutrient concentration and DOC is expected in the water in wetter zones (Müller et al. 2014).

4.2 Temporal variations in soil CO_2 efflux~~es~~

Temporal fluctuations in soil temperature and moisture not only affected the presence or absence of SWR, but were likely to be also responsible for the variability in soil respiration and C fluxes. The CO_2 efflux measurements at the study sites were conducted each year from June until November with only a few early measurements in spring during 2015. Thus no information is available on soil CO_2 efflux~~respiration~~ during the winter season. All early spring and late autumn measurements, however,

5   showed lower soil CO_2 efflux ~~respiration rates~~ than during the warmer period. During the colder and typically wetter part of the year, primary productivity, soil biological activity and therefore soil respiration is typically low (Davidson and Janssens, 2006). Considering the seasonal fluctuation, but also noting the positive correlation between soil CO_2 efflux~~es~~ and soil temperatures, it is clear that the latter constitute the main factor affecting soil respiration, which is consistent with many previous studies (Gaumont-Guay et al., 2009; Yvon-Durocher et al., 2012; Karhu et al., 2014). The positive response of CO_2

10 efflux to increasing soil temperature reflects the greater activity of roots and decomposing microorganisms, but can also involve long-term changes in microbial population communities and higher substrate supply from photosynthesis in response to longer-term trends as expected, for example, with global warming (Davidson and Janssens, 2006; Gaumont-Guay et al., 2009). At both study sites soil CO_2 efflux ~~respiration~~ increased with rising temperatures, but only until a maximum level was reached, after which a notable decrease was observed. The occasions when soil CO_2 efflux~~es~~ were no longer dictated by

15 temperature occurred during the summer when the soil was exposed not only to relatively warm, but also dry conditions for prolonged periods, suggesting that soil moisture was the restricting factor. The effect was observed only at times of uniformly low ~~soil water content~~SWCs when persistence of SWR was consistently high. On the occasions of measurements with low, but spatially variable water content, soil respiration was high and followed an increasing trend with temperature. A reduction in soil moisture availability is known to reduce microbial activity and root respiration (Or *et al.*, 2007) and~~ P~~ prolonged

20 summer droughts have been recognised in many studies as the cause of a decrease primarily in heterotrophic respiration ~~which, according to (~~ Borken et al. (2006). ~~could cause increases in the storage of soil organic C in this forest type.~~

4.3 Effect of soil moisture and SWR on soil CO_2 fluxes

Soil CO_2 efflux~~es~~ were found to respond to changing SWC~~soil moisture content~~ particularly at higher soil temperatures (Fig.

25 5b~~7~~) and ~~, but~~ the variability in CO_2 efflux remained high especially for intermediate soil moisture contents. Only after long

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dry spells when soil moisture availability was low, were soil respiration rates significantly reduced. At intermediate~~high soil water content~~SWCs, soil CO_2 efflux was high but also very variable most likely due to frequent wetting and drying events resulting in very heterogeneous soil moisture distribution (Gaumont-Guay et al., 2009). Given that both soils are very susceptible to development of SWR we expect that high variability in CO_2 efflux at intermediate SWCs can be the result of

5 uneven ~~The variable~~ soil water distribution caused by presence of SWR.

Previous studies have already shown that SWR can protect C from decomposing microorganisms (Goebel et al., 2005; Goebel et al., 2007; Bachmann et al., 2008; Lamparter et al., 2009; Goebel et al., 2011), which results in reduced soil respiration. These laboratory-based studies focused mainly on the severity of SWR of homogeneous soil and therefore did not explore the wide range of scenarios to which natural soil is exposed. Most studies exploring SWR present the results based on overall

10 median or mean WDPT values, which does not allow identification of the naturally rather common and important situation when SWR variability is very high. SWR distribution, as used in this study, shows the proportion of soil affected by most extreme SWR and proportion of soil pores most affected by pore water movement and distribution, which allows better prediction of hydrological behaviour. The SWR conditions presented here not only include soil wettability with (a) uniformly wettable soil and (b) high (extreme) SWR, but also identifies (c) the critical intermediate stages when soil is dominated either

15 by wettable soil with patches of extremely water-repellent soil or *vice versa* as presented in a conceptual figure (Fig. 6). ~~and inconsistent response in soil respiration with temperature and moisture content, can be explained by the presence of SWR, which is known to substantially affect soil water distribution and thus processes where water is involved (de Jonge et al., 2009), including microbial activity and therefore soil respiration.~~ At both study sites CO_2 efflux was low when soil was in wettable state (Fig. 6a), which occurred under two different conditions: during early spring and late autumn when soil temperature was

20 too low for SWR development, or during the summer when due to frequent rainfall SWR disappeared and high moisture was recorded. On both occasions low CO_2 efflux was mainly caused by either low temperature or high moisture content, which in any wettable soil would cause a similar type of response.

Soil CO_2 efflux was also low on occasions when soil was extremely water-repellent with SWR distribution close to 1 (Fig. 6c), occurring during prolonged dry spells when soil temperatures were high and low soil moisture contents. In the latter case,

25 it is reasonable to expect that the reduction of CO_2 efflux was caused mainly by low SWC, which caused reduced microbial

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activity. Previous laboratory studies have reported low respiration rates in similarly highly water-repellent soil (Goebel et al., 2007; Lamparter et al., 2009). Owing to low water availability, microbial and enzymatic activity is reduced (Or et al., 2007; Moyano et al., 2013; Moyano et al., 2012), or it ceases entirely when extremely low matric potentials are reached and water films in soil pores become disconnected (Goebel et al., 2007). According to Or et al. (2007), diffusion rates of extracellular

5 enzymes produced by microbes to access organic matter are proportional to the thickness of the water film surrounding soil particles and this thickness is substantially reduced by SWR (Churaev, 2000; Goebel et al., 2011). Obstruction of microbial movement and reduction in diffusion results in physical separation of microorganisms from substrates and nutrients, which can lead to long-term starvation (Kieft et al., 1993). At the sites investigated here, such a situation was observed only on a few occasions following long dry spells, suggesting that under the current humid-temperate, this soil condition is not very common

10 here. the It is, however, very common in climates with distinct dry seasons or more prolonged dry periods (Doerr et al., 2003; Doerr and Moody, 2004; Leighton-Boyce et al., 2005; Stoof et al., 2011) and may become more common in the future in the UK according to future climate predictions (IPCC, 2013). It is also an important scenario to be considered during rewetting of extremely water-repellent soils after drought, as reported by Muhr et al. (2010, 2008) a slow regeneration of CO_2 fluxes observed following wetting could have been caused by SWR.

15 The highest CO_2 efflux was recorded at intermediate SWR distribution (SWR distribution 0.2-0.8) when SWR and consequently soil moisture distribution was very patchy (Fig. 6b). Variable SWR can be associated with patchy pore water distribution which create zones of soil with water-filled pores near water-repellent soil zones. Water-filled soil pores are expected to have a good supply of water and concentrated nutrients, which if compared to preferential flow paths are expected to harbour larger bacterial densities (Vinther et al., 1999) and activities (Pivetz and Steenhuis, 1995) than the adjacent soil

20 matrix. The water-repellent soil zones with air-filled pores are anticipated to provide optimal routes for gas transfer where the O_2 and CO_2 released by the decomposing microorganisms can easily be exchanged between the soil and atmosphere (Or et al., 2007; Kravchenko et al., 2015).

Some previous studies have already shown that SWR can protect C from decomposing microorganisms (Goebel et al., 2005; Goebel et al., 2007; Bachmann et al., 2008; Lamparter et al., 2009; Goebel et al., 2011) and result in reduced soil respiration.

25 These laboratory-based studies focused mainly on the severity of SWR of homogeneous soil and therefore did not explore the

wide range of scenarios to which natural soil is exposed. Most studies exploring SWR present the results based on overall median or mean WDPT values, which does not allow identification of the naturally rather common and hence important condition when SWR variability is very high. Presenting water repellencySWR distribution rather than the mean or median value (Fig. 8) is therefore hydrologically more meaningful. It includes soil wettability conditions with uniformly low (wettable) and high (extreme) water repellencySWR, but also identifies the intermediate stages when soil is dominated either by wettable soil with patches of extremely water repellentwater-repellent soil or *vice versa*.

The results demonstrate for the first time that (i) there are different responses of soil CO_2 fluxes to different patterns of SWR distribution (i.e. SWR does not simply reduce soil CO_2 fluxes) and (ii) that the effects are consistent across a range of temperatures. Based on these findings, we present a new conceptual model for CO_2 flux behaviour (Fig. 9) that accounts for the more realistic effect of SWR observed in this field study and includes three main SWR-sensitive hydrological condition. Wettable soil (Fig. 9a), represents a condition observed when a soil water repellencySWR is absent due to frequent wetting events and therefore high soil moisture contents, or a situation when the temperatures are too low for water repellencySWR to develop. Under these conditions, soil water is relatively uniformly distributed and soil pores are either fully or partly filled with water. Owing to low temperatures and/or high soil water contentSWCs microbial activity is limited resulting in low soil CO_2 production. Water-filled pores also result in restricted gas exchange between the soil and atmosphere and thus low CO_2 efflux.

Uniformly extreme water repellentwater-repellent soil (SWR distribution equal to 1) (Fig. 9c) is associated with consistently low moisture content and soil CO_2 fluxes. Several laboratory studies have reported low respiration rates in similarly highly water repellentwater-repellent soil (Goebel et al., 2007; Lamparter et al., 2009). Owing to low water availability, microbial and enzymatic activity is reduced (Or et al., 2007; Moyano et al., 2013; Moyano et al., 2012), or it ceases entirely when extremely low matric potentials are reached and water films in soil pores become disconnected (Goebel et al., 2007). According to Or et al. (2007), diffusion rates of extracellular enzymes produced by microbes to access organic matter are proportional to the thickness of the water film surrounding soil particles and this thickness is substantially reduced by SWR (Churaev, 2000; Goebel et al., 2011). Obstruction of microbial movement and reduction in diffusion results in physical separation of microorganisms from substrates and nutrients, which can lead to long-term starvation (Kieft et al., 1993). At the sites

~~investigated, such a situation was observed only on a few occasions following long dry spells, suggesting that under the current~~ ~~humid-temperate, this soil condition is rare here. Uniformly high SWR is, however, very common in climates with distinct dry~~ ~~seasons or more prolonged dry periods (Doerr et al., 2003; Doerr and Moody, 2004; Leighton-Boyce et al., 2005; Stoof et al.,~~ ~~2011) and may become more common in the future in the UK according to climate predictions (IPCC, 2013).~~

5   ~~The third, intermediate situation, which is examined in this context for the first time here, is the hydrological status of variably~~ ~~water-repellent soil (SWR distribution 0.2-0.8) where soil is dominated by wettable or water-repellent soil patches.~~ In a humid temperate climate with soils susceptible to SWR, this likely to be the most common soil condition, while in climates with distinct dry seasons or common dry spells it <u>could</u> represent the state of change between wettable and water-repellent taking place between wet and dry seasons or periods (Leighton-Boyce et al., 2005; Stoof et al., 2011).

10   <u>Considering the whole soil volume examined in this study, we can therefore reject the hypothesis that presence of SWR unequivocally reduces soil respiration also under 'real world' field conditions. The response of soil respiration to the presence of SWR is more complex than it has been originally anticipated and its effects are clearly more complex as discussed below.</u>~~Under such conditions, soil is exposed to pronounced preferential flow where water infiltrates the soil via selected zones, leaving other areas completely dry (Fig. 9b).~~

15   ~~Supply of water and nutrients in these flow paths is very high and soil areas near flow paths harbour larger bacterial densities (Vinther et al., 1999) and activities (Pivetz and Steenhuis, 1995) than the adjacent soil matrix. The strongly water-repellent soil zones near flow paths with air-filled pores provide routes for gas transfer where the O_2 and CO_2 released by the decomposing microorganisms can easily be exchanged between the soil and atmosphere (Or et al., 2007; Kravchenko et al., 2015). Very favourable conditions for microbial respiration, as well as gas exchange through air-filled pores parallel to~~

20   ~~preferential water paths, thus allow the highest CO_2 efflux. Understanding of soil respiration under the intermediate status of SWR distribution shows that SWR reduces soil respiration only under very extreme uniform SWR conditions whereas, when enhanced preferential flow is encouraged by hydrophobic particle surfaces, the opposite effect applies.~~

Future studies investigating C dynamics in ~~water repellent~~<u>water-repellent</u> soil are still needed to explore further the effect of hydrophobic particle or soil pore surfaces on soil CO_2 fluxes. For example, further insights could be gained by more frequent

25   or near continuous monitoring of soil respiration together with SWR and soil moisture. This would allow better understanding

of soil respiration during the wetting and drying processes in soils that exhibit SWR and thus restricted water infiltration. We consider the proposed conceptual model depicted in Fig. 9 to be sufficiently simple to be fundamentally applicable to a wide range of ~~water repellent~~water-repellent soils. However, given the potential importance of SWR to affect soil respiration and ultimately soil C storage under changing land uses and a changing climate, further field investigations involving different soil types and environmental conditions would be valuable in determining how widespread and temporally common this scenario is.
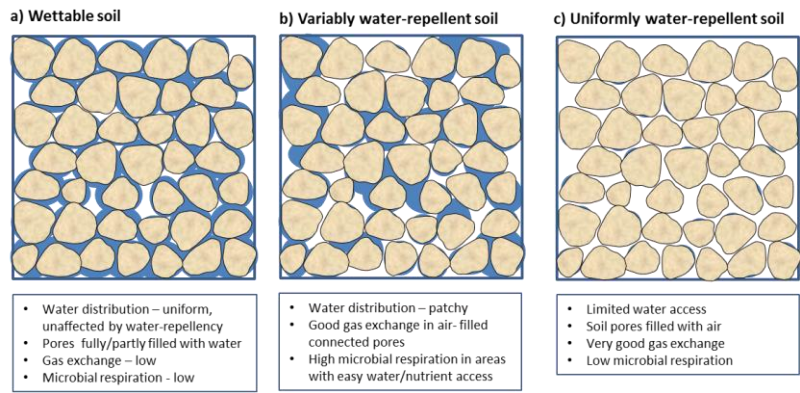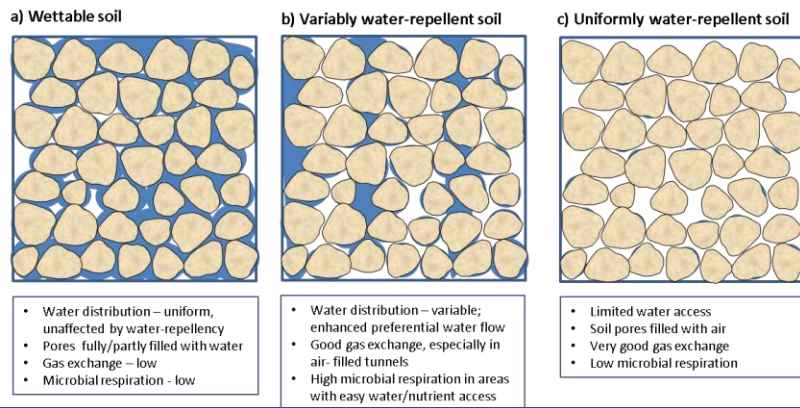
a) Wettable soil

b) Variably water-repellent soil

c) Uniformly water-repellent soil

- Water distribution – uniform, unaffected by water-repellency
- Pores fully/partly filled with water
- Gas exchange – low
- Microbial respiration - low

- Water distribution – variable; enhanced preferential water flow
- Good gas exchange, especially in air- filled tunnels
- High microbial respiration in areas with easy water/nutrient access

- Limited water access
- Soil pores filled with air
- Very good gas exchange
- Low microbial respiration

a) Wettable soil

b) Variably water-repellent soil

c) Uniformly water-repellent soil

- Water distribution – uniform, unaffected by water-repellency
- Pores fully/partly filled with water
- Gas exchange – low
- Microbial respiration - low

- Water distribution – patchy
- Good gas exchange in air- filled connected pores
- High microbial respiration in areas with easy water/nutrient access

- Limited water access
- Soil pores filled with air
- Very good gas exchange
- Low microbial respiration

Figure 96: Theoretical framework of soil water distribution at three different conditions of SWR and its potential effects on soil CO_2 production and transport. Soil CO_2 flux responses under three distinct hydrological situations associated with different soil water repellency (SWR) states and their associated soil water distribution.

5 Conclusions

This study reports for the first time how seasonal changes in SWR distribution affect soil respiration and demonstrates that the presence of SWR does not simply leads to a reduction in soil CO_2 efflux. The sites investigated in the UK under grassland and pine forest exhibit a strong presence of SWR during warmer periods, which is also dominated by high spatial variability in

5 SWR persistence. Frequent wetting and drying events, common in humid-temperate climates, result in high patchiness of SWR, and only when soil is exposed to longer dry spells does it become~~s~~ severely and uniformly ~~water repellent~~water-repellent. As the hydrological consequences of variable SWR spatial distribution are unique, it is necessary to recognise their distinctiveness as well as the hydrological conditions associated with entirely wettable or water-repellent soil. The data collected here suggest that the response of soil CO_2 efflux strongly depends on soil wettability status and the distribution of

10 water-repellent patches. Very high SWR levels throughout were ~~are~~ indeed ~~is~~ associated with low soil CO_2 efflux, caused by reduced CO_2 production by water-stressed microbial communities. However, variable SWR distribution, results in the highest CO_2 fluxes, most likely due to microbial communities being concentrated in the water and nutrient 'hotspots' close to infiltration ~~bordering preferential flow~~ paths coupled with and very favourable gas exchange conditions in hydrophobicity-controlled air-filled pores. A wettable soil state only occurred at the study sites when soil temperatures were low or there was

15 high frequency of rainfall events, and was associated with low CO_2 fluxes. The hypothesis that presence of ~~water repellency~~SWR unequivocally reduces soil respiration, also under the 'real world' field conditions examined for the first time here, is therefore rejected.

SWR clearly has an important effect on soil respiration, but its impact is more complex than previously assumed, with its spatial variability likely to be the most influential factor. The presence of SWR can not only reduce soil respiration in affected

20 soil zones. It can actually lead to enhanced respiration from soil zones exhibiting high spatial variability in SWR. When examining SWR, this should therefore not be restricted to simply recording whether soil is wettable or ~~water repellent~~water-repellent with a certain persistence or severity level. Its spatial (and temporal) variability is of paramount importance. This combined knowledge should then allow prediction of the response of soil respiration to different temperature and moisture conditions.

In view of current climatic predictions and expectations that SWR will become even more widespread globally than is the case at present, it is important to include analysis of the spatio-temporal characteristics of SWR in long-term respiration studies so that a comprehensive understanding of the specific effects of SWR on soil C dynamics under current conditions can be gained and a firmer foundation for prediction under future climatic scenarios can be established.

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