Soil water repellency and its implications for organic matter decomposition : is there a link to extreme climatic events?

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Impact of extreme climatic events on soil water repellency and its implications for organic matter decomposition – A potential feedback mechanism?

Running title: Extreme events and soil water repellency

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Abstract

Current climate models predict a global temperature increase and an increasing occurrence of extreme events such as droughts and heat waves caused by high levels of greenhouse gases in the atmosphere. The carbon balance of soils likely is more affected by the impact of such extremes than by general changes in soil temperature (T_s) or soil water content (θ_s). One parameter influenced by drying/rewetting cycles or changes in T_s is the wettability of soils. Recently, some studies provided evidence that the stability of organic matter is affected by soil wettability showing that carbon mineralization in water repellent soils can be significantly reduced. In this discussion paper, we hypothesize that soil water repellency (SWR) is an important factor in the stabilization of soil organic matter (SOM), which can potentially affect future climate and in turn may itself be influenced by a changing climate with increasing frequency of extreme events. We demonstrate the global significance of SWR and discuss wettability-induced changes in soil moisture distribution as well as the stabilizing effect of SWR on soil aggregates as the main mechanisms to explain reduced mineralization of SOM with increasing SWR. Results from laboratory and field studies showed that low θ_s particularly in combination with high T_s can increase SWR, thus decreasing the accessibility of SOM for microorganisms. We conclude that extreme climatic events such as drought and heat waves likely enhance SWR sustainably, which may cause long-term effects on soil moisture dynamics. This can potentially lead to a reduction of SOM mineralization on a global scale causing a negative feedback mechanism.

Introduction

Combustion of fossil fuels and changes in land use are strongly affecting the global carbon cycle (Luo & Zhou, 2006; Le Quéré *et al*., 2009) leading to a change in global climate. The associated release of greenhouse gases, such as CO_2, N_2O, and CH_4 already has increased global temperature by 0.6°C since the late 19th century (Meehl *et al.*, 2007). Depending on the climate model and scenario used, mean global temperature is projected to increase by another 2.4 to 5.6°C by the end of the 21st century. This rise in temperature is predicted to increase global mean precipitation (Kundzewicz *et al.*, 2007), but with substantial spatial and seasonal variations. Significant increases are expected at high latitudes and in the inner tropics and significant decreases in the Mediterranean region (Rowell & Jones, 2006), the Caribbean and Central American region (Neelin *et al*., 2006), and the subtropical western coasts of each continent (Meehl *et al*., 2007). In addition, changing climate is associated with increasing temporal variability and occurrence of extremes (Meehl & Tebaldi, 2004; Heimann & Reichstein, 2008). Longer drought periods and more extremely dry years (Meehl *et al*., 2007) as well as heat waves (Ganguly *et al*., 2009) are predicted to become more frequent in the future. The change in global climate may lead to a global shift of vegetation and ecological zones (Peñuelas & Boada, 2003; Mueller *et al*., 2005) and is expected to have various adverse direct and indirect impacts on human health (Haines *et al*., 2006; Rabie *et al*., 2008; Kurane, 2009). Improving the capacity of soil to act as carbon sink is one option to mitigate global climate change due to elevated atmospheric CO_2 (Lal *et al.*, 2007*;* Lal, 2008).

Soil organic matter (SOM) as a major component of the world's surface carbon reserves plays an important role in the global carbon cycle (Gruber *et al*., 2004; Davidson & Janssens, 2006; Heimann & Reichstein, 2008). The amount of carbon that is stored in soils depends on the balance of carbon inputs and carbon outputs (Chapin *et al*., 2006). Soil respiration constitutes the main carbon loss pathway and is dominated by aerobic microbial decomposition of SOM. To a lesser extent leaching of dissolved organic carbon also contributes to the carbon loss from soils (Schiff *et al.*, 1997). Soil respiration accounts for approximately two-thirds of total carbon loss from terrestrial ecosystems (Luo & Zhou, 2006) and is generally sensitive to changes in temperature and precipitation (Davidson & Janssens, 2006). Besides soil temperature (T_s) and soil water content (θ_s), aerobic heterotrophic decomposition of SOM is controlled by the availability of nutrients (Hadas *et al*., 1998) and oxygen (Paul, 2007), as well as the stability of SOM (von Lützow *et al*., 2006). Soil organic matter stability is determined by (i) its chemical composition, (ii) interactions with particle surfaces and metal ions, and (iii) its spatial accessibility (Sollins *et al.*, 1996). The latter depends on soil physical properties like particle and pore size distribution, pore continuity and structure.

In addition to the architecture of soils, determined by texture and aggregation (Young *et al*., 1998; Six *et al*., 2000, 2002; Strong *et al*., 2004), the spatial accessibility and degradability of SOM also depends on the availability and spatial distribution of water in the soil matrix (Young & Ritz, 2000). Water governs the advective and diffusive transport of nutrients, substrates and enzymes, microbial motility, the aeration status of the soil (Or *et al.*, 2007) and is crucial for all microbial uptake mechanisms (Marschner & Kalbitz, 2003). It was shown that the availability and distribution of water in the soil matrix depend on soil particle wettability (Goebel *et al.*, 2007; Bachmann *et al*., 2008). In strongly water repellent soils water tends to form droplets rather than continuous water films on the particle surfaces (Goebel *et al.*, 2007). Even if water films are present, their thickness can be reduced significantly with increasing soil water repellency (SWR) (Churaev, 2000). This may reduce microbial motility (Wong & Griffin, 1976) and diffusion of solutes and enzymes, which is highly sensitive to changes in water film thickness (Derjaguin & Churaev, 1986). As an additional effect, SWR favors the protection of aggregates (Hallett & Young, 1999), thus enhancing the stability of occluded SOM (Tisdall, 1996). Although this clearly shows the potential relevance of SWR for SOM stability, there are only few studies, explicitly investigating the impact of SWR on microbial decomposition of SOM.

Soil water repellency was shown to be affected by θ_s and T_s (Doerr *et al*., 2000). In general, the longer a soil is dry and the higher is T_s, the larger is its wetting resistance. The dependence of SWR on θ_s and T_s makes it susceptible to changing climatic conditions. Thus, it is likely that increasing mean global temperatures and a more frequent occurrence of droughts and heat waves will have an effect on the extent and time-dependent dynamics of SWR, as does a changing precipitation pattern. There are various definitions of drought found in the literature (Heim, 2002), and likewise there is no universal definition of a heat wave (Meehl & Tebaldi, 2004). In the context of this paper, we understand drought as the temporary lack of water caused by abnormal climate conditions (Kallis, 2008), which results in exceptional low θ_s for an extended period of time. Heat waves are episodes of several consecutive high-temperature days and nights leading to unusual high T_s.

So far, there has been limited discussion on the role of SWR as an important, climate change sensitive, soil property that affects the carbon sink strength of soils and its mitigating effect on climate. The aim of this paper is to analyze the potential feedbacks between changing climate and the dynamics of SWR by considering the recently published literature. Specific objectives are (i) to give a short overview of the significance of SWR phenomena, (ii) to discuss important SOM protection mechanisms affected by SWR, (iii) to assess the potential impact of extreme climatic events on the development and dynamics of SWR, (iv) to combine these insights and discuss the impact of extreme events on wettability-related SOM stabilization mechanisms, and finally, (v) to identify the most relevant parameters determining the extent and the temporal dynamics of SWR with respect to an implementation of SWR in terrestrial ecosystem models.

Soil water repellency – its origin and significance

If a solid is not completely wettable by water, it is considered to be water repellent. For water repellent solids water beads up when it makes contact with the surface and a solid–water contact angle (α_{sw}) can be measured at the three-phase (i.e. gas–liquid–solid) boundary line (Bachmann *et al*., 2003). Accordingly, in this paper, we define SWR as being present if $\alpha_{sw} > 0°$. Soils with $\alpha_{sw} < 90°$ show reduced wettability, that is, infiltration of water into the soil matrix is decreased. Values of $\alpha_{sw} > 90°$ indicate extreme SWR, which is also termed soil hydrophobicity (Fig. 1). In hydrophobic soils water does not spontaneously enter the matrix. However, after some time SWR may eventually break down (i.e. $\alpha_{sw} < 90°$) and water can infiltrate into the soil. Such time-dependent dynamics of wettability are frequently termed as persistence of SWR (Dekker *et al*., 2001).

Please insert Fig. 1

Soil water repellency is caused by low solid surface free energy (γ_{sg}) resulting in a weak attraction between particles and the liquid phase (Roy & McGill, 2002). Generally, pure soil minerals have high-energy surfaces (Lewin *et al*., 2005), but under natural conditions they are often covered by organic substances with low surface free energy (Doerr *et al*., 2000). This may result in a large number of non-polar sites on the particle surfaces (Tschapek, 1984; Drehlich, 1997). Several studies showed that SWR is positively correlated with the soil organic carbon (SOC) content (Mataix-Solera & Doerr, 2004; Moral Garcia *et al*., 2005; Varela *et al*., 2005). However, some authors found a more complex relationship (Ellerbrock *et al*., 2005), no general relationship (Woche *et al*., 2005), or even an inverse relationship (Eynard *et al*., 2006) between SWR and SOC indicating that the composition of SOM can be more important than the total amount of SOC. According to Ellerbrock *et al*. (2005), the amount of hydrophobic C-H groups relative to that of hydrophilic C=O, C-OH, and C-NH_2 groups at the solid-liquid interface of a few Ångström thickness (Ferguson & Whitesides, 1992) determines the hydrophobicity of the organic compounds. Organic molecules with amphiphilic properties, like long chain fatty acids, fulvic and humic acids and waxes are the main causes of SWR (Ma´shum *et al*., 1988; Franco *et al*., 2000). These substances may originate from fungal hyphae (McGhie & Posner, 1980; Sun *et al*., 1999; Feeney *et al*., 2006), microbial biomass (Bond & Harris, 1964; Chan, 1992), or decomposed plant materials (McGhie & Posner, 1981). Fungi in general (e.g. basidiomycetes) have been identified to cause SWR (York & Canaway, 2000; Zhang *et al*., 2007), whereas bacteria may reduce SWR by degradation of hydrophobic compounds (Roper, 2004). Soil water repellency can also be caused by the presence of hydrophobic interstitial particulate organic matter (Franco *et al*., 1995), but to a lesser extent as compared to repellency due to organic coatings (Bisdom *et al*., 1993).

Another important parameter affecting SWR is soil pH (Wallis & Horne, 1992). For example, Woche *et al.* (2005) found a slight tendency of increasing SWR with decreasing pH for a series of six arable and eight forest soils. In line with this, de Jonge *et al.* (1999, 2007) and Hurraß & Schaumann (2006) reported a negative correlation between pH and SWR at least for some of their investigated soils. This might be explained by a decreasing polarity of SOM functional groups due to protonation at low pH, as was described by Horne & McIntosh (2000) and Terashima *et al.* (2004) for amphiphilic molecules such as humic acids.

The existence of water repellent soils has been known for many years and there are indications that under certain conditions most soils show SWR to some degree. At first, SWR was reported mostly from semi-arid regions, but in the last decade it has also been observed in humid regions (Jaramillo *et al*., 2000; Johnson *et al*., 2005). This suggests that this phenomenon is not confined to relatively dry climates (Doerr *et al*., 2000), but that at least low levels of repellency are more the rule than the exception (de Jonge *et al*., 2009). For instance, about 75% of grassland and arable soils in the Netherlands (Dekker & Ritsema, 1994) and about 2 million ha of sandy soil in southern and western Australia (Franco *et al*., 2000) are affected by SWR. It covers a wide range of severity and is often too weak to be detected by visual diagnosis. However, even if the soil appears to take up water readily, infiltration and water distribution may be substantially affected. The phenomenon was primarily ascribed to sandy soils, although it has also been observed in loam, clay, peat, and volcanic ash soils (Wallis & Horne, 1992; Ellies & Hartge, 1994; Ritsema *et al*., 1997; Jaramillo *et al*., 2000; Mataix-Solera & Doerr, 2004).

Significance of soil water repellency for organic matter decomposition processes

Soil water repellency affects hydrological processes and potentially all processes where water is involved (de Jonge *et al.*, 2009). With respect to carbon mineralization, SWR may have important direct and indirect consequences. It affects the distribution and continuity of the liquid phase in the soil matrix, which is crucial for the accessibility of SOM and the availability of water, oxygen, and nutrients. Further, it increases the stability of soil aggregates against water-slaking, which can be important for the accessibility of aggregate-occluded SOM. The relevance of these effects for carbon mineralization processes are illustrated in Fig. 2 and will be discussed in the following sections.

Please insert Fig. 2

Wettability-induced changes in water distribution and availability - an important factor in controlling microbial decomposition processes

The activity of all microorganisms in soil is governed by the availability of water and was found to be linearly related to θ_s (Orchard & Cook, 1983). Hence, any change in water availability will have fundamental consequences for biological activity (Feeney *et al.*, 2006). Diffusion rates of extracellular enzymes to SOM and of dissolved substrates back to the microbial cells are proportional to the thickness of the water film surrounding soil particles (Davidson & Janssens, 2006). Increasing SWR has been found to reduce water film thickness on particle surfaces (Churaev, 2000). For various mineral-water and glass-water systems, Derjaguin & Churaev (1986) reported a considerable decrease of water film thickness with increasing α_{sw}. Measured isotherms of water films on quartz surfaces indicated that at 98.5% relative humidity water film thickness on slightly water repellent quartz particles (α_{sw} = 10°)

is reduced by a factor of 5 as compared to completely wettable quartz particles (α_{sw} = 0°) (Churaev, 2000). This suggests that already small differences in wettability may have a strong impact on water film thickness and thus on microbial decomposition of SOM.

The impact of wettability on microscopic water distribution and connectivity of the liquid phase is illustrated in Fig. 3 showing environmental scanning electron microscopy (ESEM) images (Quanta 200, FEI Company, Eindhoven, the Netherlands) of water condensed on hydrophobic (α_{sw} = 158°) and slightly water repellent glass beads (α_{sw} = 48°) with a mean diameter of 0.10-0.11 mm (B. Braun Biotech International GmbH, Melsungen, Germany). On the hydrophobic particle surfaces, the water condensed as small drops. Consequently, there was a reduced water connectivity between individual particles confined by the diameter of water drops formed between them. Contrastingly, the slightly water repellent surfaces were uniformly wetted which led to a higher water connectivity between the particles. The liquid menisci formed between the slightly water repellent particles had a larger cross-sectional area as compared to the water drops formed between the hydrophobic particles. This illustrates that for strongly water repellent material the water connectivity on individual particles as well as between the particles can be markedly reduced, which may have important consequences for diffusion processes (Mills & Powelson, 1996).

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Please insert Fig. 3

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It was shown by Poll *et al*. (2008) that the extent and intensity of the active zone of bacterial decomposition was directly related to diffuse and advective solute transport, with slow solute transport at low θ_s. Generally, bacterial utilization of labile carbon compounds seems limited mainly by short-distance advective and diffusive transport processes (Ekschmitt *et al*., 2008). At a water film thickness of <1 μm bacterial movement was negligible (Kieft *et* *al*., 1993), and solute diffusion rate was reduced by more than 50% relative to saturated conditions in a loamy soil (Griffin, 1981). The reduction of substrate and enzyme diffusion with decreasing θ_s and water film thickness can be caused by several mechanisms, such as film straining in thin water films (Zevi *et al*., 2005), attachment to the air-water interface (Torkzaban *et al*., 2006a), increasing attachment to the solid-water interface (Torkzaban *et al*., 2006b), and retention at the air-water-solid interface (Steenhuis *et al*., 2006). Generally, if the water film thickness is similar or smaller than the diameter of bacteria, retardation of bacterial movement can be expected (Wan & Tokunaga, 1997). Both the obstruction of active bacterial movement and the reduction in diffusion result in a physical separation of bacteria from substrates and nutrients and may cause dormancy and long-term starvation in the microorganisms (Kieft *et al*., 1993). In contrast, many fungi can be active under these conditions (Griffin, 1969), as their hyphae can translocate water from wetter parts of the soil and can actively explore the soil for nutrients. This suggests that the impact of SWR on water film thickness and continuity could be less effective for fungi.

As shown by Hallett *et al*. (2004) water repellent properties could induce very high levels of small-scale variability in soil water movement. The exclusion of water from water repellent soil domains can, however, also be effective on larger scales (see Fig. 2). The formation of preferential flow paths, for example, is favored in soils with water repellent properties (Dekker & Ritsema, 1994). Preferential flow paths may result in irregular wetting patterns with wet and dry soil domains (Dekker & Ritsema, 1995; Täumer *et al.*, 2005; Zavala *et al*., 2009) and may also affect the distribution of dissolved organic matter and subsequent SOM mineralization throughout the soil. In the dry soil domains, which can persist for months (Dekker & Ritsema, 1996) residing SOM may effectively be protected. These findings suggest that SWR can contribute to the formation of biologically non-preferred soil domains on different spatial scales where decomposition rates are slow or where decomposition is frequently interrupted.

Another important factor, which can be affected by SWR is enzyme efficiency. Ekschmitt *et al*. (2005) suggested that the decomposition of SOM could substantially be limited due to saturation of enzyme efficiency, which is reached when the microbial energy expenditure for basic maintenance and enzyme production equals the energy yield from the decomposition products. According to Schimel & Weintraub (2003), the reduction and eventually saturation of enzyme efficiency can be explained by diffusion losses. Given that the secretion of exo-enzymes is only induced when they can be effective, Ekschmitt *et al*. (2005) concluded that many bacteria remain ineffective in an unfavorable diffusion environment, even if substrate is available. Consequently, domains where water is constrained, as typically found in water repellent soil, may allow a more efficient utilization of substrates as the chance for exo-enzymes to get lost would be markedly reduced. This may result in enhanced microbial decomposition, provided that enough substrates, nutrients and water are available. However, as a confined water distribution will also reduce the supply of fresh substrates, it can be assumed that a possible enhancement of microbial decomposition will be a short-term effect. It is also important to note that the reduction in conducting liquid pathways with increasing SWR is accompanied by increasing soil air content and liquid-vapor interfacial area resulting in enhanced gaseous diffusion and exchange with the atmosphere (Or *et al.*, 2007), which may improve the conditions for aerobic microbial decomposition. Generally, these considerations suggest that SWR will not necessarily lead to a reduced microbial activity but at least to a more heterogeneous distribution of microbial life.

To date, only few studies have directly investigated the role of SWR for carbon mineralization processes. A study by Goebel *et al.* (2005) in which carbon mineralization from different topsoil horizons was related to soil wettability revealed decreasing CO_2 efflux rates with increasing SWR. However, the authors pointed out that the measured effect was not necessarily due to the impact of SWR on water distribution and availability but could also be a result of chemical stability of the SOM itself. To exclude these effects, Goebel *et al.* (2007) mixed natural topsoil material with a mixture of silt particles, which were partly hydrophobized. Different mixing ratios of the wettable and the hydrophobized silt particles led to a defined variation of wettability by ensuring same amounts and composition of SOM in the resulting three-component soil mixtures. Laboratory incubation experiments carried out with the three-component soils adjusted to same bulk water content revealed decreasing CO_2 efflux with increasing SWR of the material (Goebel *et al.*, 2007). In one particular mixture, the authors found that the addition of 25% hydrophobic silt particles, which resulted in a moderate increase of α_{sw} from 0° to 22°, caused a pronounced reduction in cumulative CO_2 release of approx. 75%. Recently, Lamparter *et al*. (2009) stressed the importance of the wetting history for the effectiveness of SOM stabilization by SWR. After rewetting initially dry soil to a water potential of -31.6 kPa the authors found decreasing CO_2 release rates with increasing SWR, whereas no significant relation could be observed for the same soils coming from a moist state and dried to -31.6 kPa. This indicates that the strength and duration of soil drying which may be influenced by extreme climatic events can be important for the stabilization of SOM by SWR.

Impact of water repellency on the stabilization of soil organic matter occluded in aggregates

Another important feature of SWR with respect to carbon mineralization is its influence on aggregate stability. Dynamics of SOM in aggregate fractions correlate well with the lifetime of the aggregates themselves (Besnard *et al*., 1996), and thus any change in aggregate stability can be expected to affect SOM decomposition rates. A number of studies have shown that increasing SWR favors the stability of aggregates (e.g. Sullivan, 1990; Zhang & Hartge, 1992), which may increase the protection of occluded organic substances against microbial decomposition (Tisdall & Oades, 1982; Tisdall, 1996). The protection of aggregates due to SWR is mainly related to the reduction of the initial wetting rate, which diminishes the build-up of air-pressure in soil pores, thus reducing the slaking stress (Zhang *et al*., 2007).

Capriel *et al*. (1990) and Capriel (1997) found that a decrease of hydrophobic SOM compounds such as lipids was accompanied by a decrease of aggregate stability. This was also confirmed by the findings of Piccolo & Mbagwu (1999) who demonstrated that aggregate stability increased after the application of hydrophobic substances. Goebel *et al*. (2005) showed that a difference in α_{sw} of only 13° can significantly reduce water uptake rates and enhance aggregate stability of air-dry aggregates immersed in water. The authors concluded that wettability was a better predictor of the initial aggregate breakdown dynamics than the total SOC content, particularly for very low amounts of SOC. Mataix-Solera & Doerr (2004) also demonstrated for soils with similar SOC contents that aggregate stability is enhanced with increasing SWR. Furthermore, a positive correlation between aggregate stability and SWR was also observed by Arcenegui *et al*. (2008) for calcareous soils immediately after wildfires in southeastern Spain.

Evidence that aggregation physically protects SOM from decomposition due to a reduced accessibility for microorganisms has been provided by a multitude of aggregate disruption studies (Powlson, 1980; Elliott, 1986; Gupta & Germida, 1988; Gregorich *et al*., 1989; Hassink, 1992; Goebel *et al*., 2009). Huygens *et al.* (2005), for example, found a negative relationship between carbon mineralization and aggregate stability and suggested that physical protection of SOM in soil aggregates was an important SOM stabilization process in Andisols from southern Chile. A recent study by Lamparter *et al.* (2009) found evidence that the SOM stabilizing effect of aggregates depends on soil water potential. At a water potential of -31.6 kPa, where oxygen diffusion is not limited, mineralization from crushed aggregates exceeded that of intact aggregates 7-fold, highlighting the physical protection of SOM in aggregates. Conversely, at a water potential of -6.3 kPa, where oxygen diffuses less freely, the authors found larger mineralization rates from intact aggregates as compared to corresponding crushed aggregates. This was explained by the larger amount of macropores and thus the better oxygen supply in soils with intact aggregates.

Role of abiotic environmental factors in the dynamics of soil water repellency

Besides the amount and composition of SOM and pH as important influencing factors, SWR is also affected by θ_s and T_s, resulting in a coupled dynamic behavior. Given its dependence on θ_s and T_s, it is conceivable that SWR will be affected by climate change and particularly by extreme climatic events. As models predict that soil moisture will be significantly reduced in many temperate and subtropical regions by 2070 (Gerten *et al.*, 2007), drought events, which frequently will coincide with heat waves (Zampieri *et al*., 2009), are likely to become increasingly important for the development and dynamics of SWR in the future. Another important feature with respect to SWR, which is related to climate change and likely to be promoted by drought and heat waves, is the increasing risk of wildfires (Mouillot *et al.*, 2002; Goetz *et al.*, 2005). The mechanisms and consequences of these climate change induced modifications in the dynamics of θ_s and T_s for SWR are illustrated in Fig. 4 and will be discussed in the following sections.

Please insert Fig. 4

Impact of soil moisture on the dynamics of water repellency

Several authors reported a negative relationship between θ_s and SWR and concluded that air-dry soils repel water most strongly (Dekker & Ritsema, 1994; Dekker *et al*., 1998; Coelho *et al*., 2005; Keizer *et al*., 2005; Leighton-Boyce *et al*., 2005; Thwaites *et al*., 2006). The reduction of SWR with increasing θ_s can be explained by the reorientation of amphiphilic molecules due to the interaction of their polar functional groups with water (Ma'shum & Farmer, 1985). In contrast, when soils are drying out the polar ends of amphiphilic molecules may associate with each other and interact through hydrogen bonds. This forces the molecules to adopt a position in which their polar functional groups are attached to the mineral surface and the non-polar hydrophobic ends are oriented outwards (Ma'shum & Farmer, 1985; Valat *et al.*, 1991).

Consequently, SWR generally increases during dry weather, while it is reduced or completely eliminated after prolonged or heavy precipitation (Doerr *et al.*, 2000). For example, Buczko *et al*. (2005) reported for sandy forest soils in northeast Germany a pronounced seasonal variability in SWR from being strongest in summer to weakest in autumn, after an extended wet period. In general, with increasing rainfall, the wetting resistance of the soil is reduced when θ_s reaches a threshold, called the 'critical θ_s' (θ_{crit}) (Dekker & Ritsema, 1994). Values of θ_{crit} can range from 2% by volume for a dune sand (Dekker *et al*., 2001) to about 40% by volume for a SOM-rich silt loam soil (Dekker & Ritsema, 1995) (see Table 1). Actually, θ_{crit} is not found to be a sharp threshold but rather a transition zone (Dekker *et al*., 2001), which is a consequence of the hysteretic nature of SWR, breaking down and reestablishing at different θ_s (Leighton-Boyce *et al*., 2005). Investigations of Täumer *et al*. (2005) have shown that θ_{crit} of a sandy Anthrosol linearly increases with increasing SOC content. This is consistent with Fig. 5 showing θ_{crit} as a function of the SOC content for a set of soils with different texture. For the sandy soils, θ_{crit} is linearly related to the SOC content in the range from 0.5 to 18% by mass, independently of the soil type (see Table 1). When including a clayey peat soil with very high SOC contents from 40 to 70% by mass the relationship can be described by an exponential function.

Please insert Table 1

In contrast to the generally decreasing SWR with increasing θ_s reported by many authors, several researchers found a more complex behavior with one or two SWR maxima in relation to θ_s (King, 1981; de Jonge *et al*., 1999; Doerr *et al*., 2002; Goebel *et al*., 2004; Regalado & Ritter, 2005). For example, de Jonge *et al*. (2007) found that samples from a coarse sandy soil were completely wettable near field capacity (i.e. -30 kPa) and showed a marked increase in SWR at water potentials around -300 kPa. With further decreasing soil moisture, SWR first decreased (around -100 MPa) and then increased again for even lower water potentials. Several mechanisms and processes were proposed to explain this complex non-linear behavior (see Fig. 4), for example, an enhanced microbial activity with increasing relative humidity (e.g. growth of actinomycetes or fungi with hydrophobic hyphae) (Roberts & Carbon, 1971; Jex *et al*., 1985), solvent-induced changes in the molecular conformation of SOM accountable for hydrophobicity (Wallis *et al*., 1990; Roy & McGill, 2000), or the reorientation of hydrophobic functional groups of previously disrupted molecules due to the energy release from vapor condensation, which can be relevant at high relative humidity (Doerr *et al*., 2002). Bayer & Schaumann (2007) reported that the behavior of SWR in relation to θ_s depends markedly on the initial state of wettability under field moist conditions and also on the T_s during drying.

Please insert Fig. 5

Impact of soil temperature on the development and variation of water repellency

Soil water repellency was shown to be affected by heat (Doerr *et al*., 2000). For instance, Dekker *et al*. (1998) reported increasing SWR of sandy soil samples after heating at 65°C and proposed that the amount and composition of SOM are decisive for heat-induced repellency. Crockford *et al*. (1991) found increased SWR after exposing sandy clay loam soils to 43°C for two hours. It was suggested by Valat *et al*. (1991) that heat input might increase SWR by an improved alignment of hydrophobic molecules. Franco *et al*. (1995) suggested an alternative mechanism where at high T_s waxes originating from particulate organic matter migrate onto mineral surfaces, thereby inducing or increasing SWR (see Fig. 4). The authors also noted that SWR increased with increasing number of wetting/heating cycles. Doerr & Thomas (2000) concluded that heat-induced enhancement of SWR may be an important mechanism in areas where T_s reach high levels, such as in arid and semi-arid climate zones.

In this context the occurrence of wildfires during drought periods can be very important. Several authors have reported that previously wettable soils became water repellent by the impact of fire (Huffman *et al*., 2001; Moral Garcia *et al*., 2005; Varela *et al*., 2005; Arcenegui *et al.*, 2008; Zavala *et al.*, 2009). The heat during a fire is thought to enhance the bonding of hydrophobic organic molecules to soil particles (Savage *et al*., 1972) and chemically exacerbate their hydrophobicity by pyrolysis (González-Pérez *et al.*, 2004; Knicker, 2007). DeBano *et al.* (1970) showed that burning can cause hydrophobic substances to be translocated from the vegetation litter layer downward rendering the subsoil water repellent (see Fig. 4).

Significance of extreme climatic events for organic matter stabilization mechanisms related to soil water repellency

The discussion above clearly demonstrates that θ_s and T_s are important abiotic factors determining the dynamics of SWR. Both factors are prone to be affected by climate change in various ways (Gerten *et al*., 2007; Mellander *et al*., 2007), and particularly by extreme events like drought and heat waves. Consequently, some authors have argued that under current trends in climate change, the impact of SWR would likely become more pronounced (Lichner *et al*., 2007; Hallett, 2008; Gordon & Hallett, 2009). Particularly under relatively dry conditions, small changes in θ_s can result in drastic changes in SWR as shown, for example, by Doerr *et al*. (2002), Goebel *et al*. (2004) and Leelamanie & Karube (2007). In addition, frequent changes in soil moisture conditions, such as increasing number of wetting/drying cycles can enhance SWR (Franco *et al*., 1995).

In general, θ_s and T_s are closely related to each other (Almagro *et al*., 2009) with high T_s usually associated with low θ_s, while at higher moisture content T_s is damped by evapotranspiration. For a temperate forest site in the northeastern United States, Davidson *et al*. (1998) reported that θ_s was negatively correlated with T_s at moderate to high soil moisture content. During prolonged drought events, evaporative cooling is strongly reduced. The increasing frequency and intensity of coinciding drought and heat waves (Zampieri *et al*., 2009) can therefore be expected to have strong effects on SWR.

Heat-induced enhancement and reestablishment of SWR may be particularly effective in regions where T_s at the soil surface reach high levels, such as in arid and semi-arid climate zones. For instance, Rose (1968) reported a surface T_s of more than 50°C for a loamy sand soil in central Australia, and Garratt (1992) noticed surface T_s of more than 60°C for a sandy loam soil located in a coastal area near Melbourne (Australia). Doerr & Thomas (2000) measured maximum T_s (averaged over the top 2 cm of soil) of around 33°C for bare soil and

25°C for covered sandy loam and loamy sand forest soils in Portugal. The authors assumed that T_s at the very surface of the bare soils in their study may well have approached 50°C and could have potentially contributed to the establishment of SWR.

Besides the general impact of high T_s on the development and/or enhancement of SWR, the increased risk of wildfires due to climate change as reported for Mediterranean and boreal regions (Mouillot *et al*., 2002; Goetz *et al*., 2005; Kasischke & Turetsky, 2006) can be important. As reported by Novak *et al*. (2009) SWR seems to be affected by the period (dry or wet) in which the fire occurs. From a study conducted on forest and meadow soils in central Europe the authors concluded that wildfires occurring during or shortly after a wet period would not enhance SWR. In contrast, wildfires occurring after long drought periods may have a pronounced impact on SWR as the cooling effect of evaporating water (Chandler *et al*., 1983) will be reduced.

Several studies reported a seasonal variation of SWR with high levels in summer and low levels in winter (Buczko *et al*., 2005; Keizer *et al*., 2005; Leighton-Boyce *et al*., 2005; Keizer *et al*., 2007), which is typically attributed to changes in θ_s and T_s. Recent findings of Buczko *et al*. (2007) indicate that the actual level of SWR is strongly affected by the weather conditions that prevail immediately before the samples were taken. This suggests that the time scales on which changes in SWR can be triggered can be rather short (approx. 3 days), and moreover, that SWR can be affected even by moderate changes in precipitation and slightly elevated temperatures. The change in SWR due to moderate fluctuations in precipitation and temperature usually are reversible. Extreme events, however, may have irreversible effects on SWR. According to Bayer & Schaumann (2007), long drought periods may lead to a disruption of thin water films on the particle surface, which could induce partly irreversible conformational changes or even condensation reactions. During prolonged heat and drought periods, which are predicted to occur more frequently in future decades in western and central

Europe (Zampieri *et al*., 2009), it is conceivable that soils dry out to such an extent that severe SWR can develop and previous soil moisture levels cannot be restored during subsequent wetter periods, thus promoting a self-amplification of SWR (see Fig. 4).

In wettable soils, even small amounts of precipitation may cause a short-term respiration pulse (Birch, 1958; Austin *et al*., 2004; Huxman *et al*., 2004; Lee *et al*., 2004; Cisneros-Dozal *et al*., 2007), which originates mainly from microorganisms located on or just beneath the soil surface. In water repellent soils or soil regions, such short-term respiration pulses may be suppressed (van Straaten *et al*., 2010) as infiltration of rain water is reduced, occurs via preferential flow paths, or is even absent. As a soil dries out from the surface and T_s is highest directly at the surface, SWR will develop initially within a thin soil surface layer. For water repellent soils, even heavy rainfalls following prolonged drought periods can be virtually ineffective for microbial activity, as most water will run-off on the soil surface and only small amounts will infiltrate into the soil. Moreover, in water repellent soils, aggregate disruption due to water-slaking will be small, thus reducing the accessibility of aggregate-occluded SOM during heavy rain events. On the contrary, the development of a water repellent surface layer can also reduce subsequent drying of deeper soil layers. Even a thin water repellent surface layer (<1 cm) was shown to reduce evaporation considerably (Bachmann *et al*., 2001). As a result, soil moisture below the water repellent surface layer declines almost only via plant water uptake and soils dry out more slowly, potentially avoiding severe water stress and maintaining microbial activity.

Intensive and long-lasting drying during drought can cause a shift in soil microbial community structure towards fungal dominance (Jensen *et al*., 2003) as fungi can survive drought stress better than bacteria (Wilson & Griffin, 1975). Because of their chemical nature, the dominance of fungi can potentially increase SWR and may give rise to a positive feedback loop: if soil moisture remains at a lower level, this promotes a further shift to fungal dominance and increases SWR. However, because fungi are primarily located on the outer aggregate surfaces and therefore are more strongly exposed to drought effects as compared to bacteria (Denef *et al*., 2001), also the opposite effect is possible, which may give rise to a more bacteria-dominated microbial community. In addition, as SWR will retard water infiltration into dry soil, microorganisms may have more time to equilibrate with their environment and to restore their metabolism (Borken & Matzner, 2009). This could reduce the stress for microorganisms during rewetting of dry soil (Halverson *et al.*, 2000; Schimel *et al*., 2007), and be particularly important for fungi, which have been shown to be more negatively affected by excess water than bacteria (Harris *et al.*, 2003).

The discussion above suggests that extreme climatic events can induce or enhance SWR, which in turn may increase the stability of SOM against microbial decomposition and reduce the release of CO_2 from soil. These effects are likely to become more important in the future as in a generally warmer climate with increased mean temperatures heat waves and drought periods are predicted to become more intense, more frequent, and longer lasting (Meehl & Tebaldi, 2004; Meehl *et al*., 2007). Particularly in regions most susceptible to extreme climatic events in the present climate, such as the western and southern United States, central Asia and the Mediterranean region, SWR can become enhanced. But also in temperate regions, such as the northwestern United States as well as western and central Europe with a predicted increase of heat wave and drought severity in the 21st century, increasing SWR can become an important issue (e.g. Fowler *et al*., 2003). Consequently, in addition to a general trend of a drought-induced reduction of cumulative carbon mineralization in all ecosystems on the annual scale (Borken & Matzner, 2009), SWR may contribute to a negative feedback of soil respiration to climate change. On the other hand, increased SWR may also reduce the amount of plant available nitrogen as increasing intensity and duration of drought was shown to decrease nitrogen mineralization (Borken & Matzner, 2009). A reduced water and nitrogen availability in water repellent soils may have negative effects on plant productivity, which would decrease carbon sequestration. However, as experimental evidence from field experiments is lacking it is difficult to assess the actual effect of SWR on the carbon balance in response to extreme climatic events.

Consideration of soil water repellency in terrestrial ecosystem models

To date, SWR has not been considered in SOM models. However, as the phenomenon is likely to become more important under future climate change, it would be desirable for specific ecosystems, such as grasslands and forests, to implement a set of parameters describing the dynamics of wettability in current models. The most important parameter in this context is θ_s. Summing up the results from the literature, it turns out that SWR depends on θ_s in a complex non-linear fashion. Usually, soils are wettable close to field capacity and with decreasing θ_s they become increasingly water repellent up to a local or global maximum near the wilting point. From this maximum onward, SWR decreases monotonically or rises again near the oven-dry state (Regalado & Ritter, 2009a). An important feature of the SWR-θ_s relationship to be considered in carbon exchange models is the θ_s value at which a soil turns from wettable to water repellent (i.e. θ_{crit}). Because of the hysteretic nature of the SWR-θ_s relationship, θ_{crit} is not a single value but rather a value range. The non-linear behavior and the hysteretic nature of the SWR-θ_s relationship complicate the development of an empirical SWR model. Despite these problems there are some recent approaches describing the dependence of SWR on θ_s which will be discussed in the following.

To obtain detailed information about the wetting characteristics related to soil moisture, Regalado & Ritter (2005) measured α_{sw} on a series of 140 samples from volcanic ash topsoils as a function of θ_s. The most significant parameter to differentiate between the wettability of the samples was defined by integrating the α_{sw}-θ_s function in the range from field capacity to air dryness. The integral was found to be significantly correlated with θ_s at minimum repellency (which was close to field capacity) and at maximum repellency, and with the SOC content (Regalado & Ritter, 2005), which was also revealed by de Jonge *et al*. (1999). Recently, Regalado & Ritter (2009a, b) developed a multiple linear bimodal model for describing the SWR-θ_s relationship for a series of organic topsoils with SOC contents ranging from about 22 to 81% by mass. After calibrating the model with a subset of randomly selected data pairs the model successfully predicted the moisture dependent variation of SWR of the remaining samples.

Täumer *et al.* (2005) found for a Hortic Anthrosol with high and very heterogeneously distributed SOC contents that a prediction of soil wettability by θ_s alone is not possible. Based on these findings they suggested an approach for calculating θ_{crit} as a function of the SOC content. Their data show that θ_{crit} was directly related to the SOC content, which is consistent with Fig. 5 and with the general observation that SWR increases with increasing amount of SOC as reported in several studies (Mataix-Solera & Doerr, 2004; Moral Garcia *et al.*, 2005; Varela *et al.*, 2005). Bachmann *et al.* (2007) re-analyzed the data from Täumer *et al.* (2005) and found that the SWR-θ_s relationship follows a third-order polynom and is similar in shape for different SOC contents. However, in this context it is important to note that SWR is not only affected by the total quantity of SOM but also by its chemical composition and its amount in relation to clay content (i.e. its effectiveness) (Ellerbrock *et al.*, 2005). Particularly for very low SOC contents (<1% by mass) SWR was found to increase again with decreasing amount of SOC.

A general problem associated with most approaches is that the SWR-θ_s relationship is typically determined for soil coming from a wet state (drying branch) and therefore does not account for hysteresis which is frequently observed (e.g. Doerr & Thomas, 2000). This problem was addressed by Bachmann *et al.* (2007) who developed a conceptual model describing the relationship between α_{sw} and θ_s which includes the effect of hysteresis. Their model also considers the time-dependent behavior of α_{sw} at fixed θ_s, which is closely related to the soil moisture level and the wetting history, that is, whether a soil currently dries out or is wetted.

Summarizing the approaches and findings presented above, a general behavior of SWR in relation to θ_s can be derived (Fig. 6). For θ_s near field capacity a soil can be expected to be wettable (Bachmann *et al*., 2007). As the soil dries out, wettability will not change until θ_{crit} is reached, where the soil becomes water repellent to some degree. The values of θ_{crit} can be expected to be close to, but above the θ_s at the permanent wilting point (Bachmann *et al*., 2007) and can be estimated by the SOC content (see Fig. 5). When the soil dries out further wettability will decrease until a maximum of SWR is reached, which is mainly determined by the SOC content. In addition, the soil pH can be important as for example in acidic soils the functional groups of SOM are mostly protonated (Horne & McIntosh, 2000), which is likely to enhance SWR. When a dry soil is wetted again, wettability will not change until θ_{crit} is reached. From this point onward, a further increase of θ_s will gradually decrease SWR. Both the increase of SWR upon drying and the decrease of SWR upon wetting (which is usually referred to as 'persistence of SWR') are time-dependent processes due to conformational changes of SOM (Ma'shum & Farmer, 1985), which depend on the composition of SOM, the prevailing T_s and the present θ_s. As T_s during drying usually is greater than during wetting the conformational changes upon drying may proceed faster as compared to the processes upon wetting (Bayer & Schaumann, 2007), as indicated by the steeper slope of the drying branch in Fig. 6. The time dependence of these processes may in part explain the hysteretic nature of the SWR-θ_s relationship, i.e. that θ_{crit} typically is not found to be a single value but rather a range of values depending on whether a soil is drying or wetting, that is, the wetting history.

Please insert Fig. 6

Consequently, the most important parameters affecting the extent and dynamics of SWR are: (i) precipitation and temperature, which determine current θ_s as well as wetting history, (ii) SOC content, which mainly determines θ_{crit}, and (iii) soil texture and pH, which in combination with the SOC content determine the degree of SWR. As these parameters are usually considered in ecosystem models and information is easily available, it should be possible to include a set of empirical relations for estimating the extent and temporal dynamics of SWR for a certain soil. The effect on SOM decomposition is less clear since mechanisms exist that both may enhance or decrease decomposer activity. More research is needed in this context.

Conclusions

In this paper, we highlighted the impact of extreme climatic events on SWR and discussed possible climate change-triggered variations in wettability and their significance for carbon mineralization. We put forward that SWR may have important consequences for carbon mineralization due to changes in soil water distribution and availability on the one hand, and to its impact on aggregate stability on the other hand. Both effects can potentially reduce the microbial accessibility of SOM and will become effective particularly during the rewetting of dry soil. Furthermore, it was shown that SWR is potentially sensitive to extreme climatic events, which gives rise to a possible feedback between climate change and SWR. Particularly after long drought events in combination with high temperatures it is conceivable that a formerly wettable soil will not regain complete wettability, but remains water repellent to some degree. In this context, the occurrence of wildfires, which are likely to be promoted by extreme climatic events, can intensify SWR. This may cause long-term effects on soil moisture dynamics with low θ_s even during the wet season. Such scenarios are likely to become more important in the future particularly in regions with a semi-arid climate. Thus far, temperate and boreal ecosystems have been less affected by severe droughts, but future changes in precipitation with increasing frequency of summer droughts may have important effects on SWR also in these regions.

We conclude that there is a potential impact of extreme events on SWR and that SWR in turn has the potential to reduce carbon mineralization. On the other hand, a reduced nitrogen and water availability in water repellent soils can have a negative impact on plant productivity and may offset the positive effect of SWR on carbon sequestration. Since experimental evidence from field experiments is lacking it is difficult to assess the net effect of SWR on the carbon balance in response to extreme climatic events at the present time. However, as SWR is likely to become more significant under future climate change, it would be desirable to consider it in ecosystem and climate modeling to account for its effects on carbon mineralization.

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References

Almagro M, López J, Querejeta JI, Martínez-Mena M (2009) Temperature dependence of soil CO_2 efflux is strongly modulated by seasonal patterns of moisture availability in a Mediterranean ecosystem. *Soil Biology and Biochemistry*, **41**, 594-605.

Arcenegui V, Mataix-Solera J, Guerrero C, Zornoza R, Mataix-Beneyto J, García-Orenes F (2008) Intermediate effects of wildfires on water repellency and aggregate stability in Mediterranean calcareous soils. *Catena*, **74**, 219-226.

Austin AT, Yahdjian L, Stark JM, *et al.* (2004) Water pulses and biogeochemical cycles in arid and semiarid ecosystems. *Oecologia*, **141**, 221-235.

Bachmann J, Deurer M, Arye G (2007) Modeling water movement in heterogeneous water-repellent soil: 1. Development of a contact angle-dependent water-retention model. *Vadose Zone Journal*, **6**, 436-445.

Bachmann J, Guggenberger G, Baumgartl T, *et al.* (2008) Physical carbon-sequestration mechanisms under special consideration of soil wettability. *Journal of Plant Nutrition and Soil Science*, **171**, 14-26.

Bachmann J, Horton R, van der Ploeg RR (2001) Isothermal and nonisothermal evaporation from four sandy soils of different water repellency. *Soil Science Society of America Journal*, **65**, 1599-1607.

Bachmann J, Woche SK, Goebel M-O, Kirkham MB, Horton R (2003) Extended methodology for determining wetting properties of porous media. *Water Resources Research*, **39**, 1353, doi: 10.1029/2003WR002143.

Bayer JV, Schaumann GE (2007) Development of soil water repellency in the course of isothermal drying and upon pH changes in two urban soils. *Hydrological Processes*, **21**, 2266-2275.

Besnard E, Chenu C, Balesdent J, Puget P, Arrouays D (1996) Fate of particulate organic matter in soil aggregates during cultivation. *European Journal of Soil Science*, **47**, 495-503.

Birch HF (1958) Further aspects of humus decomposition. *Nature*, **182**, 1172-1172.

Bisdom EBA, Dekker LW, Schoute JFT (1993) Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. *Geoderma*, **56**, 105-118.

Bond RD, Harris JR (1964) The influence of the microflora on physical properties of soils. I. Effects associated with filamentous algae and fungi. *Australian Journal of Soil Research*, **2**, 111-122.

Borken W, Matzner E (2009) Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. *Global Change Biology*, **15**, 808-824.

Buczko U, Bens O, Hüttl RF (2005) Variability of soil water repellency in sandy forest soils with different stand structure under Scots pine (Pinus sylvestris) and beech (Fagus sylvatica). *Geoderma*, **126**, 317-336.

Buczko U, Bens O, Hüttl RF (2007) Changes in soil water repellency in a pine-beech forest transformation chronosequence: Influence of antecedent rainfall and air temperatures. *Ecological Engineering*, **31**, 154-164.

Capriel P (1997) Hydrophobicity of organic matter in arable soils: influence of management. *European Journal of Soil Science*, **48**, 457-462.

Capriel P, Beck T, Borchert H, Harter P (1990) Relationship between soil aliphatic fraction extracted with supercritical hexane, soil microbial biomass, and soil aggregate stability. *Soil Science Society of America Journal*, **54**, 415-420.

Chan KY (1992) Development of seasonal water repellence under direct drilling. *Soil Science Society of America Journal*, **56**, 326-329.

Chandler C, Cheney P, Thomas P, Trabaud L, Williams D (1983) *Fire in Forestry. Vol I. Forest Fire Behaviour and Effects*. John Wiley & Sons, New York.

Chapin FS, Woodwell GM, Randerson JT, *et al.* (2006) Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems*, **9**, 1041-1050.

Churaev NV (2000) *Liquid and Vapor Flows in Porous Bodies - Surface Phenomena*, *Topics in Chemical Engineering*, *Vol. 13*. Gordon and Breach Science Publishers, Amsterdam.

Cisneros-Dozal LM, Trumbore SE, Hanson PJ (2007) Effect of moisture on leaf litter decomposition and its contribution to soil respiration in a temperate forest. *Journal of Geophysical Research-Biogeosciences*, **112**, G01013, doi: 10.1029/2006JG000197.

Coelho COA, Laouina A, Regaya K, *et al.* (2005) The impact of soil water repellency on soil hydrological and erosional processes under Eucalyptus and evergreen Quercus forests in the Western Mediterranean. *Australian Journal of Soil Research*, **43**, 309-318.

Crockford H, Topalidis S, Richardson DP (1991) Water repellency in a dry sclerophyll eucalypt forest - measurements and processes. *Hydrological Processes*, **5**, 405-420.

Davidson EA, Belk E, Boone RD (1998) Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Global Change Biology*, **4**, 217-227.

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, **440**, 165-173.

de Jonge LW, Jacobsen OH, Moldrup P (1999) Soil water repellency: Effects of water content, temperature, and particle size. *Soil Science Society of America Journal*, **63**, 437-442.

de Jonge LW, Moldrup P, Jacobsen OH (2007) Soil-water content dependency of water repellency in soils: Effect of crop type, soil management, and physical-chemical parameters. *Soil Science*, **172**, 577-588.

de Jonge LW, Moldrup P, Schjonning P (2009) Soil infrastructure, interfaces and translocation processes in inner space ('soil-it-is'): towards a road map for the constraints and crossroads of soil architecture and biophysical processes. *Hydrology and Earth System Sciences*, **13**, 1485-1502.

DeBano LF, Mann LD, Hamilton DA (1970) Translocation of hydrophobic substances into soil by burning organic litter. *Soil Science Society of America Proceedings*, **34**, 130-133.

Dekker LW, Doerr SH, Oostindie K, Ziogas AK, Ritsema CJ (2001) Water repellency and critical soil water content in a dune sand. *Soil Science Society of America Journal*, **65**, 1667-1674.

Dekker LW, Ritsema CJ (1994) How water moves in a water repellent sandy soil.1. Potential and actual water repellency. *Water Resources Research*, **30**, 2507-2517.

Dekker LW, Ritsema CJ (1995) Finger-like wetting patterns in 2 water-repellent loam soils. *Journal of Environmental Quality*, **24**, 324-333.

Dekker LW, Ritsema CJ (1996) Uneven moisture patterns in water repellent soils. *Geoderma*, **70**, 87-99.

Dekker LW, Ritsema CJ, Oostindie K, Boersma OH (1998) Effect of drying temperature on the severity of soil water repellency. *Soil Science*, **163**, 780-796.

Denef K, Six J, Bossuyt H, Frey SD, Elliott ET, Merckx R, Paustian K (2001) Influence of dry-wet cycles on the interrelationship between aggregate, particulate organic matter, and microbial community dynamics. *Soil Biology and Biochemistry*, **33**, 1599-1611.

Derjaguin BV, Churaev NV (1986) Properties of water layers adjacent to interfaces. In: *Fluid Interfacial Phenomena* (ed Croxton CA), pp. 663-738. John Wiley & Sons, New York.

Doerr SH, Dekker LW, Ritsema CJ, Shakesby RA, Bryant R (2002) Water repellency of soils: The influence of ambient relative. *Soil Science Society of America Journal*, **66**, 401-405.

Doerr SH, Shakesby RA, Walsh RPD (2000) Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews*, **51**, 33-65.

Doerr SH, Thomas AD (2000) The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. *Journal of Hydrology*, **231**, 134-147.

Drehlich J (1997) Static contact angles for liquids at heterogeneous rigid solid surfaces, *Polish Journal of Chemistry*, **71**, 525-549.

Ekschmitt K, Kandeler E, Poll C, *et al.* (2008) Soil carbon preservation through habitat constraints and biological limitations on decomposer activity. *Journal of Plant Nutrition and Soil Science*, **171**, 27-35.

Ekschmitt K, Liu MQ, Vetter S, Fox O, Wolters V (2005) Strategies used by soil biota to overcome soil organic matter stability - why is dead organic matter left over in the soil? *Geoderma*, **128**, 167-176.

Ellerbrock RH, Gerke HH, Bachmann J, Goebel M-O (2005) Composition of organic matter fractions for explaining wettability of three forest soils. *Soil Science Society of America Journal*, **69**, 57-66.

Ellies A, Hartge KH (1994) Change of wetting properties of soils due to different crops and varying time. *Journal of Rural Engineering and Development*, **35**, 358-364.

Elliott ET (1986) Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. *Soil Science Society of America Journal*, **50**, 627-633.

Eynard A, Schumacher TE, Lindstrom MJ, Malo DD, Kohl RA (2006) Effects of aggregate structure and organic C on wettability of Ustolls. *Soil and Tillage Research*, **88**, 205-216.

Feeney DS, Crawford JW, Daniell T, *et al.* (2006) Three-dimensional microorganization of the soil-root-microbe system. *Microbial Ecology*, **52**, 151-158.

Ferguson GS, Whitesides JM (1992) Thermal reconstruction of the functionalized interface of polyethylene carboxylic acid and its derivatives. In: *Modern Approaches to Wettability – Theory and Applications* (eds Schrader ME, Loeb GI), pp. 143-177. Plenum Press, New York.

Fowler HJ, Kilsby CG, O'Connell PE (2003) Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system. *Water Resources Research*, **39**, 1222, doi: 10.1029/2002WR001778.

Franco CMM, Clarke PJ, Tate ME, Oades JM (2000) Hydrophobic properties and chemical characterisation of natural water repellent materials in Australian sands. *Journal of Hydrology*, **231**, 47-58.

Franco CMM, Tate ME, Oades JM (1995) Studies on non-wetting Sands. 1. The role of intrinsic particulate organic matter in the development of water-repellency in non-wetting sands. *Australian Journal of Soil Research*, **33**, 253-263.

Ganguly AR, Steinhaeuser K, Erickson DJ, *et al.* (2009) Higher trends but larger uncertainty and geographic variability in 21st century temperature and heat waves. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 15555-15559.

Garratt JR (1992) Extreme maximum land surface temperatures. *Journal of Applied Meteorology*, **31**, 1096-1105.

Gerten D, Schaphoff S, Lucht W (2007) Potential future changes in water limitations of the terrestrial biosphere. *Climatic Change*, **80**, 277-299.

Goebel M-O, Bachmann J, Woche SK, Fischer WR (2005) Soil wettability, aggregate stability, and the decomposition of soil organic matter. *Geoderma*, **128**, 80-93.

Goebel M-O, Bachmann J, Woche SK, Fischer WR, Horton R (2004) Water potential and aggregate size effects on contact angle and surface energy. *Soil Science Society of America Journal*, **68**, 383-393.

Goebel M-O, Woche SK, Bachmann J (2009) Do soil aggregates really protect encapsulated organic matter against microbial decomposition? *Biologia*, **64**, 443-448.

Goebel M-O, Woche SK, Bachmann J, Lamparter A, Fischer WR (2007) Significance of wettability-induced changes in microscopic water distribution for soil organic matter decomposition. *Soil Science Society of America Journal*, **71**, 1593-1599.

Goetz SJ, Bunn AG, Fiske GJ, Houghton RA (2005) Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *Proceedings of the National Academy of Sciences of the United States of America*, **102**, 13521-13525.

González-Pérez JA, González-Vila FJ, Almendros G, Knicker H (2004) The effect of fire on soil organic matter - a review. *Environment International*, **30**, 855-870.

Gordon DC, Hallett PD (2009) Rise in CO_2 affects soil water transport through repellency. *Biologia*, **64**, 532-535.

Gregorich EG, Kachanoski RG, Voroney RP (1989) Carbon mineralization in soil size fractions after various amounts of aggregate disruption. *Journal of Soil Science*, **40**, 649-659.

Greiffenhagen A, Wessolek G, Facklam M, Renger M, Stoffregen H (2006) Hydraulic functions and water repellency of forest floor horizons on sandy soils. *Geoderma*, **132**, 182-195.

Griffin DM (1969) Soil water in ecology of fungi. *Annual Review of Phytopathology*, **7**, 289-310.

Griffin DM (1981) Water potential as a selective factor in the microbial ecology of soils. In: *Water Potential Relations in Soil Microbiology* (eds Parr JF, Gardner WR, Elliott LF), pp. 141-151. Soil Science Society of America, Madison (Wisconsin).

Gruber N, Friedlingstein P, Field CB et al. (2004) The vulnerability of the carbon cycle in the 21st century: an assessment of carbon-climate-human interactions. In: *The Global Carbon Cycle: Integrating Humans*, *Climate and the Natural World* (eds Field C, Raupach M), pp. 46-76. Island Press, Washington D.C.

Gupta V, Germida JJ (1988) Distribution of microbial biomass and its activity in different soil aggregate size classes as affected by cultivation. *Soil Biology and Biochemistry*, **20**, 777-786.

Hadas A, Parkin TB, Stahl PD (1998) Reduced CO_2 release from decomposing wheat straw under N-limiting conditions: simulation of carbon turnover. *European Journal of Soil Science*, **49**, 487-494.

Haines A, Kovats RS, Campbell-Lendrum D, Corvalan C (2006) Harben Lecture - Climate change and human health: impacts, vulnerability, and mitigation. *Lancet*, **367**, 2101-2109.

Hallett PD (2008) A brief overview of the causes, impacts and amelioration of soil water repellency – a review. *Soil Water Research*, **3**, S21-S29.

Hallett PD, Nunan N, Douglas JT, Young IM (2004) Millimeter-scale spatial variability in soil water sorptivity: Scale, surface elevation, and subcritical repellency effects. *Soil Science Society of America Journal*, **68**, 352-358.

Hallett PD, Young IM (1999) Changes to water repellence of soil aggregates caused by substrate-induced microbial activity. *European Journal of Soil Science,* **50**, 35-40.

Halverson LJ, Jones TM, Firestone MK (2000) Release of intracellular solutes by four soil bacteria exposed to dilution stress. *Soil Science Society of America Journal*, **64**, 1630-1637.

Harris K, Young IM, Gilligan CA, Otten W, Ritz K (2003) Effect of bulk density on the spatial organisation of the fungus Rhizoctonia solani in soil. *FEMS Microbiology Ecology*, **44**, 45-56.

Hassink J (1992) Effects of soil texture and structure on carbon and nitrogen mineralization in grassland soils. *Biology and Fertility of Soils*, **14**, 126-134.

Heim RR (2002) A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society*, **83**, 1149-1165.

Heimann M, Reichstein M (2008) Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature*, **451**, 289-292.

Horne DJ, McIntosh JC (2000) Hydrophobic compounds in sands in New Zealand - extraction, characterisation and proposed mechanisms for repellency expression. *Journal of Hydrology*, **231**, 35-46.

Huffman EL, MacDonald LH, Stednick JD (2001) Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes*, **15**, 2877-2892.

Hurraß J, Schaumann GE (2006) Properties of soil organic matter and aqueous extracts of actually water repellent and wettable soil samples. *Geoderma*, **132**, 222-239.

Huxman TE, Snyder KA, Tissue D, *et al.* (2004) Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. *Oecologia*, **141**, 254-268.

Huygens D, Boeckx P, van Cleemput O, Oyarzun C, Godoy R (2005) Aggregate and soil organic carbon dynamics in South Chilean Andisols. *Biogeosciences*, **2**, 159-174.

Jaramillo DF, Dekker LW, Ritsema CJ, Hendrickx JMH (2000) Occurrence of soil water repellency in arid and humid climates. *Journal of Hydrology*, **231**, 105-111.

Jensen KD, Beier C, Michelsen A, Emmett BA (2003) Effects of experimental drought on microbial processes in two temperate heathlands at contrasting water conditions. *Applied Soil Ecology*, **24**, 165-176.

Jex GW, Bleakley BH, Hubbell DH, Munro LL (1985) High humidity-induced increase in water repellency in some sandy soils. *Soil Science Society of America Journal*, **49**, 1177-1182.

Johnson MS, Lehmann J, Steenhuis TS, de Oliveira LV, Fernandes ECM (2005) Spatial and temporal variability of soil water repellency of Amazonian pastures. *Australian Journal of Soil Research*, **43**, 319-326.

Kallis G (2008) Droughts. *Annual Review of Environment and Resources*, **33**, 85-118.

Kasischke ES, Turetsky MR (2006) Recent changes in the fire regime across the North American boreal region - Spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters*, **33**, L09703, doi: 10.1029/2006GL025677.

Keizer JJ, Coelho COA, Matias MJS, Domingues CSP, Ferreira AJD (2005) Soil water repellency under dry and wet antecedent weather conditions for selected land-cover types in the coastal zone of central Portugal. *Australian Journal of Soil Research*, **43**, 297-308.

Keizer JJ, Doerr SH, Malvar MC, Ferreira AJD, Pereira V (2007) Temporal and spatial variations in topsoil water repellency throughout a crop-rotation cycle on sandy soil in north-central Portugal. *Hydrological Processes*, **21**, 2317-2324.

Kieft TL, Amy PS, Brockman FJ, Fredrickson JK, Bjornstad BN, Rosacker LL (1993) Microbial abundance and activities in relation to water potential in the vadose zones of arid and semiarid sites. *Microbial Ecology*, **26**, 59-78.

King PM (1981) Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. *Australian Journal of Soil Research*, **19**, 275-285.

Knicker H (2007) How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. *Biogeochemistry*, **85**, 91-118.

Kobayashi M, Shimizu T (2007) Soil water repellency in a Japanese cypress plantation restricts increases in soil water storage during rainfall events. *Hydrological Processes*, **21**, 2356-2364.

Kramers G, van Dam JC, Ritsema CJ, Stagnitti F, Oostindie K, Dekker LW (2005) A new modelling approach to simulate preferential flow and transport in water repellent porous media: Parameter sensitivity, and effects on crop growth and solute leaching. *Australian Journal of Soil Research*, **43**, 371-382.

Kundzewicz ZW, Mata LJ, Arnell N et al. (2007) Freshwater resources and their management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE), pp. 173-210. Cambridge University Press, Cambridge.

Kurane I (2009) The emerging and forecasted effect of climate change on human health. *Journal of Health Science*, **55**, 865-869.

Lal R (2008) Soil carbon stocks under present and future climate with specific reference to European ecoregions. *Nutrient Cycling in Agroecosystems*, **81**, 113-127.

Lal R, Follett F, Stewart BA, Kimble JM (2007) Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science*, **172**, 943-956.

Lamparter A, Bachmann J, Goebel M-O, Woche SK (2009) Carbon mineralization in soil: Impact of wetting-drying, aggregation and water repellency. *Geoderma*, **150**, 324-333.

Le Quéré C, Raupach MR, Canadell JG, *et al.* (2009) Trends in the sources and sinks of carbon dioxide. *Nature Geoscience,* **2**, 831-836.

Lee X, Wu HJ, Sigler J, Oishi C, Siccama T (2004) Rapid and transient response of soil respiration to rain. *Global Change Biology*, **10**, 1017-1026.

Leelamanie DAL, Karube J (2007) Effects of organic compounds, water content and clay on the water repellency of a model sandy soil. *Soil Science and Plant Nutrition*, **53**, 711-719.

Leighton-Boyce G, Doerr SH, Shakesby RA, Walsh RPD, Ferreira AJD, Boulet AK, Coelho COA (2005) Temporal dynamics of water repellency and soil moisture in eucalypt plantations, Portugal. *Australian Journal of Soil Research*, **43**, 269-280.

Lewin M, Mey-Marom A, Frank R (2005) Surface free energies of polymeric materials, additives and minerals. *Polymers for Advanced Technologies*, **16**, 429-441.

Lichner L, Hallett PD, Feeney DS, Dugova O, Sir M, Tesar M (2007) Field measurement of soil water repellency and its impact on water flow under different vegetation. *Biologia*, **62**, 537-541.

Luo Y, Zhou X (2006) *Soil Respiration and the Environment*. Academic/Elsevier, San Diego.

Ma'shum M, Farmer VC (1985) Origin and assessment of water repellency of a sandy south australian soil. *Australian Journal of Soil Research*, **23**, 623-626.

Ma'shum M, Tate ME, Jones GP, Oades JM (1988) Extraction and characterization of water-repellent materials from Australian soils. *Journal of Soil Science*, **39**, 99-110.

Marschner B, Kalbitz K (2003) Controls of bioavailability and biodegradability of dissolved organic matter in soils. *Geoderma*, **113**, 211-235.

Mataix-Solera J, Doerr SH (2004) Hydrophobicity and aggregate stability in calcareous topsoils from fire-affected pine forests in southeastern Spain. *Geoderma*, **118**, 77-88.

McGhie DA, Posner AM (1980) Water repellence of a heavy-textured Western-Australian surface soil. *Australian Journal of Soil Research*, **18**, 309-323.

McGhie DA, Posner AM (1981) The effect of plant top material on the water repellence of fired sands and water repellent soils. *Australian Journal of Agricultural Research*, **32**, 609-620.

Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, **305**, 994-997.

Meehl GA, Stocker TF, Collins WD et al. (2007) Global climate projections. In: *Climate Change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* (eds Solomon S, Qin D, Manning M et al.), pp. 747-845. Cambridge University Press, Cambridge.

Mellander PE, Lofvenius MO, Laudon H (2007) Climate change impact on snow and soil temperature in boreal Scots pine stands. *Climatic Change*, **85**, 179-193.

Mills AL, Powelson DK (1996) Bacterial interactions with surfaces in soils. In: *Bacterial Adhesion – Molecular and Ecological Diversity* (ed Fletcher M), pp. 25-57. Wiley-Liss Inc., New York.

Moral Garcia FJM, Dekker LW, Oostindie K, Ritsema CJ (2005) Water repellency under natural conditions in sandy soils of southern Spain. *Australian Journal of Soil Research*, **43**, 291-296.

Mouillot F, Rambal S, Joffre R (2002) Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. *Global Change Biology*, **8**, 423-437.

Mueller RC, Scudder CM, Porter ME, Trotter RT, Gehring CA, Whitham TG (2005) Differential tree mortality in response to severe drought: evidence for long-term vegetation shifts. *Journal of Ecology*, **93**, 1085-1093.

Neelin JD, Munnich M, Su H, Meyerson JE, Holloway CE (2006) Tropical drying trends in global warming models and observations. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 6110-6115.

Novak V, Lichner L, Zhang B, Knava K (2009) The impact of heating on the hydraulic properties of soils sampled under different plant cover. *Biologia*, **64**, 483-486.

Or D, Smets BF, Wraith JM, Dechesne A, Friedman SP (2007) Physical constraints affecting bacterial habitats and activity in unsaturated porous media - a review. *Advances in Water Resources*, **30**, 1505-1527.

Orchard VA, Cook FJ (1983) Relationship between soil respiration and soil moisture. *Soil Biology and Biochemistry*, **15**, 447-453.

Paul EA (2007) *Soil Microbiology, Ecology, and Biochemistry* (3^{rd} ed.). Academic Press, San Diego.

Peñuelas J, Boada M (2003) A global change-induced biome shift in the Montseny mountains (NE Spain). *Global Change Biology*, **9**, 131-140.

Piccolo A, Mbagwu JSC (1999) Role of hydrophobic components of soil organic matter in soil aggregate stability. *Soil Science Society of America Journal*, **63**, 1801-1810.

Poll C, Marhan S, Ingwersen J, Kandeler E (2008) Dynamics of litter carbon turnover and microbial abundance in a rye detritusphere. *Soil Biology and Biochemistry*, **40**, 1306-1321.

Powlson DS (1980) The effects of grinding on microbial and non-microbial organic matter in soil. *Journal of Soil Science*, **31**, 77-85.

Rabie T, el Tahir S, Alireza T, Sanchez Martinez G, Ferl K, Cenacchi N (2008) The health dimension of climate change. Background paper for *Adapting to Climate Change in Europe and Central Asia* (eds Fay M, Block RI, Ebinger J). World Bank, Washington, D.C.

Regalado CM, Ritter A (2005) Characterizing water dependent soil repellency with minimal parameter requirement. *Soil Science Society of America Journal*, **69**, 1955-1966.

Regalado CM, Ritter A (2009a) A bimodal four-parameter lognormal linear model of soil water repellency persistence. *Hydrological Processes*, **23**, 881-892.

Regalado CM, Ritter A (2009b) A soil water repellency empirical model. *Vadose Zone Journal*, **8**, 136-141.

Ritsema CJ, Dekker LW, Heijs AWJ (1997) Three-dimensional, fingered flow patterns in a water repellent sandy field soil. *Soil Science*, **162**, 79-90.

Roberts FJ, Carbon BA (1971) Water repellence in sandy soils of South-Western Australia. II. Some chemical characteristics of the hydrophobic skins. *Australian Journal of Soil Research*, **10**, 35-42.

Roper MM (2004) The isolation and characterisation of bacteria with the potential to degrade waxes that cause water repellency in sandy soils. *Australian Journal of Soil Research*, **42**, 427-434.

Rose CW (1968) Water transport in a soil with a daily temperature wave. I. Theory and experiment. *Australian Journal of Soil Research*, **6**, 31-44.

Rowell DP, Jones RG (2006) Causes and uncertainty of future summer drying over Europe. *Climate Dynamics*, **27**, 281-299.

Roy JL, McGill WB (2000) Flexible conformation in organic matter coatings: An hypothesis about soil water repellency. *Canadian Journal of Soil Science*, **80**, 143-152.

Roy JL, McGill WB (2002) Assessing soil water repellency using the molarity of ethanol droplet (MED) test. *Soil Science*, **167**, 83-97.

Savage SM, Heaton C, Osborn J, Letey J (1972) Substances contributing to fire-induced water repellency in soils, *Soil Science Society of America Proceedings*, **36**, 674-678.

Schiff SL, Aravena R, Trumbore SE, Hinton MJ, Elgood R, Dillon PJ (1997) Export of DOC from forested catchments on the Precambrian Shield of Central Ontario: Clues from ^{13}C and ^{14}C. *Biogeochemistry*, **36**, 43-65.

Schimel J, Balser TC, Wallenstein M (2007) Microbial stress-response physiology and its implications for ecosystem function. *Ecology*, **88**, 1386-1394.

Schimel JP, Weintraub MN (2003) The implications of exoenzyme activity on microbial carbon and nitrogen limitation in soil: a theoretical model. *Soil Biology and Biochemistry*, **35**, 549-563.

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, **241**, 155-176.

Six J, Elliott ET, Paustian K (2000) Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, **32**, 2099-2103.

Sollins P, Homann P, Caldwell BA (1996) Stabilization and destabilization of soil organic matter: Mechanisms and controls. *Geoderma*, **74**, 65-105.

Steenhuis TS, Dathe A, Zevi Y, *et al.* (2006) Biocolloid retention in partially saturated soils. *Biologia*, **61**, S229-S233.

Strong DT, De Wever H, Merckx R, Recous S (2004) Spatial location of carbon decomposition in the soil pore system. *European Journal of Soil Science*, **55**, 739-750.

Sullivan LA (1990) Soil organic matter, air encapsulation and water-stable aggregation. *Journal of Soil Science*, **41**, 529-534.

Sun YP, Unestam T, Lucas SD, Johanson KJ, Kenne L, Finlay R (1999) Exudation-reabsorption in a mycorrhizal fungus, the dynamic interface for interaction with soil and soil microorganisms. *Mycorrhiza*, **9**, 137-144.

Täumer K, Stoffregen H, Wessolek G (2005) Determination of repellency distribution using soil organic matter and water content. *Geoderma*, **125**, 107-115.

Terashima M, Fukushima M, Tanaka S (2004) Influence of pH on the surface activity of humic acid: micelle-like aggregate formation and interfacial adsorption. *Colloids and Surfaces A-Physicochemical and Engineering Aspects*, **247**, 77-83.

Thwaites LA, de Rooij GH, Salzman S, *et al.* (2006) Near-surface distributions of soil water and water repellency under three effluent irrigation schemes in a blue gum (Eucalyptus globulus) plantation. *Agricultural Water Management*, **86**, 212-219.

Tisdall JM (1996) Formation of soil aggregates and accumulation of soil organic matter. In: *Structure and Organic Matter Storage in Agricultural Soils* (eds Carter MR, Stewart BA), pp. 57-96. Advances in Soil Science, CRC Press, Boca Raton.

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, **33**, 141-163.

Torkzaban S, Hassanizadeh SM, Schijven JF, de Bruin HAM, Husman A (2006a) Virus transport in saturated and unsaturated sand columns. *Vadose Zone Journal*, **5**, 877-885.

Torkzaban S, Hassanizadeh SM, Schijven JF, van den Berg H (2006b) Role of air-water interfaces on retention of viruses under unsaturated conditions. *Water Resources Research*, **42**, W12S14, doi: 10.1029/2006WR004904.

Tschapek M (1984) Criteria for determining the hydrophilicity-hydrophobicity of soils. *Journal of Plant Nutrition and Soil Science*, **147**, 137-149.

Valat B, Jouany C, Riviere LM (1991) Characterization of the wetting properties of air-dried peats and composts. *Soil Science*, **152**, 100-107.

van Straaten O, Veldkamp E, Kohler M, Anas I (2010) Spatial and temporal effects of drought on soil CO_2 efflux in a cacao agroforestry system in Sulawesi, Indonesia. *Biogeosciences*, **7**, 1223-1235.

Varela ME, Benito E, de Blas E (2005) Impact of wildfires on surface water repellency in soils of northwest Spain. *Hydrological Processes*, **19**, 3649-3657.

von Lützow M, Kögel-Knabner I, Ekschmitt K, Matzner E, Guggenberger G, Marschner B, Flessa H (2006) Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - a review. *European Journal of Soil Science*, **57**, 426-445.

Wallis MG, Horne DJ (1992) Soil water repellency. *Advances in Soil Science*, **20**, 91-146.

Wallis MG, Horne DJ, McAuliffe KW (1990) A study of water repellency and its amelioration in a yellow-brown sand. 1. Severity of water repellency and the effects of wetting and abrasion. *New Zealand Journal of Agricultural Research*, **33**, 139-144.

Wan JM, Tokunaga TK (1997) Film straining of colloids in unsaturated porous media: Conceptual model and experimental testing. *Environmental Science and Technology*, **31**, 2413-2420.

Wilson JM, Griffin DM (1975) Water potential and respiration of microorganisms in soil. *Soil Biology and Biochemistry*, **7**, 199-204.

Woche SK, Goebel M-O, Kirkham MB, Horton R, van der Ploeg RR, Bachmann J (2005) Contact angle of soils as affected by depth, texture, and land management. *European Journal of Soil Science*, **56**, 239-251.

Wong PTW, Griffin DM (1976) Bacterial movement at high matric potentials. 1. Artificial and natural soils. *Soil Biology and Biochemistry*, **8**, 215-218.

York CA, Canaway PM (2000) Water repellent soils as they occur on UK golf greens. *Journal of Hydrology*, **231**, 126-133.

Young IM, Blanchart E, Chenu C, *et al.* (1998) The interaction of soil biota and soil structure under global change. *Global Change Biology*, **4**, 703-712.

Young IM, Ritz K (2000) Tillage, habitat space and function of soil microbes. *Soil and Tillage Research*, **53**, 201-213.

Young T (1805) An essay on the cohesion of fluids. *Philosophical Transactions of the Royal Society of London*, **95**, 65-87.

Zampieri M, D'Andrea F, Vautard R, Ciais P, de Noblet-Ducoudre N, Yiou P (2009) Hot European summers and the role of soil moisture in the propagation of Mediterranean drought. *Journal of Climate*, **22**, 4747-4758.

Zavala LM, Gonzalez FA, Jordan A (2009) Fire-induced soil water repellency under different vegetation types along the Atlantic dune coast-line in SW Spain. *Catena*, **79**, 153-162.

Zevi Y, Dathe A, McCarthy JF, Richards BK, Steenhuis TS (2005) Distribution of colloid particles onto interfaces in partially saturated sand. *Environmental Science and Technology*, **39**, 7055-7064.

Zhang B, Yao SH, Hu F (2007) Microbial biomass dynamics and soil wettability as affected by the intensity and frequency of wetting and drying during straw decomposition. *European Journal of Soil Science*, **58**, 1482-1492.

Zhang HQ, Hartge KH (1992) Effect of differently humified organic matter on aggregate stability by reducing aggregate wettability. *Journal of Plant Nutrition and Soil Science*, **155**, 143-149.

Ziogas AK, Dekker LW, Oostindie K, Ritsema CJ (2005) Soil water repellency in north-eastern Greece with adverse effects of drying on the persistence. *Australian Journal of Soil Research*, **43**, 281-289.

Table 1 Critical soil water contents (θ_{crit}) determined for a set of soil types with different texture and soil organic carbon (SOC) content

Country	Soil type	Depth (cm)	Texture	SOC (%mass)	θ_{crit} (%vol)	Reference
Australia	Lithosol	0.0–30.0	Sand	–	6.0–8.0	Kramers *et al.* (2005)
Germany	Luvisol	0.0–10.0	Sand	2.8–5.0[*]	7.4–10.3[*]	Buczko *et al.* (2007)
Germany	Arenosol	0.0–7.8	Sand		14.0–16.0	Greiffenhagen *et al.* (2006)
		>7.8	Sand		5.0–6.0	
Greece	–	0.0–5.0	Sand	–	9.3–15.0	Ziogas *et al.* (2005)
	–	7.0–12.0	Sand	–	7.3–15.0	
The Netherlands	Anthrosol	45.0–70.0	Sand	5.2–5.5[*]	~11.0[*]	Dekker *et al.* (1998)
The Netherlands	Gleysol	0.0–2.5	Sand	18.0[*]	18.0–23.0[*]	Dekker *et al.* (2001)
		2.5–5.0	Sand	10.0[*]	14.0–20.0[*]	
		7.0–12.0	Sand	0.5[*]	3.0–8.5[*]	
		14.0–19.0	Sand	0.5[*]	2.0–5.5[*]	
		25.0–30.0	Sand	–	~2.5	
		35.0–40.0	Sand	–	~2.0	
Portugal	Leptosol	0.0–20.0	Loamy sand	5.0–17.6[*]	14.0–27.0[*]	Leighton-Boyce *et al.* (2005)
The Netherlands	Fluvisol	0.0–5.0	Silt loam	–	~40.0	Dekker & Ritsema (1995)
		10.0–15.0	Silt loam	–	~24.0	
		20.0–35.0	Silt loam	–	~20.0	
Japan	Cambisol	0.0–50.0	Clay loam	–	~29.0	Kobayashi & Shimizu (2007)
The Netherlands	Histosol	10.0–15.0	Clayey peat	40–70[*]	34.0–38.5[*]	Dekker & Ritsema (1996)

[*]Data used for preparation of Fig. 5.

Fig. 1 Schematic showing the solid–water contact angle (α_{sw}) as a measure of soil water repellency. The contact angle is related to the interfacial free energies (γ) of the three-phase (gas–liquid–solid) system by Young's equation (Young, 1805), where the indices g, l, and s denote the gas, liquid, and solid phase, respectively. A value of α_{sw} = 0° indicates complete wettability of a surface, values of α_{sw} > 0° indicate soil water repellency, which is also termed hydrophobicity for α_{sw} > 90°.

Fig. 2 Schematic showing the impact of soil water repellency on processes relevant for organic matter decomposition. It illustrates how water repellency affects infiltration and evaporation as well as the distribution and connectivity of the water phase in the soil which in turn influence the accessibility of organic matter as well as the conditions for microbial activity as the most important factors controlling the decomposition of soil organic matter.

Fig. 3 Environmental scanning electron micrographs showing water condensed on hydrophobic glass beads (α_{sw} = 158°) treated with 40 µL dichlorodimethylsilane per 100 g soil (left), and slightly water repellent glass beads (α_{sw} = 48°) washed with acetone (right).

Fig. 4 Schematic showing the potential effects of extreme climatic events on the development of soil water repellency. It demonstrates the interplay between climatic extremes, soil water repellency and the decomposition of soil organic matter and illustrates possible positive (indicated by (+) symbols) and negative (indicated by (-) symbols) feedback effects between them.

Fig. 5 Critical soil water content (θ_{crit}) as a function of the organic carbon content for soils with different texture. The data originate from Dekker & Ritsema (1996), Dekker *et al.* (1998, 2001), Leighton-Boyce *et al.* (2005), and Buczko *et al.* (2007) (see Table 1).

Fig. 6 Schematic diagram illustrating the dynamics of soil water repellency as a function of the water content (θ_{crit} is the critical soil water content, *PWP* is the permanent wilting point, and *FK* is the field capacity).