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Review

Review of the remediation strategies for soil water repellency

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ABSTRACT

Many regions of the world are predicted to experience water scarcity due to more frequent and more severe droughts and increased water demands. Water use efficiency by plants can be negatively affected by soil water repellency (SWR). It is timely to review existing techniques to remedy SWR. Ideally remediation addresses the origins of a problem. However, the fundamental mechanisms of how and why SWR develops are still poorly understood. In this review it was hypothesized that SWR occurs where the balance of input–decomposition of organic matter is impaired, due to either increased input or decreased decomposition rates of hydrophobic substances. Direct and indirect strategies to remedy SWR were distinguished. While direct remediation aims at abolishing the causes of SWR, indirect strategies seek to manage sites with SWR by treating its symptoms. The 12 reviewed strategies include applying surfactants, clay, slow-release fertilizers, lime, and fungicides, bioremediation of SWR through stimulating earthworms, choosing adapted vegetation, irrigation, cultivation, soil aeration and compaction. Some of the techniques have been applied successfully only in laboratory experiments. Our review highlights that it is not straightforward to cure SWR based on easily measurable and site-specific soil and vegetation properties, and that long-term, large-scale field experiments are required to improve the understanding of the evolution of SWR as cornerstone to develop cost-effective and efficient remediation strategies. We also identified current research gaps around the diagnosis and prevention of SWR.

Contents

Abbreviations: CA, contact angle; MED, molarity of ethanol droplet; MPN, most probable number; SOM, soil organic matter; SWR, soil water repellency; WDPT, water drop penetration time.

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1. Introduction

The wettability of soils is a dynamic surface property that is interlinked with many other biological, chemical and physical soil properties. It can be quantitatively measured, for example, by the equilibrium contact angle (CA) between water and a soil surface in air. The results allow defining three different wetting situations: Spontaneous complete wetting (hydrophilicity), for which the CA is zero, and partial wetting with $0^\circ < CA \leq 90^\circ$ and $CA > 90^\circ$, which are referred to as subcritical soil water repellency (SWR) and hydrophobicity, respectively. Water repellency of peat soil has been observed in The Netherlands as early as in the 11th century, when the first polders were built and Dutch engineers noted that the soils did not wet up spontaneously once the polders had been drained (Kirkham, 2005). In the 1940s, research on SWR focused on the identification of vegetation types leading to SWR and developing quantitative measurement techniques for the degree and persistence of SWR. Evidence on the occurrence of SWR under various soil types, climates and land-use scenarios has been gathered in over 50 countries worldwide (Dekker et al., 2005b). SWR occurs in soils of different texture and across a variety of climatic conditions ranging from tropical to subarctic (DeBano, 2000b; Deurer et al., in press; Doerr et al., 2000, 2006; Woche et al., 2005). For example, a recent survey conducted under pastoral land use in New Zealand found no impact of climate on the occurrence of SWR (Deurer et al., in press). Similarly, Jaramillo et al. (2000) based on investigations in the arid Middle Rio Grande Basin in New Mexico (USA) and the humid Piedras Blancas Watershed in Colombia, had to reject their hypothesis that SWR predominantly occurs in dry climates. SWR affects land used for agricultural and pastoral production, coastal dune sands, parks and golf courses (Doerr et al., 2006; Wallis and Horne, 1992) but has also been shown to occur under different types of forest and shrubland (DeBano, 2000b; Doerr et al., 2007). The phenomenon of SWR is an 'emerging' issue in the sense that it has received increasing attention internationally in recent years, with the enhanced awareness of global water scarcity and a more regular occurrence of extreme droughts (Doerr et al., 2000, 2007).

SWR is not a static soil property, because the soil water content can alter the wetting properties. Conceptually, three key site-, soil- and climate-specific properties need to be known to predict the phenomenon of soil water repellency in soils:

1. *The degree of SWR* in form of the CA of the air-dry soil. This maximum CA describes the maximum SWR for the site that might be reached after prolonged dry periods.
2. *The persistence of SWR* in form of the time that is needed for water to infiltrate a water-repellent surface. During rewetting the maximum CA of a water repellent air-dry soil gradually decreases until water can infiltrate.
3. *The critical water content* below which the degree and persistence of SWR are functions of the soil water content. It is neither clear what factors determine the critical water content of a site nor if it is a constant value within a year or over the longer term.

Irregular patterns of degree and persistence of SWR with depth have been reported (Keizer et al., 2007; Ritsema and Dekker, 1998; Woche et al., 2005). Rodríguez-Alleres et al. (2007) found a decrease of the degree of SWR with depth. Generally, the top few centimeters of a soil profile often exhibit the highest SWR (DeBano, 2000b; Vogelmann et al., 2010). The surface soil layer links pedosphere and atmosphere, and SWR has a significant impact on various soil-water related processes that occur at the interface between the two spheres. SWR thereby threatens different key ecosystem services that soils provide, including support of plant growth for food and fiber production (Bond, 1972), water retention, facilitation of high infiltration rates as a way to avoid flooding and erosion (Doerr et al., 2000; Müller et al., 2010; Shakesby et al., 2000; Wallis and Horne, 1992), and the provision of clean drinking water by filtering of agrichemicals (Aslam et al., 2009). This renders SWR an important issue for primary industries, especially for those with permanent vegetation like the pastoral industry in locations without access to irrigation.

However, under specific circumstances, SWR can also be an advantageous soil property. It has been attributed a positive role in sustaining the stability of aggregates (Blanco-Canqui and Lal, 2009; Wang et al., 2000), and the sequestering of organic carbon (Piccolo and Mbagwu, 1999). Recent research highlighted the positive impact of subcritical soil water repellency on aggregate stability in no-tillage arable farming (Blanco-Canqui, 2011), and in vineyards (Bartoli and Dousset, 2011). In addition, SWR reduces the loss of soil water by evaporation (Hallett, 2007), which might be significant in arid and semi-arid climates. Another beneficial aspect of SWR is the ecohydrological advantage of certain tree species over shallow-rooted herbaceous species: In semi-arid southeast Utah, Robinson et al. (2010) found that the shaded leaves of a two-needle pinyon pine (*Pinus edulis* Engelm.) – Utah juniper [*Juniperus osteosperma* (Torr.) Little] woodland led to seasonal SWR in the fine sandy loam resulting in channeling of rainwater into deeper depths where water uptake of shallow-rooted competitive vegetation was reduced. Organically derived hydrophobicity as a bioengineering tool of deep-rooted tree and shrub species to optimize their water and nutrient command was discussed (Verboom and Pate, 2006). These few examples demonstrate that a true understanding of the ecological significance of SWR is still limited, mainly because the occurrence of SWR is spatially and temporally very variable (Regalado and Ritter, 2008; Ritsema and Dekker, 1998; Täumer et al., 2005), and because its effects at larger scales, i.e. catchment or regional scales, have not been fully investigated (Doerr et al., 2003).

Similarly, our understanding of what causes soils to become water-repellent is still incomplete (Dekker et al., 2005b) even though numerous research projects have had the sole objective of determining the evolution of SWR. There is universal agreement that SWR is caused by an accumulation of hydrophobic organic substances relative to the soil's specific surface area. Inconclusive findings on correlations between soil organic matter content and quality with SWR (Doerr et al., 2005; Horne and McIntosh, 2000; Mainwaring et al., 2004; Morley et al., 2005) indicate that the development of SWR is influenced by site-specific conditions. While laboratory experiments demonstrated the dependence of degree and persistence of SWR on soil water content (Czachor et al., 2010; De Jonge et al., 2007; Kawamoto et al., 2007), field data highlighted that although soil water content was an important factor, it could not always account for the observed temporal variations of the degree of SWR (Deurer et al., in press; Keizer et al., 2007). In the meantime, laboratory studies revealed that other temporally variable environmental factors including, for example, pH (Diehl et al., 2010), temperature (Bayer and Schaumann, 2007), humidity (Wallach and Graber, 2007) and biological activities (Schaumann et al., 2007) affect the occurrence and severity of SWR.

Since the end of the 1950s, amelioration of water-repellent soils has been a research topic driven predominantly by the golf course industry, the occurrence of fire-induced soil water repellency, and by Australian soil scientists who battle with infertile soils that cover large areas of south-eastern Australia and which are incapable of retaining water for much of the year. The separation of mitigation strategies into physical, chemical and biological ones was first proposed by Hallett (2008). It also aligns with the concept of soil quality that is represented by a soil's physical, chemical and biological functioning (Karlen et al., 1997) that might be reduced by SWR. Additionally, all mitigation approaches can be separated into direct or indirect remediation strategies. An indirect method aims at managing soil water-repellent soils by treating its symptoms. Examples are regular irrigation combined with the application of surfactants. Direct methods aim at abolishing SWR at a site by addressing its underlying mechanisms. An example is an acceleration of the decomposition of water-repellent substances by introducing or enhancing specialized soil organisms which is termed bioremediation.

The aim of this paper is to review existing remediation strategies for SWR. At the moment, it is not possible to explain or predict the occurrence of SWR at a site even when many biological, chemical and physical soil properties are known. Due to this dilemma, the problem of mitigating SWR was approached from two perspectives: (1) Provide an overview of already tested remediation strategies and assess their performance; and (2) Formulate and discuss a new universal hypothesis for the occurrence of SWR based on a synthesis of knowledge reported in the literature as a starting point for any efficient mitigation of SWR. Additionally, we provide a list of specific research topics that need to be addressed for developing efficient mitigation strategies for SWR.

2. SWR – obesity syndrome of soils? Excessive input of hydrophobic compounds and the lack of their biological digestion

It is known that SWR is caused by natural soil organic matter (SOM), which either covers the mineral grains as thin coatings (Bisdom et al., 1993) or exists as particulate organic matter (Franco et al., 2000a), reducing potentially in both cases the wettability of the soils. But correlations between total SOM content and degree or persistence of SWR are inconsistent (Mataix-Solera and Doerr, 2004; Teramura, 1980) highlighting that the quantity of SOM alone is not always a reliable predictor for the occurrence of SWR. For example, in a study with subcritically water repellent soils, no correlation between SOM content and SWR was found (Woche et al., 2005). Similarly, Doerr et al. (2006) did not detect a correlation between the degree of SWR and SOM content when analyzing a range of soils with different texture and varying degree of SWR, while Deurer's team (in press) reported a positive correlation between the degree of SWR and SOM content in their survey, which included 49 pastoral soils with contact angles above 90°. This inconsistency can be explained by the fact that not all organic carbon compounds are hydrophobic. Soils containing hydrophobic substances do not necessarily express SWR, vice versa. Early on, the quality of SOM, thus, has been recognized as an important contributing factor to the occurrence of SWR (Wallis and Horne, 1992). But in spite of the advancements in molecular analysis techniques, a breakthrough in the identification of the chemical compounds causing SWR has not been achieved yet (Atanassova and Doerr, 2010; Doerr et al., 2005; Horne and McIntosh, 2000; Ma'shum et al., 1988). The most important generic chemical classes assumed to cause SWR are aliphatic hydrocarbons (Atanassova and Doerr, 2010; Horne and McIntosh, 2000; Ma'shum et al., 1988; Savage et al., 1972) and amphiphilic molecules (Graber et al., 2009; Horne and McIntosh, 2000), which have an affinity to both aqueous and non-aqueous media. Recent research around the molecular basis of SWR investigates the relative abundance and arrangement of specific compounds (e.g., Atanassova and Doerr, 2011).

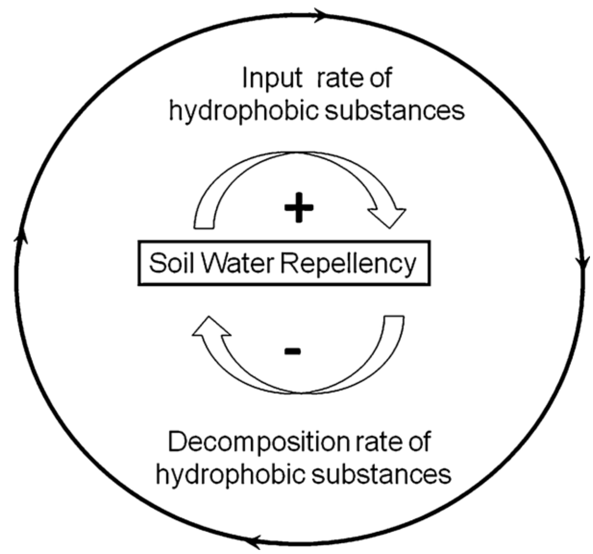

Fig. 1. Cycling of organic matter and its impact on the development of soil water repellency.

As all primary production systems have hydrophobic organic matter as a residue, the new hypothesis proposed in this review is that SWR develops where the soil and site specific balance of input–decomposition of organic matter and especially its hydrophobic component is impaired (Fig. 1). As a result organic matter of an inferior quality accumulates, and hence, the comparison of this process with obesity. This can be due to either an increase of residues or a decrease of the decomposition rate of hydrophobic substances. Below, these two aspects of our hypothesis are detailed.

2.1. *Excessive input of hydrophobic organic substances by vegetation and microorganisms*

Hydrophobic compounds in SOM may derive directly from the decomposition of plant leaves that contain considerable amounts of waxes, aromatic oils, resins and other hydrophobic compounds (Doerr et al., 2000; Scott, 2000), which are generally more resistant to microbial degradation than hydrophilic substances. Accordingly, SWR has been associated with certain plant species including, for example, pine trees (*Pinus* spp.), gum trees (*Eucalyptus* spp.), oak trees (*Quercus* spp.), and *Vaccinuum* spp. (Doerr et al., 2000; Ferreira et al., 2000; Mataix-Solera and Doerr, 2004). Moreover, certain grass species and legumes such as, for example, bentgrass (*Agrostis* spp.), subterranean clover (*Trifolium subterannum*), alfalfa (*Medicago sativa*) seem to promote SWR which might be explained by specific plant-microbial community associations (DeBano, 2000b). Another important plant-derived source of hydrophobic compounds in SOM may be the accumulation of hydrophobic organic acids released as root exudates. The reason for some root exudates to be hydrophobic is their allelopathic function like, for example, suppressing the germination of competing vegetation (Stevens and Tang, 1985). A second important source of hydrophobic substances is the soil's microbial community. The decomposition of organic litter by microbial organisms may lead to hydrophobic substances (McGhie and Posner, 1981). Furthermore, fungal or microbial by-products as well as exudates can be hydrophobic (Hallett and Young, 1999; Urbanek et al., 2007). Rillig et al. (2010) provided the first evidence for a causal link between arbuscular mycorrhizae fungal mycelium growth and SWR of soil aggregates.

An increase of organic residues (Fig. 1) and thus, most likely also an increase of hydrophobic substances might incur, for example, during the transition phase from regular plowing to no-till management practice in arable agricultural systems (Blanco-Canqui, 2011) or after fire (DeBano, 2000a; Huffman et al., 2001; Mataix-Solera and Doerr, 2004).

2.2. Lack of biological digestion of hydrophobic organic substances

The soil's biological activity is dependent on many factors that are influenced by land use, site management, climate, soil and other site-specific conditions. In this review, based on former research (Aslam et al., 2009), shifts in the microbial community composition rather than a general decrease in the soil's microbiological activity are hypothesized to cause decreasing decomposition rates of hydrophobic substances. This may, for example, be a change in the bacteria to fungi ratio or the lack of earthworms at a site due to changing environmental conditions (e.g., decrease in soil pH). Schipper et al. (2010) recently highlighted the sensitivity of carbon sequestration and loss to management practices in pastoral systems. Carbon loss corresponded to intensive dairying systems with high stocking rates, fertilizer inputs and high productivity, while carbon sequestration was observed in extensive hill country pasture systems and was explained by long-term recovery of the sites from erosion and disturbance following the clearance of the native bush about a century ago.

For developing efficient management strategies for sites with SWR, knowing both the origin of water-repellent substances and the reason for the lack of their decomposition at a site would be advantageous.

3. Indirect remediation strategies for SWR

The aim of indirect remediation strategies is to manage the apparent symptoms of SWR. While indirect remediation strategies for SWR (Table 1) might offer a temporary solution to improve soil water infiltration, they do not address the underlying factors causing SWR.

3.1. Chemical indirect remediation strategies for SWR

3.1.1. Application of surfactants/wetting agents/soil conditioners

Mechanism: Surfactants are surface-active substances capable of reducing the surface tension of the liquid in which they are dissolved. Through lowering the surface tension of water and decreasing the CA between water and the soil surface, they increase the driving force for the absorption of water by hydrophobic soils. Different types of surfactants have been developed (Gardner et al., 1975). All surfactants are amphipathic molecules meaning that they contain a strongly polar group (hydrophilic) and a strongly non-polar hydrocarbon group (hydrophobic). This leads to amphipathic adsorption of the surfactant molecule by the soil: The hydrophobic group is repelled by the water and is oriented towards the hydrophobic soil particles while the hydrophilic polar group extends outwards to the water into the pore space.

Recently, Moore and Moore (2005) reviewed the development of soil wetting agents. The original patented wetting agent AquaGro® (patent applied for in 1954 and issued in 1959) was based on a blend of non-ionic surfactants including an alkylphenol ethoxylate (APE). Other more recent wetting agents' formulations contain EO/PO block copolymer surfactants, non-ionic materials with ethylene oxide and propylene oxide units. These are long chain polymers of varying structural complexity, molecular weights and chain lengths with a non-ionic hydrophilic and a hydrophobic end. Most surfactants used nowadays in soil applications contain non-ionic compounds because they are less phytotoxic than cationic or anionic surfactants, and their solubility in water can be regulated more precisely. The market for surfactants is not regulated, and a vast number of products with different formulations (e.g., liquid and granular), different active ingredients at various concentrations and carrier compounds (e.g., silica, zeolite, kaolinite, and smectite) have been developed. The specific properties of surfactants are dependent on the molecular weight, polarity and balance between the hydrophilic and hydrophobic groups in the compound. Recent developments in the soil surfactant industry include not only modifications of product formulations but also new patent-pending chemistry (Moore and Moore, 2005). Progress in surfactant chemistry has been driven by increasing the efficacy of the products, reducing the phytotoxicity of the products, ameliorating environmental concerns with regard to contamination of soil and water resources by surfactants, and costs.

Examples of the application of surfactants to remedy SWR: Surfactants were introduced to agriculture in the early-1950s (De Boodt, 1972). They have been suggested as a strategy for overcoming problems related to SWR in soils (Cisar et al., 2000; Kostka, 2000; Thomas and Karcher, 2000). They are mainly used on golf courses but are also widely used to improve wettability of peat-based horticultural substrates (Handreck, 1992; Osborn et al., 1969). The performance of surfactants on sandy soils under turf has been studied extensively since the 1960s (Table 2). Ideal surfactants prevent the development of water-repellent soil conditions and increase initial water infiltration rates, but they also have a long-term effect on infiltration, resulting in higher and more homogeneous soil water contents within the root zone. The positive impact on water dynamics is linked to improved turf growth and quality.

Researchers found that the performance of surfactants varied greatly even within the same class of surfactants based upon the particular formulation, application rate, dilution rate used for the application and environmental conditions during, before and after the application (Cisar et al., 2000; Kostka et al., 2007). The experiments conducted by Leinauer et al. (2007) demonstrated the importance of multiyear and multisite research to improve the general understanding of how surfactants perform under different conditions. Studies comparing a range of products are scarce (Leinauer et al., 2007; Soldat et al., 2010). A large comparative study has been conducted in 2003/2004 and tested the ten most commonly used wetting agents in the US at nine different locations on golf greens (Henle et al., 2007). The main outcome was that no product performed best at all locations and at all times, but the efficacy of the products depended on weather and location (Henle et al., 2007). While it is often assumed that SWR is

Table 1
Overview on remediation strategies for soil water repellency. The mechanisms of the amelioration strategy can be direct (D) or indirect (ID). They have been developed and tested in the laboratory (L) or in the field (F).

Remediation strategy	Mechanism	Disadvantage	Positive side-effects	Negative side-effects	Use	ScaleF/L
Surfactants	ID	Continuous applications are needed to sustain effect; high costs	Turf quality, seedling emergence, yields, efficacy of agrichemicals, homogeneous wetting of soil, water storage and distribution	Phytotoxicity, contamination of water resources, effects on soil structure and biological communities?	Yes	F/L
Claying	ID (D)	Costs if clay is not available in subsoil or close to site	Yields, pH, CEC, soil fertility, microbial activity, water holding capacity	Soil structure; compaction, copper immobilization, other trace elements?	Yes	L/F
Slow-release fertilizers	D	Costs; no successful field application reported		Not known	No	L/F
Liming	D	Costs	pH, soil fertility, microbiological activity, microbial diversity, earthworms	Not known	No	F
Fungicides	D	Costs	Soil fertility	Not always effective; environmental risk (drift during application, transport to water resources)	Yes	L/F
Bio-remediation	D	Costs, application not practical			No	L/F
Stimulation of earthworms	D	Costs, application		Soil fertility	No	
Vegetation choice	ID	Not everywhere feasible	Water harvesting	May lead to changes in land use system	Yes	F
Irrigation	D	Costs; water availability	Yields		Yes	F
Cultivation	ID	Short-term effect		Subsoiling decreases SOM-content of topsoil, elevated greenhouse gas emissions, erosion	Yes	L/F
Soil aeration	ID	Short-term effects, labor-intensive	Stimulation of microbial communities	Not known	Yes	F
Compaction	ID			Soil structure, soil quality	No	L

a surface phenomenon (Kostka, 2000), Dekker et al. (2004), *inter alia*, demonstrated that SWR in sand under turf can extend beyond 200 mm depth. Oostindie et al. (2008) found convincing evidence of SWR reduction after four applications of a methyl-capped triblock copolymer surfactant to a sandy soil under turf during one summer. They reported that the treatments led to a more homogeneous wetting pattern, increased water uptake and higher moisture levels in the topsoil, and the elimination of actual SWR to a depth of 250 mm (Table 2). In contrast, Dekker et al. (2005a) found that the more homogeneous wetting of a sandy soil treated with a block copolymer was limited to its surface layer. In their experiments, the differences between lowest and highest soil water content were even larger in the treated than the untreated plot. The newer surfactant formulation in the study by Oostindie et al. (2008) might have allowed a deeper penetration of the surfactant into the soil profile.

In conclusion, it is difficult to draw general conclusions about the efficacy of wetting agents. While wetting agents may provide the most immediate solution to SWR in sandy water-repellent soils, their positive impacts are often only short-term effects, and applications have to be repeated regularly throughout the summer. However, additional research is needed to assess whether applying granular soil wetting agents sparingly and more frequently enhances their performance (Barton and Colmer, 2011). Even if the surfactants bind to the topsoil (residual effect), they are biodegradable compounds. Wetting agents are costly, and it might not be an economic solution for ameliorating SWR in agricultural settings.

Limitations and side-effects of the application of surfactants: Wallis and Horne (1992) discussed the phytotoxicity of surfactants in their review paper on SWR. For many surfactants used in the golf course industry, heavy irrigation after application is recommended to limit the potential phytotoxic effects of the surfactants to the turf. Thus, the use of surfactants requires access to water for the application itself and the subsequent irrigation to overcome the surfactants' phytotoxicity. However, it might allow the introduction of deficit irrigation schemes.

Limited research has been conducted on the impacts of surfactants on crop yield and quality in an agricultural context. Early research has found convincing positive impacts on hydraulic properties of agricultural soils (bu-Zreig et al., 2003). Many soils in Western and Southern Australia suffer from severe SWR. Crop and pasture establishment (e.g., germination and emergence) on sites suffering from SWR is very difficult. This led to the development of methods for using surfactants in agriculture situations, such as combining physical amelioration strategies like press wheels with surfactant applications or band applications of surfactants to reduce the volumes of surfactants required and thereby reduce costs (Wallis and Horne, 1992). For barley (*Hordeum vulgare*), the application of a banded wetting agent while furrow seeding with press wheels increased seedling emergence by 55%, dry matter production by 43% and grain yield by 33%, despite more weeds occurring (Crabtree and Gilkes, 1999a). For pasture, the use of a wetting agent plus press wheels increased seedling emergence by 77%. Early pasture production increased six-fold. The wetting agent applied two years previously had a large residual effect on pasture composition. For example, the proportion of subterranean clover increased from 6 to 33% when the wetting agent was used (Crabtree and Gilkes, 1999b). Wetting agents used in irrigated carrots (*Daucus carota*) and alfalfa (*M. sativa*) have increased yields by up to 15 and 20%, respectively (http://www.aquatrols.com/agriculture/products/soil-surfactants/irrigaid-gold/?LOCALE=INT; last accessed 30/03/2011). In a field experiment on sandy soils with SWR in New Zealand pasture, establishment was significantly higher when a surfactant was applied at seeding (Wallis and McAuliffe, 1990).

Hallett (2007) rightly pointed out that the wider environmental consequences of applying soil surfactants have hardly been assessed. He suggested that the soil structure might suffer from soil

Table 2
Selection of field and laboratory studies on the efficacy of surfactants applied to water-repellent soils under pasture or turf.

Type of surfactants/trade name	Soil type/vegetation	Experimental setup	Observations[a]	References
Block copolymer/Aqueduct®	Sand/*Agrostis stolonifera*	0.36 m^2 plots, 2 applications within a month at 27 L ha^{-1}	Volumetric soil water content (0) Water infiltration rate (+)	Thomas and Karcher (2000)
Methyl-capped triblock copolymer/Revolution®	Sand (Typic Psammaquent)/*Festuca* spp.; *Poa annua*	Transect of 60 m length and 0.26 m depth, monthly applications at 19 L ha^{-1} for 4 months	Volumetric soil water content (+) Actual WDPT (0–250 mm) (+) Turf quality[b] (+)	Oostindie et al. (2008)
Block copolymer/Aqueduct® Block copolymer/Primer®604 Methyl-capped triblock copolymer/Revolution®	Sand/*Agrostis stolonifera* L.	3.24 m^2 plots, monthly applications at 19 L ha^{-1} irrigated at 30% of potential evapotranspiration (ET_{pot}) for 4 months (2 years); controls irrigated at 30 and 100% of ET_{pot}	Turf quality[b] (−/+)[c] Volumetric soil water content (0) Homogeneity of soil water content (+) Actual WDPT (10 mm depth) (0/+)[d]	Soldat et al. (2010)
Block copolymer/Primer®604	Sand/*Agrostis* spp.	36 tees (3 tees at 9 holes), monthly applications at 0, 12.5 and 18.5 L ha^{-1} for 3 months	Homogeneity of soil water[e] (+) Turf quality, % of dry patches (+) WDPT at air-dried cores (4 depths, 0–40 mm) (+)	Kostka (2000)
Alkylphenol ethoxylate (APE)/AquaGro®; LescoWet®	Sand/golf green	Information not provided	Severity of dry patches (+)	Danneberger and White (1988)
EO/PO triblock copolymers (hydroxyl-terminated and alkyl-terminated formulations)/n.a.	Sand/–	Surfactant solutions at 4, 6, and 8 g L^{-1} were leached through columns (5 mm ID × 600 mm length) filled with severely water-repellent sand	Water infiltration rate was significantly increased by the alkyl-terminated formulation	Kostka et al. (2007)
EO/PO triblock copolymers (hydroxyl-terminated and alkyl-terminated formulations)/n.a.	Sand/*Agrostis stolonifera* L.	Plots, monthly applications at 1.94 L ha^{-1} hydroxyl-terminated formulation and 0.65, 1.29, 1.94, 2.59 L ha^{-1} alkyl-terminated formulation for 4 months	Turf quality (+)[f] WDPT at air-dried cores (4 depths, 0–40 mm) (+)[f]	Kostka et al. (2007)
EO/PO triblock copolymers (hydroxyl-terminated and alkyl-terminated formulations)/n.a.	Sand/*Agrostis stolonifera* L.	Plots (0.81 m^2), monthly applications at 1.94 L ha^{-1} hydroxyl-terminated or alkyl-terminated formulation	Volumetric soil water content to a depth of 50 mm (+) Homogeneity of soil water (+)	Kostka et al. (2007)
Block copolymer/Primer®604	Typic Psammaquent (sand)/grass	Plots (125 m^2), 12 applications in 8 months at 18 L ha^{-1}	Actual WDPT (6 depths, 0–190 mm) (+ in 5 mm; 0/− in deeper depths) Homogeneity of soil water (+ surface, 0) Critical water content (0–5 mm) (+) Wetting rate measurements (25 mm columns set at −25 mm pressure) (+)	Dekker et al. (2005a)
Alkylphenol ethoxylate (APE)/AquaGro® Block copolymer/Aqueduct® Block copolymer/Primer®604	Sand/*Cynodon dactylon* × *Cynodon transvaalensis*	Plots (1 m^2), weekly applications at 25, 25 and 19 L ha^{-1}, respectively and as combinations at standard rates for 1 month, followed by monthly applications	Turf quality (+/−)[g], % of dry patches (+) WDPT at air-dried cores (4 depths, 0–40 mm) (+)	Cisar et al. (2000)
Experimental formulations	Sand/Research green	Plots (1 m^2), weekly applications at 25 L ha^{-1}	Turf quality (+/−)[g] WDPT at air-dried cores (4 depths, 0–40 mm) (+)	Cisar et al. (2000)
Block copolymer/Aqueduct®	Sand/*Agrostis stolonifera*	Plots (6 m^2), application at 25 L ha^{-1} at weekly intervals for a month	Volumetric soil water content (+) WDPT at air-dried samples (+: 0–10 mm; 0: 10–100 mm) Turf quality[b] (+)	Aamlid et al. (2009)

Table 2 (*Continued*)

Type of surfactants/trade name	Soil type/vegetation	Experimental setup	Observations[a]	References
Block copolymer/Primer®604 Nonylphenol ethoxylate (NPE)/LescoFlo® Block copolymer/Aqueduct® Non-ionic surfactant/Cascade®	Sand/Research green	Plots (1 m^2), applications: Primer monthly at 25 L ha^{-1}; Lesco once at 25 L ha^{-1}; Aqueduct monthly at 19 L ha^{-1}; Cascade once at 50 L ha^{-1}	Turf quality, % of dry patches (+)[g]	Cisar et al. (2000)
Proprietary (mix of) non-ionic surfactant(s); propylene oxide–ethylene oxide block polymer; ethylene glycol butyl ether	Sand/*Pennisetum clandestinum*	Pot experiments to select 4 granular wetting agents out of 10 products to be used in a plot experiment (10 m^2) with 9 and 32% SOM-content (young and old grass); application rates as per label; deficit irrigation regime	For all products except ethylene glycol butyl ether which had no effect: MED (0–25 mm) (−); VWC (+); turfgrass growth & quality (+)[g]; strong positive correlation between MED and amount of active ingredients applied	Barton and Colmer (2011)

[a] + = improved (for WDPT, this means a shorter time); 0 = unchanged; − = deteriorated.
[b] Visual inspection of turf quality.
[c] Depending on year and with which irrigated control the treated plot was compared. The well-irrigated plots outperformed all treatments.
[d] Primer®604 had no impact in one of the two years of the study. Only Revolution® was superior to the well-irrigated control in 2007. For 2008, this was the case for Aqueduct®.
[e] Visual inspection of soil cores (depth not specified).
[f] Alkyl-terminated formulation outperformed the hydroxyl-terminated formulation dependent on application rates and sampling times.
[g] Dependent on product, application rates and times.

surfactants. SWR has been shown to play an important role in the structural stability of soils (von Lutzow et al., 2006). The effect of wetting agents on aggregate stability of a sandy loam has also been investigated and discussed by Mustafa and Letey (1969). Moreover, the impact of surfactants on water balances by increasing evaporation rates could be worth investigating.

Positive side effects of surfactant applications could be their impact on the performance and transport of agrichemicals in water-repellent soils. Nektarios (2002) investigated the impact of surfactants on the water flow pattern in a sand slab chamber in the laboratory. Surfactant treatment resulted in a more uniform infiltration and greater retardation of the breakthrough of two tracers (chloride and a weakly reactive dye) compared with the untreated control. The results, however, also indicated that existing preferential flow pathways were not changed through surfactants. The water-dissolved surfactants were transported in the existing preferential flow pathways instead of wetting the dry soil. The field experiments by Dekker et al. (2005a) similarly illustrated that even regular surfactant application to a hydrophobic sandy soil did not equalize the uneven soil moisture distribution in the soil below the top 5 mm. The application of a soil surfactant reduced the occurrence of SWR and preferential flow in a sandy soil of a golf course fairway in the Netherlands (Oostindie et al., 2008). Sharma et al. (1985) demonstrated that surfactants reduced the mobility of several phosphorus pesticides in a sandy loam and a silt loam. Surfactants reduced fungicide leaching (active ingredients: iprodione and azoxystrobin combined with propiconazole) from water-repellent sand and sand mixed with garden compost lysimeters under golf greens (Larsbo et al., 2008). The surfactants also reduced the persistence of SWR, increased water infiltration and homogenized the distribution of soil water. Information on the effects of surfactants on the fate of agrichemicals is limited.

To the best of our knowledge, no studies have analyzed potential ecological consequences of wetting agents, like, for example, impacts on soil microbial communities. In summary, the potential benefits of using surfactants in agriculture require careful consideration of the environmental, ecological and economic impacts.

3.1.2. Adding clay minerals

Mechanism: Claying ameliorates SWR through a masking of hydrophobic surfaces (Blackwell, 2000), and is based on the fact that most clay minerals are hydrophilic (Tschapek, 1984), have large specific surface areas, and a negative charge. In numerous laboratory experiments, clay minerals were added to sands (naturally water-repellent sands or sands made water-repellent by adding different organic materials) and tested for their ability to decrease SWR (Dlapa et al., 2004; Li et al., 2008; Lichner et al., 2002; Ma'shum et al., 1989; McKissock et al., 2000; Roper, 2005; Ward and Oades, 1993). These experiments contributed to understanding the mechanisms by which clay interacts with organic/sand surfaces and thereby modifies the hydrophobic nature of soils.

Ma'shum et al. (1989) postulated that the efficacy of claying on SWR depends on the ability of clay minerals to disperse. Clay dispersion depends on the crystal structure, particle shape of the clay mineral and the chemistry of the soil solution (e.g., pH, electrical conductivity, sodium adsorption ratio). Clay minerals with a high surface charge flocculate while clay minerals with a low charge remain dispersed on sand surfaces. Clay minerals that disperse upon wetting (e.g., kaolinite, illite) expose a greater surface area than clays that tend to aggregate (e.g., montmorillonite, smectite) and thereby reduce the overall surface area available for physically masking hydrophobic surfaces and facilitating water absorption. The higher the surface area of the added clay, the higher is its impact on SWR. This hypothesis was supported by Ward and Oades' (1993) findings that for claying to be effective, wetting and drying cycles after applying clay are necessary. The wetting allows clay to disperse and, during the drying period, clay particles can mask the hydrophobic soil particles. Various laboratory investigations have confirmed that the efficacy of clay amendments depends on clay mineralogy. In repeated wetting and drying cycles, clays dominated by kaolinite were much more effective in reducing SWR than clay mixtures dominated by montmorillonite (McKissock et al., 2000). After performing a wetting and drying cycle on clay-amended highly hydrophobic sands, Dlapa et al. (2004) even reported an increase in WDPT through the addition of Ca-montmorillonite while kaolinite additions reduced WDPT. Similarly, Ma'shum et al. (1989) showed a high effectiveness of kaolinite. In contrast, in sands that were made highly water-repellent with cetyl alcohol, montmorillonite was more effective than kaolinite (Ward and Oades, 1993). This apparent contradictory result can be explained by the fact that flocculation and dispersion of clays are also affected by the nature of the exchangeable cations present in the soil solution. The tendency of flocculation will increase with increasing cationic charge. This could explain why adding the same clay type to a range of soils can lead to different results. Lichner et al. (2002) concluded from their laboratory experiments with sand that was made water-repellent with different humic acids and in which kaolinite applied at 5 and 10% by weight was not unambiguously effective in alleviating SWR.

This short overview highlights that the mechanisms of how and if claying affects SWR have not been investigated fully. Claying is classified as an indirect remediation technique because it disguises hydrophobic organic compounds instead of breaking them down. However, the additional benefits of the clay addition on other soil properties may in the long term promote the degradation of hydrophobic material through increasing soil fertility and microbiological activities (Blackwell, 2000).

Examples of the application of claying to remedy SWR: Many soils in Western and Southern Australia are sandy soils and suffer from severe SWR. The addition of clay to topsoils (claying) either by deep plowing into clayey subsoil or by a top dressing with clay, is successfully and widely used in Australia. Application rates in SE Australia range between 100 and 250 t ha^{-1} on hills and 40 and 100 t ha^{-1} on flats (Cann, 2000). McKissock et al. (2000) reported that additions of 1–2% clay can prevent SWR. These figures demonstrate that the amounts of clay required to eliminate SWR are high. The use of clay is only economical if clay is readily available and can be either brought to the top by deep plowing or brought to the site from close by for topdressing. The incorporation of the clay material to 10–15 cm is recommended for achieving long-lasting effects. Residual effects of claying of up to 30 years have been reported in the literature (Cann, 2000).

Limitations and side-effects of claying: Claying was tested for its ability to increase yields of crops grown on water-repellent soils in field experiments (Cann, 2000). Water-repellent pastures on sandy soils contain few, if any, legumes and produce as little as 400 kg ha^{-1} dry matter compared with clayed pastures (3250 kg ha^{-1}) which are sub-clover or lucerne based. In wide areas of South Australia, amelioration of SWR by clay spreading generally doubled cropping yields (Cann, 2000). Additional benefits of claying sandy soils are the provision of nutrients (availability and retention) to the infertile sands, the improvement of the cation exchange capacity of soils, and increased soil pH.

On the negative side, Xiong et al. (2005) found that water-repellent soils amended with clay had an increased adsorption capacity for copper while desorption of copper was reduced, and this might lead to reduced bioavailability of copper. The authors pointed out that this may be important when considering wastewater application to clay-amended water-repellent sands, a common practice in arid regions where SWR is widespread. So far, the amelioration of SWR by adding clays has been limited to sandy soils, predominantly in Australia. SWR, however, occurs independent of soil texture (Doerr et al., 2006). Whether claying can be recommended for heavier soils has to be carefully researched with regard to its potential negative effects on soil physical properties, including a decrease in permeability and an increase in compaction.

3.2. Biological indirect remediation strategies for SWR

3.2.1. Adaption

Mechanism: One of the oldest remediation strategies is to select plant species that are naturally adapted to droughts and water-repellent soils (Blackwell, 2000).

Examples of adaption to remedy SWR: Blackwell (2000) gave the example of Blue Lupine (*Lupinus consentinii*), a pasture species that is able to germinate and establish on the soil surface. Increased germination rates were reported in water-repellent soils.

Limitations and side effects of adaption: This remediation strategy has to be considered from a whole-farm and longer-term perspective, especially for drought-prone regions. For example, it might not be possible to maintain pasture production and stocking rates when switching to plant species which are adapted to droughts and water-repellent soils.

3.3. Physical indirect remediation strategies for SWR

3.3.1. Cultivation

Mechanism: Historically, cultivation has been recommended to dilute repellent topsoil with non-repellent soil (Holzhey, 1969). This will, however, depending on the soil type, not only reduce the symptoms of SWR but also decrease the SOM content of the topsoil, leading to a reduced water- and nutrient-holding capacity. In the case of sandy topsoils overlaying clayey substrates, this 'subsoiling' method has been shown to be very effective.

Cultivation causes the abrasion of soil particles and this can remove hydrophobic coatings from water-repellent soil surfaces (Buczko et al., 2006). In the laboratory, abrasion of water-repellent sand through shaking samples in end-over-end shakers significantly reduced SWR of the sand (Wallis and Horne, 1992). This effect, however, was not lasting.

Minimum tillage methods can affect SWR (Blackwell, 2000). On the one hand, the accumulation of plant residues on the soil surface can protect the topsoil from drying out, which might assist in preventing the occurrence of SWR. On the other hand, tillage has also been seen as a physical solution to SWR.

Examples of cultivation to remedy SWR: As shown by Doerr et al. (2006) for humid temperate climates, cultivated soils are virtually unaffected by SWR in comparison to permanently vegetated soils. By using full cultivation in a pasture/crop rotation on a highly hydrophobic soil new pastures initially performed satisfactorily (MacGillivray in Slay, 2008). However, dry patches re-appeared some 3–5 years later in areas that previously showed symptoms of SWR indicating a poorly understood 'memory' effect for SWR in soils.

Limitations and side-effects of cultivation: Cultivation might exacerbate the problem of not only erosion in pastoral production systems, especially in hill-country pasture systems but also on fine-textured cropped soils. Also, cultivation might lead to elevated greenhouse gas emissions.

3.3.2. Turf/soil aeration

Mechanism: There is a range of tractor-mounted/towed mechanical 'aerators' being used to assist with the breakdown of surface thatch.

Examples of turf/soil aeration/water harvesting to remedy SWR: Mechanical tools for sports turf have been around for many years

Fig. 2. Photos of mechanical tools used in the golf industry to mitigate SWR. Tumble corer (top left) for aeration and decompaction for soils of golf course fairways (top right). Vibramole (bottom left) and de-thatcher or scarifier (bottom right).
Photos by Geoff Walker.

and include corers and scarifiers for thatch control, and slicers, spikers, vibramoles, and deep rippers to improve water infiltration (Fig. 2). All these methods are part of the usual management practices on golf courses (Beard, 1973). They have been reviewed by Wallis and Horne (1992). In the agricultural context, combinations of points, discs and press-wheels are used to make furrows before sowing. The idea behind it is that preferential flow is diverted over the water-repellent surface into the furrows to the seeds (Blackwell, 2000).

3.3.3. Compaction

Mechanism: Bryant et al. (2007) examined the impact of compaction on the wettability of water-repellent silt loam soils in compression cells of 76 mm diameter in laboratory experiments. Compaction of the air-dried water-repellent soils (up to 1570 kPa) significantly increased the wettability of the soil surface temporarily (for 20 days) as measured by the WDPT test. The phenomenon was explained by the observed reduction of the surface roughness through the compaction. Increased surface roughness was shown to increase SWR of bare soils (Quere et al., 2003).

Examples of compaction to remedy SWR: It has to be stressed that these positive mitigation results achieved by compacting topsoils are restricted to a single laboratory experiment. No field experiments support these results. It is known that soil compaction can have negative effects on soil structure, soil quality and on the biological activities in soils.

4. Direct remediation strategies for SWR

Direct remediation strategies (Table 1) aim at either reducing the input of hydrophobic substances to soil or increasing their decomposition or both.

4.1. Chemical direct remediation strategies for SWR

4.1.1. Liming

Mechanism: Lime is known to increase the size and activity of microbial populations, especially in acidic soils, by raising the soil pH to more favorable neutral–alkaline levels (Kennedy et al., 2004; Lupwayi et al., 2009). A larger and possibly more diverse microbiological and mesofaunal community enhances the decomposition of hydrophobic organic substances, thus reducing SWR.

In a laboratory experiment, the addition of lime to moist soils resulted in an initially rapid decrease of SWR followed by a much more gradual reduction of SWR (Roper, 2005). The observed two-stage response was explained by a first rapid physical interaction of the lime with the sand covering hydrophobic surfaces followed by a biological process, namely the increased decomposition of hydrophobic compounds by wax-degrading bacteria. How lime interacted with the wax-degrading bacteria remained unclear. The nutritional and pH effect of lime were discussed. The explanation for the two-stage response was supported by an at least 10-fold increase of the populations of wax-degrading bacteria in the soils. A reduction of SWR by adding lime to dry soil was much slower but it was similarly accompanied by increased numbers of wax-degrading bacteria. The number of wax-degrading bacteria was estimated applying a most probable number (MPN) assay that selects specifically for the function of wax degradation in bacteria (Roper and Gupta, 2005).

Examples of the application of liming to remedy SWR: In field experiments with sandy soils in Australia, Roper (2006) found that liming at rates between 3 and 15 t ha^{-1} significantly reduced the degree of SWR. The effect increased with the amounts of lime applied and lasted for at least 4 years. High pH treatment was also found to ameliorate water-repellent soil on sand-based golf greens. Karnok et al. (1993) saturated the topsoil (to a depth of 500 mm) with 0.1 M NaOH and subsequently flushed the soil with one pore volume of water. Even though the treatment reduced the SWR, the potential phytotoxicity of NaOH might limit the applicability of this method.

Limitations and side-effects of liming: Pawlett et al. (2009) suggested that liming might significantly alter the ecological interactions between earthworms and microbial communities. In their experiments, adding earthworms significantly reduced the effect of glucose on microbial activities. If the soil was limed at the same time as the earthworms were added, this effect was removed. Another potential problem linked to the increase of the generic microbial activity of a site is the risk of losing organic matter stocks and increasing the rate of greenhouse gas emissions. However, recent studies from Australia and New Zealand showed that liming an acidic soil under pasture did not increase N_2O emissions (Galbally et al., 2010; Zaman and Nguyen, 2010).

4.1.2. Application of fungicides

Mechanism: SWR has been suggested as being associated, *inter alia*, with fungal growth and exudates (Hallett, 2007). An illustrative example is the basidiomycete-caused 'fairy ring', circles of mushrooms observed in established turf that often lead to a zone of water-repellent soils (Fidanza et al., 2007; York and Canaway, 2000).

Examples of the application of fungicides to remedy SWR: However, whether or not fairy rings are present, spraying fungicides (such as one with the active ingredient flutolanil or captan (Pestanal®)) had no effect on reducing SWR in an arable loamy sand (Karnok and Tucker, 2001).

4.1.3. Application of slow-release fertilizers

Mechanism: The theoretical background for using slow-release fertilizers (e.g., nitrogen and phosphorus) to ameliorate the symptoms of SWR is to promote soil biological activity which results in increased decomposition rates of organic material including hydrophobic compounds. This principle has been used successfully for the clean-up of sandy soils contaminated with crude oil (Prince et al., 2003).

Examples of the application of slow-release fertilizers to remediate SWR: In pot experiments with bare, naturally hydrophobic sand, applications of each of the commercially available slow-release fertilizers, MaxBac® (N:P:S 22:5.7:0.6) and MagAMP® (N:P:K:Mg 7:20:5:9) at 0.5, 1.0 and 2.0 g kg^{-1} soil combined with claying (sodic kaolinite) at 5 g kg^{-1} soil significantly reduced SWR (Franco et al., 2000b). The results were explained by the apparent stimulation of wax-degrading bacteria present in the sand through the fertilizers. The experiments were conducted under controlled temperature (diurnal rhythm 10–25 °C) and moisture conditions (8%, w/w). Subsequent plot experiments on a water-repellent sandy, pastoral hill site with the same fertilizers applied at the same rates in autumn failed to reproduce these results, possibly due to the interactions of the clover (*Trifolium* spp.) plants sown directly after the fertilization. Moreover, in the field experiment the environmental conditions were comparatively unfavorable for microbial activities. More research is needed on potential impacts of fertilization on ameliorating SWR.

4.2. Biological direct remediation strategies for SWR

4.2.1. Bioremediation

Mechanism: Recently, a biological approach for ameliorating SWR was proposed: Based on the understanding that SWR in soils can be caused by waxy coatings on soil particles (Doerr et al., 2000), McKenna et al. (2002) attempted to exploit the fact that actinobacteria are able to use a wide range of organic materials as sole sources of carbon for energy and growth (Williams et al., 1989). They used a mixture of *Bacillus* and *Streptomycetes* phages to selectively isolate wax-utilizing non-streptomycete actinomycetes and managed to grow the isolated bacteria on a medium containing beeswax as sole carbon source. Enriching water-repellent soils with these actinomycetes significantly reduced SWR in a laboratory experiment (McKenna et al., 2002).

The bioremediation approach has been furthered and tested by researchers in Australia and Germany (Dunkelberg et al., 2006; Roper, 2004). In a number of laboratory experiments, wax-degrading bacteria were isolated from naturally water-repellent sandy soils or soils deliberately enriched with large quantities of hydrophobic compounds including sewage sludge, sewage effluents, animal fats, wool wax, feces or composted animal manure (Dunkelberg et al., 2006; Roper, 2004). Generally, for enriching the populations of the isolated wax-degrading bacteria, a culture medium with beeswax or wool wax as the only carbon source was used. Identification of wax-degrading bacteria isolated from various sources was done by cultural and microscopic examination, biochemical tests and PCR (Roper, 2004). Finally, the selected wax-degrading bacteria were inoculated in water-repellent soil samples in high concentration (e.g., 10^{10} cells per kg soil; Roper, 2004). Hydrophobicity of the soil was determined after incubation of the soil samples by measuring the WDPT (water drop penetration time) (Dunkelberg et al., 2006) or the CA using the sessile drop method (Dunkelberg et al., 2006) or MED (molarity of ethanol droplet) test (Roper, 2004) at different times during the incubation periods lasting between 60 and 250 days. To date, isolates from the following wax-degrading actinobacteria significantly reduced SWR in controlled laboratory experiments: *Streptomyces* spp. (Dunkelberg et al., 2006; McKenna et al., 2002; Roper, 2004), *Rhodococcus* spp. (McKenna et al., 2002; Roper, 2004), and *Mycobacterium* spp. (Dunkelberg et al., 2006; Roper, 2004).

The hypothesis postulated based on these laboratory results is that SWR can be reduced by bacteria which are capable of metabolizing waxes that have been diffused onto sand grain surfaces during wetting/heating/drying cycles. Roper (2007) investigated how wax-degrading by bacteria functions. She distinguished two general types of bacteria and mechanisms: (1) bacteria with a hydrophobic cell surface (*Streptomyces* spp., *Mycobacterium* spp.), and (2) bacteria that produce biosurfactants (*Rhodococcus* spp.). Roper (2007) explained the mechanism of the first type of wax-degrading bacteria as follows: In wet sands, bacteria with a hydrophobic cell surface live on the air–water interface while bacteria with a hydrophilic cell surface are suspended in the aqueous phase. When the sand starts to dry out, hydrophilic bacteria are drawn into the pore spaces, while hydrophobic bacteria are deposited onto sand surfaces. When the sand has dried out completely, actinobacteria will form spores or resting stages that allow them to survive the dry and hot conditions. When the sand is heated during the drought new waxes are transferred from plant material or soil organic matter onto sand surfaces and can block soil pores. Upon rewetting of the soil, water infiltration into soil pores is restricted, but once water reaches the hydrophobic bacteria on the surface of sand particles, the bacteria will be reactivated. They then can utilize the wax as a carbon source. This leads to an amelioration of the symptoms of SWR. An example for the second type of wax-degrading bacteria is *Rhodococcus* spp. The bacteria respond to alkanes (non polar) by producing biosurfactant molecules that improve their ability to utilize hydrophobic compounds as growth substrates (Lang and Philp, 1998; Roper, 2004; Walter et al., 1991). The biosurfactants increase the apparent aqueous solubility of hydrophobic compounds, which also releases hydrophobic coatings from sand surfaces. The biosurfactants produced by the bacteria are glycolipids containing trehalose as carbohydrate. They are among the most potent biosurfactants known (Lang and Philp, 1998).

Roper and Gupta (2005) hypothesized that the capacity for bioremediation of water-repellent soils by wax-degrading bacteria is related to the size of the populations of the wax-degrading bacteria. Thus, to develop effective bioremediation strategies, an understanding of the seasonal dynamics and regulating factors for the wax-degrading bacteria population size would be required. They developed a MPN method for wax-degrading bacteria that could be used as indicator of the potential for bioremediation of SWR. The advantage of an MPN method compared with plating techniques is that this technique combines the expression of function for the organisms being counted (here: the wax-degradation of the bacteria) with the ability of the organisms to grow (Alexander, 1982). The MPN method was successfully applied to pure cultures and natural populations of wax-degrading bacteria (Roper and Gupta, 2005).

Examples of bioremediation to remedy SWR: Two approaches to remedy SWR using bioremediation were explored in the field (Roper, 2005, 2006): (1) inoculation of water-repellent soils with wax-degrading bacteria, and (2) application of management strategies (compost, lime, fertilizer applications) that promote populations of naturally occurring wax-degrading bacteria at a site. While the inoculation of water-repellent soils with selected wax-degrading bacteria resulted in significant reductions of the degree of SWR at two sites in both plot and field experiments, the author argued that the improvements in SWR were relatively small compared with the costs of producing and applying the bacteria. The inoculations were conducted at high rates 10^9–10^{12} ha^{-1}. Combining the inoculation with liming at 1 t ha^{-1} significantly increased the soils' wettability (Roper, 2006). Managing naturally occurring wax-degrading bacteria by providing favorable nutrient/environmental conditions and/or managing soil moisture appears to be the more practical and economic approach. In a set of field experiments, the addition of lime to water-repellent sands was shown to increase the numbers of naturally occurring wax-degrading bacteria by up to an order of magnitude, and to reduce SWR significantly and substantially for at least 4 years (Roper, 2005; refer to Section 4.1.1). Other management practices that could promote biological activity include, for example, mulching, application of compost and minimum tillage. *Rhodococcus* spp. were found to be the most effective group of bacteria in reducing water repellency in field experiments with Western Australian soils.

4.2.2. Stimulating earthworms

Mechanism: Another important component of soil biology with respect to SWR is the earthworm. High earthworm populations have three beneficial effects with regard to ameliorating SWR: They mix water-repellent topsoil with non-water-repellent subsoil through their mixing activities. Moreover, worm casts provide organic matter of high quality that have a priming effect on microbial activities. This means worm casts enhance microbial activities which in turn increase the decomposition of organic substances including hydrophobic organic substances. Earthworm burrows will also increase water infiltration rates into hydrophobic soils and thereby reduce overland flow. Low worm populations are often associated with low calcium levels. For example, soils with the highest degree of hydrophobicity at Maraetotara (Hawke's Bay, New Zealand) had pH levels of 3–4 and earthworms cannot survive in these conditions (Stockdill, 1984). Adding organic material and liming (adding the macro-nutrient calcium) will, for example, encourage earthworms. Soil moisture and temperature can be optimized through aeration of water-repellent topsoils. Consequently, earthworms could be re-introduced to such sites that can support earthworms but lack them due to poor soil management (e.g., low pH, compaction; Lavelle and Spain, 2001). Earthworms are best 'harvested' from pasture sites with high densities of earthworms. It has to be mentioned that the spreading of earthworms is slow.

4.3. Physical direct remediation strategies for SWR

4.3.1. Irrigation/reduced drying

Mechanism: The best method of preventing SWR is to maintain high topsoil moisture levels by frequent irrigation (Cisar et al., 2000). SWR is also a major problem that reduces irrigation efficiency, leading to the heterogeneous (re)distribution of water (Tarchitzky et al., 2007).

Examples of irrigation/reduced drying to remedy SWR: Wallis and McAuliffe (1990) demonstrated that shorter irrigation return intervals at lower irrigation rates improved plant growth in water-repellent sands by maintaining the surface soil water content above the site-specific critical soil water content (see Section 1). This kind of irrigation scheme is, however, only economic/feasible for highly intensive horticultural production systems or turf irrigation. Special moisture sensor-controlled irrigation schemes matching plants' water requirements have been developed to reduce unnecessary irrigation and at the same time maintain the soil water content above the threshold for SWR (Augustin and Snyder, 1984). Park et al. (2007) examined the applicability of a device for measuring spectral reflectance to document normal and progressive water stress in turf grown on water-repellent sand. They found that determining the near infrared/red ratio allowed for real-time, site-specific water stress evaluation before it is visually identifiable. Drip irrigation systems have been shown to be a more efficient irrigation system in potato (*Solanum tuberosum*) production on sandy soils than overhead sprinkler irrigation systems (Cooley et al., 2007).

5. Conclusions and research needs

5.1. Conclusions

The significance of SWR to agricultural production is increasingly recognized throughout the world, and changes in global water availability will probably further increase the problem.

In spite of decades of intensive research on the problem of SWR, there are still considerable knowledge gaps and a lack of understanding of the general principles of SWR. Technical advancements for characterizing SOM have contributed to considerable progress in the identification of hydrophobic compounds in water-repellent soils. The molecular basis of SWR, however, is still poorly understood. In addition, the role of micro- and macro-organisms, and especially their influence on the degradation processes for the expression of SWR are also not well conceptualized. Studying interactions between vegetation, soil biological communities and site factors require novel quantitative approaches. It is well known that SWR evolves during dry periods and that it can disappear during wet periods, but the mechanisms involved in this rewetting process, thresholds of water contents for the onset and disappearance of SWR and their underlying conditions are still not understood. In this review, it was hypothesized that SWR develops where the balance of input–decomposition of organic matter is impaired.

Several direct and indirect mitigation strategies of SWR applying chemical, biological and physical methods have been developed. Most of the remediation strategies have been tested under various conditions in different countries with varying degrees of success. Some of the mitigation strategies, however, have been applied successfully only in laboratory experiments under controlled conditions. Our literature review clearly demonstrated that there is no easy recipe to cure soils from the occurrence of SWR. The decision about which remediation strategy to apply at a site will depend on site-specific factors including, for example, soil texture, soil properties such as pH and soil fertility status, and the profit margin of the agricultural production system. For example, in pasture renovation schemes, the use of surfactants, which is a costly remediation strategy due to the price of the products and repeated applications needed, might be viable, while for hill-country sheep and beef farming it is out of question. Ranking the mitigation strategies, thus, seems to be futile. Table 1 provides an overview on the main limitations, positive and negative side-effects of the different strategies. It is evident that each single mitigation strategy (with the exception of adaption to the hydrophobic conditions by choosing drought-tolerant plant species) increases production costs. The calculation of break-even points for choosing the best option for a site might therefore be advisable. A break-even point would be the point where the positive impact of a mitigation strategy (e.g., yield increase through increased water storage and overall more efficient use of rainwater) is equal to its costs. Investigations into efficacy and impact (on yield, product quality, soil fertility, soil quality, etc.) of different mitigation strategies are scarce.

5.2. Research needs

5.2.1. Better understanding of the ecological significance of SWR

- When do plant residues cause SWR? The interactions between vegetation (e.g., source of hydrophobic substances), soil biology (e.g., lack of decomposition of hydrophobic substances or source of hydrophobic substances) and soil properties of topsoils that seem to enhance SWR (e.g., low pH) need to be investigated further to identify key factors causing SWR in soils and to further our understanding of how SWR develops at different sites.
- Does SWR make sense in natural eco-systems? Some positive aspects of subcritical SWR have been reported including promoting carbon sequestration, water harvesting, increased aggregate stability, and reduced evaporation rates. What is the ecological significance of subcritical SWR in natural systems? Is it a feedback mechanism induced by plants and/or soil fauna as protection during drought phases or other stress situations (e.g., temperature, pH)? Investigating the role of subcritical SWR in natural systems might help to use it in a beneficial way for agricultural production systems. It might also help to prevent interfering with natural functioning feedback mechanisms.

5.2.2. Better diagnosis of SWR

- How can the *obesity syndrome of soils* be diagnosed? A method needs to be developed to measure directly at a field site both processes underlying the SWR mechanism: (1) rate of generation of hydrophobic residues, and (2) decomposition rate of hydrophobic residues. This could be achieved by comparing the rates from soils of hydrophobic sites with rates of soil(s) that do not suffer from SWR. Typical rates for 'non-degraded' soils are needed as a reference. This could form the basis for the decision about which remediation strategy is the most appropriate at a site.
- How can SWR measured and mapped at larger scales? A method is needed to quantify the spatial extent and continuity of SWR characteristics (e.g., degree, persistence) at the larger scale that is relevant for remediation purposes (e.g., field scale). Currently, SWR is measured only at the microscopic scale. The patchiness of SWR has been highlighted in several field studies where measurements of SWR were conducted with a high spatial resolution. Spatial correlations with other soil properties have not yet been established. A method to quantify the spatial extent and continuity of SWR characteristics at the field scale or a method to upscale small-scale results would form the basis for the decision about which areas need a remediation treatment most, and if a treatment needs to be applied across the entire area or only to isolated patches. This knowledge could tie in with precision agriculture techniques for the application of remediation strategies.
- What makes SWR such a transient phenomenon? Only the influence of water on the transient character of SWR is conceptualized. Understanding the complex interactions of different soil environmental factors affecting the transient character of SWR is poor, but it could help with the timing of mitigation strategies. This requires more detailed process-based laboratory studies as well as long-term field experiments under different land-use systems, soil types and environmental conditions.

5.2.3. Better prevention of SWR

The most economic way of mitigating SWR is prevention. This is an area that is currently lacking in research:

- What is the correlation between plant species and the occurrence of SWR? More knowledge about which vegetation components (e.g., specific grasses, trees) increase the amounts of hydrophobic residues in soils is needed. This could then be considered by selecting species with low hydrophobic residues when re-sowing pastures, especially in drought-prone areas.
- What kind of species distribution of soil organisms is needed to mitigate SWR? A better understanding of which species/group of species or lack of which species/group of species of soil organisms leads to a decrease in the decomposition rate of hydrophobic organic residues (e.g., earthworms, bacteria) is required. This could form part of both a risk assessment and prevention strategy for the occurrence of SWR.

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