CSIRO PUBLISHING

Soil Research, 2015, **53**, 786–806
http://dx.doi.org/10.1071/SR14330

Management options for water-repellent soils in Australian dryland agriculture

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Abstract. Water-repellent ('non-wetting') soils are a major constraint to agricultural production in southern and south-west Australia, affecting >10 Mha of arable sandy soils. The major symptom is dry patches of surface soil, even after substantial rainfall, directly affecting agricultural production through uneven crop and pasture germination, and reduced nutrient availability. In addition, staggered weed germination impedes effective weed control, and delayed crop and pasture germination increases the risk of wind erosion. Water repellency is caused by waxy organic compounds derived from the breakdown of organic matter mostly of plant origin. It is more prevalent in soils with a sandy surface texture; their low particle surface area : volume ratio means that a smaller amount of waxy organic compounds can effectively cover a greater proportion of the particle surface area than in a fine-textured soil. Water repellency commonly occurs in sandy duplex soils (Sodosols and Chromosols) and deep sandy soils (Tenosols) but can also occur in Calcarosols, Kurosols and Podosols that have a sandy surface texture. Severity of water repellency has intensified in some areas with the adoption of no-till farming, which leads to the accumulation of soil organic matter (and hence waxy compounds) at the soil surface. Growers have also noticed worsening repellency after 'dry' or early sowing when break-of-season rains have been unreliable.

Management strategies for water repellency fall into three categories: (*i*) amelioration, the properties of surface soils are changed; (*ii*) mitigation, water repellency is managed to allow crop and pasture production; (*iii*) avoidance, severely affected or poorly producing areas are removed from annual production and sown to perennial forage. Amelioration techniques include claying, deep cultivation with tools such as rotary spaders, or one-off soil inversion with mouldboard ploughs. These techniques can be expensive, but produce substantial, long-lasting benefits. However, they carry significant environmental risks if not adopted correctly. Mitigation strategies include furrow-seeding, application of wetting agents (surfactants), no-till with stubble retention, on-row seeding, and stimulating natural microbial degradation of waxy compounds. These are much cheaper than amelioration strategies, but have smaller and sometimes inconsistent impacts on crop production. For any given farm, economic analysis suggests that small patches of water repellency might best be ameliorated, but large areas should be treated initially with mitigation strategies. Further research is required to determine the long-term impacts of cultivation treatments, seeding systems and chemical and biological amendments on the expression and management of water repellency in an agricultural context.

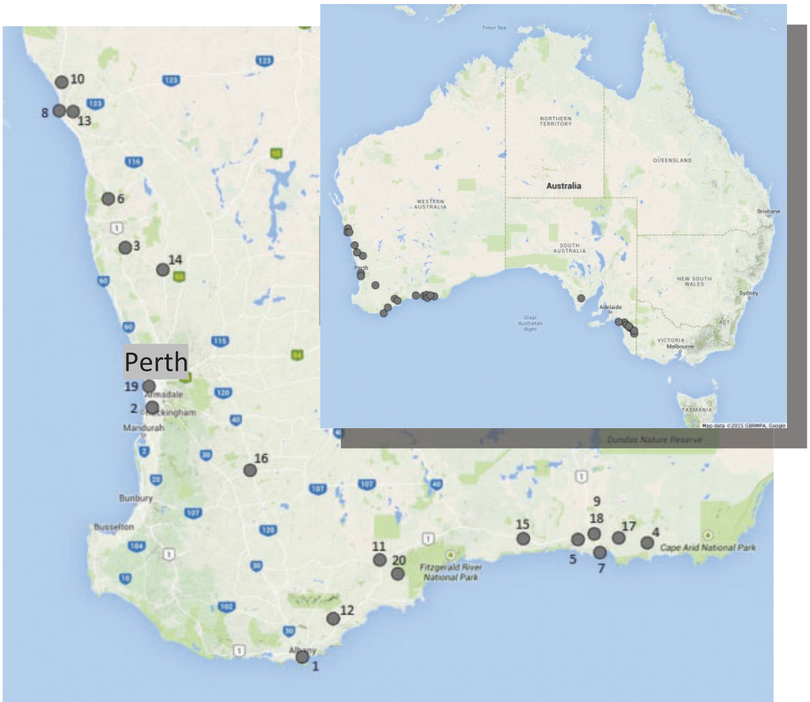
Additional keywords: hydrophobic, non-wetting sand, organic matter, water repellence.

Received 20 May 2014, accepted 21 May 2015, published online 14 October 2015

Introduction

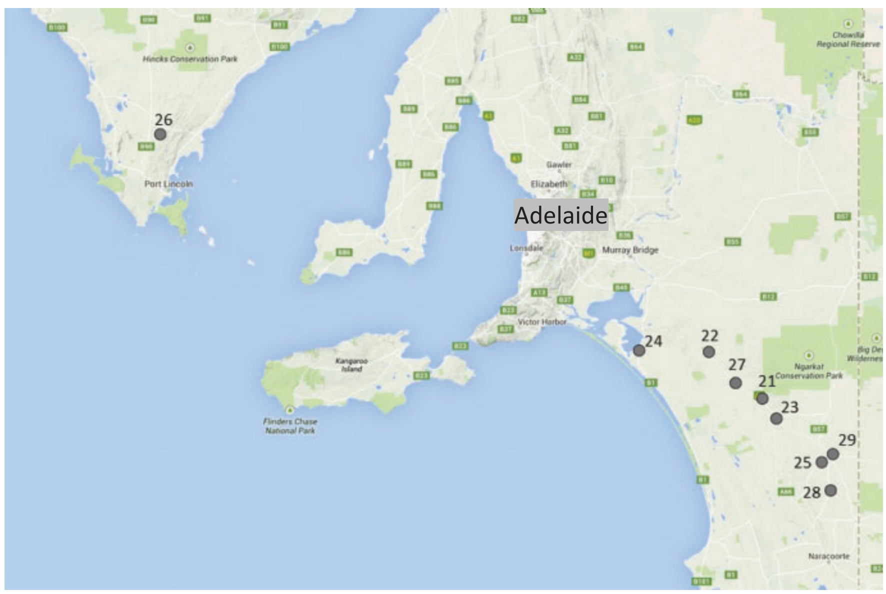
Soil water repellency is a worldwide phenomenon. This review draws on literature from around the world; however, it focuses on Australian agricultural systems. Much of the research in Australia on soil water repellency in agricultural systems has been done in Western Australia and, to some extent, in South Australia, but the management options developed have application elsewhere in southern Australia. Figure 1 shows the locations of field studies across southern Australia reported in this review.

It is estimated that in the south-west of Western Australia, 10.2 Mha of arable land is at risk of repellency with 3.3 Mha considered to be at high risk and another 6.9 Mha at moderate risk (van Gool *et al*. 2008). This estimate is based on the area of coarse sandy-textured topsoils with <5% clay content and is derived from the Department of Agriculture and Food Western



	WA locality	Reference
1	Albany	Carter & Hetherington (1994)
		Roberts & Carbon (1971)
2	Anketell	Roper MM (2005)
		Roper MM (2006)
3	Badgingarra	Crabtree & Henderson (1999)
		McKissock et al. (1998)
		Roberts & Carbon (1971)
		Scanlan et al. (2013)
4	Condingup	Crabtree & Henderson (1999)
5	Dalyup	Crabtree & Henderson (1999)
		Hall (2010)
6	Eneabba	Crabtree & Henderson (1999)
7	Esperance	Roberts & Carbon (1971)
		Spadek et al. (1994)
8	Geraldton	Blackwell P (1993)
9	Gibson	Crabtree & Henderson (1999)
10	Isseka	Crabtree & Henderson (1999)
11	Jerramungup	Harper (1994)
12	Kojaneerup	Crabtree & Henderson (1999)
13	Moonyoonooka	Crabtree & Henderson (1999)
14	Moora	Blackwell P (1993)
		McKissock et al.(1998)
15	Munglinup	Roper et al. (2013a)
16	Narrogin	McGhie (1980)
17	Neridup	Crabtree & Henderson (1999)
18	North Gibson	Crabtree & Gilkes (1999)
19	University of WA	Barton & Colmer (2011)
20	Wellstead	Crabtree & Gilkes (1999)

	SA locality	Reference
21	Coombe	Franco et al. (2000a)
		Franco et al. (1995)
22	Coonalpyn	Betti et al. (2015)
23	Keith	Franco et al. (2000b)
		Rebbeck et al. (2007)
24	Meningie	Bond RD (1964)
25	Mundalla	Cann MA (2000)
26	Eyre Peninsula	King (1981)
27	Tintinara	Bond RD (1964)
		Ma'shum et al. (1988)
28	Western Flat	Franco et al. (2000b)
		Franco et al. (1995)
		Ward & Oades (1993)
29	Bordertown	Betti et al. (2015)



Map data 2015 © Google

Fig. 1. Location of field sites referred to in this review.

Australia soil-landscape map (DAFWA 2015; www.agric.wa.gov.au/water-repellence/soil-water-repellence-overview). A further 2 Mha is estimated to be repellent in South Australia (Cann 2000). In Victoria and southern New South Wales, the area affected is less certain.

Water repellency generally occurs in the surface layers of sandy soils where hydrophobic materials of plant origin occur as particulate organic matter and as waxy coatings on sand particles (Ma'shum *et al.* 1988; Franco *et al.* 1995) and where fungal hyphae proliferate, especially in no-tilled soils (Chan 1992). Repellency results in uneven wetting of soils due to the lateral flow of water in runoff, or concentration into micro-ponds where the pressure-head encourages localised entry of water into the soil profile along preferred pathways such as old root systems and macropores (Ritsema and Dekker 1994, 1996; Dekker and Ritsema 2000; Doerr *et al.* 2000). As a result, significant volumes of adjacent repellent soil remain dry (Ritsema and Dekker 1994; Doerr *et al*. 2000), causing delayed germination of crop and pasture plants, poor stand establishment, and increased risks from wind and water erosion (Bond 1964; King 1981; Tate *et al*. 1989). Crop and pasture losses due to soil water repellency can be significant, particularly in dry years; for example, it has been estimated that the annual average loss of dry-sown lupin production can be 30% (Blackwell *et al*. 1994*a*; Abadi Ghadim 2000).

Water-repellent soils are often referred to by the farming and agricultural communities as 'non-wetting', 'hydrophobic' or 'oily' soils. Throughout this review, we refer to 'water-repellent soils' or 'water repellency'.

The aim of this review is to evaluate existing and developing management strategies in Australian dryland agricultural regions to mitigate (reduce the symptoms) or ameliorate (remove) repellency of repellent soils. Optimal strategies are suggested, combining different management approaches and taking into account the influence of seasonal conditions to maximise returns on investment and minimise risk of incurring farm debt. The review begins with a brief account of the nature and behaviour of water-repellent soils, followed by a comprehensive evaluation of management strategies: how they work, benefits and disadvantages, interactions in combination, barriers to adoption, integration with other important soil management strategies, and future research needs.

Causes (hydrophobic compounds), occurrence and measurement

Water repellency in soils generally increases in severity with increasing organic carbon content (Bisdom *et al*. 1993; Harper *et al*. 2000; Blanco-Canqui and Lal 2009; Roper *et al*. 2013*a*) and with decreasing soil-particle surface area (Harper *et al*. 2000; Matějková and Šimon 2012). Harper *et al*. (2000) quantified the impacts of these factors and demonstrated that soil surface area and the amount of soil organic matter accounted for up to 63% of the variation in water repellency. Sands, with their large grain size and low surface area : volume ratio, are the most susceptible to repellency, especially in environments where topsoils become dry for parts of the year (DeBano 1969; Harper *et al*. 2000). In Australia, soil types most strongly affected by water repellency include pale deep sands (Bleached Tenosols; Australian Soil Classification, Isbell 2002), and sandy duplex soils (Sodosols and Chromosols, and occasionally Calcarosols, Kurosols and Podosols) (van Gool *et al*. 2008), but globally, repellency can occur in other soil types (Müller and Deurer 2011). For example, severe repellency has been observed in finer textured soils, such as the 'mallett' clay soils in Western Australia, which have loamy-textured topsoils (18–22% clay) and before clearing were covered by natural stands of *Eucalyptus astringens*, or 'brown mallet' (McGhie and Posner 1980). Here, we report on soils with <3% clay in the surface soil horizon, unless otherwise indicated (Hall 2009).

Organic matter in soils is derived mostly from plants, which contain a mixture of readily decomposable compounds (that tend to be hydrophilic) as well as more complex waxy (hydrophobic) materials that previously protected the plant from desiccation. Some fungi also produce hydrophobic substances (Bond and Harris 1964; Chan 1992; Chau *et al*. 2012; Young *et al*. 2012). The waxy components coat soil particles (Ma'shum *et al*. 1988; Franco *et al*. 1995) and cause water repellency, by diffusion of hydrophobic substances onto sand surfaces during heating and especially during wetting–heating–drying cycles (Franco *et al*. 1995). Researchers have extracted and characterised hydrophobic compounds from repellent soils and found several different waxy molecules including unbranched and branched C_{16}–C_{32} fatty acids and esters, alkanes, phytanols, phytanes and sterols (Spadek *et al*. 1994; Franco *et al*. 2000*a*; Horne and McIntosh 2000; Morley *et al*. 2005; Atanassova and Doerr 2011). Because these compounds are common components of soil organic matter, water repellency is generally confined to the topsoils where organic matter accumulates. It is in this zone, too, that plant roots proliferate and produce root exudates that may also contribute to repellency after drying cycles as described above (Hallett *et al*. 2003, 2009; Moradi *et al*. 2012).

Water-repellent soils typically wet up unevenly via preferential flow paths, sometimes called 'finger flow' (Dekker and Ritsema 1994, 1996, 2000; Ritsema and Dekker 2000). Surface micro-relief and areas of low potential repellency, including cracks in the soil or root pathways, are conduits for finger flow bypassing large volumes of adjacent soil, which remains dry (Ritsema and Dekker 1994; Doerr *et al*. 2000). Once water reaches the more hydrophilic subsoils, lateral diffusive flow of water can occur, allowing a slow wetting of surface layers from the moist soil below (Doerr *et al*. 2000). In undisturbed soils, preferential flow pathways tend to persist once established and water flow recurs along the same pathways during subsequent rainfall events (Ritsema *et al*. 1998). Because large volumes of soil remain dry, plants are unable to access nutrients contained therein, resulting in poor early nutrient-use efficiency in these soils. However, such dry patches of surface soil can help to reduce evaporative loss of soil water from the subsurface (Blackwell *et al*. 1994*b*), and delayed wetting may mobilise previously unavailable nutrients later in the season when plants are more advanced and demand for nutrients is greater.

There are several methods for measuring the severity of soil water repellency (or wettability of soils). Soil–water contact angles (CA), measured directly or determined by capillary rise, increase proportionally with increasing hydrophobicity (Bachmann *et al*. 2003; Lamparter *et al*. 2010) with CA >90° considered repellent. Tension infiltrometer discs measure the sorptivity of infiltrating liquids (Dellar *et al*. 1994; Hunter *et al*. 2011). Low-field nuclear magnetic resonance measures the time at which amplitude peaks occur after the addition of a small drop of water to the soil surface; for water-repellent soil, the time can be up to 1000 ms, compared with <100 ms for wettable soils (Manalo *et al*. 2003). The most commonly used measures of repellency in agricultural systems are water-drop penetration times (WDPT) (McKissock *et al*. 1998; Dekker *et al*. 2009; Flores-Mangual *et al*. 2011) and molarity of ethanol drop (MED) (Roy and McGill 2002; Douglas *et al*. 2007). MED is the molarity of ethanol in water that enters the soil within 10 s (King 1981; Moody and Schlossberg 2010). Wettable soils have a MED of zero. Scales of repellency are: low, MED >0–1.0; moderate, MED 1.2–2.2; severe, MED 2.4–3.0; and very severe, MED >3 (King 1981).

Effects of soil water repellency in agriculture: land-use and environmental effects

Water-repellent soils occur across a range of land-management systems and natural ecosystems including turf grass, forestry and agriculture (DeBano 1969; Wallis and Horne 1992). Repellency is often associated with native vegetation (McGhie and Posner 1980; Crockford *et al*. 1991; Blackwell 1993; Doerr *et al*. 1998; Scott 2000) and can be an important mechanism for the selection and survival of native species (Blackwell 1993). When land under native vegetation has been cleared for agricultural purposes, reductions in repellency have been observed (McFarlane *et al*. 1992; Wang *et al*. 2010). For example, McFarlane *et al*. (1992) reported an average increase in sorptivity of soil from 8.0 to 24 mm $h^{-0.5}$ when water was added at 10-mm suction. Increases in soil wettability following land clearing are possibly due to major disturbance and tillage practices mixing water-repellent topsoil with wettable subsoil. However, with the adoption of minimum tillage and no-tillage practices during the latter part of the 20th Century, the concentration of soil organic matter (and associated waxes) near the soil surface has increased the incidence of repellency-related problems in agricultural soils (Šimon *et al*. 2009; Blanco-Canqui 2011). Surface soils under no-till cropping can be 1.5–40 times more repellent than soils under conventional tillage (Blanco-Canqui 2011; Roper *et al*. 2013*a*).

Because water-repellent soils wet up unevenly, crop and pasture seeds sown into them germinate at different times, resulting in patchy and delayed emergence, poor crop establishment and reduced grain yields (Blackwell *et al*. 1994*a*; Abadi Ghadim 2000; Hall *et al*. 2010). In Australian farming systems, water repellency is suggested to cause an annual average loss of 40% in crop production (Blackwell *et al.* 1994*a*; Abadi Ghadim 2000), but solid estimates are not available. Weed-seed germination can also be delayed and patchy, which results in poor weed control (Carter and Hetherington 1994); this increases the risk of developing herbicide resistance because of the need for multiple applications of herbicides (Moore and Blackwell 2004). Dry soil patches with little or no plant cover are susceptible to wind and water erosion (Moore and Blackwell 2004).

Both environmental conditions and agricultural land use can alter the severity and/or expression of water repellency in soils.

Environmental conditions

Potential water repellency (the repellency value measured at 20°C or ambient temperature in a laboratory after oven-drying at a standard temperature) varies seasonally (Leighton-Boyce *et al*. 2005; Roper 2005; Hardie *et al*. 2012), sometimes by up to 1.5 MED units (Roper 2005). Wetting and drying patterns have a significant effect on water repellency (Crockford *et al*. 1991; Franco *et al*. 1995), with repellency becoming most severe in soils exposed to hot and dry conditions when new waxes become fused onto sand surfaces (Franco *et al*. 1995). The expression of water repellency is greatest at low temperatures (King 1981) and higher relative humidity (Doerr *et al*. 2002; Leelamanie *et al*. 2008). However, if soils are wet before exposure to high relative humidity, repellency can decrease (Roberts and Carbon 1971). For these reasons, water repellency can be particularly severe under Mediterranean-type climatic conditions. The hot dry summer establishes the waxy coating on the sand grains, and cooler humid conditions at the break of the season maximise the expression of water repellency.

Drying climates and climate variability may alter the impacts of water repellency. Smaller and less frequent rainfall events at the start of the season lower the probability of the seedbed wetting up evenly over time. For example, Western Australia has experienced a significant decrease (of 21%) in winter rainfall since the late 1960s (Smith *et al*. 2000). This period coincides with seeding and crop establishment. In water-repellent sands, the crop often undergoes several germinations at different times coinciding with each rainfall event. If the rainfall events become smaller and less frequent, so too do the opportunities for germination.

The impacts of elevated CO_2 on water repellency are less clear. Gordon and Hallett (2009) reported small increases in repellency with elevated CO_2, but Müller *et al*. (2010) found no significant differences between ambient and elevated CO_2 on soil water repellency or soil water contents.

Agricultural land use

Conversion of tillage practices from cultivation to minimum or no-tillage can worsen repellency, because organic matter containing waxes becomes concentrated in surface soil layers (Harper *et al*. 2000; Roper *et al*. 2013*a*). Plant species can significantly alter the expression of repellency. Organic matter from native species such as *Eucalyptus* spp. and *Banksia* spp. can induce water repellency at a significantly ($P < 0.01$) greater rate than similar amounts of organic matter from agricultural species (McKissock *et al*. 1998; Harper *et al*. 2000). Legumes (crop and pasture species) have been found to induce greater repellency (CA 71–90°) than cereal crops (CA 59–67°) in soils with 2% organic matter added (McGhie and Posner 1981; Blackwell 1993; Moore and Blackwell 2004). The most severe repellency (MED 4.0) was found in surface (0–5 cm) soils following blue lupins (*Lupinus cosentinii*) compared with other legume species grown at the same site (MED range 1.0–1.1) (Loss *et al*. 1993; Moore and Blackwell 2004).

Animal manures vary in their potential to alter repellency (Pagliari *et al*. 2011). Zhao *et al*. (2007) found that sheep decreased water repellency, but anecdotal reports from Western Australia suggest the contrary, possibly due to undigested alkanes and long-chain fatty acids passing through the animals and accumulating in sheep manure. Pietola *et al*. (2005) measured increased repellency associated with grazing cattle. Studies on the effect of grazing intensity on soil water infiltration are also contradictory. Trampling of water-repellent soils by hard-hoofed animals may reduce waxy layers on sand surfaces by mechanical abrasion (Roberts and Carbon 1971), but is more likely to decrease water infiltration by destroying soil structure and preferential flow pathways (Kölbl *et al*. 2011). The impacts of smaller animals such as ants and termites are varied. Cammeraat *et al*. (2002) concluded that ant nests can act as sinks for water under slightly humid to wet conditions, but under very dry conditions, water movement is inhibited because ant nests generally have higher organic matter and associated water repellency than the surrounding soil.

Perhaps the greatest body of work internationally on water-repellent soils has concerned the impact of fire and post-fire management on repellency. Fire almost always alters repellency, but the nature of the change depends on the severity and intensity of the fire. Several studies have shown that soil temperatures ranging from 50°C to 150°C cause an increase in water repellency, whereas temperatures >200°C will reduce repellency (Doerr *et al*. 2005; Dlapa *et al*. 2008; Zavala *et al*. 2010). Losses of soil organic matter and nutrients, and susceptibility to erosion, are typical consequences of fires in any system (Certini 2005; Ferreira *et al*. 2005; Shakesby 2011). During intense wildfires, temperatures can exceed 300°C at the soil surface, but steep temperature gradients occur with depth. Organic substances that are vaporised during combustion move downward into underlying layers where they condense, forming a distinct water-repellent layer below the surface (DeBano 2000). This scenario results in a burned surface, which is vulnerable to erosion, and a water-repellent layer below the surface, which impedes water infiltration. Early establishment of vegetation cover post-fire is critical to reducing erosion losses and developing structural stability (Cerdá and Doerr 2005).

In agricultural systems, fires are generally ‘cool’ controlled burns of short duration to reduce stubble loads before seeding. However, controlled burns can still exceed 300°C, albeit briefly, and cause significant breakdown of soil structure and loss of soil organic matter (Albalasmeh *et al*. 2013). In a continuous cropping system on the south coast of Western Australia, an intense fire caused by a lightning strike significantly reduced soil organic matter and water repellency in a water-repellent sandy soil. This effect was prolonged in an experiment, by annual low-intensity burning of stubble before seeding (Roper *et al*. 2013*a*). Although there was a 50% decrease in repellency in the burned treatments, losses of structural stability and organic carbon (33%) resulted in significant erosion, reduced soil water content (by 2–4%) and grain yield losses of up to 50% compared with stubble-retained treatments.

Much of the preceding discussion has focused on the negative aspects of water repellency. However, there can be benefits. Water-repellent soil can effectively ‘harvest’ water into the furrow, maximising the effectiveness of small rainfall events by concentrating water into the plant root-zone. Preferential flow plays an important role in the rapid conduction of water into the soil, particularly during rainfall of short duration and low intensity (Zhou *et al*. 2002). This concentrates soil water below the surface (Robinson *et al*. 2010) where it can be protected from evaporation by a ‘dry-mulch’ effect of the repellent surface layers (Yang *et al*. 1996; Moore and Blackwell 2004). Both of these characteristics may be important for water supply to plants in drying and warming climates. For example, Yang *et al*. (1996) concluded that the use of furrows with a wetting agent could reduce evaporation from a water-repellent sand by 50% compared with a level, water-repellent soil surface.

Managing water repellent soils

A wide range of management strategies has been developed to offset the impacts of water repellency on agricultural production in broadacre dryland systems. Strategies vary in the longevity of their effects and may have positive and negative impacts on the expression of soil water repellency. Tools for managing repellent soils include short- to long-term mitigation (Table 1), medium- and long-term amelioration (Table 2), and avoidance by alternative land use (Table 3). Mitigation strategies minimise or reduce the effects of water repellency on agricultural production without markedly altering the repellency status of the soil. Amelioration strategies change the properties of surface soils and the benefits are usually longer term (≥3 years).

Mitigation tools

Water harvesting (furrow sowing)

In modern farming systems, all seeding operations result in furrows, albeit sometimes small. This section considers the impacts of furrows in their own right, largely from an historical perspective during the 1990s, when experiments were done on large furrows created to manage repellency. Other aspects of seeding operations (e.g. no-tillage) will be considered separately.

Furrow sowing (Table 1) has been used to manage water-repellent soils because it allows water harvesting from the ridges into the furrow and allows placement of the seed deeper in the soil, either in the lower topsoil or shallow subsoil, which is often more wettable. Ponding within the furrow creates a positive hydraulic head, which assists infiltration of water (Feng *et al*. 2001). Furrow sowing has been shown to improve plant emergence significantly (by up to 40% in lupin and 130% in pasture) compared with conventional, level sowing or ‘flat planting’ (Crabtree and Gilkes 1999; Crabtree and Henderson 1999; Blackwell 2000). However, the benefits of furrow sowing are relatively short-lived (1–5 months; Table 1) because of furrow infill. Where furrows are created by press-wheels, compaction may also benefit water entry by changing soil-surface characteristics (Bryant *et al*. 2007). Risks associated with furrow sowing include herbicide concentration and fertiliser leaching. Adjustments to the size of furrows and timing of fertiliser applications may minimise the risk, but this has not been quantified (Blackwell 2000). A greater risk is erosion and wind shear at the ground surface. Raindrop impact can erode ridge material into the furrow, and if volumes of water are large enough, water movement down a slope can cause rill erosion and expose or remove seed.

With the adoption of knife-points for seeding in the mid-1990s, it was noticed that furrows in water-repellent sands were wetting up poorly (Davies *et al*. 2012). Those authors speculated that dry, water-repellent soil was falling behind the knife-point into the slot with the seed, and that this would be more likely during dry seeding when the soil is less cohesive. They proposed that the addition of wings to the knife-point or seeding boot might help to grade the dry, repellent topsoil into the ridges away from the furrow. When tested in the field, seeding with winged knife-points or boots improved grain yield by 5–20% compared with use of knife-points without wings (Blackwell *et al*. 2014).

Soil wetting agents (surfactants)

Wetting agents contain surface-active agents (surfactants), which can reduce the surface tension of water at the soil surface and improve water entry into repellent soil (Dekker *et al*. 2005; Barton and Colmer 2011; Lehrsch *et al*. 2011). For example, Barton and Colmer (2011) demonstrated that application of either granular or liquid surfactant before the commencement

Table 1. Mitigation tools for managing soil water repellency

Mitigation: minimisation of the effects of water repellency but repellency remains. Soil classification according to Isbell (2002)

Management tool	Soil type	Operating cost (excluding capital)	Timing	Longevity of benefits	Problems or issues with the management tool	Other major benefits
Improved furrow sowing	All repellent soils	Cost of winged points or boots *v.* standard knife points	Sowing	1–5 months	• Furrow infill • Repellent soil around seed • Herbicide damage • Variable efficacy	• Water harvesting maximises capture and use by crops of small rainfall events • Repellent soil in inter-row may act as a mulch reducing evaporation
Furrow sowing with banded-applied wetting agents	All repellent soils	\$10–12 ha^{-1} $year^{-1}$	Sowing	2–3 months	• Cost (ongoing) • Lack of industry expertise • Incompatible machinery • Unstable furrows • Variable efficacy	• Wetting agent could be used as a carrier for cheap and efficient delivery of other beneficial inputs such as micro-nutrients or fungicides
Blanket-applied wetting agents	Loamy Chromosols and Sodosols	\$25–50 ha^{-1} $year^{-1}$ depending on rate required	Pre-sowing	2 years	• Cost (ongoing) • Lack of industry expertise • Efficacy soil type specific	• Some weed control benefits if blanket wetting agent improves synchronous germination of weeds
No-till and full stubble retention	All except rocky and stony soils	Predominantly capital cost	Sowing	Ongoing	• Suitability for a wide range of soil types and landscapes • Root disease • Poor herbicide incorporation • Residue management • Concentration of nutrients at surface • 'Thatching' effect reduces soil water from low rainfall events	• Reduced risk of wind erosion • Increased microbial activity • Water retention via mulching • Increased soil carbon
Liming	All acidic and repellent sandy soils	~\$75 ha^{-1} for 2 t ha^{-1}, but varies depending on transport distance	Usually pre-sowing	Ongoing if optimum pH is maintained	• May require high lime rates • Severity of soil repellency reduced but not eliminated • Some nutrients become less available	• Improved availability of some nutrients • Prevention and/or amelioration of aluminium toxicity • Improved weed control
On-row *v.* inter-row	All repellent soils	Predominantly capital cost	Sowing	1–2 months	• Stubble handling • Increased risk of stubble and root-borne pests and disease associated with previous crop row • Lack of 2-cm accuracy with autosteer	• Zones of enhanced fertility created as nutrients and organic matter and associated biology concentrated in same row each year

Table 2. Amelioration tools for managing soil water repellency in the medium and long term

Amelioration: correction or removal of topsoil water repellency for three or more years. Soil classification according to Isbell (2002). Estimated cost in Australian dollars based on contractor rates in 2012

Management tool	Soil type	Operating cost (excluding capital)	Timing	Longevity of benefits	Problems or issues with the management tool	Other major benefits
Soil inversion (mouldboard ploughing)	Tenosols	\$100–120 ha^{-1}	• One-off inversion • Pre-sowing • Late autumn-mid winter	5–10+ years	• Wind erosion risk on sands until cover crop is established • Seeding depth difficult to control in loosened soil • Loss of soil moisture during cultivation • Poor inversion can reduce efficacy • Unknown impact of buried water repellent layer on soil water	• Weed control • Reduced subsoil compaction • Reduced stubble-borne disease • Enhanced water- and possibly nutrient-holding in the subsurface soil in the root-zone (particularly in pale sands) • Nutrient, lime and organic matter incorporation into the profile
Rotary spading (deep cultivation) (partial amelioration)	Tenosols	\$150 ha^{-1}	• One-off deep cultivation • Pre-sowing • Late autumn–midwinter	Unknown but likely to be 3–7 years	• High cost • Wind erosion risk on sands until cover crop is established • Seeding depth control in loosened soil • Loss of soil moisture during cultivation	• Some control of certain weeds • Reduced subsoil compaction • Nutrient, lime and organic matter incorporation into the profile
Clay delving	Chromosols and Sodosols (suitable clay within delving depth)	~\$300–600 ha^{-1}	Pre-sowing	15+ years	• High cost • Soil type suitability • Subsoil incorporation • Higher biomass can enhance haying-off risk • Lack of industry providers • Clay-rich subsoil may contain toxic levels of salt or boron or extreme pH • Difficult to control rate of clay at the surface	• Moderate (indirect) benefit in controlling weeds • Increased soil pH if alkaline subsoil is applied • Reduced subsoil compaction • Nutrient addition, often K, S and B from some clay-rich subsoil • Increase in nutrient and water-holding capacity of the topsoil
Clay spreading	• Tenosols • Chromosols and Sodosols (suitable clay source in paddock)	\$500–900 ha^{-1}	Pre-sowing	15+ years	• High cost • Subsoil incorporation • Higher biomass can enhance haying-off risk • Clay availability • Soil compaction • Clay-rich subsoil may contain toxic levels of salt or boron • Difficult to control rate of clay at the surface	• Moderate (indirect) benefit in controlling weeds • Increased soil pH if alkaline subsoil is applied • Nutrient addition, often K, S and B from some clay-rich subsoil • Increase in nutrient and water-holding capacity

Table 3. Management of water repellent soils through adaptation and alternative land use (avoidance)
Soil classification according to Isbell (2002)

Management tool	Soil type	Operating cost (excluding capital)	Timing	Longevity of benefits	Problems or issues with the management tool	Other major benefits
Trees, tagasaste, permanent pasture	Tenosols	Not available	System change	Ongoing	• System change • High cost • Profitability	• Mitigated subsoil compaction • Increased water- and nutrient-use efficiency on high leaching soils • Reduced risk of erosion • Possible increase of soil carbon (mainly pastures)

of irrigation reduced the severity of soil water repellency by 30–60%. McGhie and Tipping (1983) used a rainfall simulator on bare, water-repellent soil and demonstrated that wetting agents could increase the depth of infiltration from 3 to 25 mm after the application of the equivalent of 25 mm rainfall. Use of surfactants has been shown to be particularly beneficial during drought, resulting in a much greater uniformity of soil water content than in untreated soils (Soldat *et al*. 2010). Furthermore, surfactants can improve the effectiveness of pesticides and herbicides by aiding their entry to the soil (Fidanza *et al*. 2007). However, soil-wetting agents are less effective at treating water-repellent sands with significant levels of organic matter (~30%) than those with lower organic matter contents (<10%) (Barton and Colmer 2011). A potential negative side-effect of surfactant application is that the reduced surface tension of the water could result in a lower plant-available water capacity in the soil and could subsequently increase the risk of deep drainage and solute transport to groundwater. More research is necessary to quantify the risk further (Blackwell 2000). A combination of surfactant and water-retaining compounds may help to overcome this, and this is currently being tested. In some situations, owing to their chemical nature, accumulation of surfactants can lead to an increase in the severity of repellency (Fernández-Gálvez and Mingorance 2010), but this is more likely in turf-grass systems where large quantities of wetting agents are used.

Much of the research on surfactants has been done to reduce the impacts of repellency on sand-based, turf-grass systems. However, wetting agents have also been used to improve crop and pasture emergence. In cropping systems, wetting agents can be banded, that is, applied at the base of the furrow behind the press-wheels, or blanket-applied to the entire surface using a boom-spray (Table 1). Both banded and blanket-applied wetting agents were found to be effective in improving crop establishment by up to 100% in lupin and wheat (Blackwell *et al*. 1994*c*). The longevity of the benefits in subsequent years and impact on crop yield were variable (Sullivan *et al*. 2009), although significant increases (6-fold) in early production of pastures were observed in association with banded wetting agents (Crabtree and Gilkes 1999) and a residual effect remained 2 years on.

The use of blanket-applied wetting agents is costly (Table 1) at the rate used in the above experiments (50 L ha^{-1}) and is a key reason for reducing the application area to a narrow band in the base of the furrow. Application rates of 0.5–8.0 L ha^{-1} of banded wetting agent were assessed in numerous experiments, and cereal crop establishment was found to improve by 10–18% with rates of 2–8 L ha^{-1}, respectively (Crabtree and Henderson 1999). However, yield losses were measured in some trials, possibly due to poor water retention and enhanced nutrient leaching (Blackwell *et al*. 1994*a*). Since then, shorter lasting, biodegradable, banded wetting agents have been used to reduce the impact of lower soil-water retention and leaching of nutrients, while still providing better wetting-up of the soil and improved crop germination (S. L. Davies, unpubl. data). To be successful, wetting agents need to be applied as a continuous band to the base of the furrow. Furrow infill, soil throw from neighbouring seeding tines, or placement onto soil that is still moving can all reduce the efficacy of the banded surfactant. Furrow shape as determined by press-wheel design can affect furrow stability, with V- or broad U-profile press-wheels providing greater stability (Blackwell *et al*. 1994*a*).

No-tillage and stubble retention

Root systems can create networks of preferential flow (Blackwell 2000; Dekker and Ritsema 2000; Ghestem *et al*. 2011; Roper *et al*. 2013*a*); therefore, management strategies that leave plant roots intact are likely to increase soil-water contents in water-repellent soils.

No-tillage (or zero tillage) has been adopted by growers to improve the timeliness of operations and reduce costs, but other benefits include reduced erosion (Flower *et al*. 2008) and improved soil carbon content (Campbell *et al*. 1996; Blanco-Canqui *et al*. 2010). However, in sandy soils, retention of crop residues (stubble) can aggravate repellency (Harper and Gilkes 1994; Urbanek *et al*. 2007; Blanco-Canqui 2011) because no-till concentrates organic matter and associated waxes in surface-soil layers. Harper and Gilkes (1994) found a linear relationship between log(WDPT) and log(organic carbon). Despite this, water infiltration into water-repellent sands has been shown to improve under no-tillage and stubble retention, increasing soil-water contents by 2–4% v/v compared with annual cultivation and stubble removal, and this resulted in improvements in grain yield of up to 50% in some years (Roper *et al*. 2013*a*). Under no-tillage, biopores formed by roots are preserved, creating channels for water movement (Fig. 2*a*). In a cultivated soil, these biopores are broken up, restricting water entry (Fig. 2*b*). Root channels persist under no-till, even after the crops have matured, conducting water into the soil well after the establishment of the new season's crop (Fig. 2*c*). Where the soil is cultivated, water entry in crop rows depends on the development of new root channels by the emerging crop, but the

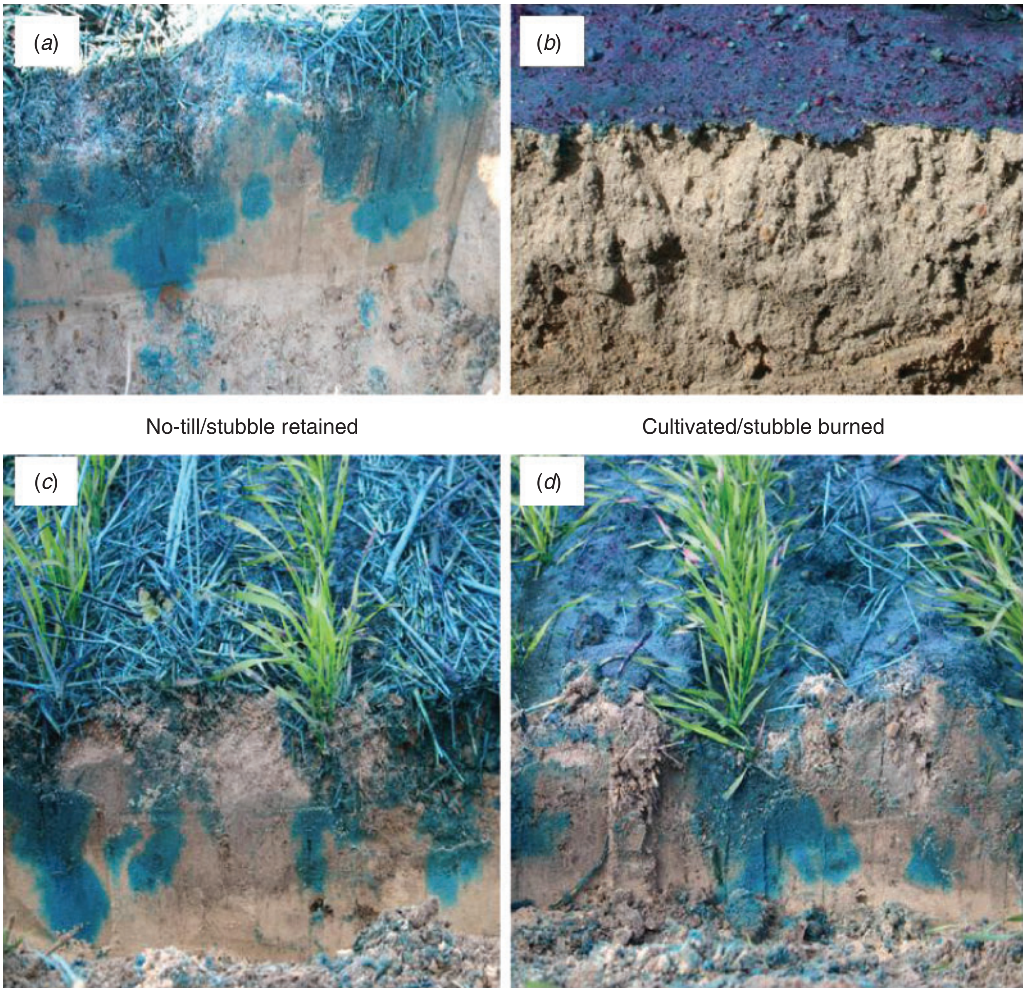


Fig. 2. Flow of blue dye (*a*, *b*) immediately after stubble treatment, and (*c*, *d*) 3 months later in July. Treatments are: (*a*, *c*) under no-tillage–stubble retention, and (*b*, *d*) after cultivation–stubble burned. Blue dye solution could enter the repellent soil (Sodosol) only via biopores formed by old and new root channels, leaving pockets of dry soil between the root pathways. Source: Roper *et al*. (2013*a*) (reprinted with permission).

surface soil between the new rows remains dry (Fig. 2*d*). In addition to preserving root pathways, no-tillage conserves macropores dug by beetles, ants and termites, allowing water to infiltrate deeper into the soil where it is protected from evaporative losses and is available to plants (Evans *et al*. 2011; Badorreck *et al*. 2012).

No-tillage is suitable for a wide range of soil types (Table 1) and provides good protection against water and wind erosion. On the negative side, no-tillage and stubble retention can exacerbate plant diseases through carryover of infected plant material (Melloy *et al*. 2010), and nutrients may be concentrated at the surface. However, where repellency is the major limiting factor for crop production, no-tillage can significantly improve crop performance with minimal ongoing cost after the initial capital investment.

Although they can be a source of waxes, crop residues can increase soil-water contents by functioning as a mulch (Yang *et al*. 1996; García-Moreno *et al*. 2013), moderating soil-surface temperatures and improving water infiltration over summer (Lichner *et al*. 2012), and reducing evaporative losses (Yang *et al*. 1996; Ji and Unger 2001). Yang *et al*. (1996) observed that under stabilised ridges of water-repellent soil, soil temperatures at seed depth were 2°C less and evaporation was reduced by 3 mm over 6 days compared with a level soil surface. Crop residues may also moderate the local soil climate. For example, Ward *et al*. (2013) found that where crop residues were removed each year over a 5-year period, the minimum soil water content at the end of a dry summer was more than 2% v/v lower than in stubble-retained treatments. A significant impact of the removal of crop residues was the loss of soil organic carbon (down from 1.5% to 1% carbon) (Roper *et al*. 2013*a*), and this potentially reduced the water-holding capacity of the soil (Lal and Kimble 1997). This could also have implications for soil microbial function, including microbial wax degradation (see *Microbial inoculation for wax decomposition*).

On-row seeding

If remnant root systems provide pathways for water entry to soil, seeding on or close to the previous year's crop row (on-row seeding; Table 1) is likely to provide greater access to water for an emerging plant than seeding between rows, particularly in a dry season. Dead plant crowns and root systems from a previous crop can persist well into the next growing season (Blackwell 2000; Roper *et al*. 2013*a*), resulting in significantly improved plant performance. Benefits of on-row seeding can be seen early in the season, particularly in dry years, with plant emergence 2–6 times that in inter-row-seeded crops (Fig. 3) and crop differences continuing well into the growing season (Fig. 4*a, b*). Improvements in crop establishment can be significantly greater from on-row seeding than from banded wetting agents (Fig. 3; Davies *et al*. 2012); however, those authors did not report yields. Anecdotal reports from growers indicate that these benefits sometimes translate to noticeable yield differences. Recent advances in tractor guidance technology, when combined with an independent system for seeder guidance, mean that farmers can now sow on the row to an accuracy of 2 cm (P. Hicks, pers. comm.). Controlled traffic systems reduce the percentage of the field that may be compacted by machinery tyres, and this lack of contact may further preserve the pathways of preferential flow. Seeding on the previous year's row requires careful consideration of rotations to avoid consecutive crops with similar disease susceptibility.

Microbial inoculation for wax decomposition

Soil microorganisms can alter the wettability of soils (Zhang *et al*. 2007). Surface-attached microorganisms in biofilms can be either hydrophobic or hydrophilic and can impose these characteristics on the wettability of the soil (Schaumann *et al*. 2007). Other research has directly linked repellency with populations of soil fungi (Bond and Harris 1964; Chau *et al*. 2012; Young *et al*. 2012) including arbuscular mycorrhizal fungi (Rillig *et al*. 2010). The most studied group are the basidiomycete fungi

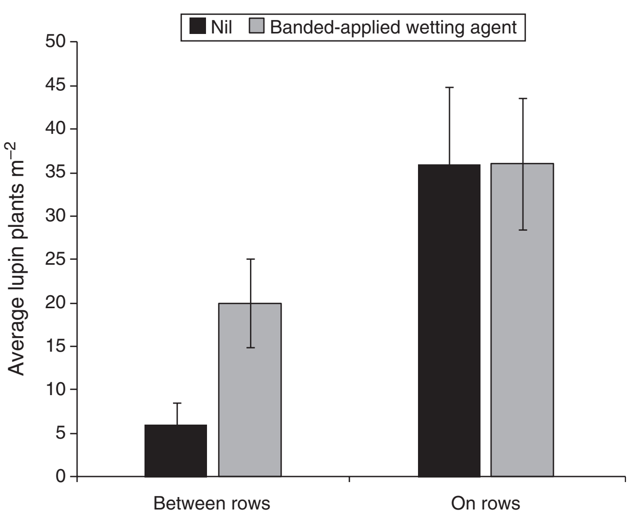


Fig. 3. Crop establishment (plants m^{-2}) when sown either between or on the previous year's rows on water-repellent sands. Lupin after wheat, with or without application of banded wetting agent at Balla, Western Australia, on deep yellow, water-repellent Tenosol in 2011. Capped lines are ± standard error of the mean ($n \geq 8$). Adapted from: Davies *et al*. (2012). (© Western Australian Agriculture Authority)

(ubiquitous in soils across the world) in golf greens, where they have been shown to induce very severe repellency (MED >3.0) (York and Canaway 2000; Spohn and Rillig 2012); however, some of these fungi have been shown to reduce repellency by up to 50% (Hallett *et al*. 2006; Chau *et al*. 2012).

Decomposition of waxes on soil-particle surfaces by wax-degrading bacteria may be a mechanism for biological control of repellency. The screening of soils and other materials containing waxes revealed a large group of bacteria capable of wax degradation, most of which belong to the actinobacteria (McKenna *et al*. 2002; Roper 2004). Many of these wax-degrading actinobacteria produce bio-surfactants capable of releasing hydrophobic coatings from sand surfaces, thereby assisting microbial wax decomposition (Roper 2004). Inoculation of selected actinobacteria into water-repellent soils in the laboratory under controlled conditions reduced repellency from severe (MED 2.7) to low (MED 1.0) after 150 days compared with the non-inoculated control, which did not change during the course of the experiment (Roper 2004). In the field, improvements in soil wettability following inoculation were less successful, likely due to competition from natural microflora and adverse environmental conditions (Roper 2006). Field data suggested that enhancing existing populations of wax-degrading actinobacteria was more promising.

Enhancing existing populations of wax-degrading bacteria in soils

Irrigation. Clearly, one of the most limiting conditions for any microorganisms in water-repellent soils is the availability of water. In field experiments conducted in the south-west of Western Australia, potential water repellency was reduced under irrigation, and the size of the reduction was proportional to the time of exposure to irrigation. For example, at one field site, soil that was never irrigated was very severely repellent (MED 4.0), but after 7 years of irrigation, MED of the same soil was almost halved (Fig. 5; Roper 2005). In rainfed systems, soil-water contents are entirely dependent on rainfall, but in wetter years, significant reductions in severity of water repellency (up to 1.5 MED units) have been measured by the end of the wet winter season (Roper 2005; Roper *et al*. 2013*a*).

Liming. Farmer observations that lime noticeably improved soil wettability in the south-west region of Western Australia led to experiments in the laboratory and in the field demonstrating that the addition of lime to water-repellent soils reduced repellency by 1–3 MED units (Roper 2005, 2006). For example, in the laboratory under controlled moisture and temperature conditions, treatment of very severely repellent (MED 4.0) soil with lime resulted in significant improvements in wettability (to MED <1.0) over 150 days. Field experiments indicated a two-phase effect of lime. Initially, liming caused a more rapid wetting-up of soils after the opening rains of the season compared with untreated controls. This was followed by a steady decline in repellency during the wet winter months, with significantly greater improvements in wettability (at least 1.5 MED units) in limed treatments than in non-limed controls. The first phase was likely due to changes in soil particle size following liming (Wallis and Horne 1992; Harper *et al*. 2000). The slower, second phase was coupled with 10-fold increases in populations

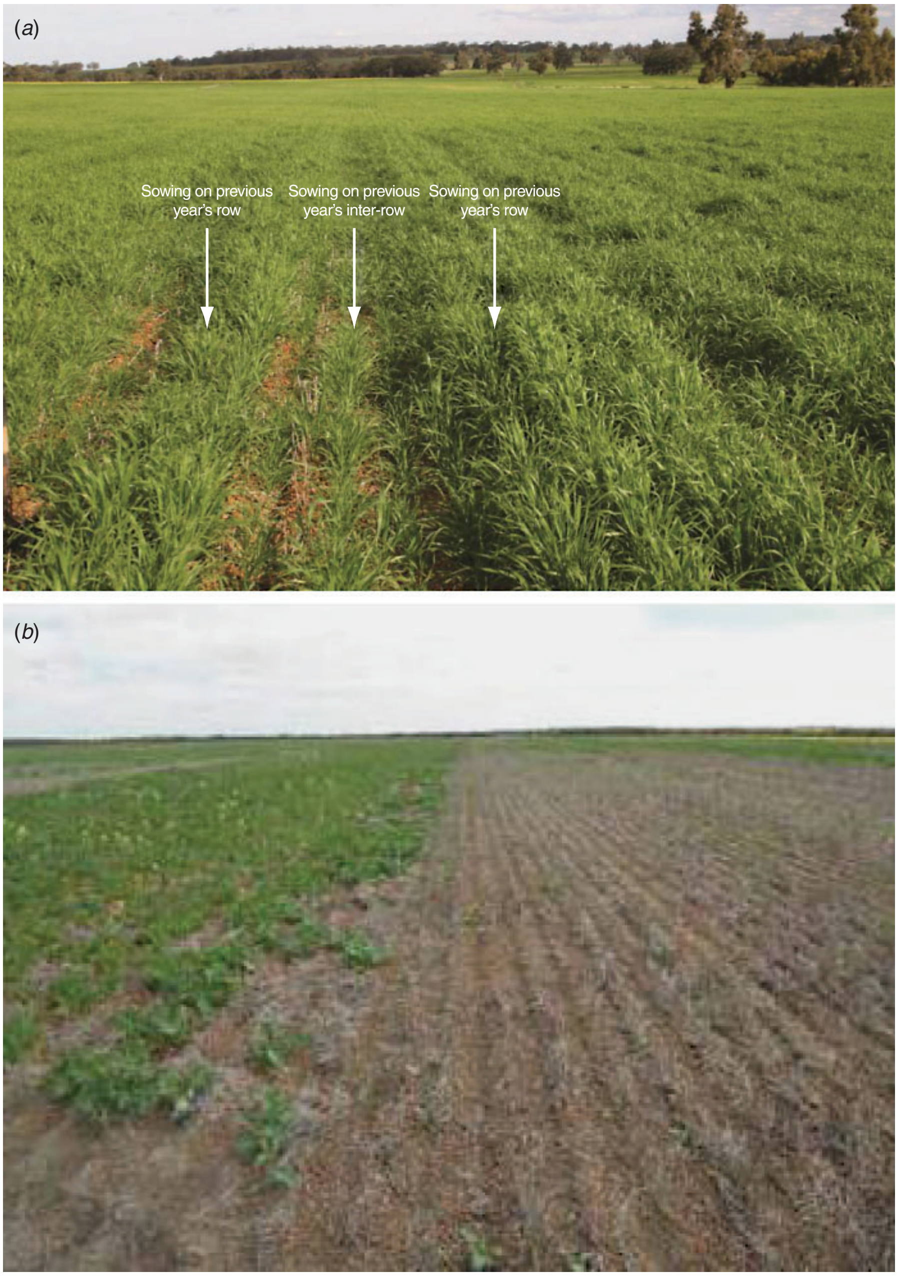


Fig. 4. Plant establishment on water-repellent soil (Red Chromosol) was improved when seeds were sown on the previous year's row compared with the previous inter-row. (*a*) Barley crop where seeder width was not matched to previous year's row width. Source: S Waters (Calingiri) and M Roper (CSIRO). (*b*) Canola crop sown into old furrow (left of photo) and between the old rows (right of photo). Source: P. Hislop and D. Bakker, DAFWA (reproduced with permission).

of wax-degrading bacteria in limed treatments compared with the control (Roper 2005). There are two likely mechanisms by which wax-degrading actinobacteria respond to liming: (*i*) the nutritional requirement for calcium (Ca^{2+}) (Matthiessen *et al*. 2004), and (*ii*) a more favourable pH for microbial activity (El-Tarabily *et al*. 1996). Indeed Mataix-Solera *et al*. (2007) and Diehl *et al*. (2010) found soil pH to be the most significant factor explaining differences between water-repellent and wettable conditions in sandy soils, and this may be due in part to changes in mineralisation of organic carbon (Wallis and Horne 1992; Harper *et al*. 2000). Application of lime can be costly depending on distance from lime sources (Table 2), and improvements in soil wettability can be variable (Blackwell *et al*. 1994*c*). However, on acid sandy soils, other benefits are likely such as crop nutrition and prevention/amelioration of aluminium toxicity. On some of the more alkaline Sodosols, lime application may not be as effective as on the Tenosols and acidic Sodosols.

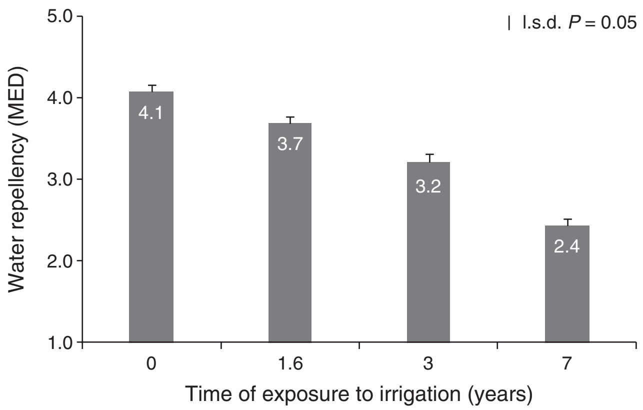


Fig. 5. Water repellency (MED) of field soils (Tenosol) with different histories of spray irrigation from 0 to 7 years. After commencement of irrigation, soils were kept wet by irrigating for ~1 h daily, equivalent to 14 mm, except during periods of rainfall when irrigation was reduced to supplement rainfall to 14 mm. Capped lines are standard errors of the mean ($n = 6$); l.s.d. ($P = 0.05$) = 0.25. Source: Roper (2005).

Fertilisers. There are few studies on the effect of fertilisers on water repellency, and the findings are contradictory. Franco *et al.* (2000*b*) observed that slow-release fertilisers containing nitrogen (N), phosphorus (P), potassium (K) and sulfur (S) resulted in a significant decline in soil water repellency from severe to moderate (on a MED scale) in a sandy soil over the wet winter period in a Mediterranean-type climate, but repellency returned over the dry summer. The authors attributed the changes during winter to degradation of waxes or the movement of dissolved organic matter. Hallett and Young (1999), on the other hand, observed increased water repellency associated with the development of soil aggregates and suggested that nutrient amendment promoted biological activity and production of water-repellent materials. Blanco-Canqui and Schlegel (2013) similarly observed that applications of N of >90 kg ha^{-1} increased aggregate formation and water repellency. There is clearly room for more research in this area.

Amelioration tools

Amelioration tools change the properties of surface soils resulting in long-term benefits (Table 2).

Claying

The earliest recorded experiment in Australia on application of clay to improve the wettability of water-repellent sands was reported by Roberts (1966), in which addition of 2.5% of clay to the topsoil improved pasture emergence by a factor of 5–100 in a trial near Perth. At around the same time, Clem Obst, a farmer near Bordertown in South Australia noticed that deep ploughing improved the behaviour of his soils, and in 1968, he began to spread clay over repellent sandy patches (Obst 1994). He observed immediate impacts on water repellency and was able to grow clover and lucerne where previously this was not possible. Subsequently, he extended clay spreading to a larger area of his farm where soil water repellency was a problem, which resulted in long-lasting amelioration (Cann 2000).

Water-repellent sands typically have very low clay contents (McKissock *et al.* 2000; Hall 2009). Sands, by definition, have a diameter in the range 2.0–0.02 mm, whereas clay particles are <0.002 mm (or <2 µm) in diameter (McIntyre and Loveday 1974). Therefore, relative to clays, sands have a low surface area that readily becomes saturated with hydrophobic compounds derived from organic matter (Wallis and Horne 1992; Harper *et al.* 2000; McKissock *et al.* 2000). In addition, clay particles carry a surface charge rendering them hydrophilic or wettable (van Olphen 1963). Application of clay to water-repellent sands increases the surface area of the soil and masks the waxy surfaces of the repellent sand particles (Ward and Oades 1993). An increase in clay content to 3–6% will alleviate repellency in most sandy soils (Cann 2000; Hall *et al.* 2010), but additions of just 1–2% clay can reduce repellency (Ward and Oades 1993; McKissock *et al.* 2000). However, not all clays are the same. Sodium (Na^+)-dominated kaolinitic clays have been observed to be the most effective in reducing repellency, with less benefit from other clays such as smectite (Ward and Oades 1993; McKissock *et al.* 2000; Hall 2009), whereas Ca^{2+}-dominated montmorillonite clay appears to have little or no benefit (Ward and Oades 1993; Dlapa *et al.* 2004). Benefits of application of clay to water-repellent soils include increased productivity due to more even wetting of the soil, even germination of weeds, increased water retention, increased cation exchange capacity and nutrient retention, improved soil stability, and increased soil organic carbon (Cann 2000; Carter and Hetherington 2006; Hall *et al.* 2010) and microbial biomass (M. M. Roper, unpubl. data).

Clay can be applied to the soil by clay spreading on the surface or by clay delving (Hall 2009).

Clay spreading. This technique involves excavating clay from the subsoil in a pit close to a deep sandy area and spreading it (by using a scraper, carry grader or multi-spreader, for example) onto the soil surface. The clay-rich subsoil is then incorporated soon after it is applied. The incorporation can be achieved with tines, off-set discs, heavy harrows, rotary hoe or rotary spader. It is important that incorporation is thorough, because poorly incorporated clay can result in surface sealing and poor root exploration into the subsoil, which, when coupled with increased evaporation, can often result in haying off of crops on clayed paddocks due to lack of water during grain filling (Hall 2009; Davies *et al.* 2012). Application of heavy, clay-rich subsoil at rates of ≥200 t ha^{-1} is difficult to incorporate and more costly to apply given the high volumes that need to be excavated and spread. Under these circumstances, deeper incorporation with tools such as rotary spaders can help to dilute excess clay through more of the profile (Davenport *et al.* 2011; Davies et al. 2013*a*).

Clay delving. This alternative technique can be used in Sodosols and Chromosols where the top of the clay layer is within 50–60 cm of the soil surface (Davenport *et al.* 2011). The delving implement penetrates the soil and breaks into the clay layer, lifting clods of clay to the surface. The clay-rich subsoil is then incorporated back into the water-repellent surface sand. Clay delving machines use large, sloping, broad-bladed deep-ripping tines, up to 2.5 m in length and typically set at a 45° angle, to lift and bring clay-rich subsoil to the surface (Davenport *et al.* 2011). Aside from improving the wettability of surface soils, delving has a deep-ripping effect that can further benefit crop yields (Hall *et al.* 2010; Betti *et al.* 2015), resulting in additional wheat yields of up to 1 t ha^{-1} (Rebbeck *et al.* 2007). Greater water-holding capacity and hence heat storage in clayed soils has been shown to reduce frost damage in wheat by increasing topsoil and canopy-height temperatures by an average of 0.4°C (Rebbeck *et al.* 2007).

Before claying is undertaken, the subsoil needs to be tested for clay content and type and for the presence of toxic concentrations of sodium chloride, boron or carbonate, or extremes of pH (Davenport *et al.* 2011). Both clay spreading and clay delving are expensive (Table 2), with the largest cost being transport in the case of clay spreading. However, these are one-off amelioration techniques expected to last >15 years (Davies *et al.* 2012; C. Obst, pers. comm.). Clay addition can increase soil strength and cause problems with seedling emergence; however, this is often associated with non-uniform application or poor incorporation of clay (Harper and Gilkes 2004).

One-off deep cultivation

Water repellency predominantly occurs in the top layers of the soil profile where waxes from organic matter accumulate (Roper *et al.* 2013*a*). Therefore, theoretically, mixing of topsoil with subsoil should dilute repellency, and this was observed by Nadav *et al.* (2012). However, the physics of repellency is more complex. Steenhuis *et al.* (2005) demonstrated that if a soil is strongly repellent at the surface, mixing with the subsoils can make the entire profile repellent, and they attributed this phenomenon to the 'percolation theory' whereby large-scale flow is dependent on heterogeneities at the pore scale.

Researchers (Davies *et al.* 2013*a*) and farmers (Davies *et al.* 2013*b*) in Western Australia have been experimenting predominantly with two different forms of one-off deep cultivation through full or partial inversion of the soil, typically using mouldboard ploughs or rotary spaders. These deep cultivation techniques engage with the non-repellent subsoil and bring it to the surface, creating wettable layers or pathways for water entry in addition to any dilution that may occur. The impact of one-off cultivation depends on the extent and depth of cultivation and the amount of subsoil lifted to the surface (Fig. 6).

Mouldboard ploughing. This technique overcomes water repellency by burying the repellent topsoil and bringing wettable subsoil to the surface (Davenport *et al.* 2011; Davies *et al.* 2013*a*). Water can readily enter the soil, and after sufficient rainfall, the buried topsoil fully wets-up (Fig. 7) and becomes inhabited by crop roots. This buried topsoil then stays wetter for longer than if it remained at the soil surface, because evaporation is reduced, resulting in improved plant access to nutrients in the buried topsoil (Scanlan *et al.* 2013). Other advantages include burying herbicide-resistant weeds (Peltzer and Matson 2006), and removing compaction and burying nutrients and lime into acidic subsoils (Davies *et al.* 2013*a*). Greater benefits are likely if the subsoil contains some clay (~4–8%). Complete soil inversion is required to bury weed seeds and water-repellent soil completely and achieve optimum benefits (Davies *et al.* 2013*a*). This would be expected to be a one-off amelioration tool in a Tenosol, but would not be applicable in Chromosols or Sodosols. Growers then revert to a stubble retention–minimum

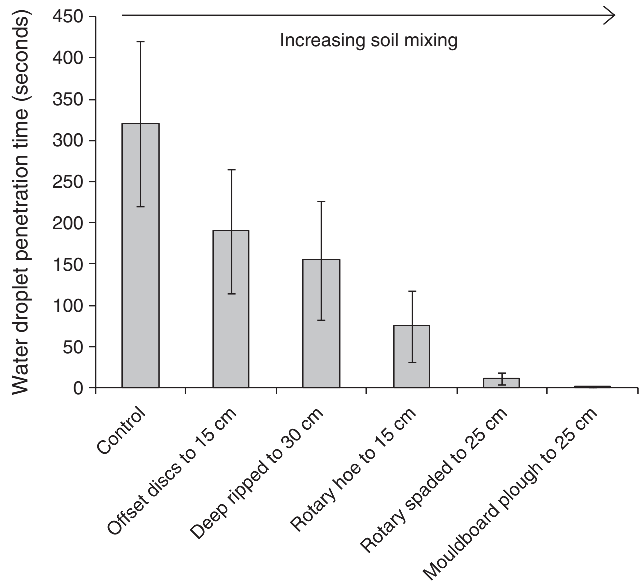


Fig. 6. Impact of one-off cultivation of different intensities on soil water repellency of a Tenosol at Badgingarra as measured in the laboratory using the water-droplet penetration time. Capped lines are ± standard error of the mean ($n=4$). Adapted from: Davies *et al.* (2010). (© Western Australian Agriculture Authority)

tillage system. In 2011, >10 000 ha of sandplain soils (Tenosols) in the northern wheatbelt region of Western Australia was inverted using a mouldboard plough (Davies *et al.* 2012). In that year, those authors measured an average positive grain yield response in wheat of 0.5 t ha^{-1} across 16 farmer fields. They also measured a reduction in leaf disease pathogens such as *Septoria* spp. compared with an untreated control, possibly due to burial of pathogen spores. In the longest, continuously running mouldboard-plough trial, established in 2007 on mildly repellent Tenosols, cereal grain-yield benefits of 0.2–0.4 t ha^{-1} were measured for five seasons after a one-off mouldboard ploughing, but there was no response in the lupin and canola break-crop years (Davies *et al.* 2013*a*). In a highly repellent Tenosol at Badgingarra, crop yield increases of ≥1 t ha^{-1} were measured for 3 years following soil inversion with a mouldboard plough (Davies *et al.* 2013*b*). On the south coast of Western Australia, ~3000 ha has been mouldboard-ploughed (D. Hall, unpubl. data); however, the major limitation to adoption is wind erosion post-ploughing of the fine sandy soils that are predominant in this region (Overheu *et al.* 1993).

Rotary spading. Spading combines a degree of soil inversion with soil mixing, and like mouldboard ploughing, it is most suited to the Tenosols. The spades on a rotary spader lift seams of subsoil to the surface, creating an increased number of preferred pathways for water entry and improving the wetting up of the soil (Fig. 8). Additional mixing or homogenisation of these soils may destroy these preferred pathways and needs to be avoided so the benefits are not lost. In 2011, rotary spading increased grain yields in 12 trials by an average of 0.6 t ha^{-1} (Davies *et al.* 2012). Although complete soil inversion with a mouldboard plough is better at controlling weeds and more thoroughly reduces repellency, the rotary spader is more successful when incorporating clay and/or lime into the soil

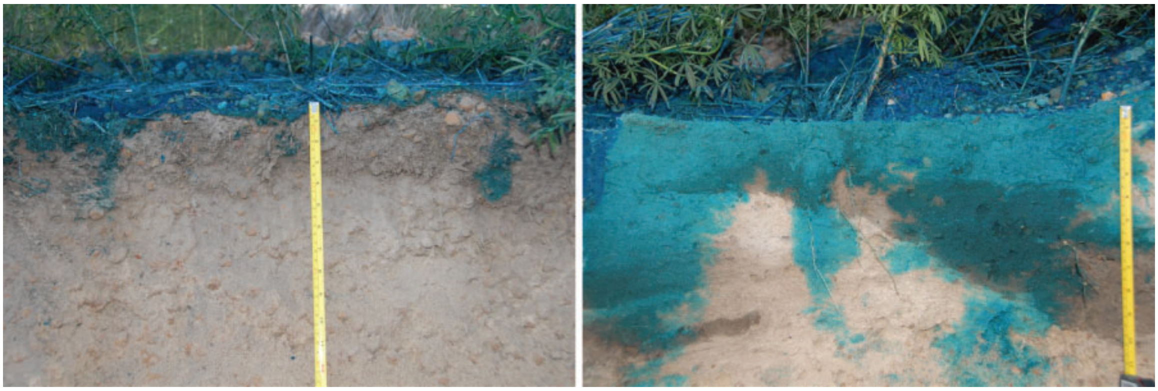


Fig. 7. Infiltration of water containing blue dye into a water-repellent sandy gravel (Tenosol) that is either untreated (left panel) or has been inverted using a mouldboard plough (right panel). Source: S. Davies, DAFWA (reproduced with permission).

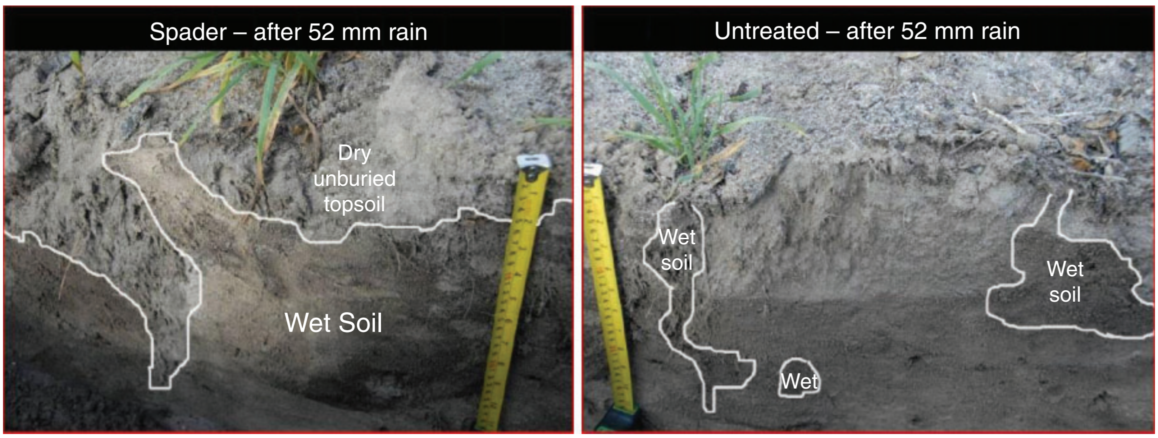


Fig. 8. Spaded soil (left panel) compared with untreated soil (right panel) after 52 mm of rain on a Tenosol. Source: S. Davies, DAFWA (reproduced with permission).

because these amendments are distributed throughout the working depth instead of being buried in a layer at depth. Rotary spaders are one of the few tools able to incorporate high rates ($\geq$250 t ha^{-1}) of clay-rich subsoil effectively (Davies *et al*. 2013*a*).

An immediate risk with either mouldboard ploughing or rotary spading is wind erosion in the year of application (Table 2). There is no way to avoid the risk completely; however, it can be minimised by applying these treatments only when the soil is wet and by seeding immediately with a cereal crop (Davies *et al*. 2012). Lupins, canola or other broadleaf crops should be avoided because of their sensitivity to sand blasting. It is important to retain stubble from the first year's cover crop to protect the soil from erosion.

Further research is needed to evaluate these deep cultivation methods fully, including the impacts of burying organic matter and nutrients at depth and how this alters soil physical, chemical, hydrological and biological behaviour. Long-term benefits can legitimately be claimed only after rigorous measurement over several years. It is critical to understand the mechanisms of change due to dilution treatments, to ensure that mixing of repellent topsoils with wettable subsoils does not have negative impacts on repellency of the entire soil profile as found by Steenhuis *et al*. (2005) and in the field by Roper *et al*. (2013*a*).

Avoidance: adaptation and alternative land use

In certain soils and environments, crop or pasture production may not be economically viable or sustainable. For example, Tenosols in low-rainfall zones are often not productive and alternative management options need to be considered to prevent land degradation (Table 3). Perennial plant species offer a lower risk alternative to annual species because they are not required to germinate each year, but can be established in more favourable seasons (Cransberg and McFarlane 1994) and provide year-round growth and soil cover with minimal soil disturbance (Ward *et al*. 2014).

In recent years, farmers have begun to grow subtropical perennial grass pastures on poor water-repellent Tenosols. For example, in the wheatbelt region of Western Australia, kikuyu grass (*Pennisetum clandestinum*) has become well established in the cooler south coast region, and Rhodes (*Chloris gayana*)–panic (*Panicum* spp.) grass mixtures are common in the north

(Moore *et al.* 2006; Lawes *et al.* 2014). Tenosols are stabilised by the establishment of kikuyu pastures that produce deep-rooting systems (McDowall *et al.* 2003; Nie *et al.* 2008) and these protect and even increase soil carbon (Roper *et al.* 2013*b*). Deep-rooted perennial pastures can use water when annual species are dead (Ward *et al.* 2014) and can provide soil cover and root mass to restrict soil loss from erosion. The 'green-leafiness' of subtropical species over summer compared with annual species increases the potential for production from grazing systems, particularly where both winter-dominant annual species and summer-dominant subtropical species coexist (Moore *et al.* 2006; Nie *et al.* 2008; Ward *et al.* 2012).

The most common fodder shrub grown on water-repellent sands is tagasaste (*Cytisus proliferus*), but it requires a specific seeding technique to ensure successful establishment (Wiley 2000) and expensive canopy management to maintain production (Lefroy *et al.* 2001).

Farm-management choices as affected by scale of water repellency

Most agricultural economic calculations are based on a whole-farm budget, and therefore, the best economic choice for repellency management may not lie in productivity improvements on a per-hectare basis but rather on a whole-farm basis (Abadi Ghadim 2000). Options for management of repellency range from one-off, long-term amelioration methods, such as claying, which are relatively expensive per hectare, to less expensive, annual mitigation methods, such as a change of seeding-point or boot design, which can improve productivity over a larger area of the farm but may not give the highest yield increases on a per hectare basis (Blackwell *et al.* 2014).

Amelioration options are more likely to give large production improvements per hectare, in the order of $\geq$50%, whereas the mitigation options may only provide small production improvements, in the order of <10%. However, the differences in area of application, within the limits of available finance, can make very large differences to the annual improvements to farm profit. For example, an area of 500 ha of claying with 50% yield increase will not provide as much profit as 6000 ha of cropping with improved seeding equipment and a 10% yield increase.

When ameliorating only a portion of a farm, it makes sense to modify seeding equipment to benefit the whole farm and improve earnings from yields that can go towards covering the costs of amelioration (Blackwell *et al.* 2014). Such interactions are very dependent on the scale and pattern of repellency on specific farms. The contrast in scale can range from all of the cropped soil being repellent, to a minority of paddocks and even to repellent patches in paddocks with very variable soil types. Targeted application of amelioration to patches of repellent soil in an otherwise non-repellent paddock may be the best strategy for such a small scale of repellency, and no investment in mitigation methods may be necessary. The whole-farm approach utilising a careful mix of amelioration and mitigation is more easily applied to farms where all of the cropping soil is repellent.

Care therefore needs to be taken in choices of water-repellency management options according to the scale at which repellency affects individual farms, and it is important to calculate the beneficial effects on a whole-farm basis to ensure that profitable use of low-cost mitigation is not omitted. In a whole-farm economic model, Abadi Ghadim (2000) emphasised that owing to costs of amelioration of repellency, much greater yield responses may be required for economical adoption of innovations on most farms. Furthermore, even after undertaking expensive amelioration methods, problems such as surface sealing due to poor clay incorporation, nutrient deficiencies (or toxicities) in subsurface clays, or damage from unexpected wind-erosion events can greatly decrease benefits. Nonetheless, Hall *et al.* (2010) showed that even on the worst water-repellent soils, claying was profitable, although it sometimes took up to 7 years post-claying to break even. Where claying has been successful, long-term benefits (at least 45 years) have been observed (C. Obst, pers. comm.).

Future research needs

Growers are becoming increasingly aware of a wide range of potential management strategies for water-repellent soils, and yet many of them still cite water repellency as their single most significant impediment to crop productivity (Davies *et al.* 2013*b*). Many factors contribute to this. Amelioration of water repellency by claying is potentially the most beneficial method in the long term, but the costs are substantial, and in some cases, prohibitive. Furthermore, little is known about the longevity of amelioration strategies. The impacts of rotary spading and mouldboard ploughing on water repellency have been tested only in the medium term, up to 5 years (Davies *et al.* 2013*a*). Further assessment is required to evaluate changes in the soil profile in the longer term and to determine whether repellency re-develops over time, particularly if subsoil with low clay content has been brought to the surface. Does repeated mouldboard ploughing or spading after 5–10 years cause enough mixing to bring into effect the 'percolation theory' (Steenhuis *et al.* 2005) whereby small percentages of hydrophobic grains can drastically change the flow behaviour in soil and render the entire profile water-repellent? Long-term studies need to be undertaken to answer these questions and to understand the mechanisms involved. The impact of deep cultivation on soil carbon levels in the soil surface needs to be measured over time. Furthermore, the fate of buried organic matter and its role in nutrient and water retention in the crop root-zone requires further investigation because these may be drivers of longer term productivity benefits. For all of the amelioration strategies, a greater understanding is needed of their impacts on crop nutrition and soil microbial function immediately after treatment and in the following years.

There is still much to be learnt about mitigation strategies. No-tillage has been shown to benefit soil water infiltration, but not all growers are seeing the same benefits. Is this due to subtle differences in their no-tillage practices or are differences in soil type responsible? In Australia, repellent soils can range from deep sands (Tenosols), to duplex (sand over clay) (Chromosols and Sodosols), with varying depths of sand over a gravel layer and loamy or sandy gravels. In addition, research to date indicates that 3 years after restoration of no-tillage and stubble retention following 4 years of stubble removal and/or cultivation, there has been no recovery of the previously stubble-burnt treatments in terms of soil carbon or soil water content

(M. M. Roper, unpubl. data). It is important to know the rates of recovery of soil carbon and soil water, particularly after major perturbations such as a decision by a grower to burn stubble or after major soil disturbance such as mouldboard ploughing. Such perturbations may have much longer term impacts than expected, but information on this is not yet available.

Research on no-tillage systems has highlighted the benefits of seeding close to the previous year's row to take advantage of water flow down old root pathways, particularly in times of low rainfall. Early research has shown benefits of increased emergence in on-row seeded crops compared with inter-row sown crops. However, further work is required to understand the processes in years of different rainfall and temperatures and to ensure that risks of disease do not predominate.

Banding of soil wetting agents at seeding provides a cost-effective way of improving the effectiveness of furrow sowing in overcoming water-repellency in soils. Further work is needed to assess the effectiveness of banded soil wetting agents across the range of soils affected by water repellency. There is a need to understand how banded wetting agents are affected by soil moisture at seeding and the timing of subsequent rainfall events. In addition, research is required to improve understanding of the properties, characteristics and agronomic impact of different chemical formulations of soil wetting agents, as well as their impact on soil-nutrient access by different crop species.

Dry or early seeding before opening rains is becoming much more common to ensure rapid development of crops once winter rains commence. Many growers have observed that in water-repellent soils, dry-seeded rows remain dry whereas the undisturbed inter-row wets up. Davies *et al*. (2012) hypothesised that this was due to water-repellent topsoil falling back over the seed into the slots behind the seeding point. Follow-up studies are exploring adding wings to the knife-points or seeding boots to grade the dry repellent soil away from the row onto the ridges (S. L. Davies, unpubl. data). Initial field results are promising, but further field evaluation is needed to understand better the movement of repellent soil and its relationship to seed placement under various moisture conditions and repellent soil types. Further investigation is also needed to understand the physical, chemical and biological mechanisms by which repellency is worsened if soil is disturbed when dry, so that mitigation strategies can be developed.

Actinobacteria can be effective in decomposing waxes responsible for repellency. Although these bacteria occur naturally in all soils including water-repellent soils, their ability to decompose waxes can be limited by environmental conditions and population vigour. Liming of soils and/or strategic fertiliser use can be beneficial for bacterial wax decomposition; however, research on the impact of fertilisers on soil water repellency is sparse and contradictory and requires further investigation. Other additives such as biochar have been shown to have variable effects on soil wettability (Abel *et al*. 2013) and further research may be warranted.

Combinations of different strategies are likely to ensure greater success than individual treatments. Innovative farmers are experimenting with the combination of surfactant and on-row seeding with considerable success. Use of crop species with dense or extensive root systems together with no-tillage and on-row seeding is likely to enhance water infiltration and stabilise soil, and could be implemented following mouldboard ploughing or extensive claying works. Integration with other useful management strategies includes (*i*) employment of controlled traffic cropping to minimise re-compaction of deep-cultivated and clayed soils, and (*ii*) deep incorporation of lime when subsoils are too acid. These combinations need to be tested for a range of soils and climates.

Finally, in developing management solutions for water-repellent soils, it is critical that we understand the physical, chemical and biological mechanisms behind the 'solutions' so they can be applied to achieve maximum benefits over a wide range of soil and climatic types. This then provides a firm basis on which to communicate findings to growers.

Conclusions

Significant advances have been made in developing and assessing a range of strategies to mitigate (reduce the symptoms of) and ameliorate (alter the soil-surface properties of) water-repellent soils in agricultural systems. Growers are becoming increasingly aware of these strategies through targeted extension activities, but adoption has been slow. Significant risks remain in adopting the amelioration strategies, in particular the high costs of implementation and risk of soil erosion; however, future research highlighted above should ease these concerns. Growers need to find a balance between (*a*) using expensive amelioration strategies to improve yield greatly over a small area, and/or (*b*) using lower cost and lower risk mitigation strategies to achieve smaller yield increases over a greater land area.

Acknowledgements

The authors acknowledge funding from GRDC for the preparation of this review and support from CSIRO and DAFWA (Department of Agriculture and Food Western Australia).

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