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Under no-tillage and stubble retention, soil water content and crop growth are poorly related to soil water repellency

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ABSTRACT

In southern and western Australia up to 10 million hectares of farmed land is water repellent or at risk of developing repellency. The majority of these soils are sandy. Their high susceptibility to erosion has led to the adoption of practices such as no-tillage and stubble retention. However, retention of stubbles can lead to increases in soil organic matter and consequently aggravate soil water repellency. In a 4-year study on sandy soils on the south coast of Western Australia, soil organic C (LECO), soil water repellency (measured by the Molarity of Ethanol Drop (MED) method), soil water contents (using a hand held time domain reflectometer (TDR)) and crop performance (emergence and grain yields) were monitored in four treatment combinations; no-tillage, stubble retained or burnt; cultivated, stubble retained or burnt. Over time, higher levels of soil organic C were measured under no-tillage than cultivation, and under stubble retention than stubble burning. Soil water repellency followed a similar pattern to soil organic C with the most severe repellency under no-tillage and stubble retention and least under stubble burning and cultivation (R^2 = 0.67). However, soil water contents measured in the field contradicted the findings on water repellency and indicated that water infiltration was best under no-tillage and stubble retention and poorest under stubble burning and cultivation, and this impacted on crop performance. The results suggest that mechanisms other than just soil water repellency are involved in determining soil water content and crop performance. Visualisation of water infiltration using blue dye indicated that under no-tillage, old and current crop rows provide pathways for water movement in the soil, thereby by-passing the repellent surface layer. These findings challenge traditional thinking on soil water repellency and have implications for crop management.

1. Introduction

In the mid 1990s, soil water repellency was estimated to affect more than 5 M ha of sandy soils in agricultural regions of southern and south-west Australia (Blackwell, 1993). More recent estimates indicate that in south-west Australia alone, 3.3 M ha and 6.9 M ha of farming land are at high and medium risk respectively of developing repellency (van Gool et al., 2008). Water repellency generally occurs in surface sandy soils where hydrophobic materials of plant origin coat soil particles (Franco et al., 1995). This property restricts water infiltration into the soil and results in diversion of rainfall either laterally in runoff or vertically as concentrated flow in preferred pathways (Ritsema and Dekker, 1994, 1996; Dekker and Ritsema, 2000; Doerr et al., 2000). Cracks in the soil and root holes often initiate preferential flow which passes through the hydrophobic layer of soil in a 'finger flow' pattern, leaving significant volumes of adjacent repellent soil dry (Ritsema and Dekker, 1994; Doerr et al., 2000). As water reaches lower depths in the soil profile, hydrophobicity of the soil decreases and there is potential for subsurface lateral spreading of water (Doerr et al., 2000).

Uneven soil wetting and limited water retention in these soils causes poor crop and pasture establishment resulting in increased susceptibility to wind and water erosion (Bond, 1964; Tate et al., 1989). Reduced tillage practices along with stubble retention have been enthusiastically adopted by farmers in southern Australia, driven largely by well-documented reductions in soil erosion (Malinda, 1995; Flower et al., 2007). In south-west Australia, significant erosion events in the 1980s (Goddard et al., 1981) prompted a steady trend of adoption, and by 2003 more than 86% of farmers in this region were using no-tillage (D'Emden and Llewellyn, 2006). Additional benefits of this practice can include

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higher levels of soil carbon (Campbell et al., 1996; Bachmann et al., 2008), which in many soil types, result in greater water and nutrient holding capacity (Lal and Kimble, 1997). However, in sandy soils, increased levels of soil carbon derived from retained crop residues have been linked to more severe water repellency (Harper and Gilkes, 1994; Šimon et al., 2009; Blanco-Canqui, 2011).

The impact of stubble retention and no-tillage practices on soil water dynamics in soils prone to water repellency has not previously been studied in the field. In this research, we test the following hypotheses for a sandy soil in the south-west of Australia: (1) no-till and stubble retention leads to greater levels of soil carbon; (2) greater levels of soil carbon are associated with increased severity of water repellency; and (3) increased severity of water repellency is associated with lower and more variable soil water content.

2. Materials and methods

2.1. Site details

A 4-year field experiment, begun in April 2008, was conducted in a farmer's paddock (33°35.212′S; 120°48.221′E) on a non-wetting bleached sand, with slight ironstone gravel at the surface and increasing gravel with depth (Ferric mesonatric yellow sodosol: Isbell, 2002) on the south coast of Western Australia. The region has a Mediterranean-type climate characterised by hot dry summers and cool wet winters. Average annual rainfall at the nearby 'Munglinup' Bureau of Meteorology weather station (33°42.6′S; 120°52.2′E) was 522.4 mm (1970–2011) (Bureau of Meteorology web site, accessed 16.01.12). Rainfall (mm) during the years of the experiment was 465.4 in 2008, 415.6 in 2009, 523.8 in 2010 and 711.9 in 2011. The experiment was divided into 2 sections within which tillage (no-tillage and annual cultivation) were each replicated 4 times in plots 12 m × 12 m in size. On one section, where the paddock had previously been burnt from a lightning strike in December 2004, stubble was burnt each year during the experiment just prior to seeding. Dates of burning were 13 April 2008, 14 May 2009, 6 May 2010 and 26 May 2011. On the other section which had not been burnt during the lightning storm, stubble was retained throughout the experiment. Immediately after the burning treatments (usually on the same day), 'cultivated' treatments were tilled to a depth of ~75 mm by a single pass of a light-duty International disc plough. Approximately 75% of the stubble was incorporated by cultivation which also mixed repellent surface layers with less repellent soil below to a depth of 7.5–10 cm. 'No-till' treatments were undisturbed. All treatments were then seeded using the farmer's seeding equipment (a 'zero-till' Gessner Bar with Walker triple discs) which resulted in minimal soil disturbance. Therefore, there were a total of four treatments: no-till, stubble retained (NTR); cultivated, stubble retained (CTR); no-till, stubble burned (NTB); and cultivated, stubble burned (CTB). Winter season crops planted were Canola cv. Surpass 501TT (1 May 2008); Barley cv. Dash (15 May 2009); Canola cv. 45y82 IT hybrid (7 May 2010); Wheat cv. Mace (28 May 2011). Prior to the commencement of the experiment, baseline measurements were determined for all parameters monitored throughout the experiment. Details of these measurements are given in the following sections. Individual plots were harvested by a contractor using a plot harvester (Massey Ferguson 31, Germany) at maturity in late November or December each year.

2.2. Sample collection

Soil samples were collected for soil depths of 0–0.05 m and 0.05–0.10 m using a soil corer (25 mm diameter). Nine sets of samples were collected at random locations within each plot next to crop rows and combined for each depth. The samples were air dried and sieved (<2.0 mm) in preparation for analyses detailed below. Samples were collected pre-season (March 2008; February 2009–2011), during the growing season just after seeding (April/May), again in June/July, and at anthesis/peak biomass (late September–early October).

2.3. Soil carbon and pH

Air-dried soil samples were sent to CSBP Limited laboratories (Bibra Lake, Perth, Western Australia) for determinations of organic C% (LECO Combustion Analyser, Laboratory Equipment Corporation, St. Joseph, MI) and soil pH ($CaCl_2$, 0.01 M). Soil pH was determined for the baseline sampling only.

2.4. Soil water repellency

Soil water repellency was determined using the Molarity of Ethanol Drop (MED) test described in King (1981). Droplets of aqueous ethanol (at concentrations increasing by 0.2 M intervals from 0 to 5 M) were placed on the soil surface and the concentration at which the solution entered the soil within 10 s was recorded. Wettable soils have a MED of 0, but as repellency increases the MED value can increase to >4. Soils were prepared for measurement using 2 methods of drying: (1) air dried only and (2) air dried followed by 48 h at 105 °C. Consistent with the findings of Roper (2005) MED measures were quite comparable between both drying temperatures but less variable when dried at 105 °C and therefore, these values only are reported.

2.5. Soil water content

Soil water content (0–0.12 m) was measured in the field using a hand held time domain reflectometer (HHTDR) (HydroSense; Campbell Scientific, Logan, Utah) on the same days as the soil sampling described above. Soil water contents were calculated from dielectric properties using the standard calibration supplied with the instrument. Pairs of soil water measurements (in the crop row, and immediately adjacent in the crop inter-row) were taken at 10 random locations (20 measurements) within each plot. With zero-till seeding the disc sliced through the soil leaving no perceptible difference in topography between the row and the inter-row. Variability and distribution of soil water content were determined from an additional grid of measurements in which soil water content was measured at 0.1 m intervals along 1.0 m lengths of two adjacent crop rows and associated inter-row locations (40 measurements per plot).

2.6. Visualisation of soil water infiltration

Patterns of water entry into soils under no-tillage versus cultivation were observed using a blue dye. Five litres (equivalent to 10 mm of rainfall) of a 1% solution of 'Brilliant Blue' dye (All Colour Supplies Pty Ltd., Sydney, Australia) in water was applied to an area 0.7 m × 0.7 m using a Hill's Garden Sprayer (Bunnings Warehouse, Australia) with the nozzle adjusted to deliver the equivalent of 30 mm h^{-1} of solution. After ~2 h vertical cuts across the planting rows were made using a spade and patterns of blue dye were recorded photographically.

2.7. Crop performance

Crop emergence was measured 2–4 weeks after seeding. The number of plants on either side of a 1 m rule was counted at 6 locations within each plot. The distance between adjacent seeding rows was used to calculate the number of emerged plants m^{-2}. At crop maturity, machine harvested grain yields were recorded.

2.8. Statistical analyses

Data for soil organic C, soil water repellency and soil water content were summarised for each year of the experiment by averaging the data over 4 sampling dates ranging from pre-season (February/March) to anthesis (September/October). Because burning treatments were not allocated randomly, results were analysed as a split plot ANOVA with stubble management, tillage treatment and sampling depth (where applicable) as factors using the statistical package GenStat (version 13.1, VSN International Ltd.).

3. Results

3.1. Baseline measurements

Samples for baseline measurements were collected on 26 March 2008 at the beginning of the experiment just prior to imposing the first burning or cultivation treatments. In the 'retained stubble' treatment plots, soil organic C contents averaged 1.28% (0–0.05 m) and 0.74% (0.05–0.10 m). In the 'burnt stubble' treatment plots, the effects of the single burning event caused by the lightning strike in 2004 were still evident with soil organic C contents of 0.88% (0–0.05 m) and 0.66% (0.05–0.10 m).

Soil water repellency (as MED) was moderately severe, and at 0–0.05 m and 0.05–0.10 m averaged 2.6 and 1.4 in the 'retained stubble' plots and 2.5 and 1.6 in the 'burnt stubble' plots, respectively. Soil pH ($CaCl_2$, 0.01 M) averaged 4.8 (0–0.05 m) and 4.7 (0.05–0.10 m). The first full set of measurements of soil water content was done on 2 July 2008, 2 months after seeding. At this time soil water contents in both 'retained stubble' treatments were similar and averaged 6.7% (v/v); both the 'burnt stubble' treatments averaged 7.3% (v/v).

3.2. Soil organic carbon

In 2008, there was a significant ($P < 0.001$) effect of the 2004 burning event and 2008 burning treatment on soil carbon, but there were no significant tillage effects ($P = 0.475$) (Fig. 1a). Both the 'retained stubble' treatments contained an average of 1.46% C in the surface 0.05 m and 0.99% C at 0.05–0.10 m. The two 'burnt stubble' treatments were statistically similar to each other and contained an average of 1.01% and 0.72% organic C at 0–0.05 m and 0.05–0.10 m respectively. In subsequent years, some differentiation developed amongst the tillage treatments. In 2009 (Fig. 1b) and 2010 (Fig. 1c) there were significant tillage effects ($P < 0.05$). By 2011 (Fig. 1d) the level of significance increased to $P < 0.001$. The no-tillage treatments (NTR and NTB) maintained significant differences between the two sampling depths in all four years of the experiment. The effect of cultivation was 2-fold. Mixing of C to depth resulted in distribution of organic C with depth resulting in no significant differences between depths by 2011, but there was also an overall decline in the amount of organic C in both the cultivated treatments (CTR and CTB). The combination of burning and cultivation (CTB) resulted in the lowest soil organic C content with a steady decline at both sampling depths.

3.3. Soil water repellency

Soil water repellency (MED, Fig. 2) responded to burning and cultivation during 2008 (Fig. 2a) compared with the baseline measures in March 2008 which were not significantly different

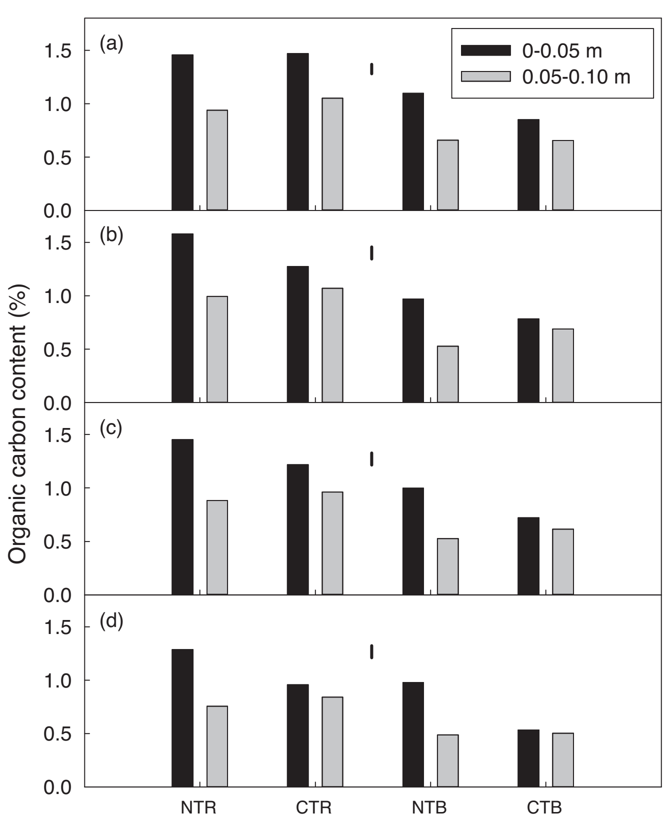

Fig. 1. Soil organic carbon (%) in the 0–0.05 m and 0.05–0.10 m layers for four tillage and stubble treatments: no-till, stubble retained (NTR); cultivated, stubble retained (CTR); no-till, stubble burned (NTB); and cultivated, stubble burned (CTB), in (a) 2008; (b) 2009; (c) 2010; and (d) 2011. Vertical bars indicate LSD ($P = 0.05$) values.

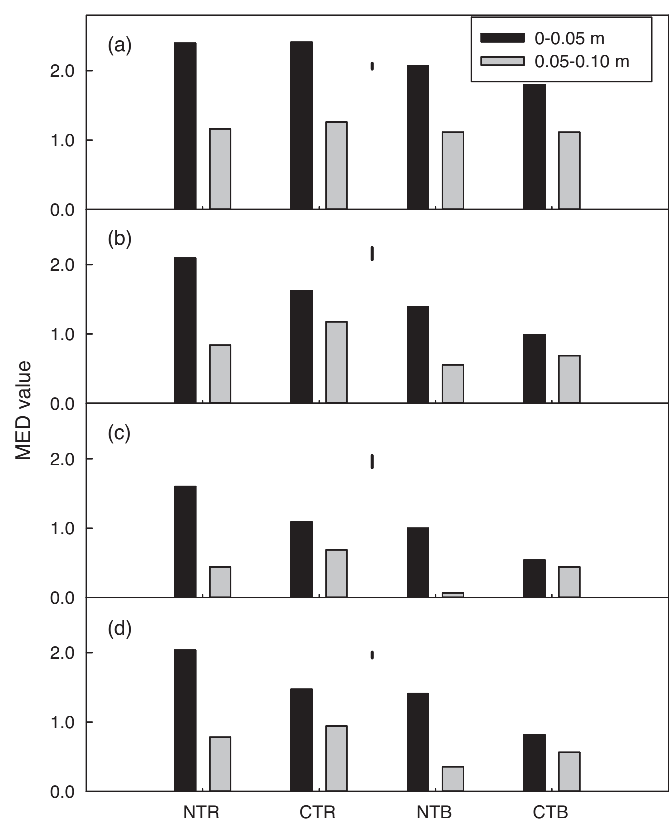

Fig. 2. Soil water repellency (MED value) in the 0–0.05 m and 0.05–0.10 m layers for four tillage and stubble treatments: no-till, stubble retained (NTR); cultivated, stubble retained (CTR); no-till, stubble burned (NTB); and cultivated, stubble burned (CTB), in (a) 2008; (b) 2009; (c) 2010; and (d) 2011. Vertical bars indicate LSD ($P = 0.05$) values.

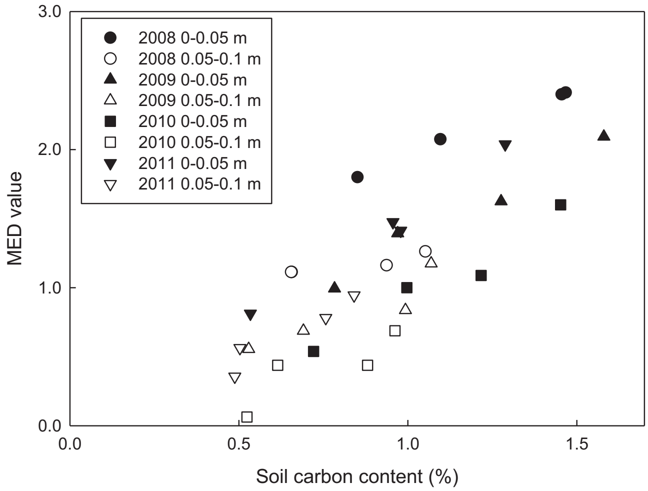

Fig. 3. Correlation between soil organic carbon content (%) and soil water repellency (MED) ($R^2 = 0.67$).

from each other. By the 2nd year of the experiment (2009, Fig. 2b) some clear patterns emerged and persisted for the remainder of the experiment (Fig. 2c and d). In particular, water repellency in the top 0.05 m was highest under NTR and reduced successively for CTR, NTB and CTB treatments. In both treatments under no-tillage, repellency was most concentrated in the top 0.05 m and was much less severe at 0.05–0.10 m. Cultivation resulted in some redistribution of the repellent layer into the 0.05–0.10 m depth. Combined over all four years, there was a good correlation ($R^2 = 0.67$) between soil water repellency and soil organic C content (Fig. 3).

3.4. Soil water content

Soil water contents (v/v) for each year averaged 7.5% (2008), 8.7% (2009), 16.1% (2010) and 6.9% (2011). 2010 was very wet early in the season and soils were water-logged during May resulting in soil water contents that exceeded field capacity. In 2008, there was little difference in soil water content between the treatments (comparing treatments with the LSD (5%) values indicated in Fig. 4) although soil in crop rows in the NTR treatment was significantly ($P < 0.05$) wetter than in the other three treatments, and soil in inter-row locations was drier in the cultivated treatments (CTR and CTB) (Fig. 4a). This pattern was repeated in 2009, but with larger differences between the treatments ($P < 0.01$) (Fig. 4b).

In 2010 and 2011 (Fig. 4c and d), soil water contents were significantly ($P < 0.001$) higher (2–4%, v/v) in the NTR and CTR treatments, and within these 'stubble retained' treatments, soil water content under the crop row was greater than soil water content in the inter-row locations ($P < 0.05$). There was no difference in soil water content between crop rows and inter-row locations for treatments NTB and CTB.

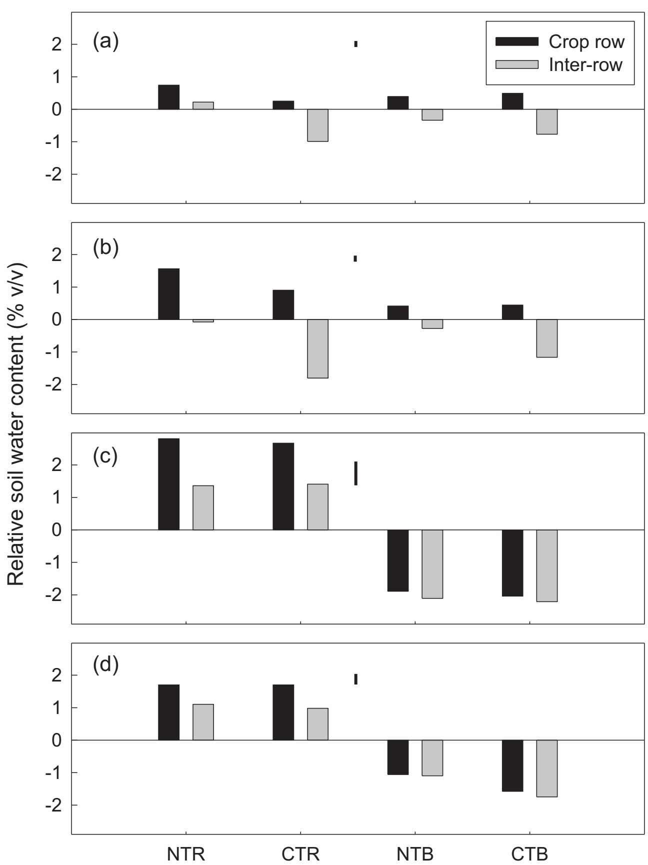

Fig. 4. Soil water content (%v/v) in the 0–0.12 m layer relative to average measured soil water content for four tillage and stubble treatments: no-till, stubble retained (NTR); cultivated, stubble retained (CTR); no-till, stubble burned (NTB); and cultivated, stubble burned (CTB), in (a) 2008 (average soil water content 7.5%); (b) 2009 (average soil water content 8.7%); (c) 2010 (average soil water content 16.1%); and (d) 2011 (average soil water content 6.9%). Vertical bars indicate LSD ($P = 0.05$) values.

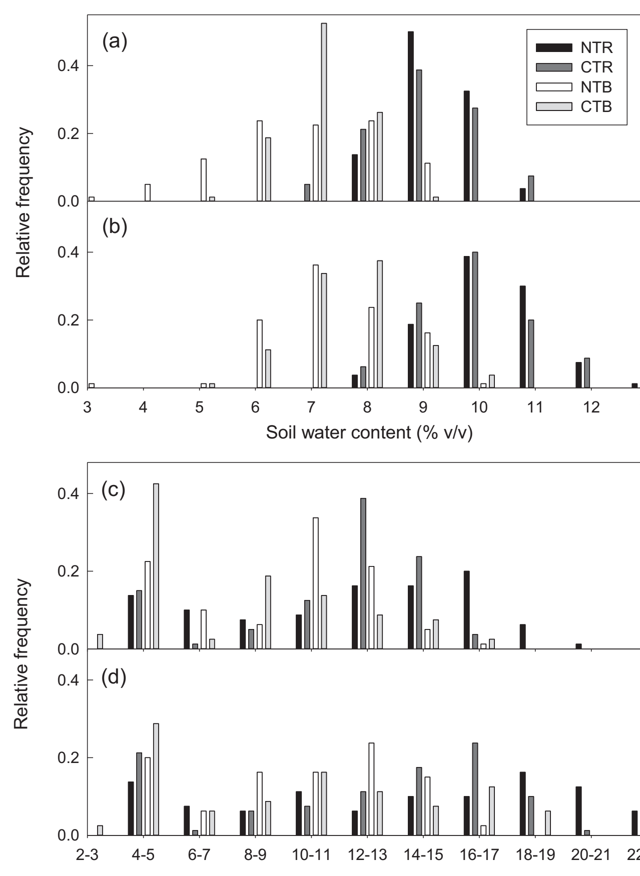

Fig. 5. Frequency distribution of soil water content (%v/v) in the 0–0.12 m soil layer for four tillage and stubble treatments: no-till, stubble retained (NTR); cultivated, stubble retained (CTR); no-till, stubble burned (NTB); and cultivated, stubble burned (CTB), in (a) and (b) April 2011; (c) and (d) July 2011, for inter-row positions (a) and (c); and in-row positions (b) and (d).

Distribution of soil water content was determined for all times of measurement, but only data for measurements in April 2011 and July 2011, after differences between the stubble management treatments became apparent, are presented. Before the April 2011 measurements, 25 mm of rainfall was received in the previous 14 days, and the majority of soil water content measurements were between 6% and 11% (v/v) (Fig. 5a and b). For all treatments, and for both row (Fig. 5b) and inter-row positions (Fig. 5a), soil water contents were approximately normally distributed, and there was no significant difference in standard deviation of soil water content between the treatments ($P = 0.39$). Average soil water in the rows was approximately 1% higher than soil water content in the inter-rows, and average soil water content was approximately 2% higher in NTR and CTR than in NTB and CTB.

In July 2011 (Fig. 5c and d), soil water contents were higher than in April (Fig. 5a and b). On this occasion, soil water contents followed a bimodal distribution, with a narrow peak at 4–5% (v/v) and a broader peak centred around 12–13% (v/v) for inter-row locations, and 14–15% (v/v) for row locations. Once again, there was no evidence for a change in variability associated with the various treatments ($P = 0.39$), but there was a general shift towards higher soil water content values for treatments with retained stubble. Similarly, for all other times of measurement, there was no significant difference in standard deviation of soil water content (data not shown).

3.5. Visualisation of soil water infiltration

In April 2011, just prior to seeding, infiltration of the dye solution was clearly seen in the undisturbed rows from the previous season under NTR (Fig. 6a), but where the soil had been recently disturbed by cultivation (CTR), the dye was unable to enter the repellent soil layer and remained on the surface where it dried into a crust (Fig. 6b). By July 2011, 2 months after seeding, infiltration had developed within the new cropping rows (Fig. 6c and d). Infiltration was still evident in the previous year's row (the current inter-row) in NTR (Fig. 6c), but in CTR only occurred in the new row with the new inter-row remaining dry (Fig. 6d).

3.6. Crop performance

Crop performance was evaluated in all years by measuring plant emergence (Table 1) and grain yields at maturity (Table 2). Crop emergence of canola in 2008 (Table 1) was greatest for the NTR treatment and the least in the CTB treatment. The effects of burning and tillage were both significant ($P < 0.001$ and $P < 0.05$, respectively). At harvest on 5 December 2008 (Table 2), the crop had compensated somewhat and the only significant difference ($P < 0.001$) was between the 'stubble retained' and 'stubble burnt' treatments.

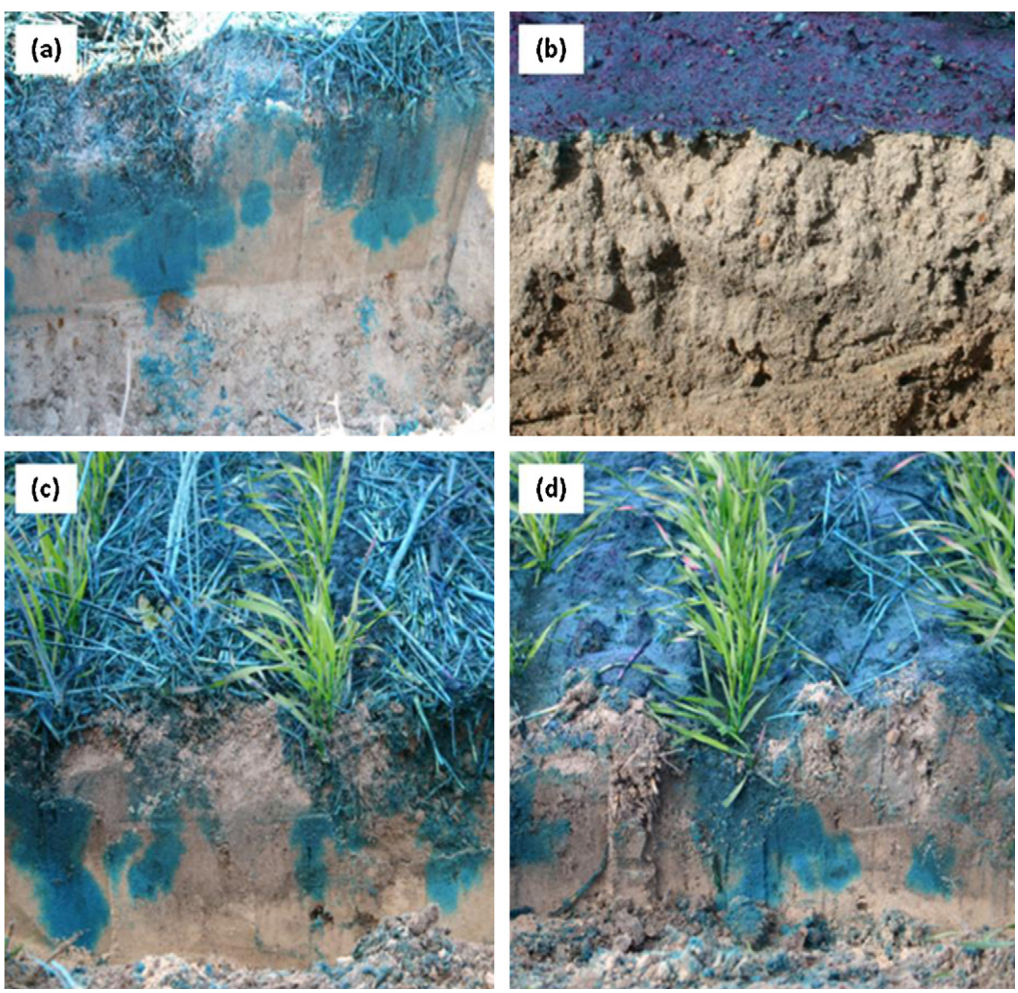

Fig. 6. Entry of a 1% blue dye solution into soil under no-tillage (a and c) and cultivation (b and d) immediately after tillage treatment in April 2011 (a and b) and in July 2011, 2 months after seeding (c and d). Blue dye solution entered the soil via bio-pores formed by root channels, leaving pockets of dry repellent soils at the surface in between the root pathways.

Table 1
Crop emergence for four tillage and stubble treatments: no-till, stubble retained (NTR); cultivated, stubble retained (CTR); no-till, stubble burned (NTB); and cultivated, stubble burned (CTB), in 2008–2011.

Year	Crop	Crop emergence (plants m^{-2})				L.S.D. ($P = 0.05$)
		Treatments				
		NTR	CTR	NTB	CTB	
2008	Canola	24.63	19.46	11.55	9.45	3.32
2009	Barley	66.20	50.50	53.90	35.30	9.57
2010	Canola	23.09	5.09	7.67	2.83	2.51
2011	Wheat	95.85	100.69	122.01	118.38	11.70

In 2009, the emergence of barley (18 June 2009) was greatest in the NTR treatment and least in the CTB treatment. Both effects of tillage and burning were significant ($P < 0.001$ and $P < 0.01$ respectively). By harvest (25 November 2009) some of the differences had resolved but there was a significant interaction ($P < 0.05$) between stubble burning/retention and tillage.

Canola IT hybrid, grown in 2010, emerged in greatest numbers under NTR when measured on 22 June 2010. Cultivation significantly reduced emergence ($P < 0.001$) and so did burning ($P < 0.001$). The effect of cultivation persisted through to harvest on 17 November 2010, but at this time burning was no longer significant ($P = 0.831$). No-till favoured crop yields ($P < 0.001$) and there was a significant ($P < 0.05$) interaction between burning and tillage.

Wheat was sown in 2011 and emergence counts (16 June 2011) indicated a significant burning effect ($P < 0.001$) with higher emergence in the 'stubble burnt' treatments compared with the 'stubble retained' treatments. However, as the season progressed the performance of the crop improved in the 'stubble retained' treatments relative to the 'stubble burnt' treatments. Grain yields from machine harvest (28 November 2011) indicated a significant burning effect ($P < 0.001$) in favour of the 'stubble retained' treatments. Within each stubble retention/removal treatment, cultivation produced significantly ($P < 0.05$) better yields than no-till in 2011.

4. Discussion

No-tillage practices where crop residues are retained have the potential to increase soil water repellency and this has been attributed to increases in hydrophobic compounds associated with accumulated organic carbon (Blanco-Canqui and Lal, 2009; Pikul et al., 2009; Blanco-Canqui, 2011). However, anecdotal evidence in cropping areas of the south coast of Western Australia indicates that under stubble retention and no-tillage, the negative impacts of water repellency "disappear" and crops emerge and perform uniformly. Our study was designed to test this. During the 4-year field experiment, agronomic regimes generated the expected results in terms of soil carbon and water repellency, but the impact on soil water and crop growth differed markedly from expectation and supported the anecdotal evidence.

Table 2
Grain yields in four tillage and stubble treatments: no-till, stubble retained (NTR); cultivated, stubble retained (CTR); no-till, stubble burned (NTB); and cultivated, stubble burned (CTB), in 2008–2011.

Year	Crop	Grain yield (t ha^{-1})				L.S.D. ($P = 0.05$)
		Treatments				
		NTR	CTR	NTB	CTB	
2008	Canola	1.73	1.73	1.52	1.60	0.07
2009	Barley	3.36	2.81	2.72	2.95	0.32
2010	Canola	0.94	0.25	0.74	0.42	0.15
2011	Wheat	3.75	4.47	2.74	3.50	0.49

Comparisons between the four treatment combinations (NTR, NTB, CTR, and CTB) indicated the development of differences in soil organic carbon, mainly due to a decline in C under combinations of stubble burning and tillage treatment and not an increase under no-tillage and stubble retention. Prior to the beginning of the trial in 2008, no-tillage and stubble retention had been practised for more than 20 years and hence it is possible that organic carbon levels were close to their peak for this particular management and soil type. Any changes in practices (soil disturbance or stubble removal) were likely to produce a loss in soil C as observed in cultivated soils elsewhere (Rasmussen and Collins, 1991; Dalal and Chan, 2001; Roper et al., 2010). This has been associated with the deterioration of aggregate structure (Cambardella and Elliott, 1993; Six et al., 1998, 1999), particularly in sands in which aggregation is poor and unstable (Chivenge et al., 2011).

Soil water repellency is generally confined to the upper layers of the soil where hydrophobic materials of plant origin coat soil particles (Franco et al., 1995). In agreement with earlier findings of others such as Blanco-Canqui and Lal (2009) and Pikul et al. (2009), our experiments showed that soil water repellency was more severe in soil samples from no-tillage than cultivated treatments. Repellency was consistently higher in soil under NTR than any other tillage and stubble management combination, and was least under CTB.

Rainfall, and consequently soil water contents, impacted on overall repellency but did not change the pattern of differences between treatments. During 2010, district rainfall was significantly higher than the average and 241 mm fell during the warmer months between January and May compared with an average for that period of 180.4 mm. The resultant moist warm conditions, which are uncharacteristic for Mediterranean-type environments, are likely to have favoured bacterial decomposition of waxes responsible for water repellency (Roper, 2004, 2005) resulting in an overall reduction of repellency in all treatments that year. However, with hot and dry conditions at the end of 2010, soil water repellency increased again most likely due to diffusion of waxes from organic matter and plant material during heating and drying (Franco et al., 1995). Despite this, there was a correlation ($R^2 = 0.67$) between soil organic carbon contents and soil water repellency, which held across all treatments and weather conditions.

Based on the soil water repellency data, soil water contents measured in the field were expected to be highest under CTB and least under NTR. However, the opposite was found. The most repellent soils under NTR contained more water throughout the year than the less repellent soils under CTB. This effect became more pronounced in the last two years of the experiment as differences in carbon content and MED also became larger. Possibly the loss of organic matter in the NTB and CTB treatments reduced the water holding capacity of the soil, causing the observed differences in soil water between the treatments (Lal and Kimble, 1997). Alternatively, retention of organic matter on the soil surface may have reduced evaporative losses of water, leading to the higher water contents measured (Ji and Unger, 2001; O'Leary and Connor, 1997). However, recent research (Ward et al., 2009, 2012) suggests that stubble retention has a limited direct role in reducing evaporation under semi-arid conditions, because of the length of hot dry summers in Mediterranean-type environments. During the growing season, however, stubble may conserve soil water in the short-term (Ward et al., 2012). Reduced tillage and stubble retention have been linked with greater soil water availability in several studies (e.g. Bescansa et al., 2006; Malhi and O'Sullivan, 1990; Monzon et al., 2006) but these studies were performed on soils of finer texture where water repellency was not present.

There is no doubt that water repellency leads to variation in field soil water content (Ritsema and Dekker, 1994, 1996; Doerr et al., 2000). In our study, a bimodal distribution of soil water content was observed, but there was no relationship between severity of soil water repellency and variability of soil water content. Standard deviations of soil water contents were similar for all treatments regardless of MED value ($P = 0.39$), and differences between the treatments were due to a shift in the mean soil water content. This suggests that even relatively mild water repellency (e.g. 2010, Fig. 2c) is sufficient to induce variation in soil water content, and that more severe water repellency does not induce greater variation in soil water content. Therefore, management practices that increase water infiltration are likely to be beneficial for crop growth regardless of the severity of water repellency.

Crop performance generally reflected soil water contents although there were likely other factors as well. Both 2008 and 2009 were relatively dry years with 57 mm and 106.8 mm less rainfall respectively compared with the district annual average (522.4 mm). Therefore, in those years any treatment that favoured higher soil water contents was likely to benefit crop performance. In 2008, canola performed best under stubble retention regardless of tillage, but in 2009, yield of barley was clearly higher under NTR than in the other three treatment combinations, and reflected the soil water contents measured in Fig. 4b. Years 2010 and 2011 were significantly wetter years than the previous 2 years, with 523.8 mm and 711.9 mm of rainfall respectively. Water-logging in 2010 during the early stages of the canola crop was a significant inhibitor of performance. Emergence of canola under NTR was more than 3 times that of the other treatments. Both no-tillage treatments had less water lying on the surface whereas the treatments under cultivation appeared to have slumped in the landscape and carried significant quantities of above-ground water which severely reduced crop emergence. The effects on canola emergence carried through to harvest although there was some compensation particularly in the NTB treatment. Therefore, the results indicate that on these non-wetting soils, no-tillage is best under both wet and dry conditions. In 2011, the wheat crop emerged in greater numbers in both burnt treatments compared with the stubble retained treatments. With a wet start early in the season (104 mm in May alone) it is possible that allelopathic effects from decomposing stubbles (Wu et al., 2001) limited wheat emergence in the stubble retained treatments. However, as the season progressed, wheat in the 'stubble retained' treatments overtook those in the 'stubble burnt' treatments to yield significantly ($P < 0.001$) better at harvest.

The results suggest that mechanisms other than soil water repellency impacted on soil water infiltration. It is hypothesised that under no-tillage, bio-pores formed by roots and soil fauna are preserved and provide pathways for water movement in the soil. This hypothesis was supported by observations of infiltration using blue dye solutions. Blue dye was only observed down the soil profile where continuous root channels were present, including those of dead plants from the previous season. This finding concurs with suggestions by Blackwell (2000) that under zero-till cropping systems, more uniform wetting of repellent soils occurs at the base of dead plants and down dead root systems. Our findings indicated that cultivation destroyed these pathways and redevelopment only occurred with the emergence of the new season's crop (Fig. 6). Disruption of water pathways prior to seeding potentially limits the entry of water from early season rainfall thus restricting the growth of crops at this stage. Emergence data (Table 1) supported this notion with significantly lower emergence in cultivated treatments compared with no-till in the drier years (2008 and 2009). In 2010 and 2011, with significant early-season rainfall, availability of water was not a limitation for the emerging crop. The importance of animal pathways for water infiltration has been demonstrated by Evans et al. (2011) who measured significant increases in soil water content associated with ants and termites compared with adjacent exclusion plots where a synthetic insecticide was used. Any cultivation would disrupt these pathways as well.

It is possible that slumping of cultivated treatments below the level of the rest of the trial, observed during very wet conditions early in the 2010 season, was also due to the destruction of bio-pores formed by continuous root channels and insect tunnels, all of which would normally contribute to the physical framework of the soil.

Whether standing stubble can act as a significant conduit for water infiltration is uncertain. However, cultivation and/or burning would remove that possibility. Apart from the possibility of reducing soil water evaporation, surface stubble may reduce temperatures in the upper layers of soil (Azooz et al., 1997) thus reducing the potential for deposition of waxes onto soil particle surfaces (Franco et al., 1995).

Although a zero-till system was used in the experiments reported here, it is likely that the findings would hold for minimum/no-tillage systems, where seeding is done using knife points. In our experiments, crops were seeded on the previous year's inter-row resulting in no disturbance of the remnant root systems from the previous year. Seeding with knife points in the old inter-row is unlikely to disturb remnant root systems either. Infiltration of water down preferred pathways formed by root channels can be rapid (Dekker and Ritsema, 2000) and once water reaches more wettable subsurface layers there is potential for lateral water movement (Doerr et al., 2000) and therefore wetting of surface layers from below. The results highlight another question on whether it would more beneficial to seed on or close to the previous year's row to more quickly access water conducted down the profile by dead roots. In choosing to take this approach growers must consider how much their seeding systems disturb the soil and determine the 'safest close distance' to avoid breaking the continuity of root channels. Also, there needs to be consideration of the possibility of disease carryover to a new crop when consecutive crops are susceptible to the same disease, e.g. Fusarium crown rot which is transferred to new crops via stubble (Melloy et al., 2010). In the latter case, sowing in the previous year's inter-row may be a preferred option to reduce contact with pathogens.

The findings of this field experiment challenge traditional thinking around the impact of soil water repellency on water infiltration and availability and may have significant implications for cropping systems used in water repellent sandy soils which are so prone to erosion. Several farmers on the south coast of Western Australia are successfully managing their water repellent sands with no-tillage and stubble retention to grow excellent crops.

5. Conclusions

Research findings in field experiments on water repellent sands on the south coast of Western Australia support the first two hypotheses tested: (1) no-till and stubble retention leads to greater levels of soil carbon, and (2) greater levels of soil carbon are associated with increased severity of water repellency. However, the third hypothesis, that increased severity of water repellency is associated with lower and more variable soil water content, was not supported by the results. Despite being more repellent, treatments with no-tillage and stubble retention contained more soil water than other less repellent combinations of tillage and stubble treatment and this impacted on crop performance. The results present important possibilities such as near- or on-row seeding using no-tillage for the effective management of non-wetting soils.

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