Changing the physical properties of texture-contrast soils by clay delving

Thesis submitted by

Giacomo Betti

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Abstract

Summary

Texture-contrast soils are important in Australian agriculture but they are known for their low chemical and physical fertility, and their consequent low productivity. *Clay delving*, a soil modification that combines mixing of clay-textured subsoil into the topsoil with deep ripping, is widely practiced on texture-contrast soils in agricultural regions across southern Australia. Success in terms of crop productivity has been mixed but there is a general consensus that clay delving increases yields, at least in the short term. A review of the available literature reveals that the practice of clay delving is based primarily on trial-and-error experience reported in the so-called 'grey' literature, which focusses mainly on chemical fertility and largely ignores the role of soil physical properties and their effects on plant available water. Until we understand how delving influences soil physical properties, this practice will remain more in the realm of art than in science.

The present study set out to first characterise the changes in physical properties caused by delving and then to evaluate how these changes influence infiltration, water re-distribution in the soil profile, and ultimately soil water availability and root growth. **Chapter 1** reviews the literature on texture contrast soils and outlines their primary limitations for agricultural production. The practice of clay delving is then reviewed and the major gaps in our understanding of this practice are identified. A set of hypotheses is presented, which form the basis for the experimental work outlined in subsequent chapters of this thesis.

The work outlined in **Chapter 2** is based on the hypothesis that clay delving strongly modifies the soil profile, disrupting the interface between A and B horizons and mixing subsoil with the topsoil. The morphology of the new soil profiles differ greatly from the originals (un-delved) with direct effects on soil physical characteristics. In particular, the distribution of these properties is changed both in the vertical and lateral directions. To address this hypothesis, I characterised the physical changes in a typical texture-contrast soil five years after delving, and found indeed that the extensive morphological disruption produced an entirely new soil profile with different soil physical characteristics from the original texture-contrast soil. On a small (profile) scale, bulk density in the delved profiles was highly variable and ranged between that for the A-horizon sand (1360 kg m^{-3}) and

that for the subsoil clay (<1800 kg m^{-3}). Because of the great variability in composition there was no correlation between bulk density and average clay content of the soil. As might be expected the regions having large clods of subsoil (mainly below 0.25 m) had greater mean clay content than regions containing smaller clods (mainly above 0.25 m). The saturated hydraulic conductivity, K_s, in the upper part of the delved profile was significantly reduced (several orders of magnitude) and variability was greater. The abrupt reduction in K_s at the A/B boundary in the un-delved soil became more gradual (and variable) in the delved profiles. Mean soil resistance to penetration was inversely related to soil water content and directly related to clay content in the disturbed zone immediately above the delving line (although the effect diminished with lateral distance between delving lines (off line). Using the IWC concept (taking into account all limiting soil physical factors), high soil resistance was shown to be the single greatest factor limiting soil water availability; where delving reduced soil resistance, available water increased. At a larger (field-transect) scale, results were consistent with the small (profile) scale findings. Furthermore (based on aggregate size and clay content distributions) an average of nearly 500 t ha^{-1} of clay was brought up into the top 0.1 m by delving – this significantly exceeded current recommendations for clay spreading (300 t ha^{-1}). Water repellence in the top 0.1 m was significantly reduced in delved soil (on the delve line and off line) and this significantly increased infiltration rates and reduced the time to reach steady state infiltration. Field penetrometer measurements showed delving significantly reduced soil resistance in the top 0.45 m (especially in the V-shaped zone) but the effect diminished with distance from the delve line. Visual images of the soil profiles confirmed what was found by directly measuring (laboriously) aggregate size and clay content distributions and suggested delving could increase available water in the root zone by between 12 and 23 mm.

Chapter 3 was based on the hypothesis that inserting 'new' clay from the subsoil into the sandy topsoil will decrease surface water repellence and significantly increase the wettability of the entire soil profile. In addition, disrupting the hard A / B horizon interface will allow water that would otherwise pond at the horizon boundary to move significantly deeper in the soil profile. To evaluate this hypothesis, I applied a blue-dye solution (using a rainfall simulator) to the surface of delved and un-delved soils then photographed the dye-stained soil profiles and conducted a digital analysis of the images. Under relatively dry conditions I found that delving significantly increased the wettability of the topsoil and that under wetter conditions water moved to greater depths in the profile. These findings were published as:

Betti G, Grant C, Churchman G, Murray R 2015. Increased profile wettability in texture-contrast soils from clay delving: case studies in South Australia. *Soil Research* **53**:125-136. https://doi.org/10.1071/SR14133.

Chapter 4 was based on the hypothesis that the modification of the soil, in particular, the disruption of the A/B boundary caused by delving contributes to deeper plant root growth and enhances root distribution in the soil profile, especially immediately below the delving line. To evaluate this hypothesis, I collected soil core samples down the entire soil profile of three delved and un-delved soils and collected root samples. I then measured total root length, root length density (RLD) and root mean diameter (RMD), and although the results were highly variable, RLD in the delved soils was significantly greater than that in the un-delved soils; the effects were particularly evident at the A / B horizon boundaries. At two of the three sites examined, the mean root length density (RLD) was significantly greater (and more uniformly distributed) down the profile in the delved soils compared with the un-delved controls. Furthermore, there were no significant differences between RLDs directly under the delving line and the regions between the lines. This suggested the benefits of delving are manifest laterally well beyond the delving lines and indicated that optimum tine-spacing could be evaluated by measuring RLDs as a function of distance from the delving line – the absolute maximum distance at a site would be that where the RLDs differ significantly from those directly under the delve line. At all three sites, roots were significantly thinner (as measured by root mean diameter, RMD) in the delved soils relative to the un-delved controls (both directly under the delve line as well as laterally). This is consistent with the root-thickening effect brought on by high soil strength typically found in un-delved soils, particularly in the subsoil.

Chapter 5 was based on the hypothesis that when mixing clay-rich material with sandy soil by delving, the physical characteristics of the mixture are not influenced exclusively by the changes in clay content but also by the size of the clay-rich aggregates incorporated in the sand. While the average clay content of the topsoil increases by delving, many of the clay-rich clods and aggregates remain discrete entities rather than becoming mixed intimately with the sand. This hypothesis was tested in the laboratory by mixing different sizes and amounts of subsoil with sand and measuring soil physical properties relevant to plant-available water. The work demonstrated that both the mean clay content and the size of the subsoil clods significantly influenced the physical properties and the plant available water of the delved soils. The classical measure of plant available water, PAW, increased in mixtures containing more subsoil clay, particularly when smaller aggregates were used (< 6 mm). However, when the potential physical restrictions on PAW were taken into account using the integral water capacity, the benefits of adding clay reached a peak at ~40% incorporation, beyond which IWC declined towards that of pure subsoil clay. Furthermore, the smaller the aggregates the less effective they were at increasing IWC, particularly in the practical range of application rates (< 20% by weight). This indicates that excessive post-delving cultivation may not be warranted and may explain some of the variability found in crop yields after delving. This work was published as:

Betti G, Grant CD, Murray RS, Churchman GJ (2016) Size of subsoil clods affects soil-water availability in sand-clay mixtures. Soil Research **54**:276-290. doi.org/10.1071/SR15115.

The final **Chapter 6** summarises the principal findings of the work and makes recommendations for future research based upon questions raised by each experiment.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Dated: September 6, 2018 ______________________________

Giacomo Betti

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ti amo.

Publications arising from this thesis

Betti G, Grant C, Churchman G, Murray R 2015. Increased profile wettability in texture-contrast soils from clay delving: case studies in South Australia. *Soil Research* **53**:125-136. https://doi.org/10.1071/SR14133

Betti G, Grant CD, Murray RS, Churchman GJ 2016. Size of subsoil clods affects soil-water availability in sand–clay mixtures. *Soil Research* **54**:276-290. https://doi.org/10.1071/SR15115

Chapter 1 Introduction and literature review

1.1 Introduction

The research proposed here is intended to aid understanding of the practice of clay delving. A better understanding of this methodology and, in particular, of the "new soil" produced by this process, is a necessary step toward optimizing this useful technology for soil management. In particular, this research has the objective of adding new information to those parameters already discussed in previous works and of filling research gaps relating to the physical characteristics in delved texture-contrast soils.

This chapter introduces the literature review, which provides the bases for the research hypotheses and provides an overview of the experimental aims.

1.2 Literature review

The following literature review has been divided into two sections where the two main topics of the research proposal will be discussed. In the first part, there is a brief literature review of texture-contrast soils focusing on the main problems in their management and their significance for Australian agriculture. The second section reviews the literature on clay delving, gives a description of this particular soil modification and considers investigation to date on its effects on the characteristics and behaviour of texture-contrast soils.

Texture-contrast soils: definition and impact on the Australian farming system

Stace *et al*. (1968) first introduced the term "texture-contrast" in *A Handbook of Australian Soils* to define soils with strong texture-contrast between the A and B horizons.

The Australian soil classification (Isbell 2002) refers to soils with strong texture-contrast as those having a "clear or abrupt textural B horizon", such as the orders of the Chromosol, the Sodosol and the Kurosol. Quoting the definition given by Isbell (2002) in the Australia soil classification, the strong texture-contrast occurs "a) *if the clay content of the material above the clear, abrupt or sharp boundary is less than 20%, (and/or has a field texture of sandy loam or less) then the clay content immediately below must be at least twice as high. However, there must be a minimum of 20% clay (and/or a minimum field texture of sandy clay loam) at the top of the B horizon*" and "b) *if the* *material above the transition has 20% clay or more but less than 35% clay (and/or has a field texture of sandy clay loam or greater but less than light clay), then the material below must show an absolute increase of at least 20% clay, eg. 25% increasing clearly, sharply or abruptly to at least 45%, (and/or a field texture of light medium clay or greater). Note that a clear or abrupt textural change is not allowed within the clay range*"

In Australia, soils with strong texture-contrast are often called "duplex" (Hardie *et al*. 2012). The term "duplex" was defined by Northcote (1979) as a primary profile in his Factual Key classification. He described a group of texture-contrast soils where the B horizon is dominated by a texture class one and a half (or more) classes finer than the A horizon. In addition, the clear to sharp change between the two horizons must occur within 0.1 m (Northcote, 1979 cited in Tennant *et al*. 1992). The diagnostic properties used by Northcote for the definition of duplex soils consider only the soil texture (texture-contrast and type of boundary between the A and B horizons). Therefore, duplex soils fit in a broad range of soil orders in the different taxonomic systems.

Although all of the above definitions do not strictly coincide, the use of the terms "texture-contrast" and "duplex" are interchangeable most of the time as they all describe soils with strong change in texture between the A and B horizons. For this reason and to avoid confusion, this thesis will refer to these soil by only using the term "texture-contrast" as considered more consistent with the Australian Soil Classification and recent publications.

Texture in texture-contrast soils is highly variable, with the topsoils ranging from coarse sand to clay loam and the subsoils from light to heavy clay (Gardner *et al.* 1992; Tennant *et al.* 1992). Some texture-contrast soils are distinguished by the presence of an A2 bleached horizon, a characteristic also used by Northcote (1979) as a diagnostic key for the distinction between these types of soils.

In Australia, texture-contrast soils cover around 20% of the total land (Chittleborough 1992) and are often associated with sodic/saline characteristics in the subsoil (**Fig. 1.1**). Of this area, a large part is farmed. In South Australia, Gardner *et al.* (1992) estimated that 0.5 million ha of the red-brown earths (texture-contrast) and 0.31 million ha of texture-contrast soils with bleached A2 horizons were under crop during the biennium 1983-84. In the south-west agricultural area of Western Australia (WA), texture-contrast soils occupy 57% of the total area (Tennant *et al.* 1992). In Victoria approximately 1 million ha of texture-contrast soils are cultivated (McGuinness 1991).

The distribution of texture-contrast soils in other parts of the world is not easily quantified, due to the different classifications used to describe these soils. However, the works of Brown *et al.* (1985) and others suggest such soils are widespread in the USA and probably elsewhere. Chittleborough (1981) showed that texture-contrast soils (duplex) could be present as Luvisols (FAO 1974) in many regions around the world with strong seasonal climates.

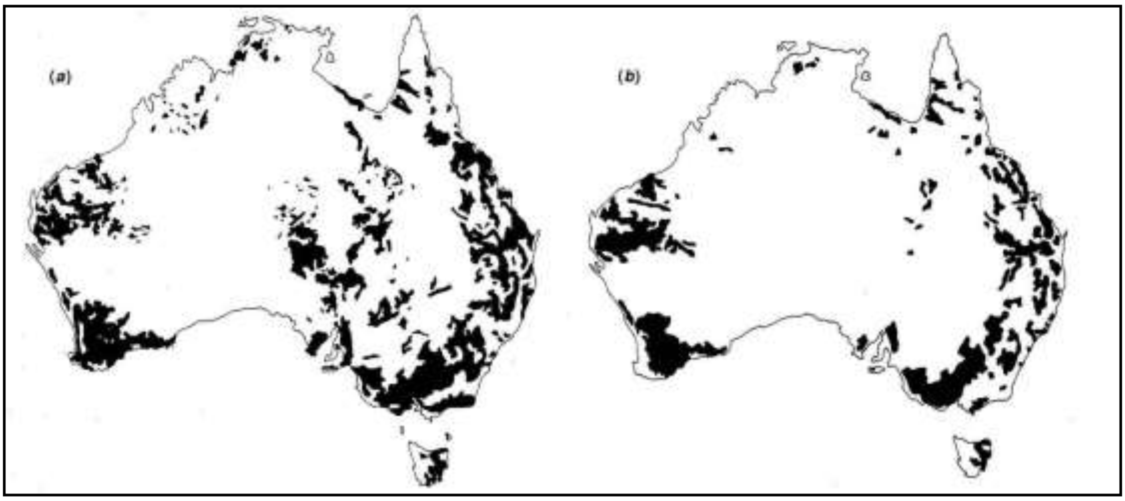

Fig. 1.1 Distribution of (a) texture-contrast soils and (b) sodic texture-contrast soils in Australia (Chittleborough 1992).

Texture-contrast soils have an important impact on Australian agriculture but they are generally poorly regarded by farmers for their low productivity and the difficulty of management (Gardner *et al.* 1992). Most of the negative properties of texture-contrast soils are related to their physical characteristics that frequently determine the chemical properties (Tennant *et al.* 1992).

Three aspects are usually highlighted in scientific literature as the main factors influencing the productivity of texture-contrast soils: generally low chemical fertility, limited plant root growth due to low physical fertility, and plant stress associated with soil water behaviour.

Due to the severely leached nature of their sandy A horizons, texture-contrast soils are naturally low in many of the nutrients necessary for plant growth, such as nitrogen, phosphorus, potassium and other secondary elements (Belford and Gregory 2005).

Compared with uniform or gradational profiles, the distribution of these elements with depth also differs in texture-contrast soils due to the different capabilities of the two horizons to hold nutrients. Examples are shown for three texture-contrast soils in Table 1.1. Apart from that associated with increased organic matter near the surface, the total cation exchange capacity (CEC) increases greatly in the subsoil as a consequence of the increase of clay content. Nonetheless, clay subsoils frequently have high exchangeable sodium and toxic elements, such as boron, can be present.

The sandy texture of the A horizons (where clay content is commonly under 10%) confer larger hydraulic conductivity and also have a great impact on soil water storage in the root zone. Studies of plant available water content (PAW) in sandy surface profiles in Western Australia have shown values in the range 20-120 mm/m, far below the values of most textural classes (Hamblin and Tennant 1987; Tennant *et al.* 1992). At such levels of PAW, even minor changes in clay content in the topsoil (Tennant *et al.* 1992) or increased access to subsoil water could considerably enhance soil water storage and availability for crops, increasing the productivity (Dracup *et al.* 1992).

While soil texture/structure characteristics of the A horizon particularly influence nutrient and water availability, root growth and soil water behavior in texture-contrast soils are mainly consequences of the peculiar boundary between the two horizons. Compared with soils with gradational profiles, in texture-contrast soils the sharp boundary between the two horizons separates areas of the profile with extremely different physical properties.

Compacted layers at the horizon interface frequently compromise wheat root growth in shallow texture-contrast soils and the great majority of the roots are usually found in the topsoil (Lorimer 1989; Dracup *et al.* 1992). The penetration depth of root systems is an essential factor in crop growth, especially where the water-holding capacity is limited as in texture-contrast soils (Gregory *et al.* 1992).

For instance, in texture-contrast soils in Western Australia, researchers found that 40 per cent of yield variation in wheat could be attributed to a linear relationship between root depth and water extracted from the subsoil (Belford, Tennant and Dracup cited in Dracup *et al.* 1992). In Northern Victoria, potentially high yields of irrigated soybean (*Glycine max*) were significantly limited by physical constraints to root growth in B horizons; even when water availability was not an issue (Willatt and Olsson 1982).

Moreover, as reported by some authors (Hamblin and Hamblin 1985; Hamblin and Tennant 1987) root systems in texture-contrast soils are not just shallower compared to other soils but also have smaller volumes, probably due to generally less favorable conditions for root growth. Although this latter issue has been reported with contrasting opinions (Whitfield *et al.* 1992), practices that encourage root exploration, such as deep ripping, should be considered as a priority for soil improvement in shallow texture-contrast soils (Gardner *et al.* 1992).

Mechanical impedance due to high soil strength at the top of the B horizon is a major problem for root growth and access to subsoil water and nutrients (Bengough and Mullins 1990). Roots of many plants, of course, possess the ability to penetrate subsoils using old root channels and other biopores (Stirzaker *et al*. 1996) to varying degrees. However, the subsoils of many Australian texture-contrast soils are often alkaline and sodic (Chittlebourough 1992) so root channels, cracks and biopores may be completely absent (Hamblin and Tennant 1987). Even where they exist, their presence is insufficient to be of any use to most crops.

Table 1.1 Chemical characteristics of three texture-contrast soils in the south east of South Australia (source: Rural Solutions SA)

a) Bleached, Calcic, Brown Chromosol (Kennion, SA)

Horizons [1]	Depth cm	pH_{H2O} [2]	pH_{CaCl2}	CO_3 %	$EC_{1:5}$ dS/m [3]	EC_e dS/m	Cl mg/kg	Org.C %	$NO_3 + NH_4$ mg/kg	Avail. P mg/kg	Avail. K mg/kg	SO_4-S mg/kg	React Fe mg/kg	Ext Al mg/kg	Boron mg/kg	Trace Elements mg/kg (EDTA) Cu	Fe	Mn	Zn	Sum cations cmol (+)/kg	Exchangeable Cations cmol(+)/kg Ca	Mg	Na	K	Est. ESP [4]
A1	0-20	5.9	5	0	0.05	-	7	2.31	5	19	44	9.3	254	1	0.6	0.25	26	0.23	0.2	5.1	4.17	0.75	0.06	0.11	1.2
A2	20-35	6.4	5.1	0	0.01	-	6	0.24	2	6	15	5.3	55	0.3	0.3	0.19	17	0.28	1.16	0.7	0.52	0.12	0.02	0.05	2.8
B	35-60	5.9	5.2	0	0.04	-	7	0.19	7	18	14	15	74	0.7	0.3	0.22	28	0.32	0.25	0.8	0.55	0.14	0.03	0.03	4
	60-80	7.4	6.7	0	0.11	-	19	0.37	11	4	111	13.1	439	0	1.3	0.18	40	2.13	0.15	13.3	8.92	3.47	0.65	0.31	4.9

b) Calcic, Mottled-Subnatric, Yellow Sodosol (Cannawigara, SA)

Horizons [1]	Depth cm	pH_{H2O} [2]	pH_{CaCl2}	CO_3 %	$EC_{1:5}$ dS/m [3]	EC_e dS/m	Cl mg/kg	Org.C %	$NO_3 + NH_4$ mg/kg	Avail. P mg/kg	Avail. K mg/kg	SO_4-S mg/kg	React Fe mg/kg	Ext Al mg/kg	Boron mg/kg	Cu	Fe	Mn	Zn	Sum cations cmol (+)/kg	Ca	Mg	Na	K	Est. ESP [4]
A1	0-12	6.8	5.9	0	0.13	0.91	32	1.74	32	19	325	4.3	467	0	1	0.62	98	5.29	0.92	7.6	4.86	1.68	0.23	0.82	3
A2	12-32	6.2	5	0	0.02	0.19	4	0.28	3	5	50	1.7	407	1.9	0.3	0.17	113	0.92	0.26	1.9	1.46	0.25	0.09	0.11	4.7
	32-55	7.8	6.8	0	0.12	0.8	37	0.58	4	2	347	3.6	772	0	2.1	0.25	66	0.81	0.19	13.9	7.87	3.71	1.41	0.91	10.1
B	55-100	8.8	7.6	0	0.18	0.8	41	0.28	5	2	414	6.6	485	0	5.1	0.1	22	3.88	0.09	21.7	8.52	8.86	3.14	1.13	14.5
	100-120	9.3	8.4	18	0.33	0.91	44	0.28	3	2	378	6.7	528	0	6.3	0.14	11	1.1	0.14	24.5	9.52	9.72	4.23	1.02	17.3

c) Calcic, Hypernatric, Yellow Sodosol (Tatiara, SA)

Horizons [1]	Depth cm	pH_{H2O} [2]	pH_{CaCl2}	CO_3 %	$EC_{1:5}$ dS/m [3]	EC_e dS/m	Cl mg/kg	Org.C %	$NO_3 + NH_4$ mg/kg	Avail. P mg/kg	Avail. K mg/kg	SO_4-S mg/kg	React Fe mg/kg	Ext Al mg/kg	Boron mg/kg	Cu	Fe	Mn	Zn	Sum cations cmol (+)/kg	Ca	Mg	Na	K	Est. ESP [4]
A1	0-8	6.3	5.5	0	0.11	1.26	53	1.47	8	22	286	28.7	774	0	1	0.7	129	5.5	0.6	9.2	5.96	2.15	0.35	0.72	3.8
A2	8-15	7	6	0	0.05	0.61	14	0.36	2	6	29	5.2	253	0	0.4	0.2	88	1.2	0.2	1.7	0.83	0.49	0.26	0.07	15.8
	15-55	8.6	7.6	0	0.3	1.49	118	0.3	2	2	378	31.6	522	0	5.1	0.2	29	10.7	0.2	18.8	3.55	9.19	5.07	1.01	26.9
B	55-85	9.5	8.7	7	0.76	3.31	333	0.21	2	2	366	80.3	422	0	7.8	0.3	13	1.3	0.2	24.6	6.82	9.54	7.21	1.04	29.3
	85-140	9	8.2	0	0.73	3.51	465	0.25	3	2	393	80.9	361	0	7.5	0.3	26	15.3	0.2	22.2	2.45	10.1	8.63	1.03	38.9

[1] The soil horizons were allocated afterwards to the original tables and their designations are based on the interpretation of the chemical characteristics of the layers.
[2] pH_{H_20} and pH_{CaCl_2} represent pH measurements from 1:5 soil:water suspension and 1:5 soil:0.1M $CaCl_2$ suspension respectively.
[3] $EC_{1:5}$ and EC_e are soil electrical conductivities measured respectively in a 1:5 soil:water suspension and in a saturated soil paste extract.
[4] ESP is the Exchangeable Sodium Percentage.

Mechanical impedance to root growth is not the only negative effect that results from the sharp change of physical characteristics between the two horizons. Tennant *et al. (1992)* identify the low permeability of the B horizon as a soil property with major impact on the behavior of texture-contrast soils; in fact they describe the problems with texture-contrast soils as "*permeability contrast*", rather than "*texture-contrast*". In effect, most of the concerns with these soils appear to be the consequence of their peculiar hydraulic properties.

In fact, the low permeability of the B horizon has been indicated as the major factor in the incidence of waterlogging (Barrett-Lennard and Nulsen 1989). Perched water-logging develops easily in soils with poor drainage and soil water storage in high rainfall areas (Cox and McFarlane 1990) and in Western Australia this is considered to be the main limiting factor to agricultural production (Bakker *et al.* 2010).

In addition to the poor water storage properties of the A horizon, water-logging and perched water tables seem to represent the main constraints to crop production associated with the hydraulic properties of texture-contrast soils. Edwards (1992), describes this issue as the irony with texture-contrast soil: where root development limited by waterlogging during the wet season has a negative impact during the dry seasons when roots only have access to water in the sandy topsoils with their limited water storage.

As shown in the literature, texture-contrast soils are associated with several limitations for crop productivity in Australian agriculture. Many of these issues are related to the particular physical properties of these soils. If the sharp contrast in physical and chemical properties between A and B horizon could be reduced in these soils, many of the problems in crop production could be addressed (excluding in soils where subsoils are saline or rich in boron *etc*) For this reason different proposals for the management and modification of these soils have been made in the past in order to reduce at least one of the limiting factors in texture-contrast soils. Of these, we can cite clay spreading, where clay (from external field sources) is added to the topsoils in order to ameliorate their chemical and physical properties and/or correct issues such as water repellence in sandy soils; deep ripping, where deeper water infiltration and root growth are enhanced after the disruption of the hardpans between A/B horizons; tile drainage, where drainage pipes are installed below the surface in order to remove excess water from the soil.

The next section reviews the literature on clay delving, a particular soil modification that has been developed in Australia in recent decades for the amelioration of texture-contrast soil. In this way soil profiles are deeply modified using machines (delvers) which combine the addition of clay (from the subsoil) and deep ripping.

Soil modifications through clay delving

First introduced in Australia in the early 1990's (Bailey, unpublished work), clay delving is becoming a valid alternative to clay spreading for the treatment of water repellent soils (Bailey 2007; Tonkin 2010; Davenport *et al.* 2011). In texture-contrast soils, delving is an effective technique for mixing clay from the B horizon with the sandier textured soil of the A horizon.

Delvers (**Fig. 1.2**) are ripper-like machines where the tines have been modified in design in order to bring subsoil clay to the surface (Desbiolles *et al.* 1997, cited in Bailey *et al.* 2010). Most delvers are produced locally (often by the same contractors) and present two to four tines with spacing ranging from 0.5 m to 1.8 m, with 1.5 m as the average (Eldridge 2007 and Bailey, unpublished work). To be able to bring clay subsoil to the surface, delving tines are wider than those of a standard ripper, having an average of about 25 cm. The maximum delving depth is variable and depends on the design of the machine. Moreover, a common feature of delvers is the opportunity to adjust the tine depth continuously using an hydraulic system.

While clay spreading is primarily associated with the correction of water repellent sandy soils, clay delving is rising in popularity due to additional advantages in the amelioration of sandy topsoils with poor properties. May (2006) has reported that the main advantages of clay delving are deeper mixing of clay through the soil profile and the disruption of hardpans in texture-contrast soils (**Fig. 1.3**). This latter effect of deep ripping has the potential to improve root exploration and crop yields on compacted subsoils (Schneider *et al.* 2017).

Root growth is anecdotally reported to be generally much deeper into the soil profile (May 2006; Bailey 2009). Moreover, the effect of clay delving on the spatial distribution and density of plant root systems are still unknown. The effect of clay addition and the mixing of A2 bleached horizons with the more fertile A1 horizon has also been reported to greatly increase root penetration, carbon storage and crop yield (Bailey 2007; Eldridge 2007; Schapel *et al*. 2016).

Fig. 1.2 Example of delving machines (above, source: http://www.gumlea.net.au/) and a texture-contrast Sodosol after delving (below) showing the large clods of subsoil clay brought up to the soil surface by the delver tines.

Field trials in Western Australia (Government of Western Australia 2010) and South Australia (Rebbeck *et al.* 2007; Tonkin 2010) have also show the positive impact of clay delving in reducing the risk of frost damage in cereals by maintaining higher topsoil and canopy temperatures compared with fields that have not been delved, probably due to the increased heat capacity from water held by new clay.

In addition to these advantages, clay delving is also a cheaper method of claying than clay spreading (May 2006). These promising advantages are the reason behind the gain in popularity of clay delving in Australia as demonstrated by the increasing number of contractors in WA, SA and Victoria offering this service. Increased interest in this methodology is further confirmed by investigations in areas suitable for clay delving, such as that of the South Australian Government (**Fig. 1.4**).

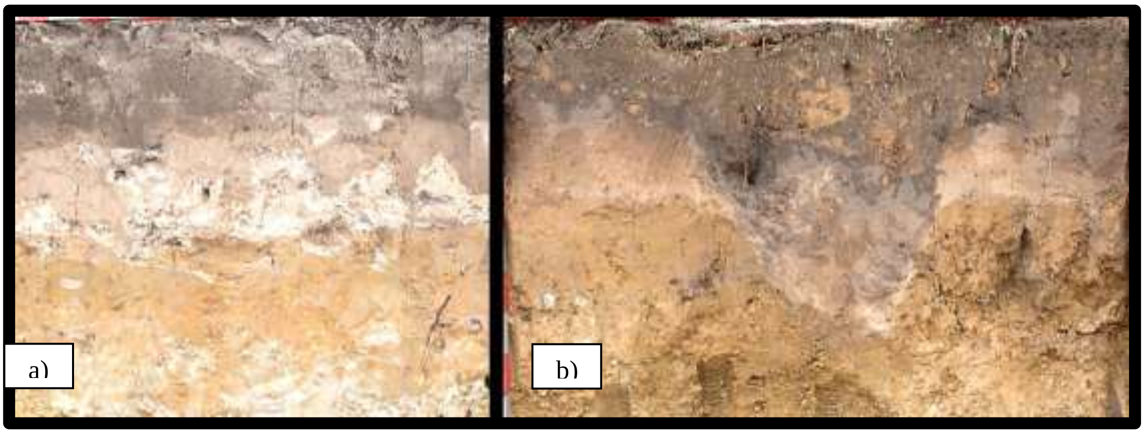

Fig. 1.3. Representation of the effects of clay delving on a texture-contrast soil profile. a) Before clay delving and b) After clay delving.

However, clay delving is appropriate only in those areas where the subsoil clay is accessible to the tines of the delver machines. Some authors (Bailey 2009; Bailey *et al.* 2010) indicate this limit occurs for clay subsoils deeper than 30-55 cm while others suggest clay delving is possible in soils with clay up to 80 cm deep in the profile (Fogden 2010). Presumably, these contrasting opinions result from the performance of different delvers and the great physical variability of the soils concerned.

Depth of subsoil also influences another important factor: the amount of clay integrated in the topsoil profile. Recent field trials (May 2006; Carter 2004, cited in May 2006; Davenport *et al.* 2011) suggest that increases of clay content in the top profile to 3% are optimal, with 6% resulting in problems such as hard setting. Nevertheless, further information is missing, such as the actual % clay incorporated through delving…

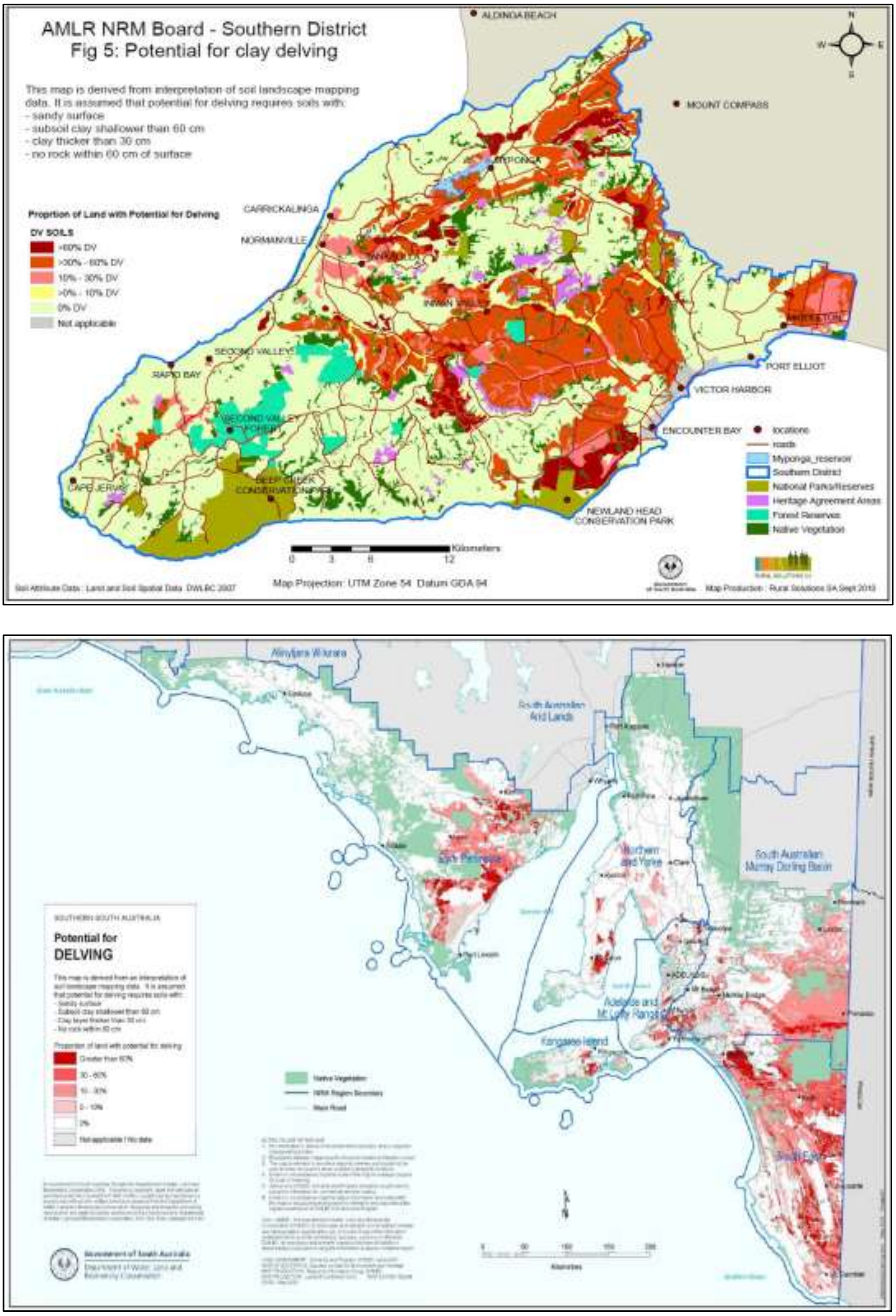

Fig. 1.4. Suitable sites for clay delving in South Australia (source: Department of Water, Land and Biodiversity Conservation SA)

… at different sites, its distribution in the profile (vertically and laterally), the quality of the mixing, and the physical and chemical composition of the subsoil. The difficulty in estimating the actual amount of clay added into the profile and the quality of the incorporation have also been reported as one of the main disadvantages of clay delving when compared with clay spreading (Bailey 2009; Fogden 2010; Davenport *et al.* 2011). Without effective mixing of clay, the benefits of delving can be limited or delayed in time influencing the cost-benefits of the operation (May 2006; Bailey *et al.* 2010). For this reason, in recent years, machinery such as off-set disc cultivators or spaders have been used following clay delving for better mixing of the clay in the topsoil (usually up to 0.3 m deep, Fogden 2010). As these operations after delving are now considered essential for best and timely outcomes, this proposal will include practices such as spading (or similar operations) as part of the definition of "clay delving", unless otherwise specified.

A few Government agencies have been involved in recent decades in investigations of clay delving and its potential benefits for farming. In particular, reports on field trials have focused their attention on the effects of clay delving on crop yields and soil fertility. As in the case of clay spreading, addition of clay soil to sandy topsoil has the potential to increase the total exchange capacity of the topsoil and consequently its ability to hold more nutrients (Bailey 2009; Tonkin 2010). In most cases soil productivity increases after clay delving and wheat yields often increase by a factor of two or more from the first season after treatment (Eldridge 2007; Bailey 2009; Fogden 2010).

Also, in the Mallee District of South Australia, Eldridge (2007) found a correlation between crop yield and delving tine spacing, where higher yields resulted from treatments with smaller spacing (0.7 m). Although it is assumed that increased crop yields result from increased soil fertility and water availability, the individual impacts of these factors have not been delineated. Moreover, improvements delivered by delving can vary significantly and in some cases can even be negative. Potential problems arise from the quality of the clay, subsoil pH and toxicity due to the presence of high levels of salt or boron (May 2006; Tonkin 2010). It is also possible that some compaction results from clay delving, although there is little evidence in the literature to support this at present.

Because these factors will potentially affect the soil in the long term or even permanently, particular care needs to be taken before clay delving (May 2006; Fogden 2010). Therefore, as with clay spreading, clay delving must take into account the chemical characteristics of subsoil clay, such as carbonate content, sodicity, toxic elements (i.e. B, Al) pH and salinity (May 2006).

Texture-contrast soils tend to develop preferential water flows that are dependent on the antecedent soil moisture content, the presence of non-wetting sands and the permeability of the A/B horizon interfaces (Hardie *et al.* 2011 and 2012). This behaviour can contribute to lateral water flows along the A horizons or the upper B horizons, with the potential for accumulation in perched water tables.

The consequence of clay mixing and disruption of the A/B interface on water movement, preferential flows and soil hydraulic conductivity in the profile are still unknown, as well as their influence on crop root growth.

Conclusions

In the last two decades, clay delving has attracted great practical interest in dryland agriculture. Surprisingly, however, little has been published in the peer-reviewed scientific literature. For this reason, many of the references cited here are from so-called 'grey' literature. The study and characterization of clay delving practices have been conducted mainly within and for the primary industry sector supported by consulting agencies collaborating directly with farmers. For example, in South Australia, prior to the production of this thesis and its publications, the only two significant contributions to the grey literature came from *Rural Solutions SA* (supported by the Grains Research & Development Corporation, GRDC), *viz:*

1) *Clay spreading and delving on Eyre Peninsula / a broadacre clay application manual for farmers, contractors and advisors* (May 2006) and

2) *Spread, Delve, Spade,Invert: A Best Practice Guide to the Addition of Clay to Sandy Soils* (Davenport *et al.* 2011).

Aside from the above, most of the information on clay delving available at the outset of the current research thus came primarily from field reports, agriculture-dedicated web-sites/magazines and from personal communications. These focus primarily on aspects relevant to primary producers: increased crop yield, increased soil fertility, and delving methods (**Table 1.2**). Moreover, most of this literature presents the outcomes of clay delving with little reference to the processes involved or the basic research methods.

Furthermore, in many cases, soil properties after delving are presented separately with minimal focus on the resulting spatial variability created within the soil profile. While texture-contrast soils are characterized predominantly by a vertical variability of soil properties, after delving soil profiles must also present variability in lateral directions. This new morphology is a direct consequence of the delve/spade methods and the initial soil profile characteristics. It is reasonable to expect consequences of this spatial variability for soil characteristics and plant growth. However, limited information on the morphology and other physical characteristics of delved soils is available in the grey literature.

Furthermore, the effects of clay delving on soil water behaviour have not been investigated. As this review suggests, many of the limitations on crop productivity in texture-contrast soils are a consequence of their low water storage capability and their complex hydrology, which influences soil water movement and leads to major issues such as water-logging. These problems reflect the physical properties of texture-contrast soils, and in particular the texture of the topsoil and the sharp physical changes between the two horizons. Clay delving affects both of these properties, changing the clay content in the A horizon and disrupting the A/B interface.

Further studies are needed for an understanding of the effects that this soil modification has on soil water storage and soil behaviour, with attention to water availability for plants during the year and water movement along the profile.

In conclusion, clay delving is costly and although it generally brings positive outcomes in terms of crop yields, the factors or dynamics leading to these improvements are still not clear. A better understanding of them has the potential to optimize this practice with minor changes that could bring great improvements to help offset the initial high costs.

Table 1.2. Summary of the research topics on clay delving from literature review

Research Topic	***Source***
Effect of clay delving on crop yield	May 2006; Eldridge 2007; Rebbeck *et al.* 2007; Bailey 2009; Bailey *et al.* 2010; Fogden 2010; Davenport *et al*. 2011
Soil pH changes in the A horizon after delving	May 2006; Bailey *et al.* 2010; Tonkin 2010
CEC changes in A horizon after delving	May 2006; Bailey *et al.* 2010; Tonkin 2010
Comparison of soil chemical characteristics before/after delving in sites in south-eastern South Australia	Rural Solutions SA *personal comm.*
Effect of clay delving and/or clay spreading on non-wetting sands	Cann 2000; Harper and Gilkes 2004; May 2006; Eldridge 2007; Rebbeck *et al.* 2007; Bailey *et al.* 2010; Fogden 2010; Hall *et al.* 2010; Davenport *et al*. 2011
Risk of boron toxicity on delved soils	May 2006; Davenport *et al*. 2011
Effects of delving in soils with saline or sodic B horizons	May 2006; Davenport *et al*. 2011
Quantity of subsoil mixed in topsoil	May 2006; Davenport *et al*. 2011
Effects of delving organic carbon	May 2006; Bailey *et al.* 2010: Schapel *et al.* 2017
Effects of delver spacing on crop yield	Eldridge 2007
Effect of different combinations of delving and spading on crop yields	May 2006; Eldridge 2007; Tonkin 2010; Davenport *et al*. 2011
Effect of timing on mixing of clay after delving	May 2006

1.3 Research aims and hypotheses

The hypotheses on which the research goals are based include:

Hypothesis 1. Clay delving strongly modifies the soil profile, disrupting the interface between A and B horizons and mixing subsoil with the topsoil. The morphology of the new soil profiles differ greatly from the originals (un-delved) with direct effects on soil physical characteristics. In particular, the distribution of these properties is changed both in the vertical and lateral directions.

Alternative hypothesis: clay delving changes the morphology of texture-contrast soils but the effects on soil physical properties and water storage are not significant.

*Research aim 1 (Experiment 1, **Chapter 2**)*

To characterise the morphology of a delved soil profile by comparison with the original un-delved profile in relation to the spatial distribution of physical characteristics. Of particular interest is the vertical and lateral spatial distribution of re-distributed clay material and their effects on the soil hydraulic properties.

Hypothesis 2. Through the addition of new clay to the sandy topsoil, clay delving has the potential to decrease the water repellence of the sandy topsoil and thereby significantly increase the wettability of the entire soil profile. Moreover, the strong soil profile modification and the disruption of the hardpan between A and B horizons significantly alters the movement of soil water to depth.

Alternative hypothesis: clay delving does not significantly reduce water repellence and/or does not significantly increase wettability of the soil profile. Moreover, the disruption of the A/B horizon by clay delving is not sufficient to significantly affect the movement of water to depth.

*Research aim 2 (Experiment 2, **Chapter 3**)*

To evaluate the effect of clay delving on soil profile wettability.

Hypothesis 3. The substantial soil modification and the disruption of the hardpan between A and B horizons obtained by clay delving contributes to deeper plant root growth and enhances root growth distribution in the soil profile, in particular below the delving line.

Alternative hypothesis: clay delving does not promote greater root growth or affect root distribution in the soil profile.

*Research aim 3 (Experiment 3, **Chapter 4**)*

To evaluate the effect of clay delving on root growth (and distribution) in the soil profile in relation to the spatial distribution of physical and chemical characteristics of delved profiles.

Hypothesis 4. The quantity and quality of clay-mixing in the topsoil during delving affects the physical characteristics of the delved top soils. The extent to which the soil physical characteristics change after clay delving depends on factors such as:

a) The *quantity* of clay-rich subsoil mixed into the topsoil
b) The *degree* to which the subsoil is mixed with the topsoil (fine or coarse mixing), which depends on method (*e.g.* timing, spacing of delving tines) and the design of machines used for delving and spading.

Alternative hypothesis: The physical characteristics of the delved topsoil are not affected by the degree to which the subsoil is mixed with the topsoil but only by the quantity of subsoil clay.

Research aim 4 (Experiment 4, ***Chapter 5****)*

To evaluate the potential effects of different mixing of subsoil clay (in terms of the quantity and quality of clay mixing) with the topsoil in controlled environments compared with the un-delved topsoil;

1.4 Theoretical framework and experimental sites

The research approach is based on the assumption that clay delving on texture-contrast soils creates a new soil profile with new physical characteristics that are variable in space, both in lateral and vertical directions. In a delved soil profile the latter variability is the consequence of the creation of two main zones: along the delved lines and between the delved lines. However, the transition between these two areas is not necessarily sharp; especially in those top layers where a further mixing of soil has occurred through the use of machinery such has spaders.

For the best description of a delved soil profile, this research proposes the identification of a representative profile area of a delved soil (**Fig. 1.5**).

The representative area is a section of soil profile perpendicular to the delved lines. This section includes the area along the delved lines, between delved lines and the transition area within these two (**Figs 1.5** and **1.6**). The width would be equal to the spacing of the delving tines (i.e. variable in different sites) and the depth would be of 0.6 m, basing this measure on the average maximum depth of clay delving.

Fig. 1.5. Representative profile of delved soil (red dotted line represent the delving line)

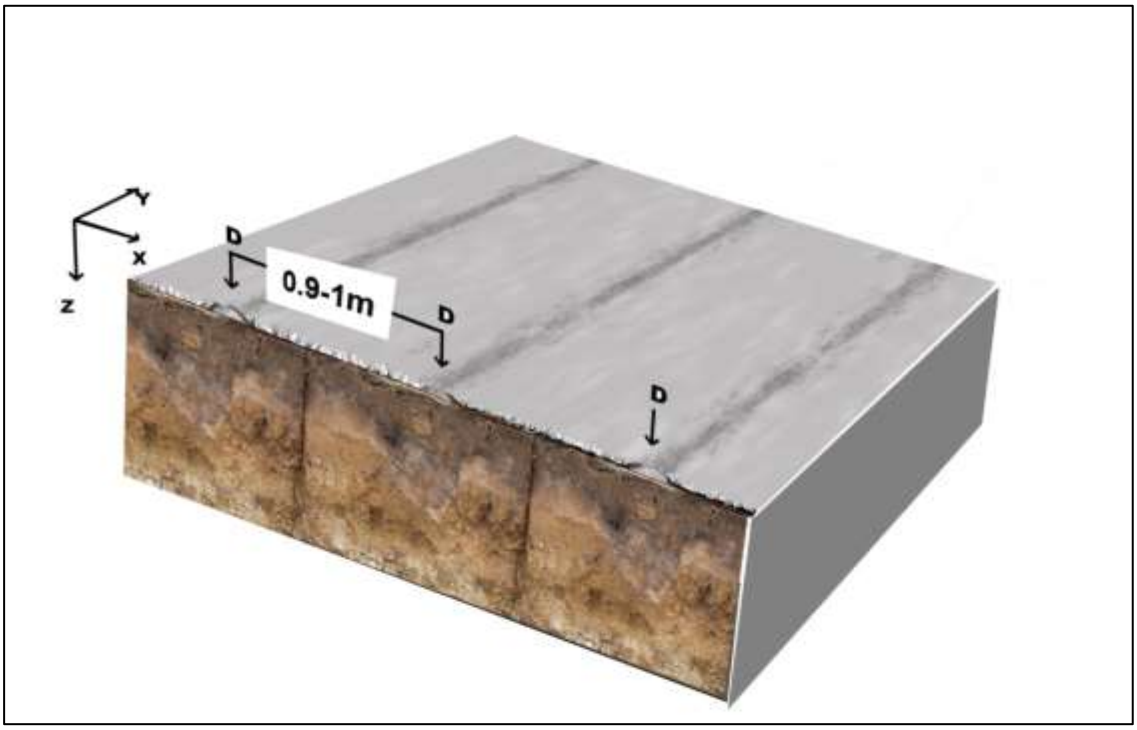

Fig. 1.6. 3-dimensional representation of delved soil with three representative delved soil profiles (D represents the delving lines).

The description of the representative area of delved soil and sampling strategy is further discussed in the material and methods of Experiment 1 in **Chapter 2**.

For the field experiments (experiments 1, 2 and 3) four representative sites in South Australia were selected with the following criteria:

- Sites having both delved and un-delved soils (original texture-contrast soil profile) of similar type and farm management for treatment comparisons.
- Sites included in the medium-high rainfall (>350 mm/year) region of South Australia.
- Permission to access the site during the time of field experiments.

The location of the sites is shown in **Fig. 1.7**, while **Table 1.3** shows a more detailed list of the sites and where each field experiment was conducted.

Fig. 1.7. Map of South Australia showing the sites where the field experiments were conducted

Table 1.3. List of the sites used for the field experiments

Site name	*Location and geographic coordinates*	*Soil classification*[1]	Field experiments		
			Experiment 1 (**Chapter 2**)	Experiment 2 (**Chapter 3**)	Experiment 3 (**Chapter 4**)
Site A	Coonalpyn (35°41'28"S 139°53'05"E)	Sodosol	✓	✓	✓
Site B	Bordertown (36°12'52"S 140°42'08"E)	Sodosol	✓	✓	✘
Site C	Coonalpyn (35°44'0.6"S 139°55'46"E)	Sodosol	✘	✓	✘
Site D	Karoonda (35° 5'30"S 139°53'40"E)	Chromosol	✘	✘	✓

[1] According to the Australian Soil Classification (Isbell 2002). ✓ and ✘ indicate for a given experiment whether or not data were collected.

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Chapter 2 Physical changes in a texture-contrast soil after clay delving

2 Introduction

The effects of clay delving on soil fertility and crop yield have received considerable attention (*e.g.* May 2006, Rebbeck *et al*. 2007, Bailey *et al.* 2010, Hall *et al.* 2010, Davenport *et al.* 2011) but less attention has been paid to understanding the effects of this practice on soil physical properties. Given that soil physical properties exert a major influence on water movement, water retention and water use efficiency of crops, a thorough understanding of how clay delving modifies them is crucial. To this end, **Chapter 3** of the present thesis outlines a case study in which clay delving was found to increase the wettability of the entire profile of some texture-contrast soils (Betti *et al*. 2015). Similarly, **Chapter 5** of the present thesis describes a laboratory study in which the size of subsoil clods was shown to influence soil water availability in sand-clay mixtures (Betti *et al.* 2016). Many changes in soil physical properties occur after clay delving, so this chapter offers a quantitative description of these changes along a field transect on a farm in the southeast of South Australia. Of particular interest is the effect that changes in texture and structure have on soil hydraulic conductivity, water retention, penetration resistance, and soil water availability as described in terms of Groenevelt *et al.*'s (2001) integral water capacity, IWC.

2.1 Materials and methods

The site was a paddock located in a broadacre farm near Coonalpyn, South Australia (35°41′28″S, 139°53′05″E), and Table 2 (Site A) of Betti *et al*. (2015) – **Chapter 3** of this thesis – lists many of the relevant soil properties. The soil was a Bleached Yellow Sodosol (Isbell, 2002) or Stagnic Solonetz (WRB IWG 2007) with a bleached A2e horizon above a sodic, clay-rich B horizon at about 0.25 m. Typical crop rotations included wheat, barley, lentils, sunflower and canola. Clay delving occurred in 2007 (5 years before sampling for this project occurred) as part of a management strategy to improve poor soil productivity and reduce topsoil water repellence. Sampling of the un-delved control was conducted in a region directly adjacent to the delve line and off line regions on the same soil and with the same crop rotations but lying just outside the reach of the delving equipment (**Fig. 2.1**).

The physical changes to the soil caused by delving were characterised at two different scales: changes at the scale of a soil profile, and changes at the scale of a field transect (**Fig. 2.1**). At the soil profile scale (described below) samples were collected in a delved profile to measure bulk density, soil resistance, saturated hydraulic conductivity and plant available water in the upper horizons of the texture-contrast soil. At a field transect scale (described below) a spatial analysis of the vertical and lateral distribution of water infiltration, soil resistance, and visual, morphological image-analysis of the profiles was made along two transects close to the soil profiles described above.

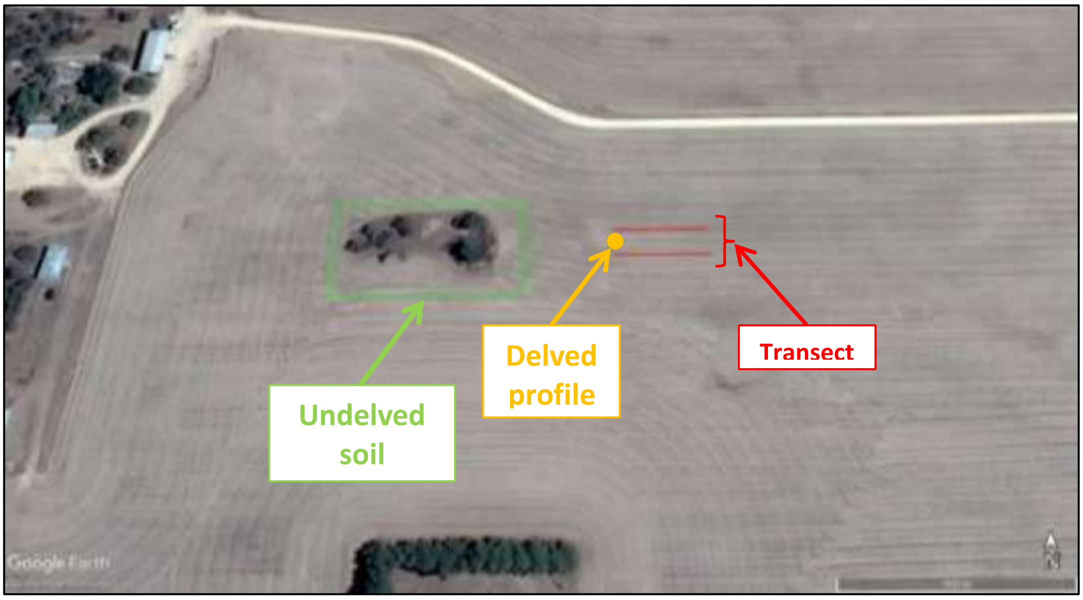

Fig. 2.1. Satellite image of the Coonalpyn site (source: Google® Earth Pro®)

Soil profile scale

i) Sample collection

In early autumn before the paddock was sown, a soil profile that crossed the delving lines was excavated and a metal frame (0.9 m wide and 0.6 m high) was fixed in position on the exposed vertical surface of the profile centred on the delving line (**Fig. 2.2**). The soil was manually wet up prior the excavation as the water repellent topsoil was not fully moist at the time of sampling. This was done to facilitate easy extraction of the undisturbed cores, in particular from the loose sandy topsoil. The size of the frame encompassed a complete representative profile of the delved soil such that the width was equal to the distance between the delving tines and the depth included the average maximum depth of delving (0.35 to 0.40 m).

A horizontal surface, of breadth 0.1 m and width 0.9 m across the frame, was prepared. Nine stainless steel rings (0.07 m internal diameter and 0.05 m height) were inserted vertically into the horizontal surface at equal distances to extract undisturbed soil cores from left to right across the frame (**Fig. 2.2**). When one set of 9 soil cores was extracted, the soil was carefully excavated to prepare another horizontal surface 0.1 m immediately below, and the process repeated until 5 sets of 9 cores were extracted. Each soil core was assigned an alpha-numeric code as follows (*cf.* **Fig. 2.3**): A-1 down the profile to A-5, B-1 down the profile to B-5 and so forth horizontally from left to right across the frame with the last set being I-1 down the profile to I-5.

Considerable morphological variability was observed down the delved profile so additional undisturbed soil cores (in slightly smaller rings, 0.05 m internal diameter and length) were taken in the proximity of the main delved profile using the same approach based on the grid (**Fig. 2.3**); this allowed all the data from samples collected at the same depth in the profile to be averaged. The soil cores were individually packed (with a protective layer of soil) into bags and transported in an insulated container to the laboratory, where saturated hydraulic conductivity, volumetric water retention, soil resistance, bulk density, subsoil aggregate size distribution and particle size distribution were subsequently measured. Particle size distribution data are reported in **Chapter 5**.

Fig. 2.2. Exposed profile of delved soil: visual changes to profile (top left), two different core sizes (top right, lower left), and sampling frame (lower right).

Shown in **Fig. 2.3** are the morphological changes after clay delving showing the two main morphological regions comprising this profile:

a) The *delving line* region, where most soil disturbance occurred and where the subsoil aggregates were most intensively mixed with the A1 and the bleached A2 horizons. Directly below this, the delving tines created the typical V-shaped area in the B horizon, where the subsoil was replaced by sand-rich soil from the topsoil (**Fig. 2.3**).

b) The *off-line* regions on both sides of the delving line characterised by a lower degree of soil disturbance which occurs mainly near the surface, leaving most of the A2e and B horizons undisturbed.

A comparison of soil properties between the delving line region (columns D, E, and F of the grid) and the off-line region (columns A, B, C, G, H and I of the grid) was facilitated by averaging the results from samples within each region and at each depth.

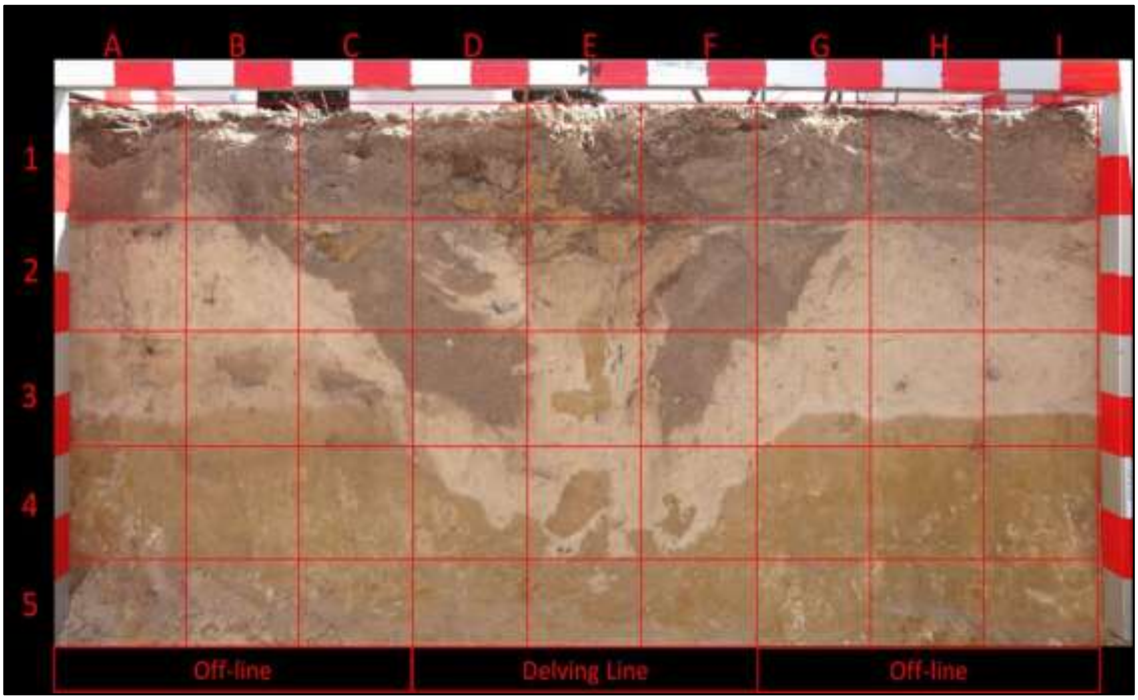

Fig. 2.3. Cross section of a delved profile showing the alpha-numeric grid to identify the spatial location of soil samples and the separation of the two main morphological regions ('delving line' and 'off-line'). The red lines and squares superimposed on the image are 0.1m x 0.1m

ii) Bulk density, size of subsoil aggregates and clay content

The bulk density of each sample was calculated from its total oven dry mass divided by the volume of its sampling ring (measured during or after the water retention measurements, discussed below). After recording the total mass of soil for the bulk density measurements, the soil from each ring was placed on a nest of sieves: 20, 6.7, 4.75 and 2 mm and jostled by hand to separate sand from clods of clay with minimal input of energy. The weights of the different size-portions were determined for each individual soil sample and classed into two groups called: "Fine soil" (samples having < 10% by weight of *large* subsoil aggregates > 6.7 mm) and "Coarse soil" (samples having > 10% by weight of *large* subsoil aggregates > 6.7 mm). The terminology "fine" and "coarse" used here may at first seem counter-intuitive because these terms are commonly used to describe soil textures. However, the primary focus here is on soil <u>aggregates</u>, not <u>primary particles</u>. Aggregates of sodic clay-rich subsoil form massive clods, which are thus "coarse", while the sand-rich material does not form many cohesive aggregates; rather they separate into small aggregates and primary particles that are much smaller by comparison, thus “fine”.

This empirical separation of the data into “Fine” and “Coarse” was done to evaluate the extent to which changes in soil properties were influenced by the degree of mixing of the delved subsoil clay into the surface sand. For example, if the subsoil clay separated into mainly large aggregates, any changes in soil physical properties could be attributed to a minimal degree of mixing, whereas if the clay separated into mainly small aggregates, changes in soil physical properties could be attributed to a greater degree of mixing.

All soil samples were subsequently passed through a 2 mm sieve and the total clay content (< 2 µm particles) was measured by mechanical separation and sedimentation (Smith and Tiller 1977).

iii) Saturated hydraulic conductivity

The saturated hydraulic conductivity, K_s, was measured on each soil core contained within its sampling ring using a constant head method (Reynolds *et al*. 2000). An extension was fastened to each ring to establish a constant hydraulic head using an inverted 1 litre bottle filled with reverse-osmosis deionized (RO) water. A protective filter paper was positioned on the soil surface prior to establishing the hydraulic head to minimize soil disturbance. A piece of fabric (38 µm mesh) was secured at the lower end of each ring to contain the soil and allow measurement of the flux of water. The volume of water passing through the cross sectional area of the soil core per unit time was measured when the flux reached steady state (occurring within a few minutes to several hours). As soon as the K_s measurements were taken, each soil core was placed on a series of different saturated ceramic plates to measure water retention at different matric heads (described below).

iv) Soil resistance to penetration

Soil resistance to penetration (SR, MPa) was measured on each sample in its ring as soon as it was removed from each of the pressure plates held at different matric heads. Measurements were made using a LF-plus penetrometer (Lloyd Instruments, Bognor Regis, UK) with a 2.5 mm stainless steel cone (30° angle) having a 2-mm-diameter recessed shaft advanced at 3 mm min^{-1}. A custom made perforated plastic lid was placed on the rings to minimise evaporative loss of water during the replicated penetrometer measurements. The penetrometer cone (2 mm diameter) was much smaller than the soil cores and the duplicate measurements taken at each matric head were taken at locations approximately 10 times greater than the diameter of the penetrometer needle, which is considered sufficient to avoid soil modified by previous penetrations (Whiteley and Dexter 1981). The average measured force (N) within the central 20-mm-depth section of the soil of each sample was converted to pressure using the cross sectional area of the cone base.

Soil resistance, SR, was plotted as a function of the matric head, *h*, and fitted to a power function:

$$\mathrm{SR}(h) = \sigma\, h^{\mathrm{b}} \qquad [\mathbf{2\text{-}1}]$$

where the coefficients σ and *b* are fitting parameters calculated using a Levenberg–Marquardt least-squared optimisation procedure in mathematical software, Mathcad 14.

v) Water retention data and soil water availability models (PAW and IWC)

Volumetric water retention (θ, m^3 water m^{-3} total) was measured at seven different matric heads: for the larger cores the matric heads were h = 0.1, 0.3, 1, 5, 10, 50, 150 m and for the smaller cores they were h = 0.01, 0.1, 0.5, 1, 5, 10 and 150 m. The water contents at matric heads up to 1m were obtained using saturated ceramic plates connected to hanging columns of water, while for greater matric heads the samples were placed on saturated ceramic plates in water-extraction chambers connected to pressurised N_2 gas. When samples were deemed to reach static equilibrium at each pressure (*e.g.* 7 days for h = 1 m, ≥ 60 days for h = 150 m), they were weighed, and then replaced at the same pressure for 48 h until the weights did not change significantly (i.e. ≤ 0.1%). Hydraulic contact between the soil in the cores and the pressure plates was established each time using a saturated layer of fine diatomaceous earth. Once all water retention data were collected, samples were oven dried in their metal rings at 105 °C for 48 hours (after removing the fabric mesh etc) to obtain the oven-dry weights. Gravimetric water contents were then calculated and converted to volumetric water contents using the individual sample bulk densities and assuming the specific gravity of the water at 20 C was 1000 kg m^{-3}.

Using the mathematical software, Mathcad 14 (Parametric Technology Corporation 2007), the water retention curves were created by fitting the measured volumetric water contents to the Groenevelt–Grant equation (Grant *et al*. 2010) anchored at the nominal wilting point, $h_a = 150$ m, in the relation:

$$\theta(h) = \theta_a + k_1 \cdot \left\{ \exp\left[-\left(\frac{k_0}{h_a}\right)^n \right] - \exp\left[-\left(\frac{k_0}{h}\right)^n \right] \right\} \quad [\mathbf{2\text{-}2}]$$

where θ_a and h_a are, respectively, the volumetric water content and the matric head at the chosen anchor point, *a* (h_a = permanent wilting point = 150 m), k_1 and *n* are dimensionless fitting parameters, and k_0 is a fitting parameter having the same units as the matric head, *h* (m). The differential water capacity, C(h) ≡ $d\theta/dh$, was determined as the first derivative of **Eqn 2-2** and used to calculate the conventional *Plant Available Water*, PAW ($m^3\ m^{-3}$) as:

$$\mathrm{PAW} \equiv \int_{h=\mathrm{FC}}^{h=\mathrm{WP}} \frac{d\theta}{dh} dh \quad \text{or simply } \mathrm{PAW} \equiv (\theta_{FC} - \theta_{WP}) \quad [\mathbf{2\text{-}3}]$$

where FC is field capacity (*h* = 1 m), WP is the permanent wilting point (*h* = 150 m) and $\frac{d\theta}{dh}$ is the differential water capacity, C(h).

The differential water capacity was also used in the *Integral Water Capacity*, IWC, to calculate soil water availability after Groenevelt *et al*. (2001):

$$\mathrm{IWC} \equiv \int_0^{\infty} \left(\prod_{i=1}^{n} \omega_i (h) \right) C(h) d(h) \quad [\mathbf{2\text{-}4}]$$

where $\omega_i(h)$ are weighting functions (i = 1 to *n*) with values ranging between 1 (no limitation to water availability) and 0 (complete limitation) to account for multiple possible soil physical restrictions that limit water availability to plants.

The soil restrictions for which weighting functions were applied in this study were similar to those presented in Groenevelt *et al*. (2001) and Nang (2012), as follows:

1) Poor soil aeration, $\omega_a(h)$, which accounted for limitations to plant water extraction due to reduced or inhibited plant root activity caused by anaerobic conditions.

2) *Soil resistance to penetration*, ω_{SR}(h), which accounted for limitations to water extraction due to increasingly large soil resistance that reduces or completely impedes root exploration.

3) *Rapid and slow soil hydraulic conductivity*, $\omega_{k\text{-WET}}(h)$) and $\omega_{k\text{-DRY}}(h)$, which took into account the limitations to water extraction caused by rapid drainage in wet soils (due to

excessively large hydraulic conductivity), and by slow movement of water in drying soils (due to excessively small unsaturated hydraulic conductivity).

A detailed description of the methods and calculations used to determine the weighting functions is presented in **Chapter 5**, published as Betti *et al*. (2016). The integral water capacity, IWC, was calculated according to **Eqn 2-4** taking into account the effects of each of the three physical restrictions on soil water availability, individually and in combination to distinguish single and interacting effects. Calculations were completed using a customised Mathcad worksheet to facilitate multiple automatic computations, which were required for PAW, IWC and its weighting functions (**Appendix A** and **B**).

Field transect scale

i) Sample collection

Soil sampling was conducted under winter conditions (with naturally moist soil) along two field transects, approximately 30 m long and 15 m apart at the centre of two parallel delving lines (refer to schematic in **Fig. 2.4**) to evaluate surface water repellence, infiltration, soil resistance to penetration and to quantify the amount of subsoil clay aggregates in the topsoil.

Bulk samples of topsoil from 0-0.1m depth were collected along the two transects to measure the distribution of subsoil aggregates in the surface horizons of the delved soil. The samples were subdivided into five groups based on their distance from the delving line, following the same approach of the grid shown in **Fig. 2.3**. For example, the first group included samples collected along the delving line and corresponded to the position E-1 in the spatial grid in **Fig. 2.3**; the second group included samples collected from 0.1 m apart from the delving line and corresponded to the cell F-1 (or D-1) of the spatial grid. This was done until the fifth group, 0.4 m from the centre of the delving line, corresponding to the cells A-1 or I-1 of the spatial grid. As per the soil collection from the representative delved profile, samples from the A (or I), B (or H), C (or G) positions were used for the “off-line” region and the samples from the D, E and F position used for the “delving line” region.

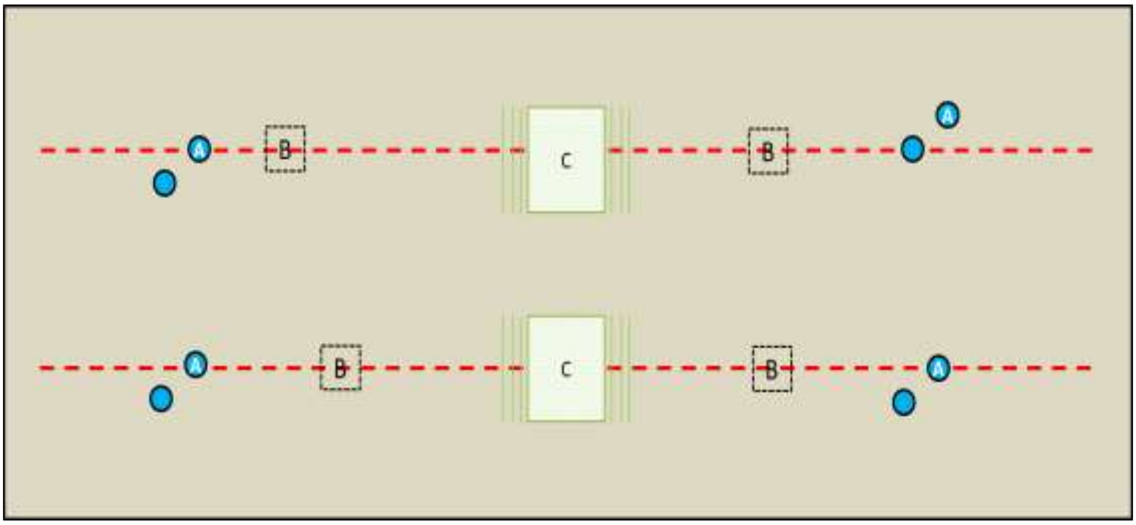

Fig. 2.4. Schematic representation of the two field transects used for sampling (30 m long and 15m apart). Blue dots containing "A" = approximate location of the metal rings used for the infiltration measurements. Black squares containing "B" = approximate location of the areas of soil sampling for water repellence analysis. Large green squares containing "C" = approximate location of soil pits from which the digital images of the delved profiles were taken.

The soil samples were transported in bags to the laboratory and oven dried at 105° C. The oven dried samples were placed on a nest of sieves (50, 20, 6.7, 4.75 and 2 mm) and agitated gently by hand to separate the fraction of "fine" soil from the "coarse" subsoil aggregates. The weights of the portion of soil retained on each sieve was used to determine the total amount of "coarse" subsoil aggregates and their distribution by size in the topsoil relative to the distance from the centre of the delving line. The soil from each group was later passed through a 2 mm sieve in preparation for measuring the total clay content as described above.

From this information the quantity of subsoil, M_S, kg ha^{-1}, brought into the top 0.1 m by delving can be estimated as follows:

$$M_S = (C_{A_f} - C_{A_i}) \times \frac{\rho_{A_f} \times V_A}{C_S} \qquad \textbf{[2-5]}$$

where C_{A_f} is the total % clay measured in the samples collected in the top 0.1 m after delving (final), C_{A_i} is the total % clay measured in the A horizon prior to delving (initial), C_S is the total % clay measured in the subsoil, ρ_{A_f} is the mean bulk density of the A horizon after delving (final, kg m^{-3}, which was essentially the same as that of the initial un-delved A horizon) and V_A is the volume (m^3) of 0.1 m of soil in one hectare.

The quantity of clay, M_C, kg ha^{-1}, brought into the top 0.1 m by delving was estimated as the difference between the clay contents before (initial) and after (final) delving, *viz.* $M_C = \left(M_{C_f} - M_{C_i}\right)$, where $M_{C_i} = \frac{\rho_{A_i} V_A C_{A_i}}{100}$, and $M_{C_f} = \frac{\rho_{A_f} V_A C_{A_f}}{100}$. Given that $\rho_{A_f} = \rho_{A_i}$, we can say: $M_C = \frac{V_A \ \rho_A}{100}\left(C_{A_f} - C_{A_i}\right)$.

Soil from the "delving line" and "off-line" regions were compared quantitatively for aggregate size distribution and mass of subsoil per hectare brought up into the topsoil.

The severity of water repellence in the topsoil of both delved and un-delved soils was measured in the laboratory on air-dried samples using the water droplet penetration time method, WDPT, of Dekker *et al.* (2009) and classified according to Bisdom *et al.* (1993). Samples were taken at two different depths within the A1 horizon, 0 to 0.05 m and 0.05 to 0.1 m, in random locations in the un-delved soil (10 samples from each depth). In the delved soils, two areas along both transects were selected and, from each of these, 10 samples were collected from the same two depths, both in the "delving line" and the "off-line" regions (**Fig. 2.4, B**).

Large, single metal rings (0.15 m long, 0.3 m diameter) were used to estimate the average steady-state infiltration rate at the soil surface along the transects (Reynolds and Elrick 1990; Erickson *et al*. 2013) at two random locations in both the "delving line" and "off line" regions (**Fig. 2.4, A**). In the un-delved soil, infiltration rate was measured at three randomly selected locations. Before infiltration was measured, the soil was wetted for a time considered sufficient to overcome the initial water repellence of the surface soil. The time taken for the water level in the rings to decline 5 cm from the top of the rings was measured and used to calculate an infiltration rate.

Soil penetration resistance, SR, kPa was measured to a depth of 0.6 m at 10 mm intervals under moist (winter) conditions at random locations along the two transects in both the "delving line" and "off line" regions (**Fig. 2.4**) using a CP40II field cone penetrometer (Rimik Electronics, Toowoomba QLD, Australia), as well as in the un-delved soil.

ii) Digital Images of soil profiles

In addition, two large pits were excavated (**Fig. 2.4, C**) with a backhoe at the centre of the two transects to obtain high resolution digital images to quantify the morphological changes caused by clay delving. At approximately 0.3 m intervals in both pits, five vertical faces (centred on the delving line) were manually prepared as representative profiles.

The metal frame 0.9 m wide by 0.6 m high was positioned against the surface of each profile and photographs were taken using a digital SLR camera at maximum resolution in RAW format. Using the metal frame as a reference scale, each photo was corrected for lens distortion and perspective with the software packages: Gimp (www.gimp.org) and Adobe Photoshop-CS (www.adobe.com/au/products/photoshopfamily.html). As shown in **Figs 2.5,** the software Adobe Photoshop-CS was then used to select and separate (using *select by colour range* and *magic wand* tools) three main components by soil type in the profile images, based on the following distinctive colours:

1) dark soil, composed predominantly of what was originally the organic-rich A1 horizon;

2) visible subsoil aggregates (brown-yellow) mixed in the topsoil;

3) brown-yellow soil, belonging to the B horizon.

All three components were individually converted to binary format (**Fig. 2.5**) using the Fiji image processing package of the Image J64 software (http://imagej.nih.gov/ij/).

A quantitative visual comparison was made of the spatial distribution of organic-rich A1-horizon material down the profile for both the “delving line” and “off line” regions. Firstly, the 0.9m wide images of the delved profiles were subdivided into two images, 0.56m and 0.34m wide, representing the off-line and delving line regions respectively (**Fig. 2.5**). Then, the areal proportion of black pixels (representing organic-rich A1-horizon material) was calculated for each vertical slice of the profile at 0.05 m depth increments using the ImageJ64 software. A similar approach was used to compare the spatial distribution of the subsoil aggregates in the “delving line” and “off-line” regions., The analysis tool, *Analyze particles,* in the Fiji package of ImageJ 64 calculated the surface areas of the individual visible aggregate sections in each profile image; nominal diameters were then calculated from the respective surface areas, assuming spherical aggregate shapes.

The proportion of the total cumulative surface area of the aggregates (measured at 0.05 m depth increments) was then calculated by including only aggregates with nominal diameter > 2 mm (this allowed small clay aggregates to be distinguished from the smallest clusters of pixels representing potential ‘noise’ in the digital images. The visible subsoil aggregates were also separated into a group called *large aggregates* with nominal diameter > 6.7 mm, in a manner similar to the treatment of undisturbed samples collected from the representative delved profile.

The percentage cross sectional area of subsoil aggregates brought into the A horizon seen in the digital images are discussed here in terms of their proportion by volume to allow comparison with the spatial distribution of subsoil aggregates measured by sieving the undisturbed samples, which were also expressed as % volume, V_S, using the relation:

$$V_S = \frac{M_S/\rho_S}{V_t} \times 100 \qquad \textbf{[2-6]}$$

where M_S is the total mass (g) of subsoil aggregates with nominal diameters > 2 mm measured in the undisturbed samples, ρ_S is the mean bulk density of the subsoil estimated from the samples collected in the delved profile (1780 kg m^{-3}) and V_t is the total volume of the undisturbed sample (cm^3).

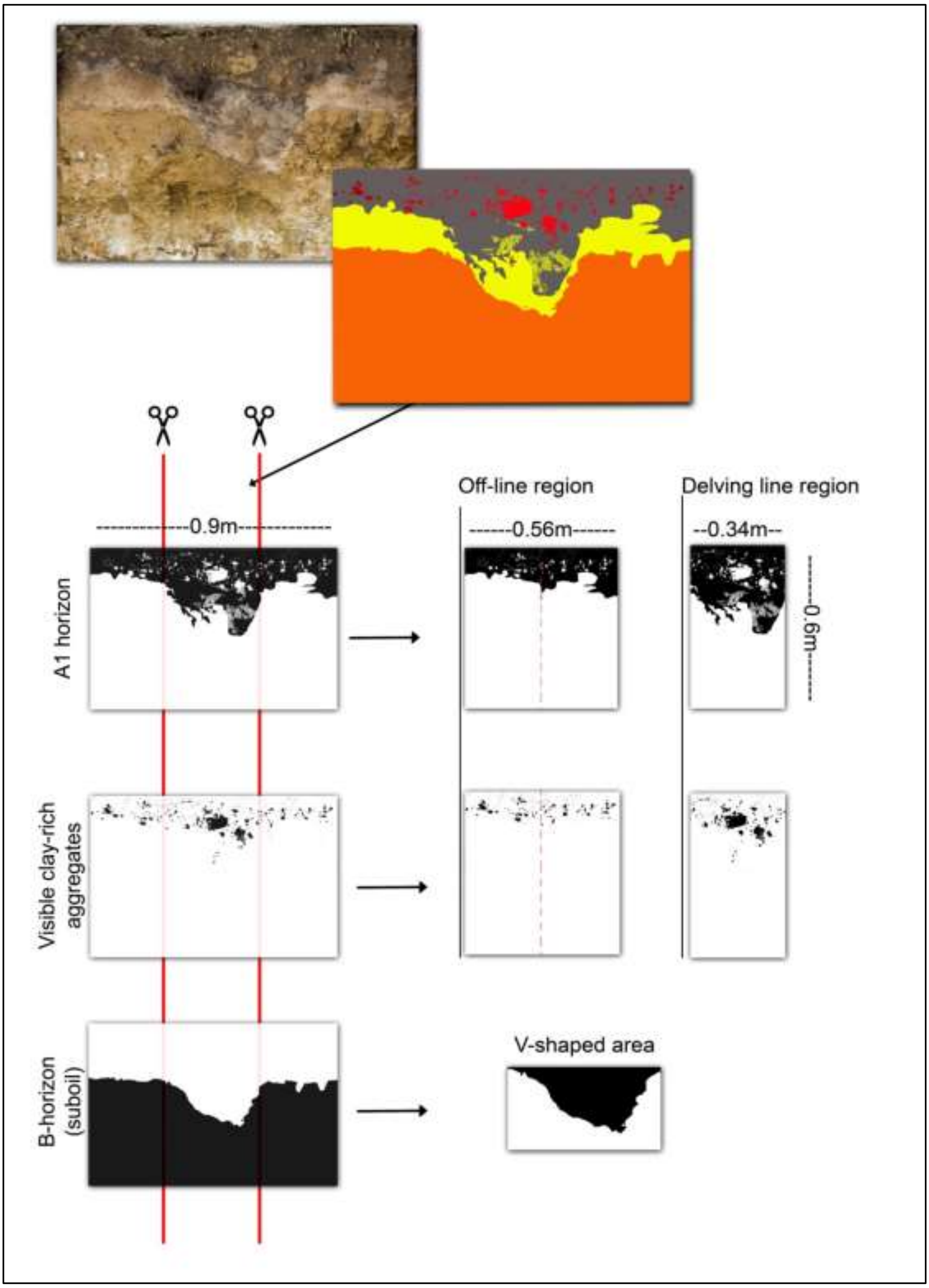

Fig. 2.5. Schematic diagram showing how the digital images of the delved profiles for different soil types were selected and converted to black and white binary images for quantitative analysis of the off-line and the delving-line regions using ImageJ 64.

From the images of the B horizon, binary images were generated for the V-shaped areas along the delving lines (**Fig. 2.5**). Two replicas of the missing upper sides along the perimeters of the V-shaped areas were manually traced onto each individual profile image taking into account the mean depth of the B horizon calculated from the “off-line” regions. The cross sectional areas of the V-shaped regions were used to calculate another estimate of the average mass of subsoil, M_S (kg m^{-2}), brought up from the B horizon by the delver:

$$M_S = \frac{A}{L} \times \rho_S \qquad \textbf{[2-7]}$$

where A is the ‘cross sectional area’ of the V-shaped region (m^2), L is the digital transect length (0.9 m) calculated from the images, and ρ_S is the independently measured mean bulk density of the subsoil (1780 kg m^{-3}).

As discussed in the literature review (**Chapter 1**), texture-contrast soils are frequently associated with water-logging. Under wet winter conditions, plant roots growing in texture-contrast soils can experience anaerobic stress due to the excess of soil water ponding over the relatively impermeable subsoil; previous studies (McFarlane *et al*. 1989; McFarlane and Cox 1992; Rameshwar *et al*. 1988) have shown that changes in the depth and duration of the water table within the top 0.3 m of soil can significantly affect plant root growth, in particular during the early stages of plant development.

Since it has often been observed that clay delving reduces the occurrence of water logging in texture-contrast soils (or at least mitigates its negative effects on plant growth) it was thought this might be related to the deep ripping effect produced by the delving tines.

The hypothesis was that the disruption of the B horizon by clay delving allows for a greater quantity of water to move downward as the soil in the sand filled V-shaped area becomes more permeable. As a consequence, the depth of water ponding above the impermeable B horizon will decrease (as shown in the graphical representation in **Fig. 2.6**) and the extent of it would depend on the total soil pore volume of the sandy soil filling the V-shaped area.

To test this hypothesis I quantified the potential reduction in the depth of water-ponding over the B horizon using digital images of the V-shaped areas in the delved profiles, using the relation:

$$D = \frac{A}{L} \times \left(1 - \frac{\rho_{sand}}{\rho_p}\right) \qquad \textbf{[2-8]}$$

where D (m) is the depth of water filling the soil pores in a fully saturated V-shaped area (equivalent to the reduced depth of water that would pond over the B horizon), A (m^2) is the cross sectional surface area of the V-shaped region, L is the width of the digital image (0.9 m), ρ_{sand} is the bulk density of the sandy material in the V-shaped region, estimated independently from the samples collected in the delved profile (1540 kg m^{-3}) and ρ_p is the average specific gravity of the soil, assumed to be 2650 kg m^{-3}.

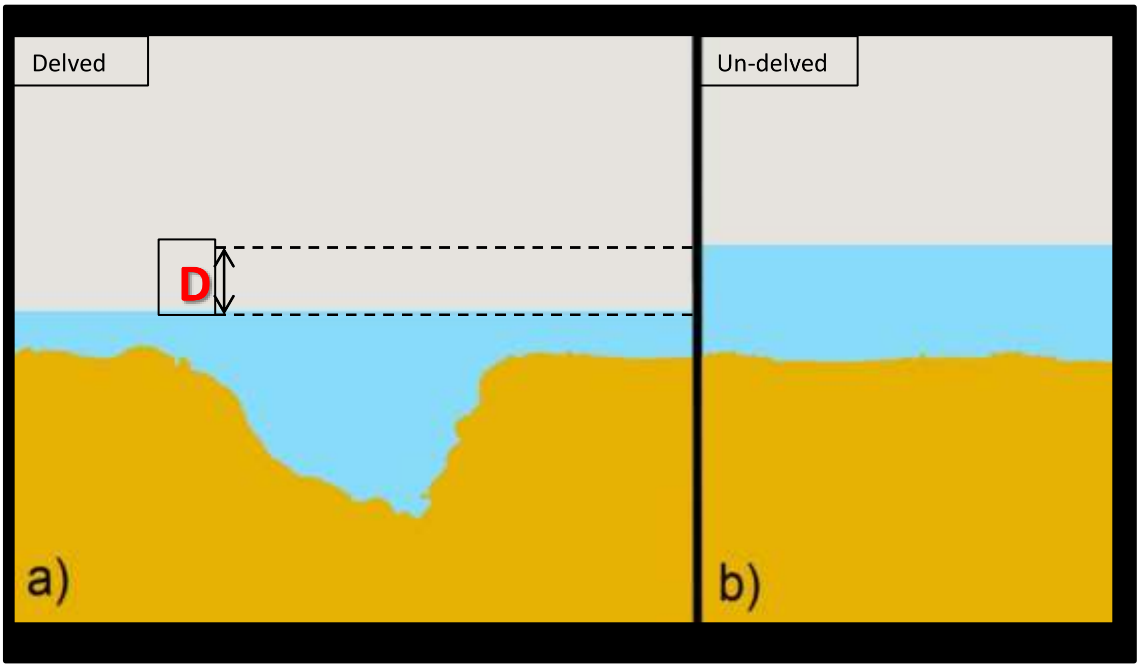

Fig. 2.6. Visual representation of the theoretical effect of the V-shaped area in decreasing the depth of water (blue area) ponding over the impermeable B horizon (orange area) in a delved soil (a) in comparison to an un-delved soil (b). D was calculated from **Eqn 2-8**

2.2 Results and discussion

Soil profile scale

Results are presented here for each soil property and the data are given in greater detail in Appendix A and Appendix B.

i) Bulk density, size of subsoil aggregates and clay content

Although delving increased the clay content of the disturbed soil, this appeared to have no significant effect on bulk density measured using core samples (**Fig. 2.7**). The bulk density was highly variable and ranged between that for the sandy surface soil (1360 kg m^{-3}) and that exceeding the value for the subsoil clods (> 1800 kg m^{-3}). The poor correlation between clay content and bulk density was not unexpected because it reflected the pronounced morphological variability between and within samples. The components, of course, came from two very different soils (sandy material from the A horizon and subsoil material from the B horizon) that were mixed to varying degrees by the delving process and by post-delving cultivation. In such complex mixtures, the arrangement of the soil aggregates and the cohesion between the soil particles were expected to be complex and to cause great variability in packing even for samples with similar clay content.

The regression coefficients for the relations between clay content and bulk density were quite small because two distinct groups of soil are represented in **Fig. 2.7**: one group comprises mixtures dominated by sand and a small amount (< 10%) of large subsoil clay aggregates (*Fine soil*); the other group comprised larger amounts (> 10%) of subsoil clay (in large chunks) and some sand (*Coarse soil*). In general, the samples containing *Coarse soil* tended to have greater clay contents than the samples containing *Fine soil*, which subsequent results will highlight.

The rings of soil collected from the top 0.3 m of the delved profile comprised mainly (i.e. > 80%) “fine” material and 10 to 20% “coarse” material. (**Table 2.1**). The variability in the quantity and type of subsoil aggregates in the samples was very great (shown by the large standard deviation of the mean values in **Table 2.1**).

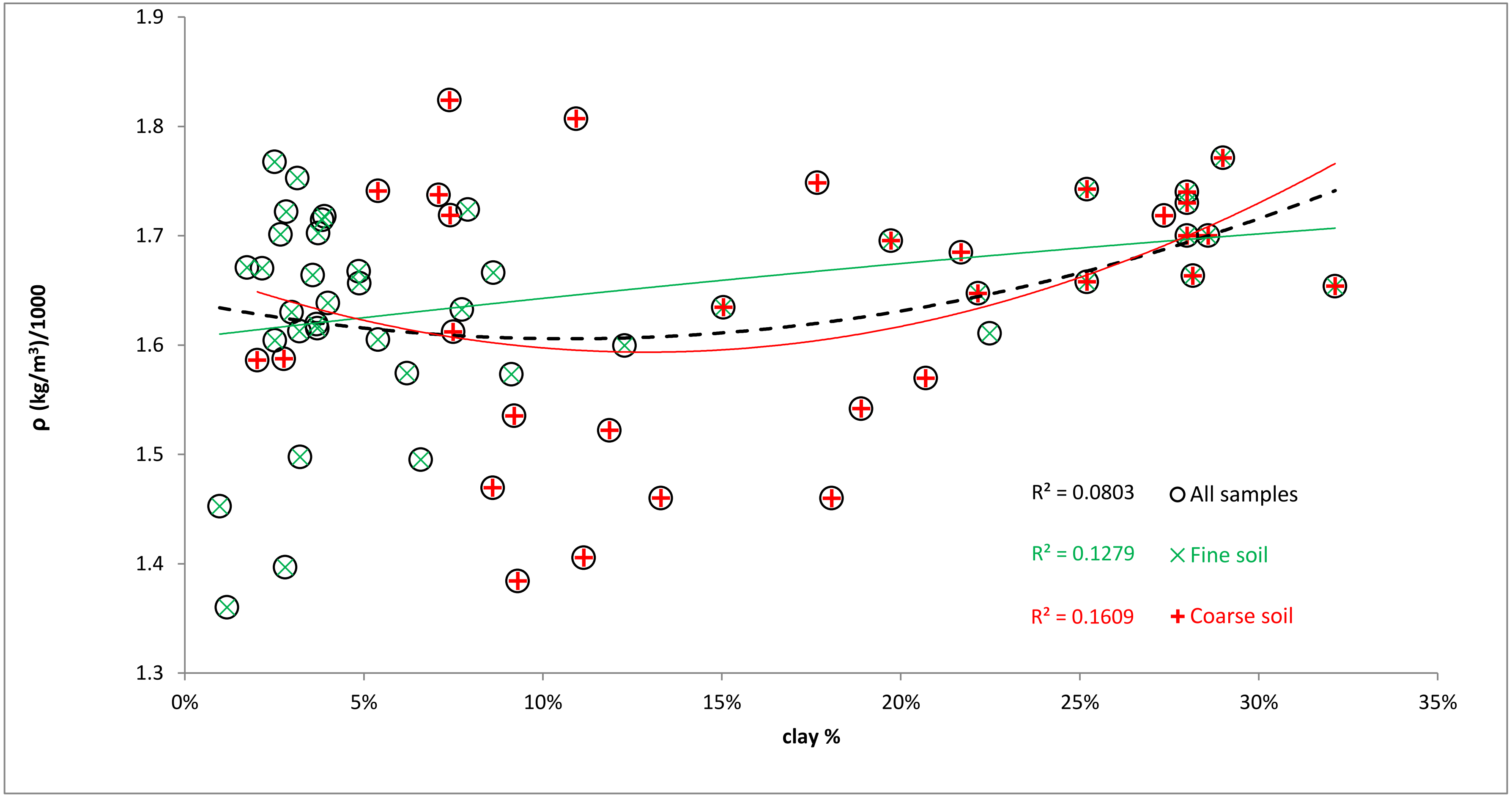

Fig. 2.7. Relationship between total % clay content of the delved soil and its bulk density, ρ.

The average total clay content of soil collected from the top 0.1 m and 0.2 m was variable in the range 8 to 10% (**Table 2.1**), which is significantly greater than before clay delving (< 3%). The enormous variability in both clay content and aggregate size distribution both between and within samples has a significant bearing on changes to other soil physical properties, as discussed below.

Fig. 2.8 (right), shows a graphical representation (Excel® Surface chart , Microsoft® Excel® 2007) of the spatial distribution of the total clay content (% by weight) in the delved profile (using spatial interpolation of the data from the reference grid in **Fig. 2.3**); a comparative representative section of the original un-delved soil is presented in **Fig. 2.8 (left)**. Incorporating subsoil from the B horizon into the A horizon is shown here to significantly increase the clay content in the delving line region relative to the off-line region (and the un-delved soil) and there are significant differences in spatial variability of clay content between the delving line and off-line regions.

The trends are also illustrated in **Fig. 2.9**, which shows that, within the top 0.1 m, the clay content increased from about 2% in the un-delved soil up to approximately 10% and 9% in the delving line and off-line regions. From 0.1 m down to the A/B horizons interface at about 0.3 m, the clay content in the delving line and off-line regions increased, on average, by about 5%. Below this depth the clay content resembled that of the B horizon and so was similar to that of the un-delved soil. By contrast, the clay content on the delving line decreased in the 0.3m to 0.4m depth, where sand back-filled into a V-shaped area after delving

Table 2.1. Aggregate size distribution (%) and average clay content (%) of delved soil within the top 0.3 m. Values in parentheses represent standard deviations.

Profile depth (m)	*% clay in "fine" material*			*% clay in "coarse" material*		Average clay content
	< 2 mm	2 - 4.75 mm	4.75 - 6.7 mm	6.7 - 20 mm	> 20 mm	
0 to 0.1	81 (15)	3 (2)	3 (3)	10 (9)	4 (6)	10 (4)
0.1 to 0.2	85 (18)	1.6 (2)	2 (2)	7 (9)	5 (12)	8 (5)
0.2 to 0.3*	90 (12)	1 (1)	1 (1)	4 (6)	5 (10)	5 (3)

*samples collected from the delving-line region only

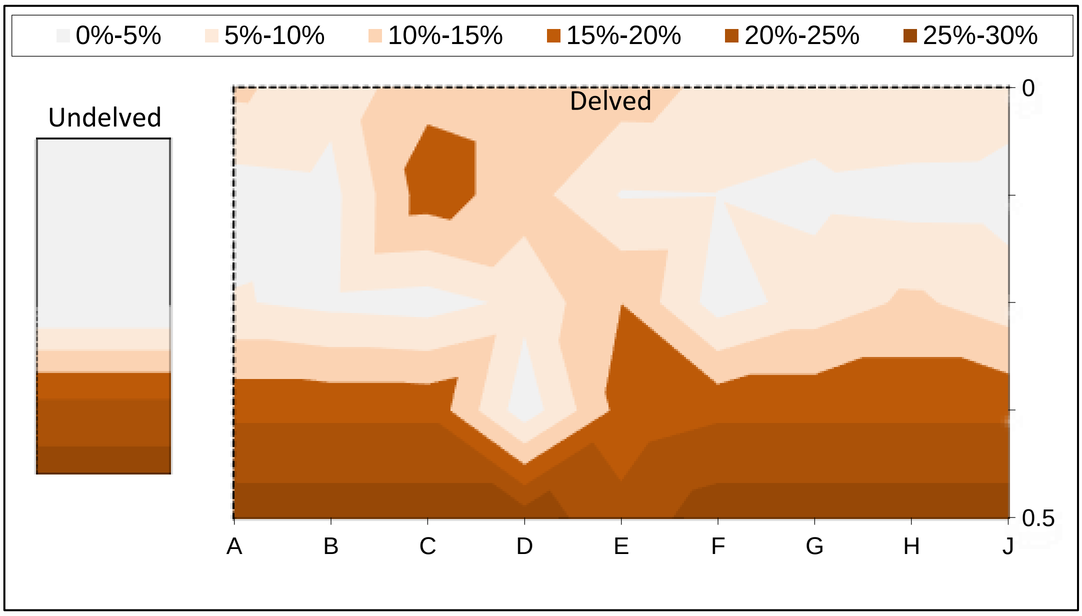

Fig. 2.8. Spatial variability in mean clay content in the delved soil profile (right) compared with a representative section of the original un-delved soil (left).

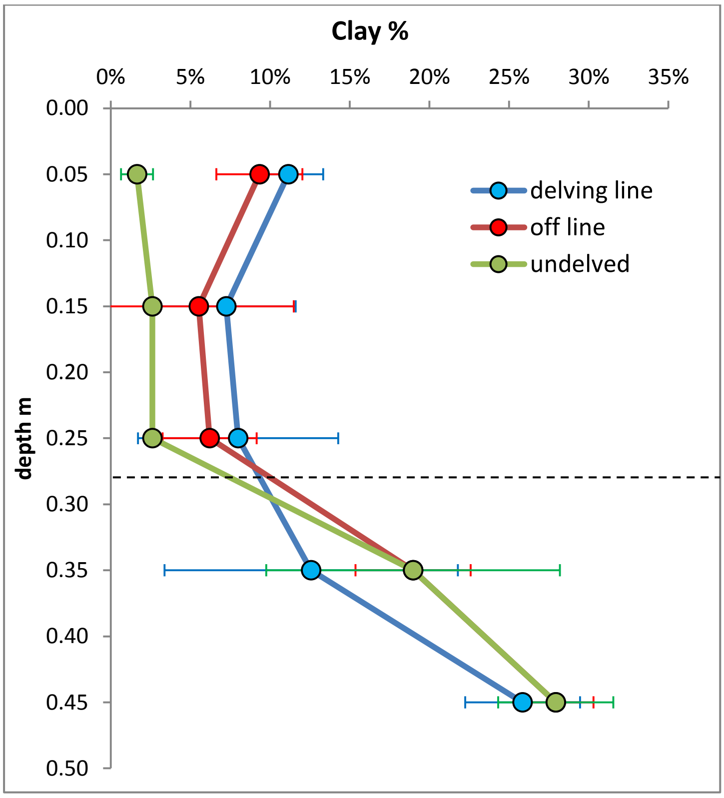

Fig. 2.9. Quantitative comparison of the mean clay content (% by weight) at different depths in the delving line and off-line regions of delved soil, and in the un-delved soil. The horizontal dashed line represents the approximate location of the boundary between the A and B horizons. Error bars represent standard deviations of the mean.

ii) Saturated hydraulic conductivity

The increase in clay content caused by delving, significantly reduced the saturated hydraulic conductivity, K_s. Total clay content was highly (negatively and exponentially) correlated with K_s (**Fig. 2.10**, R^2=0.82). The mean K_s declined by several orders of magnitude as clay content increased, and variability was somewhat greater for samples containing > 10% of large aggregates (Coarse soil, R^2 = 0.71) relative to samples containing < 10% of large aggregates (Fine soil, R^2 = 0.94). Presumably, the samples with greater quantities of large aggregates contained significant regions of sand between the large aggregates, allowing for water movement in continuous large pores. The variability in both the quantity and spatial distribution of large aggregates generates highly variable hydraulic conductivities, both K_s and K_{unsat}, which have implications for plant available water, considered below in terms of the IWC concept.

A visual representation of the spatial distribution of mean K_s in the delved and un-delved profiles is shown in **Fig. 2.11**. Compared to a typical un-delved profile (left) where K_s changes abruptly from the very sandy topsoil into the subsoil, the delved soil profile (right) shows far greater spatial variation in mean K_s both vertically and horizontally. Delving decreased K_s (in both the delving line and off line regions) to the depth of at least 0.35 m relative to the un-delved soil (**Fig. 2.12**), below which there was little significant difference between the off-line and un-delved profiles. In the delving line region K_s showed a slightly diminished reduction with depth, presumably because of the back-filling of sand in the V-shaped region between 0.3 m and 0.4 m depth. The effect of the V-shaped area on the wettability in depth of delved soils is further discussed in **Chapter 3**, published as Betti *et al*. (2015).

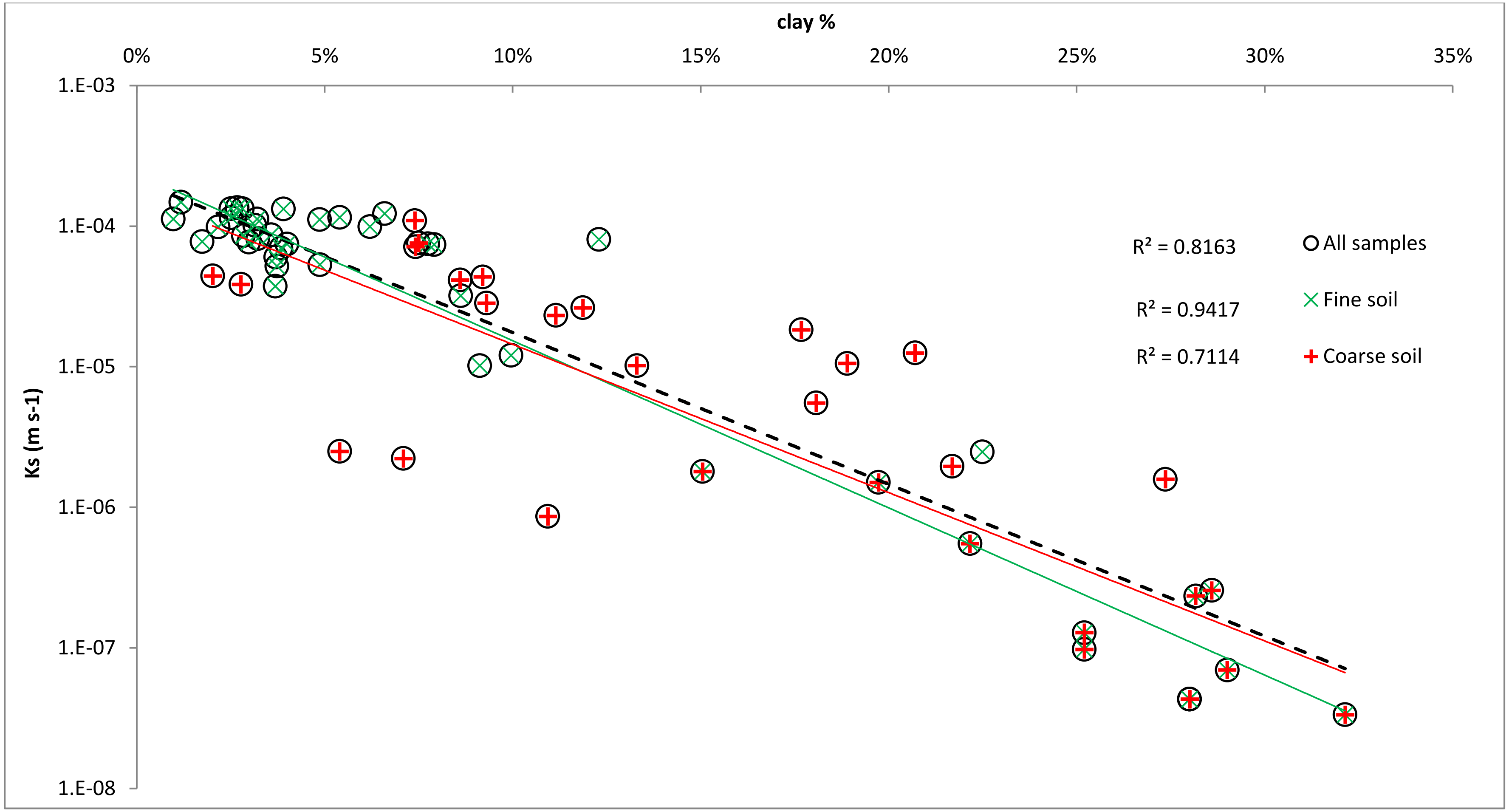

Fig. 2.10. Effect of increasing total clay content by delving on saturated hydraulic conductivity, K_s.

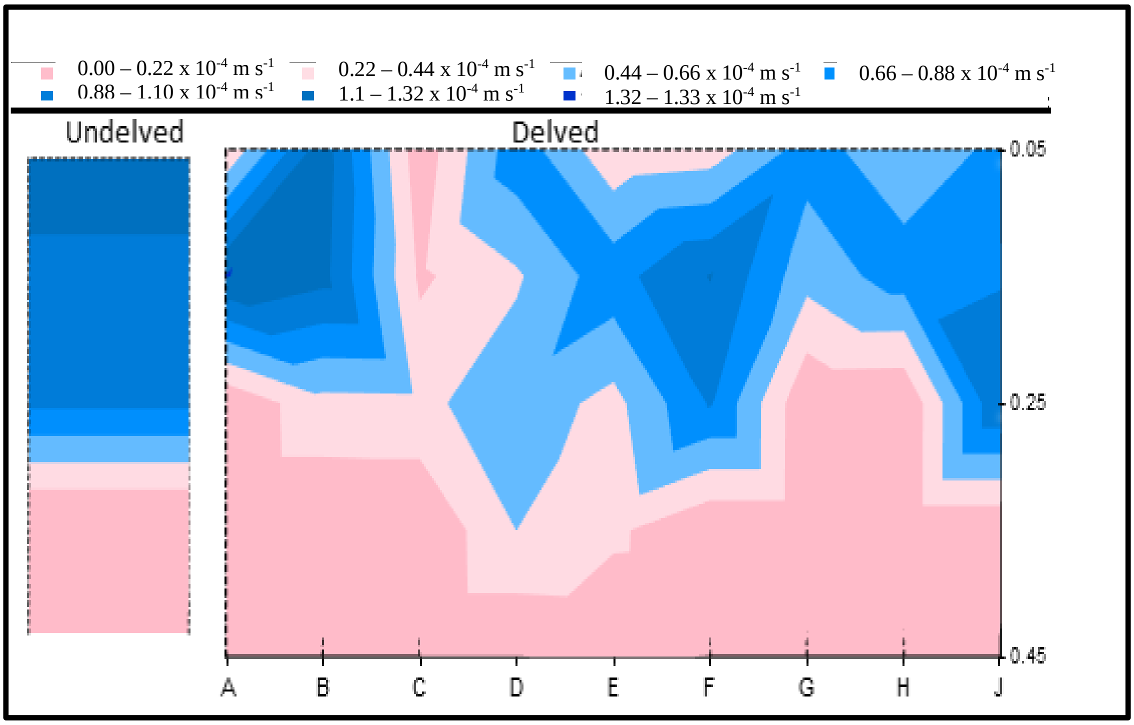

Fig. 2.11. Visual representation of spatial variability in mean K_s (m s^{-1}) for delved (right) and un-delved (left) soil profiles.

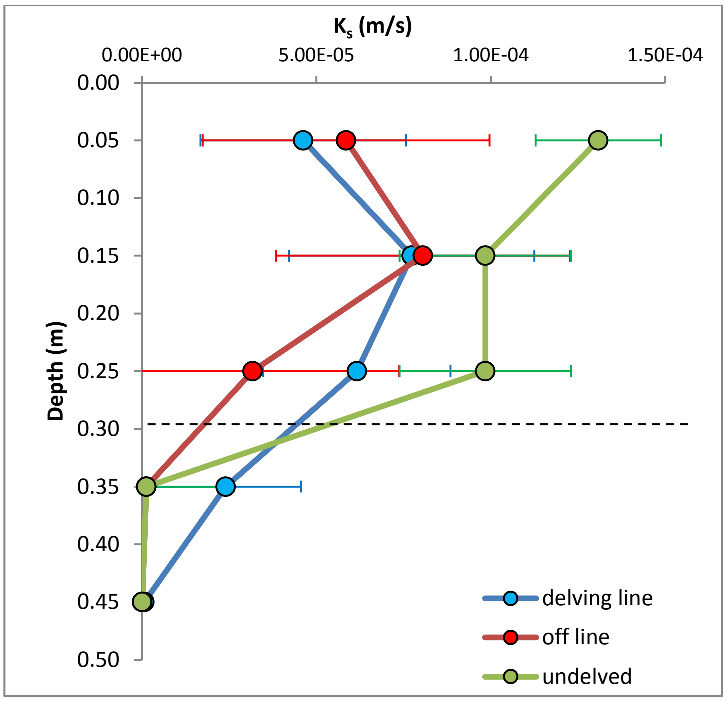

Fig. 2.12. Mean K_s as a function of depth for the delving-line and off-line regions, and un-delved soil. The horizontal dashed line represents the approximate location of the boundary between the A and B horizons

iii) Soil resistance to penetration

Increasing clay content significantly increased soil resistance to penetration, SR, although this depended on the soil matric head (**Fig. 2.13** versus **Fig. 2.14**). For example, there was no significant relationship between penetrometer resistance and clay content in moist soil (*e.g.* h = 1 m**, Fig. 2.13**), especially for samples containing >10% large aggregates (Coarse soil, R^2 = 0.01), and furthermore, regardless of clay content or degree of mixing, all SR were well below 2.5 MPa, which is considered a critical value for plant roots (represented by the upper horizontal black dashed lines in **Fig. 2.13** and **Fig. 2.14**). For samples held at a matric head of 1.5 MPa, a stronger but highly variable relationship occurred between clay content and SR (**Fig. 2.14**), in which the soil resistance increased to values far exceeding the critical 2.5 MPa. The Coarse soil samples (with >10% large aggregates) showed the greatest variability in SR with increasing clay content (lowest R^2=0.41) which, of course, reflects the lower probability of the probe intercepting a large hard subsoil aggregate in the softer sandy matrix. Plant roots tend to spread around large, hard barriers to grow in the softer regions. The implications for soil water availability are discussed below in relation to IWC.

Visual representations of the spatial distribution of mean SR values at 1 m and 150 m matric head in the delved and un-delved profiles are shown in **Figs 2.15** and **2.16** while a quantitative comparison between the soil profiles is presented in **Fig. 2.17**. Similarly to what was observed with K_s, the delved soil is characterised by a greater spatial variation in mean SR in both vertical and horizontal directions. With wet soil at 1m matric head (**Fig. 2.17 left**), the mean values of SR did not exceed 1MPa throughout the profile to the depth of 0.5 m. In the top 0.2 m of soil (A horizon) there was no significant difference between the soils. However, between 0.2 and 0.3 m depth, corresponding to the upper part of the B horizon, the values in the delving line region were much lower when compared to the off-line region and the un-delved soil and this was due to the presence of the sand filled V-shaped area. The presence of the V-shaped area in the delving line region was particularly evident with drier soil at 150 m matric head (**Fig. 2.17 right**), where the abruptness of the A/B horizon interface kept the value of SR below 2.5 MPa up to 0.3 m depth. On the other hand, SR rapidly increased below 0.2m depth (corresponding to the upper part the B horizon) in the off-line region and the un-delved profile.

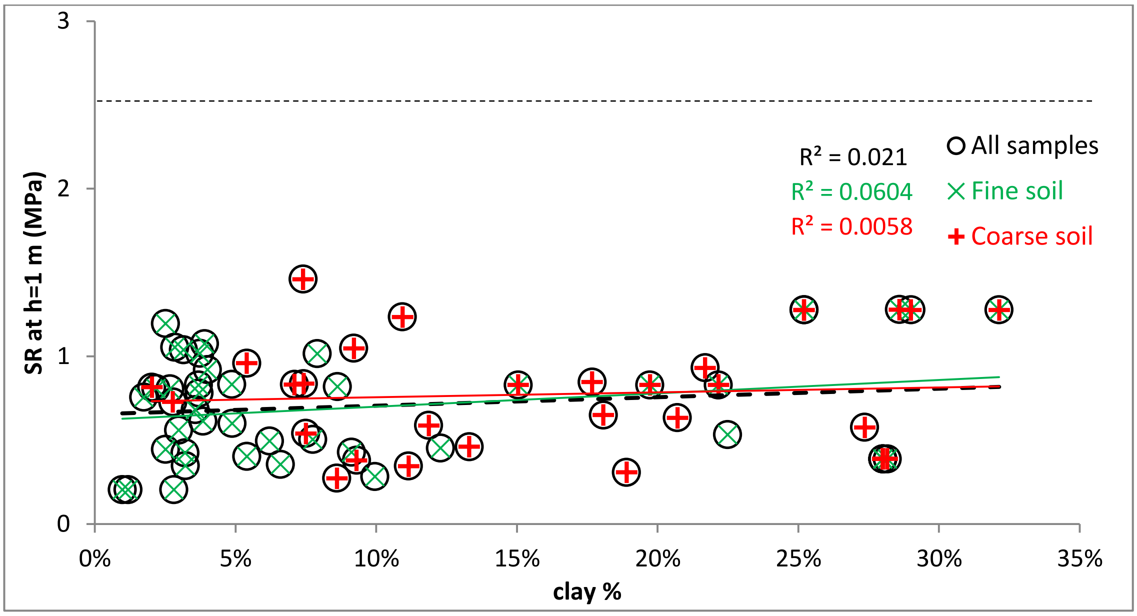

Fig. 2.13. Soil resistance, SR, at 1m matric pressure, as a function of % clay.

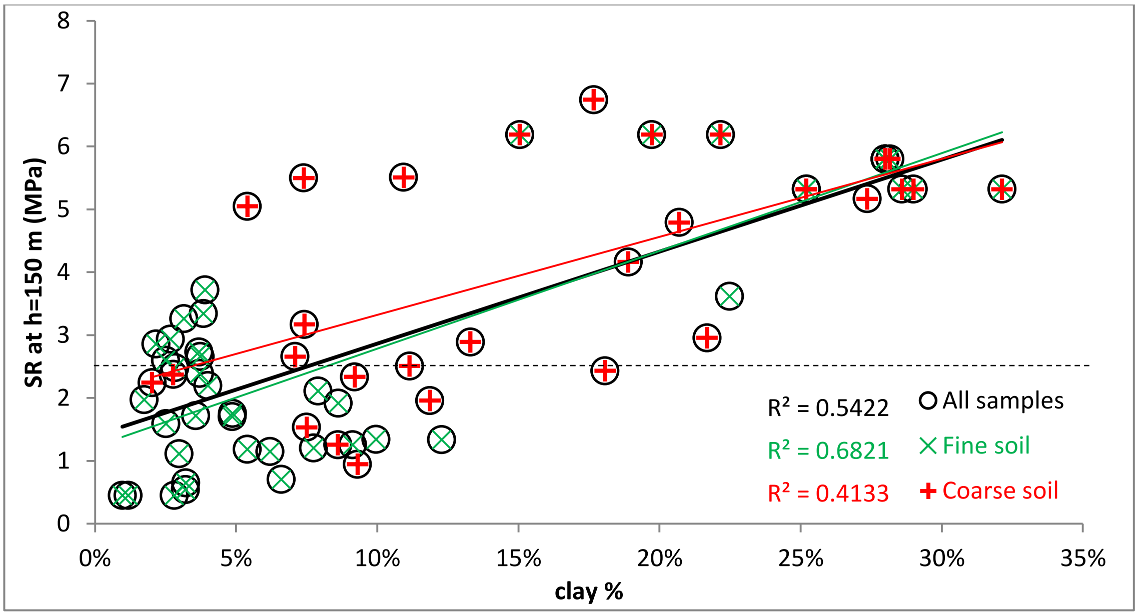

Fig. 2.14. Soil resistance, SR, at 150 m matric head, as a function of % clay.

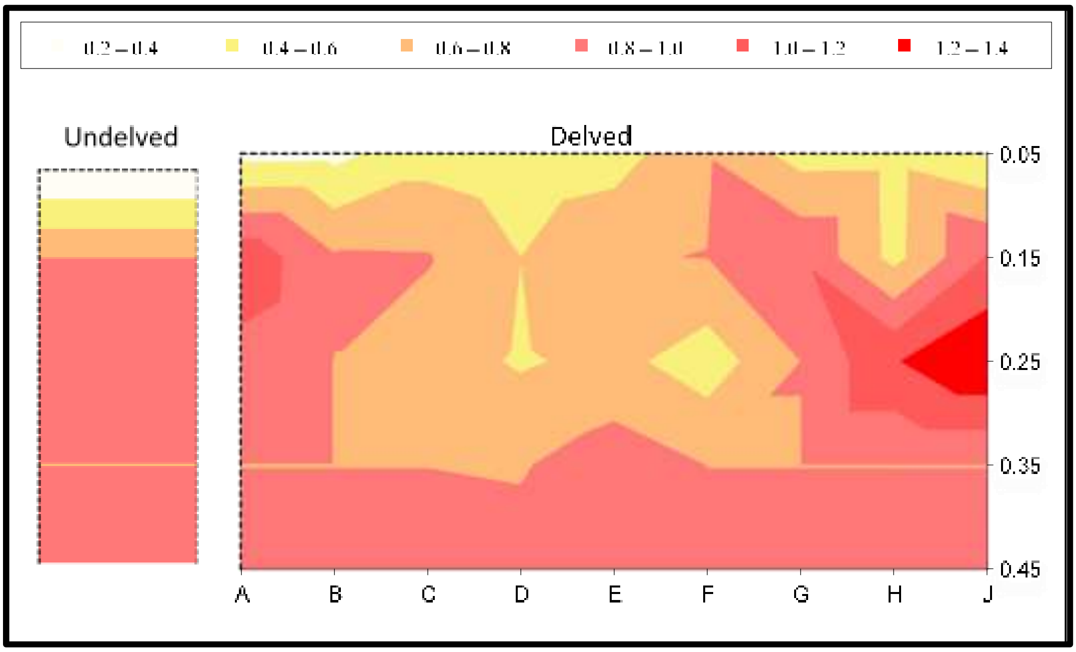

Fig. 2.15. Mean soil resistance to penetration (SR) at a matric head of 1 m in a delved profile (right) relative to a representative un-delved profile (left).

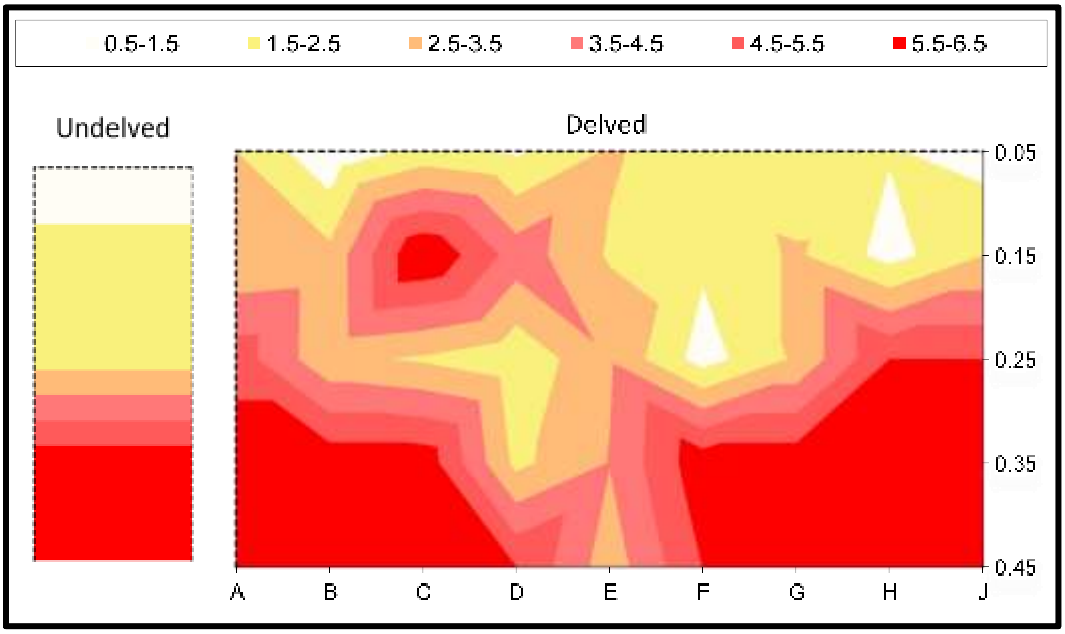

Fig. 2.16. Mean soil resistance to penetration (SR) at a matric head of 150 m in a delved profile (right) relative to a representative un-delved profile (left).

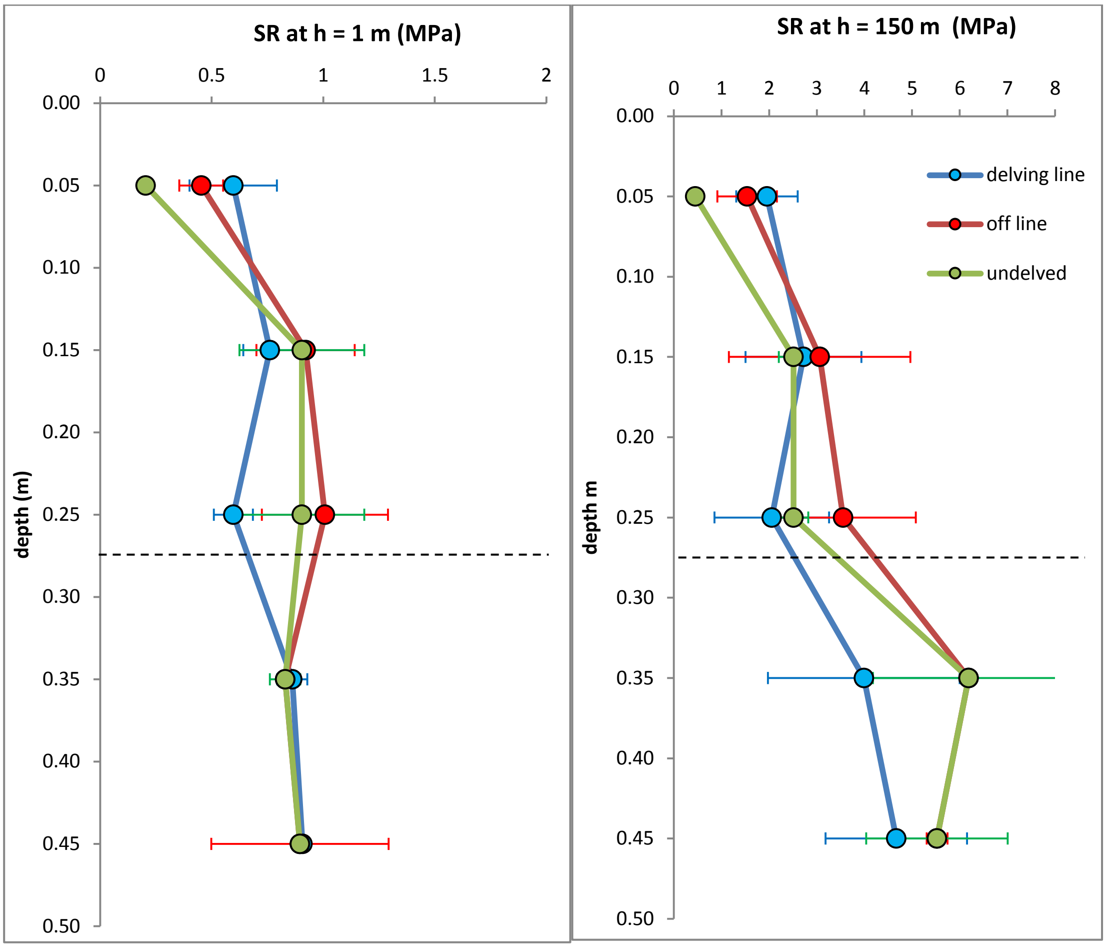

Fig. 2.17. Mean soil resistance (SR) as a function of depth at a matric head of 1 m (left) and at a matric head of 150 m (right) in un-delved soil and on the delving-line and off-line regions of delved soil. The horizontal dashed line represents the approximate location of the boundary between the A and B horizons

iv) Plant available water, PAW, and integral water capacity, IWC

Plant-available water, PAW, which takes no account of soil physical limitations to water uptake at matric heads between 'field capacity' (h = 1 m) and 'permanent wilting point' (h = 150 m), exhibited a good correlation (R^2 = 0.76) with mean total clay content (**Fig. 2.18** and **Appendix A**). PAW increased with increasing clay content in a power-function relationship showing stronger increase for samples having < 10% clay, although variability increased with increasing clay content. Variability appeared to be smallest for the Fine soil (R^2 = 0.80), whereas it was greater for the Coarse soil (R^2 = 0.70). Furthermore PAW appeared to increase more with clay content for samples containing

Fine soil compared with samples containing Coarse soil. In the ‘Fine soil’ samples, it is hypothesised that the small aggregates of subsoil clay combined with sand in such a way as to produce intimate mixtures containing pores of sizes predominantly in the plant-available range (i.e. those corresponding to matric heads in the range h = 1 to 150 m). By contrast, where the subsoil occurred as large discrete clods within a sandy matrix, it is hypothesised the clods retained mainly micro-pores outside the plant-available range (i.e. pores holding water at matric heads > 150 m) while the sandy matrix consisted of macro-pores draining at matric heads < 1 m. Such a ‘bimodal’ pore size distribution thus effectively reduced plant available water compared with samples containing Fine soil in the same range of clay content. This hypothesis is explored further in **Chapter 5**, published as Betti *et al*. 2016.

The extent of the morphological changes created by clay delving on PAW can be seen in **Fig. 2.19** and **Fig. 2.20**, particularly in the top 0.3 m of the delved profile, especially in the delving line region compared to the un-delved soil.

When various soil physical factors (*e.g.* poor soil aeration, high soil resistance, and high and low hydraulic conductivity) were taken into account to calculate soil water availability, a poor correlation was shown between the integral water capacity (IWC) and increasing clay content from delving (**Fig. 2.21** and **Appendix B**), even when Fine and Coarse soil was evaluated separately.

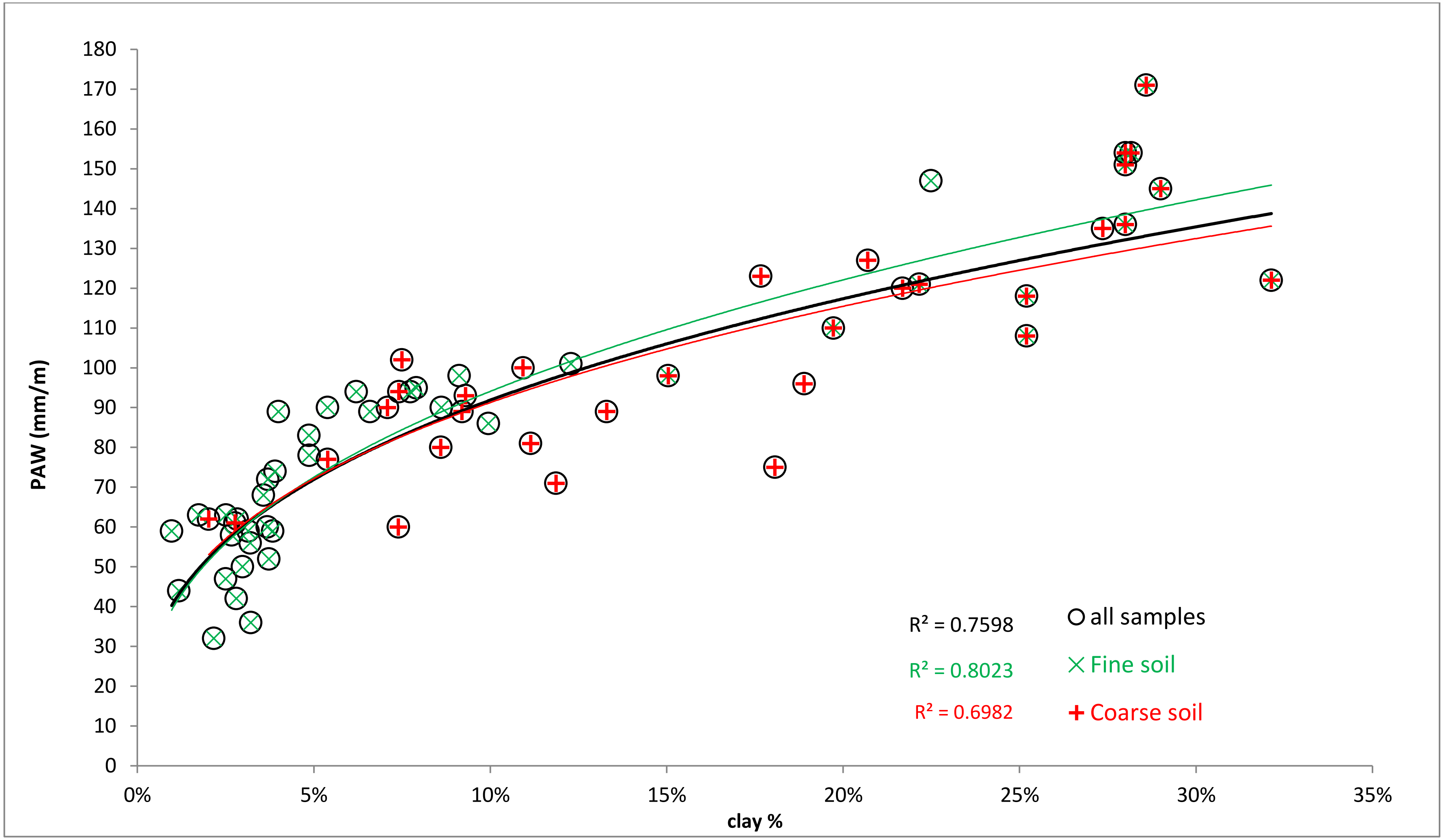

Fig. 2.18. Effect of increasing total clay content by delving on Plant Available Water (PAW).

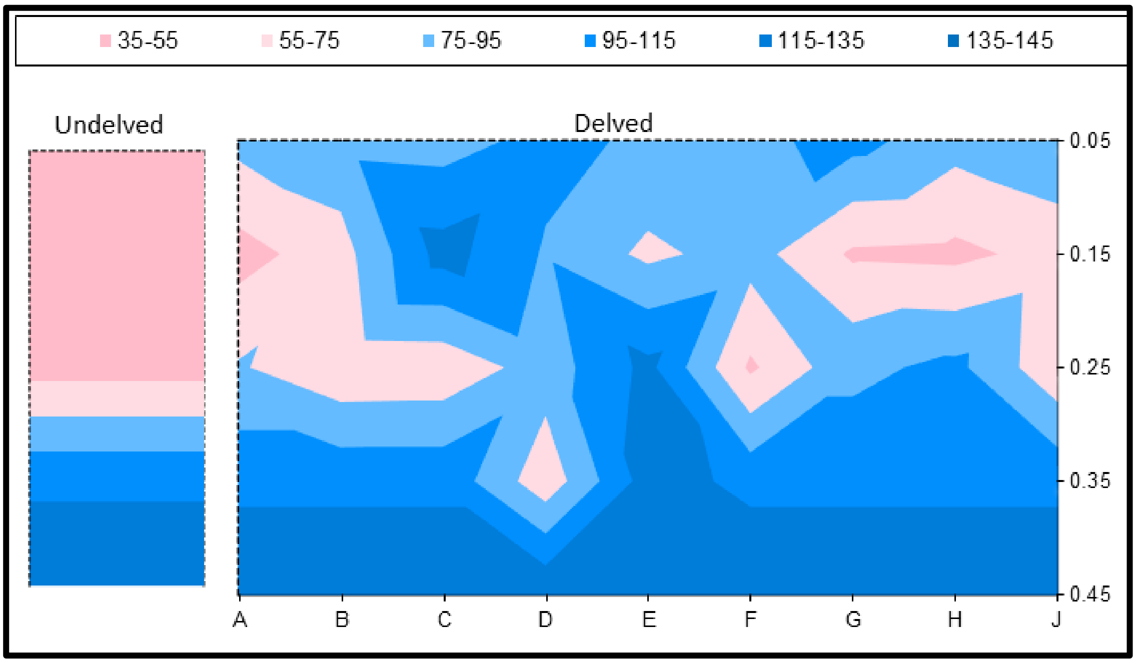

Fig. 2.19. Spatial variability of mean PAW (mm/m) in delved soil compared with a representative un-delved soil.

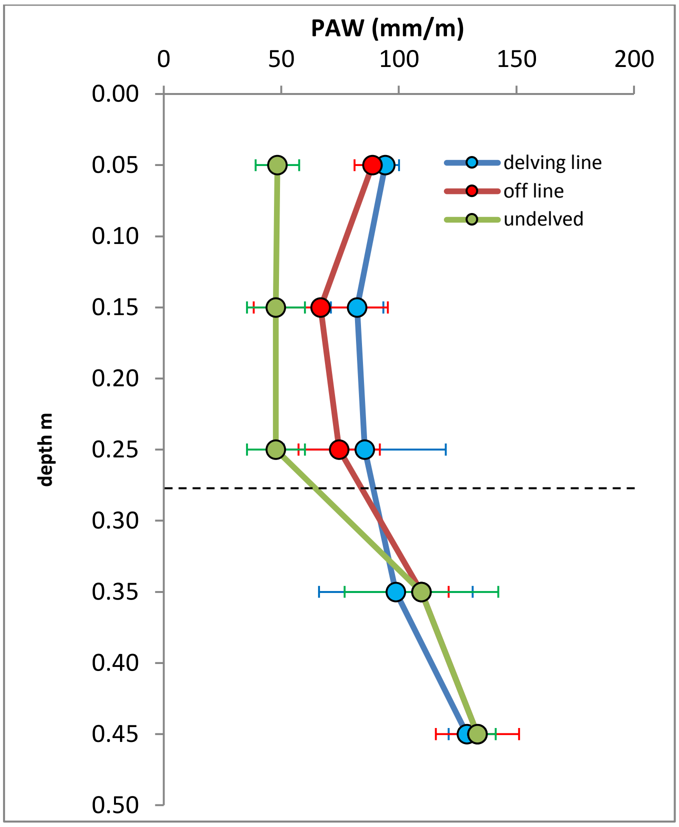

Fig. 2.20. Mean PAW as a function of depth in un-delved soil and in the delving-line and off-line regions of delved soil. The horizontal dashed line represents the approximate location of the boundary between the A and B horizons

In general, IWC increased rapidly with increasing clay content in all soil samples until the clay content reached 10%. Above 10% clay, IWC decreased significantly and in some cases it even declined to nearly zero. This is consistent with trends shown elsewhere in which plant available water is greatest in soils of loamy textures and less for heavy clays and least for sands (*e.g.* Marshall *et al.* 1996). **Fig. 2.22** shows IWC where each individual limiting factor is considered separately:

i) IWC_a, considering only poor soil aeration (**Fig. 2.22 a**),

ii) IWC_{ks}, considering only limitations due to high or low hydraulic conductivity (**Fig. 2.22 b**) and

iii) IWC_{sr} , considering only soil resistance to penetration as limiting factor (**Fig. 2.22 c**).

As with the IWC that included all limiting factors, the correlations between clay content and IWC_a, IWC_{ks} and IWC_{sr} were poor, regardless of whether the *Fine* and *Coarse* soil was distinguished, which confirmed the complexity and very heterogeneous texture and structure of the samples.

Nevertheless, the IWC_{sr} curve in **Fig. 2.22c** shows that soil resistance (SR) was the single most important limiting factor for plant available water with increasing clay content. In particular, the reduction in IWC_{sr} with increasing clay content was more strongly correlated in samples containing *Fine soil* (R^2=0.60) when compared to the samples containing *Coarse soil* (R^2=0.32), and is consistent with previous results in this thesis. Moreover, mean values of soil resistance can mask heterogeneity in soil strength found in binary matrices of hard/soft material, which plant roots can fully exploit (they do not travel in straight lines the way a penetrometer does); this is in contradistinction to the way plant roots cope with uniformly high values of soil strength.

The above arguments, of course, also apply to the other limiting factors present where aggregates are either finely or coarsely distributed in a binary mixture, and this is further discussed in **Chapter 5**, published as Betti *et al.* 2016.

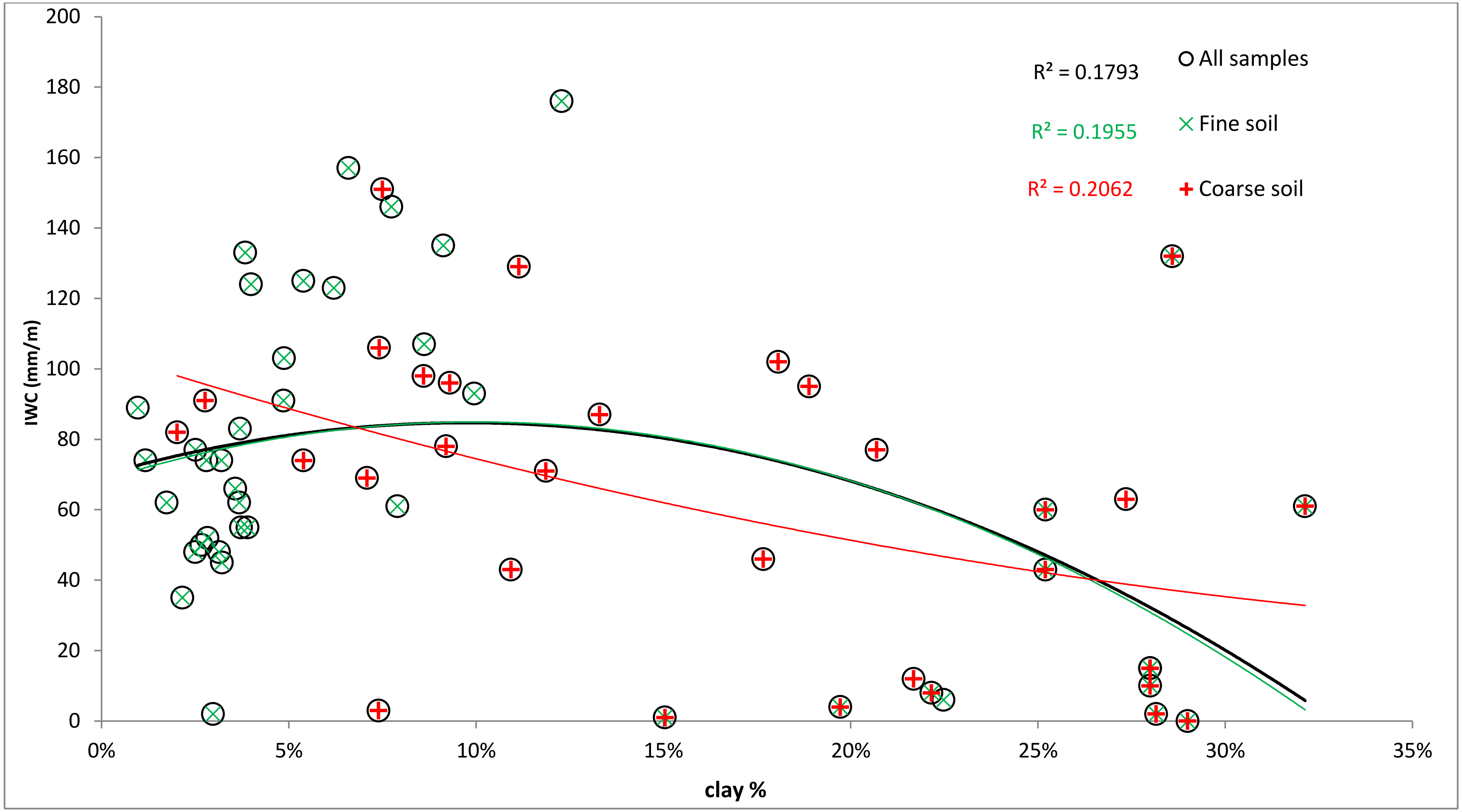

Fig. 2.21. Integral water capacity, IWC, as a function of increasing clay content

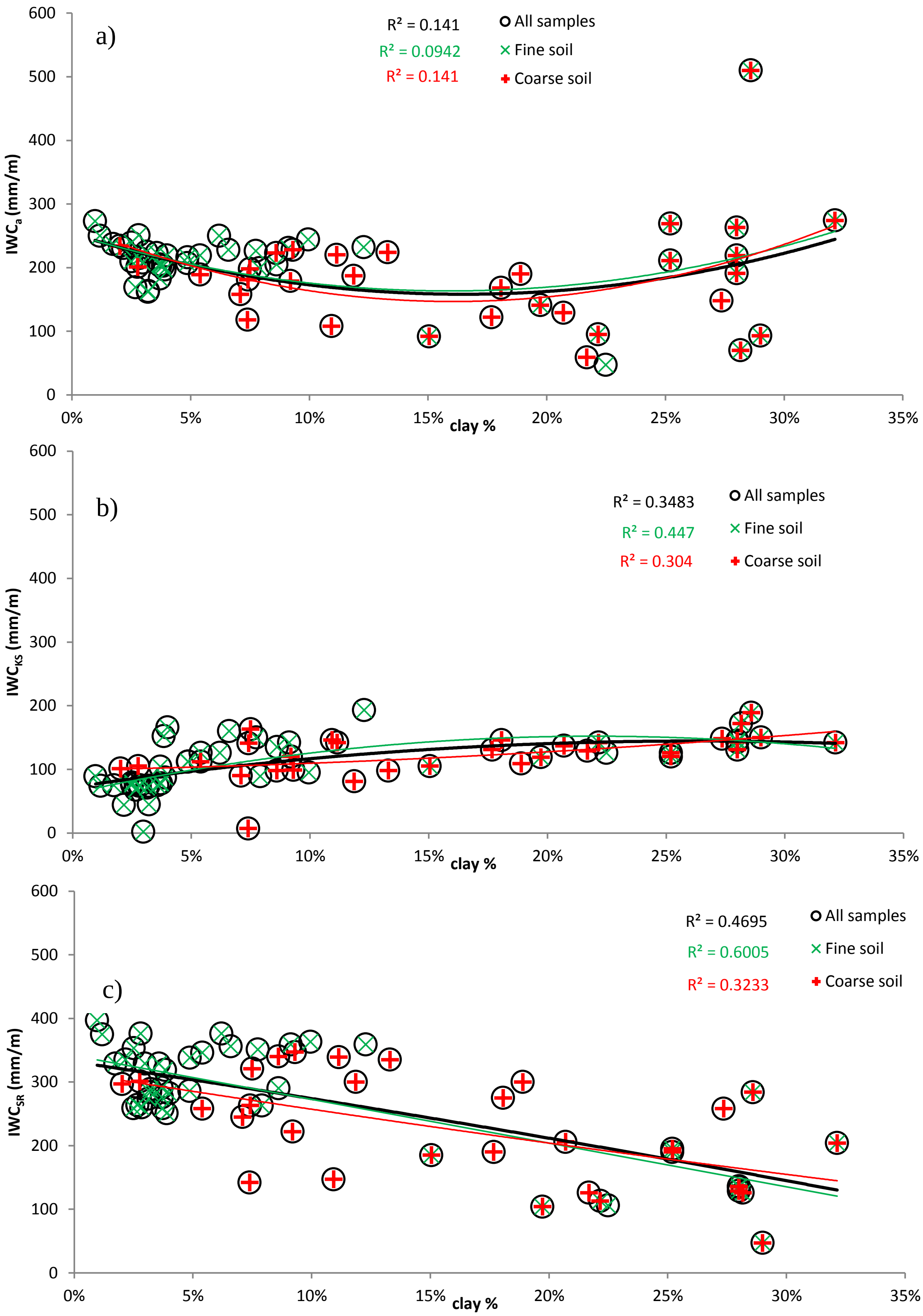

Fig. 2.22. Integral water capacity, IWC, as a function of clay content, taking into account the individual limitations: a) poor soil aeration, b) excessively large or small hydraulic conductivity, and c) large soil resistance to penetration.

Field transect scale

i) Soil sampling and field measurements

Table 2.2 shows the mean aggregate size distribution and clay contents from the samples collected in the top 0.1 m along the two field transects. The size distribution of the subsoil aggregates and mean clay contents in the topsoil of the entire delved profile were consistent with those obtained from samples collected in the representative delved profile at the same depth (**Table 2.1**). Comparing the off-line with the delving line regions, clay contents and the size distribution of aggregates were very similar, showing that the post-delving cultivation (executed perpendicularly to the clay delving; John E. Wilson personal communication) was indeed effective in uniformly distributing the subsoil clay in the A horizon.

Nevertheless, in the top 0.1m of the delving line region, the mean clay content was greater than in the off-line region and there were more large aggregates > 6.7mm (17.9% and 12.1% in the delving line versus the off-line regions respectively, **Table 2.2**). Using **Eqn 2-5** it was estimated that approximately 494 t ha^{-1} of subsoil was incorporated into the top 0.1m of soil, which is a very large amount considering that current guidelines recommend rates of only up to 300 t ha^{-1} (Davenport *et al*. 2011). The mass of subsoil incorporated on the delving line was even greater (**Table 2.2**); thus a very small difference in mean clay content (1.3%) between the delving-line and off-line regions requires a large difference in the mass of subsoil incorporated in the topsoil (80 t ha^{-1}).

The severity of soil water repellence in the A1 horizon of the un-delved soil measured by the WDPT method (**Table 2.3**) was classified as "strongly water repellent" (ranging from "strongly" to "severely" water repellent, Bisdom *et al*. 1993) with no significant differences between the 0-0.05m and 0.05-0.10m depths. Water repellence in the un-delved soil was very severe and highly variable, with values ranging from 380s to 800s. Delving of subsoil into the topsoil significantly reduced the severity of water repellence ($p < 0.05$); WDPTs for both the delving line and off-line regions were significantly less than for the un-delved soil with no significant differences between the two depths of sampling. No significant differences were also found between the two regions of the delved soil but the mean WDPT was lower and less variable in the delving line region than in the off-line region at both 0 – 0 .05m and 0.05 – 0.1m depths (smaller standard deviation in **Table 2.3**). These findings are consistent with the small differences in clay contents found between the two regions discussed above.

Table 2.2. Field-transect aggregate size distribution, average clay content and estimated mass of subsoil incorporated into the top 0.1m by delving. Values in parentheses are standard deviations

Region of soil profile	*Fine soil*			*Coarse soil*		Total Clay	Subsoil (t ha^{-1}) **Eqn 2-5**
	< 2mm	2-4.75mm	4.75-6.7 mm	6.7-20 mm	> 20 mm	%	
Off-line	82% (3%)	4% (1%)	2% (1%)	7% (0%)	5% (0%)	9% (1%)	452
Delving-line	78% (2%)	4% (0%)	2% (0%)	8% (0%)	7% (2%)	11% (1%)	572
Average profile	81% (3%)	4% (1%)	2% (1%)	7% (1%)	6% (2%)	10% (1%)	494

Table 2.3. Water drop penetration times (WDPT), severity of soil water repellence, and surface infiltration rates for un-delved soil and for the off-line and delving line regions of delved soil. Values in parentheses represent standard deviations; superscripts denote distinct data groups.

Parameter	Depth (m)	Un-delved	Delved regions	
			Delving-line	*Off-line*
WDPT (s) and severity of water repellence[1]	0 – 0.05	564^{a} (137) Strongly water repellent	32^{b} (29) Slightly water repellent	58^{b} (66) Slightly water repellent
	0.05 – 0.1	496^{a} (110) Strongly water repellent	11^{b} (10) Slightly water repellent	39^{b} (41) Slightly water repellent
Infiltration rate (mm h^{-1})	surface	256 (29)	276 (58)	242 (75)

[1]According to the classification of Bisdom *et al.* (1993)

Delving increased the average steady-state infiltration rate at the soil surface (particularly on the delving region) though not by a statistically significant amount (**Table 2.3**). It was nevertheless observed that the time needed for water to reach steady-state flow was much greater in the un-delved soil compared to the delved one, especially in the delving-line region. The greater time (and volume of water) required to reach steady state in the un-delved soil was, of course, related to its greater severity of water repellence.

Soil resistance increased with depth in the off-line region of the delved soil as well as in the un-delved soil (**Fig. 2.23**), reflecting the abrupt change in soil texture and structure encountered at the A/B horizon interface. In both delved and un-delved soils, soil resistance was < 2.5 MPa within the sandy A horizon, and in the top 0.1 m mean soil resistance in delved soil (both regions) was less than in the un-delved soils, although the difference was not statistically significant at $p = 0.05$.

In the A2e horizon (0.1 – 0.2 m) soil resistance increased with depth to as high as 2.5 MPa in both the un-delved soil and the off-line region of the delved soil. From approximately 0.23 m downward, where the subsoil started in both the un-delved and off-line region of delved soil, soil resistance exceeded 2.5 MPa (shown as a vertical dashed black line in **Fig. 2.23)**. On the delving line, by contrast, the changes in soil resistance with depth (especially from 0.24 to 0.45 m) were consistent with extensive morphological changes produced by delving. For example the ripping effect in the A2e horizon of the delving line region reduced soil resistance by up to 1 MPa compared to the off-line regions and the un-delved soil. The main area of reduced soil resistance corresponded to the V-shaped area right along the delving line. Here, the displacement of the clay subsoil, replaced by sandy material dropping from the A horizon, significantly reduced soil resistance by at least 2 MPa compared with the off-line region and the un-delved soil. Below this maximum depth of the delver (approximately 0.34 m), soil resistance increased abruptly to values > 2.5 MPa at depth of 0.39 m. The field penetrometer data clearly indicate that disrupting the A/B horizon interface and creating a V-shaped zone of mixed soil effectively increased the depth of soil accessible to roots by at least 0.2 m relative to the off-line region and the un-delved soil. The implications of soil resistance and other soil constraints for root growth are covered further in **Chapter 4**.

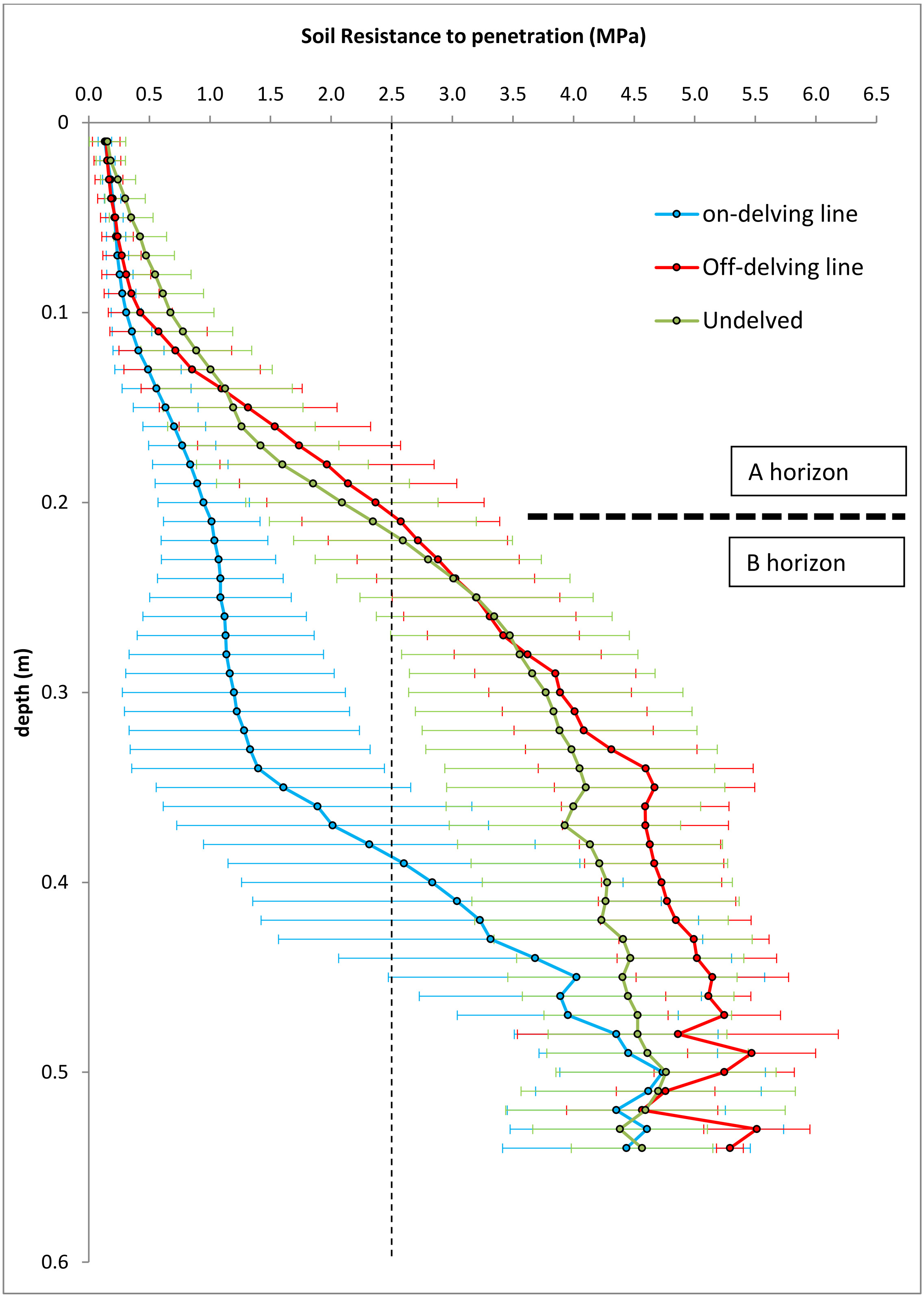

Fig. 2.23. Soil resistance in delved and un-delved soil measured under winter-wet conditions.

ii) Digital image analysis of delved soil profiles

The main morphological changes produced by clay delving occurred in the delving line region. The morphology of the topsoil in this region was most strongly altered, whereby the organic-rich A1 horizon sand was mixed with bleached A2e sand plus subsoil clay and then substantially re-distributed to depth. Digital images of the delved profiles were prepared to quantify the extent to which the soil from the A1 horizon was dispersed through the off-line and delving-line regions. The percentage of soil profile area occupied by the dark organic-rich sand from the A1 horizon is shown in **Fig. 2.24**.

As expected, larger differences were found between the delving-line and off-line regions. Most of the organic layer in the off-line region (and the un-delved soil) remained in the top 0.1 – 0.15 m. By contrast, the dark organic-rich A horizon soil was found at depths below 0.4 m on the delving-line regions. The mean total area of all the digital profile images occupied by the dark organic layer in the delving-line region was found to be significantly greater (176%; $p > 0.05$) than for the off-line region within the top 0.4 m of the profile. The organic layer was shown to be well mixed and dispersed over a large volume of soil, there being no other source of organic material.

The practical consequences of moving the organic-rich soil downward and the subsoil upward are important: the water repellent surface soil was diluted within a much larger volume of soil on the delving line region, in a way similar to the way spading and other types of cultivation reduce the effects of water repellence (Hall *et al*. 2009; Davenport *et al*. 2011). The greater dispersion of the water repellent organic soil also explains why the severity of water repellence was less variable, and the surface infiltration rate in the delving line region was somewhat greater (though not significantly at $p = 0.05$) compared to the off-line region. The implications of the morphological changes of the delved profile on soil profile wettability are further discussed in **Chapter 3**, published as Betti *et al.* (2015).

The distribution (% by volume) of the visible subsoil aggregates (nominal diameter >2mm) at 0.05m depth increments, as estimated from digital profile images is shown in **Fig. 2.25 (left)**. Subsoil aggregates were present in the profile to a depth of 0.05 – 0.4 m and their highest proportion by volume of soil was found at depths ranging 0.05 – 0.1 m and 0.1 – 0.15 m (12.8% and 1.6% respectively). The distribution by volume of the subsoil aggregates estimated from the digital images were very variable but also consistent with the results applying **Eqn 2-6** on the samples collected in the representative delved profile.

Nevertheless, both methods produced highly variable results, as shown by the large standard deviations in **Fig. 2.25**. The greater difference between the two estimates was found in the near surface soil (0 - 0.1 m) where digital images underestimated the presence of subsoil aggregates. This was not surprising, however, because identifying visible aggregates near the surface of the digital images was difficult (particularly in the top 0.05 m depth) due to the higher degree of soil disturbance and the presence of large pieces of organic material, such as plant stubble.

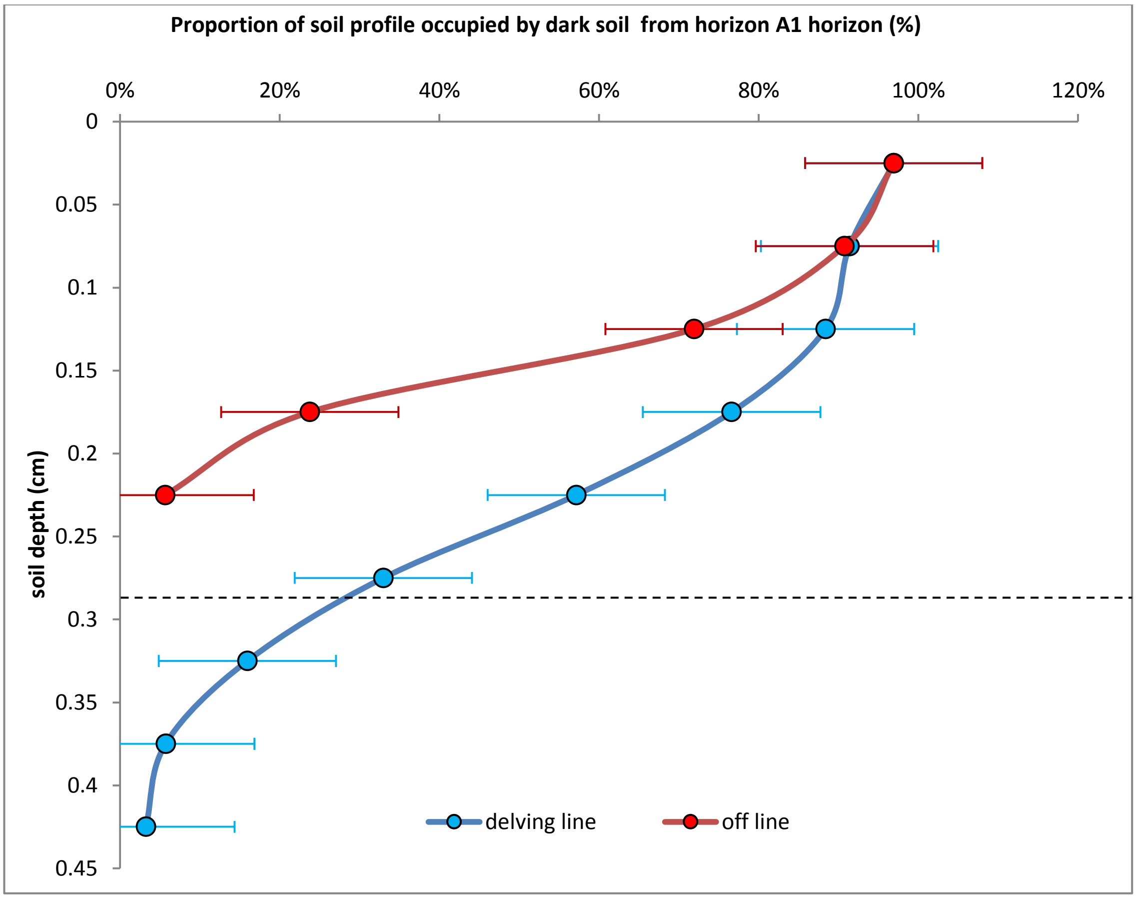

Fig. 2.24. Proportion of cross sectional profile area occupied by organic-rich soil from the A1 horizon in the delving-line and off-line regions of delved profile. Error bars are least significant differences The horizontal dashed line represents the approximate location of the boundary between the A and B horizons.

Comparison of the two main regions of the delved profile (**Fig. 2.25 right**) showed that the delving line region had significantly ($p > 0.05$) greater volume occupied by subsoil aggregates. The greatest proportion of visible aggregates in the entire delved profile was found in the delving-line region, particularly at 0.1 to 0.25 m, where aggregates occupied 15 – 20% of the soil volume. As expected, the visible aggregates in the off-line region were confined to the top 0.15 m of soil and on average did not exceed 12% of the total soil volume. Moreover, visual inspection of the digital images revealed that most of the aggregates found between 0.1 and 0.2 m in the off-line region (A2e horizon) were closer to (or in the vicinity of) the delving line region.

The digital images also showed that the greatest proportion by volume of visible aggregates comprised *large aggregates* (estimated nominal diameter > 6.7 mm, diamond markers), in particular at depth below 0.15 m (**Fig. 2.25, right**). Below this depth, mixing by post-delving cultivation was less effective and nearly all of the subsoil aggregates remained in large clods.

A quantitative analysis of the binary images of the B horizon in the delved soil is presented in **Table 2.4**. The binary images revealed that the mean depth at which the A/B horizon interface occurred was 0.22 m, with very little variation between the profiles (small standard deviations in **Table 2.4**). The maximum depth of clay delving (lowest part of the V-shaped area) was also quite uniform between the soil profile images. Clearly, the delving tines were quite effective at disturbing only the top 0.15 m section of the B horizon. Nevertheless, the disruption of the B horizon and the creation of V-shaped regions in the profile were highly variable in terms of both visual observations and the highly variable estimates of the quantities of subsoil moved from the V-shaped areas according to **Eqn 2-7** (i.e. 470 to 968 t ha^{-1}).

Table 2.4. Quantitative analysis of digital images of B horizon and V-shaped area of delved profiles (values in brackets are standard deviations)

A/B horizon interface depth (m)	Maximum Delving depth (m)	Equivalent depth of water in saturated V-shaped area (mm)	Equivalent mass of subsoil moved from V-shape area by delving (t ha^{-1})
0.22 (0.02)	0.37 (0.04)	16.2 (3.5)	687 (148)

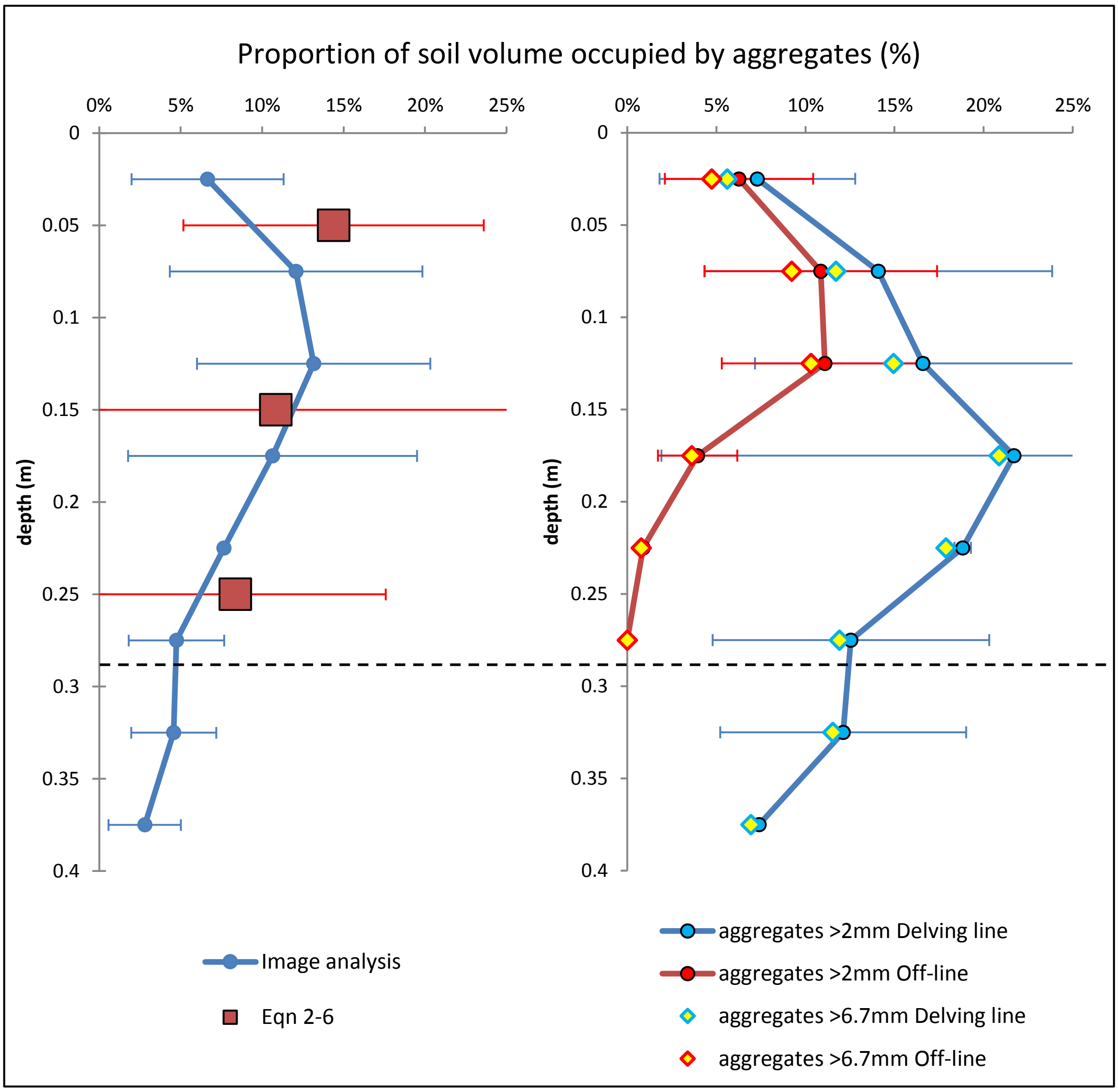

Fig. 2.25. Left: % subsoil aggregates in the delved profile estimated using **Eqn 2-6** and independently by digital image analysis. Right: % by volume of subsoil aggregates seen in the digital images for the two regions of the delved profile (delving-line and off-line) in two size groups: > 2 mm and > 6.7 mm. The horizontal black dashed line represent the approximate location of the A/B horizons boundary.

The quantity of subsoil clay was estimated by two methods (partly independent of each other): one using **Eqn 2-7** from the digital images of the V-shaped areas; the other obtained by combining digital image analysis with soil sampling. As previously noted, below 0.1 m (the region of post-delving cultivation) most of the subsoil aggregates had large (diameters > 6.7 mm), so it was assumed the proportion of subsoil aggregates that were not visible in the digital images in this region was negligible. **Eqn 2-7** was therefore used to estimate the average mass of subsoil aggregates (t ha^{-1}) below 0.1 m using the surface areas of the subsoil aggregates seen in the digital images. This result was combined with the estimated mass of subsoil clay within the top 0.1 m by applying **Eqn 2-5** to soil samples collected in the field (**Table 2.2**). The comparison in **Fig. 2.26** shows that although there was considerable variability in the two estimates, they were comparable in magnitude.

The combined method of using soil samples and digital images (red-blue column in **Fig. 2.26**) showed that delving incorporated 703 t ha^{-1} of subsoil aggregates into the top 0.4 m of the profile, which compared favourably to the 687 t ha^{-1} calculated by digital images alone. Thus approximately 70% of the subsoil delved from the B horizon ended up being incorporated into the top 0.1 m. Using the (far easier) digital image method over the very time-consuming soil sampling approach to estimate the effects of delving can thus be recommended.

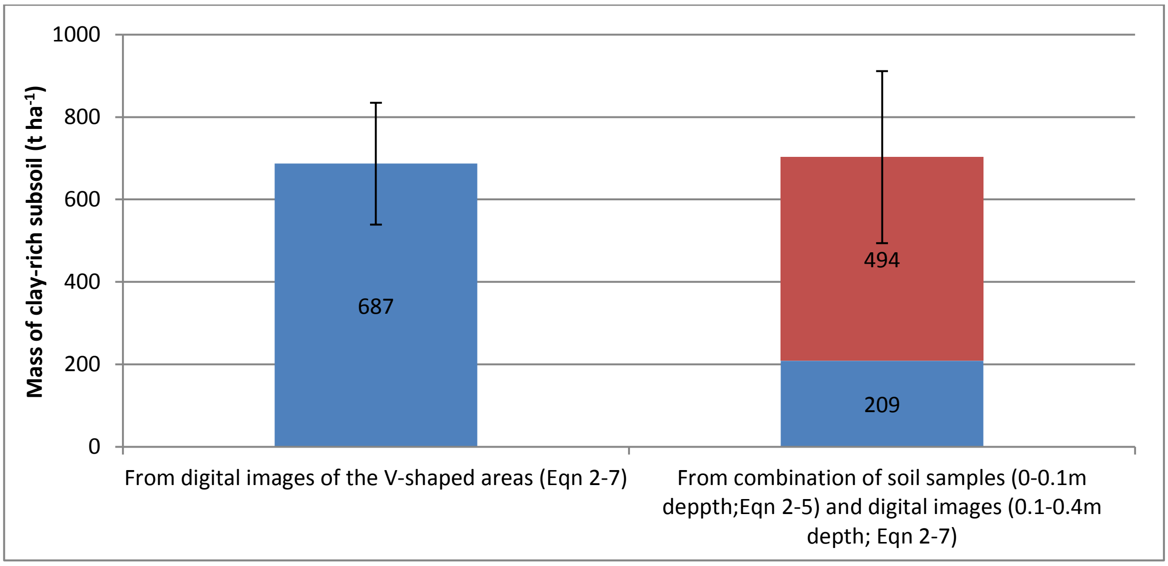

Fig. 2.26. Estimates of total mass of subsoil incorporated through the delved profile (blue columns show results from **Eqn 2-7** using digital images; red column shows results from **Eqn 2-5** using soil samples collected from the top 0.1m of soil)

It was originally hypothesised that the V-shaped zone created below the A/B interface would facilitate greater downward movement of water during saturating events (which occasionally occur in winter), and thus reduce waterlogging in the plant root zone. Using **Eqn 2-8** supports this hypothesis, whereby the V-shaped areas in the delved profile produced sufficient pore space to accommodate between 11 and 23 mm of water (average of 16 mm, **Table 2.4**). This is comparable to about 10% of the total thickness of the shallow A horizon, and although 16 mm is a modest amount of water, even small reductions in the depth and duration of saturated conditions in the upper 0.3 m can significantly influence root growth (McFarlane *et al*. 1989; McFarlane and Cox 1992; Rameshwar *et al.* 1988). Of course, delving has also been found to increase lateral movement of water in the V-shaped zone, so the above estimates represent the minimum benefits of delving. It is possible that slight modifications to the depth and direction of delving may therefore reduce water ponding in the soil profile in quantities that are comparable to installing artificial agricultural drain lines (McFarlane and Cox 1992).

2.3 Conclusions

One of the main reasons for clay delving is to ameliorate the properties of the sandy topsoil (hydrophobic, low water retention) by bringing up and incorporating the subsoil from the B horizon (hydrophilic, high water retention). The extensive morphological disruption produced by clay delving in texture-contrast soils effectively produces an entirely new soil profile. Compared to an un-modified texture-contrast soil, where the soil physical properties change drastically with abrupt changes in soil texture, the extensive morphological changes in delved soils create enormous (and highly variable) changes in soil physical properties (both vertically and horizontally). This study showed that combining clay delving with surface cultivation incorporated very large quantities of subsoil clay (at least 500 t ha^{-1}) in the top 0.1 m of soil. Incorporating subsoil significantly increased the mean clay content of the top 0.1 m by 2 to 10%, and drastically altered the morphology of the region directly under the delving-line; this region contained more and larger subsoil aggregates and very large clods at depth compared with the off-line regions.

Addition of subsoil clay significantly reduced water repellence (Bisdom *et al*. 1993) from 'strongly' to 'slightly' non wetting; infiltration rates were reduced from excessively large values to far more modest values (explored in **Chapter 3**), and plant available water was increased despite significant increases in mean soil resistance. Greater soil strength, however, was attributed to the penetrometer encountering more large clay clods in the delved regions, and this was dismissed as a problem for plant water uptake because roots can grow around large, impenetrable clods of clay while still extracting water from them (even though they may expend more carbon/energy doing so). In comparison to the off-line region where the texture-contrast is unaltered, the V-shaped zone significantly reduced soil resistance below the A/B horizon interface depth, as measured by a field penetrometer and on undisturbed soil samples. The implications for plant root growth are covered in **Chapter 4**. A more detailed analysis of the effects of larger clods on soil physical properties and plant available water was undertaken in the laboratory (**Chapter 5**, published as Betti *et al*. 2016).

By combining traditional field sampling measurements with quantitative analysis of digital images of delved soil profiles, good estimates of the amounts of clay moved within soil profiles were obtained; furthermore, the method of digital image analysis was confirmed as a superior alternative to the far more laborious manual soil sampling. Digital characterisation simply required an initial identification of two morphologically distinct regions in the delved profile: a delving-line region, which was strongly altered by delving, and two off-line regions either side of line, which were only modestly altered. Using image analysis proved to be a valid method for rapid assessment of the approximate amount of subsoil (t ha^{-1}) the clay delving brought to the topsoil from the B horizon. By this technique, the V-shaped area was shown to reduce the depth of water ponding above the B horizon by as much as 20 mm, mainly by creating extra pore space via back-filling, even though delving did not increase the infiltration properties of the undisturbed B-horizon below. In shallow, texture-contrast soil greater lateral movement of water plus a reduction in water-logging, has potential to greatly enhance root growth in delved soils.

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Chapter 3 Increased profile wettability in texture-contrast soils from clay delving: case studies in South Australia

Published as Betti *et al.* 2015

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Principal Author

Name of Principal Author (Candidate)	Giacomo Betti		
Contribution to the Paper	Devised, designed and conducted all the experimental work in consultation with co-supervisors, assembled and processed all the data, interpreted the data and drafted the paper.		
Overall percentage (%)	90%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	6 September 2018

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Cameron D Grant		
Contribution to the Paper <u>5%</u>	I was principal supervisor of the candidate along with Churchman and Murray. I discussed the nature of the problem, the design of the experiments and the results and outcomes. I read drafts of the manuscript and made minor suggestions/corrections before submission to the journal. I also acted as corresponding author for the paper and dealt with minor corrections in consultation with the candidate, who had left the University to take up a job in WA.		
Signature		Date	6 September 2018
Name of Co-Author	Gordon Jock Churchman		
Contribution to the Paper <u>2.5%</u>	I was co-supervisor of the candidate along with Grant and Murray. I discussed the nature of the problem, the design of experiments and the results and outcomes. I read drafts of the manuscript and made minor suggestions/corrections before submission to the journal.		
Signature		Date	6 September 2018
Name of Co-Author	Robert S Murray		
Contribution to the Paper <u>2.5%</u>	I was co-supervisor of the candidate along with Grant and Churchman. I discussed the nature of the problem, the design of experiments and the results and outcomes. I read drafts of the manuscript and made minor suggestions/corrections before submission to the journal.		
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Increased profile wettability in texture-contrast soils from clay delving: case studies in South Australia

Giacomo Betti[A], *Cameron Grant*[A,B], *Gordon Churchman*[A], *and Robert Murray*[A]

[A]Waite Research Institute, School of Agriculture Food and Wine, University of Adelaide, PMB 1 Glen Osmond, SA 5064, Australia.
[B]Corresponding author. Email: cameron.grant@adelaide.edu.au

Abstract. Clay delving is becoming a popular practice to increase productivity of texture-contrast soils in southern Australia. The practice brings subsoil clay to the surface to be mixed with the sandy topsoil, and unlike clay spreading, it combines the addition of hydrophilic material with a ripping effect that disrupts the sharp boundary between the sandy topsoil and clayey subsoil. Our objective was to evaluate the magnitude of effects caused by delving on the spatial distribution of water through the profile for three Sodosols (Stagnic Solonetz soils) in the south-east of South Australia. We also wished to evaluate the extent to which clay delving might reduce water ponding at the A–B horizon interface. We wetted both delved and undelved texture-contrast soils with a Brilliant Blue dye solution under initially dry and wet conditions (to evaluate the effect of antecedent water content), and then took digital images of the stained profiles for quantitative comparison of the wetted areas.

The stained soil profiles indicated that clay delving reduced preferential water flow (finger flow) and resulted in deeper and more uniform wetting of the A horizon, particularly under initially dry conditions. Under wet conditions (where water repellence was largely overcome), finger flow was significantly reduced regardless of delving but it still occurred to varying degrees depending on site characteristics. Delving significantly reduced ponding of water at the A–B horizon boundary and allowed greater penetration into the B horizon. At all sites, greater effects occurred directly on the delving lines and diminished with distance, implying that closer spacing of delving tines would increase uniformity of wetting throughout the profile. The effectiveness of delving on profile wetting was highly variable across the three sites, indicating that the outcome depends *inter alia* on the intrinsic soil characteristics and the delving equipment used in the field.

Additional keywords: duplex soil, dye tracer, soil modification, soil water, water-repellent sand.

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Introduction

Texture-contrast soils (Isbell 2002) cover ~20% of Australia and many are intensively cropped (Chittleborough 1992). For example, in southern South Australia, ~1.6 Mha of texture-contrast soils (historically called ‘duplex’ soils, with bleached A2 horizons; Northcote 1979) are used for broadacre agriculture and horticulture. In the south-western agricultural area of Western Australia, texture-contrast soils occupy 57% of the total area (Tennant *et al*. 1992), and in Victoria ~1 Mha of these soils are cultivated (McGuinness 1991). Texture-contrast soils have a ‘clear or abrupt textural B horizon’ (Isbell 2002) where a strong change in clay concentration occurs between two horizons, normally with a sharp boundary between the A and the B2t (National Committee on Soil and Terrain 2009).

The sharp boundary between the sandy A horizon and the heavy clay B horizon creates physical conditions that limit annual crop productivity (Barrett-Lennard and Nulsen 1989). The surface of the sandy A horizon is often water-repellent and has a low water-holding capacity and low chemical fertility. Poor water penetration at the surface is also accompanied by finger flow and uneven water redistribution throughout the profile (Imeson *et al*. 1992; Ritsema and Dekker 2000; Hardie *et al*. 2011). Ironically, the clayey subsoil is often hydraulically impermeable, which means that it becomes waterlogged during winter and structurally hard and impenetrable by roots in spring. Roots are thus largely restricted to the physically and chemically infertile A horizon (Edwards 1992). Compared with soils having gradational profiles, the texture-contrast profile creates a ‘permeability contrast’, with two distinct regions of soil having extremely different hydraulic properties (Tennant *et al*. 1992). Poor drainage and perched watertables are common during wet seasons (Cox and McFarlane 1990), and in higher rainfall regions of Western Australia, waterlogging on texture-contrast soils is considered the main limiting factor in agricultural production (Bakker *et al*. 2010).

The problem of surface water repellence can be overcome by clay spreading, and much good work has been conducted over the last two decades to optimise this practice (Ma’shum *et al*. 1989; Cann 2000; Doerr *et al*. 2000; Franco *et al*. 2000; McKissock *et al*. 2000; Dekker *et al*. 2005; Rebbeck *et al*. 2007; Wallach and Jortzick 2008; Bailey *et al*. 2010; Hall *et al*.

2010; Davenport *et al*. 2011; Müller and Deurer 2011). Clayey subsoil is simply transported and spread over a water-repellent soil surface then mixed into the topsoil.

The low water-holding capacity of the A horizon and the impenetrable nature of the B horizon, however, are not overcome by surface clay spreading alone. A much more disruptive practice called 'clay delving' was proposed in 1990s (e.g. Desbiolles *et al*. 1997) and used particularly in recent years to increase the volume of the root-zone and to overcome the fertility and hydrological problems with texture-contrast soils (May *et al*. 2006; Bailey *et al*. 2010; Davenport *et al*. 2011). Clay delving uses two, three or four wide tines (typically 0.2 m) inclined at ~45° and spaced ~1 m apart and able to work to a depth of ~0.6 m (Davenport *et al*. 2011; Desbiolles *et al*. 1997) or deeper. The operation breaks through the hard A–B horizon interface and redistributes clayey subsoil upward into the root-zone and onto the soil surface (May *et al*. 2006); the modified soil profiles are physically and chemically different from the original soil in both vertical and lateral directions (Fig. 1).

Delving can increase crop yields (Cann 2000; May *et al*. 2006; Rebbeck *et al*. 2007; Davenport *et al*. 2011) and the practice has been widely adopted across many agricultural regions where texture-contrast soils occur. Delving reduces surface water repellence and can reduce mechanical impedance to root growth by breaking through the physical barrier at the A–B horizon boundary. However, improvements in yield have not been reported across all studies (Davenport *et al*. 2011). This may be due to the variable effects of delving on soil physical properties, particularly water movement and storage. The complex nature of texture-contrast soils (e.g. variable depth of the A horizon) means that the effects of delving are rarely uniform, and this makes it difficult to optimise practices.

The scientific literature on the effects of delving on soil hydraulic properties is sparse, so this study was designed to quantify and evaluate the changes in infiltration brought about by delving at three different sites in South Australia. Our two primary objectives were: (*i*) to evaluate the effect of delving on infiltration patterns in some water-repellent, texture-contrast soils at high and low initial soil moisture contents; and (*ii*) to evaluate the effect of delving on reducing the occurrence of ponding at the A–B horizon boundary.

Materials and methods

Site locations and characteristics

The experiments were conducted at three sites in the south-east of South Australia: site A, near Coonalpyn (35°41′28″S, 139°53′05″E); site B, near Bordertown (36°12′52″S, 140°42′08″E); and site C, also near Coonalpyn (35°44′06″S, 139°55′46″E). The climate of the region is Mediterranean, with warm summers and cool winters. Average annual rainfalls are 450 and 429 mm at Coonalpyn and Bordertown, respectively (Bureau of Meteorology 2013*a*). All three sites have sandy topsoils of varying thickness with an A2e bleached horizon over a sandy clay loam subsoil (Coonalpyn, sites A and C) or sandy clay subsoil (Bordertown, site B). The soils are shown in Fig. 2 and classified as Brown Sodosols (Australian Soil Classification; Isbell 2002) or Stagnic Solonetz (WRB 2007). The boundary distinctness between the A and B horizons was abrupt to clear (boundary width up to 50 mm) at all sites. However, the shape of the boundary at sites A and C was generally smooth, whereas at site B the shape of the boundary was irregular to tongued (National Committee on Soil and Terrain 2009) with some deep cracks filled with sand from the A2e horizon.

The management and yield histories for sites A and B (before and after delving) were provided by local growers (Table 1) and consisted typically of barley (*Hordeum vulgare*) and wheat (*Triticum* spp.) rotations or annual pastures. Sites A and C were delved in 2007 and 2009, respectively, to an average depth of 0.55 m with large (wide) delving tines spaced 0.9 m apart. Site B was delved in 2005 to an average depth of 0.45 m with small (narrow) delving tines spaced 1.2 m apart.

Selected soil properties for the three sites were measured on samples from the original, undelved profiles (Table 2). From each horizon, 10 undisturbed cylindrical soil cores (0.05 m high, 0.05 m diameter) were collected to measure bulk density. Average particle-size distribution for each horizon was estimated on three replicas from bulk samples by using a

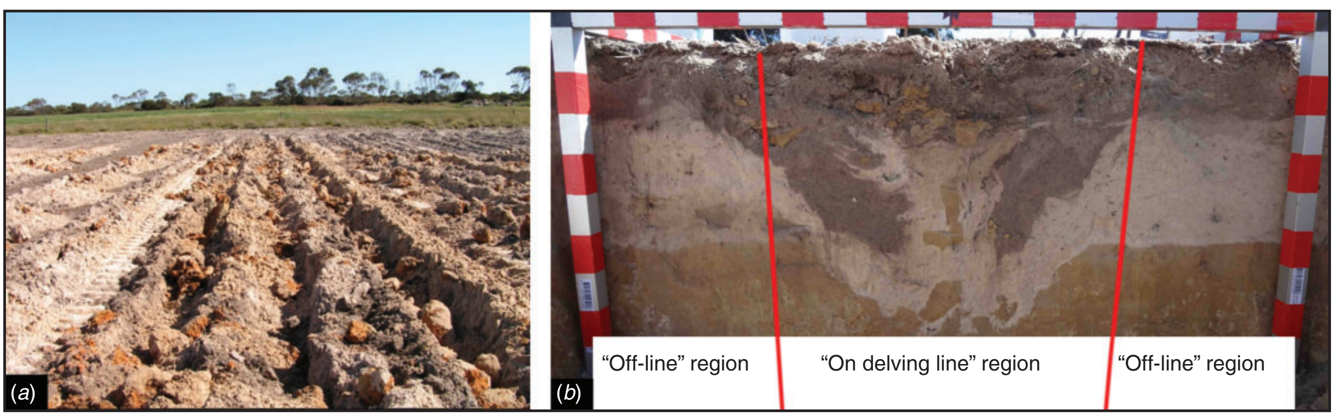

Fig. 1. (*a*) Typical soil surface immediately after delving; (*b*) delved soil profile (site A, Coonalpyn, South Australia). The frame in the photograph shows 0.05-m increments.

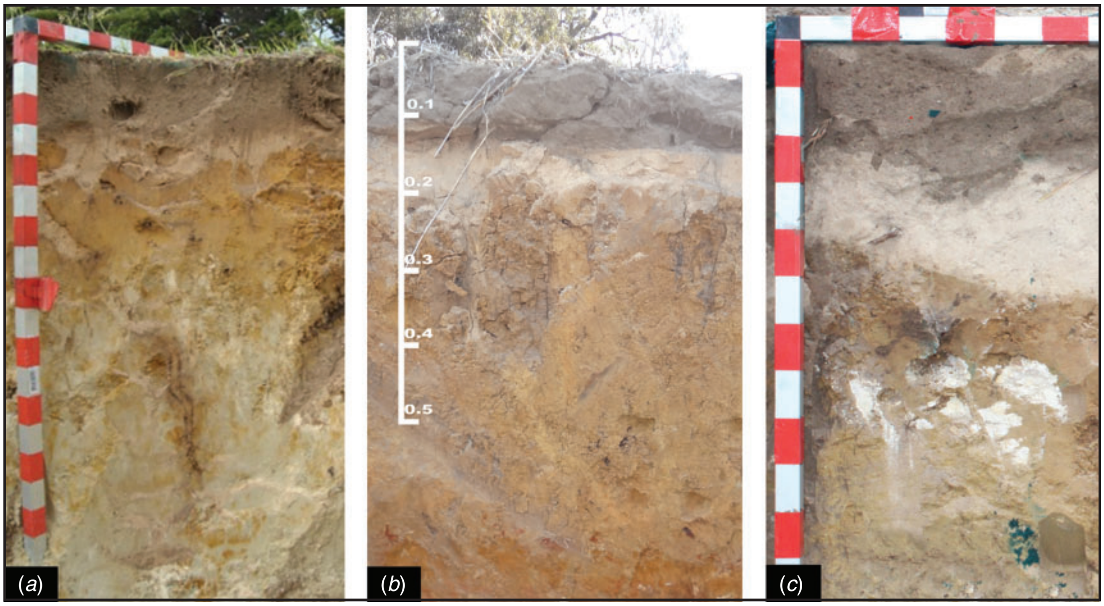

Fig. 2. Soil profiles at the experiment sites: (*a*) site A, Coonalpyn; (*b*) site B, Bordertown; (*c*) site C, Coonalpyn. The frame in the photographs shows 0.05-m increments.

Table 1. Yield history at site A and B

Values in bold represent average annual yield after clay delving. Before clay delving, site B was used as a rotation with wheat, lupins and pasture. Sunflowers, *Helianthus annuus*; lentils, *Lens culinaris*; beans, Fabaceae; canola, *Brassica napus*

Year	Site A			Site B		
	Total annual rainfall (mm)	Crop	Yield (t ha^{-1})	Total annual rainfall (mm)	Crop	Yield (t ha^{-1})
2012	**440**	**Wheat**	**3.7**	**377**	**Pasture**	–
2011	**461**	**Sunflowers**	**1.3**	**493**	**Barley**	**3.5**
2010	**566**	**Wheat**	**5.7**	**591**	**Wheat**	**4.2**
2009	**441**	**Lentils**	**0.7**	**422**	**Canola**	**1.2**
2008	**407**	**Barley**	**2.6**	**334**	**Barley**	**3.0**
2007	413	Beans	2.7	**463**	**Wheat**	**3.2**
2006	284	Wheat	0.9[A]	**236**	**Pasture**	–
2005	412	Beans	2.7	429	Wheat	2.1
2004	425	Barley	1.5	438	Lupins	1.6
2003	463	Barley	4.1	501	Pasture	–
2002	349	Lentils	0.6		n.a.	
2001	459	Barley	3.1		n.a.	
2000	457	Canola	1.4		n.a.	
1999	385	Wheat	2.1		n.a.	

[A]Frost damaged.

modified version of the pipette method of Smith and Tiller (1977). The severity of water repellence of the surface sand was assessed in the laboratory on the 10 undisturbed (air-dry) samples collected from the field according to methods outlined in Dekker *et al.* (2009), using the water-drop penetration time test (WDPT; Letey *et al.* 2000). Average saturated hydraulic conductivity was measured on the same cores used to estimate the bulk densities, immersing them in water for up to 5 days and then using a constant head method.

The average steady-state infiltration rate at the soil surface was estimated in the field by inserting four single metal rings (0.15 m high, 0.3 m diameter) to a depth of 0.02 m (Reynolds and Elrick 1990; Erickson *et al.* 2013) at random locations over the delving lines, off the delving lines, and in undelved soil. The infiltration rate was approximated (after the soil was wetted for periods exceeding the WDPT readings) by timing the water level as it declined ~5 cm from the top of the ring. Although this method risks underestimating the infiltration rate when water repellence persists in the field for longer periods (e.g. Dekker and Ritsema 1994; Vogeler and Magesan 2000; Hardie *et al.* 2012), we considered the method suitable for comparative purposes because the readings were taken after wetting the soils for periods exceeding the WDPT values.

Soil staining and soil profile images

At each site, areas of the paddock were chosen to represent the original, undelved soil profile and the delved soil profile. The sampling points for the undelved controls were close enough to the delved soil (within 20–50 m) that the soil type and cropping histories were considered the same. A representative area of the delved profile was selected and a transect was made perpendicular across the delving lines with a delving line at the centre. The size of the representative modified profile, 0.9 m wide by 0.6 m deep, was chosen to include the most common distance between the delving lines and the most common delving depth. The representative area was subsequently divided laterally into two regions based on the visual pattern following soil modification (Fig. 1*b*): (*i*) a central region called ‘on-delving-line’, where the delving tine produced the most significant soil disturbance down the profile; and (*ii*) a region called ‘off-line’, which included the two areas either side of the delving line where there was less soil disturbance, mainly near the soil surface. The soil disturbance in this off-line region was similar to that typically induced by

Table 2. Soil properties at undelved experimental sites

Bulk density values are an average of 10 replicas (values in parentheses are standard deviation). EC, Electrical conductivity

Horizon	Depth (m)	A–B horizon boundary (distinctness, shape)	Bulk density ($g\,cm^{-3}$)	Clay ($g\,kg^{-1}$)	Sand ($g\,kg^{-1}$)	pH (1 : 5 H_2O)	EC ($dS\,m^{-1}$) (1 : 5 H_2O)
			Site A				
A1	0–0.10	Sharp to abrupt,	1.56 (0.05)	14	973	6.2	0.02
A2e	0.10–0.20	smooth	1.68 (0.01)	9	979	5.9	0.01
B21t	0.20–0.35		1.75 (0.03)	282	708	7.1	0.04
B22t	0.35–0.60		1.73 (0.01)	410	561	7.5	0.09
			Site B				
A1	0–0.15	Sharp to abrupt,	1.42 (0.08)	51	923	6.6	0.08
A2e	0.15–0.22	irregular to tongued	1.60 (0.02)	15	975	6.4	0.03
B21t	0.22–0.34		1.78 (0.04)	369	614	8.1	0.12
B22t	0.34–0.70		1.81 (0.01)	438	496	8.2	0.11
			Site C				
A1	0–0.15	Sharp to abrupt,	1.40 (0.01)	43	953	7.6	0.08
A2e	0.15–0.25	smooth	1.51 (0.05)	22	948	7.3	0.04
B21t	0.25–0.40		1.64 (0.02)	206	788	7.1	0.06
B22t	0.40–0.90		1.71 (0.03)	149	844	7.4	0.04

the simple practice of clay spreading at the soil surface. The experiments were conducted in summer (‘dry’ conditions, after a long period without rainfall that penetrated the surface—at sites A and B in January and February 2012 and at site C in January 2013), and again in midwinter (‘wet’ conditions, in August 2012) at sites A and B only. At site B, the topsoil was drier than expected in winter and was highly water-repellent. A pre-treatment of 100 mm artificial rainfall over 48 h before staining was considered sufficient to re-establish wet conditions required for the experiment throughout the soil profile.

A solution containing 25 mm of water-soluble blue dye, Brilliant Blue FCF (a highly visible, low-toxicity, food colourant (Flury and Flühler 1994) was applied to the soil surface using a purpose-built rainfall simulator (with drip irrigators on a reciprocating tube, which was fed using a DC 12 V pump) placed on an area 1.05 m by 1.05 m for 2 h (average intensity 11.3 $mm\,h^{-1}$, with typical return period of 2–5 years (Bureau of Meteorology 2013*b*). The concentration of blue dye used in the ‘dry’ period treatments was 6 $g\,L^{-1}$ and in the ‘wet’ period treatments 8 $g\,L^{-1}$, based on the work of Hardie *et al.* (2011). Volumetric water contents of the ‘dry’ and ‘wet’ soil profiles were determined before dye staining (Table 3). After dye application, the soils were left for 24 h to allow hydraulic redistribution.

At each site, five or six vertical profile slices (replicates) were excavated at intervals of 0.15–0.20 m, first using a backhoe, and then manually refined. A metal-framed grid (0.9 m wide by 0.6 m high) was positioned against the surface of each vertical profile and photographs were taken with a digital SLR camera, using both manual and automatic settings at maximum resolution in RAW format. Following the method proposed by Ogawa *et al.* (2000) and adapted by Hardie *et al.* (2011), each photo was corrected for lens distortion and perspective with Gimp© (www.gimp.org/) and Photoshop© CS (www.adobe.com/au/products/photoshopfamily.html) computer software packages, and using the metal-framed grid as a spatial reference (Fig. 3*a*). The corrected images were transformed into CMYK (cyan, magenta, yellow, black) colours, which allowed the wetted areas (dye-impregnated) to be distinguished as cyan relative to the non-wetted areas using the cyan-only channel and eliminating the other channels. The images were saved to grey-scale format (.TIFF) and converted to a binary format using Image J© 64 software (http://imagej.nih.gov/ij/), in which the black areas represented the portion of wetted (dye-stained) soil and the white areas represented the dry (unstained) soil (Fig. 3*b*). The images were divided into 0.02-m depth increments and the proportion of dye-stained (wetted) soil was calculated for each vertical slice of the profile; an example is shown in Figs 3*c* and 4. The images for the delved soil were then separated into the two distinct regions of modified soil (equally sized at 0.45 m wide by 0.9 m high): the on-delving-line and off-line regions (Figs 3 and 4). The proportions of wet soil (dye-stained) from those two regions and from the undelved region were compared quantitatively. This comparison was supported by statistical analysis of variance, taking into account three sources of variation: treatment (undelved, on-delving-line and off-line regions), soil horizon (A1, A2, B21 and B22), and the interaction between treatment and horizon. A two-way analysis of variance (ANOVA) was conducted using GENSTAT® software (15th edn; VSN International: Hemel Hempstead, UK).

Table 3. Average volumetric soil-water content ($m^3\,m^{-3}$) before infiltration with blue dye

Horizon	Site A		Site B		Site C
	Dry conditions	Wet conditions	Dry conditions	Wet conditions	Dry conditions
A1	0.04	0.16	0.04	0.22	0.04
A2e	0.03	0.18	0.03	0.21	0.03
B21t	0.10	0.26	0.18	0.26	0.14
B22t	0.13	0.24	0.29	0.28	0.15

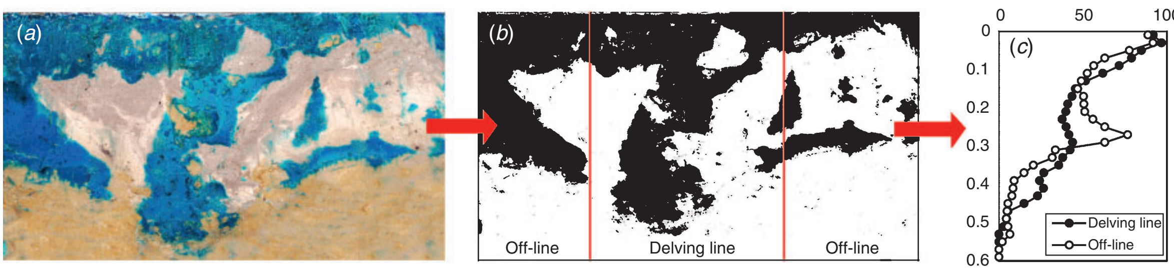

Fig. 3. (*a*) Digital photograph of a blue-stained wetted profile; (*b*) digital image converted to binary black and white image, where black areas represent wetted soil; (*c*) proportional area of the soil profile that was wetted with blue dye (*y*-axis, soil depth, m; *x*-axis, proportion of stained soil, %).

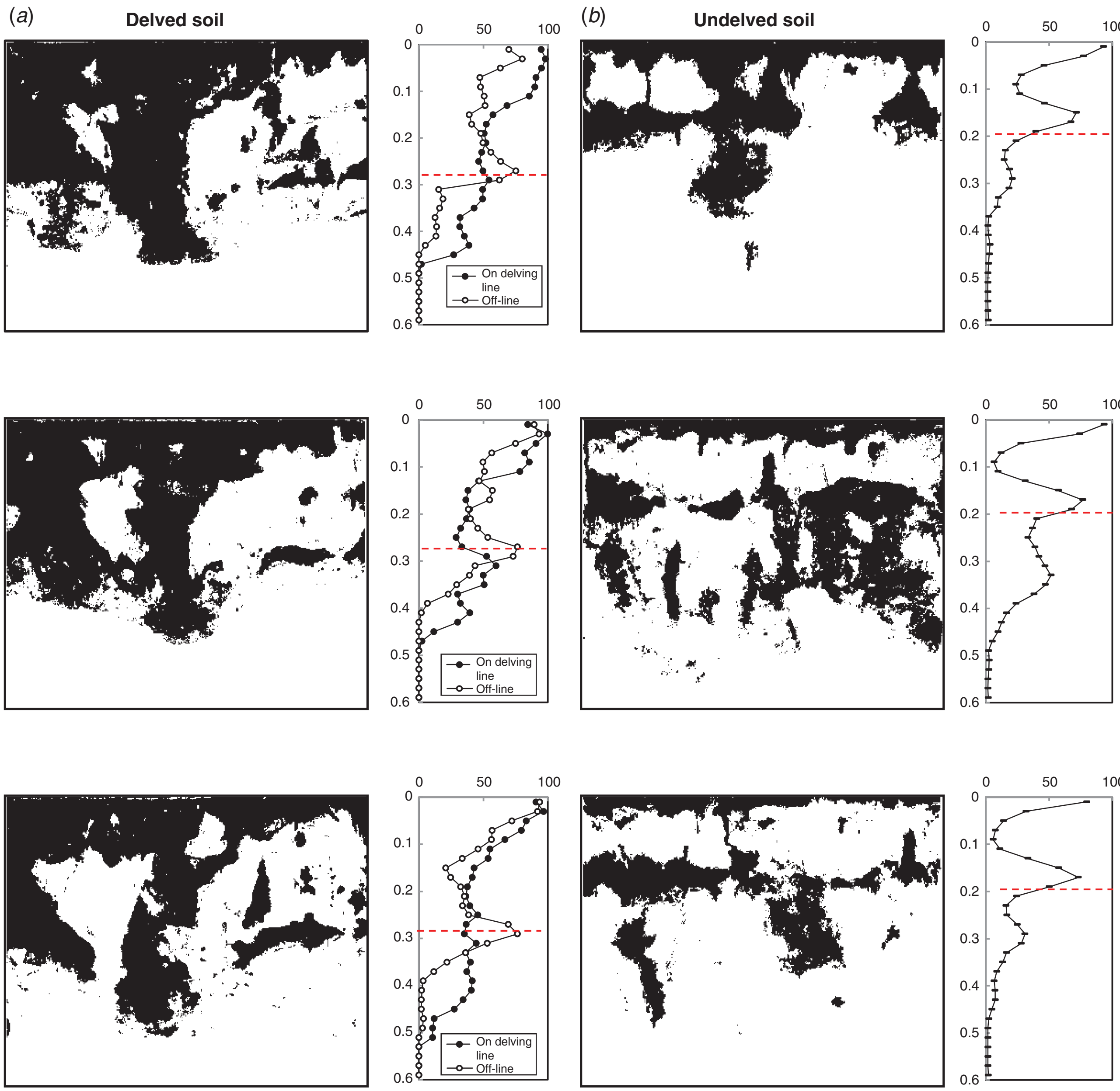

Fig. 4. Examples of binary images from three replica slides at Coonalpyn, site A, from (*a*) delved and (*b*) undelved soils after applying blue dye solution under dry (summer) conditions. The graphs at the right side of each profile represent the proportional area of the soil profile that was wetted with blue dye (*y*-axis: soil depth, m; *x*-axis: proportion of stained soil, %). The horizontal dashed line represents the location of the boundary between the A and B horizons.

Results and discussion

All three sites displayed water repellency in the A1 horizon, and this was particularly severe at sites B and C (Table 4). Delving significantly increased the average steady-state infiltration rate at the soil surface (on the delving line) at site C, and increased this rate at site A but not by a statistically significant amount; there was no apparent effect of delving on infiltration at site B (Table 4). The dye-stained soil profiles were evaluated separately and they are presented below.

Coonalpyn, site A

In the delved soil, the dye staining was consistent with the infiltration results shown in Table 4 in which greater depths of infiltration corresponded with greater infiltration rates along the delving lines. At this site, the thickness of sand over the B horizon varied somewhat across the field (across the delving treatments); for the undelved treatment, the B horizon occurred at ~0.2 m, whereas for the delved soil, the B horizon occurred nearly 0.1 m deeper where measurements were taken under dry conditions. This difference is accounted for in the discussion below and compared with the depth of the original B horizon in Fig. 6*a*, *b*. Where measurements were taken under wet conditions, there were no significant differences in A horizon thickness. To facilitate a statistical analysis of the wetting patterns for the 'dry' condition, treatment comparisons were conducted exclusively for the depth 0–0.15 m (A1 horizon; Table 6), assuming no depth effects on wetting of this layer.

The 'dry' condition experiments (Figs 5*a*, 6*a* and Tables 5, 6) showed a considerable effect of clay delving on water penetration and redistribution; the difference in the proportion of wet (stained) profile between treatments was highly significant ($P < 0.001$, Table 5). In the undelved soil, preferential flow occurred in isolated fingers, which reduced the wetted area (stained) from almost 100% near the soil surface to <20% at 0.1 m. On average, the proportion of wetted area in the undelved A1 horizon (0 to 0.14 m depth) was <50% (Table 6). In both regions of the delved soil (on the delving line and off-line) the occurrence of finger flow was greatly reduced and a larger area of soil profile was wetted, particularly on the delving-line region. In the A1 horizon, the average wetted area on the delving-line and off-line regions was significantly greater than in the undelved profile ($P < 0.05$), by 29% and 20%, respectively. The difference between the two regions of the delved profiles was not significant, indicating that both regions contributed to the total wetting of the delved topsoil.

Table 4. Soil properties at the experimental sites

Values of saturated hydraulic conductivity (K_{sat}) and water drop penetration time (WDPT) measured on soil samples in the air-dry state as taken from the field (Dekker *et al.* 2009). Severity of water repellence based on the classification proposed by Bisdom *et al.* (1993). Values in parentheses are standard deviation; n.m., not measured

Site	Horizon	K_{sat} ($m\,s^{-1}$)	WDPT (s)	Severity of water repellence	Infiltration rates ($mm\,h^{-1}$) Undelved	Delving line	Off-line
A	A1	1.3×10^{-4}	380–800	Strongly to severely water-repellent	256 (29)	276 (58)	242 (75)
	A2e	5.2×10^{-5}	2–10	Wettable to slightly water-repellent			
	B21	4.3×10^{-8}	n.m.	n.m.			
B	A1	8.5×10^{-5}	1000–2500	Severely water-repellent	152 (20)	119 (52)	113 (41)
	A2e	3.5×10^{-5}	5–15	Slightly water-repellent			
	B21	7.1×10^{-9}	n.m.	n.m.			
C	A1	6.2×10^{-5}	1200–2000	Severely water-repellent	184 (20)	310 (37)	156 (24)
	A2e	5.6×10^{-5}	2–10	Wettable to slightly water-repellent			
	B21	1.4×10^{-6}	n.m.	n.m.			

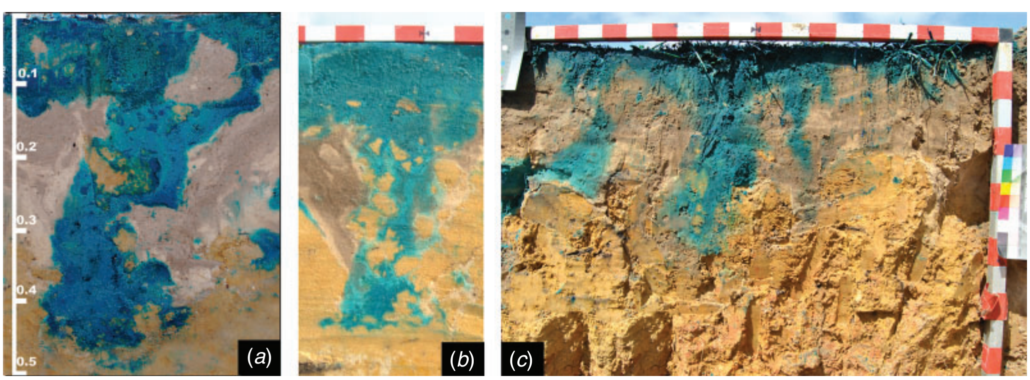

Fig. 5. Field observation of water flowing through the patterns created by clay clods added by clay delving: (*a*) site A, delving line under dry conditions; (*b*) site A, delving line under wet conditions; (*c*) site B, delving line in dry conditions. The frame in the picture shows 0.05-m increments.

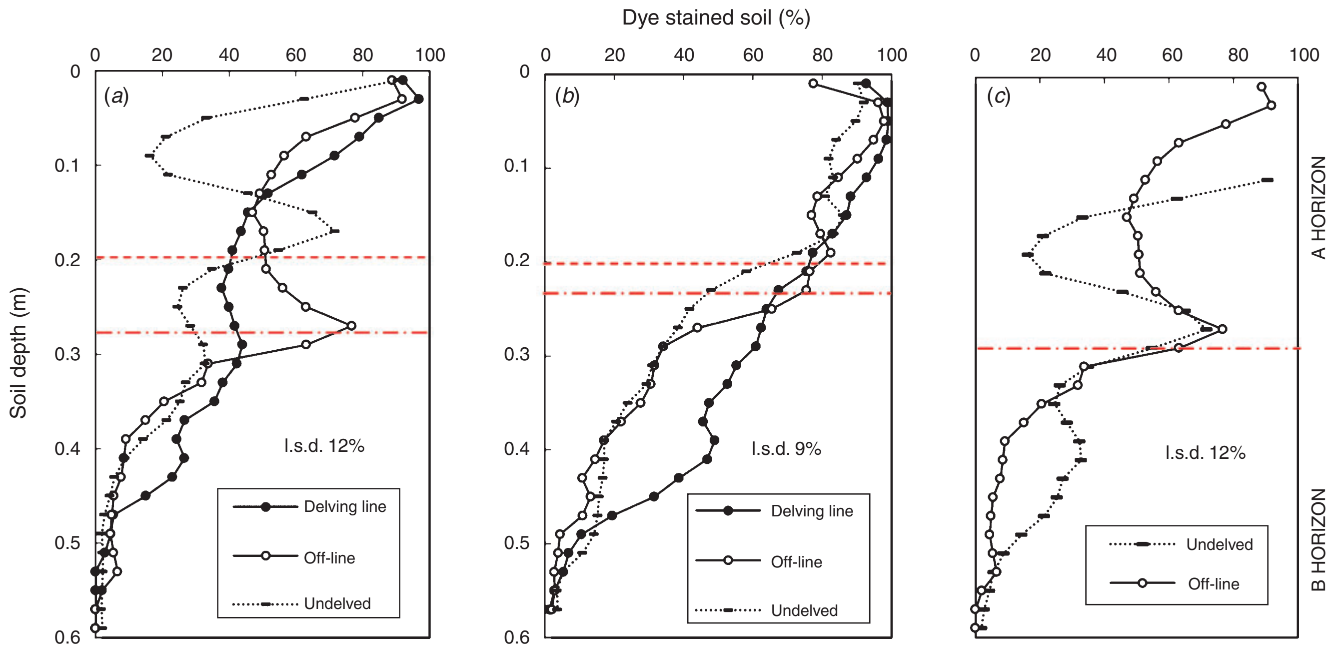

Fig. 6. Site A, average dye-stained soil (%) in the undelved profile and delved profile (on delving line and off-line regions) under (*a*) dry and (*b*) wet conditions. (*c*) Results from dry conditions where the A–B horizon interface of the undelved treatment has been transposed by ~0.1 m to match the off-line region, to observe the wetting patterns. The horizontal lines in all pictures represent the average depth of the original boundary between the A and B horizons: undelved profiles (- . - . -); delved profiles (– – –); l.s.d. = least significant difference at $P = 0.05$.

Table 5. Results from analysis of variance and relative levels of statistical significance at the three sites

At site A in dry condition, treatments were compared at 0–0.14 m depth only; n.m., not measured. *$P < 0.05$; ***$P < 0.001$

Source of variation	Site A		Site B		Site C
	Dry cond.	Wet cond.	Dry cond.	Wet cond.	Dry cond.
Treatment (delving line, off-line, undelved)	***	***	*	***	***
Depth area in the profile (approx. horizons A1, A2, B21, B22)	n.m.	***	***	***	***
Treatment × depth	n.m.	*	***	***	***

The wetting pattern of the undelved soil quite closely resembled that in the off-line region of the delved soil when the latter is transposed upward by ~0.1 m (Fig. 6*c*). In both undelved and offline regions, the dye-stained (wetted) area was minimal in the A1 to the A2e horizon, and finger flow facilitated water movement straight to the A–B boundary where free water ponded (greater proportion of stained area) because of the abrupt reduction in hydraulic conductivity, by 3 orders of magnitude (Table 4). By contrast, the A–B boundary on the delving line was broken and this allowed water to penetrate deeper into the soil with no ponding. The digital images demonstrate that the infiltration of water followed the V-shaped pattern induced by soil disturbance at and below the A–B boundary on the delving line. Thus, the delving line contributed more to wetting the soil profile than did the off-line region, particularly below the A–B boundary.

Under the 'wet' condition (Figs 5*b*, 6*b* and Tables 5, 6), soil at the surface was more uniformly wetted and little finger flow was observed (Hardie *et al.* 2011), but treatment differences were highly significant ($P < 0.001$, Table 5). The wetted areas in the A horizon on the delving line, off-line, and in the undelved soil were greater than those shown in Fig. 6*a* (dry conditions); the wetted areas also decreased less abruptly with depth than when dry. In the A1 horizon (0–0.14 m depth) and the A2e horizon (0.14–0.20 m depth), no significant differences in wetted areas occurred between the off-line region and on the delving line. Nevertheless, the wetted area in the A1 and A2e horizons on the delving line increased significantly more than in the undelved profile, by ~9% and 24%, respectively (Table 6).

In the top 0.1 m of the B horizon, both regions of the delved soil were significantly wetter than in the undelved profile (Table 6). At 0.3–0.6 m depth (B22 horizon), the disruption of the A–B boundary contributed to deeper water penetration, and the wetted area on the delving line was ~15% greater (significant at $P = 0.05$) than in the off-line region. No significant difference occurred at this depth between the undelved soil and the off-line region of delved soil; as for the 'dry' condition experiments at this site, the delving line had the major impact on overall wetting of the delved profile at depth, whereas wetting in the off-line regions behaved similarly to wetting in the undelved soil.

Bordertown, site B

The influence of clay delving on soil profile wetting was less evident at site B than at site A at Coonalpyn. Under dry conditions (Figs 5*c*, 7*a* and Tables 5, 7), smaller differences in wetted area (significant at $P = 0.05$) were found between the

Table 6. Site A: comparison of the mean wet areas (mean stained soil, %) at different depths of soil and significant differences for the three soil treatments of undelved soil, delving line and off-line

Within seasonal condition, means followed by the same letter are not significantly different at $P = 0.05$. n.m., Not measured; l.s.d., least significant difference

Horizon	Dry conditions				Wet conditions			
	Delving line	Off-line	Undelved	l.s.d. ($P = 0.05$)	Delving line	Off-line	Undelved	l.s.d. ($P = 0.05$)
A1	78a	70a	48b	12	95a	88ab	86b	9
A2e	n.m.	n.m.	n.m.		82bc	80c	58d	
B21	n.m.	n.m.	n.m.		66d	59d	31e	
B22	n.m.	n.m.	n.m.		28e	13f	11f	

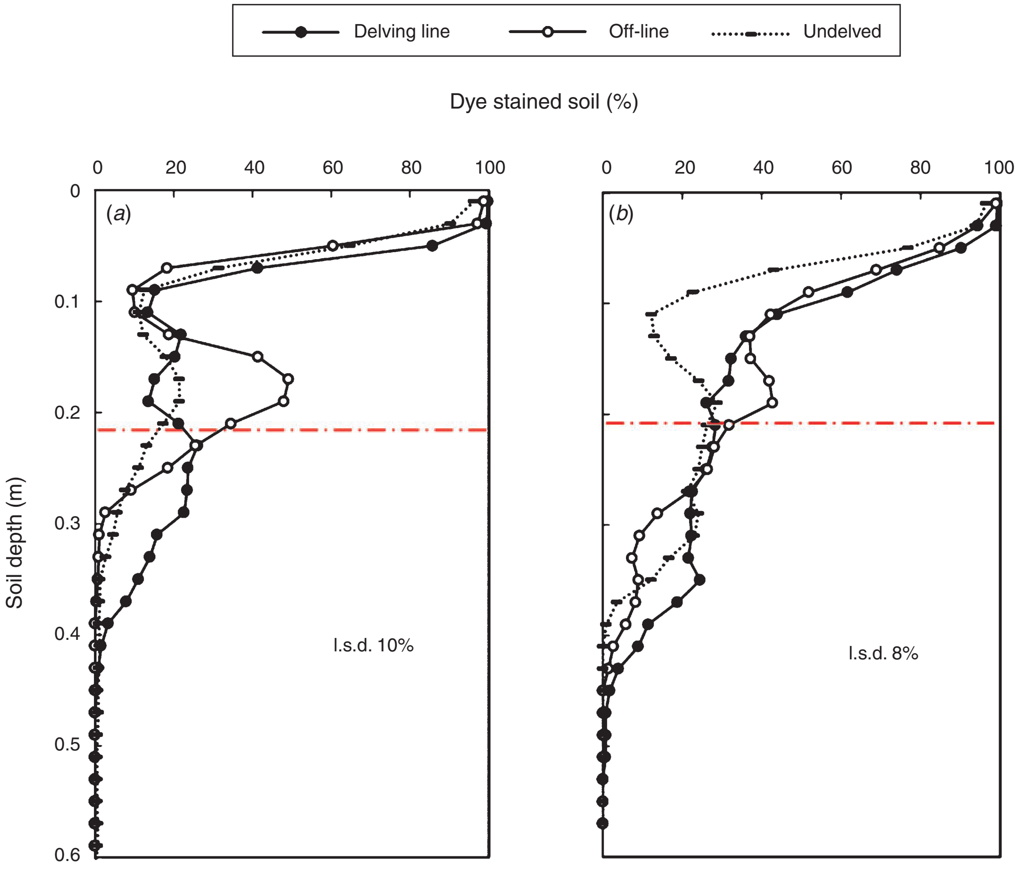

Fig. 7. Site B, average dye-stained soil (%) in the undelved profile and delved profile (on delving line and off-line regions) under (*a*) dry and (*b*) wet conditions. The horizontal line represents the average depth of the boundary between the A and B horizons; l.s.d. = least significant difference at $P = 0.05$.

two delved regions and the undelved soil. In both regions of the delved soil (on and off the delving line), a shallow, unbroken wetting front occurred just as it did for the undelved soil, largely due to severe water repellence of the surface sand at this site (Table 4) and a wider tine spacing during delving (1.2 m). In the top 0.14 m, only the soil on the delving line was significantly wetter than the undelved soil and this by only ~10%, and the wetting pattern in the A1 horizon did not differ significantly between the treatments. The A2e horizon in the off-line soil was significantly wetter than that on the delving line (as expected) because water ponded at the A–B boundary. Surprisingly, less water was observed to pond at the A–B horizon of the undelved soil than the off-line region of the delved one (Fig. 7*a*). This was due to the presence of some natural cracks in the top of the B horizon of the undelved soil, which allowed water to infiltrate deeper, reducing the overall ponding at the A/B horizon interface.

In the B21 horizon on the delving line, water infiltrated deeper as shown by the significantly greater area of wet (stained) soil than in off-line and undelved soils, by ~7% and 13%,

Table 7. Site B: comparison of the mean wet areas (mean stained soil, %) at different depths of soil and significant differences for the three soil treatments of undelved soil, delving line and off-line

Within seasonal condition, means followed by the same letter are not significantly different at $P = 0.05$. l.s.d., Least significant difference

Horizon	Dry conditions				Wet conditions			
	Delving line	Off-line	Undelved	l.s.d. ($P = 0.05$)	Delving line	Off-line	Undelved	l.s.d. ($P = 0.05$)
A1	54a	45ab	43b	10	72a	72a	51b	8
A2e	16cd	51ab	17cd		30c	44b	23cd	
B21	21c	14cd	8de		24cd	22d	22cd	
B22	2e	0.1e	1e		5e	2e	1e	

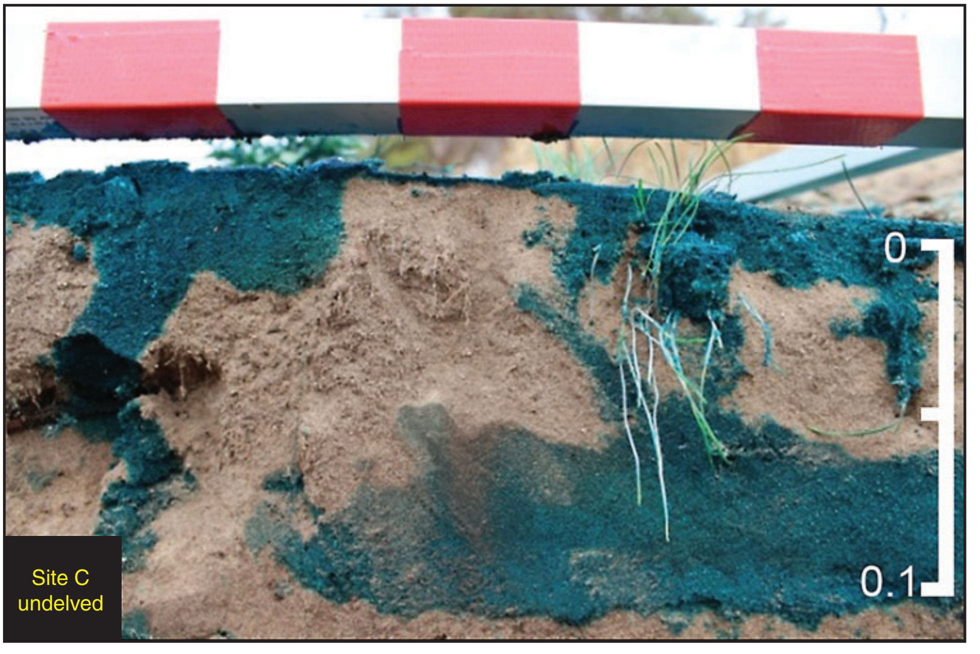

Fig. 8. Site C, undelved profile under dry conditions; the effect of the water-repellent sand produces preferential flows, and large areas of the top 0.1 m of soil remain dry even after ~23 mm of rain. The frame in the picture shows 0.05-m increments.

respectively (Fig. 7*a* and Table 7). No difference was found between treatments in the B22 horizon, where water infiltrated to a maximum depth of 0.45 m in all treatments.

Under wet conditions (Fig. 7*b* and Tables 5, 7), the soil in the A1 horizon of both the on- and off-line regions showed significantly greater wetting ($P < 0.05$) than the undelved, by 22% (Table 7). Also, the wetting patterns in the A horizon in the undelved and the off-line regions were similar (Fig. 7*b*), decreasing from the soil surface downward, with an abrupt increase above the A–B horizon where free water ponded, whereas water did not pond at the horizon boundaries on the delving line. Moreover, as shown in Fig. 7*b*, the wetted area in the B horizon tended to be greater on the delving line than off-line or in the undelved soil but the difference was not statistically significant. As with the experiment in dry conditions, some natural cracks present in the B horizon allowed part of the water to move deeper in the soil, which was similar to the effect created by the delving lines.

The contrast in wetting patterns of this soil relative to those at site A (Fig. 6*b*) may relate to the development of unstable wetting fronts (e.g. Hardie *et al.* 2012) caused by incomplete pre-wetting, but it is more likely that variations are simply due to large differences in soil composition and delving practices at the different sites.

Coonalpyn, site C

As with the other sites, at site C the differences between the treatments were significant ($P < 0.001$, Figs 8, 9 and Table 5). The addition of clay significantly reduced finger flows and increased the wetted area in the A horizon. Both the on- and off-line regions of the delved soil had significantly greater wetted areas than the undelved soil: 25% and 22%, respectively, in the A1 horizon; and both 18% in the A2e horizon (Table 8). The wet, stained area in the undelved profile was significantly smaller because of preferential flow, which bypassed large areas of the sand near the soil surface (Fig. 8) where water repellence was severe (Table 4). In general, the proportion of wetted area in the delved profile (both on- and off-line regions) was significantly greater than in the undelved region throughout the profile to a depth of 0.44 m.

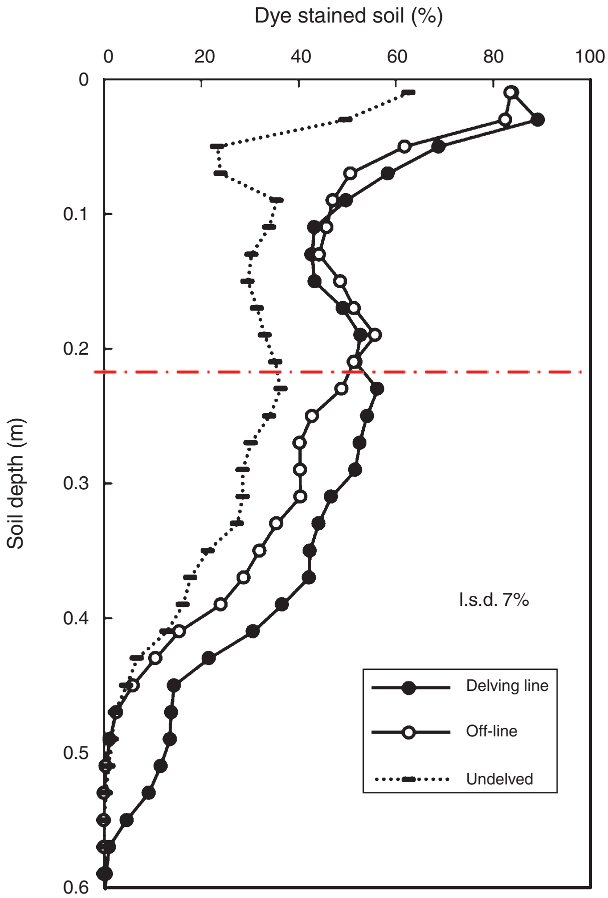

Fig. 9. Site C, average dye-stained soil (%) in the undelved profile and delved profile (on delving line and off-line regions) under dry conditions. The horizontal line represents the average depth of the boundary between the A and B horizons; l.s.d. = least significant difference at $P = 0.05$.

Table 8. Site C, dry conditions: comparison of the mean wet areas (mean stained soil, %) at different depths of soil and significant differences for the three soil treatments of undelved soil, delving line and off-line

Within seasonal condition, means followed by the same letter are not significantly different at $P = 0.05$. l.s.d., Least significant difference

Horizon	Delving line	Off-line	Undelved	l.s.d. ($P = 0.05$)
A1	62a	59a	37c	7
A2e	51b	51b	33c	
B21	46b	35c	25d	
B22	12e	4f	3f	

The reduction in hydraulic conductivity between the A and B horizons at this site was less abrupt than that at sites A and B (Table 4), so less water ponded above the A–B boundary in both the delved and undelved soils here. Nevertheless, the soil disturbance on the delving lines promoted greater wetting in the B horizon than on the off-line region and in the undelved soil. For example, there was ~11% and 20% more wetting, respectively, in the 0.24–0.40 m region (B21 horizon) and 9% more wetting in the 0.40–0.60 m region (B22 horizon), where no differences were found between the undelved soil and the off-line region (Table 8). Again, the greater penetration of water to depth, following the line of soil disturbance on the delving line, highlights the potential benefits of clay delving to reduce seasonally perched watertables.

Conclusions

At all three sites in South Australia, clay delving significantly increased the proportion of the A1 horizon that wetted up during infiltration into dry soil, and the penetration of water below the A–B horizon boundary. The effects, however, varied between sites. At site A, despite differences in the depth of the B horizon, delving significantly reduced ponding above the A–B horizon boundary while promoting infiltration into the B horizon, whereas at site B the effects of delving were more modest in both the A and B horizons, partly because the tines used were smaller and more widely spaced but also because the A–B horizon boundary was more irregular than at the other sites, reducing the degree of ponding. At site C, delving generated uniformly greater wetting throughout the soil profile. To our knowledge, this is the first report on the effects of delving on soil hydraulic properties down the profile. The implications for reducing seasonally perched watertables are obvious; the reduction in ponding at the boundary between A and B horizons caused by delving could be considered comparable to installing artificial agricultural drain lines (McFarlane and Cox 1992), and it made the lower part of the root-zone more aerobic. Furthermore, delving increased the proportion of the A2 horizon that participated in flow and storage of infiltration, which has the potential to significantly increase plant-available water in the root-zone.

Most of the increase in soil wetting from delving occurred in the area of maximum soil disturbance directly on the delving line, especially at Bordertown (site B), where the tine spacing was greater than at sites A and C. This outcome suggests that more uniform wetting of the soil profile could be achieved by narrowing the spacing of delving tines or through cross-delving and thereby reducing the extent of the off-line region, where finger flow still occurs.

Under dry conditions, clay delving significantly reduced preferential water (finger) flow, especially where water repellence at the soil surface was severe. Although finger flow was still observed, the delved profiles (especially on the delving lines) had deeper and more uniform wetting of the A1 horizon than undelved areas, which potentially could be important for more uniform crop establishment after sowing.

Under wet conditions, infiltration was more uniform than during infiltration into dry soils, and this was because water repellence was overcome by both incorporation of the clay and high antecedent soil-water content (Hardie *et al.* 2011). Nevertheless, in the A horizon the delved profiles showed significantly larger wetted areas, particularly along the delving lines, which can be crucial for plant root growth in semi-arid and Mediterranean areas (Lampurlanés *et al.* 2001).

Moreover, larger areas of wet profile at depth were achieved on the delving lines at all three sites under both dry and wet conditions by disruption of the boundary between the A and B horizons. The V-shaped area of disturbance on the delve line allowed water to penetrate deeper into the subsoil compared with both off-line regions and undelved profiles.

Although clay delving reduced finger flow and increased the uniformity of topsoil wetting plus water penetration to depth relative to undelved soil, the composition and physical properties of the delved soil were highly heterogeneous. The importance of post-delving management to reduce the heterogeneity of soil physical properties—or indeed whether heterogeneity is a problem at all—is poorly understood, particularly in relation to the plant root exploration. Evidence from studies where large differences in physical and chemical properties between A and B horizons are reduced through deep-ripping and deep placement of nutrients suggests that cereal roots explore the soil more effectively to increase cereal grain yields even in dry years (e.g. McBeath *et al*. 2010). A similar effect would be expected in other texture-contrast soils, provided the subsoil clay is not too hostile (e.g. high pH, high boron, etc.), although the delving process might dilute toxins and allow greater leaching of these (Davenport *et al*. 2011). An evaluation of the effects of delving on subsoil properties and their longevity after initial treatment merits further research.

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Chapter 4 Root growth and its distribution in delved and un-delved soils

4.1 Introduction

The increasing popularity of clay delving in Australia is certainly due to the positive responses in yields observed by a large number of farmers who have invested their energy and finance in this soil modification. Crop yields offer an important and direct measure of the agricultural and economic benefits obtained by clay delving which, as several field observations have indicated, creates conditions for deeper crop root systems (Bailey and Hughes 2012; Bailey *et al.* 2010; Davenport *et al.* 2011).

As mentioned in the literature review, the peculiar physical and chemical characteristics of texture contrast soils impose serious constraints on plant root growth so that shallow root systems are commonly observed in these soils (Dracup *et al.* 1992; Hamblin and Tennant 1987). Crops establish roots in sandy A horizons, which are generally deficient in macro- and micro-nutrients (Tennant *et al.* 1992), and are irregularly distributed throughout the soil profile (Robson *et al.* 1992). Soil acidity (mostly in the A horizon), alkalinity (mostly in the B horizon) and salinity are also regarded as major constraints to root growth when they occur (Dracup *et al.* 1992). These issues, in combination with the naturally low water holding capacity (WHC) and common water repellence of the sand, create a harsh environment for plant establishment, particularly in low rainfall areas.

Moreover, water ponding in the wet season between the A and B horizons and the high soil strength of the clay subsoil, especially in the dry season, act as a physical barrier for deep root penetration, especially at the A/B horizon interface (Dracup *et al.* 1992).

Although root growth generally declines with depth in all soils (due, for example, to declining oxygen content and increasing bulk density with depth), this is especially the case in texture contrast soils, where root exploration into the B horizon is severely restricted (e.g. **Figs 4.1a** and **4.1b**). Increases in crop yield can be achieved on texture contrast soils when more roots can grow into the B horizon, where greater water availability may occur (Crabtree 1989; Dracup *et al.* 1992; Gregory *et al.* 1992; Hall *et al.* 2010), and this is particularly important in dry growing seasons.

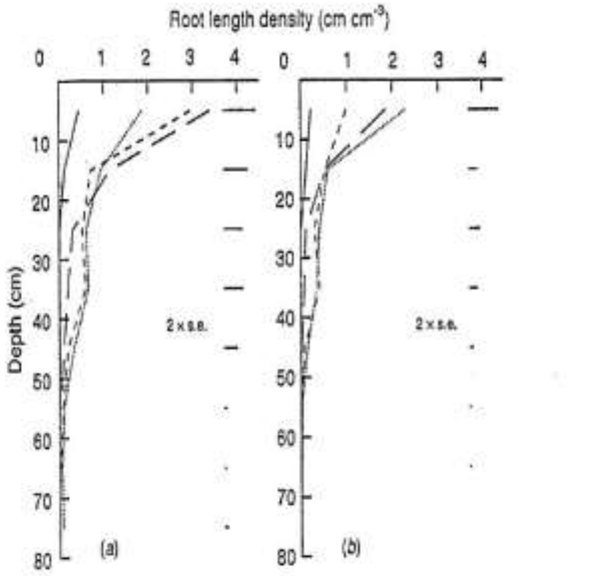

Fig. 4. Changes in the distribution of root length during the growing season for crops of (*a*) Beecher and (*b*) Gutha at East Beverely 1988; —— 27 das, --- 55 das, – – – 83 das, and ···· 111 das. Bars indicate 2×s.e. on 111 das.

Fig. 4.1a. Example of truncated root length densities in texture contrast soil profiles as observed by Gregory *et al.* (1992); ("das" ≡ days after sowing).

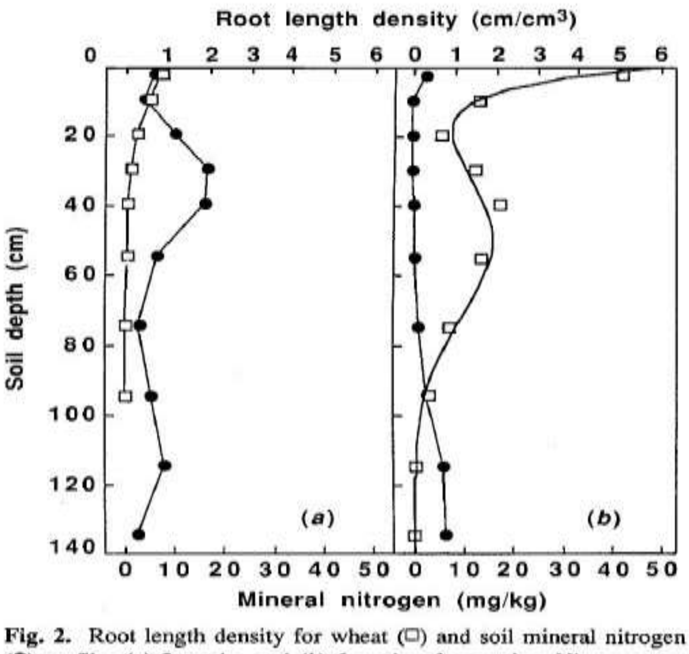

Fig. 2. Root length density for wheat (□) and soil mineral nitrogen (●) profiles (*a*) 3 weeks, and (*b*) 6 weeks after sowing. Nitrogen was added to the surface at 100 kg N/ha as $Ca(NO_3)_2.4H_2O$. Water was added at a rate of 3 cm per week. Data from Diggle and Bowden (1990).

Fig. 4.1b. Example of truncated root length densities in texture contrast soil profiles as observed by Robson *et al.* (1992).

Lampurlanés *et al*. (2001) also observed in semi-arid conditions that root growth and root depth are promoted by tillage methods that improve surface infiltration and water capacity, particularly in years having lower rainfall.

Thus, changing the physical and chemical characteristics of texture contrast soils should aim to *i)* to increase nutrient and water availability (by improving water infiltration and water holding capacity) at the soil surface for better crop establishment and *ii)* to reduce constraints in the B horizon to allow deeper root growth to access stored water.

In the previous chapters I have discussed how clay delving strongly modifies the morphology and physical properties of texture contrast soil profiles. Subsoil clay added to the sandy topsoil plays an important role in increasing nutrient and water availability as shown in **Chapter 2** and by Bailey and Hughes (2012), Bailey *et al.* (2010), Cann (2000), Davenport *et al.* (2011), and May *et al.* (2006). Soil disturbance has been shown here to improve the overall wettability of the A horizon (see **Chapter 3**), which is an important improvement for crop establishment after sowing.

There is copious literature on the effects of deep ripping on soils with clayey subsoils (e.g. Barbosa et al. 1985, Grevers and deJong 1993, Lavado and Cairns 1980, Nitant and Singh 1995, Wetter et al. 1987), which demonstrate the potential value of disturbing the subsoil to improve root growth. In texture-contrast soils, the disruption of the A/B horizon boundary along the delving lines can potentially reduce seasonal water ponding and reduce mechanical constraints for root penetration along the delving lines (see **Chapter 3**). These changes can allow root growth in the B horizon, as observed in some field reports (Bailey *et al.* 2010; Davenport *et al.* 2011). Nevertheless, a rigorous analysis of root growth and its spatial distribution in delved soil is still unavailable.

To understand how crops can take advantage of the soil modification introduced by clay delving, I evaluated root growth in three different soils in their original undelved conditions and after clay delving. The aims of the experiment were:

1) To evaluate the effect of clay delving on plant root growth in terms of root length density and mean root diameter. The question on which the experiments were based was: To what extent does clay delving improve plant root growth, particularly at depths below the A horizon in texture contrast soils?

2) To evaluate the distribution of roots in delved soils in relation to the lateral variability of soil properties imposed by delving. Because delving drastically modifies the soil morphology along the delving line, I asked: To what extent does root growth differ in and between the delve lines?

4.2 Materials and methods

Root sampling was conducted at three sites: site A (near Coonalpyn, South Australia) in September 2012 (4 years after delving), site B (near Bordertown) in September 2012 (5 years after delving), and at site D (near Karoonda) in September 2011 (2 years after delving). The soil at site A was a Bleached Yellow Sodosol, and the soil at site B was a Bleached Red Sodosol; the soil at site D was a Mottled Red Chromosol in the Australian Soil Classification (Isbell 2002). The sites where chosen based of their accessibility at the time of sampling and the presence of crops with fibrous root systems (more suitable than tap root systems when collecting samples using a soil corer).

Root length density (RLD) and root mean diameter (RMD) were chosen as the best method for the aim of the experiment. RLD is defined as root length per unit of soil volume, usually expressed as $cm \cdot cm^{-3}$, and is frequently used to describe the interaction of roots with soil characteristics and soil water uptake (Chassot *et al.* 2001; Gao *et al.* 2010; Hamblin and Tennant 1987; Martínez *et al.* 2008; Zubaidi *et al.* 1999; Zuo *et al.* 2004; Zuo *et al.* 2006) while RMD (mm) is used in this experiment for the evaluation of root fineness.

At the time of sample collection, barley was growing in the paddocks at sites A and D while pasture was growing at site B. The mean annual rainfall at sites A, B and D was 450, 454 and 339 mm respectively although in the year of collection, site D recorded significantly more rain (490 mm, mainly in February and March 2011) while site B recorded below average annual rainfall (389 mm, **Fig. 4.2**, Bureau of Meteorology 2013).

Root sample collection was done with the coring method of Rosário *et al.* (2000) (**Fig. 4.3**). Soil cores (with 0.04 m internal diameter) were collected at all sites from both the delved and undelved soils. For the delved soils, cores were placed in the delve-lines every 0.1 m starting from the centre of the line and moving to the area between the lines. The highly variable depth of the horizons as well as the variable depth and straightness of the delving operations created some uncertainty in root sampling.

To improve accuracy of sampling locations, I excavated three parallel trenches 5 m apart approximately perpendicular to the delve lines. Wooden stakes were positioned at the centre of each delving line encountered, then rope was pulled taut between stakes in the three trenches to fix sampling lines centred in, and on either side of, each delve line. Soil cores were then extracted to a depth of 0.6 m (corresponding to the average maximum depth of delving) using a drilling rig placed at several points at 0.1 m intervals that were perpendicular to the delving line (**Fig. 4.3b**). The 0.60 m long soil cores were then subdivided in the field into six sub-samples of 0.1 m depth increments. The loose structure of the topsoil (mainly coarse sand) made it difficult to subdivide the top 0.1 m section of the A horizon, especially at sites A and B. This was not a problem for samples extracted from the clay-rich B horizon. For this reason, the core segments from 0 to 0.2 m were combined into a single A-horizon depth, despite that fact that field observation indicated that most of the roots grew in the organic-rich layer (A1) rather than in the bleached A2 horizon, particularly in the undelved soils.

All samples were sealed in plastic bags and refrigerated at 4°C until they could be analysed. The roots were extracted from the soil after samples were soaked in water for approximately 24 hours to loosen clay and facilitate root separation. The roots were then separated by gently washing the soil away with a stream of water over a 1mm sieve; the water under the sieve was collected in a plastic bucket to retrieve the smaller roots using a 0.5 mm mesh sieve. Following a method similar to that of Richner *et al.* (2000), the washed roots were then placed in 2 mm of water on transparent trays (0.25 m x 0.14 m) and placed under a high definition scanner (Epson Expression 1000XL) to generate digital images. Root length (cm) and root mean diameter (RMD, mm) were estimated from the digital images using WinRhizo software (Regent Instruments Inc.). The root length of each sample was divided by the volume of the each core section of the sample to calculate root length density (RLD, cm cm^{-3}).

A statistical analysis of root length, RLD and RMD was conducted using GenStat software (VSN International 2013) taking into account two main sources of variation: i) soil treatment ("*undelved*" soil, "*delving line*" and "*off-line*" regions of the profile), ii) soil horizon (A = 0.0 to 0.2 m; horizon B = 0.2 to 0.6 m), plus two interaction effects: iii) soil horizon x soil treatment, and iv) soil depth x soil treatment.

Field observations suggested that soil within 0.2 m of the delving line (i.e. 0.1 m either side of the centre) comprised part of the "*delving line*" region, and soil outside this region was considered to comprise the *'off-line*" region (**Fig. 4.3d**).

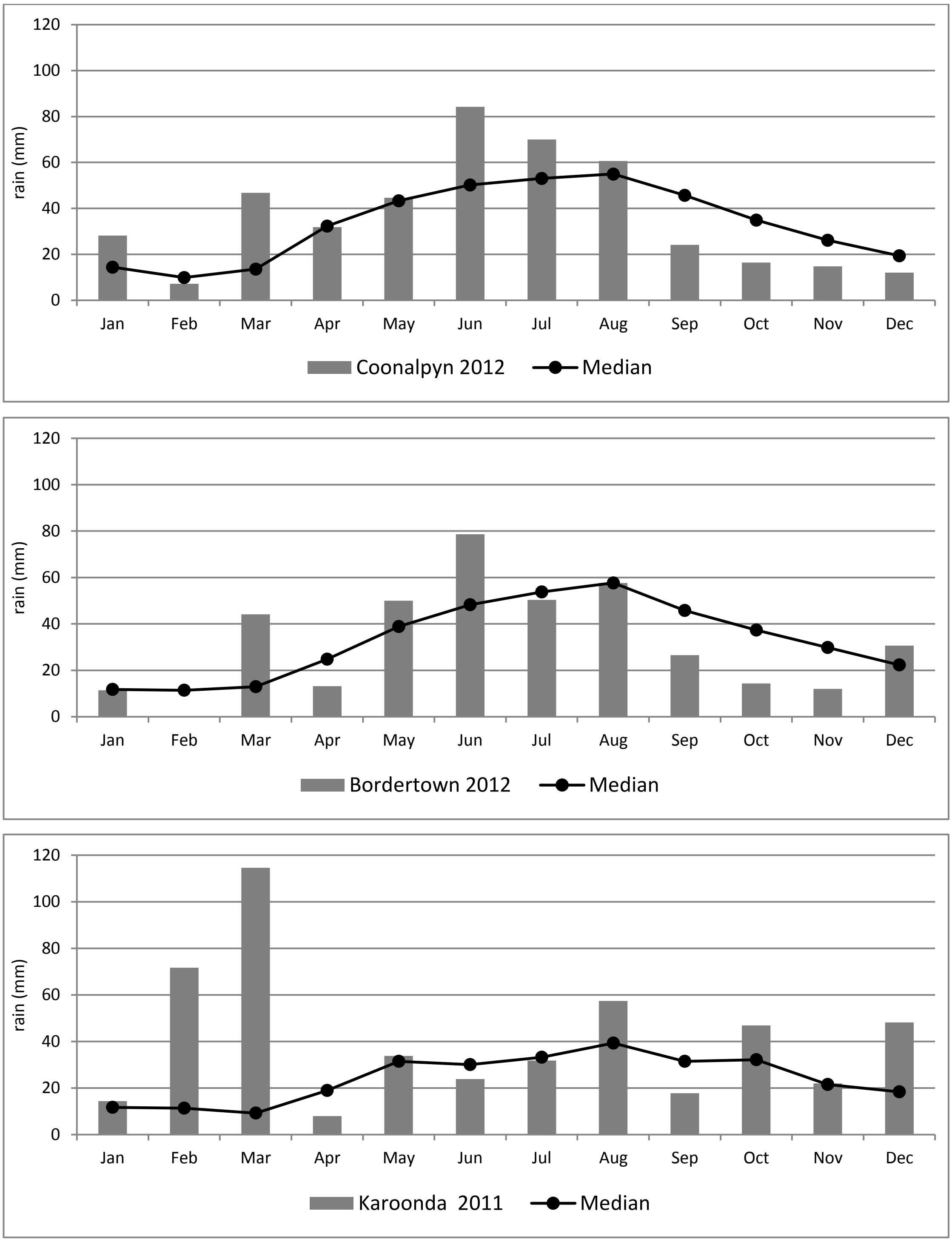

Fig. 4.2. Monthly rainfall 2011 (site D) and 2012 (sites A and B) and their respective medians, equivalent to 50th percentile (Bureau of Meteorology 2013)

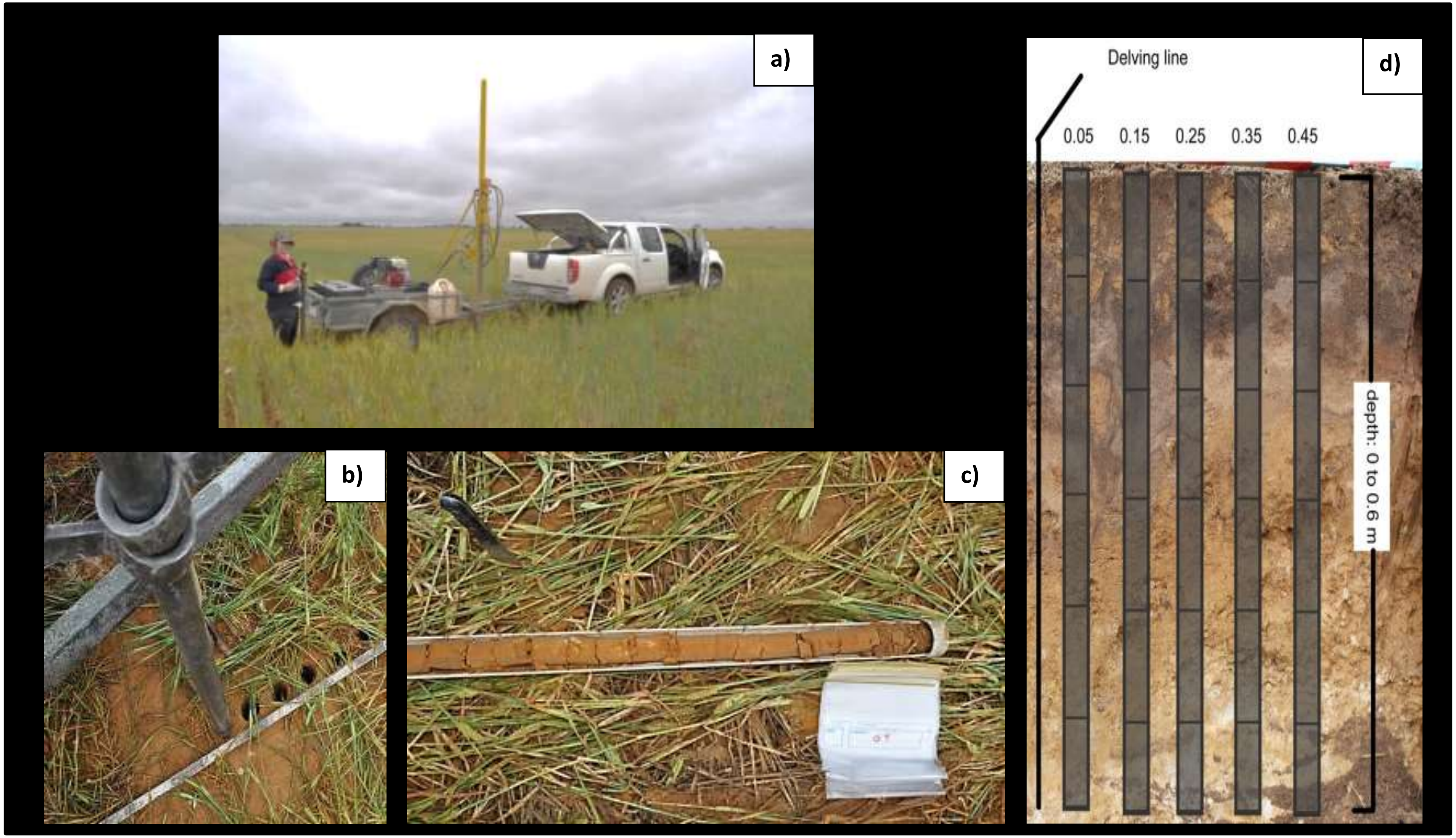

Fig. 4.3. The root sampling process showing (a) the drill machine, (b) coring of a delved soil, (c) a core extracted and (d) the position of the cores in relation to the delved profile

4.3 Results and discussion

The root length density, RLD, at the three sites was highly variable between samples. This was expected due to the high morphological variability of the soils, particularly in the delved soil. Nevertheless, significant differences in mean RLD were found between the undelved and the delved soils (**Table 4.1**). For example, at both sites A and B, the average RLD in both the "delving line" and "off-line" regions were significantly greater ($p < 0.001$) than in the undelved soils. At site B the average RLD in the delving line was significantly greater than in the off-line region. At site D, however, no statistically significant differences in mean RLD were found among treatments (**Table 4.1**). Considering site D was the most recently delved (less than 2 years before sampling), this unexpected outcome did not result from a significant reduction of the effects of delving over time. It is more likely the physical characteristics of the soil at site D differed significantly from the other sites (it was a Chromosol, unlike the Sodosols at sites A and B) and that the above-average rainfall recorded at this site in 2011 overcame the physical constraints to root growth that year, relative to the other two sites.

Table 4.1. Mean root length density (RLD, cm root cm^{-3} soil) in the top 0.6 m of soil plus analysis of variance (ANOVA) for RLD as a function of depth, location, and interactions at the three sites.

	Site A				**Site B**				**Site D**			
	On-line	**Off-line**	**Un-delved**		**On-line**	**Off-line**	**Un-delved**		**On-line**	**Off-line**	**Un-delved**	
RLD (cm cm^{-3})	3.36	3.82	1.37		4.21	3.86	2.85		1.89	1.90	2.04	
Variation source	**d.f.**	**s.s.**	**m.s.**	***p***	**d.f.**	**s.s.**	**m.s.**	***p***	**d.f.**	**s.s.**	**m.s.**	***p***
Treatmt: On, Off, Undelve	2	107.3	53.7	***	2	21.0	10.5	***	2	0.42	0.21	n.s
Horizon (A, B)	1	40.7	40.7	***	2	21.0	10.5	***	1	3.4	3.4	*
Treatmt x Horizon	2	15.3	7.6	*	2	67.2	33.6	***	2	21.8	10.9	***
Treatmt x Depth	8	23.0	2.9	n.s.	8	77.8	9.7	***	10	41.6	4.2	***

d.f.= degrees of freedom; **s.s**.= sum of squared errors; **m.s**.= mean s.s.; ***p*** = statistical significance of *p*-value (n.s.= $p > 0.05$; *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$); A horizon = 0 to 0.2 m; B horizon = 0.2 to 0.6 m.

Figs 4.4, 4.5 and **4.6,** and **Tables 4.2, 4.3** and **4.4** show the RLD with soil depth in the undelved soil, on the delving lines and in the off-line regions. At site A (**Fig. 4.4**, **Table 4.2**) both regions of the delved profile had greater RLD throughout the soil profile than the undelved soil. This applied to both the delving line and off-line regions, where RLD was significantly greater from 0.2 to 0.6m (corresponding approximately to the B horizon). There was no statistically significant difference in RLD between the delving line and the off-line regions. This was contrary to expectation because disruption of the A/B horizons boundary should have promoted greater root growth in the delving line.

At site B (**Fig. 4.5**, **Table 4.3**) the RLDs in the delving line and the off-line regions were significantly lower ($p > 0.05$) in the top 0.2 m than in the undelved soil. From 0.3 to 0.6 m, however, the RLD in both regions of the delved profile were significantly greater than in the undelved soil. At this site, the overall mean RLD for the whole profile in the delving line region was generally greater than in the off-line region, although there were no statistically significant differences between the RLDs at equal depths (**Table 4.3**). At site D (**Fig. 4.6**, **Table 4.4**) the average RLDs from both regions of the delved profile were not significantly greater than that in the un-delved soil. Consistent with site B, the average RLD in the topsoil of the un-delved profile was greater than in the delved profile, especially in the top 0.1 m (**Table 4.4**). From 0.2 m to 0.6 m, both regions of delved profile had greater RLD than that in the undelved soil but the differences were only significant (at $p < 0.05$) for the samples from the depth 0.3 m to 0.5 m of the delving line region (coinciding approximately to the V-shaped area created by the delving tines) (**Table 4.4**).

In general, the most evident change introduced by clay delving at all three sites was in the overall pattern of root growth between horizons. While roots in the un-delved soils grew mainly in the A horizon, roots in the delved soils were more uniformly distributed with depth. There was little difference in RLD at different depths within the two regions of the delved soils (**Tables 4.2, 4.3** and **4.4**).

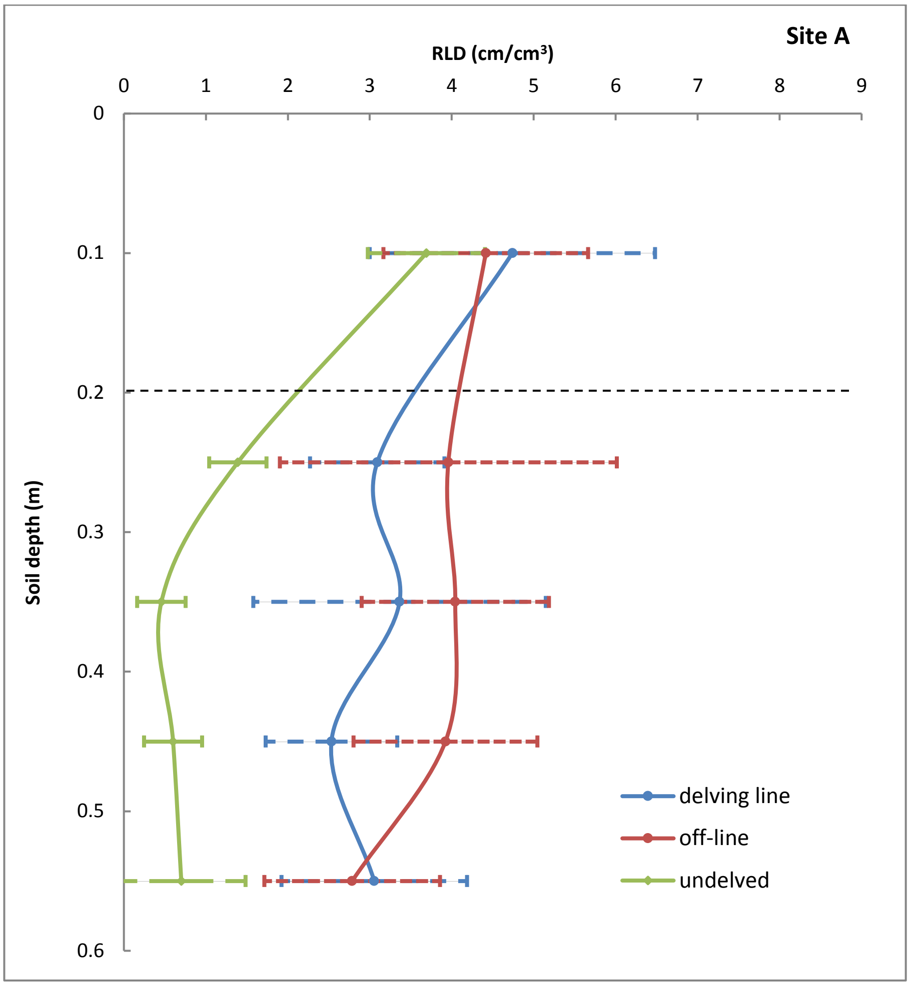

Fig. 4.4. Distribution of RLD with depth at site A. The horizontal dashed line represents the approximate location of the boundary between the A and B horizons. Error bars represent standard deviations of the means

Table 4.2. Mean root length densities, RLD (cm cm^{-3}) at site A and their least significant differences (P = 5%) from the 3 treatments (un-delved, delving line, off-line regions).

	Site A			
Depth (m)	**Delved**		**Undelved**	**LSD (at 5%)**
	Delving line	**Off-line**		
0.0-0.2	4.74^{a}	4.41^{ab}	3.69^{ab}	
0.2-0.3	3.09^{b}	3.95^{ab}	1.18^{c}	
0.3-0.4	3.36^{ab}	4.27^{ab}	0.33^{c}	**1.39**
0.4-0.5	2.53^{b}	3.92^{ab}	0.53^{c}	
0.5-0.6	2.80^{b}	2.78^{b}	0.32^{c}	
Mean 0.0-0.6	3.31^{a}	3.87^{a}	1.19^{b}	**0.63**

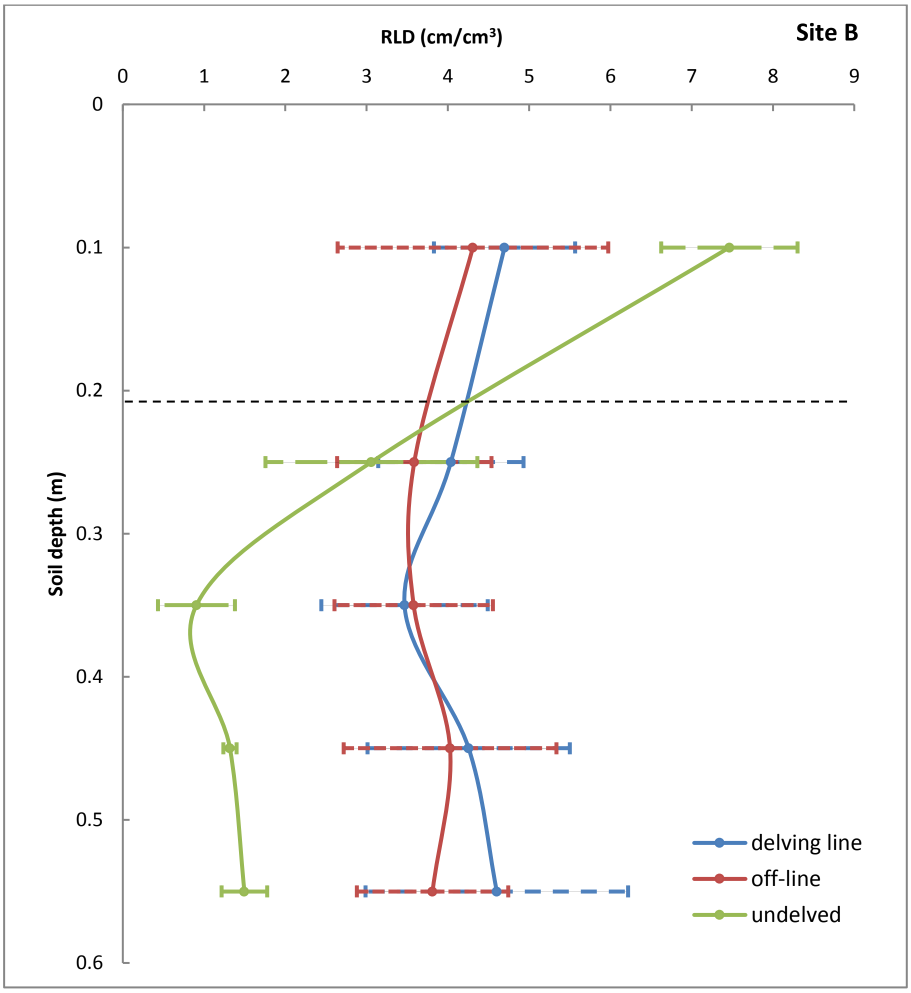

Fig. 4.5. Distribution of RLD with depth at site B. The horizontal dashed line represents the approximate location of the boundary between the A and B horizons. Error bars represent standard deviations of the means.

Table 4.3. Mean root length densities, RLD (cm cm^{-3}) at site B and their least significant differences (P = 5%) from the 3 treatments (un-delved, delving line, off-line regions).

	Site B			
	Delved		Undelved	
Depth (m)	**Delving line**	**Off-line**		**LSD (at 5%)**
0.0-0.2	4.70^{b}	4.31^{bc}	7.46^{a}	
0.2-0.3	4.03^{bc}	3.60^{bc}	3.05^{c}	
0.3-0.4	3.47^{bc}	3.58^{bc}	0.90^{d}	**1.39**
0.4-0.5	4.26^{bc}	4.03^{bc}	1.31^{d}	
0.5-0.6	4.60^{b}	3.81^{bc}	1.50^{d}	
Mean 0.0-0.6	4.21^{a}	3.86^{b}	2.84^{c}	**0.31**

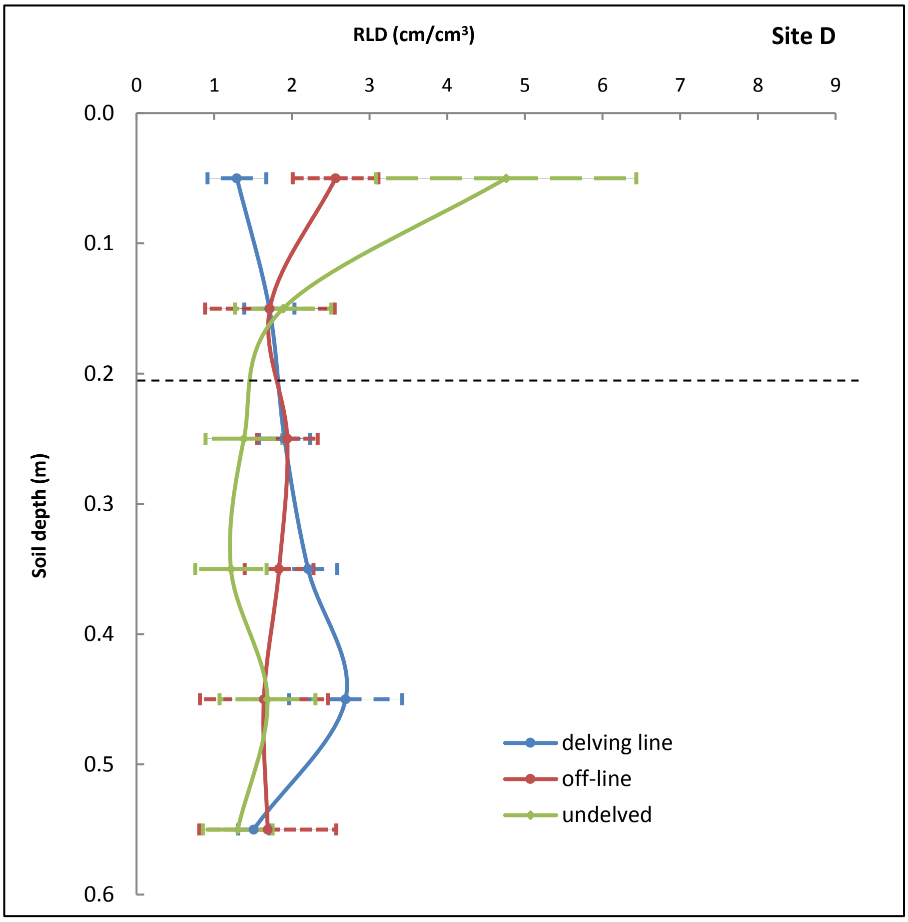

Fig. 4.6. Distribution of RLD at different depths at site D. The horizontal dashed line represents the approximate location of the boundary between the A and B horizons. Error bars represent standard deviations of the means

Table 4.4. Mean root length densities, RLD (cm cm^{-3}) at site D, and their least significant differences (P=5%) from the 3 treatments (un-delved, delving line and off-line regions).

	Site D			
	Delved			
Depth (m)	**Delving line**	**Off-line**	**Undelved**	**LSD (at 5%)**
0.0-0.1	1.29^{e}	2.56^{b}	4.76^{a}	
0.1-0.2	$1.74cd^{e}$	1.72^{de}	1.89^{cde}	
0.2-0.3	1.94^{cde}	1.94^{cde}	1.38^{e}	**0.78**
0.3-0.4	$2.21b^{cd}$	1.84^{cde}	1.22^{e}	
0.4-0.5	2.73^{b}	1.64^{de}	1.69^{de}	
0.5-0.6	1.51^{de}	1.69^{de}	1.30^{e}	
Mean 0.0-0.6	1.89^{a}	1.90^{a}	2.05^{a}	**0.32**

The difference in root distribution in the A and B horizons is also evident from the average total root lengths (cm) found in the top 0.6 m of the undelved and delved soils at all three sites (**Fig. 4.7**). Greater than fifty percent of the total mean root length in the undelved soils was found in the A horizon; at site A and site B 76% and 69% respectively of the total root length was found in the top 0.2 m of the soil profiles (**Fig. 4.7**). At site D, 54% of the roots of the undelved soil were found in the A horizon while only 27% and 37% of total root length was found in the delving line and off-line regions, respectively (**Fig. 4.7**). Again, these results could be explained by the combination of the different soil type at site D and the wet seasonal conditions of 2011 that reduced the difference in root distribution between the undelved and delved regions.

Tables 4.5, 4.6 and **Fig. 4.8** show that at all sites both regions of the delved soils had, on average, thinner roots (smaller RMD) than those in the undelved profiles. Roots in both regions of delved profiles were significantly thinner than those in the undelved soils, with one exception: the roots in the off-line region at site D were no thinner than those in the undelved soil. As for the RLD results, no statistically significant differences were found between thickness of roots in the delving line and off-line regions at all sites.

The differences in root thickness (RMD) between the undelved soils and the two regions of delved soil are more obvious below 0.2 m, where the B horizon starts (**Fig. 4.8**). Although no significant differences were found between most treatments near the soil surface (with the exception that the undelved soils showed smaller average RMD), roots from the delved soil were generally thinner than those in the undelved soil. Significant differences (at 5%) were in fact found in all sites at the depth range 0.2 to 0.6 m. This is an important result as the difference in root thickness could arise as a consequence of different levels of stress during the root growth between the undelved and delved profiles. Roots in the undelved soils may be in fact thicker in response to greater physical stresses due to greater soil strength (Azam *et al.* 2013; Bengough *et al.* 2011; Eavis 1972; Materechera *et al.* 1992) at the time roots reached the B horizon.

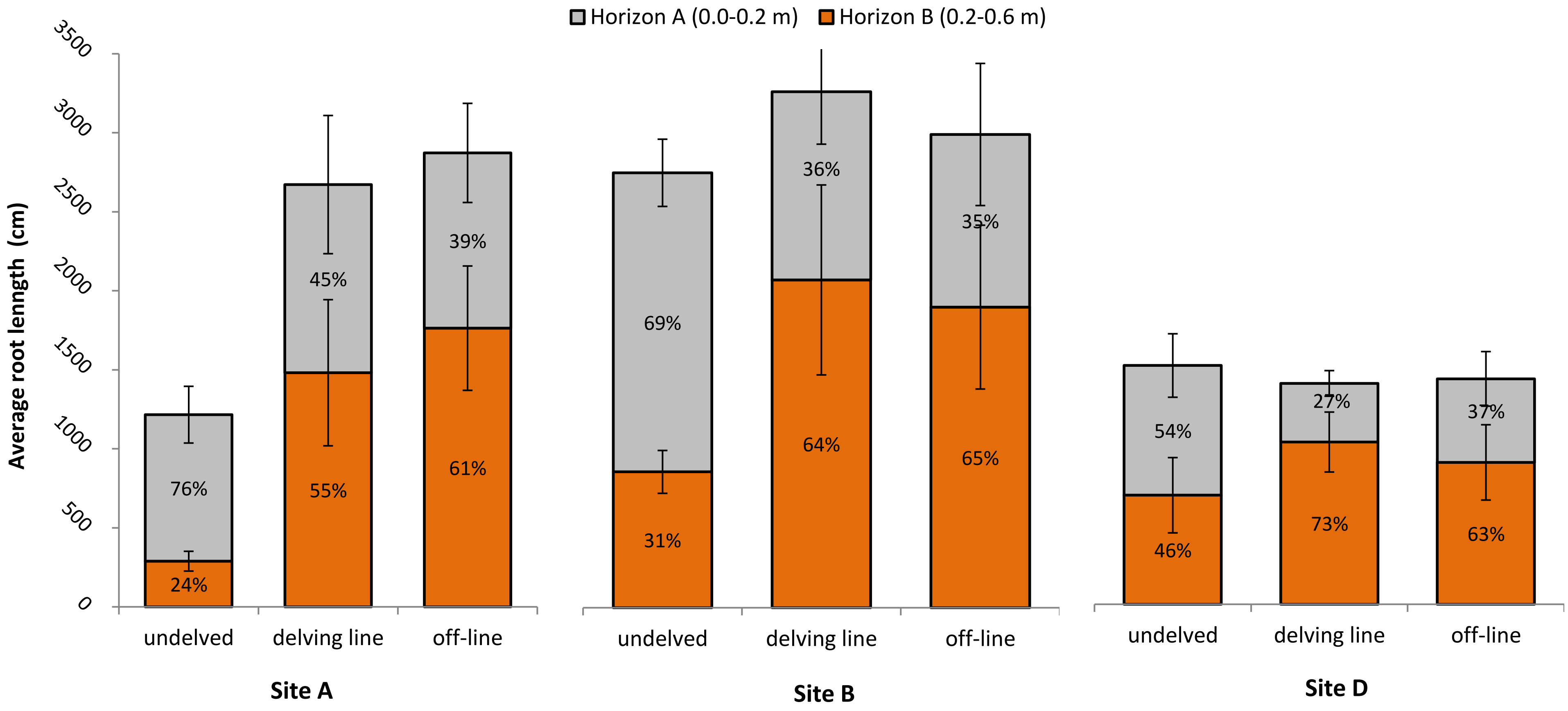

Fig. 4.7. Average total root lengths (cm) from the 0.6 m cores taken at the three sites, and their distribution (%) in the A and B horizons at three different sites: site A, site B and site D, South Australia. Error bars represent standard deviations of the means.

Table 4.5. Levels of statistical significance from ANOVA for Root Mean Diameter at 3 sites.

Source of variation for RMD	**Site A**				**Site B**				**Site D**			
	d.f.	**s.s.**	**m.s.**	***p***	**d.f.**	**s.s.**	**m.s.**	***p***	**d.f.**	**s.s.**	**m.s.**	***p***
Treatment (On delving line, Off-line, Undelved)	2	0.01	0.01	***	2	0.035	0.017	***	2	0.015	0.007	*
Depth	4	0.003	0.001	n.s	4	0.061	0.015	***	5	0.080	0.016	n.s
Treatment x depth	8	0.007	0.001	n.s	8	0.022	0.002	*	10	0.033	0.003	*

d.f.= degrees of freedom; **s.s**.= sum of squares; **m.s**.= mean s.s.; ***p***= statistical significance related to *p*-values (n.s.= p > 0.05; *=p<0.05, **=p<0.01, ***=p<0.001); A horizon=0.0-0.2 m; B horizon=0.2-0.6 m

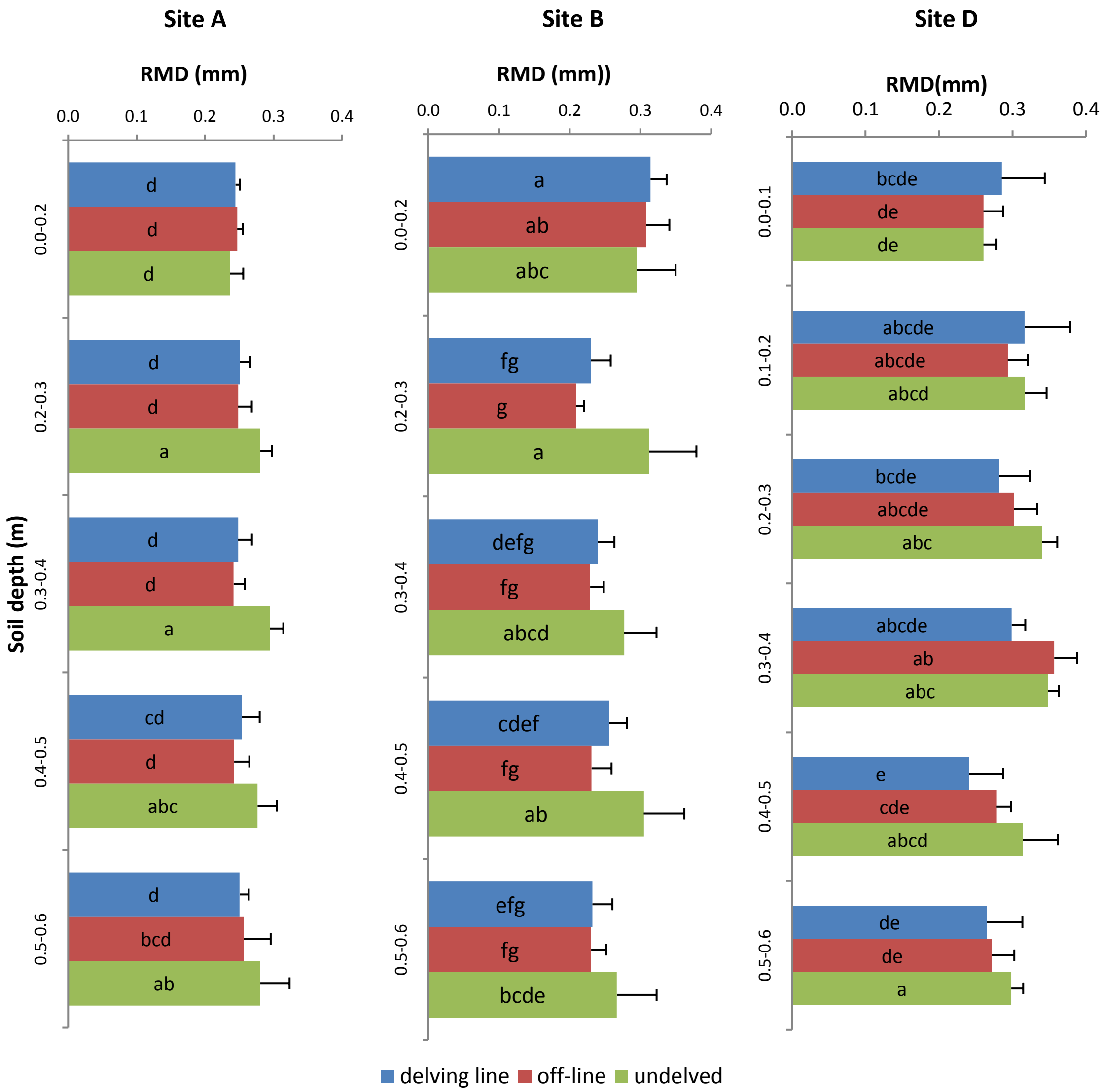

Fig. 4.8. Average root mean diameters, RMD (mm) at different depths at the three sites (significant differences estimated with Genstat). Error bars represent standard deviations of the means.

Table 4.6. Mean root diameters, RMD, mm; significant differences at P=5% at 3 sites

Site	delving line	off-line	undelved	LSD (5%)
site A	0.249[a]	0.247[a]	0.274[b]	0.011
site B	0.254[a]	0.241[a]	0.290[b]	0.018
site D	0.281[a]	0.294[ab]	0.313[b]	0.031

4.3 Conclusions

In these experiments the effect of clay delving on plant root growth was evaluated in terms of total root length, root length density (RLD) and root mean diameter (RMD).

All results were highly variable but the effect of clay delving on RLD and RMD was generally strong, particularly at sites A and B where the average RLD in the delved soil was significantly greater than that in the un-delved soil. At site D the effects were less evident and this may have been due to other factors (e.g. high salt content, high pH, Boron, etc), which diminished the benefits of delving.

At sites A and B the effect of clay delving on root growth was particularly evident in terms of root distribution above and below the B horizon. The majority of roots in the un-delved soil were found in the A horizon, with significant reductions in the B horizon. The root distributions above and below the B horizon in the un-delved soils were similar to those commonly observed in texture contrast soils by other authors (Gregory *et al.* 1992; Robson *et al.* 1992, **Fig. 4.1**). By contrast, the delved soils showed a more uniform root distribution with depth in the top 0.6 m of soil. At all sites RLDs in the delving line and the off-line regions were generally similar with depth (i.e. differences between the RLD at different depths were not statistically significant) mainly because more roots were able to access the B horizon of the delved soils whereas in the un-delved soils, all roots were restricted to the sandy A horizon. Only at site B was a statistically significant difference found in the mean RLD between the delving line and off-line regions of the delved soils.

Moreover, at all sites significant differences in the average RMD were found between the delved and un-delved soils, indicating that roots allocated resources more efficiently in the modified soil, while those in the un-delved soil could have been subjected to higher stress due to higher soil resistance to penetration (particularly in the B horizon). Except for the top 0.1 m of soil, the average root thickness (RMD) was significantly less in the delved soil compared with the un-delved soil. There were almost no significant differences in the mean RMDs between the delving line and off-line regions.

Assuming the physical characteristics of the B horizon were the same within the treatments of each site, it could be argued that the roots in the delved soils were thinner because they were able to reach the clay subsoil earlier in the season than those in the un-delved soils, when the greater water content reduced the strength of the B horizon. Based on the results from these three sites, clay delving clearly improved root growth compared to the un-delved sites (even if only minimally at site D), creating the conditions for a denser and finer root growth in the B horizon where more water was available.

Delving contributed to greater uniformity of soil properties and root growth with no clear distinctions in root growth between the delving line and off-line regions. In fact, the results did not reflect the morphological differences between these two regions and no statistically significant differences were found in terms of RLD and RMD. Although this may be surprising, it could reinforce the importance of good water infiltration and water holding capacity at the soil surface to promote root growth and uniformity with depth, as observed by Lampurlanés *et al.* (2001). Results from experiments 1 and 2 (**Chapters 2** and **3**) showed that in the top 0.10 m, the differences between the delving line and the off-line regions were minimal in terms of clay content and water distribution, which could explain the similarities in root growth between the two regions of the delved profile. It is, of course, necessary to take into account that “above-average rainfall” occurred at the beginning of the growing season, which could have mitigated the severity of water repellence and thus the differences between the two regions; it may even have contributed to a reduction in root growth in the areas with greater water holding capacity such as that observed by other authors during higher rainfall seasons (e.g. Lampurlanés *et al.* 2001; Plaza-Bonilla *et al.* 2014). It is also possible that the effects of delving on RLD and RMD extended beyond the delving line because the morphological changes that were needed to give rise to improved root growth were much less than those actually observed, and this may have implications for tool spacing and fuel expenditure.

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Chapter 5 Size of subsoil clods affects soil-water availability in sand–clay mixtures

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Principal Author

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Name of Co-Author	Cameron D Grant		
Contribution to the Paper <u>10%</u>	I was principal supervisor of candidate along with Murray& Churchman. I discussed nature of problem, design of experiments, results & outcomes. I introduced candidate to Mathcad for modelling water retention curves, read drafts of manuscript and made minor suggestions/ corrections before submission to journal. I acted as corresponding author for paper and dealt with minor corrections in consultation with candidate, who left to take up a job in WA.		
Signature		Date	6 September 2018
Name of Co-Author	Robert S Murray		
Contribution to the Paper <u>5%</u>	I was co-supervisor of the candidate along with Grant and Churchman. I discussed the nature of the problem, the design of experiments and the results and outcomes. I read drafts of the manuscript and made minor suggestions/corrections before submission to the journal.		
Signature		Date	6 September 2018
Name of Co-Author	Gordon Jock Churchman		
Contribution to the Paper <u>5%</u>	I was co-supervisor of the candidate along with Grant and Murray. I discussed the nature of the problem, the design of experiments and the results and outcomes. I read drafts of the manuscript and made minor suggestions/corrections before submission to the journal.		
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Size of subsoil clods affects soil-water availability in sand–clay mixtures

Giacomo Betti[A], *Cameron D. Grant*[A,B], *Robert S. Murray*[A], *and G. Jock Churchman*[A]

[A]University of Adelaide, School of Agriculture, Food & Wine, Waite Campus PMB 1, Glen Osmond, SA 5064, Australia.
[B]Corresponding author. Email: cameron.grant@adelaide.edu.au

Abstract. Clay delving in strongly texture-contrast soils brings up subsoil clay in clumps ranging from large clods to tiny aggregates depending on the equipment used and the extent of secondary cultivation. Clay delving usually increases crop yields but not universally; this has generated questions about best management practices. It was postulated that the size distribution of the subsoil clumps created by delving might influence soil-water availability (and hence crop yield) because, although the clay increases water retention in the root-zone, it can also cause poor soil aeration, high soil strength and greatly reduced hydraulic conductivity. We prepared laboratory mixtures of sand and clay-rich subsoil in amounts considered practical (10% and 20% by weight) and excessive (40% and 60% by weight) with different subsoil clod sizes (<2, 6, 20 and 45 mm), for which we measured water retention, soil resistance, and saturated hydraulic conductivity. We calculated soil water availability by traditional means (plant-available water, PAW) and by the integral water capacity (IWC). We found that PAW increased with subsoil clay, particularly when smaller aggregates were used ($\leq$6 mm). However, when the potential restrictions on PAW were taken into account, the benefits of adding clay reached a peak at ~40%, beyond which IWC declined towards that of pure subsoil clay. Furthermore, the smaller the aggregates the less effective they were at increasing IWC, particularly in the practical range of application rates (<20% by weight). We conclude that excessive post-delving cultivation may not be warranted and may explain some of the variability found in crop yields after delving.

Additional keywords: aggregate size distribution, soil physical limitation, sandy soils, tillage.

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Introduction

Texture-contrast soils (Isbell 2002) dominate a significant proportion of the cropping lands in the Mediterranean parts of southern Australian and present a peculiar set of soil physical and chemical problems in agriculture (Gardner *et al*. 1992; Hamblin *et al*. 1988; Harper and Gilkes 2004; Harper *et al*. 2000; Rebbeck *et al*. 2007). Typically in these soils, the sandy A horizon with <5% clay experiences severe water repellence at the soil surface, plus low fertility, and the clay-rich subsoil experiences poor soil structure. The two horizons are separated by a sharp boundary, which causes significant bypass flow (Tennant *et al*. 1992; Ritsema and Dekker 2000; National Committee on Soil and Terrain 2009; Hardie *et al*. 2011).

A common approach to ameliorate these soils is to add clay-rich material to the topsoil (Gardner *et al*. 1992; Tennant *et al*. 1992; Ward 1993; Cann 2000; Harper *et al*. 2000; Eldridge 2007; Hall *et al*. 2010; Betti *et al*. 2015), either by spreading or by delving (Desbiolles *et al*. 1997; Cann 2000; May *et al.* 2006; Hall *et al*. 2009, 2010; Bailey *et al*. 2010; Davenport *et al*. 2011). Clay spreading serves to increase soil surface wettability, whereas delving modifies the entire soil profile by bringing up clay-rich subsoil clods and aggregates into the topsoil sand.

The average clay content of the topsoil increases by delving, but many of the clay-rich clods and aggregates remain discrete entities rather than becoming mixed intimately with the sand. An implication is that the affected soil volumes may continue to behave as unmodified pure sand in which plant roots can extract water and nutrients from the clay-rich clods only by growing mainly on or close to their surfaces. If such root growth behaviour is widespread in delved soils, it presents obvious difficulties for predicting the physical and chemical fertility of these soils, because this would require accurate description of the size and spatial distributions of the clay-rich clods and aggregates. This is not a trivial task in soils where the effects of delving operations vary significantly from place to place because of differences between operators and equipment as well as inherent differences in the soil profile being delved. Nevertheless, clay delving has become widespread on texture-contrast soils, so the water retention and transport properties of the root-zone in these highly modified soils need to be understood to enable yield predictions based on plant-available water (PAW).

If it were possible to predict soil hydraulic properties from the ‘average’ physical properties of uniform mixtures of sand and clay, plenty of literature is available on which to base such predictions (e.g. Rijtema 1969; Rawls *et al*. 1982; Brown *et al*. 1985; Gill *et al*. 2004; Fernández-Gálvez and Barahona 2005; Saxton and Rawls 2006; Lipiec *et al*. 2007; Martínez *et al*. 2008; Asgarzadeh *et al*. 2010; Costa *et al*. 2013). However, soils modified by clay delving are far from texturally uniform; in fact, the clumps brought up into the root-zone range in size from tiny aggregates to very large clods as shown schematically in Fig. 1. The larger clods remain distinct from the sand and create a zone with bimodal soil physical properties rather than those of a natural soil having the same 'average' texture. Seeking guidance from the literature on the properties of natural soils having similar average texture can therefore lead to significant errors in prediction of PAW. The properties of a bimodal mixture must take into account the properties of the discrete materials involved. In this regard, the extent to which predictions of PAW could be based on bimodal *v.* uniform mixtures may depend on the size of the clay-rich aggregates. For example, smaller aggregates would be expected to produce physical properties that more closely resemble those of uniform mixtures, particularly when the aggregates of clay are of similar size to the sand particles. Any dispersion of the aggregates would further the extent of mixing with sand. Larger clods would be expected to produce bimodal properties based upon the properties of the discrete materials in proportion to the respective quantities present in the mix. Only minimal effects of dispersion from the surfaces of large clods would be expected.

Theory

The schematic mixture shown in Fig. 1*a* suggests that the average volume of water (m^3) in the mixed soil at a given soil matric head, $\theta(h)_{mix}$ (h, in metres), is approximately the sum of the volumetric water contents ($m^3\,m^{-3}$) of the separate components multiplied by the respective volumes they occupy (m^3):

$$\theta(h)_{\mathrm{mix}} V_{\mathrm{T}} \equiv \theta(h)_{\mathrm{C}} V_{\mathrm{C}} + \theta(h)_{\mathrm{S}} V_{\mathrm{S}} \qquad (1)$$

where $\theta(h)_{mix}$, $\theta(h)_C$ and $\theta(h)_S$ are, respectively, the volumetric water contents of the mixture, the clay-rich aggregates and the sand at a given h; and V_T, V_C, and V_S are their bulk volumes. Assuming that the clay-rich aggregates remain distinct from the sand, Eqn 1 can be rearranged to calculate the weighted average volumetric water content of the total mixture:

$$\theta(h)_{\mathrm{mix}} \cong \theta(h)_{\mathrm{C}} \cdot \frac{V_{\mathrm{C}}}{V_{\mathrm{T}}} + \theta(h)_{\mathrm{S}} \cdot \frac{V_{\mathrm{S}}}{V_{\mathrm{T}}} \qquad (2)$$

The bulk volume each component occupies in the mixture, V_C and V_S, is difficult to measure directly but can be estimated from their respective masses, M_C and M_S (kg), and bulk densities, ρ_C and ρ_S ($kg\,m^{-3}$), which are relatively easy to measure independently. Thus:

$$V_{\mathrm{C}} = \frac{M_{\mathrm{C}}}{\rho_{\mathrm{C}}} \quad \text{and} \quad V_{\mathrm{S}} = \frac{M_{\mathrm{S}}}{\rho_{\mathrm{S}}} \qquad (3)$$

Now, defining PAW ($m^3\ m^{-3}$) as:

$$\mathrm{PAW} \equiv \int_{h=\mathrm{FC}}^{h=\mathrm{WP}} \frac{d\theta}{dh} dh \qquad (4)$$

where FC is field capacity ($h = 1$ m) and WP is the permanent wilting point ($h = 150$ m), the PAW for the total mixture of sand and discrete clay-rich aggregates shown in Fig. 1*a*, PAW_{mix}, can be estimated as:

$$\mathrm{PAW}_{\mathrm{mix}} \cong \mathrm{PAW}_{\mathrm{C}} \times \left[\frac{V_{\mathrm{C}}}{V_{\mathrm{T}}}\right] + \mathrm{PAW}_{\mathrm{S}} \times \left[\frac{V_{\mathrm{S}}}{V_{\mathrm{T}}}\right] \qquad (5)$$

Similarly, the bulk density of the total mixture in Fig. 1*a*, ρ_{mix}, can be calculated from the bulk densities of the distinct components, ρ_C and ρ_S and their proportionate volumes in the total mixture:

$$\rho_{\mathrm{mix}} \cong \rho_{\mathrm{C}} \left[\frac{V_{\mathrm{C}}}{V_{\mathrm{T}}}\right] + \rho_{\mathrm{S}} \left[\frac{V_{\mathrm{S}}}{V_{\mathrm{T}}}\right] \qquad (6)$$

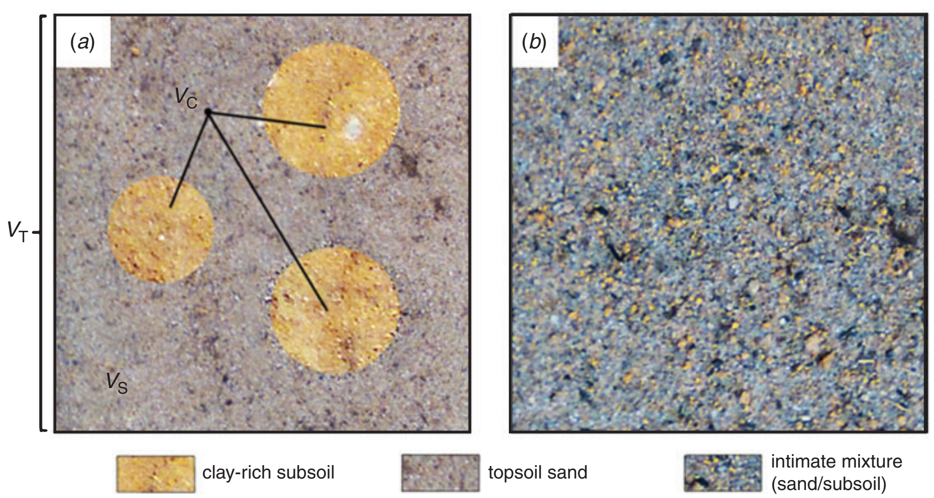

Fig. 1. Schematic representations of (*a*) distinct, clay-rich subsoil aggregates embedded in a matrix of sand, with V_S, V_C and V_T representing the respective volumes of pure sand, pure clay-rich subsoil aggregates, and the total mixture of the two; and (*b*) sand and clay-rich subsoil aggregates mixed intimately in the same proportions.

The extent to which Eqns 5 and 6 hold true for mixtures of sand and clay-rich clods or aggregates created during delving can be used to evaluate whether the delving operations significantly alter the 'texture' or whether the clay-rich aggregates remain distinct entities. This is important to understand, because if the clay-rich aggregates remain largely distinct and isolated (apart from minor dispersion around the external surfaces), any benefit of delving for crop production depends upon the probability of plant roots intercepting the clods. On the other hand, if the texture is more uniformly altered, plant roots can take advantage of potentially improved soil hydraulic properties with greater probability. Thus, if the components in the total mixture remain discrete as depicted in Fig. 1*a*, then Eqns 5 and 6 will hold true. If, on the other hand, a more intimate mixture occurs with the 'average' texture depicted in Fig. 1*b*, then Eqns 5 and 6 will not hold true and the water-holding properties of the mixed soil will reflect the new structural arrangement of the intimately mixed components. The objective of this study was to evaluate the ways in which the size and quantity of clay-rich subsoil aggregates mixed with sand influence the amount of PAW as measured by the *integral water capacity* (IWC) (Groenevelt *et al*. 2001), which modifies the differential water capacity to account for physical limitations.

Materials and methods

Preparation of mixtures of sand and clay-rich subsoil aggregates

The sand and clay-rich subsoil aggregates were collected from texture-contrast soils at two agricultural sites in South Australia, near Coonalpyn (35°41 28 S, 139°53 05 E) and near Bordertown (36°12 52 S, 140°42 08 E). Both sites have shallow sandy topsoils (0.2–0.3 m deep) with an A2e bleached horizon over a sandy clay loam subsoil (Coonalpyn) or sandy clay subsoil (Bordertown) and they were classified as Brown Sodosols (Isbell 2002) or Stagnic Solonetzs (WRB IWG 2007). The sites were chosen as representative of the typical texture-contrast soils in the South East of South Australia that are clay-delved for the amelioration of their inherently poor productivity.

Soil dry bulk density was determined on undisturbed soil cores (0.05 m diameter, 0.05 m height) taken from the sand-textured A horizon and from the upper 0.2 m of the clay-rich B horizon near the maximum depth of tine-penetration during delving. Particle-size distribution (by mechanical separation; Smith and Tiller 1977) and pH and electrical conductivity (EC) in 1 : 5 soil : water suspensions (Rayment 1992) were determined on bulk samples taken beside the soil cores in each horizon (Table 1).

To prepare mixtures that simulated the schematic soils shown in Fig. 1*a*, *b*, we chose large and small aggregates from the B horizon to mix with the sand from the A horizon at both sites. From the Coonalpyn site, four different nominal sizes of clay-rich subsoil aggregates were gathered from the B horizon: <2 mm (passed through a 2-mm sieve), 6 mm (collected between sieves having grids of 4.75 and 6.7 mm), 20 mm and 45 mm (separated manually by measuring three orthogonal diameters). The subsoil clods from the Bordertown site were generally smaller than those from Coonalpyn, so only three clay-rich subsoil aggregate sizes were possible: <2, 6 and 20 mm (illustrated in Fig. 2). The different aggregate sizes were mixed with sand in weight/weight proportions of 10%, 20%, 40% and 60%, with the exception that, for the 45-mm aggregates from Coonalpyn, the smallest possible proportion was 20% (i.e. one clay-rich clod per core) and the largest proportion possible was 40% (two clay-rich clods per core).

Air-dried samples of the different size fractions of the clay-rich aggregates were mixed with the sand by gently folding the materials together on paper, dividing the mix into quarters, re-mixing and repeating three times. The clay content of subsamples of the different mixtures was determined by dispersion and sedimentation (Table 1) and nominal textural classes were assigned. The Coonalpyn mixtures were placed in stainless-steel rings of 5 cm height and 11 cm diameter (to accommodate clods having diameters up to 45 mm), and the Bordertown mixtures were placed in smaller stainless-steel rings of 5 cm height and 5 cm diameter. To allow consolidation of the mixtures in the rings, they were subjected to three preliminary cycles of wetting and air-drying (Lipiec *et al*. 2007; Shiel *et al*. 1988). The bulk density of each mixture was calculated from its total mass (corrected for the measured water content) and the volume occupied in its ring, taking into account any irregular shapes of the upper surface caused by protruding clay-rich aggregates or clods in the mixtures by weighing a quantity of very fine sand of known bulk density required to cover the protrusions. For samples comprising 40% and 60% of clay-rich aggregates <2 mm, some shrinkage occurred away from the edges of the rings after the preliminary wetting and drying, so the sample volumes were determined by removing them from

Table 1. Physical and chemical properties of bulk samples of the A-horizon sand and the B-horizon clay-rich subsoil from Coonalpyn and Bordertown, South Australia

Values in parentheses represent standard deviation

Soil horizon	Dry bulk density (kg m^{-3})	% Clay (<2 µm)	% Sand (20–2000 µm)	pH (1 : 5 soil : water)	EC (dS m^{-1}) (1 : 5 soil : water)
		Coonalpyn, South Australia			
A-horizon sand	1551 (13)	1	97	6.2	0.02
B-horizon	1723 (21)	28	71	7.1	0.04
		Bordertown, South Australia			
A-horizon sand	1499 (11)	2	92	6.5	0.02
B-horizon	1806 (19)	47	61	8.4	0.18

Fig. 2. Image of the nominal sizes of clay-rich subsoil aggregates used in the Bordertown mixtures. The smallest aggregates passed through a 2-mm sieve, the intermediate aggregates were retained on a 6-mm sieve, and the large aggregates were retained on a 20-mm sieve.

their rings after all measurements were taken, sealing them in a paraffin coating and measuring their volumes by displacement in water.

Integral water capacity

Volumetric water retention (m^3 water m^{-3} total) was measured at saturation plus seven different matric heads (m) by using saturated ceramic plates connected to hanging columns of water or placed in water-extraction chambers connected to pressurised N_2 gas until their weights did not change. Using the software Mathcad 14 (Parametric Technology Corporation 2007), the water retention data were fitted to the Groenevelt–Grant equation (Grant *et al.* 2010) anchored at the nominal wilting point in the relation:

$$\theta(h) = \theta_a + k_1 \cdot \left\{ \exp\left[-\left(\frac{k_0}{h_a} \right)^n \right] - \exp\left[-\left(\frac{k_0}{h} \right)^n \right] \right\} \quad (7)$$

where θ_a and h_a are, respectively, the volumetric water content and the matric head at the chosen anchor point *a* (permanent wilting point, θ(150 m) in this case), k_1 and *n* are dimensionless fitting parameters and k_0 is a fitting parameter having units of the matric head (m). The differential water capacity, C(h) $\equiv d\theta/dh$, was determined as the first derivative of Eqn 7 and used to calculate the conventional PAW according to Eqns 4 and 5 (h_{FC} = 1 m, h_{PWP} = 150 m) and the IWC of Groenevelt *et al.* (2001):

$$\text{IWC} \equiv \int_0^\infty \left(\prod_{i=1}^{n} \omega_i(h) \right) C(h) dh \quad (8)$$

where $\omega_i(h)$ are weighting functions (i = 1 to *n*) that have values ranging between 1 (no limitation to water availability) and 0 (complete limitation) to account for multiple possible soil physical restrictions that limit water availability. The soil restrictions for which weighting functions were applied in this study included poor soil aeration, $\omega_A(h)$, limitations to plant water uptake due to rapid drainage (excessively large hydraulic conductivity, $\omega_{k\text{-WET}}(h)$) and excessively small unsaturated hydraulic conductivity, $\omega_{k\text{-DRY}}(h)$, and increasingly large soil resistance to penetration, $\omega_{SR}(h)$. The nature of the functions used was similar to those presented in Groenevelt *et al.* (2001) and Nang (2012). For example, the weighting function used to account for poor soil aeration was:

$$\omega_A(h) = \begin{cases} 0 & 0 < h < h_{minA} \\ \left\{ \dfrac{\log\left(\frac{h}{h_{minA}}\right)}{\log\left(\frac{h_{maxA}}{h_{minA}}\right)} \right\} & h_{minA} < h < h_{maxA} \\ 1 & h > h_{maxA} \end{cases} \quad (9)$$

where h_{minA} was the matric head corresponding to a volumetric water content $\theta_{minA} = \theta_s - 0.1$, where θ_s is the saturated volumetric water content, and 0.1 represents the minimum volumetric air content of 0.1 m^3 air m^{-3} total required by many plants (da Silva *et al.* 1994); and h_{maxA} was the matric head corresponding to a well-aerated soil with a volumetric water content $\theta_{maxA} = \theta_s - 0.15$, where 0.15 represents an adequate volumetric air content of 0.15 m^3 air m^{-3} total (Groenevelt *et al.* 2001).

The weighting function used to account for increasing soil resistance was (Groenevelt *et al.* 2001):

$$\omega_{SR}(h) = \begin{cases} 1 & 0 < h < h_{minSR} \\ \frac{2.5 - SR(h)}{2} & h_{minSR} < h < h_{maxSR} \\ 0 & h > h_{maxSR} \end{cases} \quad (10)$$

where h_{minSR} represents the matric head above which the soil resistance begins to restrict root exploration of the soil and thus access to water (corresponding to SR(h) = 0.5 MPa), and h_{maxSR} represents the matric head at which roots are completely prevented from exploring the soil and thus from taking up water (corresponding to SR(*h*) = 2.5 MPa), in accordance with evidence in the literature (Cockroft *et al.* 1969; Cockroft and Olsson 2000). To obtain the SR(*h*) function, soil resistance to penetration (SR, MPa) was measured on each sample in its ring at different matric heads over a period of months by using a LF-plus penetrometer (Lloyd Instruments, Bognor Regis, UK) with a 2.5-mm stainless-steel cone (30° angle) and a 2-mm-diameter recessed shaft advanced at 3 mm min^{-1}. The average measured force (N) within the central 20-mm section of each core was converted to pressure using the cross-sectional area of the cone base, plotted as a function of the matric head, *h*, and fitted to a power function:

$$SR(h) = \sigma h^b \quad (11)$$

where the coefficients σ and *b* are fitting parameters calculated using a Levenberg–Marquardt least-squared optimisation procedure in Mathcad 14.

For the weighting function accounting for the limitations to plant water uptake due to high and low soil hydraulic conductivity, we first estimated the unsaturated hydraulic

Table 2. Clay content, texture, measured and predicted bulk density, hydraulic conductivity and soil resistance for sand mixed with 0–100% clay-rich subsoil in different aggregate sizes (<2, 6, 20 and 45 mm)

Values in parentheses represent standard deviation for the ρ_b measured data and coefficient of variation for the K_s data. n.a., Not applicable

Clay-rich subsoil (% by wt)	Nominal diam. clay-rich aggregates (mm)	% <2 µm	Textural class	ρ_b (kg m^{-3}) Measured	ρ_b (kg m^{-3}) Predicted from Eqn 6	K_s (m s^{-1})	Rijtema K(*h*) function parameters (Eqns 12, 13) Wet-end α (m^{-1})	Rijtema K(*h*) function parameters (Eqns 12, 13) Dry-end *a* ($m^{2.4}$ day^{-1})	Parameter in $SR(h)=\sigma h^b$ (Eqn 10) σ (equal to SR(1))	*b*	SR(150) (MPa)
					Coonalpyn						
0%	n.a.	1	Sand	1551 (13)	n.a.	1.3×10^{-4} (0.14)	13.8	9.98×10^{-6}	0.42	0.02	0.46
	<2			1630 (10)		7.7×10^{-5} (0.05)	13.80		0.45	0.15	0.94
10%	6	4	Sand	1640 (10)	1630	7.9×10^{-5} (0.16)	13.80	1.73×10^{-4}	0.43	0.07	0.60
	20			1650 (20)		1.1×10^{-4} (0.04)	13.80		0.44	0.01	0.48
	<2			1610 (5)		3.2×10^{-5} (0.03)	8.22		0.48	0.28	1.94
20%	6	7	Sand	1630 (10)	1640	7.0×10^{-5} (0.01)	13.80	1.73×10^{-4}	0.48	0.05	0.61
	20			1640 (10)		9.4×10^{-5} (0.09)	13.80		0.40	0.07	0.58
	45			1660 (10)		9.1×10^{-5} (0.08)	13.80		0.46	0.17	1.01
	<2			1590 (10)		4.7×10^{-5} (0.54)	5.00		0.35	0.37	2.26
40%	6	12	Loamy sand	1620 (10)	1660	3.3×10^{-5} (0.16)	8.22	8.34×10^{-5}	0.31	0.14	0.63
	20			1670 (10)		5.0×10^{-5} (0.13)	13.80		0.36	0.11	0.62
	45			1680 (20)		7.5×10^{-5} (0.02)	13.80		0.54	0.22	1.66
	<2			1570 (10)		3.5×10^{-6} (0.01)	82.20		0.70	0.31	3.28
60%	6	18	Sandy loam	1600 (10)	1680	1.2×10^{-5} (0.04)	82.20	3.58×10^{-4}	0.33	0.25	1.16
	20			1680 (30)		5.0×10^{-5} (0.16)	8.22		0.37	0.10	0.61
100%	0< *x* <45	28	Sandy clay loam	1723 (21)	n.a.	4.3×10^{-8} (0.16)	3.53	5.71×10^{-5}	0.39	0.54	5.80
					Bordertown						
0%	n.a.	2	Sand	1499 (10)	n.a.	5.2×10^{-5} (0.10)	13.80	9.98×10^{-6}	0.47	0.03	0.55
	<2			1530 (10)		1.6×10^{-5} (0.27)	8.22		0.53	0.17	1.22
10%	6	7	Sand	1510 (5)	1517	3.0×10^{-5} (0.05)	8.22	1.73×10^{-4}	0.43	0.14	0.87
	20			1520 (20)		3.0×10^{-5} (0.13)	8.22		0.44	0.06	0.6
	<2			1510 (20)		5.3×10^{-6} (0.20)	5.00		0.42	0.35	2.40
20%	5	11	Loamy sand	1520 (10)	1545	2.4×10^{-5} (0.11)	8.22	2.6×10^{-4}	0.43	0.20	1.18
	20			1520 (20)		2.5×10^{-5} (0.06)	8.22		0.33	0.08	0.50
	<2			1530 (30)		3.1×10^{-7} (0.34)	5.62		0.32	0.41	2.56
40%	6	21	Sandy clay loam	1520 (20)	1603	9.4×10^{-6} (0.17)	5.00	4.2×10^{-4}	0.21	0.36	1.3
	20			1580 (20)		1.4×10^{-5} (0.05)	8.22		0.18	0.38	1.25
	<2			1500 (10)		1.7×10^{-7} (1.00)	2.69	3.58×10^{-4}	0.23	0.48	2.52
60%	6	30	Sandy clay loam	1500 (40)	1667	6.6×10^{-6} (0.20)	5.62	3.58×10^{-4}	0.22	0.39	1.60
	20			1620 (10)		8.6×10^{-6} (0.04)	5.00	5.33×10^{-4}	0.06	0.82	3.65
100%	0< *x* <45	47	clay	1806 (19)	n.a.	7.1×10^{-9} (0.19)	2.48	2.68×10^{-5}	0.32	0.60	6.45

conductivity function, K(h), for each sample. We used Rijtema's (1969) two functions (adapted from Gardner 1958) to create K(h) functions for soil in the 'wet' domain:

$$K_{wet}(h) = K_s \exp(-\alpha h) \quad (12)$$

and for the 'dry' domain:

$$K_{dry}(h) = ah^{-1.4} \quad (13)$$

where the values used for the fitting parameters, α (m^{-1}) and a ($m^{2.4}$ day^{-1}), depend on soil texture (published in Rijtema 1969). The saturated hydraulic conductivity, K_s, was measured on each sample, including the sand alone and the subsoil clay-rich aggregates alone (three replicates) by using a constant head method (Reynolds *et al*. 2000). Values for the coefficients α and a (Table 2) were selected empirically by matching the data collected on our mixtures (e.g. water retention) with those from soils of similar texture presented in Rijtema (1969), with the 'wet' domain set as the range of matric heads $h = 0$–1 m and the 'dry' domain was set as the range of matric heads $h = 1$–150 m. The complete K(h) curves were consequently obtained using Eqns 12 and 13, thus defined:

$$K(h) \equiv \left| \begin{matrix} K_{wet}(h), & K_{wet}(h) \geq K_{dry}(h) \\ K_{dry}(h), & K_{wet}(h) \leq K_{dry}(h) \end{matrix} \right| \quad (14)$$

The weighting function $\omega_{kWET}(h)$, accounting for the restriction to plant water uptake due to rapid drainage of water in the wet range (Groenevelt *et al*. 2001), was:

$$\omega_{kWET}(h) = \left(\frac{K_r(1)}{K_r(h)}\right) \quad 0 < h < 1 \quad (15)$$

in which $K_r(h)$ is the relative hydraulic conductivity, $K(h)/K_s$. With no other information available, the range of matric heads at the wet end was arbitrarily set between $h = 0$ and 1 m. Similarly, $\omega_{kDRY}(h)$, accounting for the restriction to plant water uptake due to low (declining) hydraulic conductivity in the dry end, was:

$$\omega_{kDRY}(h) = \frac{1 - \frac{K_r(h)}{K_r(150)}}{1 - \frac{K_r(h_{limK})}{K_r(150)}} \quad h_{limK} < h < 150\,m \quad (16)$$

where h_{limK} is the matric head from which the declining K(h) starts restricting water uptake to plants. From this point, we consider the unsaturated hydraulic conductivity to be so small that it is unable to deliver enough water to accommodate plant demand. The value of h_{limK} depends on environmental conditions and plant species, and little published information is available to determine this point. We therefore applied the

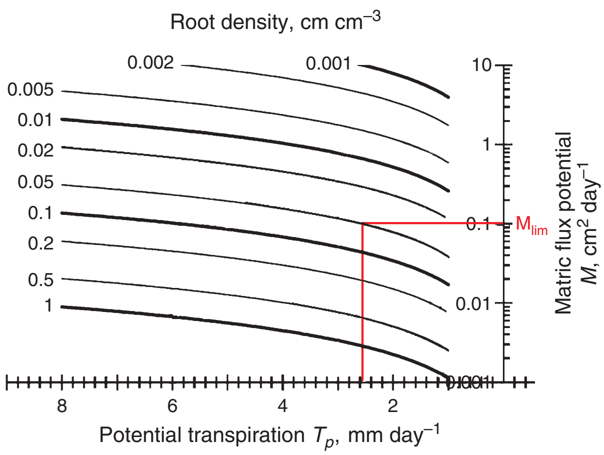

Fig. 3. Nomogram, after van Lier *et al*. (2006), showing a specified root length density and potential transpiration rate used to identify a limiting matric flux transform, M_{lim}, and thus the initial matric head at which soil hydraulic limitations begin to limit soil-water availability.

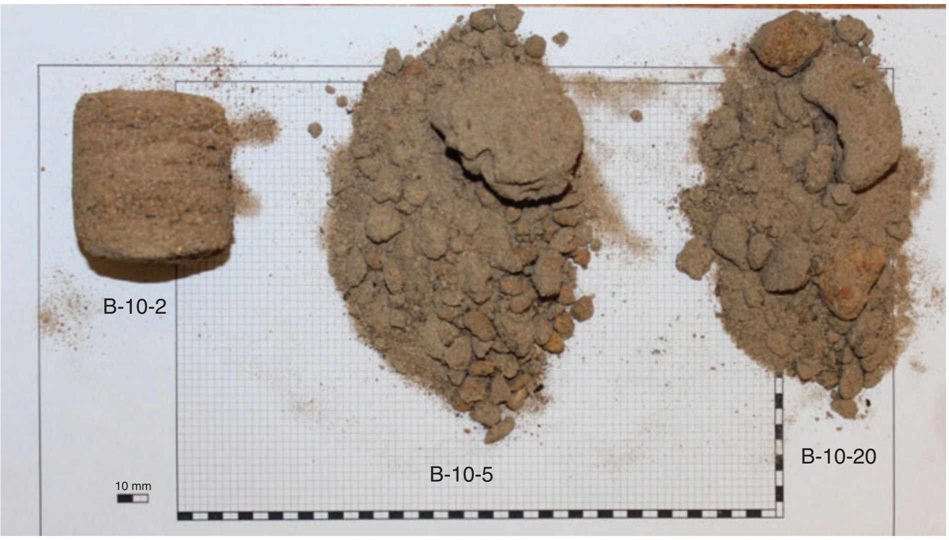

Fig. 4. Differences in visual cohesion of Bordertown soil cores containing 10% clay-rich subsoil in nominal aggregate sizes (left to right): <2 mm (B-10-2), 6 mm (B-10-5), and 20 mm (B-1-20). Observations taken immediately after soils were pushed from confining rings.

method proposed by van Lier *et al*. (2006), which determines the value of h_{limK} (which those authors call 'limiting soil hydraulic condition') through a model based on transpiration demand (mm day^{-1}) plus plant root density (m m^{-3}) and the matric flux potential ($M(h)$ cm^2 day^{-1}) as a parameter to define hydraulic demand. (Note, however, that matric flux potential, $M(h)$, is more correctly named 'matric flux transform' (see Grant and Groenevelt 2015).) van Lier *et al*. (2006) produced a nomogram to estimate the matric flux transform at which water availability starts to become limiting. For the purposes of this paper, a value of $M_{\mathrm{lim}} = 0.1$ cm^2 day^{-1} was chosen on the nomogram in Fig. 3 to define the environmental conditions. For each soil $h_{\mathrm{lim.K}}$ was calculated using the relation:

$$M_{\mathrm{lim}} = M(h_{\mathrm{limK}}) = \int_h^{150} \mathrm{K}(h_{\mathrm{limK}})dh \qquad (17)$$

The integral water capacity, IWC, was calculated according to Eqn 8 using Eqns 9, 10, 15 and 16 as required to identify individual and overall effects of the physical restrictions on soil water availability. For mixtures containing large aggregates, their proportional effects on IWC were calculated according to the approach embodied in Eqns 5 and 6, namely:

$$IWC_{mix} \equiv \int_0^{\infty} \omega_{\mathrm{A_{mix}}}(h)\left\{C_{\mathrm{C}}(h)\cdot\left[\frac{V_{\mathrm{C}}}{V_{\mathrm{T}}}\right] + [\omega_{\mathrm{SR}}(h)\cdot\omega_{\mathrm{kDRY}}(h)\cdot \omega_{\mathrm{kWET}}(h)\cdot C_S(h)]\cdot\left[\frac{V_{\mathrm{S}}}{V_{\mathrm{T}}}\right]\right\}dh \qquad (18)$$

As with Eqn 5, Eqn 18 relates to a bimodal soil mixture such as that shown in Fig. 1*a*, where $C_{\mathrm{C}}(h)$ and $C_{\mathrm{S}}(h)$ are the respective water capacities of the clay-rich subsoil and the sand, and assumes (as also observed in the field) that plant roots grow primarily in the sand near the external surfaces of the subsoil aggregates rather than within them. On this basis, no physical limitations to plant water uptake from the subsoil aggregates need to be considered for $C_C(h)$. By contrast, soil resistance and hydraulic conductivity were considered limiting factors in the sand, so their weighting functions, $\omega_{\mathrm{SR}}(h)$, $\omega_{\mathrm{KWET}}(h)$, and $\omega_{\mathrm{KDRY}}(h)$ all need to be considered for $C_{\mathrm{S}}(h)$

Table 3. Minimum and maximum matric heads (h_{min} and h_{max}, m) used as limits in Eqns 9, 10 and 16 to calculate the integral water capacity (IWC) for mixtures of sand and clay-rich subsoil

Values in parentheses represent standard deviation. n.a., Not applicable

Clay-rich subsoil (% by wt)	Nominal diam. clay-rich aggregates (mm)	Poor soil aeration Eqn 9: h_{minA} at θ_{minA} = 0.1 m^3 air m^{-3}	Poor soil aeration Eqn 9: h_{maxA} at θ_{maxA} = 0.15 m^3 air m^{-3}	Soil resistance Eqn 10: h_{minSR} at SR = 0.5 MPa	Soil resistance Eqn 10: h_{maxSR} at SR = 2.5 MPa	Hydraulic conductivity Eqn 16: h_{limK} at M_{lim} = 0.1 cm^2 day^{-1}
			Coonalpyn			
0%	n.a.	0.23 (0.00)	0.29 (0.00)	>10^3	>10^3	4.8
	2	0.31 (0.00)	0.39 (0.01)	2.0	>10^3	
10%	6	0.33 (0.00)	0.44 (0.04)	10.9	>10^3	101
	20	0.30 (0.01)	0.37 (0.01)	>10^3	>10^3	
	2	0.27 (0.03)	0.46 (0.04)	1.2	376	
20%	6	0.18 (0.01)	0.29 (0.02)	2.1	>10^3	101
	20	0.21 (0.01)	0.32 (0.01)	20.1	>10^3	
	45	0.20 (0.02)	0.30 (0.02)	1.6	>10^3	
	2	0.37 (0.02)	0.80 (0.05)	2.6	196	
40%	6	0.26 (0.01)	0.46 (0.02)	28.9	>10^3	70
	20	0.24 (0.01)	0.38 (0.02)	18.9	>10^3	
	45	0.24 (0.00)	0.36 (0.00)	0.70	957	
	2	0.29 (0.01)	0.81 (0.03)	0.3	54	
60%	6	0.11 (0.00)	0.28 (0.02)	5.0	>10^3	123
	20	0.17 (0.01)	0.33 (0.03)	19.4	>10^3	
100%	n.a.	4.3 (0.81)	21.5 (24.3)	1.6	32	53
			Bordertown			
0%	n.a.	0.32 (0.00)	0.41 (0.00)	6.5	>10^3	4.8
	2	0.34 (0.04)	0.44 (0.04)	0.68	>10^3	
10%	6	0.37 (0.01)	0.47 (0.00)	2.8	>10^3	101
	20	0.37 (0.02)	0.48 (0.01)	8.7	>10^3	
	2	0.28 (0.06)	0.46 (0.08)	1.7	169	
20%	6	0.39 (0.04)	0.54 (0.05)	2.1	>10^3	115
	20	0.41 (0.01)	0.54 (0.01)	150	>10^3	
	2	0.35 (0.01)	0.58 (0.03)	2.9	142	
40%	6	0.47 (0.10)	0.93 (0.20)	10.6	923	127
	20	0.25 (0.08)	0.43 (0.11)	13.7	946	
	2	0.36 (0.09)	0.65 (0.15)	5.2	146	123
60%	6	0.46 (0.07)	1.11 (0.18)	7.8	469	123
	20	0.21 (0.03)	0.47 (0.08)	13.7	95	131
100%	n.a.	9.8 (6.3)	44.5 (29.7)	2.1	31	23

in Eqn 18. Aeration of the total mixture, however, needs to be accounted for in Eqn 18 by placing the weighting function, $\omega_{Amix}(h)$, outside the brackets; in this context, $\omega_{Amix}(h)$ uses the water-retention curve of the sand adjusted downward to remove the fractional volume of clay aggregates, $V_C\ V_T^{-1}$, which does not contribute to aeration (so θ_{minA} of the mix equals θ_{minA} of the sand minus $V_C\ V_T^{-1}$). Similarly, θ_{maxA} of the mix equals θ_{maxA} of the sand minus $V_C\ V_T^{-1}$.

Results and discussion

Bulk density and soil cohesion

The average bulk density of all mixtures for both the Coonalpyn and Bordertown sites increased with increasing amounts of clay-rich subsoil aggregates mixed with the pure A-horizon sand (Table 2). In accordance with the model proposed in Fig. 1*a*, the Coonalpyn samples containing large clay-rich aggregates (i.e. 20 and 45 mm) produced bulk densities that were equal to (or slightly greater than) that predicted by Eqn 6 with minor exceptions for the Bordertown samples. Similarly, the samples containing small clay-rich aggregates (i.e. <2 mm, as in Fig. 1*b*) generally produced bulk densities that were less than, or equal to, that predicted by Eqn 6. Samples containing clay-rich aggregates of intermediate size (i.e. 6 mm) gave variable bulk densities, particularly with the lesser mix proportions (i.e. ≤20% by weight). However, for the greater mix proportions (i.e. 40% and 60% by weight), the bulk densities of the samples containing the intermediate 6-mm aggregates tended to behave like those having <2-mm aggregates, such that their bulk densities were less than, or equal to, that predicted by Eqn 6. This suggests that when sufficient quantities of clay-rich subsoil material are added to sand, the smaller the aggregates the more likely they are to form intimate mixtures having a lower average bulk density than their discrete components.

When lesser quantities of fine, clay-rich material are added to sand, the packing arrangements may not form intimate structural mixtures (as suggested by the bulk densities) but the cohesive behaviour is nevertheless affected. Figure 4 suggests that the

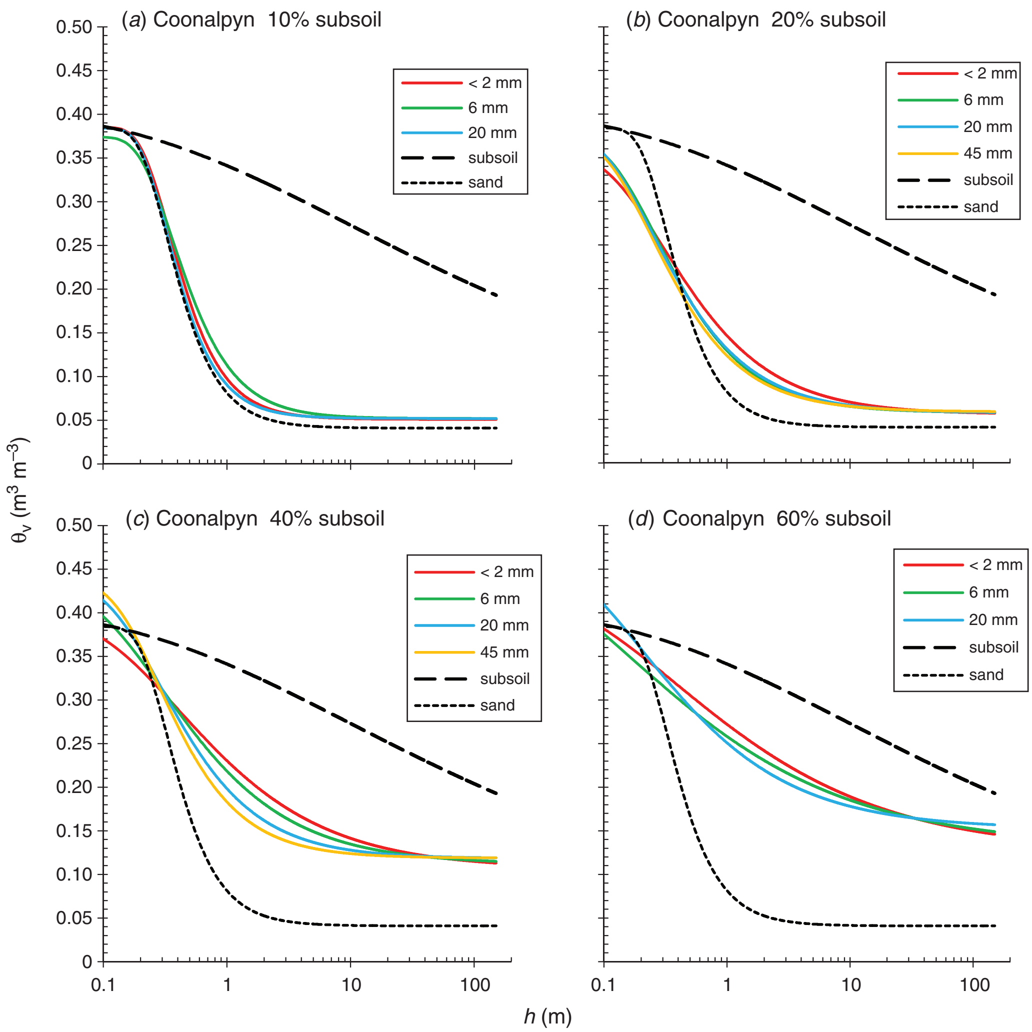

Fig. 5. Water retention curves for Coonalpyn sand mixed with increasing quantities of clay-rich subsoil (10%, 20%, 40% and 60% by weight) of different sized aggregates (<2 mm, 6 mm, 20 mm, 45 mm).

addition of only 10% <2-mm clay-rich aggregates was sufficient to generate a firm, cohesive soil core, whereas the same quantity of intermediate (6-mm) or large (20-mm) clay-rich aggregates generated very little overall cohesion; the large aggregates simply fell away from the loose sand as soon as the confining ring was removed.

Soil resistance to penetration

For both soils, resistance to penetration as a function of soil matric head, SR(h), increased with increasing amounts of clay-rich subsoil aggregates in the mix, consistent with the power function shown in Eqn 11, the parameters for which are listed in Table 2. With the exception of the two treatments containing very large aggregates (20% and 40% of 45-mm clay-rich subsoil aggregates, Coonalpyn), soil resistance increased with decreasing size of clay-rich aggregates in the mixtures, especially with aggregates <2 mm at drier soil matric heads. The SR(h) functions showed that most of the mixtures, especially the Bordertown samples, had low penetration resistance across all but the very driest soil matric heads ($h = 150$ m); even at $h = 150$ m, however, penetration resistance rarely exceeded 2.5 MPa. Despite large variability for both Coonalpyn and Bordertown samples, the mixtures that contained larger aggregates tended to offer low soil resistance to penetration, primarily because the probability of the penetrometer encountering a clay-rich aggregate was low in these mixtures (i.e. small number of large aggregates in the mix). The lower probability of hitting an aggregate was reflected in the greater standard deviation of the mean soil resistance for the mixtures with large aggregates at most suctions (data not shown).

The initial and final matric heads, h_{minSR} and h_{maxSR}, respectively, at which the value of SR(h) equalled 0.5 and 2.5 MPa for each soil mixture are reported in Table 3; these

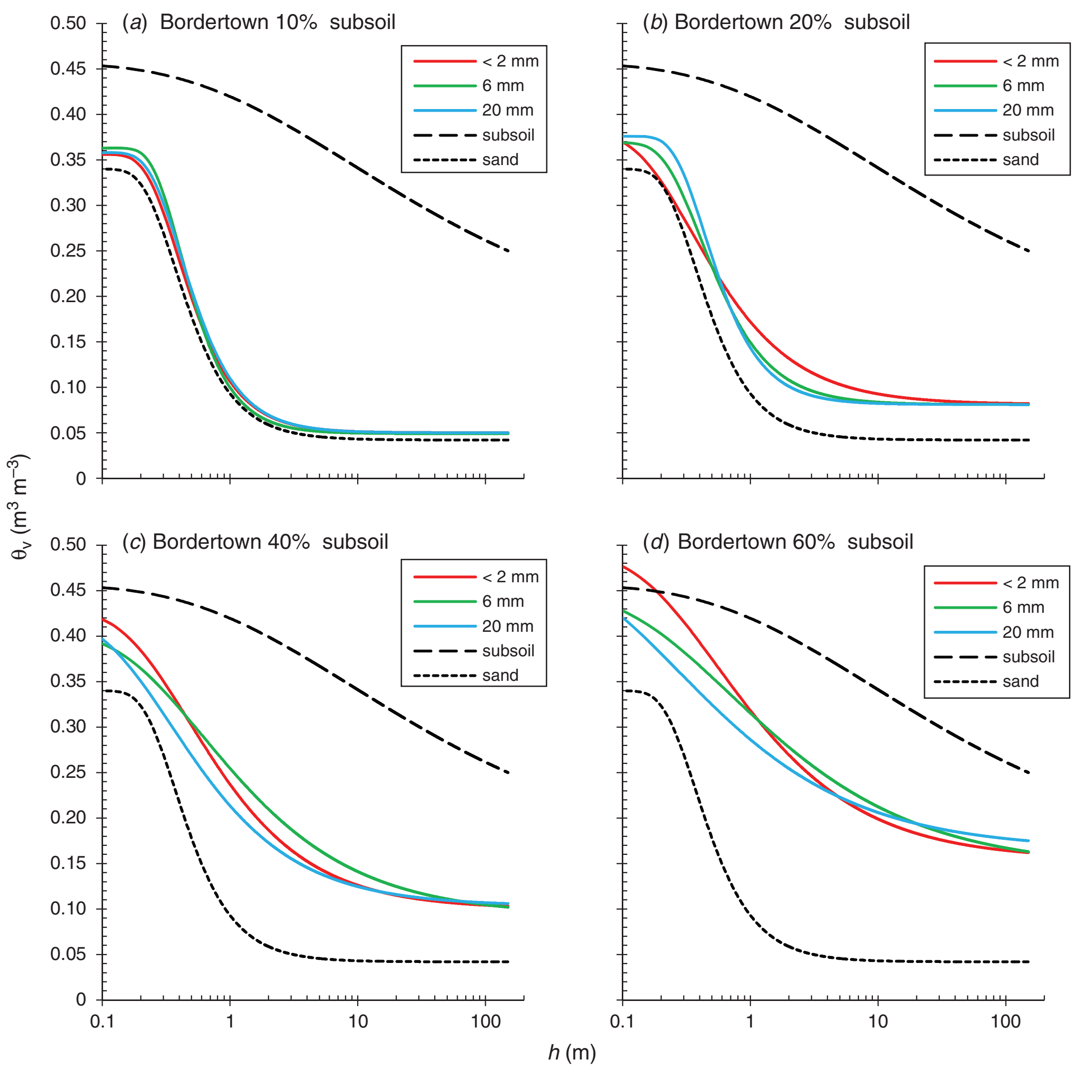

Fig. 6. Water retention curves for Bordertown sand mixed with increasing quantities of clay-rich subsoil (10%, 20%, 40% and 60% by weight) of different sized aggregates (<2 mm, 6 mm, 20 mm, 45 mm).

Table 4. Parameters from Eqn 6 to describe the water-retention curves, plus estimates of plant-available water (PAW, mm m^{-1}) from Eqns 4 and 5 for mixtures of sand and clay-rich subsoil, as well as for similar textures from the literature

Values in parentheses represent standard deviation. SSE represents the sum of square errors between the predicted and measured volumetric water contents

Site	% Clay-rich aggregates in mix	Size of clay-rich aggregates (mm)	Parameters for Eqn 6 k_0 (m)	k_1	n	θ_a	SSE	Estimates of Plant Available Water (PAW, mm m^{-1}) Eqn 4	Eqn 5	Based on soil texture		Source
Coonalpyn	0%	n.a.	0.276	0.347	1.584	0.040	4.2×10^{-4}	40 (0)	n.a.			
	10%	2	0.347	0.334	1.789	0.051	1.2×10^{-3}	47 (4)				
		6	0.366	0.322	1.549	0.052	3.1×10^{-3}	46 (6)	50 (1)			
		20	0.331	0.332	1.892	0.052	2.2×10^{-3}	39 (1)				
	20%	2	0.305	0.302	0.873	0.057	1.6×10^{-4}	89 (4)		Sand	13 to 80	1, 3
		6	0.269	0.315	1.040	0.058	1.9×10^{-3}	71 (2)	59 (2)			
		20	0.246	0.326	0.974	0.058	1.4×10^{-3}	73 (4)				
		45	0.245	0.316	1.053	0.059	2.1×10^{-3}	64 (3)				
	40%	2	0.403	0.289	0.638	0.113	3.3×10^{-4}	118 (10)				
		6	0.297	0.318	0.737	0.115	1.6×10^{-3}	103 (5)	79 (5)	Loamy sand	80	4
		20	0.286	0.315	0.980	0.119	2.0×10^{-3}	79 (6)				
		45	0.275	0.317	1.149	0.119	9.7×10^{-4}	65 (2)				
	60%	2	0.388	0.305	0.446	0.146	2.6×10^{-4}	126 (2)				
		6	0.170	0.341	0.432	0.149	1.1×10^{-3}	109 (2)	100 (7)	Sandy loam	48 to 188	2, 3, 4
		20	0.209	0.321	0.641	0.157	1.5×10^{-4}	94 (4)				
	100%	n.a.	9.534	0.344	0.248	0.193	10.0×10^{-4}	145 (13)	n.a.	Sandy clay loam	59 to 236	1, 2
Bordertown	0%	n.a.	0.367	0.313	1.67	0.043	5.4×10^{-4}	53 (0)	n.a.			
	10%	2	0.392	0.306	1.696	0.050	6.9×10^{-4}	57 (6)				
		6	0.410	0.314	1.947	0.049	6.4×10^{-4}	51 (2)	62 (1)	Sand	13 to 80	1, 3
		20	0.411	0.308	1.724	0.050	9.5×10^{-4}	60 (5)				
	20%	2	0.349	0.299	0.966	0.082	1.5×10^{-3}	90 (12)				
		6	0.409	0.288	1.461	0.081	7.9×10^{-4}	69 (8)	71 (2)	Loamy sand	80	4
		20	0.440	0.295	1.755	0.081	8.2×10^{-4}	62 (5)				
	40%	2	0.471	0.328	0.816	0.103	1.2×10^{-3}	134 (6)				
		6	0.612	0.312	0.638	0.102	1.2×10^{-3}	152 (4)	91 (5)			
		20	0.341	0.316	0.788	0.106	1.6×10^{-3}	107 (14)				
	60%	2	0.546	0.337	0.672	0.162	1.3×10^{-3}	155 (22)		Sandy clay loam	59 to 236	1, 2
		6	0.687	0.304	0.514	0.163	1.3×10^{-3}	152 (4)	113 (8)			
		20	0.275	0.310	0.544	0.175	1.4×10^{-3}	110 (15)				
	100%	n.a.	0.373	0.298	1.696	0.250	9.5×10^{-5}	161 (14)	n.a.	Clay	150 to 236	1, 4

Sources: MacGillivray and Doneen (1942); Kramer (1949, table 3, p. 61); Marshall *et al.* (1996, table 10.1, p. 251); and Or *et al.* (2012, drawn from fig. 4.8).

determined the transition points in the weighting function for high soil resistance (Eqn 10) used to calculate the integral water capacity, IWC.

Saturated hydraulic conductivity

As might be expected, the addition of increasing amounts of clay-rich aggregates to the sand reduced the mean saturated hydraulic conductivity, K_s, by several orders of magnitude for both the Coonalpyn and Bordertown soils (Table 2). Even as little as 10% clay-rich aggregates caused a significant reduction in K_s. Consistent with the model depicted in Fig. 1, smaller clay-rich aggregates reduced the mean K_s to a greater extent than larger clay-rich aggregates (Table 2). For the same quantity of clay added, the finer, more intimately mixed aggregates generated smaller pores in the mixtures, whereas the larger aggregates left significant regions of unadulterated sand with large pores to conduct water. The standard deviations of the mean K_s values shown in Table 2 were lower for the samples containing <2-mm aggregates, confirming their greater uniformity of mixing relative to the larger aggregate fractions. The effect of the unsaturated hydraulic conductivity on soil water availability using IWC is outlined below in conjunction with the other limiting soil factors.

Water-retention curves and soil water availability

The water-retention curves for the mixtures of sand and clay-rich aggregates are shown in Fig. 5 (Coonalpyn) and Fig. 6 (Bordertown), and the fitting parameters in Eqn 8 for each curve are listed in Table 4. With the exception at the wet end in the Coonalpyn samples (0–0.5 m matric head), the curves for undisturbed pure sand and for undisturbed clay-rich subsoil formed an envelope surrounding the curves for all of the mixtures. As one might expect, the water-retention curves, without exception, moved away from the pure sand and upward towards the curves for pure clay-rich subsoil as the proportion of clay-rich aggregates in each mixture increased. In general, across the range of suctions between $h = 0.1$ and 1 m, the slope of the water-retention curves increased with increasing aggregate size in the order 2 mm <6 mm <20 mm <45 mm, with the only exception of the Bordertown mixtures at 60% subsoil

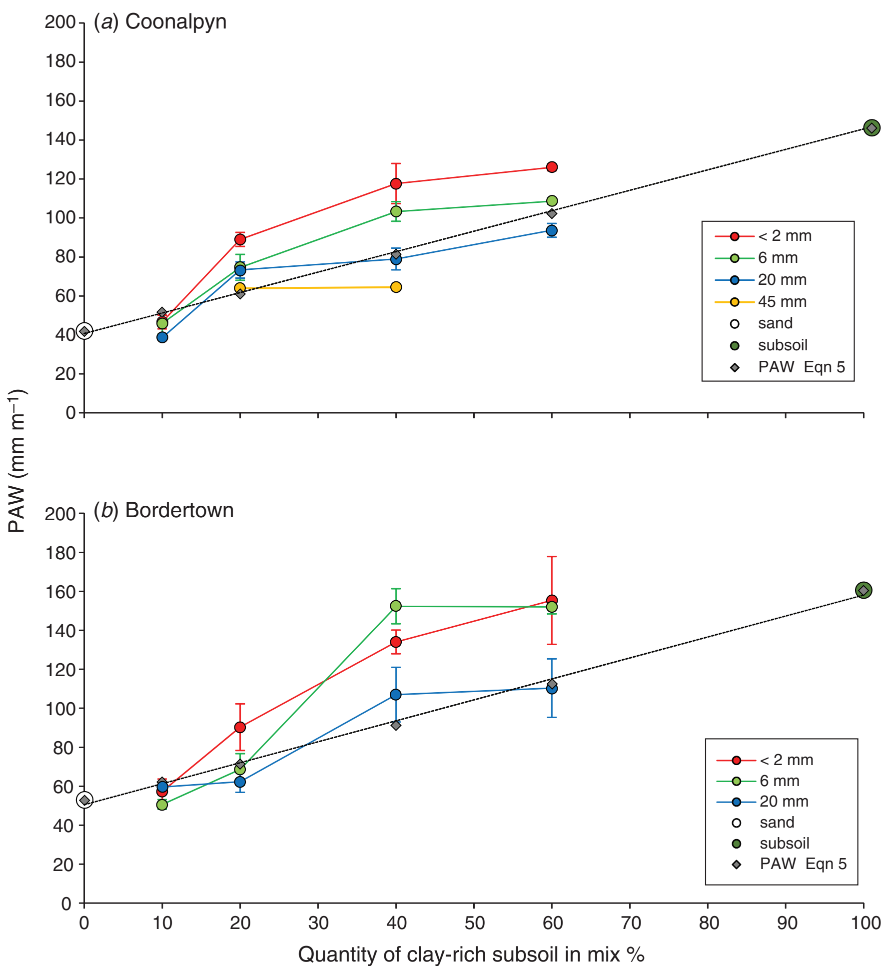

Fig. 7. Classical plant-available water (PAW), calculated from Eqn 4 and predicted from Eqn 5 for different amounts and sizes of subsoil aggregates in the mixtures for (*a*) Coonalpyn and (*b*) Bordertown.

content where the <2-mm treatments had the greatest slope (due to the much lower bulk density). The increase in slope with increasing aggregate size across this range of suctions shows that the smaller aggregates mixed intimately with the sand and created smaller pores to retain more water, whereas the larger aggregates remained discrete entities in the sand allowing for more large pores and lower water contents.

For the lowest proportions of clay-rich aggregates (10%) and the highest proportions (60%), only the smaller three aggregate sizes were available for comparison in the Coonalpyn soil (red, green and blue lines in Fig. 6*a*, *d*). The 10% clay-rich mixes (Fig. 5*a*) all behaved much like the pure sand regardless of aggregate size, and the 60% (Fig. 5*d*) clay-rich mixes behaved similar to one another and closer in shape to the undisturbed, clay-rich subsoil curve, regardless of aggregate size. For the Bordertown soil only three clay-rich aggregate sizes were used (<2 mm, 6 mm and 20 mm; larger aggregates were not available at this site), and their water retention curves followed essentially the same pattern as for the Coonalpyn soil mixtures, regardless of aggregate size.

Plant-available water and integral water capacity

Taking no account of physical limitations to water uptake from 'field capacity' ($h = 1$ m) to 'permanent wilting point' ($h = 150$ m), the PAW was low for the pure sands from Coonalpyn and Bordertown and significantly greater for the pure subsoil aggregates (observing the standard deviation bars in Fig. 7). This was in line with published values for similarly textured soils (Table 4). In general, there was no significant difference in PAW between the sands and the mixtures containing only 10% subsoil, regardless of aggregate size. However, PAW increased with increasing quantities of subsoil in the mixtures, and for any given proportion of subsoil, PAW tended to be greater for the mixtures containing smaller subsoil aggregates (Fig. 7). The lines for the different aggregate sizes are shown in Fig. 7 superimposed on the line produced by Eqn 5 for a bimodal mixture of discrete sand and subsoil. The close proximity of the lines for the 20-mm and 45-mm aggregates to that produced by Eqn 5 suggests that the larger subsoil aggregates existed as discrete entities in a 'matrix' of sand, whereas the finer (6-mm and <2-mm) subsoil

Table 5. Estimates of integral water capacity (IWC, mm m^{-1}) for the individual and combined limiting factors for mixtures of sand and clay-rich subsoil

Values in parentheses represent standard deviation. n.a., not applicable. For mixtures containing aggregates of 20 or 45 mm diameter, IWC was estimated using Eqn 18

Clay-rich subsoil (% by weight)	Nominal diameter clay-rich aggregates (mm)	$\int_0^\infty C(h)dh$	IWC from Eqns 8 and 18 accounting for all or individual limiting factors: All factors	Aeration factor only	Soil resistance factor only	$K(h)_{WET}$ factor only	$K(h)_{DRY}$ factor only
			Coonalpyn				
0%	n.a.	347 (0)	46 (0)	228 (0)	347 (0)	48 (0)	345 (0)
	2	334 (9)	80 (4)	208 (9)	334 (9)	81 (5)	334 (9)
10%	6	317 (4)	79 (7)	194 (5)	317 (4)	80 (8)	301 (8)
	≥20	348	71	219	348	76	347
	2	303 (11)	90 (3)	178 (11)	292 (10)	100 (4)	100 (4)
20%	6	329 (2)	97 (7)	211 (4)	329 (2)	99 (8)	99 (8)
	≥20	349	96	216	349	104	347
	2	289 (13)	116 (8)	162 (11)	269 (8)	141 (13)	141 (13)
40%	6	318 (9)	112 (4)	189 (10)	317 (9)	116 (6)	116 (6)
	≥20	350	146	208	350	163	349
	2	305 (2)	103 (2)	182 (3)	226 (2)	304 (2)	304 (2)
60%	6	341 (8)	110 (2)	214 (9)	323 (11)	135 (3)	135 (3)
	≥20	352	135	136	352	225	351
100%	n.a.	355 (37)	13 (3)	224 (36)	133 (4)	301 (39)	194 (5)
			Bordertown				
0%	n.a.	313 (0)	64 (0)	200 (0)	313 (0)	66 (0)	311 (0)
	2	306 (4)	69 (6)	196 (4)	303 (4)	73 (7)	306 (4)
10%	6	314 (4)	67 (2)	194 (0)	314 (4)	67 (3)	314 (4)
	≥20	312 (8)	82 (4)	185 (4)	312 (8)	87 (7)	311 (7)
	2	299 (2)	103 (13)	186 (0)	291 (2)	113 (14)	298 (0)
20%	6	288 (59)	82 (8)	165 (1)	287 (6)	83 (9)	288 (6)
	≥20	312 (14)	100 (9)	181 (8)	312 (14)	107 (15)	310 (15)
	2	328 (11)	164 (7)	213 (12)	314 (10)	187 (8)	325 (10)
40%	6	312 (6)	159 (6)	193 (12)	301 (6)	180 (10)	303 (6)
	≥20	310 (30)	137 (16)	171 (16)	310 (30)	151 (31)	309 (31)
	2	337 (7)	170 (16)	223 (4)	316 (4)	208 (23)	329 (7)
60%	6	304 (14)	148 (5)	190 (13)	278 (13)	183 (4)	284 (13)
	≥20	308 (47)	105 (16)	105 (16)	308 (47)	198 (47)	308 (48)
100%	n.a.	305 (85)	24 (39)	180 (85)	126 (59)	271 (48)	177 (718)

aggregates combined with the sand to produce more intimate mixtures rather than bimodal mixtures. On this basis, subsequent evaluation of soil-water availability using IWC involved differing assumptions for the mixtures containing 'small' aggregates (≤6 mm) and 'large' aggregates (≥20 mm), such that Eqn 18 was used to calculate IWC for the 'large' aggregates and Eqn 8 was used for the 'small' aggregates.

When poor soil aeration, high soil resistance, and high and low hydraulic conductivity are all included as limiting factors to soil-water availability (Table 5), the IWCs for the clay subsoils from both Coonalpyn (13 mm m^{-1}) and Bordertown (24 mm m^{-1}) were considerably lower than those for the pure sand at Coonalpyn (46 mm m^{-1}) and at Bordertown (64 mm m^{-1}). The IWC of the subsoil clay was also lower than for any of the sand-clay mixtures at both sites. Separating the relative importance of the limiting factors can be achieved by examining the IWCs when individual limiting factors are considered on their own (Table 5). The IWCs were lowest for the subsoil clay when only the soil resistance was taken into account (IWC = 133 and 126 mm m^{-1}, respectively for Coonalpyn and Bordertown); high soil strength could therefore be argued to be the primary limiting factor in the pure subsoil clay. Poor soil aeration at the wet end and declining unsaturated hydraulic conductivity at the dry end were also important but they were comparatively less limiting. For the pure sands at both sites (IWC = 46 and 64 mm m^{-1} at Coonalpyn and Bordertown, respectively), the primary limiting factor was the rapid drainage of water (large saturated hydraulic conductivity) in the wet range (Table 5). Hydraulic conductivity was also the main limiting factor even as the amount of subsoil clay in the mixtures increased, although the limiting effect diminished with decreasing size of the subsoil aggregates. Soil resistance was not a limiting factor at all in the pure sands and it only became somewhat limiting as large amounts of subsoil clay were added, especially in the smaller aggregate sizes.

Evaluating IWC (with all limiting factors taken into account) as a function of the amount of clay-rich subsoil in the mixture, Fig. 8*a*, *b* shows that soil-water availability generally increased with increasing additions of subsoil up to ~40%, after which the IWC plateaued. In fact, the solid and dashed black line fitted

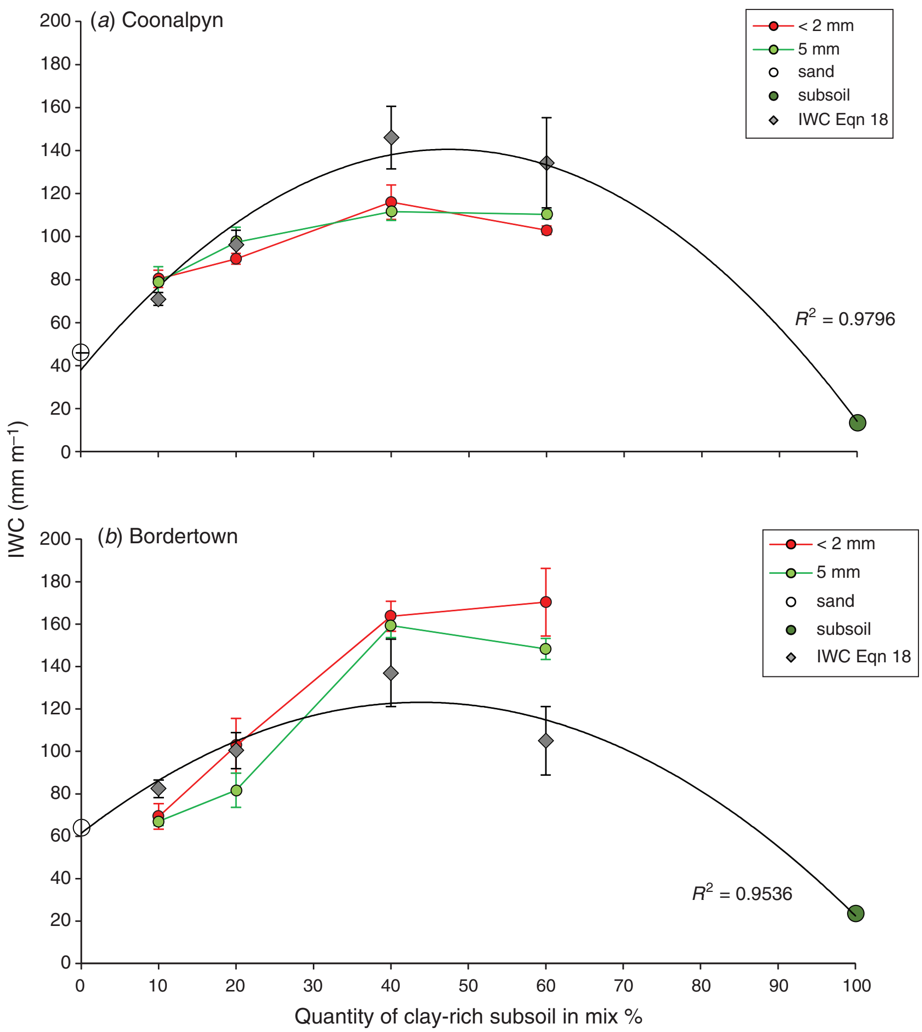

Fig. 8. Integral water capacity (IWC) calculated from Eqn 8 and predicted from Eqn 18 for different amounts and sizes of subsoil aggregates in the mixtures for (*a*) Coonalpyn, and (*b*) Bordertown.

through the points predicted from Eqn 18 for bimodal mixtures (grey diamonds) suggests that greater additions of subsoil beyond 40–60% push the IWC downward towards that for the 100% clay-rich subsoil.

Additions of these large magnitudes, however, are unlikely to be economically viable in practice, so the results in the range 0–20% are of greater practical interest than those from the 40% and 60% additions. Additions of up to 20% Coonalpyn clay-rich subsoil, for example, suggest only minor if any advantage can be had from cultivating delved soil excessively to mix the subsoil with the sand (i.e. to produce aggregates $\leq$6 mm). This suggestion is borne out even more emphatically in the Bordertown soil where additions of 10% and 20% subsoil aggregates <6 mm appeared to depress the effects on IWC relative to those produced by larger aggregates (predicted by Eqn 18). The practice of repeated cultivation after the initial delving to make it more uniform must therefore be questioned and should be evaluated in the field.

Conclusions

Mixtures of sand and subsoil clay were prepared in the laboratory from which water retention, soil resistance, and saturated hydraulic conductivity were measured. Similar studies have previously been conducted (Brown *et al*. 1985; Gill *et al.* 2004; Harper and Gilkes 2004), but to our knowledge, this was the first time that the sizes of the subsoil aggregates were taken into account when measuring the soil properties of the mixtures.

For both Coonalpyn and Bordertown soils, adding clay-rich subsoil to sand increased bulk density and soil penetration resistance, and reduced the saturated hydraulic conductivity of the mixtures towards those of the pure clay-rich subsoil. For extremely large additions of subsoil (i.e. 40–60%), the size of aggregates moderated the effects considerably. For example, small aggregates reduced the bulk density of the mixtures, presumably because they formed a more intimate mixture such that any swelling or dispersion of the clay created a greater total porosity between the sand particles. The greater porosity caused by the smaller aggregates, however, occurred at the expense of larger pores, so the hydraulic conductivity declined by at least an order of magnitude relative to that for the mixtures containing larger aggregates. Furthermore, smaller aggregates (even with only 10% subsoil) generated greater inter-particle cohesion (Fig. 4) and increased soil penetration resistance, similar to observations in analogous studies with homogeneous mixtures (Gill *et al.* 2004; Harper and Gilkes 2004).

The changes in physical properties generated by adding subsoil clay to sand also influenced the shape of the water-retention curves and the soil-water availability according to both PAW and IWC models. This is an important outcome and it confirms the initial hypothesis that predictions of soil-water availability based merely on the average soil texture can lead to unrealistic estimates for clay delved or clay spread soils.

Addition of subsoil clay in the order of 10–20% significantly increased IWC primarily by retaining more water and by reducing the excessively large hydraulic conductivity of the pure sand. In the practical range of clay additions (i.e. 10–20%), which corresponds to field quantities in the order of 150–330 t ha^{-1} (depending on assumptions of depth of incorporation and average bulk density), there appears to be an effect of aggregate size. Larger aggregates and clods increased soil-water availability more so than smaller ones, implying little benefit in excessive post-delving cultivation to bring greater uniformity of the soil texture. The addition of 10–20% subsoil clay may seem quite a lot, but these additions are not unheard of in areas where clay delving is practiced. The apparent reversal in soil-water availability predicted for extremely large additions of subsoil clay (>40–60%) implies that excessive changes to soil profiles need to be considered carefully. The extent of crop yield variability on delved soils suggests that variations in post-delving tillage may be partly responsible for this, and should be evaluated quantitatively in the field.

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Chapter 6 General conclusions

6.1 Summary and conclusions

Texture-contrast soils (also referred as “duplex” soils by Northcote 1979) cover around 20% of the total land in Australia (Chittleborough 1992). They are important soils in broad-acre agriculture but they are known for their multiple soil constraints that reduce crop production.

The literature review that I have presented in **Chapter 1** showed that the main constraints to crop productivity in texture-contrast soils come from the typical poor physical and chemical properties of their sandy topsoil and clay-rich subsoil. The topsoil is generally characterised by low fertility and low water holding capacity. In addition to this, crop establishment on these soils is frequently poor due to water repellence of the topsoil.

Their clay-rich subsoils have generally better chemical properties than the topsoil but its high soil strength (particularly in dry conditions) represents a major constraint to plant root growth. The high clay content in the subsoil also reduces its permeability and creates a physical barrier for the movement of water to depth; during the wet winter season, this is often the cause of water-logging, as the water ponds above the A/B horizons interface instead of moving deeper in the subsoil. These conditions promote poor aeration.

Clay delving was first introduced in the early 1990’s (Bailey, unpublished work) by the initiative of local South Australian farmers. The first intention was to use the in-situ clay-rich subsoil for the management of the water repellent topsoil, and thus the improvement of crop establishment, similarly (but more cost-effectively) to that achieved by clay spreading.

Unlike with clay spreading, however, the tines of a delver produce a “ripping” effect that disrupts the A/B horizon boundary while bringing up the clay-rich subsoil up to the surface. The result is the creation, in the upper part of the subsoil, of the typical “V-shaped” area, where sandy soil has back-filled the subsoil brought to the surface by the delving (an example of a typical clay delved profile is shown in **Fig. 2.3**).

Although clay delving has been known in Australia for at least three decades, the review of the available literature in **Chapter 1** showed that very little attention has been given to this practice in form of scientific publications. In fact, most of the available information on clay delving has been conducted “within and for” the Primary Industry and in the form of field reports, agriculture-dedicated web-sites/magazines or personal communications. As a consequence, the focus has been largely given to more industry-related topics such as increased crop yield, increased soil fertility and delving methodologies.

As discussed above, most of the literature has evaluated the outcomes of clay delving with little information on the changes that clay delving produces in the physical properties of texture-contrast soil. To address this research gap, I characterised the physical changes of a typical texture-contrast soil after clay delving (**Chapter 2**). The research approach was based on the hypothesis that the morphology of a clay delved profile differs greatly from the original (un-delved), with consequent effects on soil physical characteristics. In particular, it was postulated that the distribution of these properties changed both in the vertical and lateral directions.

To answer the research question and to characterise the physical changes of a delved soil, I first identified a representative area of a delved profile perpendicular to the delving lines and including two main morphological regions:

i) The “delving line” region, where most of the soil disturbance occurs and where the clay-rich subsoil aggregates are most intensively mixed with the A1 and the bleached A2 horizons. Directly below this, the delving tines create the typical V-shaped area in the B horizon, where subsoil is replaced by sand-rich topsoil;

ii) The off-line regions on both sides of the delving line are characterised by a lower degree of soil disturbance which occurs mainly near the surface, leaving most of the A2e and B horizons undisturbed. These physical changes to the soil caused by delving were then characterised at two different scales: changes at the scale of a soil profile, and changes at the scale of a field transect.

The results in **Chapter 2** confirmed the original hypothesis; indeed, the extensive morphological disruption produced by clay delving in texture-contrast soils effectively produces an entirely new soil profile. Compared to an undelved texture-contrast soil, where the soil physical properties change drastically with abrupt changes in soil texture, clay delving produces extensive (and highly variable) morphological changes that change the soil physical properties of the soil profile in both vertical and horizontal directions, particularly when comparing between the off-line and the delving line regions.

This study showed that clay delving combined with surface cultivation incorporated very large quantities of subsoil clay (> 500 t ha^{-1}) into the top 0.1 m, particularly directly over the delve-line; this procedure drastically altered the soil texture, strength and bulk density, as well as the availability of soil water. In this region, delving completely mixes the A horizon with clay-rich subsoil. It also disrupts the upper part of the B horizon so that significant changes in the physical properties on this region occur from the soil surface down to the maximum working depth of the delving lines. In the off-line regions, however, morphological changes are more limited (primarily in the top 0.1 m and primarily due to secondary tillage); below this depth, the off-line region is much less altered by the delving process and leaves similar physical properties to those of the un-delved soil.

The changes in physical properties produced by delving were also found to influence the shape of the water retention curves measured from several undisturbed soil samples collected from representative profiles. Accordingly, soil-water availability in terms of both plant available water (PAW) and the integral water capacity (IWC) models was also influenced. Interestingly, the changes in soil-water availability had no clear correlation with changes in mean clay content of the soil, as suggested by some literature on clay delving (Davenport *et al*. 2011). This finding created the bases for the hypotheses tested in **Chapter 5**.

In addition to traditional sampling measurements I introduced a novel approach with quantitative analysis of digital images of delved soil profiles (**Chapter 2**). Using image analysis proved to be a valid method for rapid assessment of the approximate amount of subsoil (t ha^{-1}) that delving brought up from the B horizon. Using this technique, I demonstrated the V-shaped area created by delving reduces the depth of water ponding above the B horizon mainly by creating extra pore space via back-filling of sand into the space previously occupied by subsoil. This work confirmed that digital analysis of images is a useful alternative to the far more laborious manual soil sampling.

One of the main reasons for clay delving is to reduce the water repellence and low water retention of the sandy topsoil by bringing up and incorporating the clay-rich soil from the B horizon. The reduction of the severity of water repellence obtained by increasing the mean clay content of the topsoil is one of the most effective methods and generally considered a permanent one (Davenport *et al.* 2011) Nonetheless, the literature review showed that the extent to which clay delving reduces water repellence and changes the wettability of surface soil, and the spatial variability of these changes, has never really been evaluated or published.

To quantify the changes in soil wettability of texture-contrast soils before and after clay delving, I designed a portable rainfall simulator (Appendix C) that allowed blue-dye solutions to be added onto delved and un-delved soils. The simulated blue-dye rain was applied to both dry and wet soils to replicate typical summer and winter conditions (**Chapter 3**, published as Betti *et al*. 2015). Digital image analysis of the dye-stained soil profiles confirmed that the delved subsoil significantly reduces preferential water flow (fingering) and increases wettability of the whole topsoil, especially under typical dry conditions when the expression of water repellence is greatest. Under wet conditions, no significant differences in wettability between delved and un-delved topsoils was found, and this was attributed to diminished water repellence at the greater antecedent soil-water content, consistent with the work of Hardie *et al.* (2011). Although delving indeed reduces the occurrence of water 'fingering' and increases topsoil wettability, most of these effects are restricted largely to the region directly on the delving line, in the area of maximum soil disturbance, consistent with the findings presented **Chapter 2**. The work also showed that the V-shaped area under the delving lines promotes the movement of water to greater depth (in particular under wet conditions), unlike the un-delved soil where water ponds above the impermeable B horizon. The outcomes of this work, combined with the findings of **Chapter 2**, suggest the V-shaped zone greatly reduces water ponding at the A/B horizon interface and thus reduces stress to plant roots due to water-logging.

As discussed in the literature review, shallow root systems are commonly observed in texture-contrast soils where the peculiar physical and chemical characteristics impose severe constraints on plant root growth (Dracup et al. 1992; Hamblin and Tennant 1987). This is because crops have to establish roots in water repellent topsoils with poor chemical characteristics and low water holding capacity. Moreover, root growth at depth in texture-contrast soils is reduced by the high strength of the subsoil (greater in the dry season) and water-ponding between the A and B horizon in the wet season, leading to poor aeration. To better understand the effect of delving on plant root growth, an experiment was conducted to measure total root length, root length density (RLD) and mean diameter of roots (RMD) extracted from soil cores of delved and un-delved soils at three sites in South Australia (**Chapter 4**).

Although the data were highly variable (as one might expect after such drastic soil disturbance) delving created significantly greater mean RLDs and smaller RMDs than in the un-delved soils. The effects were particularly evident in terms of root distribution in the A and B horizons. Consistent with the findings of Gregory *et al.* (1992) and Robson *et al.* (1992), my work showed that most roots in the un-delved soils were restricted to the A horizon, with significant reductions in the B horizon. The delved soils, by contrast, showed more uniform root distributions with depth.

With the exception of one site, RLDs in the delve-line and off-line regions were generally similar with depth, and this was because, in the delved soils, more roots were able to access the B horizon whereas in the un-delved soils all roots were restricted to the sandy A horizon. Moreover, at all sites the mean root thickness (RMD) was significantly smaller in the delved soil compared with the un-delved soil (with the exception the top 0.1 m of soil). This is consistent with root-thickening that occurs in hard soils.

The RLD and RMD results indicate that roots allocated resources more efficiently in the delved soils, while those in the undelved soils could have been subjected to higher stress due to higher soil resistance to penetration and restricted aeration in the B horizon. Assuming the physical characteristics of the B horizon were the same within the treatments of each site, I argued that the roots in the delved soils were thinner because they were able to reach the clay subsoil earlier in the season than those in the undelved soils, when the greater water content reduced the strength of the B horizon. This is an important outcome (although it still needs to be confirmed by further research) as crops with greater early development of roots at depth will be able to access more soil water from the subsoil, especially during the later stages of crop growth and in particularly dry seasons.

Delving increased the mean clay content of the topsoil by mixing clay-rich subsoil with the A horizon. Some of the available literature on clay delving (particularly field reports and agriculture-dedicated guidelines such as Davenport *et al* 2011) suggested in the past that some of the physical properties of a modified soil could be predicted simply by using the 'average' physical properties of soils with similar texture from the available literature. In other words, it was assumed that the soil physical properties (such as water holding capacity) of delved soils primarily derived from their mean clay content.

By contrast, it was hypothesised in **Chapter 5** (published as Betti *et al*. 2016) that mixing clay-rich material with sand alters the physical characteristics of the mixture not only by increasing the clay content but also by altering the size distribution of the clay-rich aggregates in the sand. That is, although the mean clay content of the topsoil increases, many of the clay-rich clods and aggregates remain discrete entities rather than becoming mixed uniformly with the sand. In this way the delving process does not afford a homogeneous change in the texture of the topsoil. To evaluate this hypothesis, I prepared laboratory mixtures of sand and subsoil in cores and measured soil water retention, soil penetration resistance, and saturated hydraulic conductivity on them. Although similar studies have previously been conducted (e.g. Brown *et al.* 1985; Gill *et al.* 2004; Harper and Gilkes 2004) this was the first time that the sizes of the subsoil aggregates were taken into account when measuring the physical properties of the mixtures.

Results demonstrated that both mean clay content and the size of the subsoil clods significantly influence soil physical properties. For example, at similar mean clay content there were significant differences in bulk density, soil strength and saturated hydraulic conductivity between fine clay-sand mixtures and mixtures where large clods of clay-rich subsoil were added to the sand. The changes in physical properties generated by adding different sizes of subsoil clods to sand also influenced the shape of the water retention curves and the soil-water availability according to both PAW and IWC models. Again, this is an important outcome because it demonstrated that predictions of soil-water availability based merely on the average soil texture can lead to unrealistic estimates for clay delved or clay spread soils. Moreover, this work demonstrated that when large clods exist as discrete entities in a 'matrix' of sand, the physical properties of each material remain discrete. Some physical properties of these bimodal sand/clay mixtures (e.g. bulk density and PAW) can therefore be estimated approximately from the distinct properties of each material, considering their respective quantities present in the mixture. The existence of large chunks of clay undoubtedly increased the concentration of small pores, which are integral to the retention of plant available water in soils. Direct measurements of the pore-size distribution of soil clods in delved soils may show this to be true.

In conclusion, the results of this thesis clearly show that delving of texture-contrast soils is a highly disruptive soil modification that effectively creates a completely new soil profile with physical properties distinctly different from the original un-delved soil. The findings on soil wettability and plant root growth (**Chapters 3** and **4**) are consistent with the spatial variability of the physical properties of a delved soil discussed in **Chapter 2**. These results, in combination with the findings of **Chapter 5**, need to be taken into consideration to improve delving methods and post-delving cultivation.

Nevertheless, further research is needed to better understand the complexity of clay delved soils and improve the methodology of clay delving and post-delving cultivation.

6.2 Future research

Delving can bring very large amounts of subsoil clay into the topsoil. Excessive amounts of clay, however, has the potential to generate negative effects on soil physical properties, especially in terms high soil strength as found in **Chapter 5**. A better understanding of the amounts of clay brought up by different delving techniques is therefore critical, and needs to take into account the thickness of the sandy A horizon and the depth-control of delving tines. If A horizon thickness and subsoil clay content were found to be important properties (and if control over these could be demonstrated in the delving process), it would provide tools for prescription mapping of different landscapes for effective delving practices or even prescribe alternative practices that only target the subsoil without adding clay to the topsoil, such as the shallower practice of deep ripping.

The work outlined in **Chapters 2** and **3** suggests that the V-shaped area below the delving lines can have an important role in reducing water-logging and thus plant root stress due to saturated water conditions. The reduction in ponding at the boundary between A and B horizons caused by delving could be considered comparable to installing artificial agricultural drain lines, and needs to be evaluated in the field. This could be done to greatest effect on soils with varying depths to clay and in landscapes of varying topography. This sort of work could contribute to the "prescription maps" suggested above.

Another area of interest is the extent of secondary tillage required after delving to maximize the benefits on soil physical properties. Evidence from **Chapter 5** suggests that too much tillage after delving may diminish the beneficial effects on soil physical properties by breaking down the clods too much. The practicalities of post-delving tillage need to be evaluated in terms of the effects of clod-size on plant available water, seedling emergence and root growth. The relation between post-delving tillage and the chemical characteristics of the subsoil brought to the surface (i.e. B horizons with high levels of boron or sodium chloride) should also be investigated as the size of the subsoil clods may also impact the way toxic elements become available in the topsoil, with negative consequences on crop production. Guidance on the appropriate tillage methodology in relation to soil type may improve soil physical and chemical properties and reduce the running costs for the farmers.

The addition of clay-rich subsoil significantly changes the soil hydraulic properties of sandy topsoils, particularly in the delving line region. As shown in **Chapters 3, 5** and **6**, delving reduces water repellence, changes the saturated hydraulic conductivity and thereby promotes more uniform wettability of both topsoil and subsoil. Such changes in soil hydraulic properties all appear to be positive. However, other soil hydraulic properties, not examined in this study, need to be evaluated for their potential negative impacts. For example, although delving increases hydraulic connectivity between the A and B horizons and allows greater drainage and reduction of ponding (especially in wet years), it also has the potential to facilitate upward movement of water by capillarity. If upward movement of water exceeds net downward movement and brings water nearer to the surface than it would in an un-delved soil, evaporative losses may significantly outweigh the benefits of drainage, particularly in dry years, when drainage is not an issue. Lysimeter studies combined with field studies in wet and dry years where a water budget is compiled and related to the extent of delving and post-delving cultivation would go some way to evaluating the potential of evaporative losses associated with this management technique.

Finally, although delving appears to significantly boost crop yields in many situations, the extent to which yield benefits are sustainable depends largely on the permanence of the changes to soil physical and chemical properties. An evaluation of the longevity of changes produced by delving therefore needs to be demonstrated to allow prediction of the frequency of such major profile modifications. This could be achieved by measuring the clay content and distribution of subsoil clods in the soil profile either in the field or in laboratory columns using simulated rainfall and modelling of colloid movement in sandy matrices. At the same time, crop yields need to be quantified in wet and dry years (simulated or otherwise) on the same soils to demonstrate any correlations between changes in soil properties and plant performance over time.

6.2 References

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Appendices

APPENDIX A % Fine and Coarse material, presence of > 10% coarse material, clay content, bulk density, saturated hydraulic conductivity, plant available water, and parameters of water retention curve down the profile in the delving-line and off-line regions of delved soil.

Depth (m)	Region	% Fine material		% Coarse material			>10% coarse material? (Y or N)	% < 2 µm	BD (g/cm³)	K_{sat} (m/s)	PAW Eqn 2.3 (mm/m)	Parameters for Eqn 2.2			
		< 2 mm	2 - 4.75 mm	4.75-6.7 mm	6.7-20 mm	> 20 mm						k0	k1	n	θ_{150}
	A off-line	99	0	0	0	0	N	0.06	1.57	1E-04	94	0.455	0.378	1.596	0.041
	B off-line	92	1	0	5	2	N	0.07	1.50	1E-04	89	0.387	0.356	1.305	0.063
	C off-line	93	2	2	4	0	N	0.09	1.57	1E-05	98	0.504	0.361	1.684	0.072
	D delving line	90	2	2	6	0	N	0.12	1.60	8E-05	101	0.481	0.361	1.532	0.062
	E delving line	77	3	11	8	0	N	0.08	1.72	7E-05	95	0.304	0.341	0.932	0.026
	F delving line	89	1	1	9	0	N	0.09	1.67	3E-05	90	0.369	0.335	1.165	0.068
	G off-line	86	3	2	6	5	Y	0.08	1.61	8E-05	102	0.501	0.329	1.429	0.057
	H off-line	89	1	2	8	0	N	0.08	1.63	8E-05	94	0.473	0.354	1.565	0.065
	I off-line	97	1	1	2	0	N	0.05	1.60	1E-04	90	0.415	0.347	1.367	0.053
0.0-0.1	A undelved	100	0	0	0	0	N	0.01	1.36	2E-04	44	0.128	0.375	1.013	0.050
	B undelved	100	0	0	0	0	N	0.03	1.40	1E-04	42	0.138	0.376	1.074	0.057
	C undelved	100	0	0	0	0	N	0.01	1.45	1E-04	59	0.100	0.397	0.781	0.052
	D off-line	74	4	2	13	7	Y	0.09	1.38	3E-05	93	0.138	0.353	0.558	0.075
	E delving line	47	5	3	35	10	Y	0.19	1.54	1E-05	96	0.275	0.316	0.759	0.146
	F off-line	66	4	2	9	20	Y	0.12	1.52	3E-05	71	0.273	0.311	1.037	0.128
	G off-line	62	5	4	19	10	Y	0.18	1.46	6E-06	75	0.279	0.293	0.952	0.168
	H delving line	73	7	4	16	0	Y	0.13	1.46	1E-05	89	0.24	0.349	0.846	0.119
	I off-line	76	3	2	19	0	Y	0.11	1.41	2E-05	81	0.242	0.345	0.926	0.122
	K delving line	88	2	1	9	0	N	0.10	1.22	1E-05	86	0.196	0.366	0.791	0.109

APPENDIX A (cont'd)

Depth (m)	Region	% Fine material	% Coarse material				>10% coarse material? (Y or N)	% < 2 µm	BD (g/cm³)	K_{sat} (m/s)	PAW Eqn 2.3 (mm/m)	Parameters for Eqn 2.2			
		< 2 mm	2 - 4.75 mm	4.75-6.7 mm	6.7-20 mm	> 20 mm						k0	k1	n	Θ_{150}
0.1-0.2	off-line	100	0	0	0	0	N	0.03	1.77	1E-04	47	0.231	0.352	1.326	0.022
	off-line	100	0	0	0	0	N	0.04	1.66	9E-05	68	0.371	0.349	1.549	0.027
	off-line	38	1	2	2	58	Y	0.18	1.75	2E-05	123	0.501	0.273	0.613	0.135
	delving line	99	0	0	0	0	N	0.04	1.71	7E-05	59	0.468	0.329	2.127	0.029
	delving line	96	1	1	2	0	N	0.03	1.75	1E-04	59	0.466	0.351	2.206	0.028
	delving line	100	0	0	0	0	N	0.05	1.67	1E-04	83	0.477	0.335	1.705	0.044
	off-line	100	0	0	0	0	N	0.04	1.70	5E-05	52	0.424	0.328	2.043	0.024
	off-line	100	0	0	0	0	N	0.03	1.63	8E-05	50	0.377	0.333	1.866	0.019
	off-line	100	0	0	0	0	N	0.03	1.72	9E-05	62	0.472	0.341	2.149	0.021
	off-line	100	0	0	0	0	N	0.02	1.67	1E-04	32	0.207	0.356	1.501	0.034
	off-line	100	0	0	0	0	N	0.04	1.72	1E-04	74	0.205	0.319	0.823	0.023
	delving line	42	5	4	25	24	Y	0.21	1.57	1E-05	127	0.602	0.262	0.662	0.164
	delving line	92	1	0	0	7	N	0.04	1.62	6E-05	72	0.343	0.307	1.233	0.052
	delving line	75	1	0	3	22	Y	0.09	1.54	4E-05	89	0.331	0.296	0.912	0.084
	off-line	100	0	0	0	0	N	0.03	1.70	1E-04	58	0.207	0.291	0.947	0.038
	delving line	90	1	1	9	0	N	0.03	1.60	1E-04	63	0.250	0.356	1.176	0.045

APPENDIX A (cont'd)

Depth (m)	Region	% Fine material < 2 mm	2 - 4.75 mm	4.75-6.7 mm	% Coarse material 6.7-20 mm	> 20 mm	>10% coarse material? (Y or N)	% < 2 µm	BD (g/cm³)	K_{sat} (m/s)	PAW Eqn 2.3 (mm/m)	Parameters for Eqn 2.2 k0	k1	n	Θ_{150}
0.2-0.3	off-line	81	0	0	1	18	Y	0.05	1.74	2E-06	77	0.456	0.316	1.631	0.042
	off-line	90	0	0	4	6	N	0.04	1.62	4E-05	60	0.429	0.331	1.914	0.030
	off-line	87	0	0	0	12	Y	0.03	1.59	4E-05	61	0.470	0.327	2.077	0.034
	delving line	100	0	0	0	0	N	0.04	1.64	7E-05	89	0.451	0.345	1.529	0.034
	delving line	70	1	1	4	24	Y	0.07	1.72	7E-05	94	0.487	0.309	1.403	0.070
	delving line	100	0	0	0	0	N	0.02	1.67	8E-05	63	0.411	0.363	1.867	0.028
	off-line	60	0	0	0	39	Y	0.07	1.74	2E-06	90	0.420	0.288	1.118	0.073
	off-line	68	0	0	0	31	Y	0.11	1.81	9E-07	100	0.549	0.241	1.031	0.093
	off-line	56	0	0	0	44	Y	0.07	1.82	1E-04	60	0.502	0.246	1.841	0.091
	delving line	0	0	0	0	100	Y & N*	0.23	1.61	3E-06	147	5.265	0.215	0.452	0.255
	delving line	81	2	2	15	0	Y	0.09	1.47	4E-05	80	0.421	0.340	1.513	0.080
	delving line	100	0	0	0	0	N	0.03	1.50	8E-05	36	0.147	0.289	1.047	0.037
	delving line	91	1	1	4	4	N	0.03	1.61	1E-04	56	0.232	0.284	1.035	0.055
0.3-0.4	off-line	0	0	0	0	100	Y & N*	0.20	1.70	2E-06	110	2.713	0.265	0.250	0.175
	off-line	0	0	0	0	100	Y & N*	0.22	1.65	6E-07	121	1.317	0.223	0.415	0.186
	delving line	85	0	0	4	11	Y	0.02	1.59	4E-05	62	0.434	0.338	1.909	0.042
	delving line	93	1	0	1	5	N	0.05	1.66	5E-05	78	0.419	0.349	1.584	0.034
	delving line	21	0	0	4	75	Y	0.27	1.72	2E-06	135	0.327	0.344	0.422	0.160
	off-line	0	0	0	0	0	Y	0.15	1.63	2E-06	98	0.185	0.317	0.246	0.248
	delving line	0	0	0	0	100	Y & N*	0.29	1.70	3E-07	171	45.282	0.637	0.153	0.185

* Samples entirely made of clay-rich subsoil are included in both Fine soil group (as if they are made of 100% fine material) and the >10% of large aggregates (as if they are made of one single large aggregate

APPENDIX A (cont'd)

Depth (m)	Region	% Fine material		% Coarse material			>10% coarse material? (Y or N)	% < 2 µm	BD (g/cm³)	K_{sat} (m/s)	PAW Eqn 2.3 (mm/m)	Parameters for Eqn 2.2			
		< 2 mm	2 - 4.75 mm	4.75-6.7 mm	6.7-20 mm	> 20 mm						k0	k1	n	Θ_{150}
0.4-0.5	delving line	17	1	1	8	72	Y	0.22	1.68	2E-06	120	1.083	0.207	0.534	0.192
	off-line	0	0	0	0	100	Y & N*	0.28	1.66	2E-07	154	1.38E+45	1566	0.022	0.215
	delving line/off-line	0	0	0	0	100	Y & N*	0.25	1.66	1E-07	108	1.85E+20	10.27	0.032	0.195
	delving line/off-line	0	0	0	0	100	Y & N*	0.25	1.74	1E-07	118	3.33E+46	1265	0.021	0.194
	delving line/off-line	0	0	0	0	100	Y & N*	0.32	1.65	3E-08	122	8.15E+53	1520	0.018	0.185
	delving line/off-line	0	0	0	0	100	Y & N*	0.29	1.77	7E-08	145	8.202	0.213	0.442	0.184
	delving line/off-line	0	0	0	0	100	Y & N*	0.28	1.73	4E-08	154	14.045	0.394	0.224	0.192
	delving line/off-line	0	0	0	0	100	Y & N*	0.28	1.70	4E-08	136	5.514	0.320	0.248	0.188

* Samples entirely made of clay-rich subsoil are included in both Fine soil group (as if they are made of 100% fine material) and the >10% of large aggregates (as if they are made of one single large aggregate

APPENDIX B Integral water capacity, IWC, soil resistance at 1 and 150 m matric heads, and Eqn 2.1 parameters down the profile in the delving-line and off-line regions of delved soil.

depth (m)	*Region*	>10% coarse material? (Y or N)	*% < 2 µm*	*IWC (mm/m) from Eqn 2.4* — *accounting for all, individual, or combined limiting factors*								*SR(h) = σh^b MPa at h= 1 and 150 m, with parameters σ and b, Eqn 2.1*			
				∫C(h)dh	IWC all	IWC_{sr}	IWC_{k}	IWC_{a}	$IWC_{(Ks;A)}$	$IWC_{(SR;A)}$	$IWC_{(Sr;Ks)}$	h=1 m	h= 150 m	σ	b
	off-line	N	6	378	123	376	126	250	126	248	124	0.494	1.148	0.49	0.17
	off-line	N	7	356	157	356	160	228	157	228	160	0.356	0.705	0.36	0.14
	off-line	N	9	361	135	359	142	231	136	230	141	0.428	1.253	0.43	0.21
	delving line	N	12	361	176	359	193	232	178	230	191	0.453	1.332	0.45	0.22
	delving line	N	8	341	61	263	89	199	89	141	61	1.016	2.106	1.02	0.15
	delving line	N	9	335	107	290	135	205	134	169	107	0.82	1.915	0.82	0.17
	off-line	Y	8	329	151	321	163	198	158	190	155	0.54	1.531	0.54	0.21
	off-line	N	8	354	146	351	150	226	149	223	147	0.505	1.202	0.5	0.17
	off-line	N	5	347	125	346	126	219	126	218	125	0.404	1.184	0.4	0.21
0.0-0.1	undelved	N	1	375	74	375	74	250	74	250	74	0.204	0.447	0.204	0.156
	undelved	N	3	376	74	376	74	251	74	251	74	0.204	0.447	0.204	0.156
	undelved	N	1	397	89	397	89	273	89	272	89	0.204	0.447	0.204	0.156
	off-line	Y	9	353	96	347	99	228	99	223	96	0.38	0.943	0.38	0.182
	delving line	Y	19	316	95	300	109	190	109	175	96	0.308	4.16	0.308	0.519
	off-line	Y	12	311	71	300	81	187	81	176	71	0.588	1.956	0.588	0.24
	off-line	Y	18	293	102	275	146	168	119	150	129	0.65	2.429	0.65	0.263
	delving line	Y	13	349	87	335	98	224	98	210	87	0.461	2.888	0.461	0.366
	off-line	Y	11	344	129	339	142	220	134	215	137	0.345	2.506	0.345	0.396
	delving line	N	10	366	93	363	95	244	95	241	93	0.283	1.337	0.283	0.31

APPENDIX B (cont'd)

depth (m)	*Region*	>10% coarse material? (Y or N)	*% < 2 µm*	*IWC (mm/m) from Eqn 2.4* — *accounting for all, individual, or combined limiting factors*								*SR(h) = σh^b MPa at h= 1 and 150 m, with parameters σ and b, Eqn 2.1*			
				∫C(h)dh	IWC all	IWC_{sr}	IWC_{k}	IWC_{a}	$IWC_{(Ks;A)}$	$IWC_{(SR;A)}$	$IWC_{(Sr;Ks)}$	h=1 m	h= 150 m	σ	b
	off-line	N	3	352	48	259	76	210	76	145	48	1.19	2.60	1.19	0.15
	off-line	N	4	349	66	329	75	223	75	205	66	0.68	1.72	0.68	0.18
	off-line	Y	18	273	46	190	131	122	112	47	62	0.85	6.74	0.85	0.41
	delving line	N	4	329	133	319	152	203	142	194	144	0.61	3.34	0.61	0.34
	delving line	N	3	351	48	274	71	225	71	169	49	1.04	3.26	1.04	0.23
	delving line	N	5	335	91	286	112	207	112	172	91	0.83	1.7	0.83	0.14
	off-line	N	4	328	55	259	78	203	78	154	55	1.02	2.66	1.02	0.19
	off-line	N	3	333	2	329	2	208	2	204	2	0.56	1.11	0.56	0.14
0.1-0.2	off-line	N	3	341	52	260	75	215	75	159	52	1.05	2.48	1.05	0.17
	off-line	N	2	356	35	335	44	231	44	210	35	0.81	2.86	0.81	0.25
	off-line	N	4	319	55	251	87	197	87	137	55	1.075	3.72	1.07	0.25
	delving line	Y	21	256	77	206	137	129	125	81	88	0.63	4.79	0.63	0.40
	delving line	N	4	307	83	276	104	183	103	156	83	0.78	2.39	0.78	0.22
	delving line	Y	9	295	78	222	120	179	120	124	78	1.05	2.33	1.05	0.16
	off-line	N	3	291	50	264	68	169	68	143	50	0.81	2.93	0.81	0.26
	delving line	N	3	356	77	353	79	239	79	237	77	0.45	1.59	0.45	0.25

APPENDIX B (cont'd)

depth (m)	*Region*	>10% coarse material? (Y or N)	*% < 2 µm*	*IWC (mm/m) from Eqn 2.4* — *accounting for all, individual or combined limiting factors*								*SR(h) = σh^b MPa at h= 1 and 150 m, with parameters σ and b, Eqn 2.1*			
				∫C(h)dh	IWC all	IWC_{sr}	IWC_{k}	IWC_{a}	$IWC_{(Ks;A)}$	$IWC_{(SR;A)}$	$IWC_{(Sr;Ks)}$	h=1 m	h= 150 m	σ	b
	off-line	Y	5	316	74	258	112	189	107	142	79	0.959	5.047	0.96	0.33
	off-line	N	4	331	62	291	78	205	78	174	62	0.829	2.731	0.83	0.24
	off-line	Y	3	327	91	301	105	201	105	180	91	0.728	2.372	0.73	0.24
	delving line	N	4	345	124	282	166	219	161	172	128	0.92	2.194	0.92	0.17
	delving line	Y	7	309	106	263	141	181	139	143	108	0.837	3.168	0.84	0.27
	delving line	N	2	363	62	329	75	237	75	210	62	0.757	1.971	0.76	0.19
0.2-0.3	off-line	Y	7	288	69	245	90	158	90	124	69	0.832	2.656	0.83	0.23
	off-line	Y	11	241	43	147	146	108	104	44	73	1.235	5.506	1.24	0.3
	off-line	Y	7	246	3	142	7	118	6	57	3	1.46	5.498	1.46	0.26
	delving line	Y & N*	23	173	6	106	126	47	19	7	86	0.533	3.614	0.533	0.38
	delving line	Y	9	340	98	340	98	223	98	223	98	0.273	1.254	0.273	0.30
	delving line	N	3	289	45	289	45	163	45	163	45	0.347	0.648	0.347	0.12
	delving line	N	3	284	74	284	74	162	74	162	74	0.424	0.539	0.424	0.05
	off-line	Y & N*	20	265	4	104	119	141	58	4	42	0.829	6.188	0.83	0.40
	off-line	Y & N*	22	223	8	113	142	95	65	8	63	0.829	6.188	0.83	0.40
	delving line	Y	2	338	82	297	101	234	100	201	82	0.816	2.241	0.82	0.20
0.3-0.4	delving line	N	5	349	103	338	112	216	112	205	103	0.599	1.754	0.6	0.21
	delving line	Y	27	344	63	258	148	148	121	64	89	0.576	5.166	0.57	0.44
	off-line	Y	15	309	1	185	105	92	36	1	40	0.829	6.188	0.83	0.40
	delving line	Y & N*	29	633	132	284	189	510	148	161	173	1.279	5.319	0.273	0.30

* Samples entirely made of clay-rich subsoil are included in both Fine soil group (as if they are made of 100% fine material) and the >10% of large aggregates (as if they are made of one single large aggregate

APPENDIX B (cont'd)

depth (m)	*Region*	>10% coarse material? (Y or N)	*% < 2 μm*	*IWC (mm/m) from Eqn 2.4* — *accounting for all, individual or combined limiting factors*								*SR(h) = σh^b MPa at h= 1 and 150 m, with parameters σ and b, Eqn 2.1*			
				∫C(h)dh	IWC all	IWC_{sr}	IWC_{k}	IWC_{a}	$IWC_{(Ks;A)}$	$IWC_{(SR;A)}$	$IWC_{(Sr;Ks)}$	h=1 m	h= 150 m	σ	b
0.4-0.5	delving line	Y	22	207	12	126	129	59	44	12	69	0.931	2.954	0.93	0.23
	off-line	Y & N*	28	223	2	126	172	70	68	2	77	0.388	5.8	0.39	0.54
	delving line/off-line	Y & N*	25	322	60	195	120	211	71	84	109	1.277	5.318	0.273	0.304
	delving line/off-line	Y & N*	25	384	43	190	126	269	55	45	113	1.277	5.318	0.273	0.304
	delving line/off-line	Y & N*	32	188	61	204	142	274	75	62	128	1.277	5.318	0.273	0.304
	delving line/off-line	Y & N*	29	213	0.01	47	150	93	40	0	38	1.277	5.318	0.806	0.494
	delving line/off-line	Y & N*	28	394	15	135	145	263	69	15	81	0.388	5.8	0.388	0.54
	delving line/off-line	Y & N*	28	320	15	136	131	191	62	15	77	0.388	5.8	0.388	0.54

* Samples entirely made of clay-rich subsoil are included in both Fine soil group (as if they are made of 100% fine material) and the >10% of large aggregates (as if they are made of one single large aggregate

APPENDIX C

Image of the portable rainfall simulator built for the application of blue dye solutions (Brilliant Blue FCF) used in experiment 2 (Chapter 3). The rainfall simulator used drippers on a reciprocating pipe with a swing action (the movement is represented in the image by the yellow arrow), delivering 4 L/h. The swinging action of the PVC tube with the drip irrigators was obtained using an electric motor attached to a rotary-oscillating motion conversion mechanism (marked by the red oval). A mini submersible pump situated in a plastic bucket (red bucket in the image marked by the green oval) was used to pump the blue dye solution to the drippers, mounted on the lower horizontal PVC pipe. Both electric motor and mini pump were powered by a common 12V car socket. The base of the rainfall simulator measured 1.05m by 1.05m.