Implications of soil water repellence for crop growth and nutrition

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Declaration

I hereby declare that the work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Simon Guo Hong Yeap

Date: 31 July 2020

Dedication

For my family and friends, and for the one whom I love, who maketh good ham.

Ad maiórem Dei glóriam.

Abstract

In water-limited environments, dryland crop and pasture production on water-repellent sandy soils is often constrained by reduced water infiltration, accentuated overland flow and soil erosion, unstable wetting patterns, and the development of preferential flow paths in the soil profile, which consequently cause considerable spatial heterogeneity in soil water content, increased prevalence of isolated dry zones, and decreased overall soil water retention. The same processes are also likely to affect soil nutrient bioavailability and plant nutrient uptake. Indeed, while problems with crop nutrition on water-repellent sandy soils have been reported by many Australian growers, the role of soil water repellence in crop nutrition has not been studied to date and the mechanisms remain unclear. While various methods exist to manage soil water repellence for improving crop and pasture production (e.g., deep soil cultivation, clay spreading, wetting agent application, stimulation of wax-degrading microorganisms, furrow/on-row sowing and water harvesting, and no-tillage and stubble retention), the outcomes for crop nutrition post-amelioration are not well understood.

Several field and glasshouse experiments were, therefore, conducted to assess the implications of soil water repellence and its management on crop growth and nutrition on several sandy soil types from the southwest region of Western Australia. Preliminary field results showed that soil water repellence, if left unmanaged, could adversely affect wheat plant density, shoot dry matter production, K nutrition, and grain yield on a Grey Bleached-Ferric Kandosol (deep grey sandy duplex soil) at Meckering with a moderate water repellence value of up to 1.6 M using the molarity of ethanol droplet (MED) test, supporting the hypothesis that soil water repellence can adversely affect crop growth, nutrition, and grain production. However, it was also revealed at another site, with a Ferric Chromosol (sandy loam yellow duplex soil) at Kojonup, that increased soil water repellence could also increase canola plant density, shoot dry matter production, Cu nutrition, and seed yield when sown with 1 L/ha of banded wetting agent, despite prolonged severe water repellence (MED of 3.4 M) throughout the growing season. Although the underlying mechanisms could not be established from this preliminary study, it was concluded that soil water repellence

may have both adverse and beneficial implications, but specific effects on nutrient availability in the root zone and crop nutrition were not defined.

Additional field studies were conducted to assess the effect of soil management practices (spading, one-way plough, subsoil clay spreading, and blanket applications of wetting agent) to alleviate soil water repellence on crop growth and nutrition. While all treatments except for one-way ploughing alleviated soil water repellence, only spading significantly improved wheat emergence, shoot dry matter, K nutrition, and grain yield on a Grey Tenosol (pale deep sandy soil) at Badgingarra. By contrast, at Moora, one-way plough treatments improved canola shoot dry matter and nutrition (Ca, S, B, Cu, and Zn contents) but did not mitigate severe water-repellence on a Ferric Chromosol (sandy ironstone gravel duplex soil), and had no effect on plant density or seed yield. However, the improvements due to soil cultivation can be attributed to the alleviation of soil compaction, given that the alleviation of soil water repellence by blanket-applied wetting agent (50 L/ha) and subsoil clay spreading treatments (250 t/ha; 50 % clay; 159 mg K/kg) had negligible effect on crop growth, nutrition, and grain production. Alleviation of soil water repellence was, therefore, not important for crop production at the Badgingarra and Moora study sites, presumably due to the presence of other soil constraints.

To avoid the confounding effects from multiple limiting factors evident in the field studies, a series of controlled glasshouse experiments were conducted to examine the effects of topsoil water repellence, topsoil thickness, fertiliser placement, variable low water supply, plant density, and/or surface topography on soil water content, soil nutrient availability, and early wheat growth and nutrition in 27 L containers. All glasshouse experiments demonstrated that severely water-repellent topsoil with a wettable furrow, which ensured uniform seedling emergence, significantly increased wheat seedling development, tiller number, shoot dry matter production, and nutrition (especially N, P, and K) during the early vegetative stage in wheat (40-51 DAS), under low but regular water supply (3.4-5.4 mm every two days). The growth stimulation was attributed to *in situ* water harvesting caused by preferential flow in the wettable furrow which increased the soil wetting and root depth relative to the completely wettable topsoil treatments that exhibited an even but shallow wetting depth. The even but shallow wetting patterns in completely wettable treatments consequently led to an

overall decrease in plant-available water and plant water use efficiency, resulting in poor wheat growth and nutrition, especially under a limited water supply. These findings underscore the high efficacy of *in situ* water harvesting for improving early wheat growth and nutrition on water-repellent soils relative to completely wettable soils, thus demonstrating a beneficial role of soil water repellence in crop growth and nutrition. Adopting *in situ* water harvesting principles (i.e., furrow sowing, banding wetting agent in the furrow, and using winged knife-points and/or press-wheels) can, therefore, be an effective strategy for managing crop growth and nutrition on water-repellent sandy soils by maximising the use efficiency of limited soil water supply during the crop establishment period.

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List of abbreviations and acronyms

AEC	Anion exchange capacity
AEP	Annual exceedance probability
ANOVA	Analysis of variance
ASC	Australian Soil Classification
CEC	Cation exchange capacity
DAS	Days after sowing
DPIRD	Department of Primary Industries and Regional Development
EC	Electrical conductivity
ECEC	Effective cation exchange capacity
GRDC	Grains Research and Development Corporation
LSD	Least significant difference
MED	Molarity of ethanol droplet
MOP	Muriate of potash
OC	Organic carbon
PBI	Phosphorus buffering index
RFRH	Ridge and furrow rainwater harvesting
RLD	Root length density
RWC	Relative water content
SSC	Surfactant seed coating
VWC	Volumetric water content
WA	Western Australia

Chapter 1: **General introduction**

1.1 Background

In contrast to the spontaneous wetting of the majority of soils that are hydrophilic, the resistance of water-repellent (hydrophobic) soils to wetting greatly impedes water infiltration rates (Roberts and Carbon 1971; Wang *et al.* 2000; Li *et al.* 2018) and causes unstable wetting patterns and the development of preferential or 'finger' flow paths (Ritsema and Dekker 1994; Dekker and Ritsema 1996b; Bauters *et al.* 1998). As a result, soil water repellence accentuates overland flow and soil erosion (Witter *et al.* 1991; Shakesby *et al.* 2000), and heightens the risk of agrichemical leaching and groundwater contamination (Hendrickx *et al.* 1993; Blackwell 2000), thus causing marked changes to the soil water balance (Bachmann *et al.* 2001; Doerr *et al.* 2003; Nunes *et al.* 2016). For soils with a 'subcritical' level of water repellence, however, wetting of the soil surface may visually appear to be spontaneous and unimpeded, but infiltration rates can be reduced by an order of magnitude (Wallis *et al.* 1991; Lamparter *et al.* 2006).

Considerable spatial heterogeneity in soil water content (Bond 1964), increased prevalence of isolated dry zones after rainfall (Blackwell 2000), and decreased soil water retention (Li *et al.* 1997; Doerr *et al.* 2006) are consequently key factors limiting the germination, establishment, growth, and yield of crops and pastures on water-repellent agricultural soils, particularly in dryland systems where soil water is limited to seasonal rainfall and stored soil moisture (Bond 1972; DeBano 1981; Müller *et al.* 2014a; Roper *et al.* 2015; Hewelke *et al.* 2018). In semi-arid (steppe) and Mediterranean environments, soil water repellence tends to be most severely expressed after the dry summer period before dissipating during the wet winter period (Crockford *et al.* 1991; Rye and Smettem 2015). However, due to the strong resistance to wetting and low hydraulic conductivity of dry, water-repellent soils, preferential flow paths can be highly persistent throughout winter, causing large volumes of soil to remain dry even after heavy rainfall (DeBano 1981; Ritsema *et al.* 1993; Ritsema and Dekker 1994). Re-establishment of soil water repellence is also possible after one week of hot dry weather, despite its break down after an initial extended period of wet weather (Crockford *et al.* 1991). In the paddock, prolonged soil dryness and delayed soil wetting can often leave seeds ungerminated or sporadically germinating throughout the season (Bond 1972; Hollamby and Davies 2012). Likewise, for weed seeds, their delayed and patchy germination would consequently reduce the effectiveness of weed control measures (Roper *et al.* 2015). Water-repellent soils with reduced plant cover, increased surface soil dryness, and increased soil surface exposure are consequently more susceptible to the impacts of wind erosion (Moore and Blackwell 2001; Moore *et al.* 2001b).

Similar problems are also experienced in the post-fire restoration of burnt natural vegetation stands whereby seed germination and seedling survival are often severely constrained by severe soil water repellence and inadequate soil water levels (Madsen *et al.* 2012b). Patchy, mosaic patterns in grass growth and localised dry spots (dead zones) due to the presence of water-repellent fairy rings, typically associated with the activity of basidiomycete fungi, also present a major problem for the management of grasslands and amenity turf grass systems, particularly golf courses (Karnok and Tucker 1999; York and Canaway 2000; Hallett *et al.* 2001; Karnok and Tucker 2003). While long-term irrigation with treated sewage effluent has been reported to induce severe soil water repellence at the 0-5 cm depth in sandy citrus orchard soils (Wallach *et al.* 2005), water repellence is largely a natural phenomenon in many soils (Doerr and Moody 2004) found on all continents, except Antarctica, under various climates (from tropical to subarctic) and land-uses (from agriculture to forestry to natural vegetation, and both burnt and unburnt areas; Doerr *et al.* 2003).

Although the exact chemical composition and structural arrangement of organic compounds responsible for soil water repellence remains unclear (Doerr *et al.* 2000; Doerr *et al.* 2005; Ellerbrock *et al.* 2005), soil water repellence is caused by the presence of hydrophobic organic coatings on sand grains or soil aggregates (Ma'shum and Farmer 1985; Doerr *et al.* 2000; Morley *et al.* 2005; Mainwaring *et al.* 2013) and/or particulate organic matter in the interstices between soil particles (Bisdom *et al.* 1993; Franco *et al.* 1995), typically of plant (McGhie and Posner 1981; Moradi *et al.* 2012; Mao *et al.* 2014; Mao *et al.* 2015; Walden *et al.* 2015; Ahmed *et al.* 2016; Cesarano *et al.* 2016) and fungal origin (Jex *et al.* 1985; Doerr *et al.* 2000; Hallett *et* *al.* 2001; Hallett *et al.* 2002; Rillig 2005; Feeney *et al.* 2006; Chau *et al.* 2012; Spohn and Rillig 2012; Young *et al.* 2012). Due to the natural accrual of organic matter in surface soil layers, soil water repellence is often expressed close to the soil surface, usually a few centimetres thick and within the upper 10 cm depth (Harper and Gilkes 1994; Keizer *et al.* 2007; Wahl 2008). Heat produced by fire and the combustion of plant litter on the soil surface can also induce or intensify soil water repellence due to the vaporisation and downward movement of hydrophobic organic substances along temperature gradients in soil and this can often result in a discrete repellent layer of variable thickness at depth (Savage 1974; DeBano 2000a; Varela *et al.* 2005).

Although soil water repellence severity may increase with increasing soil organic matter content (Mataix-Solera and Doerr 2004; Garcia *et al.* 2005; Zavala *et al.* 2009; Gao *et al.* 2018; Hermansen *et al.* 2019), this is not always the case (Teramura 1980; Harper and Gilkes 1994; Horne and McIntosh 2000; Mainwaring *et al.* 2004; Doerr *et al.* 2005; de Blas *et al.* 2010; Hallett *et al.* 2011). Literature points to water repellence being related to the composition of organic matter and the nature of the outermost layer of the organic coating on soil particles rather than the bulk of soil organic matter (McKissock *et al.* 2003). The important components of the organic matter are predominantly the long-chained amphipathic (amphiphilic) compounds that include branched and unbranched C_{16} to C_{36} fatty acids and their esters, alkanes, phytanols, phytanes, and sterols (Franco *et al.* 2000a; Horne and McIntosh 2000; Mainwaring *et al.* 2004; Morley *et al.* 2005; Daniel *et al.* 2019).

Sand and loamy sands are considered to be most susceptible to developing much thicker and more severely water-repellent layers due to their relatively larger mean particle size, smaller specific surface area, and lower clay content (typically <5 % clay) than loam and clay-textured soils (Bond and Harris 1964; Roberts and Carbon 1971; Debano *et al.* 1976). It has been found that only 3 % of sand grains need to be coated for repellence to be slightly expressed (or up to 5 % for severe water repellence; Bauters *et al.* 1998). In comparison, a far greater density of hydrophobic molecules is needed to saturate the hydrophilic sites on clay particles (Daniel *et al.* 2019). However, severe soil water repellence has also been found in finer-textured soils (18-22 % clay) under *Eucalyptus astringens* woodland in southwest Western Australia (McGhie and Posner 1980), including sandy loam soils (60 % sand and <20 % clay) under *Pinus* *pinaster* and *E. globulus* in northwest Spain (Rodríguez-Alleres and Benito 2011), and loamy to silty loam soils (40-42 % silt, and 10-13 % clay) under *P. halepensis* in southeast Spain (Mataix-Solera *et al.* 2007; Rodríguez-Alleres and Benito 2011; Jiménez-Pinilla *et al.* 2016).

It has been observed by many authors that soil water repellence is now more widespread than once believed (Wallis and Horne 1992; Doerr *et al.* 2003; Dekker *et al.* 2005b), with some considering water repellence to be the norm rather than the exception (Wallis *et al.* 1991). In Australian farming systems, average losses in crop and pasture production due to soil water repellence are estimated to be as high as 40 % (Blackwell *et al.* 1994; Abadi Ghadim 2000), with an estimated opportunity cost of lost agricultural production of *ca.* $251 million per year in Western Australia alone (Herbert 2009). Reports indicate that at least 38 % (10.2 million hectares) of the total agricultural region of southwest WA are at moderate (6.9 million hectares) to high risk (3.3 million hectares) of water repellence (van Gool *et al.* 2008). As a vast majority of grain is produced by winter crops under dryland farming systems in Australia (Gordon 2016), soil water repellence presents a major challenge for current and future grain production (Cann 2000; Unkovich *et al.* 2015).

Climate studies have also shown a declining trend in total rainfall and the frequency of heavy rainfall in the autumn and early winter, but an increasing frequency of dry days for the southwest region of WA (Suppiah and Hennessy 1998; Hope 2006; Alexander *et al.* 2007). Decreasing rainfall and increasing drought could then also add additional pressure on grain production, especially in areas affected by soil water repellence.

While much of the research to date has documented the hydrological impacts of soil water repellence on seed germination, crop establishment, final dry matter production, and grain yield (Bond 1972; Crabtree and Henderson 1999; Hall *et al.* 2010; Davies *et al.* 2012a; Davies and Blackwell 2015), few studies have attempted to quantify its effect on in-season crop growth (Li *et al.* 1997; Li *et al.* 2019) and even less is known about its relationship with soil nutrient availability and crop nutrition (Unkovich *et al.* 2015). It is, however, generally agreed upon by many authors that soil water repellence is likely to hinder plant access to soil nutrients and hence plant nutrient use efficiency as a result of prevalent dry zones, increased spatial heterogeneity in soil water content, and a reduction in plant-available water supply and water use efficiency (Sunderman 1988; Doerr *et al.* 2000; Kramers *et al.* 2005; Jordán *et al.* 2013; Scanlan *et al.* 2013; Roper *et al.* 2015; Hermansen *et al.* 2019). Apart from water, mineral nutrients (N, P, K, Ca, Mg, S, B, Cl, Cu, Fe, Mn, Mo, Ni, and Zn) are essential for plant metabolism, growth, and development (Broadley *et al.* 2012; Hawkesford *et al.* 2012) due to their key functions in plant structure and function (Kathpalia and Bhatla 2018). Therefore, unless supplemented by fertiliser applications, deficiencies in one or more nutrients can limit plant productivity (Hodges 2010; Kumar and Sharma 2013), with nutrient-stressed plants also generally having lower tolerance to pests and diseases (Dordas 2008; Huber *et al.* 2012).

Due to the deeply weathered and highly leached landscape in the southwest region of WA, most sandy soils are typically poor in fertility (e.g., nutrient deficient, low soil organic matter, low cation exchange capacity, and predominant kaolinitic and sesquioxide clay mineralogy), largely occurring as chromosols, kandosols, sodosols, and tenosols (Moore 2001). It is, therefore, common for crop production to be constrained by single or multiple nutrient deficiencies (particularly of N, P, K, S, Cu, Zn, Mn, and Mo) alongside soil water repellence (Hall *et al.* 2010; O'Callaghan 2017). However, the interactions between soil water repellence and crop nutrition do not appear to have been studied. Elsewhere in Australia, problems with crop nutrition on water-repellent sandy soils have also been widely reported by many growers, particularly in South Australia (Unkovich *et al.* 2015), where there is also a predominance of sandy surfaced, water-repellent soils. While various methods exist to manage soil water repellence for improving crop and pasture production (e.g., deep soil cultivation, clay spreading, wetting agent application, stimulation of wax-degrading microorganisms, furrow/on-row sowing and water harvesting, and no-tillage and stubble retention; Blackwell 2000; Roper *et al.* 2015), the outcomes for crop nutrition post-amelioration are also not yet well understood with current research still in its early stages (O'Callaghan 2017). Opportunities to better understand and manage potential constraints to crop nutrition on water-repellent soils are seemingly evident. It is, therefore, the aim of this thesis to explore the implications of soil water repellence and its amelioration for soil nutrient availability and crop nutrition.

1.2 Research objectives

The objectives of this research are to:

- investigate the effects of soil water repellence on soil nutrient availability and in-season crop nutrition;
- identify key nutrient availability mechanisms by which soil water repellence may affect final crop dry matter production and crop yield;
- assess the outcomes of the amelioration of soil water repellence for soil nutrient availability and crop nutrition; and,
- provide recommendations to improve current agronomic approaches for managing crop nutrition on water-repellent soils in the southwest of WA.

1.3 Thesis structure

The structure of this thesis is illustrated by Figure 1. A review of literature is presented in Chapter 2 on the mechanisms affecting soil nutrient bioavailability and plant nutrition, and the potential roles that soil water repellence and its treatment are likely to play in crop nutrition. Chapter 3 describes a preliminary investigation on the spatial and temporal variability in soil water repellence severity and its relationship with other soil properties, soil nutrient availability, in-season crop nutrition, dry matter production, and crop yield parameters on two water-repellent sandy soils located at Kojonup and Meckering in the southwest region of WA. In Chapter 4, the effects of ameliorating soil water repellence (via deep soil cultivation, clay spreading, and wetting agent application) and supplementary fertiliser treatments on early season soil nutrients, crop nutrition, dry matter production, and crop yield parameters were assessed on two different water-repellent sandy soils located at Badgingarra and Moora, WA, with an additional supplementary fertiliser study conducted at Meckering. Due to difficulties in defining the effects of soil water repellence on crop nutrition in the field, a series of controlled glasshouse experiments (detailed in Chapters 5, 6, and 7) were conducted to examine the effects of topsoil water repellence, topsoil thickness, fertiliser placement, soil water supply, plant density, and surface micro-topography on soil water and nutrient availability, and early wheat growth and nutrition, particularly in regard to the beneficial role of topsoil water repellence in water harvesting. A general discussion and conclusion of key research findings are then presented in Chapter 8, with some recommendations for growers and future research. Supplementary materials and research components are provided in Appendices.

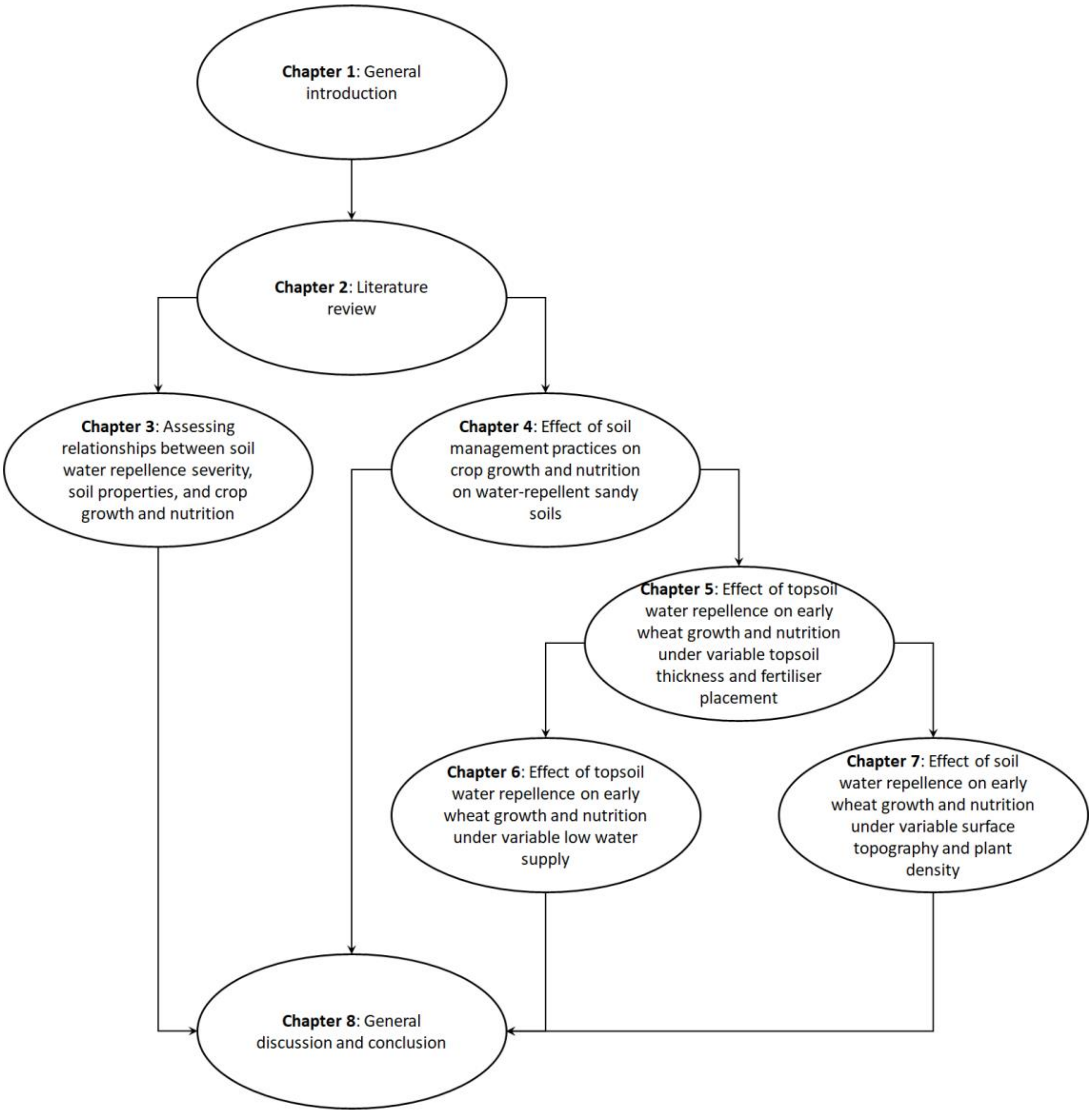

Figure 1. Thesis structure and research layout

Chapter 2: **Literature review**

2.1 Background

The characteristics, causes, and effects of soil water repellence have been extensively documented over the last few decades in natural ecosystems and forest plantations, especially fire-affected areas (Debano and Krammes 1966; Adams *et al.* 1970; MacDonald and Huffman 2004; Hubbert and Oriol 2005), grasslands and amenity turfgrass systems (Karnok and Tucker 1999; Cisar *et al.* 2000; Kostka 2000; Hallett *et al.* 2001), and agricultural crop and pasture systems (Blackwell 1993; Moore and Blackwell 2001; van Gool *et al.* 2008; Roper *et al.* 2015). However, apart from its well-established impact on soil hydrology (i.e., decreased water infiltration rates, unstable wetting patterns, and preferential flow; Ritsema *et al.* 1993; Bauters *et al.* 1998; Wang *et al.* 2000) and its adverse effect on seed germination, plant establishment, growth, and productivity (Bond 1972; DeBano 1981; Madsen *et al.* 2012b; Müller *et al.* 2014a; Roper *et al.* 2015; Hewelke *et al.* 2018; Li *et al.* 2019), there have been few studies on the effect of soil water repellence on soil nutrient availability, plant nutrient uptake, and plant nutrition. It is, however, generally agreed upon by many authors that soil water repellence is likely to hinder plant access to soil nutrients and their use efficiency as a result of dry patches within the root zone, increased spatial heterogeneity in soil water content, and a reduction in plant-available water supply and water use efficiency (Sunderman 1988; Doerr *et al.* 2000; Kramers *et al.* 2005; Jordán *et al.* 2013; Scanlan *et al.* 2013; Roper *et al.* 2015; Hermansen *et al.* 2019). Other processes, such as leaching due to preferential flow (Blackwell 2000), and enhanced runoff and soil erosion due to poor infiltration rates in water-repellent soil can also result in significant losses in nutrients, especially after fertiliser spreading (Simmonds *et al.* 2016; Müller *et al.* 2018; McDowell *et al.* 2020). This review, therefore, aims to explore the potential implications of soil water repellence for the processes controlling soil nutrient bioavailability and crop nutrition.

2.2 Implications for soil nutrient bioavailability

The capacity of the soil-plant system to supply and store nutrients is termed soil nutrient bioavailability (Barber 1995) which involves various physicochemical and biological processes controlling: (1) the release or transformation of labile nutrients from the solid phase to the soil solution (dissolution, desorption, and mineralisation); (2) the movement or transport of nutrients to the plant root system (mass flow, diffusion, and root interception); and, (3) the absorption of nutrients in soil solution by the plant root system (Comerford 2005; Gregory 2006). Given that soil nutrient bioavailability is intrinsically dependent on the soil water environment, the impacts of soil water repellence on soil wetting pattern and water availability are thus bound to have direct and indirect consequences for soil nutrient supply, plant nutrient uptake, and overall plant nutrition.

Table 1. Primary uptake forms of plant nutrients and their relative mobility in plants and soil, adapted from Barker and Pilbeam (2007), Hodges (2010), and Kumar and Sharma (2013).

Nutrient element	Symbol	Uptake form	Mobility in plant	Mobility in soil
Non-mineral element				
Carbon	C	CO_2 (g), H_2CO_3		
Hydrogen	H	H_2O (l), H^+, OH^-		
Oxygen	O	H_2O (l), O_2 (g)		
Mineral element				
Macronutrients – primary				
Nitrogen	N	NO_3^-, NH_4^+	Very mobile	Mobile as NO_3^-, variably immobile as NH_4^+
Phosphorus	P	HPO_4^{2-}, $H_2PO_4^-$	Mobile	Immobile
Potassium	K	K^+	Very mobile	Variably mobile
Macronutrients – secondary				
Calcium	Ca	Ca^{2+}	Immobile	Variably mobile
Magnesium	Mg	Mg^{2+}	Mobile	Variably mobile
Sulphur	S	SO_4^{2-}	Variably mobile	Variably mobile
Micronutrients				
Boron	B	H_3BO_3, $H_2BO_3^-$	Variably mobile	Mobile
Copper	Cu	Cu^{2+}	Variably mobile	Immobile
Iron	Fe	Fe^{2+}, Fe^{3+}	Variably mobile	Immobile
Manganese	Mn	Mn^{2+}	Immobile	Immobile
Zinc	Zn	Zn^{2+}	Variably mobile	Immobile
Molybdenum	Mo	MoO_4^{2-}	Variably mobile	Immobile
Chlorine	Cl	Cl^-	Mobile	Mobile
Cobalt	Co	Co^{2+}	Immobile	Variably mobile
Nickel	Ni	Ni^{2+}	Mobile	Variably mobile

The amount of nutrients available for plant uptake depends greatly on the quantity and form of nutrients in the soil (labile and non-labile), the reactions by which nutrients are adsorbed or contained within soil (Barber 1995), and their release into the soil solution (Comerford 2005). Virtually all mineral nutrients that are absorbed by plant roots exist in an ionic and inorganic aqueous form in the soil solution (Mengel and Kirkby 2001; Comerford 2005; Table 1). However, most of these nutrients in the bulk soil are generally present as mineral salts or organic forms which are not directly and chemically available to plants or are sorbed on the surfaces of clays, oxyhydroxides and organic matter (Huang 1980; Jackson 1998; Hamza 2008). The mechanisms by which plant-available nutrients are released and retained in soil are thus critically important for their bioavailability and these are primarily governed by: (1) the physicochemical processes of dissolution and desorption which are controlled by the solubility and sorption equilibrium between a solid and liquid, respectively (Comerford 2005; Kogge *et al.* 2019); and, (2) the biological process of mineralisation by way of microbial decomposition (Gregorich *et al.* 2001).

2.2.1 Dissolution and desorption

Dissolution is a process by which a solute (solid, liquid, or gas) is dissolved in a solvent (liquid) to form a solution (Sharpe 1963). For ionic compounds such as mineral salts, their ability to dissociate as cations and anions in solution are governed by their solubility (i.e., maximum amount of solute dissolved at equilibrium; Averill and Eldredge 2011). The solubility of most salts in water is directly affected by temperature: both the solute concentration and its dissolution rate increase as the temperature increases due to an increase in kinetic energy that overcomes the intermolecular forces of attraction between particles of the solid and their increased collision rate with solvent particles (Bewick *et al.* 2019). Upon dissolution in water, the hydrolysis of mineral salts of a weak acid and/or weak base can also yield net concentrations of either hydronium (H_3O^+) or hydroxide (OH^-) ions in solution (Speight 2018) and this consequently affects the solubility of other acidic or basic compounds by reacting with their constituent ions.

In the soil-plant environment, the resulting acidity or alkalinity of the soil solution, which is expressed by soil pH (equivalent to the negative base 10 logarithm of the H^+ ion concentration), consequently plays a major role affecting the solubility and availability of key plant nutrients in the soil solution (Lucas and Davis 1961; McCauley *et al.* 2009; Lauchli and Grattan 2012). Depending on their chemical form and quantity in the soil, most nutrients are generally more available to plants within soil pH 6 and 7.5 (UNIDO and IFDC 1998), with an increase in soil acidity (pH < 5.5) or alkalinity (pH > 8.5) likely to result in nutrient phytotoxicities or deficiencies (Lauchli and Grattan 2012). Acid soils, which are generally found to be more susceptible to developing water-repellent properties than alkaline soils (Arcenegui *et al.* 2008; Lebron *et al.* 2012; Yang *et al.* 2013), can exhibit phytotoxic levels of Al, Mn, Fe, and H (Fageria *et al.* 1990; Baligar *et al.* 2001) and deficient levels of N, P, K, Mg, and Mo (Fageria and Moreira 2011; O'Callaghan 2017). Compared with other nutrients, plant-available P can be more strongly limited under strongly acidic conditions (UNIDO and IFDC 1998) as it becomes readily sorbed by Fe, Al, and Mn (hydr)oxides and precipitated as insoluble Fe or Al- phosphate, given their increased solubility at decreasing pH (Lewis *et al.* 1981; Brady 1990; Søvik and Kløve 2005; von Wandruszka 2006). Addition of lime to increase the soil pH can help improve soil P availability by reducing P immobilisation by Fe and Al (Fernandes and Coutinho 1999). However, soil P availability may also be substantially reduced by lime due to the precipitation of Ca-P compounds which are more stable in alkaline and calcareous soils (Brady 1990; Hopkins and Ellsworth 2005). Likewise, co-precipitation, adsorption, and organic complexation of micronutrients, including Cu, Fe, Mn, Zn, Mo, Co, and Ni, may also occur in alkaline/calcareous soils which can further limit their availability in the soil solution (Alloway 1995; Rengel 2015; Kumar *et al.* 2016).

Adsorption and desorption reactions in soils are governed by surface properties of soil colloids (sorbents), the concentration and affinity of the ion or molecule (sorptives) for the sorption complex, and the pH of the soil solution (Comerford 2005). Sorption reactions generally occur on surface reactive sites of layer silicate clay minerals, metal (oxyhydr)oxide minerals, and organic matter in soil whereby cations and anions can be exchanged at the sorption complex (inner sphere surface complex; Mackay and Betts 1991; Stumm 1995; Sposito *et al.* 1999). Due to comparatively weak bonding in the outer sphere, the exchange of cations, such as Ca^{2+}, Mg^{2+}, K^+, Na^+, and NH_4^+, occurs more rapidly than that of anions, such as $H_2PO_4^-$ and to a lesser extent with SO_4^{2-}, NO_3^-, and Cl^- which under strongly acid soils with net positive charge (Havlin 2005), are bound more strongly by covalent bonds or ligand exchange (Comerford 2005; Yadav *et al.* 2012; Strawn *et al.* 2015).

In most soils, the cation exchange capacity (CEC) is greater than the anion exchange capacity (AEC) so there is net negative electrostatic surface charge (Havlin 2005). This is largely attributed to: (1) layer silicate clays which are characterised by the isomorphic substitution of lower-valence cations in tetrahedral (Al^{3+} for Si^{4+}) and/or octahedral sheets (Mg^{2+} for Al^{3+}), resulting in a net permanent negative charge of the internal crystal lattice (Yariv and Cross 1979; Sposito *et al.* 1999; Shainberg and Levy 2005), and (2) soil organic colloids which contain a large density of negatively charged sites due to the ionisation of functional groups such as carboxyl, phenolic, alcoholic, and carbonyl (Lewis 2009). Metal (oxyhydr)oxides and the broken edges of layer silicate clays can have variable charge depending on the degree of protonation which varies as a function of soil pH (Thompson and Goyne 2012). Sandy soils that have low clay and organic matter contents consequently have a limited capacity to retain nutrients such as NO_3^-, SO_4^{2-}, $B(OH)_4^-$, NH_4^+, and K^+ which can often be subject to leaching (Hodges 2010). The same soils may also exhibit soil water repellence due to their low specific surface area and hence increased risk of accumulating hydrophobic organic coatings or interstitial particulate organic matter (Bond and Harris 1964; Roberts and Carbon 1971; Debano *et al.* 1976) which could exacerbate leaching.

Under constant temperature, the sorption behaviour of an ion, which is described by its partition (or distribution) coefficient (Sheppard *et al.* 2009), is also dependent on its concentration in solution whereby sorption isotherms for most ions are linear at low concentrations but may subsequently plateau at higher concentrations as the maximum sorption capacity is reached (Giles *et al.* 1960). Accordingly, in the soil-plant environment, a decrease in K^+ concentration in soil solution due to plant uptake will consequently drive the desorption of K^+ from soil mineral surfaces, whereas an increase in K^+ concentration in solution due the application of K fertiliser will increase the amount of K^+ sorbed onto mineral surfaces. For ions of equivalent charge and concentration (e.g., Ca^{2+} and Mg^{2+}), their affinity for the sorption complex is considerably influenced by their size and ionic potential (i.e., charge density, that is the ratio of ion charge to ion radius) such that the ion's electrostatic attraction for the sorption complex increases with a decrease in ionic potential (i.e., less energy is required to remove a water molecule from the hydration sphere of a larger ion; Thompson and Goyne 2012).

Adsorption-desorption reactions are also pH-dependent such that cation adsorption increases with increasing pH while anion adsorption increases with decreasing pH (Yariv and Cross 1979; Smith 1999). Liming can, therefore, be applied to increase the cation exchange capacity of acid soils (Edmeades 1982; Hochman *et al.* 1992) and, in addition, optimise its pH to improve the solubility of plant-available nutrients and eliminate phytotoxic levels of Al^{3+} (Scanlan *et al.* 2017). Compared with dissolution, nutrient release by desorption is comparatively much faster and hence adsorption-desorption reactions are often responsible for maintaining nutrient concentrations in soil solution (Strawn *et al.* 2015). The sorption capacity of soils, therefore, plays a critical role in the release and mobility of plant-available nutrients (Dixon 1991), including the fate of heavy metals (Churchman *et al.* 2006; Caporale and Violante 2016; Uddin 2017; Ugwu and Igbokwe 2019) and other chemicals such as herbicides and pesticides (Davies and Jabeen 2002, 2003; Li *et al.* 2003).

Given that nutrient release fundamentally takes place in water wherein solutes are dissolved and ions are desorbed from the exchange complex, the quantity and rate at which nutrients are released from dissolution and desorption will, nonetheless, decrease or cease under increasing soil dryness or decreasing soil matric potential (Manzoni *et al.* 2012; Schimel 2018). A decrease in the soil water content would also consequently lead to the formation of insoluble compounds from solution (Eash *et al.* 2016). Water-repellent soils which strongly resist wetting after rain or irrigation would, therefore, directly limit overall nutrient supply in bulk soil due to the prevalence of dry zones and reduced water availability as water flow is diverted along hydraulically conductive pathways (DeBano 1981; Ritsema *et al.* 1993; Ritsema and Dekker 1994).

2.2.2 Mineralisation

The amount of nutrients released in soil from non-available organic to plant-available inorganic forms involves the biological process of mineralisation by way of microbial decomposition (Gregorich *et al.* 2001). This process is particularly important for soil N which exists mostly (95-99 %) in organic forms (Weil and Brady 2017). Soil N mineralisation comprises the ammonification of organic N to NH_4^+ by heterotrophic microorganisms (fungi and bacteria) and nitrification of NH_4^+ to NO_3^-

by autotrophic bacteria (*Nitrosomonas* and *Nitrobacter*) (Persson *et al.* 2000; Mohanty *et al.* 2013). Among a range of factors, microbial activity and soil mineralisation are largely driven by environmental factors, such as water availability and regime (wetting-drying cycles) and temperature, and edaphic properties such as soil pH (Leirós *et al.* 1999; Chen *et al.* 2003; Zaman and Chang 2004; Iovieno and Bååth 2008; Osman 2013).

Given that water is fundamental for all life, it is well-understood that the activity of microbial communities in air-dry soil is very low (Iovieno and Bååth 2008). So long as substrate availability was not limiting, soil water potential (from -0.01 to -8.5 MPa) and gravimetric soil water contents (from 5 to 35 % w/w) have been shown to be directly proportional to the rate of microbial respiration (i.e., CO_2 evolution; Orchard and Cook 1983). Under non-limiting moisture conditions, microbial growth rates are generally rapid and highly stable (Iovieno and Bååth 2008). However, slight decreases in water potential from -0.01 to -0.02 MPa can result in a 10 % decrease in microbial respiration, with a further decrease from -0.05 to -0.3 MPa causing a sharp decline in bacterial activity until its cessation at -1.5 MPa (lethal water potentials less than -8.5 MPa; Orchard and Cook 1983). The mobility and activity of bacterial communities are considerably restricted to water films (present at -0.02 to -0.1 MPa) and the diffusion of substrate and nutrients therein (Wong and Griffin 1976a, 1976b; Orchard and Cook 1983). Unlike bacteria, however, fungal communities are more resistant to drought due to the extension of hyphal structures that can actively explore micropores at far lower water potentials (Allen 2007; Bapiri *et al.* 2010; Yuste *et al.* 2011).

While it is still unclear whether the effects of drought on microbial stress and mortality are attributed to the drying or rewetting phase (Schimel 2018), severe heat stress caused by desiccation can result in the death of soil microorganisms, which in turn contributes to the accumulation of organic substrate (Kremer 2012). Upon rewetting of air-dry soil, the reactivation of soil microorganisms and rapid metabolism of available organic substrate, particularly of dead microbial biomass (necromass) and osmoregulatory substances released by soil microorganisms under hypoosmotic stress (Unger *et al.* 2010), causes a large and rapid flush in soil respiration and C and N mineralisation (often referred to the "Birch effect"; Birch 1964). This immediate flush is considered a first-order kinetic reaction in that the amount of CO_2 respired is a function of the soil organic matter content (Bottner 1985) and has been reported to result in respiration levels of up to 10 times that of constantly wet soil after a day (Butterly *et al.* 2009) or an hour (Iovieno and Bååth 2008). Earlier studies by Orchard and Cook (1983) also showed up to a 40-fold increase in respiration rates after the rewetting of dry soil as the water potential increased by more than 5 MPa. They ascribed this large increase in respiration to an increase in microbial activity rather than an increase in microbial biomass. After repeated drying and rewetting cycles, a general decrease in the size of respiration and mineralisation flushes can be observed, presumably due to an overall reduction in organic substrate, microbial activity, and/or biomass (Bottner 1985; Butterly *et al.* 2009). However, in other studies, this decline in mineralisation flushes was not observed (Miller *et al.* 2005; Xiang *et al.* 2008). Nonetheless, the frequency, duration, and intensity of drought periods will consequently have a marked influence on soil mineralisation dynamics throughout the year and the carbon balance of ecosystems (Unger *et al.* 2010), particularly in semi-arid and Mediterranean climate regions which are strongly seasonal (Kieft *et al.* 1993; Jarvis *et al.* 2007).

Where water is not strictly limiting, seasonal patterns in soil respiration and N dynamics often reflect changes in soil temperature (Rey *et al.* 2002; Contosta *et al.* 2011). In Mediterranean climates with warm, dry summers and cool, wet winters, peak mineralisation is generally observed after winter as soil temperatures rise in spring under adequate moisture (Lawson 2015). However, while mineralisation rates are typically low in summer due to drought and in winter due to low temperatures, sudden and intensive rainfall events during summer can lead to very high respiration rates and rapid soil mineralisation (Rey *et al.* 2002). In moist soils, increasing soil temperatures causes an exponential increase in microbial respiration and C and N mineralisation (Rey *et al.* 2005), with mineralisation rates almost doubling for every 10°C increase in average temperature between 5 and 40°C (Hoyle *et al.* 2006; Hoyle 2013).

Optimal temperatures for fungal and bacterial growth are typically around 25-30°C (Pietikäinen *et al.* 2005; Bárcenas-Moreno *et al.* 2009), but higher temperatures of 40-45°C can result in their decreased growth rate, especially for fungi (Pietikäinen *et al.* 2005). Fungal communities have, however, been found to be more adapted to low temperatures (-17.5 and -12.3°C) than bacterial communities (-12.1 and -8.4°C) in temperate agricultural and forest humus soils, respectively (Pietikäinen *et al.* 2005). Bell *et al.* (2009) have also found that cooler winter temperatures are more favourable to arbuscular mycorrhizal fungal activity in desert grasslands relative to warmer summer temperatures. However, they also found bacterial activity to be highest in summer and lowest in winter, with a relatively higher abundance of Gram-negative bacteria than Gram-positive bacteria in winter. Other studies have also shown significant correlations between soil surface temperature and the proportion of actinomycetes and arbuscular mycorrhizal fungi (Xue *et al.* 2018), while additional studies found no significant shift in bacterial community adaptations to temperature (Pettersson and Bååth 2003). Variation in fungal and bacterial community adaptions to soil water and temperature, therefore, plays an important role in soil ecosystem function, particularly in relation to C and N cycling (Bell *et al.* 2009; Xue *et al.* 2018).

While soil mineralisation dynamics are largely a function of soil moisture and temperature (Kirschbaum 1995; Davidson *et al.* 1998; Leirós *et al.* 1999; Rey *et al.* 2005), soil pH has also been reported to be an overriding factor in microbial growth and community structure (Higashida and Takao 1986; Fierer and Jackson 2006). Increasing soil acidity or alkalinity beyond the physiological pH range of fungal and bacterial communities can result in their reduced abundance due to cell damage and the inhibitory effects of free Al^{3+} below pH 5.0 (Rousk *et al.* 2009; Xue *et al.* 2018). Chen and He (2004) reported lower (pH 3) and upper (pH 8 to 8.5) critical thresholds beyond which microbial biomass was observed to abruptly decrease. Most soil bacteria are found to grow within a pH range found in most soils (i.e., pH 4 to 9; Luo and Zhou 2006), with the highest growth and diversity of bacterial communities generally observed at a neutral pH (Fierer and Jackson 2006; Husson 2013). For nitrifying bacteria, such as *Nitrosomonas* and *Nitrobacter*, the optimum pH can range from 7 to 9 (Kholdebarin and Oertli 1977). Due to their inhibited growth and activity under acidic conditions, the rate of soil nitrification (and release of NO_3^-) will decrease with decreasing soil pH (e.g., acid soils of pH 4.0-5.6; Nyborg and Hoyt 1978; Young *et al.* 1995).

Fungi, on the other hand, preferably grow within a pH range of 4 to 6 due to their moderately acidophilic nature (Luo and Zhou 2006; Husson 2013), with peak growth rates measured at around pH 4.5 before sharply declining as pH decreased to 4 (Rousk *et al.* 2009). Studies by Rousk *et al.* (2009) also revealed a five-fold decrease in bacterial growth and a five-fold increase in fungal growth as the soil pH decreased from 8.3 to 4.5, but found this shift in microbial community composition to decrease total C mineralisation. Unlike nitrification, however, Dancer *et al.* (1973) found no appreciable effect of pH on ammonification rates within the pH range of 4.7 to 6.6. A decrease in soil pH could, therefore, result a reduction in the relative proportion of soil NO_3^- and an increase in soil NH_4^+ and this could have implications for plant growth and nutrition (Bock 1986; Lobit *et al.* 2007; Boudsocq *et al.* 2012; Mantovani *et al.* 2018).

Under favourable growth conditions, the availability of labile organic substrate will also play a determining role on the abundance and activity of microbial communities and consequently soil N mineralisation (Sano *et al.* 2006; Ros *et al.* 2011; Abbasi *et al.* 2015; Bu *et al.* 2015). However, soil microbial growth and C and N mineralisation will, nevertheless, be limited primarily by water availability in soils that are prone to drying or water repellence. Soil organic matter can, however, be physically and biochemically protected in dry soil from microbial decomposition via micro-aggregation and the formation of recalcitrant soil organic matter compounds (Six *et al.* 2002). Soil water repellence is also understood to enhance aggregate stability due to an overall reduction in soil water content and a decrease in water film thickness and continuity caused by the hydrophobicity of soil particle surfaces (Goebel *et al.* 2004; Lamparter *et al.* 2009; Goebel *et al.* 2011), effectively limiting solute diffusion and substrate accessibility to microorganisms (Kieft *et al.* 1993; Goebel *et al.* 2005). Studies have, however, revealed that a large group of actinobacteria, such as *Actinomycetes*, are capable of decomposing hydrophobic soil organic compounds and reducing soil water repellence due to the production of biosurfactants (McKenna *et al.* 2002; Roper 2004; Roper 2005). Increased protection of soil organic matter from sudden and intense summer rainfall, which would otherwise result in large mineralisation pulses, could perhaps reduce potential leaching of NO_3^- from the bulk soil (Borken and Matzner 2009; Hoyle 2013) and this could benefit plant nutrition. Soil water repellence could, therefore, have important implications for C sequestration and C and N mineralisation dynamics, particularly in semi-arid and Mediterranean environments where soils are predisposed to frequent wetting and drying cycles

(Goebel *et al.* 2005; Iovieno and Bååth 2008; Borken and Matzner 2009; Lamparter *et al.* 2009; Goebel *et al.* 2011).

2.2.3 Nutrient transport and mobility

Water is a major factor in the availability and transport of soil nutrients to plants (Alam 1999; Halvorson 2006). The transport of nutrients through the soil to the root surface is governed by three processes: (1) mass flow, (2) diffusion, and (3) root interception (Halvorson 2006; Oliveira *et al.* 2010). Mass flow is the convective movement of dissolved nutrients to the plant root as water is absorbed for transpiration (Marschner 2002; Oliveira *et al.* 2010). Therefore, the amount of nutrients absorbed via mass flow would decrease as soil water content and plant water uptake decreases (Eash *et al.* 2016). Mobile nutrients such as NO_3^- and SO_4^{2-} which are also present in high concentration are largely transported by mass flow (Okajima and Taniyama 1980; Oliveira *et al.* 2010). Sufficient quantities of Ca and Mg can also be supplied by mass flow despite their relative immobility (Barber *et al.* 1963; Gregory 2006; Bowden *et al.* 2007; Oliveira *et al.* 2010). The relative importance of mass flow generally depends on the concentration of nutrients in the soil solution (Oliveira *et al.* 2010). Hence, due to the relatively low diffusion coefficient and mobility of P and K in soil (especially with increasing cation exchange capacity or sorption capacity; Mengel and Kirkby 2001), transport via mass flow is insufficient (Barber *et al.* 1963; Gregory 2006). The relative contribution of nutrients transported via mass flow in maize plants is: Ca (100%) > Mg (70%) > N (60%) > S (40%) > K (15%) > P ≈ Mn ≈ Zn ≈ Fe ≈ Cu (Oliveira *et al.* 2010).

While diffusion is comparatively a very slow process (Barber *et al.* 1963), it is the predominant process for transporting nutrients, such as P, K, Fe, Mn, Zn, and Cu, which are present in relatively low concentration in the soil solution (Baligar 1985; Marschner 2002; Bowden *et al.* 2007; Oliveira *et al.* 2010). Diffusion occurs in response to a concentration gradient caused by nutrient absorption at the soil-root interface by which nutrient ions move from areas of higher concentration to lower concentration (Barber *et al.* 1963). Diffusion is found to be the main transport mechanism of K (>85%), P (>99%), Fe (>99%), Mn (>99%), Zn (>99%), and Cu (>99%) (Oliveira *et al.* 2010). In dry soils, however, diffusion can be 10 to 100 times lower than, or even negligible in moist soils (Mengel and Kirkby 2001; Fitter and Hay 2002), given that the rate of diffusion declines exponentially with decreasing soil water content (Hagin and Tucker 1982; Alam 1999; Halvorson 2006; Nielsen 2006). Nutrient transport and uptake can, therefore, be considerably limited in dry soils (Kuchenbuch *et al.* 1986; Tinker and Nye 2000; McBeath *et al.* 2012). Nevertheless, the diffusive movement of most nutrients to the root surface is generally slower than their potential rate of uptake by plants (Craine et al. 2013) which can still limit plant growth despite adequate water supply (Mengel and Kirkby 2001).

Root interception, or contact exchange, can also occur when root growth comes in direct physical contact with nutrients associated with soil colloids (Oliveira *et al.* 2010; Eash *et al.* 2016). In general, it is estimated that less than 3 % of the available nutrients in the soil is in direct contact with roots, assuming that roots occupy no more than 1 % of the soil volume with the soil having one-third pore space (Barber *et al.* 1963). However, root interception can contribute to a significant proportion of a plant's requirement of Ca and Mg, given their relatively higher availability in soil and lower concentration in plant tissue, compared to other nutrients such as N, P, or K (Barber *et al.* 1963; Mengel 1995; Havlin *et al.* 2005). Root interception increases with increasing root surface area and mass (Eash *et al.* 2016), and is enhanced by amount of root-mycorrhizal surface area and its uptake characteristics (Comerford 2005). However, since plant roots occupy less than 1% of the soil volume (Eash *et al.* 2016), root interception is a minor pathway for nutrient transfer relative to mass flow and diffusion (Marschner 2002; White *et al.* 2013).

The ability of a nutrient to move freely in soil towards the absorbing root surfaces of the plant (i.e., nutrient mobility) is, therefore, a function of the soil water content and the mechanisms by which the nutrient is released and transported (Bray 1954), defined in terms of its effective diffusivity or diffusion coefficient (Drew and Nye 1969; Nye and Tinker 1977). Nutrients with relatively high mobility in the soil are not as strongly held by the soil sorption complex (having a higher diffusion coefficient) and are thus more readily available for plant uptake than immobile nutrients that are strongly sorbed (Marschner and Rengel 2012; Table 1). Such mobile nutrients include those that are primarily absorbed by roots as anions, such as NO_3^- and SO_4^{2-} (with exception to P as mono- or di-hydrogen phosphate, $HPO_4^{2-}/H_2PO_4^-$), while nutrients that are primarily absorbed as cations, such as NH_4^+, Ca^{2+}, Mg^{2+}, K^+, Cu^{2+}, Fe^{2+}, Mn^{2+} and Zn^{2+}, are relatively less mobile or immobile (Bender 2012; Eash *et al.* 2016). This is due to the sorption capacity of soils for cations (see Section 2.2.1), while precipitation and adsorption of P on mineral surfaces are predominant mechanisms which limit P mobility (Lehmann and Schroth 2003; Eash *et al.* 2016). In pale sands with low clay content, however, P and K can also be highly mobile and leach as a result of low cation exchange capacity and low nutrient retention (Hagin and Tucker 1982; Weaver *et al.* 1988; Pal *et al.* 1999; Tischner 1999; Alfaro *et al.* 2004). Soil B is also very mobile and is subject to leaching (Price 2006). This is due to the prevalence of uncharged and undissociated boric acid, H_3BO_3, at pH <7.2 (Bassett 1980; De Bussetti *et al.* 1995) and its weak adsorption by clay (Hodges 2010). By contrast, some sodic and alkaline soils in southern Australia have been found to accumulate phytotoxic levels of B, Na^+, and Cl^- in the subsoil due to their marine origin (Cartwright *et al.* 1984; Moody *et al.* 1988; Rengasamy 2002).

Frequent or heavy rainfall can, therefore, result in substantial leaching of mobile nutrients, especially N, which can limit crop nutrition and yield (van der Paauw 1962). Nutrient leaching is likely to be exacerbated in water-repellent sandy soils where the leaching of nutrients and surface-applied agrochemicals (e.g., pesticides and herbicides; Müller *et al.* 2014b) can be accelerated via narrow but highly conductive pathways, increasing the risk of contaminating groundwater supplies (Blackwell 2000; Wang *et al.* 2000; Ritsema *et al.* 2002) and surface water bodies in drained agricultural areas (Ritsema and Dekker 1994; Dekker and Ritsema 1996a). Preferential flow can develop rapidly in zones of relatively low water repellence severity (Ritsema and Dekker 1994), which could even persist throughout winter (DeBano 1981; Ritsema *et al.* 1993; Ritsema and Dekker 1994) and re-occur at the same location during successive rain events due to extreme hysteresis in the soil water retention characteristics (Ritsema *et al.* 2002).

Moreover, enhanced runoff and soil erosion due to poor infiltration rates in water-repellent soil can also result in significant losses in nutrients, such as P, especially after fertiliser spreading (Simmonds *et al.* 2016; Müller *et al.* 2018; McDowell *et al.* 2020).

By contrast, in dry regions with water-repellent soil, nutrients are left undissolved and inaccessible to the plant and this could also have adverse implications for plant nutrient uptake, growth, and overall nutrition (Sunderman 1988; Doerr *et al.* 2000; Kramers *et al.* 2005; Davenport *et al.* 2011; Jordán *et al.* 2013; Roper *et al.* 2015; Hewelke *et al.* 2018). Increased spatial heterogeneity in soil water content due to uneven wetting may also increase the tortuosity of water flow paths and hence the rate of diffusion of nutrients to the root surface (Olsen and Kemper 1968; Crabtree *et al.* 1998; Brown *et al.* 2012). Where plant-available nutrients cannot be sufficiently supplied to the soil-root interface, the plant's ability to forage for nutrients will be of high importance.

2.3 Implications for crop nutrition

2.3.1 Nutrient acquisition

Nutrients are rarely uniformly distributed in the soil profile (Robson *et al.* 1992; Gregory 2006; Hodge 2010), owing to stratified organic matter inputs and microbial decomposition which occur principally in the uppermost soil horizon (Jackson and Caldwell 1989; Hodge 2004). Under nutrient-limiting conditions, the exploration of heterogeneous soil resources becomes important and can, therefore, greatly depend on rhizosphere development and root plasticity (Richardson *et al.* 2009; Fageria and Moreira 2011). Increasing specific root length, fine root numbers, and symbiotic root-mycorrhizal surface area are understood to greatly facilitate nutrient acquisition (Bielenberg and BassiriRad 2005), particularly for mobile nutrients predominantly transported via mass flow and nutrients which are highly diffusive (e.g., NO_3-N, SO_4-S, and Ca) and/or present in high concentrations (e.g., NH_4-N and K) in the soil (Richardson *et al.* 2009). By contrast, selective root placement into new substrate, root proliferation, and root exudation are considered to be greatly important for the acquisition of immobile nutrients largely transported via diffusion, especially nutrients of low diffusivity (e.g., P, K, Fe, and Zn) and/or those present in low concentration in the soil solution (Lynch 2007; Richardson *et al.* 2009). Root hair development and mycorrhizal fungal hyphae are also known to enhance the acquisition of immobile nutrients, particularly P (Jungk 2001; Al-Karaki *et al.* 2004; Nielsen 2006; Sharma *et al.* 2011; Weil and Brady 2017). Nitrogen-fixing bacteria (rhizobia) that are contained within root nodules of leguminous plants can also enhance the growth and competitive ability of their host plant by supplying N (Okajima 2001; Gregory 2006; van der Heijden *et al.* 2008).

Under a heterogeneous soil nutrient supply, plants will actively forage for nutrients within the root zone (Okajima 2001), selecting more favourable substrates for growth, proliferating in the vicinity of nutrient-enriched zones, and increasing uptake kinetics therein relative to nutrient-deficient zones (Robson *et al.* 1992; Day *et al.* 2003b; Day *et al.* 2003c; Hodge 2004). In many studies, plants growing under heterogeneous nutrient conditions have also been reported to achieve higher early biomass, nutrient use efficiency, nutrient accumulation in shoots, and yield relative to plants growing under homogenous conditions with the same quantity of nutrients, presumably because resources were acquired more efficiently during the early stages of growth (Birch and Hutchings 1994; Hutchings and Wijesinghe 1997; Day *et al.* 2003a; Rose *et al.* 2009; Ma *et al.* 2011), even when plant uptake was suppressed from within deficient zones (Robinson 1994). Similar responses to soil nutrient heterogeneity have also been reported in various crops, including wheat (Trapeznikov *et al.* 2003; Ma *et al.* 2007; Ma and Rengel 2008), barley (Drew 1975; Drew and Saker 1978), maize (Li *et al.* 2012; Yu *et al.* 2014), canola (Rose *et al.* 2009), and lupin (Ma *et al.* 2011), and in perennial grasses (Day *et al.* 2003c). However, such yield enhancements are likely to converge over time as substrate and nutrient availability diminish and inter-plant competition increase (Day *et al.* 2003b). Nevertheless, vigorous development of the rhizosphere, particularly during early plant growth stages, is critical for avoiding potential stress and for maximising yields (Shao *et al.* 2008; Fageria and Moreira 2011).

In water-repellent soils, uneven wetting and preferential flow could thus lead to marked heterogeneity in soil water and nutrient supply due to the high variability in soil water contents and prevalent isolated dry zones. The morphological and physiological responses of plant roots to soil nutrient heterogeneity could, therefore, be more important for overcoming the potential effects of soil water repellence on plant nutrition. Compared to the bulk volume of soil, preferential paths are potentially enriched zones of water, nutrients, and organic substrate (Bundt *et al.* 2001; Guggenberger and Kaiser 2003; Morales *et al.* 2010) and could, therefore, provide ‘hotspots’ for root foraging and nutrient acquisition in water-repellent soils. However, due to increased leaching potential along these pathways, the acquisition of mobile nutrients, such as N, may be decreased due to a time lag in response of root growth relative to the leaching of nutrients from the root zone (Robson *et al.* 1992).

While increased plant root/shoot ratios (i.e., increased relative weight of roots; Davidson 1969) and enhanced root hair development are common responses to a reduction in water and nutrient availability, particularly of N and P (Mackay and Barber 1985; Brown *et al.* 2012; Marschner and Rengel 2012), isolated dry zones in water-repellent soil are likely to restrict root growth and access to nutrients therein due to low soil hydraulic conductivity, low soil water potential, and high mechanical impedance (Taylor and Ratliff 1969; Hoad *et al.* 2001; Marschner 2002; Bowden *et al.* 2007; Bengough *et al.* 2011). Prolonged soil dryness and resistance to wetting due to soil water repellence is likely to result in the cessation of root activity within the dry patches (Cisar *et al.* 2000). As the soil dries to a water potential of less than -1.5 MPa (permanent wilting point), most of the mesopores and larger micropores which contain roots would no longer retain water (Allen 2007). The complete loss of moisture would thus result in dehydration and desiccation of plant roots (Bray 1997). As a result, in addition to potential water stress, plants may not be able to efficiently acquire nutrients from these zones, resulting in poor nutrient use efficiency (Roper *et al.* 2015), even from fertilised fields (Amtmann and Blatt 2009; da Silva *et al.* 2011; Ahanger *et al.* 2016). The effects of water stress can also be compounded by increased mechanical resistance to root extension in drying soils (Taylor *et al.* 1964; Taylor and Brar 1991; Unger and Kaspar 1994; Bengough *et al.* 2011) which further limits root interception of nutrients (Pregitzer and King 2005). However, these effects are likely more severe in clayey soils rather than sandy soils (Buttery *et al.* 1998).

Hydraulic redistribution (or hydraulic lift) in plants may, however, occur as a response to mitigating water stress and maintaining root uptake and growth in zones of low moisture (Horton and Hart 1998; Wan *et al.* 2000; Bauerle *et al.* 2008; Liste and White 2008; Wang *et al.* 2009a; Whitmore and Whalley 2009). This process is driven by root and soil water potential gradients, resulting in the movement of water by roots from deep hydric (wet) soil layers to upper xeric (dry) soil layers (Dawson 1993). Therefore, so long as there is sufficient water and nutrients in parts of the root zone, dry patches in topsoils may not impede nutrient uptake (Liebersbach *et al.* 2004). Where nutrients are in low availability, plant roots may exude polysaccharides and organic acids to adjust rhizosphere pH which can increase the availability of limiting nutrients, such as P (Dakora and Phillips 2002; Lynch 2007; Whitmore and Whalley 2009). Under drought conditions, plant symbiosis with mycorrhizal fungi is also known to alleviate plant water and nutrient stress via the direct transfer of water and nutrients from hyphal structures (Khalvati *et al.* 2005), even at low soil water potentials ranging from -1.5 to -2 MPa, given the capacity for fungal hyphae to grow within micropores (<2 µm) and even large ultramicropores (<0.7 µm; Allen 2007).

Plant root systems are also highly responsive to the availability and distribution of certain nutrients in the soil (Linkohr *et al.* 2002; Rich and Watt 2013). The ability of plants to modulate the degree of root proliferation to the amount of nutrients available in patches has also been demonstrated (Jackson and Caldwell 1989). In agriculture, root proliferation of cereal crops appear to be highly responsive to N and P but are far less responsive to K (Perna and Menzies 2010). Studies have demonstrated that NO_3-N, NH_4-N, and PO_4-P are more important than K in stimulating lateral root production in barley (Wiersum 1958; Drew *et al.* 1973; Drew 1975; Drew and Saker 1978; Figure 2). In cotton plants, compensatory root growth was also found to be greatest in response to NO_3-N, followed by PO_4-P, but not in response to localised K enrichment (Brouder and Cassman 1994). Fernández *et al.* (2011) also found that the shoot and root growth of soybean responded to a localised supply of water rather than K. The lack of root proliferation response to localised K patches, therefore, suggests that K should be banded with either N or P to ensure root proliferation in the K band and hence the uptake of applied K (Murrell *et al.* 2009), or preferably in soils that have sufficient water availability (Fernández *et al.* 2011). Fertiliser composition, timing, and placement can, therefore, have particularly important implications for crop nutrition in water-repellent soils (see Section 2.3.2).

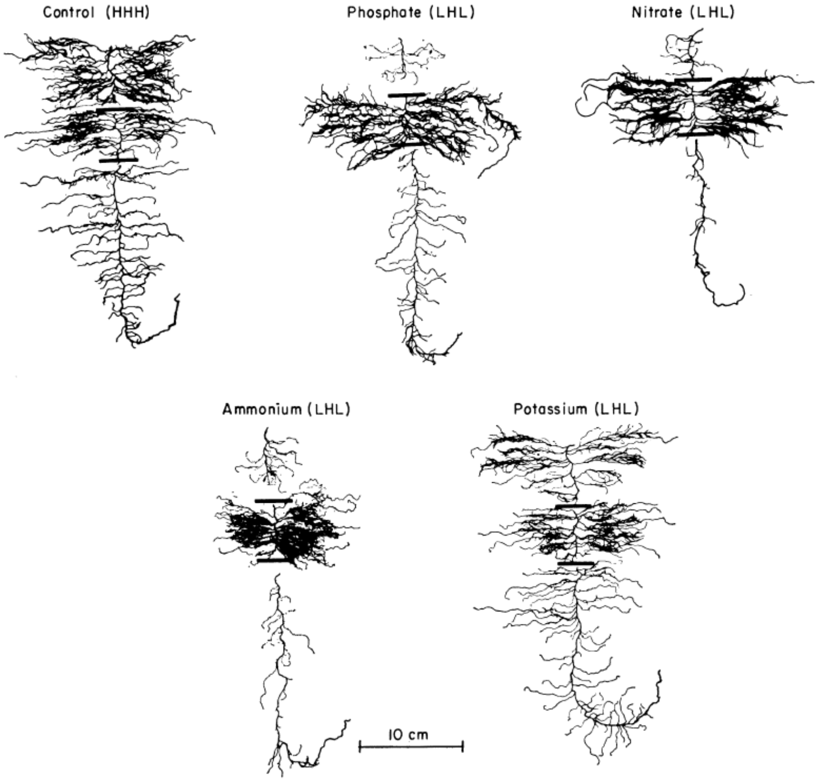

Figure 2. Effect of localised nutrient supply on root proliferation (Drew 1975). Control plants (HHH) received complete nutrient solution to all parts of the root system, whereas other roots (LHL) received complete nutrient solution only in the middle zone, with the top and bottom being deficient in the specified nutrient.

2.3.2 Fertiliser timing and placement

Since crop nutrient uptake varies with nutrient availability in the soil, a limited or untimely supply of plant-available nutrients would significantly affect crop nutrition and productivity. The timing and placement of applied fertiliser is, therefore, crucial to match supply with peak demand periods and maximise both yield and nutrient use efficiency (Jones and Jacobsen 2009; Jones *et al.* 2011; Ma and Herath 2016). Application of starter fertiliser has also been shown to effectively stimulate early crop growth (Deibert 1994), such as for corn (Mascagni and Boquet 1996; Niehues *et al.* 2004; Wortmann *et al.* 2006b), sorghum (Wortmann *et al.* 2006a), soybean (Osborne and Riedell 2006); however, in some studies, increased early growth responses to starter fertiliser may not always translate to increased grain yield (Wortmann *et al.* 2006a) or grain quality (Osborne and Riedell 2006). In water-repellent soils, nutrient availability and root accessibility may be potentially limited early in the season by reduced water infiltration and uneven wetting of plant and rooting zones. Therefore, starter fertilisers may be important for enhancing early crop vigour in these soils.

The timing of supplied nutrients, particularly N, can also greatly affect grain yield and protein response. For example, N supply during early vegetative growth to booting increases yield potential (Orloff *et al.* 2012), whereas N supply during stem elongation to anthesis increases grain protein content and this is particularly important for crops targeted for high-protein grain (Angus 2001). Early vegetative timings of N may also increase canopy size (increased tiller and ear numbers) and improve N use efficiency, but may also risk N leaching as root systems are not fully developed, especially with pre-winter doses (Poole 2005). Increased leaf retention from late stem elongation timings of N can also maximise crop photosynthetic capacity during grain fill which improves overall grain productivity (Poole 2005). On the other hand, while delayed N timings may not be able to increase canopy size, grain yield may be compensated by increased grain size and number per ear (Poole 2005).

However, late fertiliser timings or low nutrient supply can delay the growth of reproductive structures, limiting the amount of nutrients remobilised to the grain which affects both yield and quality (Jones *et al.* 2011). Delayed timings may also be further disadvantaged under unexpected drought conditions (Ma and Herath 2016) which prevents the rapid uptake of supplemented nutrients from the soil (Fischer *et al.* 1993). In some cases, impeded nutrient uptake during peak growth can result in plants requiring the continual uptake of soil nutrients through to maturation (Jones *et al.* 2011).

Nutrients positioned near the root zone are more accessible to plant roots, improving the chance that roots will intercept nutrients early in the growing season and stimulate growth and plant vigour (Mahler 1985). This is particularly important for immobile nutrients (P, K, Zn, Mn, and Cu) which tend to stratify within fertilised topsoil and cannot be sufficiently transported by mass flow or diffusion (Ma *et al.* 2009). Deep placement of fertiliser can, therefore, be effective in maximising nutrient accessibility in non-irrigated soils, which are prone to surface drying, or improving fertiliser use efficiency under crop residues in conservation tillage (Mahler 1985). Given the general lack in root growth response to banded K relative to N and P, placement of K fertiliser in the vicinity of N or P fertiliser, or in soils that have sufficient water supply, can improve K uptake and K nutrition due to root proliferation and increased root surface area (Murrell *et al.* 2009; Fernández *et al.* 2011). In water-repellent soils, placement of fertiliser below the repellent topsoil layer into moist subsoil could, therefore, improve plant uptake in comparison to surface-applied fertilisers which will be prone to soil drying and potential runoff losses, particularly for P (Simmonds *et al.* 2016; Müller *et al.* 2018; McDowell *et al.* 2020). Caution should, however, be taken as fertilisers placed too close to the seed can cause salt injury (Hanway 1966; GRDC 2011).

Enhanced efficiency, or slow-release, fertilisers may also be used to reduce damage to seedlings, to match supply with crop demand and optimise nutrient use efficiency by slowing the conversion of fertiliser to plant available forms (Jones *et al.* 2011). Such controlled release of mineral nutrients has also been demonstrated to significantly reduce nutrient losses, especially NO_3^- leaching and NH_3 volatilisation (Snyder 2017; Chen and Wei 2018), resulting in improved crop growth, nutrient use efficiency, and yield (Zhao *et al.* 2013; Tian *et al.* 2016; Noor *et al.* 2017; Sun *et al.* 2019). Likewise, in water-repellent soils, delayed mineralisation due to soil water repellence and the increased protection of aggregate-occluded organic matter (Six *et al.* 2002; Goebel *et al.* 2004; Lamparter *et al.* 2009; Goebel *et al.* 2011) may result in nutrients being released at a later stage in crop phenological development when nutrient demand is higher and root systems are more developed (Roper *et al.* 2015) as opposed to a large bulk of nutrients being released from summer fallow or early season mineralisation flushes when crop demand is low and root systems insufficiently developed to absorb available nutrients (Angus 2001; Fan *et al.* 2010).

2.3.3 Nutrient demand and crop phenology

Soil water repellence generally follows a seasonal pattern, being most severe after summer drought before dissipating after winter rain (Crockford *et al.* 1991; Hubbert and Oriol 2005; Rye and Smettem 2015). The effects of soil water repellence on soil water and nutrient availability are thus likely to vary temporally during the crop lifecycle and this could have implications for plant uptake and nutrition. Crop nutrient requirements are known to vary significantly with growth stage (Robson *et al.* 1992; Jones *et al.* 2011), generally characterised by three distinct phases in nutrient uptake throughout the growing season, such as that observed in wheat (Orloff *et al.* 2012). For N, which plays a considerable role in virtually all components of wheat development, rates of uptake are typically slow from the time of germination to tillering stage (Figure 3). During this stage in early vegetative growth, nutrients are accumulated in leaves and shoots for later use in the life cycle (Bowden *et al.* 2007). Tiller number per area is a key determinant of canopy size and potentially grain yield in cereals (Poole 2005), with 70-75 % of tillers producing a head while the remaining non-productive tillers store carbohydrate reserves (Bowden *et al.* 2007). Although N uptake during tillering can be relatively slow, water stress and N deficiency can significantly impede tiller production and photosynthetic activity (Tamaki *et al.* 1999; Abid *et al.* 2016). Limited P nutrition during early growth can also restrict tiller development (Rodríguez *et al.* 1999), root development (Boatwright and Viets 1966) and ultimately grain yield (Elliott *et al.* 1997), due to a decrease in energy storage and transfer which are essential for cell growth and plant metabolic processes (e.g., respiration and photosynthesis; Grant *et al.* 2001).

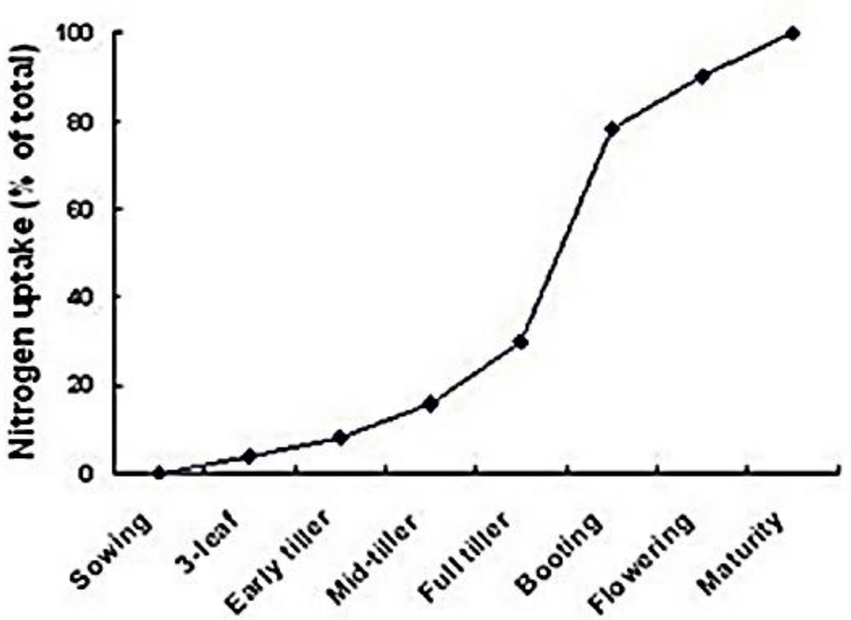

Figure 3. Cumulative nitrogen uptake (% of total) at different growth stages in wheat (Fettell et al. 2012).

Uptake of N in wheat rapidly intensifies thereafter during booting and stem elongation stages at which point the rate of N uptake is highest and the majority of the crop’s accumulated N is in vegetative organs (Angus 2001; Figure 3). For other nutrients, such as P and K, peak uptake rates may occur between tillering to ear emergence (Waldren and Flowerday 1979; Jones *et al.* 2011), with maximum P and K accumulation attained by late ear emergence (Rose *et al.* 2007). This marks a major change in the crop lifecycle from developing vegetative to reproductive structures (Murai *et al.* 2005). Rapid growth and intense competition for water and nutrients occurs during this time and thus crops can be vulnerable to environmental stress, such as water and nutrient deficiency (Bowden *et al.* 2007).

Maximum N accumulation is generally reached by the end of ear emergence where crop canopies are usually largest (Poole 2005). Most of the nutrients acquired and dry matter produced generally occurs by anthesis, with 75-100 % of the final content of N, P, K, S, Mg, Cl, and Cu taken up pre-anthesis (Hocking 1994). During the anthesis stage, a large proportion (*ca*. 50-90%) of N and P is redistributed from the leaves and stem to the developing grain, with the rest supplied from the soil (Dalling *et al.* 1976; Poole 2005; Jones *et al.* 2011). However, the contribution of pre-anthesis assimilate (carbon) to grain yield of wheat and barley can be relatively small, averaging around 12 % for watered crops and 22 % for droughted crops (Bidinger *et al.* 1977), although pre-anthesis assimilate could contribute up to 44 % of grain dry matter during a very hot and dry year in comparison to only 11 % during a wetter and cooler year (Austin *et al.* 1980). By contrast, post-anthesis assimilate can contribute to 62-92 % of the increase in grain mass (Bonnett and Incoll 1992).

Post-anthesis N uptake is relatively low as the crop progresses to maturity, contributing to a small fraction of total accumulated N in cereal crops (e.g., 18-35%; Tollenaar and Dwyer 1999). Nutrient remobilisation throughout grain fill period (milk and dough development) increases rapidly until ripening, resulting in the distinct senescence phase (Poole 2005). Other plant parts, such as the spike, glumes, and awns, have also been reported to contribute substantially to grain N, especially during grain filling (Lopes *et al.* 2006; Sanchez-Bragado *et al.* 2017). The quantity and rate at which nutrients are translocated and remobilised to the developing grain will, nonetheless, vary with each nutrient due to their relative requirement in grain and their relative mobility within plant tissue (Etienne *et al.* 2018; Table 1). In spring wheat, final grain nutrient content comprises over 70% of the N and P, 31-64 % of the Mg, S, Mn, and

Zn, and less than 20 % of the K, Ca, Na, Cl, and Fe of the plant content (Hocking 1994). Hocking (1994), however, noted that while over 70 % of the N and P, and 15-51 % of the K, Mg, S, Cu, and Zn were redistributed from stems and leaves to the developing grain, negligible amounts of Ca, Na, Cl, Fe, and Mn were redistributed from vegetative organs.

For oilseed crops, such as canola, seeds can accumulate over 70 % of the N, P, Mg, Fe, and Zn, 30-35 % of the Cu, Mn, S, Ca, and K, and less than 20 % of the Na and Cl of the plant content (Hocking and Mason 1993). However, a significant proportion of N in the leaves of canola plants may not be mobilised before leaf abscission, resulting in a higher removal of N by dead leaves and a lower contribution of N redistributed (55 %) from the leaves and stems to the seed (Hocking *et al.* 1997). In contrast to wheat plants, however, canola plants can continue to uptake nutrients later in its growth cycle with a maximum uptake of N, P, and K reported to occur post-anthesis (Barraclough 1989; Hocking *et al.* 1997; Rose *et al.* 2007). Redistribution of nutrients from the pod walls of canola plants can also contribute significantly to the seed, providing nearly 25 % of the accumulated N and P (Hocking and Mason 1993). Therefore, while the yield and quality of wheat grain and canola seed can be highly dependent on the amount of nutrients, especially N and P, that can be accumulated in the plant before grain fill, the limited capacity of wheat plants to take up nutrients post-anthesis makes it essential to ensure maximum nutrient uptake pre-anthesis (Hocking 1994).

Nutrient remobilisation from senescing leaves to actively growing tissue is particularly important for plants to conserve nutrients in infertile soils (Hill 1980; Proctor 2004). However, for nutrients such as Ca, B, Cu, and Zn which are not readily redistributed within the plant, their deficiency may result in impaired root growth (relative to shoot growth) given their role in maintaining membrane permeability and root function when supply is depleted (Robson *et al.* 1992). Internal cycling of nutrients and carbohydrates also requires water for their dissolution and redistribution (Singh and Singh 2004) and, hence, water deficit due to prolonged drought could significantly affect this process. If soil water repellence is most severe at the start of the growing season, the prevalence of isolated dry zones and increased heterogeneity in soil water and nutrients could, therefore, have potential adverse implications for grain yield and quality by impeding early crop growth and nutrition in addition to decreasing crop germination and seedling establishment. Under long-term drought stress, however, water availability will, nevertheless, be the main factor limiting plant growth rather than nutrient availability (He and Dijkstra 2014).

2.3.4 Water stress on crop productivity

While plants have various mechanisms to cope with low soil nutrient availability and mobility (e.g., up-regulation of nutrient uptake by roots, increased root exploration, root exudation, and microbial symbiosis; Etienne *et al.* 2018; see Section 2.3.1), water stress poses the most serious constraint of all other environmental factors for crop growth and productivity in dryland agricultural systems (Alam 1999; Van Duivenbooden *et al.* 2000; Karim and Rahman 2015). Water stress reduces the efficiency of key plant physiological and biochemical processes (e.g., protein synthesis, photosynthesis, respiration, and nucleic acid synthesis), inhibits enzyme activity, and suppresses cell expansion and growth (Bray 1997; Alam 1999; Shao *et al.* 2008; Jaleel *et al.* 2009; Lata *et al.* 2015). Reduced leaf water potential and turgor loss from water stress consequently reduces transpiration and CO_2 assimilation by stomatal closure (Hsiao 1973; Osakabe *et al.* 2014), impairing active transport and membrane permeability and, hence, a decline in root-absorbing power and use efficiency for water and nutrients (Alam 1999; Farooq *et al.* 2009; Oliveira *et al.* 2010).

Decreased root length and nutrient influx due to water deficit would also reduce the total amount of nutrients absorbed by roots, transported to shoots, and assimilated in vegetative tissue (Seiffert *et al.* 1995; Marschner 2002; Singh and Singh 2004; Garg and Burman 2011). As a result, water stress can often be associated with plant nutrient deficiencies (da Silva *et al.* 2011; Surbanovski and Grant 2014; Bista *et al.* 2018). Reduced plant metabolism and energy availability would also inhibit the assimilation of nutrients, such as NO_3^-/NH_4^+, PO_4^{3-}, and SO_4^{2-}, as these ions require conversion in energy-dependent processes prior to plant use (Farooq *et al.* 2009). Disruption of nutrient remobilisation to the grain may also occur, resulting in reduced grain quality (Garg and Burman 2011). By contrast, mild water stress has been observed to hasten plant development in cereal crops, presumably due to increased leaf temperature in accompaniment with reduced evapotranspiration, relative to severe water stress which impedes plant development due to the disruption of physiological processes (Angus and Moncur 1977; Hodges 1991).

The sensitivity of crop to water stress varies among plants and with growth stage, but tends to peak during periods of maximum evapotranspiration (e.g., during heading and anthesis in wheat; Sarto *et al.* 2017). For most cereal crops, the relative sensitivity of growth stages to water stress can be generally illustrated by Figure 4. The early stages in crop growth, which are critical determinants of plant establishment and yield potential, are very sensitive to water stress (Aslam *et al.* 2013; Lata *et al.* 2015). Impaired germination and seedling emergence are the first and foremost effects of drought and water stress (Farooq *et al.* 2009; Sarto *et al.* 2017) and no amount of effort made during later stages of crop development are likely to compensate for low seedling emergence, especially where crops cannot compensate by tillering (Finch-Savage and Bassel 2016). Early crop vigour and development of deeper root systems are, therefore, important for successful crop establishment and drought avoidance in dryland agriculture in semi-arid and Mediterranean regions (Harris *et al.* 1999; Bengough *et al.* 2011; Baloch *et al.* 2012). Thereafter, water stress during vegetative growth (i.e., tillering stage) inhibits tiller initiation and development, and the survival of ear-bearing tillers which consequently limits the number of grain-producing tillers per plant (Maas *et al.* 1994; Bowden *et al.* 2007; Farooq *et al.* 2009; Akram 2011).

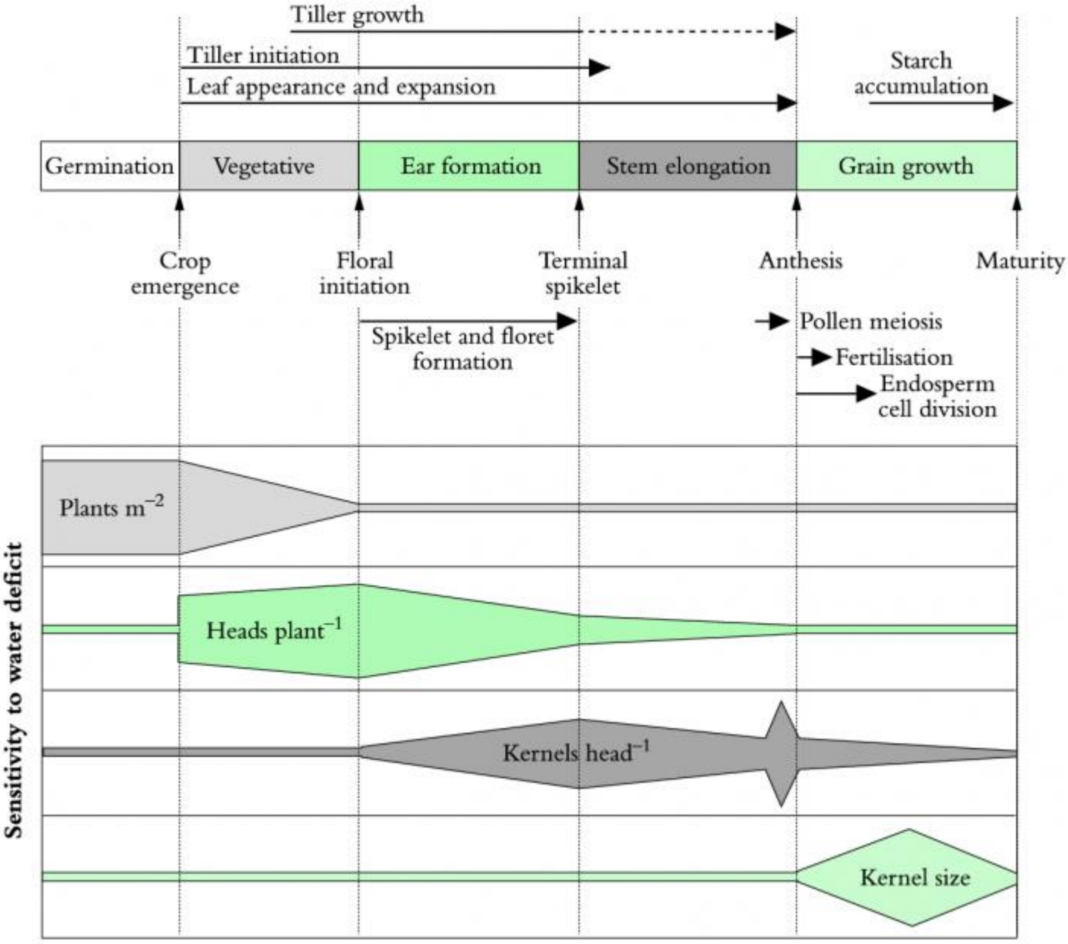

Figure 4. Relative sensitivity of cereal crop growth stages to water stress (Atwell et al. 1999).

Given that the majority of nutrient and carbohydrate reserves are assimilated in vegetative tissue prior to anthesis for grain filling (Gebbing and Schnyder 1999), pre-anthesis water stress (e.g., during stem elongation) can limit assimilate supply and thus floret formation and fertility, resulting in reduced grain number (Al-Ajlouni *et al.* 2016). Although water stress may result in grain abortion during early grain development (Mitchell *et al.* 2013), grain number is generally unaffected by post-anthesis water stress (Fischer and Turner 1978). The main effect of post-anthesis water stress on final grain yield is predominantly due to a reduction in grain size and weight (i.e., small and shrivelled grain) as a result of decreased assimilate supply and shortened duration of the grain filling period (Abdoli *et al.* 2013; Mitchell *et al.* 2013; Farooq *et al.* 2014). As a result, grain nutrient uptake in wheat can be reduced considerably under post-anthesis water deficit (Razzaghi and Rezaei 2015; Rezaei and

Razzaghi 2015), with grain K, P, Ca, and Mg content decreasing by an average of 51, 41, 67, and 60 %, respectively (Rezaei and Razzaghi 2015), and grain Fe, Zn, Mn, and Cu decreasing by an average of 50, 36, 43, and 16 %, respectively (Razzaghi and Rezaei 2015).

The relative impact of water stress on yield reductions can, however, differ during different growth stages (Akram 2011), whereby water stress (leaf water potential at -1.5 MPa) induced during the planting to jointing stage (early elongation) of wheat resulted in the highest reduction in grain yield (33.5 %) relative to stress induced during jointing to anthesis (26.0 %) and anthesis to maturity (22.6 %) stages (Singh and Malik 1983). However, other studies have also shown that water stress during reproductive development can be equally injurious (Qadir *et al.* 1999), or more detrimental to grain yield, especially if compounded by heat stress (Kaur and Behl 2010). Nevertheless, repeated water stress during both vegetative and reproductive stages will cause a severe reduction in wheat yield and yield components (Akram 2011) and this would have major limitations to dryland cropping systems which are heavily dependent on stored soil water (Chenu *et al.* 2011; Mitchell *et al.* 2013).

Topsoils that are prone to drying are thus likely to restrict soil nutrient bioavailability (i.e., release, transport, and acquisition), plant growth, plant nutrition, and grain development due to reduced soil water availability and increased water stress (Seiffert *et al.* 1995; Pregitzer and King 2005; Ma *et al.* 2009; Singh and Singh 2009; He and Dijkstra 2014; O'Callaghan 2017), even in fertilised fields (Amtmann and Blatt 2009; da Silva *et al.* 2011; Ahanger *et al.* 2016). In water-repellent soils, such adverse implications for crop growth and nutrition may likely be exacerbated by poor soil wetting, reduced soil water retention, increased spatial heterogeneity in soil water content, and the prevalence of isolated dry soil in the root zone. Implementation of appropriate management strategies to overcome soil water repellence and its potential limitations on soil water and nutrient availability is, therefore, required to improve crop and pasture production, and to address the gaps between actual and potential yields, particularly in dryland agricultural systems (Anderson *et al.* 2016).

2.4 Managing soil water repellence

Various physical, chemical, and biological approaches exist for managing soil water repellence which have been thoroughly reviewed by Blackwell (2000), Hallett (2008), Müller and Deurer (2011), and Roper *et al.* (2015). These approaches can be classified into three general categories (Roper *et al.* 2015): (1) amelioration, which involves the alteration of surface soil properties to improve soil wettability; (2) mitigation, such that water repellence is managed to improve water entry into the soil, but is not necessarily altered or removed; and, (3) avoidance, whereby severely affected areas are left for establishing trees or fodder shrubs rather than for crop production. In other cases, avoidance may also involve the grading of water-repellent topsoil from the furrow to the inter-row so that seeds or seedlings may be sown into non-repellent furrow (Blackwell 2000).

Amelioration of soil water repellence can be achieved by masking or diluting the concentration of hydrophobic compounds through clay amendment (Ma'shum *et al.* 1989; Ward and Oades 1993; Cann 2000), deep ripping (Hall *et al.* 2010), and soil cultivation with tools such as rotary spaders or one-off soil inversion with mouldboard ploughs (Davies *et al.* 2011; Betti *et al.* 2015; Davies and Blackwell 2015; Roper *et al.* 2015). Lime may also be applied, however, field trials suggest this to be relatively ineffective for improving soil wettability, especially in comparison to claying (Moore and Blackwell 2001). While amelioration via claying and soil cultivation can produce substantial long-lasting benefits, they are typically expensive for broadacre systems and may also carry a level of risk of increased soil erosion if not applied correctly (Davies *et al.* 2012a; Roper *et al.* 2015). The potential adverse implications of these amelioration methods for crop nutrition are addressed in Section 2.4.3.

Mitigation techniques, on the other hand, are relatively low cost although they can have smaller and sometimes inconsistent impacts on crop production (Davies *et al.* 2012a; Roper *et al.* 2015). These include the application of surfactants or wetting agents (Cisar *et al.* 2000; Kostka 2000; Dekker *et al.* 2003; Dekker *et al.* 2005a; Lehrsch and Sojka 2011), slow-release fertilisers (Franco *et al.* 2000b), fungicides (Karnok and Tucker 1999; Hallett *et al.* 2001; Karnok and Tucker 2001b; Fidanza *et al.* 2007), zero-tillage and stubble retention (Blackwell 2000; Roper *et al.* 2013), furrow sowing for water harvesting (Yang *et al.* 1996; Hallett *et al.* 2011), on-row zero-tillage sowing (Ward *et al.* 2015), and natural wax-degrading microorganisms which can be enhanced by lime application (Roper 2004; Roper 2005; Roper 2006).

Of the various management options available, current practices involving water harvesting, avoidance, and masking of hydrophobic organic matter by claying and cultivation have made a considerable improvement to sustainability and productivity of farming systems on water-repellent soils in Australia (Roper *et al.* 2015). A brief review of amelioration and mitigation strategies for soil water repellence is thus presented.

2.4.1 Amelioration

Clay

In sandy agricultural soils, clay-rich subsoil application and incorporation in the topsoil has been reported to provide a long-term solution to ameliorating soil water repellence and improving soil nutrient and water retention, seed germination, establishment, crop yield (Hall *et al.* 2010), and the effectiveness of herbicides (Cann 2000). The method of clay application used is dependent upon the depth to clay-rich subsoil. For instance, in Chromosols where clay is present within 30-60 cm from the surface, delvers can be used to lift clay to the surface which can then be spread and incorporated into topsoil by a rotary spader or inversion plough (e.g., mouldboard plough; Davenport *et al.* 2011). Where clay is present within the 30 cm depth, a rotary spader, mouldboard plough, or deep ripper can be used to lift and incorporate clay (Davenport *et al.* 2011). However, in Tenosols where clay is too deep for delving (>60 cm depth), subsoil clay must be excavated from clay pits and then spread over the soil surface and incorporated into topsoil (Davenport *et al.* 2011).

Claying raises the specific surface area of water-repellent sands which effectively dilutes or masks the hydrophobic substances in treated topsoil to the extent that water infiltration is no longer retarded (Hall *et al.* 2009). Dispersive or non-swelling clays, such as kaolinite, have been shown to be more effective in reducing soil water repellence than other clays, such as smectite which have larger surface areas (Ma'shum *et al.* 1989; McKissock *et al.* 2000; McKissock *et al.* 2002; Lichner *et al.* 2006), due to their ability to remain dispersed as the soil dries (Cann 2000) and which hinders the formation of persistent organic multilayers (Daniel *et al.* 2019). Sodic (Na^+-saturated) kaolinitic clays are ideally suited for masking soil water repellence given that they readily disperse (Ward and Oades 1993; Hall *et al.* 2009). Dispersible sodic clays are also more effective than Ca^{2+}-saturated clays (Ma'shum *et al.* 1989; Ward and Oades 1993). However, clay mineralogy and clay content appear to have more significant influence on reducing soil water repellence than exchangeable Na percentage and clay dispersibility (McKissock *et al.* 2000).

On the contrary, studies by Leelamanie and Karube (2007) found that soil water repellence disappeared in soils amended with montmorillonite, but not with kaolinite. This was similar to findings by Lichner *et al.* (2002) whereby kaolinite was not very effective in reducing the persistence of soil water repellence despite additions of 5 and 10 % clay. Nonetheless, experimental trials in Western Australia and South Australia have shown that large amounts of clay (e.g. 100 t/ha; Blackwell 1993) are typically required to remove water repellence. Clay spreading and incorporation on broadacre cropping systems are expensive and would thus only be economical if clays are naturally occurring at the site to be treated (Roper 2005; Hallett *et al.* 2011). For the sandplain soils of south-west Australia, soil water repellence is often negated by raising the clay content to above 3-5 % in the topsoil (Hall *et al.* 2009). Other compounds, such as lime, may also have a similar effect (see Section 2.4.2).

Deep soil cultivation

Deep ripping and soil cultivation by rotary spading or mouldboard ploughing provide additional effective long-term solutions to ameliorating soil water repellence and subsoil compaction (Davenport *et al.* 2011; Davies and Lacey 2011; Hall *et al.* 2018). Amelioration of soil water repellence can be achieved via: (1) abrasion of hydrophobic organic coatings on the surface of sand grains; (2) dilution or burial of water-repellent topsoil and exposing wettable subsoil; and, (3) increased water entry via subsoil seams (Wilson 2009; Blackwell and Davies 2011; Hallett *et al.* 2011; Hollamby and Davies 2012; Davies and Blackwell 2015). Although one-off deep soil cultivation can be effective for improving the uniformity of soil wetting, additional mixing of these soils may also destroy these preferred pathways (Roper *et al.* 2015). Indirectly, soil cultivation may also stimulate an increased activity of wax-degrading microorganisms which can result in the decomposition of hydrophobic organic matter, especially when lime is incorporated to optimise soil pH levels (Roper 2005; Roper 2006).

Considerable positive grain yield responses of 500-1200 kg/ha have also been reported from spading and mouldboard ploughing in water-repellent sandplain soils of WA (Davies *et al.* 2011). The same authors suggest that, in addition to reduced soil water repellence, there are many possible factors which may have resulted in the large yield response (e.g., increased crop emergence, improved soil pH and N mineralisation conditions, reduced soil strength, and reduced weed competition and plant diseases). The incorporation of subsoil clay by deep soil cultivation has, nevertheless, been applied extensively across southern Australia to ameliorate soil water repellence (Harper and Gilkes 2004; Davenport *et al.* 2011; Davies *et al.* 2015), with claying and deep ripping resulting in additive yield responses, almost doubling yields, despite achieving only 50-70 % of the rainfall-limited yield potential on marginally fertile soils (Hall *et al.* 2010).

2.4.2 Mitigation

Surfactants and wetting agents

Surfactants (surface active agents) or wetting agents are chemical substances that lower the surface tension of water, allowing increased water infiltration in water-repellent soil (Hall *et al.* 2009). Surfactants are also amphiphilic molecules and, therefore, act as detergents by binding with non-polar hydrophobic substances which aids the wetting of soil surfaces (Madsen *et al.* 2012b). Increased available soil moisture in the root zone by surfactant application can thereby greatly improve seedling emergence and survival (Madsen *et al.* 2012b).

The prophylactic use of chemical surfactants has generally been to treat soil water repellence in amenity turfgrass systems, such as golf courses (Cisar *et al.* 2000; Hallett *et al.* 2001; Karnok and Tucker 2003; Karnok and Tucker 2004; Oostindie *et al.* 2008; Aamlid *et al.* 2009a), and less commonly in agricultural systems (Roper 2005). However, there is an increasing interest in banding wetting agents at low doses in conjunction with furrow sowing for improved crop emergence and establishment in some regions of Western Australia and South Australia (Blackwell 2000; Davies *et al.* 2012a). Surfactant use has shown improvement in agricultural soil conditions and crop germination (Mohamed 2014), water and nutrient use efficiency (Lowery *et al.* 2002; Kelling *et al.* 2003; Lowery *et al.* 2005; Cooley *et al.* 2009), and the efficiency of water harvesting under zero-tillage, in conjunction with furrows (Blackwell 2000). However, the benefits from water harvesting (furrow sowing) for crop production on water-repellent soils can be relatively short-lived due to furrow infill (e.g., 1-5 months; Roper *et al.* 2015).

Although the concept of seed coating is not new and has been around since 1868 (Burgesser 1950), innovative surfactant seed coating (SSC) technologies have emerged in recent years to improve the reseeding success of post-fire restoration efforts in wildlands, particularly for overcoming soil water repellence, by restoring soil hydrologic function and increasing seedling emergence and early seedling development (Madsen *et al.* 2010; Madsen *et al.* 2012a; Madsen *et al.* 2016). In severely water-repellent soil, Madsen *et al.* (2012a) reported a dramatic improvement in the survival rate of crested wheatgrass (35.7 %) and bluebunch wheatgrass seedlings (38.4 %) treated with SSC relative to non-coated seeds (0.8 %) by the end of the study due to decreased runoff (by 59 %), increased percolation (by more than 3-fold), and increased soil water content (by 68 %). In another study, Madsen *et al.* (2013) also showed SSC to significantly improve turfgrass density (by 1.7-fold), coverage (by 7.5-fold), root biomass (by more than 5-fold), and shoot biomass (by more than 3-fold) on severely water-repellent soils due to the amelioration of soil water repellence and increased soil water content (by 2-fold).

Seed coating with various combinations of fertiliser, herbicide, fungicide, insecticide, or growth-promoting substances has, therefore, been developed for the enhancement of seed germination and seedling development (Vartha and Clifford 1973; Scott 1975; Taylor and Harman 1990; Taylor *et al.* 1998; Corlett *et al.* 2014). Application of SSC technologies in combination with other management techniques to overcome soil water repellence could thus be an effective strategy for improving crop establishment and productivity on water-repellent agricultural soils (Scott 1989).

Slow-release fertilisers

Laboratory and glasshouse experiments by Franco *et al.* (2000b) showed that the application of slow-release fertilisers (MaxBac® (N:P:K:S 22:5.7:0:0.6) and MagAMP® (N:P:K:Mg 7:20:5:9)) in the absence of subterranean clover (*Trifolium subterraneum* cv. Junee) resulted in a significant drop in soil water repellence severity, presumably due to stimulation of wax-degrading microorganisms naturally present in the soil. However, where plants were present, they found no significant difference between fertilised and unfertilised soils. In field soils growing subterranean clover pasture, Franco *et al.* (2000b) also found a slight but significant decrease in soil water repellence severity at the 0-5 cm depth in soils fertilised with the highest rates of MaxBac® relative to unfertilised soils, but soil water repellence had recovered back to levels similar to that of unfertilised soils by the end of summer during which time temperatures were elevated. It was postulated by the authors that the presence of plant growth was a key factor in the lack of a sustained effect of fertiliser as plant uptake would have reduced the amount of nutrients available for microbial activity.

Fungicides

Soil water repellence and localised dry spot conditions in amenity turfgrass systems are often attributed to symptomatic Type I and II fairy rings (Fidanza *et al.* 2007). This is specifically caused by basidiomycete fungi (Karnok and Tucker 1999) which can be frequently observed under hot and dry summer conditions (Fidanza 2007a; Fidanza 2007b). Curative treatments using fungicides, such as Flutolanil, have been used to control fungal growth, but fungicide alone cannot ameliorate soil water repellence (Karnok and Tucker 2001a; Elliott *et al.* 2002). Studies have, however, demonstrated that fungicide treatment in conjunction with surfactants can effectively treat soil water repellence caused by fairy ring fungi (Hallett *et al.* 2001; Karnok and Tucker 2001b; Fidanza *et al.* 2007). Surfactant application has also shown to dramatically decrease fungicide leaching primarily due to reduced preferential flow, but also increased sorption of fungicides by organic matter (Larsbo *et al.* 2008; Aamlid *et al.* 2009b).

Furrow and on-row sowing

Mitigation of soil water repellence via furrow sowing has been demonstrated to be very effective as a means of small-scale rainfall harvesting by diverting water from ridges into seeding rows (Hall *et al.* 2009; Hallett *et al.* 2011; Davies *et al.* 2012a; Blackwell *et al.* 2014). This strategy maximises water use efficiency in the root zone and the effectiveness of small rainfall events (Roper *et al.* 2015). Numerical modelling has also suggested ridge and furrow systems can reduce soil evaporation and temperature fluctuations (Yang *et al.* 1996). Studies have demonstrated crop emergence and soil wettability can be significantly improved when furrow sowing is used in combination with no-till (Blackwell *et al.* 2014), banded wetting agents (Davies *et al.* 2012a), and press wheels (Crabtree and Henderson 1999). Furrow sowing improved wheat and lupin emergence by an overall average of 16 and 41 %, respectively (Crabtree and Henderson 1999). While furrow sowing did not increase grain yield, furrow sowing in combination with press wheels increased grain yield by 30% (Crabtree and Henderson 1999). Furrow sowing with press wheels also increased pasture emergence by 133% with an additional 44% increase using banded wetting agents (Crabtree and Gilkes 1999b).

Furrow sowing can be significantly improved when using winged-type knife-points or boots which throw water-repellent soil from the furrow to the ridges (GRDC 2014a; Unkovich *et al.* 2015) unlike the conventional knife-point seeder which allows dry, water-repellent soil to fall behind the tyne on top of the seed, resulting in poor wetting of the seed (Davies *et al.* 2012a). On-row sowing by disc openers has also been observed to considerably improve crop establishment since the standing straw and remnant root systems from previous crops direct rainfall infiltration to the seed zone via preferential flow along old root channels (Davies *et al.* 2012a; Blackwell *et al.* 2014; Ward *et al.* 2015). This allows emerging plants greater access to water (compared to seeding between rows) particularly during the dry season (Roper *et al.* 2015). By contrast, Ward *et al.* (2015) did not find a significant positive yield response to on-row sowing although soils were comparatively less severely water-repellent in the on-row than inter-row sowing treatment, suggesting that on-row seeding could be a viable and low-cost strategy for the long-term management of soil water repellence in cropping systems.

No-tillage and stubble retention

Soil water repellence can be more severe under no-tillage and stubble retention treatments than under stubble burning and soil cultivation (Roper *et al.* 2013) due to increased soil organic carbon concentration near the surface (0-10 cm (Harper *et al.* 2000). However, Roper *et al.* (2013) found that the most repellent soils under no-tillage and stubble retention treatments also contained significantly greater water contents than the less repellent soils under stubble burning and soil cultivation. This appears to contradict current understanding that soil water repellence decreases with increased soil moisture (Hallett *et al.* 2011). Dye infiltration studies suggest increased water infiltration into the soil when residual root systems are undisturbed in zero-tillage planting with disk openers enabling preferential flow pathways for water along the old root channels (Davies *et al.* 2012a; Roper *et al.* 2013). Retaining above-ground residues may also minimise evaporation and soil drying, hence decrease the development of soil water repellence (Blackwell 2000; Scott *et al.* 2010). Moreover, studies also indicate no-tillage and, to a lesser extent, minimum-tillage can obtain high yields while still preserving soil organic carbon and nutrient levels in the topsoil (Martin-Rueda *et al.* 2007). No-tillage and stubble retention can, therefore, provide an effective way to improve water infiltration and soil water storage for crop production in water-repellent soils, provided sowing is done with zero-tillage openers that do not disrupt the old root channels.

Wax-degrading microorganisms and enzymes

Wax-degrading bacteria can be utilised to alleviate soil water repellence by direct consumption of hydrophobic organic substances or indirectly by producing biosurfactants (Franco *et al.* 2000a; Franco *et al.* 2000b; Roper 2004; Roper 2005; Roper 2006). Direct enzyme application to soils has also been shown to remediate soil water repellence in turfgrass systems (Liu *et al.* 2013; Zeng *et al.* 2014). In the sandplain soils of south-western Australia, inoculation with wax-degrading bacteria significantly reduced soil water repellence severity, especially in the presence of lime (Roper 2006). Increasing the soil pH to more favourable neutral-alkaline conditions stimulates soil microbial and enzyme activity (Acosta-Martínez and Tabatabai 2000;

Roper 2005; Fuentes *et al.* 2006; Mühlbachová and Tlustoš 2006; Müller and Deurer 2011). Populations of wax-degrading bacteria were found to be significantly greater in soils treated with lime by up to 10-fold than in untreated soils (Roper 2005).

Lime

Lime amendments (e.g., oxides, hydroxides, carbonates, and silicates of Ca or Ca-Mg mixtures), which are commonly used to ameliorate soil acidity (Uchida and Hue 2000; Moore *et al.* 2001a; Goulding 2016), have also been observed to reduce soil water repellence severity (van't Woudt 1959; Wallis and Horne 1992; Roper 2005; Roper 2006). This can be largely explained by the physical effect of lime on soil surface area, similar to that of clay, due to its fine particle size and hence the potential to mask hydrophobic coatings on sand surfaces (Moore and Blackwell 2001; Unkovich *et al.* 2015), and its biological effect by raising the soil pH and stimulating the activity, growth, and population of wax-degrading bacteria (actinomycetes belonging to *Rhodococcus* spp. and *Mycobacterium* spp.) by up to 10-fold under more favourable neutral-alkaline conditions (Roper 2005). Moreover, lime could also alter soil surface charge characteristics that improve the soil's affinity for water absorption (Hodge and Michelsen 1991) in that the negative surface charge density of soil would increase due to the deprotonation of surface sites under an increasing soil pH, resulting in a decrease in soil water repellence severity (Bayer and Schaumann 2007; Diehl *et al.* 2010). However, other field and incubation trials have suggested that lime applications were relatively ineffective for improving soil wettability (Hodge and Michelsen 1991; Shanmugam *et al.* 2014), especially in comparison to clay amendments (Moore and Blackwell 2001). In amenity soils, high pH treatments using sodium hydroxide have also been effective in alleviating soil water repellence (Karnok *et al.* 1993).

2.4.3 Implications from amelioration

While the amelioration of soil water repellence by subsoil claying and deep soil cultivation can provide a long-term solution for improving crop production on water-repellent soils, they can also carry a potential level of risk for crop growth and nutrition if not applied correctly (Harper and Gilkes 2004; Davies *et al.* 2012a; Roper *et al.*

2015). Risks due to claying may be associated with the properties of subsoil clay applied (e.g., adverse pH, salinity, sodicity, and toxicity) and/or the method of application. While soils may no longer be repellent after claying, high application rates and/or inadequate incorporation of clay into topsoil can result in surface sealing, crusting, hardsetting, compaction, and decreased water use efficiency particularly from light rainfall events due to poor water infiltration, decreased wetting depth, and increased rate of evaporation of soil water from the surface soil layer (Davenport *et al.* 2011; Masters 2014). This would consequently limit plant root development into the subsoil (Davies *et al.* 2012a). High application rates (e.g., 150 t/ha) of high pH, calcareous clays can also lead to nutrient fixation relative to non-calcareous clays which can result in trace element deficiency, particularly in manganese (Davenport *et al.* 2011; Masters 2014). Fixation of P and K by clay and calcium carbonate could also have implications for plant P and K nutrition (Weil and Brady 2017). Sodic, alkaline subsoils can also contain high levels of Na and B which are potentially toxic to plants (Cartwright *et al.* 1984; Rengasamy 2002) and thus their incorporation in topsoil could have injurious effects on crop production in the short to medium term until they are leached deeper into the soil profile given sufficient rainfall (Davenport *et al.* 2011). Likewise, introduction of acidic subsoils could also adversely affect crop production due to Al and Mn phytotoxicity and nutrient imbalance, particularly of P (Rahman *et al.* 2018). By contrast, field trials have shown significant improvements in plant K nutrition by amending sandy soils with subsoil clay, predominantly of kaolinite which is inherently high in exchangeable K, relative to untreated soils (Carter *et al.* 1998; Hall *et al.* 2010; Hall *et al.* 2015), but this response was generally limited to soils initially low in Colwell K (<60 mg/kg; Bell *et al.* 2018).

Soils that have been spaded or mouldboard ploughed may also result in the dilution or redistribution of plant-available nutrients, especially immobile nutrients such as P which are stratified near the soil surface, and this could result in reduced topsoil P availability and consequently impact on crop P nutrition (Davies *et al.* 2010b; Scanlan *et al.* 2012; O'Callaghan 2017; Scanlan and Davies 2019). By contrast, topsoil burial from spading or mouldboard ploughing may also increase the availability of nutrients in the subsurface root zone which is less susceptible to soil drying compared to nutrients that are concentrated near the soil surface (Davies *et al.* 2012b; Davies and Johnston 2012). Loosening of soil due to spading or mouldboard ploughing may, however, result in poor seed-soil contact and reduced seeding depth control which consequently reduces crop emergence and establishment, despite the amelioration of soil water repellence and soil compaction (Davies *et al.* 2010a; Davies and Hollamby 2011). By contrast, significant increases in early plant biomass production could result in an increased risk of haying off due to limited plant-available water during the season and/or a dry finish to the season (Davies *et al.* 2010b; Hall *et al.* 2015; Roper *et al.* 2015), although this may also be negated by greater access of the crop to subsoil water supply (Kirkegaard *et al.* 2007).

Due to the permanent changes in soil physical and chemical properties from subsoil claying and deep soil cultivation, the potential introduction of new constraints from poor application of practices could thus have long-term implications for crop growth and nutrition. It is, therefore, important to make informed decisions from soil test results or experimental trials to assess the potential long-term risks and benefits involved in claying and/or deep soil cultivation for crop growth and nutrition.

2.5 Conclusion

To date, much research has been primarily focused on the impacts of soil water repellence on soil hydrologic processes and their adverse consequences for seed germination, seedling survival, plant establishment, plant growth, and plant productivity in burnt and unburnt natural ecosystems and forest plantations, grasslands and amenity turfgrass systems, and agricultural crop and pasture systems. However, the effect of soil water repellence on crop nutrition in water-repellent agricultural soils has not been directly assessed and little is known about its influence on in-season soil nutrient availability and plant nutrient uptake in both untreated and treated soils. Given the fundamental role of soil water in soil nutrient release, nutrient transport, and plant nutrient acquisition, changes in soil hydrologic processes and the spatial distribution of soil water content due to soil water repellence (i.e., decreased soil water infiltration, water flow diversion, unstable wetting patterns, and accelerated vertical water transport via preferential pathways) are bound to affect soil nutrient bioavailability, plant uptake mechanisms, crop nutrition, and ultimately crop yields. However, the direct and indirect effects of soil water repellence on crop nutrition have not been systematically studied. A review of literature identifies several ways in which plant nutrition could be affected on water-repellent soils, including:

- decreased quantity of nutrients released to the soil solution (via dissolution, desorption, and mineralisation) due to decreased wettable soil volume and decreased water availability caused by flow diversion (runoff and leaching);
- decreased rate of nutrient transport (via mass flow and diffusion) due to decreased soil water availability, decreased nutrient diffusion rates, and increased spatial heterogeneity in soil water content, resulting in the increased tortuosity of water and nutrient flow and root growth pathways;
- isolated dry patches in the root zone which can physically inhibit root growth and the acquisition of nutrients therein;
- suppressed plant root-absorbing power and use efficiency for water and nutrients due to increased water stress, particularly in dry patches; and,
- accelerated water and nutrient loss via runoff and leaching along conducive pathways, especially after heavy rainfall events.

Limitations to crop growth and yield on water-repellent soils could, therefore, be attributed to reduced soil nutrient bioavailability and poor crop nutrition in addition to decreased seed germination and crop establishment. By contrast, a delay in wetting of significant proportions of topsoil may conserve nutrients by avoiding leaching losses from sandy soils during periods of heavy rainfall and increase their acquisition during periods of highest crop demand. The soil water repellence effects on crop nutrition are also likely to be more pronounced in semi-arid (steppe) and Mediterranean dryland systems which are strongly dependent on stored soil water and susceptible to water stress. Research is thus needed to better understand and manage the potential constraints to crop nutrition on water-repellent agricultural soils. In addition, effects of amelioration methods on crop nutrition also need to be better understood.

Chapter 3: Assessing relationships between soil water repellence severity, soil properties, and crop growth and nutrition

3.1 Introduction

In many dryland crop and pasture systems in southern Australia, soil water repellence is a major constraint to seed germination, seedling emergence, plant establishment, dry matter production, and crop yield (Bond 1972; DeBano 1981; Müller *et al.* 2014a; Roper *et al.* 2015). These constraints to crop and pasture production are predominantly due to poor water infiltration and uneven soil wetting at the start of the growing season (Roberts and Carbon 1971; Wang *et al.* 2000; Li *et al.* 2018), particularly in areas where seeds are dry sown (Roper *et al.* 2015; Fletcher *et al.* 2016). As a result, water-repellent soils exhibit high spatial variation in soil water contents, typically characterised by distinct dry zones contiguous with very wet zones (Bond 1964; Letey 2001). Such uneven wetting in the seeding row and root zone consequently causes the poor establishment of crops and pastures and their uneven growth and maturation in the field (Bond 1972; Doerr *et al.* 2007; Hall *et al.* 2009).

Variation in soil water content and wetting patterns will also affect the bioavailability of soil nutrients given the fundamental role of water in the physical, chemical, and biological processes controlling nutrient release (dissolution, desorption, and mineralisation), nutrient transport (mass flow and diffusion), and root uptake mechanisms in the soil-plant environment (Comerford 2005; Gregory 2006). Since virtually all mineral nutrients that are absorbed by plant roots exist in an ionic and inorganic aqueous form in the soil solution (Mengel and Kirkby 2001; Comerford 2005), plants cannot access nutrients in dry soil (Kuchenbuch *et al.* 1986; Tinker and Nye 2000; McBeath *et al.* 2012) and extended periods of drought are known to limit plant nutrition, even in fertilised fields (Amtmann and Blatt 2009; da Silva *et al.* 2011; Ahanger *et al.* 2016).

Stress from hydrological and nutritional drought would consequently inhibit plant physiological processes and retard early growth (Uchida 2000; da Silva *et al.* 2011) which further impedes root-absorbing power and use efficiency for water and nutrients (Alam 1999; Farooq *et al.* 2009; Oliveira *et al.* 2010). In cereal crops, nutrient deficiencies (particularly P deficiency) have been reported to inhibit tiller emergence and decrease crop productivity (Rodríguez *et al.* 1999; Prystupa *et al.* 2003). This could probably be due to a high proportion of total P (50-60 %) already taken up by wheat plants when shoots have developed only 20-35 % of their total dry matter (Römer and Schilling 1986). As such, nutrient deficiencies during early crop growth are likely to affect yield potential more greatly than deficiencies later in the season (Grant *et al.* 2001), but this is more likely for wheat than for canola given that canola plants are known to continue taking up P and K later in its growth cycle (Rose *et al.* 2007). Water stress may, nonetheless, decrease nutrient assimilation and redistribution, further compromising grain yield and nutrition (Rezaei and Razzaghi 2015).

Given the potential for soil water repellence to exacerbate drought by diverting rainfall, soil water repellence could play a significant role in plant growth and nutrition in dryland agricultural systems. However, the effects of soil water repellence on crop nutrition have not been studied despite a general agreement among many authors that soil water repellence is likely to hinder plant access to soil nutrients and hence plant nutrient use efficiency as a result of increased spatial heterogeneity in soil water content, and a reduction in plant-available water supply and water use efficiency (Sunderman 1988; Doerr *et al.* 2000; Kramers *et al.* 2005; Jordán *et al.* 2013; Scanlan *et al.* 2013; Roper *et al.* 2015; Hermansen *et al.* 2019). It is, therefore, the hypothesis of this dissertation that soil water repellence will adversely affect crop growth and nutrition. To quantify this effect, a preliminary field investigation was undertaken to assess the spatial and temporal variability of soil water repellence severity and its possible relationships with other soil properties, soil nutrient availability, in-season crop nutrition, dry matter production, and crop yield parameters on two water-repellent sandy soil types located in the southwest region of WA.

3.2 Materials and methods

3.2.1 Study site and climate

A preliminary investigation was conducted to assess the spatial and temporal variability of soil water repellence severity in the crop row (furrow) and its possible relationship(s) with crop growth and nutrition on two sandy soil types in the wheatbelt of southwest Western Australia (WA; Figure 5). Canola, *Brassica napus* (cv. Pioneer® 45Y25 (RR)), was grown over 191 days, from 1 May to 7 November 2016, in 20 cm row spacings on a water-repellent sandy loam yellow duplex soil (Ferric Chromosol, Australian Soil Classification (ASC); Isbell 2016) at Kojonup (33°41’08.83” S, 117°01’54.01” E), WA. Although 1 L of banded wetting agent /ha was applied by the farmer at sowing at this site (Justin Elliott, personal communication), soil water repellence was still severely expressed (MED 3.4 at the 0-5 cm depth; see Section 3.3.1). Wheat, *Triticum aestivum* (cv. Scepter), was grown over 161 days, from 28 June to 5 December 2016, in 35 cm row spacings on a water-repellent deep grey sandy duplex soil (Grey Bleached-Ferric Kandosol, ASC) at Meckering (31°37’38.22” S, 116°52’16.53” E), WA, located approximately 228 km north of the study site at Kojonup.

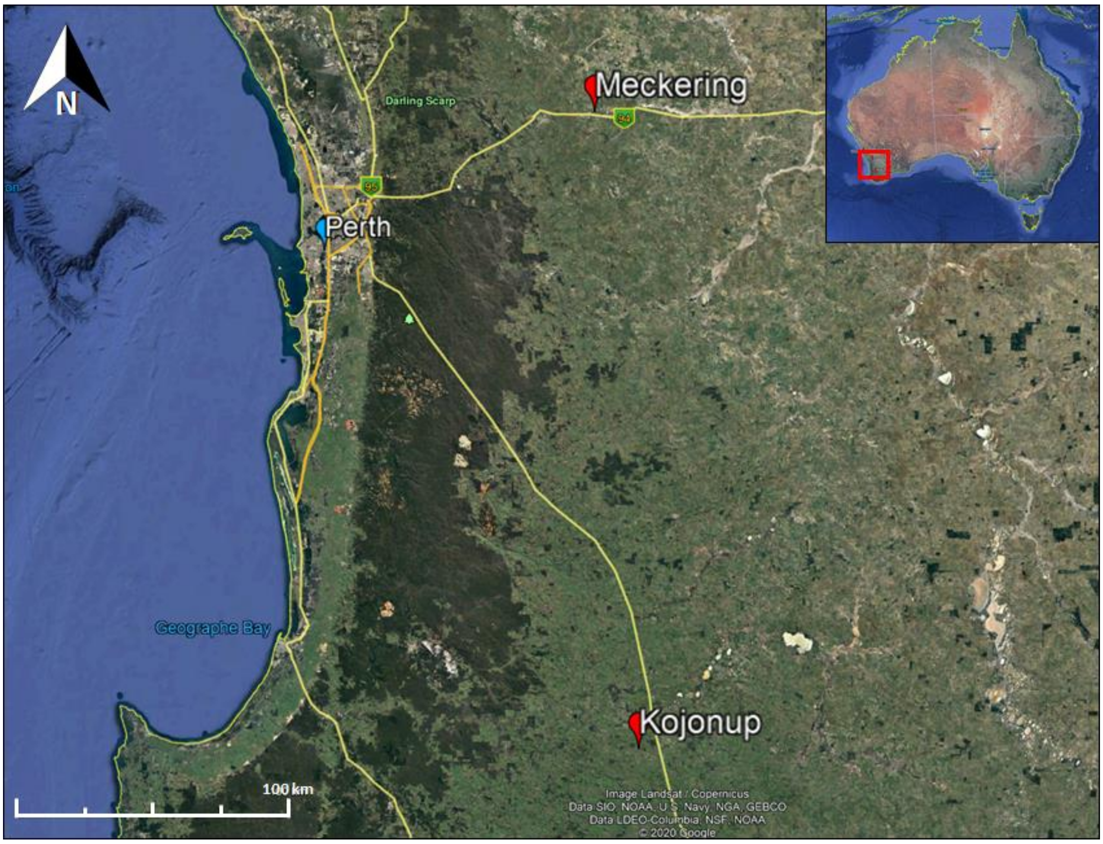

Figure 5. Location of study sites at Kojonup and Meckering, Western Australia.

The climate in Kojonup and Meckering is Mediterranean (classified by the Köppen-Geiger system as *Csb and Csa*, respectively), with mean monthly temperatures of 14.7 to 29.6°C (Figure 6a) and 17.4 to 34.5°C (Figure 6b), respectively. In 2016, annual rainfall recorded was 710 mm at Kojonup which was higher than the mean annual rainfall of 483 mm (between 1985 and 2015). Note, heavy rainfall was recorded in January at Kojonup (114 mm) which was the highest on record since 1985, with March and August rainfall also higher than average. At Meckering, annual rainfall in 2016 was 475 mm which was higher than the mean annual rainfall of 378 mm (between 1985 and 2015). Relatively high rainfall was recorded in January (61 mm), March (76 mm), April (52 mm), and May (52 mm) in this region, with March 2016 rainfall being the highest on record over the past three decades. Given substantial amounts of rainfall early in the season, the potential effect of soil water repellence on crop growth and nutrition may not be clearly observed.

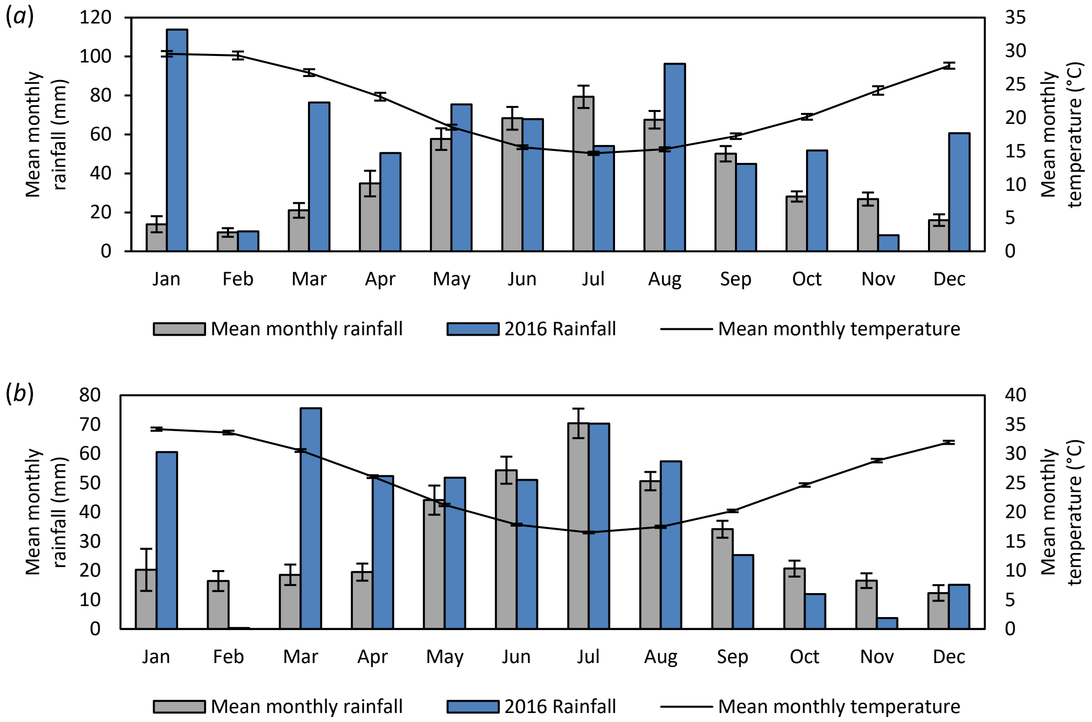

Figure 6. Mean monthly rainfall and temperature at (a) Kojonup and (b) Meckering, Western Australia, with mean values (± standard error) based on records from 1985 to 2015 at the Kojonup weather station and Mount Noddy weather station, respectively.

3.2.2 Soil and plant sampling

At Kojonup, soil and plants were systematically sampled from 20 plots (8 × 5 m) in a 40 × 20 m grid (Figure 7). The grid was positioned where canola plant density was highly variable to capture the variability in plant growth and nutrition, which was hypothesised to be attributed to differences in the severity of soil water repellence. Note, however, that the northern (upper) five sampling locations were only established during the canola stem elongation stage (95 days after sowing, DAS) after the aerial drone image was taken (Figure 7) as it identified additional areas with lower plant densities. The initial data collected during canola emergence (16 DAS) and leaf production (53 DAS) were, therefore, limited to the lower 15 sampling locations.

At Meckering, soil and plants were systematically sampled from 18 plots (7.5 × 2.4 m), distributed across three 45 × 2.4 m transects which were positioned within buffer zones of a pre-existing trial site established by the Western Australian Department of Primary Industries and Regional Development (DPIRD; formerly the Department of Agriculture and Food WA; Figure 8). Soil and plant leaf tissue were sampled progressively within each plot throughout the season during the major crop growth stages (Table 2).

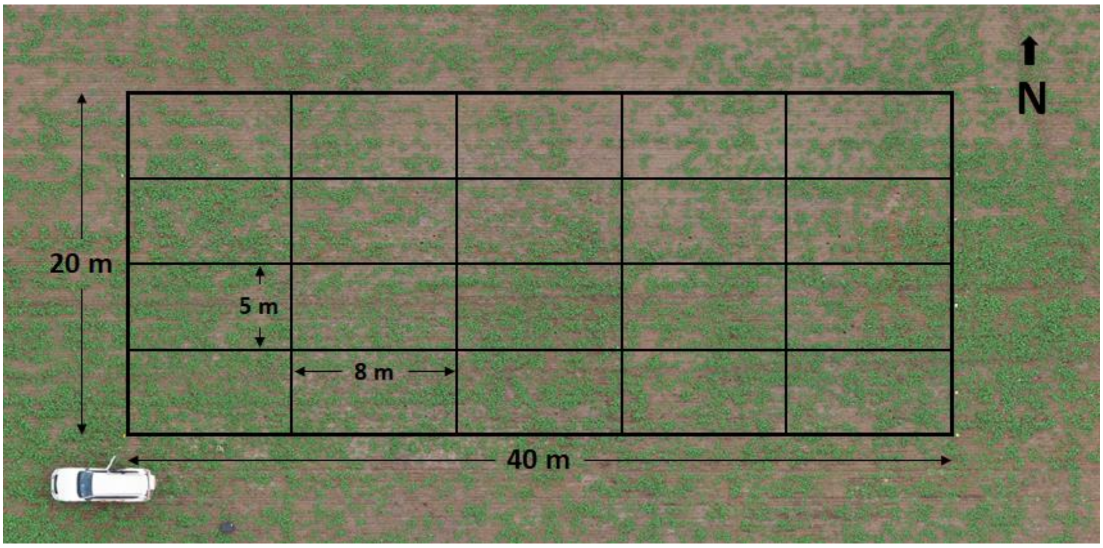

Figure 7. Systematic sampling of soil and plants in a 40 × 20 m grid at Kojonup in 2016. Aerial drone image provided by Stanley Sochacki during the canola leaf production stage.

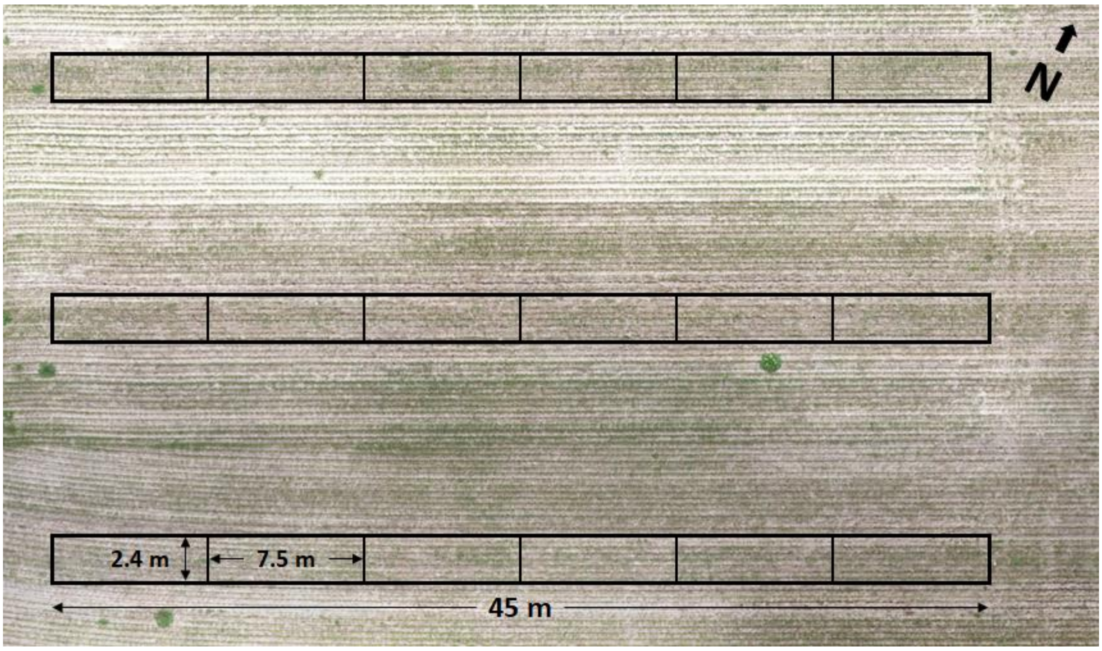

Figure 8. Systematic sampling of soil and plants along three 45 × 2.4 m transects at Meckering in 2017. Aerial drone image provided by Stanley Sochacki during the wheat tillering stage.

Soils were sampled in furrows at the 0-5 and 5-10 cm depths using a soil corer (*ca*. 75 mm diameter) followed by the bulking of two core samples from each plot. Soil water repellence is most severely expressed in the upper 10 cm layer of soil (Harper and Gilkes 1994; Keizer *et al.* 2007; Wahl 2008; Walden *et al.* 2015). The 'potential' soil water repellence severity of all soil samples (air-dried at 40°C and sieved to ≤2 mm) at the 0-5 and 5-10 cm depths were assessed in the laboratory using the molarity of ethanol droplet, MED, test (King 1981). Five droplets of standardised ethanol solution with a droplet volume of 0.034 ml were applied to the soil surface using a Pasteur pipette at 0.2 M increments. Soil water repellence severity is then denoted by the MED concentration that penetrates the soil surface within 10 seconds.

Gravimetric soil water content (% w/w) was determined in the laboratory (Rowell 1994) on soil samples at the 0-5 and 5-10 cm depths, with gravimetric gravel (>2 mm) content (% w/w) also determined at the 0-5, 5-10, 10-20, and 20-30 cm depths for the Ferric Chromosol at Kojonup. Soil chemical properties from the 0-10 cm depth were analysed as bulk samples at three different growth stages (Table 2), using standard methods (Rayment and Lyons 2011) by CSBP Soil and Plant Analysis Laboratory. Youngest, fully matured leaves of canola and wheat plants were collected within a 1 m^2 quadrat from each plot (corresponding with soil sample location) at several major growth stages (Table 2) and analysed for nutrient composition using standard methods (Rayment and Lyons 2011) by CSBP Soil and Plant Analysis Laboratory.

Table 2. Sampling (days after sowing, DAS) at different crop growth stages in 2016. Decimal growth scales provided for canola (Edwards and Hertel 2011) and wheat (Zadoks et al. 1974).

Plant (study site)	Growth stage	DAS
Canola (Kojonup)	0.8: Emergence*	16
	1.10: Leaf production[†]	53
	3.3: Stem elongation / green bud*[†Δ]	95
	4.8: Anthesis[†Δ]	116
	5.5: Pod development*[†Δ]	143
	6.3: Seed maturity	191
Wheat (Meckering)	Z12: Emergence*	22
	Z21: Tillering[†]	64
	Z45-57: Booting / ear emergence*[†Δ]	100
	Z65-67: Anthesis[†Δ]	113
	Z75: Grain development*	134
	Z91: Grain maturity	161

* Soil samples analysed for chemical properties.
[†] Plant leaf samples analysed for nutrient composition.
[Δ] Plant leaves assessed for relative water content.

Plant density was recorded during early vegetative growth and at crop maturity within quadrats of 1 m × 3 rows – i.e., 0.6 m^2 for canola at Kojonup (row spacing of 20 cm) and 1.05 m^2 for wheat at Meckering (row spacing of 35 cm). At maturity, canola was harvested by hand (cut from the base of the stem) from 1 m × 2 rows due to the large size of plants, while wheat was harvested from 1 m × 3 rows. Canola pods and wheat heads were then threshed by hand using a rubber lined board to assess for final oilseed/grain yield. Shoot dry matter of mature plants was also assessed (excluding the oilseed/grain).

3.2.3 Determination of leaf relative water content

Hydration status of canola and wheat plants were assessed throughout the growing season, from early vegetative to reproductive growth, by measuring the relative water content (RWC, %) or ‘relative turgidity’ in leaves (Barrs and Weatherley 1962; Mullan and Pietragalla 2012). Six young fully expanded leaves were collected from different plants in each sampling location at solar noon (±2 hours). The top and bottom section of the leaves were cut off with secateurs, sealed in pre-weighed plastic tubes, and retained in an insulated cooler. Samples were measured for fresh weight in the laboratory and subsequently placed in the refrigerator for 24 hours, with 20 ml distilled water added to each sample tube for leaves to reach full turgor. Leaves were then removed from tubes, carefully dried with an adsorbent paper towel, and measured for turgid weight. Samples were oven-dried at 70°C and re-measured for dry weight. The RWC was calculated from the following equation:

$$Leaf\ RWC\ (\%) = \frac{Leaf\ fresh\ weight - Leaf\ dry\ weight}{Leaf\ turgid\ weight - Leaf\ dry\ weight} \times 100 \qquad [1]$$

3.2.4 Statistical analysis

Parametric statistical analyses were carried out using SPSS Statistics version 21.0 (IBM Corporation, Armonk, NY, USA) to determine the effect of soil water repellence severity on soil properties, plant growth, and plant nutrition on water-repellent, sandy agricultural soils in southwest WA. Data were assessed for normality and homogeneity prior to statistical analysis. Soil water repellence severity (MED value) at different sampling depths (0-5 and 5-10 cm) and crop growth stages were analysed in a repeated measures analysis of variance, ANOVA (two-tail), test in SPSS, with repeated measures for sampling depth and growth stage as within-subjects variables. Several classes of water repellence severity at the 0-5 cm depth were observed (King 1981): Class 1 (negligible/slightly repellent: MED 0.0 to 1.0), Class 2 (moderately repellent: MED 1.2 to 2.2), Class 3 (severely repellent: MED 2.4 to 3.0), Class 4 (very severely repellent: MED 3.2 to 3.8), and Class 5 (extremely repellent: MED $\geq$ 4.0). To identify distinct characteristics of water-repellent soils, soil chemical properties (0-10 cm depth) and plant parameters were grouped according to soil water repellence severity class and tested for differences using a univariate ANOVA. Soil water and gravel content were analysed in a mixed model ANOVA in SPSS, using soil water repellence severity class as the between-subjects variable and repeated measures for sampling depth and growth stage as within-subjects variables. Post hoc analysis was performed using Fisher's least significant difference (LSD) at $P < 0.05$ to determine significant differences among severity classes and/or growth stages. Bivariate correlation analysis was also conducted in SPSS to study key relationships between the observed parameters and soil water repellence severity, with significant correlations (two-tailed) interpreted by the Coefficient of Determination (R^2) at the 95 and 99 % confidence intervals. Note that among a range of parameters and statistically significant observations, only key factors which were found to be important for crop growth and nutrition will be of main focus in this chapter, while those that are generally of lesser importance will be provided in C.1 as supplementary data.

3.3 Results

3.3.1 Kojonup

Soil water repellence

Water repellence severity of the Ferric Chromosol at Kojonup generally ranged from absent (MED 0.0) to extreme levels (MED 4.6), with the median soil being very severely repellent (MED 3.4) at the 0-5 cm depth and moderately repellent (MED 1.6) at the 5-10 cm depth. Soil water repellence severity was significantly greater at the 0-5 cm depth (MED 3.4; very severely repellent) than at the 5-10 cm depth (MED 1.3; moderately repellent; $P < 0.001$; Table 3) but was not affected by growth stage. Note that results during canola emergence (16 DAS) were not included in the analysis due to soil samples being accidentally bulked at the 0-10 cm (MED 2.7).

Table 3. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil water repellence severity (molarity of ethanol droplet, MED) at Kojonup in 2016, with repeated measures for sampling depth and growth stage as within-subjects variables. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Source of variation	*F*
Growth stage	2 ^{ns}
Sampling depth	416****
Growth stage × Sampling depth	1 ^{ns}

^{ns} Not significant ($P > 0.05$).

Soil water content

Results showed that soil water content was significantly affected by the three-way interaction of growth stage × sampling depth × soil water repellence severity class ($P < 0.05$; Table 4) in the Ferric Chromosol at Kojonup. During canola leaf production, soil water content at the 0-5 cm depth was significantly greater in Class 2 (moderately repellent; 20.8 %) and 3 (severely repellent; 19.7 %) soils than in Class 4 soils (very severely repellent; 12.2 %; Table 5), but there was no difference in soil water content between Class 2 and 3 soils. During other growth stages, soil water content was not affected by soil MED class, regardless of sampling depth. In Class 2 (moderately repellent) and 3 (severely repellent) soils, soil water content was significantly greater at the 0-5 cm depth (16.2-20.8 % and 12.9-19.7 %, respectively) than at the 5-10 cm depth (10.7-12.4 % and 9.1-12.5 %, respectively; Table 5), except during crop maturity when soil water content was significantly greater at the 5-10 cm depth (2.8 and 2.5 %, respectively) than at the 0-5 cm depth (2.0 and 1.6 %, respectively). In Class 4 (very severely repellent) soils, soil water content was also significantly greater at the 0-5 cm depth (15.9 %) than at the 5-10 cm depth (11.8 %) during anthesis but significantly greater at the 5-10 cm depth (2.5 %) than at the 0-5 cm depth (1.9 %; Table 5) during crop maturity. Regardless of soil water repellence severity class and sampling depth, soil water content was significantly lower during crop maturity (1.6-2.8 %) than during other growth stages (9.1-20.8 %; Table 5).

Table 4. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil water content at Kojonup in 2016, with soil water repellence (SWR) severity class as a between-subjects variable and repeated measures for sampling depth and growth stage as within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	*F*
Growth stage	109****
Sampling depth	69****
SWR severity class	2 ^{ns}
Growth stage × Sampling depth	27****
Growth stage × SWR severity class	2 ^{ns}
Sampling depth × SWR severity class	5*
Growth stage × Sampling depth × SWR severity class	3*

^{ns} Not significant ($P > 0.05$).

Table 5. Effect of soil water repellence (SWR) severity class on soil water content (%, w/w) in the furrow at the 0-5 and 5-10 cm depths during different growth stages in canola at Kojonup in 2016. Mean values based on an average sample size of 5 (unequal sample sizes). Significant differences based on the least significant difference (LSD) at $P < 0.05$.

SWR severity class	Depth	Leaf production (53 DAS)	Stem elongation (95 DAS)	Anthesis (116 DAS)	Pod development (143 DAS)	Maturity (191 DAS)
Class 2 (moderate)	0-5 cm	$20.8^{a1\dagger}$	$16.2^{a1\dagger}$	$18.7^{a1\dagger}$	$16.5^{a1\dagger}$	$2.0^{b1\dagger}$
	5-10 cm	12.3^{a1}	10.7^{a1}	12.4^{a1}	11.2^{a1}	2.8^{b1}
Class 3 (severe)	0-5 cm	$19.7^{a1\dagger}$	$12.9^{b1\dagger}$	$19.4^{a1\dagger}$	$17.6^{a1\dagger}$	$1.6^{c1\dagger}$
	5-10 cm	12.5^{a1}	9.1^{b1}	11.8^{a1}	11.2^{a1}	2.5^{c1}
Class 4 (very severe)	0-5 cm	12.2^{ab2}	11.7^{a1}	$15.9^{b1\dagger}$	13.9^{ab1}	$1.9^{c1\dagger}$
	5-10 cm	11.2^{a1}	10.8^{a1}	11.8^{a1}	11.6^{a1}	2.5^{b1}

Different superscript letters denote significant differences between growth stages ($P < 0.05$).
Different superscript numbers denote significant differences between SWR severity class ($P < 0.05$).
† Significantly different from the 5-10 cm depth ($P < 0.05$).

Bivariate analysis, however, showed no correlation between soil water repellence severity (MED) and soil water content in this Ferric Chromosol at Kojonup (data not shown), but soil water and gravel content were negatively correlated at the 0-5 ($R^2 = 0.39$; $P < 0.01$; Figure 9a) and 5-10 cm depths ($R^2 = 0.18$; $P < 0.01$; Figure 9b).

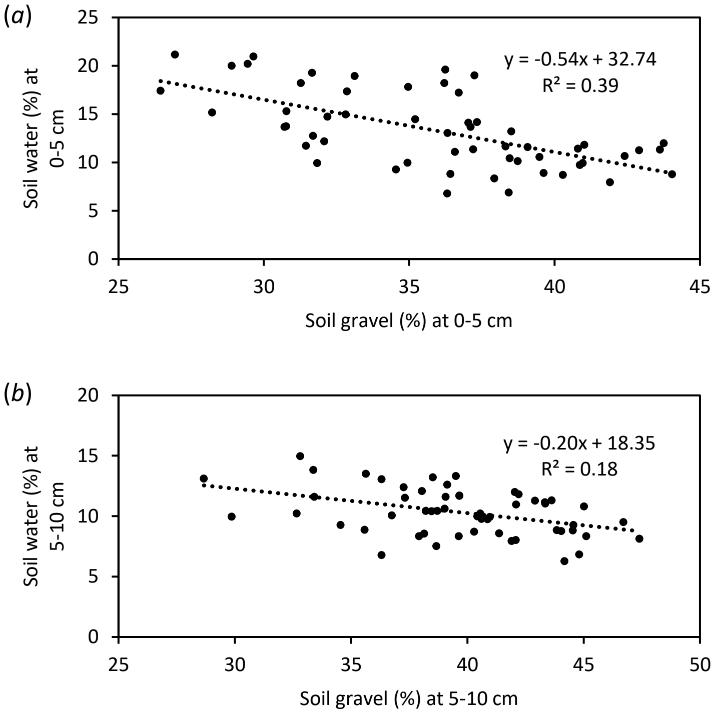

Figure 9. Relationship between soil water (%, w/w) and gravel content (%, w/w) at the (a) 0-5 cm and (b) 5-10 cm depths in a Ferric Chromosol at Kojonup in 2016.

Soil gravel content

In the Ferric Chromosol at Kojonup, gravel content increased with depth ($P < 0.001$; Table 6) from 34.3 % (0-5 cm depth) to 38.6 % (5-10 cm depth; Figure 10), with a sharp increase at the 10-20 cm depth (52.0 %). There was no difference in gravel content between the 10-20 and 20-30 cm depths. However, there was no difference in gravel content between soil water repellence severity class (Table 6) and no correlation between gravel content and soil water repellence severity (MED; data not shown).

Table 6. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil gravel content (%, w/w) at Kojonup in 2016, with soil water repellence (SWR) severity class as a between-subjects variable and repeated measures for sampling depth and growth stage as within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	*F*
Growth stage[†]	1 ^{ns}
Sampling depth	96****
SWR severity class	1 ^{ns}
Growth stage × Sampling depth	0 ^{ns}
Growth stage × SWR severity class	0 ^{ns}
Sampling depth × SWR severity class	2 ^{ns}
Growth stage × Sampling depth × SWR severity class	0 ^{ns}

[†] Only stem elongation and pod development stages.

^{ns} Not significant ($P > 0.05$).

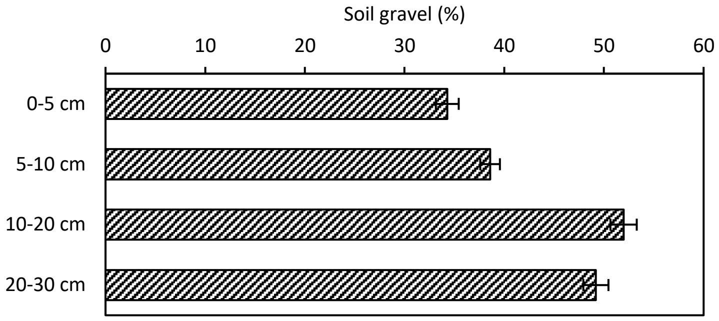

Figure 10. Mean soil gravel content (% w/w, ± standard error) at the 0-5, 5-10, 10-20, and 20-30 cm depths in a Ferric Chromosol at Kojonup in 2016.

Soil chemical properties

Soil EC, pH_{Ca}, Mn concentration, and exchangeable Ca and Al percentages at the 0-10 cm depth were significantly affected by the two-way interaction of growth stage × soil water repellence severity class ($P < 0.05$; Table 7). However, effects on soil Mn concentration, exchangeable Al concentration and percentage, and exchangeable Ca percentages were not discussed in this chapter as they were not found to relate to crop nutrition of canola growth (see Appendix B.1.1). During canola emergence (16 DAS), soil EC at the 0-10 cm depth was significantly greater in Class 2 soils (moderately repellent; 0.13 dS/m) than in Class 3 (severely repellent; 0.10 dS/m) and Class 4 soils (very severely repellent; 0.06 dS/m; Table 8), but there was no difference due to soil water repellence severity class during later growth stages.

Table 7. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between growth stage and soil water repellence (SWR) severity class on soil properties at the 0-10 cm depth at Kojonup in 2016. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Soil properties	Growth stage	SWR severity class	Growth stage × SWR severity class
Organic carbon	6***	2 ^{ns}	1 ^{ns}
Electrical conductivity	26****	5***	4**
pH_{Ca}	2 ^{ns}	5**	3*
NH_4-N	4*	0 ^{ns}	2 ^{ns}
NO_3-N	64****	1 ^{ns}	2 ^{ns}
Colwell P	2 ^{ns}	0 ^{ns}	1 ^{ns}
Colwell K	6**	0 ^{ns}	1 ^{ns}
Extractable S	13***	2 ^{ns}	2 ^{ns}
Extractable B	1 ^{ns}	1 ^{ns}	1 ^{ns}
Extractable Cu	3 ^{ns}	1 ^{ns}	1 ^{ns}
Extractable Fe	1 ^{ns}	3*	1 ^{ns}
Extractable Mn	11****	2 ^{ns}	3*
Extractable Zn	1 ^{ns}	3 ^{ns}	1 ^{ns}
Exchangeable Ca concentration	3 ^{ns}	1 ^{ns}	1 ^{ns}
Exchangeable Mg concentration	3 ^{ns}	2 ^{ns}	0 ^{ns}
Exchangeable K concentration	7***	0 ^{ns}	1 ^{ns}
Exchangeable Na concentration	3 ^{ns}	2 ^{ns}	1 ^{ns}
Exchangeable Al concentration	1 ^{ns}	4**	2 ^{ns}
Effective cation exchange capacity	3 ^{ns}	0 ^{ns}	1 ^{ns}
Exchangeable Ca percentage	8***	1 ^{ns}	4*
Exchangeable Mg percentage	2 ^{ns}	1 ^{ns}	1 ^{ns}
Exchangeable K percentage	8****	1 ^{ns}	1 ^{ns}
Exchangeable Na percentage	1 ^{ns}	2 ^{ns}	0 ^{ns}
Exchangeable Al percentage	3 ^{ns}	4*	3*

^{ns} Not significant ($P > 0.05$).

Table 8. Effect of soil water repellence (SWR) severity class on soil electrical conductivity (EC) and pH ($CaCl_2$) at the 0-10 cm depth during different canola growth stages at Kojonup in 2016. Mean values based on an average sample size of 5 (unequal sample sizes). Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Growth stage	SWR severity class	Soil EC (dS/m)	Soil pH_{Ca}
Emergence (16 DAS)	Class 2 (moderate)	0.13^{a1}	5.0^{a1}
	Class 3 (severe)	0.10^{a2}	4.9^{a1}
	Class 4 (very severe)	0.06^{a3}	5.0^{a1}
	Class 5 (extreme)^{a}		
Stem elongation (95 DAS)	Class 2 (moderate)		
	Class 3 (severe)	0.04^{b1}	4.7^{a1}
	Class 4 (very severe)	0.04^{a1}	5.0^{a12}
	Class 5 (extreme)	0.04^{a1}	5.2^{a2}
Pod development (143 DAS)	Class 2 (moderate)	0.05^{b1}	5.6^{b1}
	Class 3 (severe)	0.04^{b1}	5.0^{a2}
	Class 4 (very severe)	0.04^{a1}	5.0^{a2}
	Class 5 (extreme)	0.04^{a1}	5.0^{a2}

^{a} Plots with Class 5 water repellence were sampled from 95 DAS and thereafter

Different superscript letters denote significant differences between growth stages within respective SWR severity class ($P < 0.05$).

Different superscript numbers denote significant differences between SWR severity class within respective growth stage ($P < 0.05$).

Bivariate correlation analysis also showed that soil EC at the 0-10 cm depth was negatively correlated with soil water repellence severity at the 0-10 cm depth during canola emergence ($R^2 = 0.67$; $P < 0.01$; Figure 11). Soil EC at the 0-10 cm depth was also strongly negatively correlated with soil water repellence severity at the 5-10 cm depth during canola stem elongation ($R^2 = 0.43$; $P < 0.01$) and pod development stages ($R^2 = 0.49$; $P < 0.01$; Figure 12), but was not correlated with soil water repellence severity at the 0-5 cm depth.

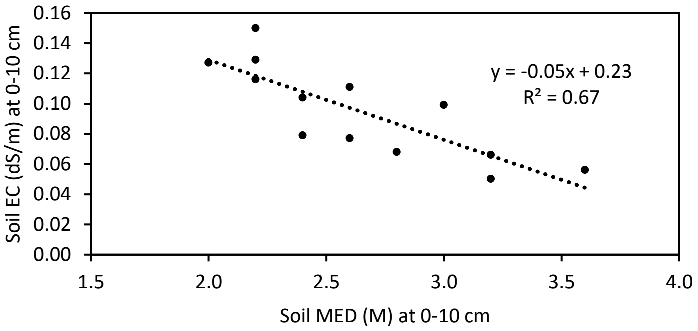

Figure 11. Relationship between soil water repellence severity (MED, M) and soil electrical conductivity (EC, dS/m) at the 0-10 cm depth during canola emergence (16 DAS) in a Ferric Chromosol at Kojonup in 2016.

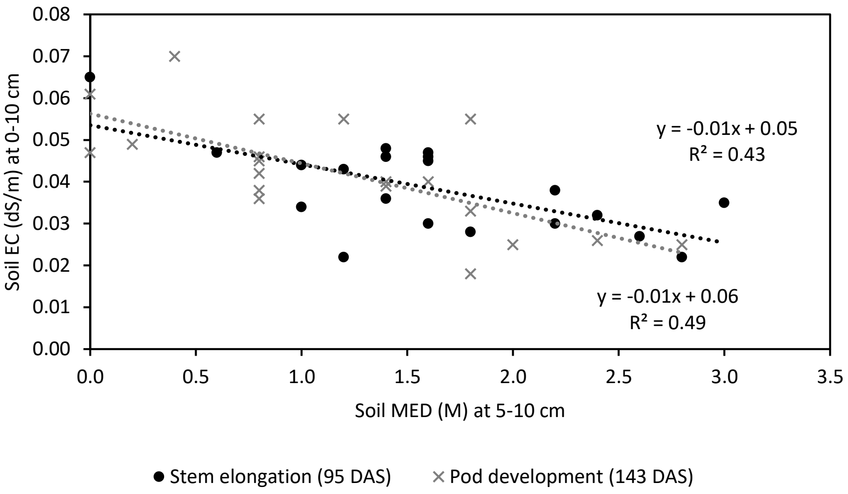

Figure 12. Relationship between soil water repellence severity (MED, M) at the 5-10 cm depth and soil electrical conductivity (EC, dS/m) at the 0-10 cm depth during canola stem elongation (95 DAS) and pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

By contrast, soil EC at the 0-10 cm depth was positively correlated with soil water content at the 0-5 cm depth during canola stem elongation ($R^2 = 0.49$; $P < 0.01$) and pod development ($R^2 = 0.40$; $P < 0.01$; Figure 13).

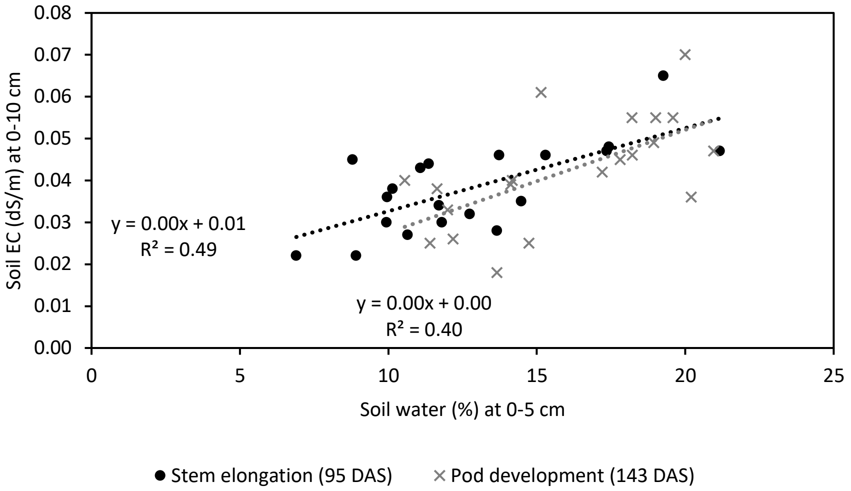

Figure 13. Relationship between soil water content (%, w/w) at the 0-5 cm depth and soil electrical conductivity (EC, dS/m) at the 0-10 cm depth during canola stem elongation (95 DAS) and pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

During canola stem elongation (95 DAS), soil pH_{Ca} at the 0-10 cm depth was significantly greater in Class 5 soils (extremely repellent; pH_{Ca} 5.2) than in Class 3 soils (severely repellent; pH_{Ca} 4.7; Table 8). However, during canola pod development (143 DAS), soil pH_{Ca} at the 0-10 cm depth was significantly greater in Class 2 soils (moderately repellent; pH_{Ca} 5.6) than in higher soil water repellence severity classes (pH_{Ca} 5.0; Table 8). By contrast, there was no difference in soil pH_{Ca} between soil water repellence severity classes during canola emergence (16 DAS). Bivariate correlation analysis, nevertheless, showed that soil pH_{Ca} at the 0-10 cm depth was positively correlated with soil water repellence severity at the 0-5 cm depth during canola stem elongation (R^2 = 0.47; $P < 0.01$; Figure 14) but not during canola emergence or pod development (data not shown).

Soil Fe concentrations at the 0-10 cm depth were significantly greater ($P < 0.05$; Table 7) in Class 2 soils (moderately repellent; 39 mg/kg) than in Class 5 soils (extremely repellent; 34 mg/kg; Table 9). Bivariate correlations also showed that soil Fe concentrations at the 0-10 cm depth were negatively correlated with soil water repellence severity at the 0-5 cm depth during stem elongation (R^2 = 0.33; $P < 0.01$; Figure 15) but not during emergence or pod development (data not shown). However, soil Fe concentrations were positively correlated with soil water content at the 0-10 cm depth during canola emergence ($R^2 = 0.41$; $P < 0.05$; 16 DAS; Figure 16).

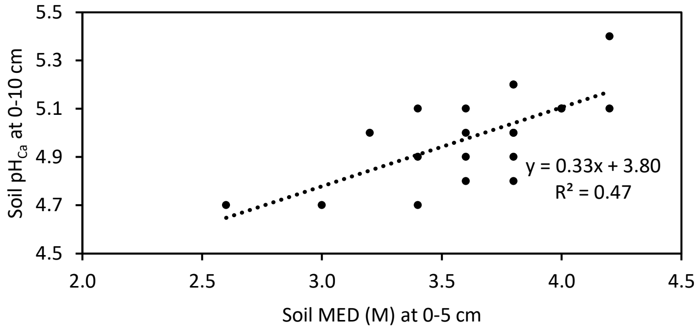

Figure 14. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and soil pH$_{Ca}$ (CaCl$_2$) at the 0-10 cm depth during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

Table 9. Relationship between soil water repellence severity class and soil iron concentration (Fe, mg/kg) at the 0-10 cm depth at Kojonup in 2016. Mean values based on an average sample size of 14 (unequal sample sizes). Significant differences based on the least significant difference (LSD) at P < 0.05.

Soil properties	Class 2 (moderate)	Class 3 (severe)	Class 4 (very severe)	Class 5 (extreme)
Soil Fe (mg/kg)	38.6^{ab}	39.5^{a}	36.7^{ab}	33.7^{b}

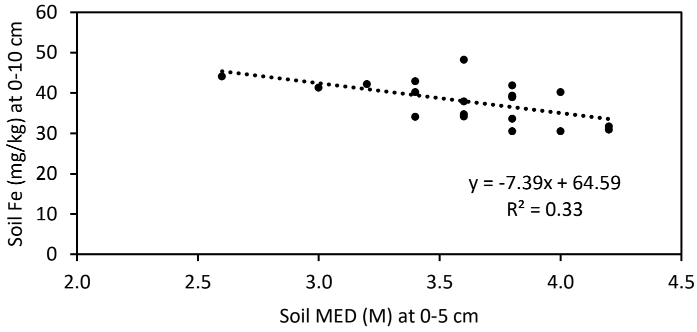

Figure 15. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and soil iron concentration (Fe, mg/kg) at the 0-10 cm depth during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

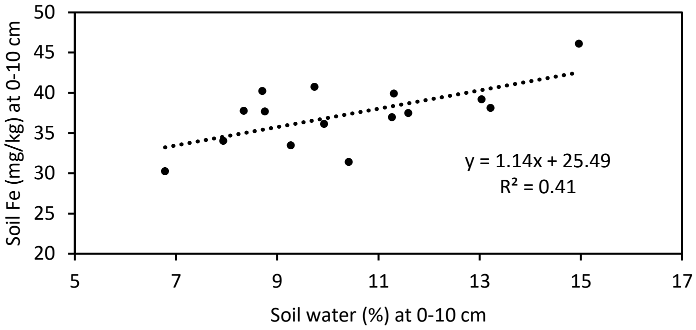

Figure 16. Relationship between soil water content (%, w/w) and soil iron concentration (Fe, mg/kg) at the 0-10 cm depth during canola emergence (16 DAS) in a Ferric Chromosol at Kojonup in 2016.

Although various nutrient parameters were not directly correlated with soil water repellence severity, they were positively correlated with soil EC at the 0-10 cm depth, including: (1) soil NO_3-N concentrations during canola emergence ($R^2 = 0.65$; $P < 0.01$; 16 DAS), stem elongation ($R^2 = 0.38$; $P < 0.01$; 95 DAS), and pod development ($R^2 = 0.55$; $P < 0.01$; 143 DAS; Figure 17); (2) soil Colwell K and exchangeable K concentrations during pod development ($R^2 = 0.20$ and 0.42, respectively; $P < 0.05$; 143 DAS; Figures 18a and b, respectively); and, (3) soil S concentrations during canola emergence ($R^2 = 0.39$; $P < 0.05$; 16 DAS) and pod development ($R^2 = 0.56$; $P < 0.01$; 143 DAS; Figure 19).

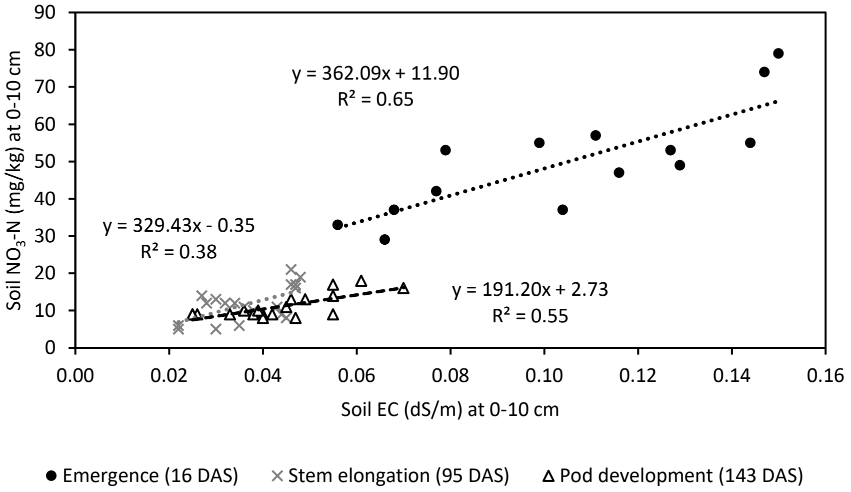

Figure 17. Relationship between soil electrical conductivity (dS/m) and soil nitrate-nitrogen concentration (NO_3-N, mg/kg) at the 0-10 cm depth during canola emergence (16 DAS), stem elongation (95 DAS), and pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

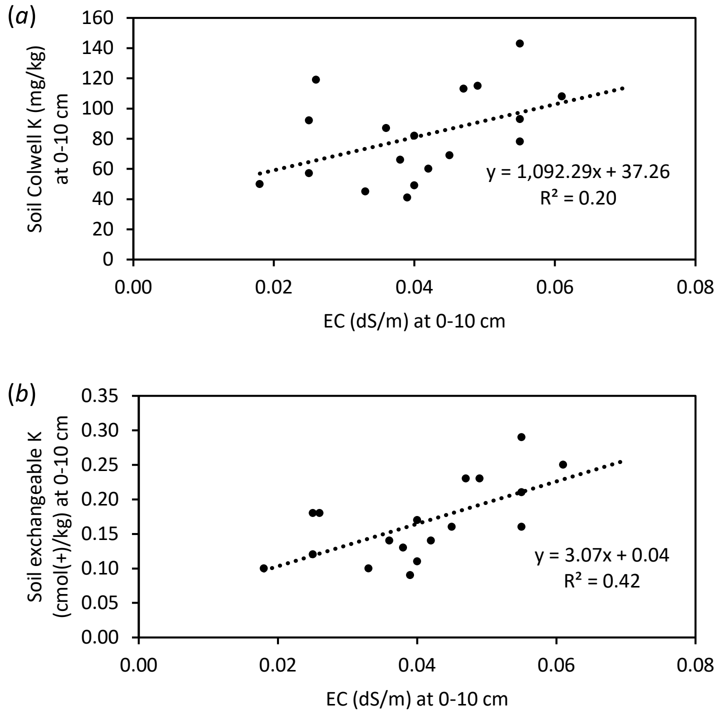

Figure 18. Relationship between soil electrical conductivity (dS/m) and (a) soil Colwell potassium concentration (K, mg/kg) and (b) soil exchangeable potassium concentration (K, cmol(+)/kg) at the 0-10 cm depth during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

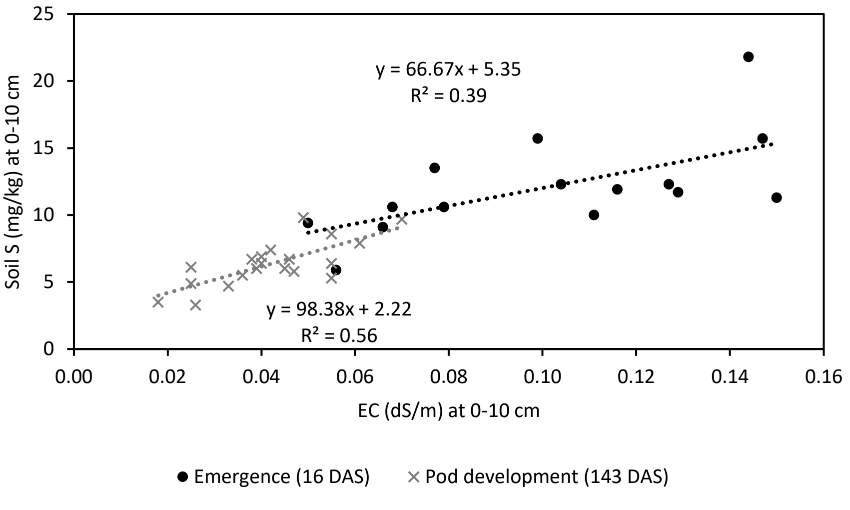

Figure 19. Relationship between soil electrical conductivity (dS/m) and soil sulphur concentration (S, mg/kg) at the 0-10 cm depth in a Ferric Chromosol at Kojonup in 2016.

Soil water contents at the 0-5 and 5-10 cm depths were also positively correlated with various soil nutrients at the 0-10 cm depth, including: (1) soil NO_3-N concentrations during canola stem elongation ($R^2 = 0.50$ and 0.26, respectively; $P < 0.05$; 95 DAS; Figure 20); (2) soil exchangeable Ca concentrations during canola emergence ($R^2 = 0.34$; $P < 0.05$; 16 DAS), stem elongation ($R^2 = 0.25$ and 0.46, respectively; $P < 0.05$; 95 DAS), and pod development ($R^2 = 0.69$ and 0.56, respectively; $P < 0.01$; 143 DAS; Figures 21a and b); and, (3) soil Colwell K and exchangeable K concentrations during canola emergence ($R^2 = 0.31$ and 0.41, respectively; $P < 0.05$; 16 DAS; Figures 22a and b, respectively).

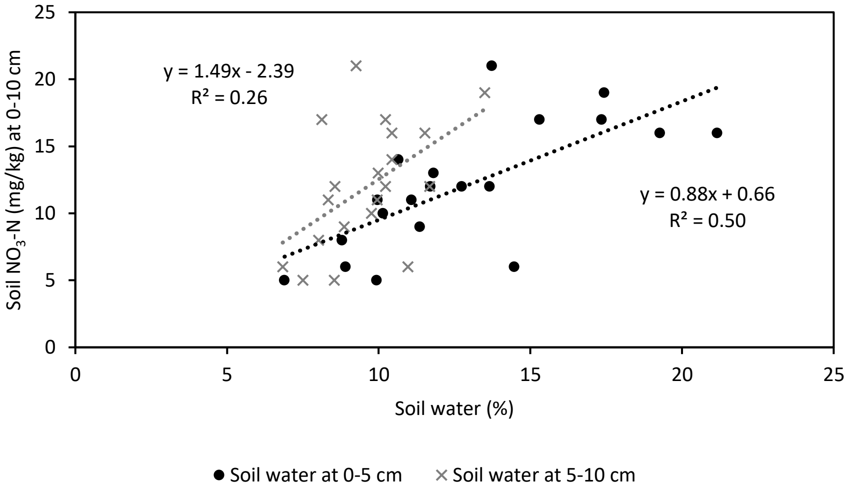

Figure 20. Relationship between soil nitrate-nitrogen concentration (NO_3-N, mg/kg) at the 0-10 cm depth and soil water content (%, w/w) at the 0-5 cm and 5-10 cm depths during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

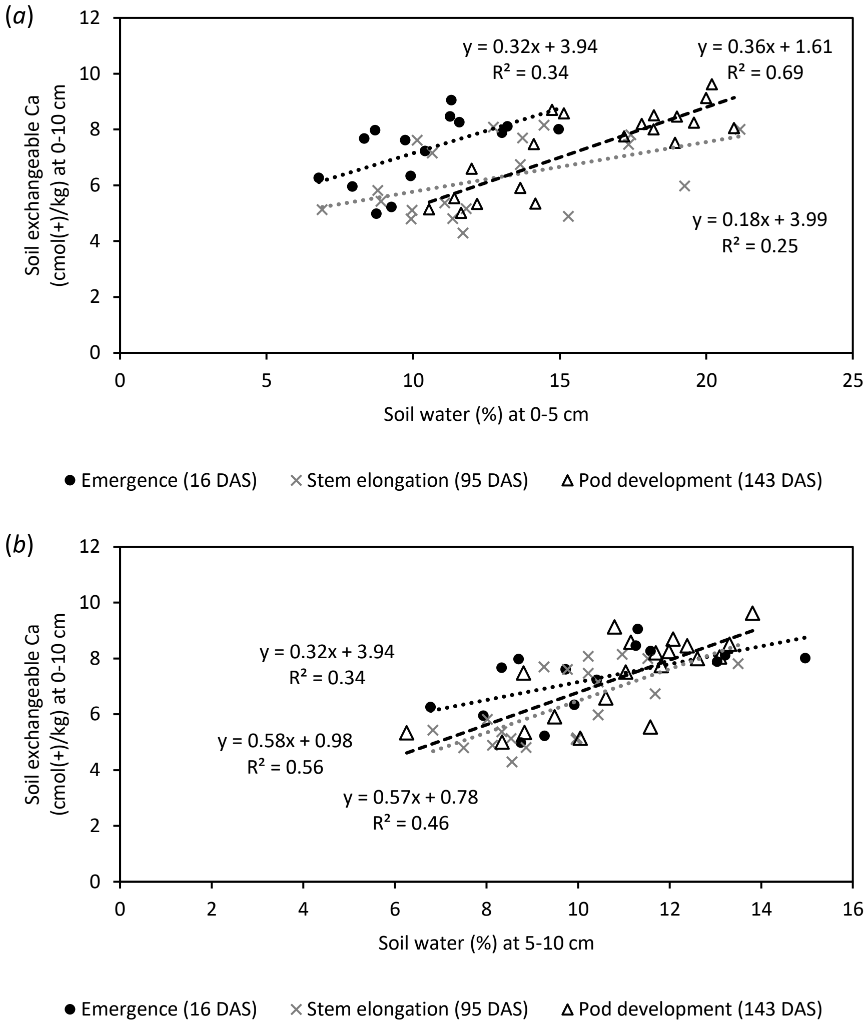

Figure 21. Relationship between soil exchangeable calcium concentration (Ca, cmol(+)/kg) at the 0-10 cm depth and soil water content (%, w/w) at the (a) 0-5 cm and (b) 5-10 cm depths in a Ferric Chromosol at Kojonup in 2016. Note, soil water content during canola emergence (16 DAS) was from the 0-10 cm depth.

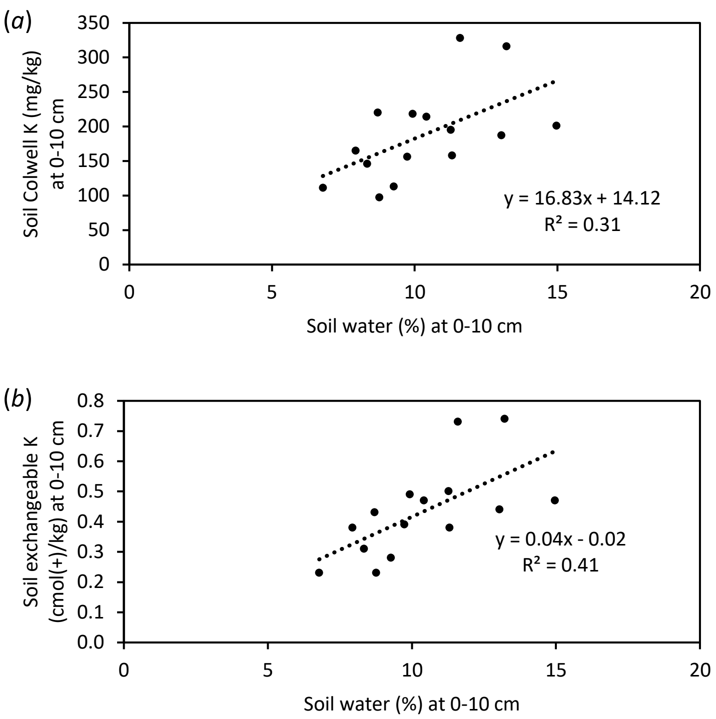

Figure 22. Relationship between soil water content (%, w/w) and (a) soil Colwell potassium concentration (K, mg/kg) and (b) soil exchangeable potassium concentration (K, cmol(+)/kg) at the 0-10 cm depth during canola emergence (16 DAS) in a Ferric Chromosol at Kojonup in 2016.

Although soil OC at the 0-10 cm depth was not significantly different between soil water repellence severity classes, bivariate correlation analysis showed that soil OC at the 0-10 cm depth was positively correlated with soil water repellence severity (MED) at the 5-10 cm depth during canola stem elongation ($R^2 = 0.38$; $P < 0.01$; 95 DAS) and pod development ($R^2 = 0.26$; $P < 0.05$; 143 DAS; Figure 23). By contrast, soil S concentration at the 0-10 cm depth was negatively correlated with soil water repellence severity at the 5-10 cm depth during canola pod development ($R^2 = 0.38$; $P < 0.01$; 143 DAS; Figure 24). Although soil NH_4-N concentrations were not correlated with soil water repellence severity or soil water content (data not shown), soil NH_4-N concentrations were positively correlated with soil OC at the 0-10 cm depth during canola emergence ($R^2 = 0.46$; $P < 0.01$; 16 DAS; Figure 25).

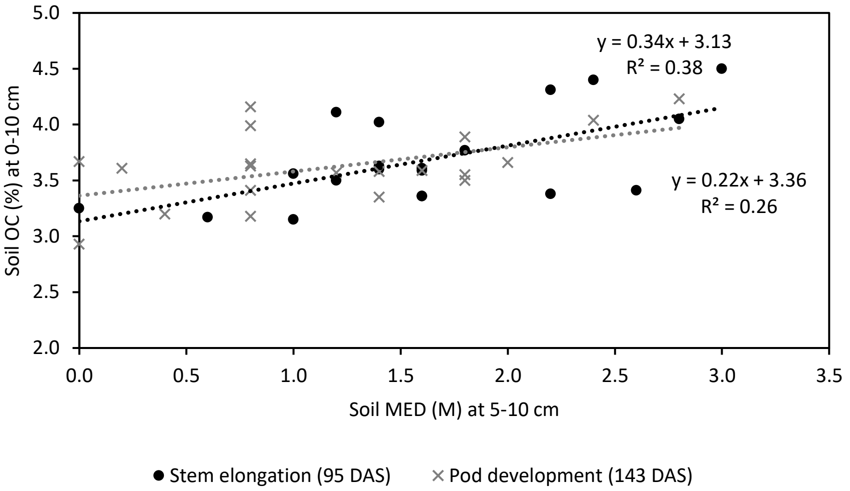

Figure 23. Relationship between soil water repellence severity (MED, M) at the 5-10 cm depth and soil organic carbon content (OC, %) at the 0-10 cm depth in a Ferric Chromosol at Kojonup in 2016.

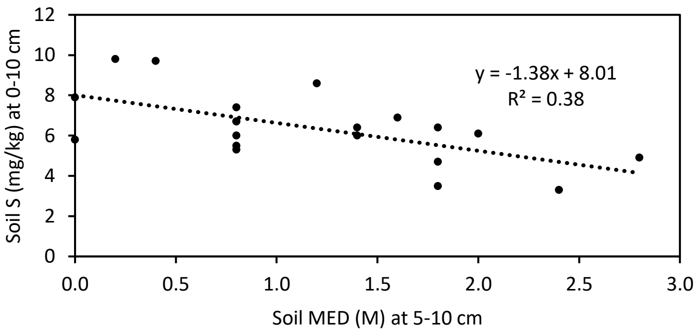

Figure 24. Relationship between soil water repellence severity (MED, M) at the 5-10 cm depth and soil sulphur concentration (S, mg/kg) at the 0-10 cm depth during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

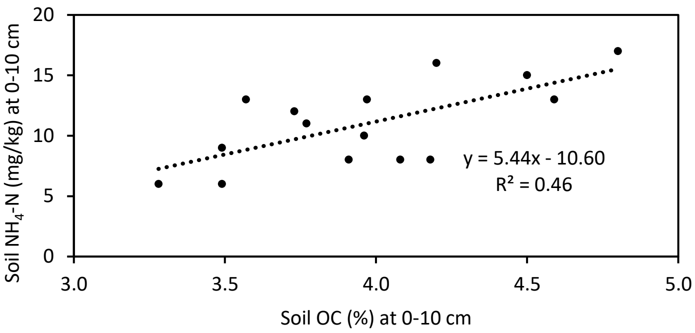

Figure 25. Relationship between soil organic carbon content (OC, %) and soil ammonium-nitrogen concentration (NH_4-N, mg/kg) at the 0-10 cm depth during canola emergence (16 DAS) in a Ferric Chromosol at Kojonup in 2016.

Crop growth and yield parameters

Results showed no significant effect of soil water repellence severity class on canola plant density during leaf production (8-37 plants/m^2; 53 DAS), plant density at crop maturity (10-30 plants/m^2; 191 DAS), leaf RWC throughout the season (87-95 %), shoot dry matter (4.7-17.2 t/ha; 191 DAS), 1000-seed weight (3.27-4.35 g; 191 DAS), or seed yield (1.6-5.1 t/ha; 191 DAS; Table 10).

Table 10. Analysis of variance, ANOVA, test (F values with significance level) for the main effect of soil water repellence (SWR) severity class on canola plant density and yield parameters at Kojonup in 2016. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Parameter	*F*
Plant density at leaf production (53 DAS)	1 ^{ns}
Plant establishment at crop maturity (191 DAS)	1 ^{ns}
Leaf RWC at stem elongation (95 DAS)	0 ^{ns}
Leaf RWC at anthesis (116 DAS)	2 ^{ns}
Leaf RWC at pod development (143 DAS)	1 ^{ns}
Shoot dry matter at crop maturity (191 DAS)	3 ^{ns}
1000-seed weight (191 DAS)	3 ^{ns}
Seed yield (191 DAS)	3 ^{ns}

^{ns} Not significant ($P > 0.05$).

By contrast, bivariate correlation analysis showed that canola plant establishment, shoot dry matter, and seed yield at crop maturity (191 DAS) were positively correlated with soil water repellence severity at the 0-10 cm depth during canola emergence ($R^2 = 0.50$, 0.55, and 0.48, respectively; $P < 0.01$; 16 DAS; Figures 26a-c). Canola 1000-seed weight was, however, found to be negatively correlated with soil water repellence severity at the 0-5 cm depth during crop maturity ($R^2 = 0.27$; $P < 0.05$; 191 DAS; Figure 27). Canola plant establishment, growth, and seed yield parameters were not correlated with soil water or gravel content (data not shown).

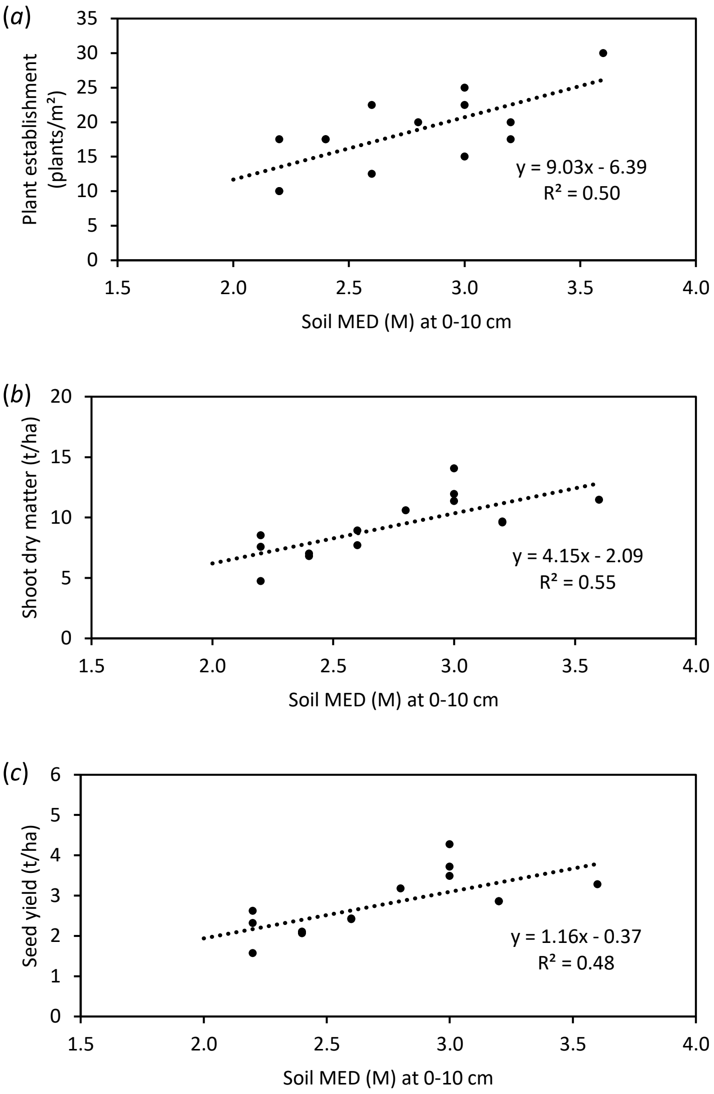

Figure 26. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth during canola emergence (16 DAS) and (a) plant establishment (plants/m^2), (b) shoot dry matter (t/ha), and (c) seed yield (t/ha) at crop maturity (191 DAS) in a Ferric Chromosol at Kojonup in 2016.

Canola plant establishment, shoot dry matter, and seed yield at crop maturity were positively correlated with soil Cu concentration during canola stem elongation ($R^2 = 0.34$, 0.46, and 0.40, respectively; $P < 0.01$; 95 DAS; Figures 28a-c), but were not correlated with any other soil parameter. However, canola leaf Cu concentrations were not correlated with canola yield parameters or soil Cu concentrations at the 0-10 cm depth (data not shown).

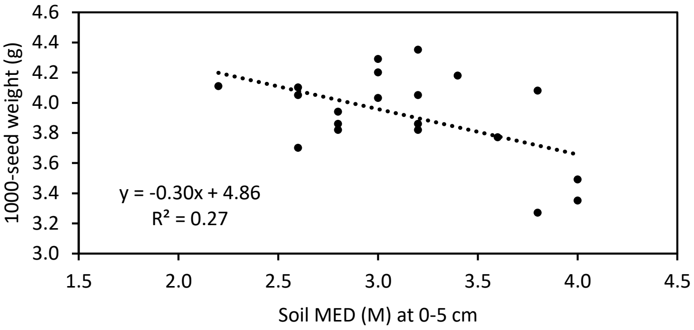

Figure 27. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and canola 1000-seed weight (g) during crop maturity (191 DAS) in a Ferric Chromosol at Kojonup in 2016.

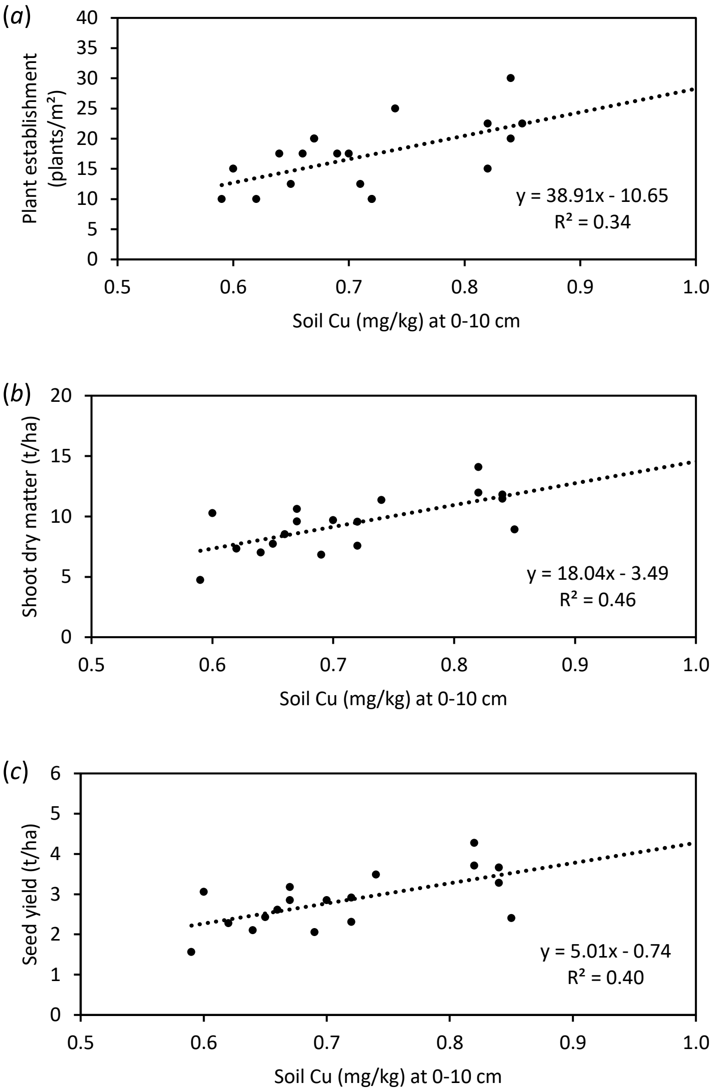

Figure 28. Relationship between soil copper concentration (Cu, mg/kg) at the 0-10 cm depth during canola stem elongation (95 DAS) and (a) plant establishment (plants/m^2), (b) shoot dry matter (t/ha), and (c) seed yield (t/ha) at crop maturity (191 DAS) in a Ferric Chromosol at Kojonup in 2016.

Leaf nutrient concentrations

An assessment of nutrient concentrations in young, fully matured canola leaves found that canola plants at Kojonup were relatively deficient in Cu during the vegetative (<6 mg/kg) and anthesis stages (<5 mg/kg; Reuter and Robinson 1997; Appendix A.2), despite having relatively adequate pre-anthesis leaf concentrations (4-25 mg/kg) and adequate soil Cu levels (>0.35 mg/kg DTPA; Brennan *et al.* 2019). During anthesis, leaf N was also deficient (<4.0 %) and Zn marginally deficient (<25 mg/kg) but both were generally adequate during the vegetative and pre-anthesis stages

(3.5-5.5 % N and 21-55 mg Z/kg). Soil Zn levels were also adequate (>0.35 mg/kg DTPA). Concentrations were relatively adequate for other key nutrients. In general, ANOVA tests showed no effect of soil water repellence severity class on leaf nutrient concentrations (Table 11), but leaf Cu and Mn concentrations were positively correlated with soil water repellence severity at the 5-10 cm depth during canola pod development ($R^2 = 0.40$ and 0.54, respectively; $P < 0.05$; 143 DAS; Figures 29a and b). However, leaf Cu concentrations were not correlated with canola yield parameters (data not shown). Leaf N and Zn concentrations were also not correlated with either soil water repellence severity or canola yield parameters (data not shown).

Table 11. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between growth stage and soil water repellence (SWR) severity class on canola leaf nutrient concentrations at Kojonup in 2016. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Leaf nutrient concentration	Growth stage	SWR severity class	Growth stage × SWR severity class
N	131****	0 ^{ns}	1 ^{ns}
P	168****	1 ^{ns}	1 ^{ns}
K	54****	1 ^{ns}	1 ^{ns}
Ca	88****	2 ^{ns}	1 ^{ns}
Mg	23****	1 ^{ns}	0 ^{ns}
S	69****	1 ^{ns}	1 ^{ns}
Na	44****	2 ^{ns}	2 ^{ns}
Cl	14****	1 ^{ns}	1 ^{ns}
B	165****	2 ^{ns}	0 ^{ns}
Cu	61****	2 ^{ns}	1 ^{ns}
Fe	41****	0 ^{ns}	0 ^{ns}
Mn	4**	1 ^{ns}	1 ^{ns}
Zn	76****	1 ^{ns}	1 ^{ns}

^{ns} Not significant ($P > 0.05$).

By contrast, leaf P concentrations were negatively correlated with soil water repellence severity at the 5-10 cm depth during canola leaf production ($R^2 = 0.29$; $P < 0.05$; 53 DAS) and stem elongation ($R^2 = 0.31$; $P < 0.05$; 95 DAS; Figure 30). Leaf Ca concentrations were also negatively correlated with soil water repellence severity at the 5-10 cm depth during canola pod development ($R^2 = 0.37$; $P < 0.01$; 143 DAS; Figure 31). Nevertheless, canola leaf P and Ca concentrations were not correlated with canola yield parameters (data not shown).

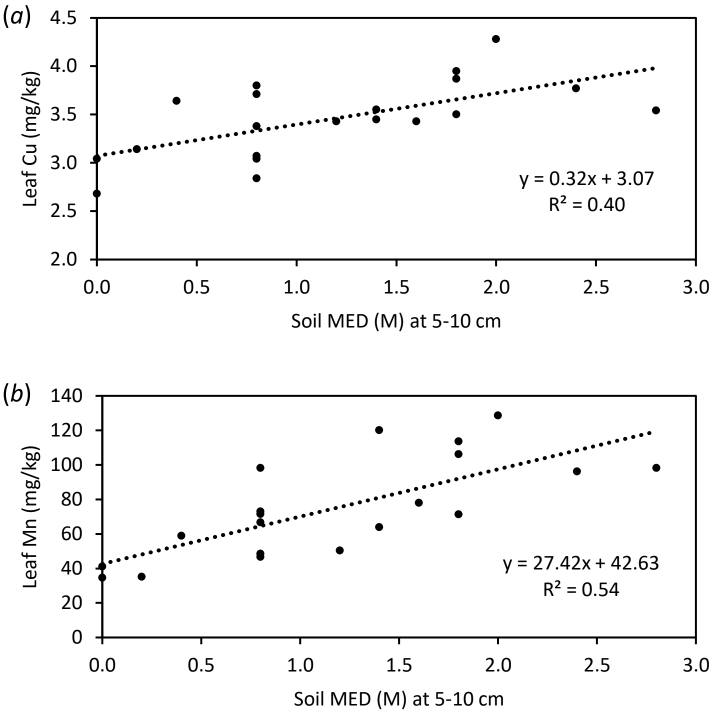

Figure 29. Relationship between soil water repellence severity (MED, M) at the 5-10 cm depth and (a) canola leaf copper concentration (Cu, mg/kg) and (b) leaf manganese concentration (Mn, mg/kg) during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

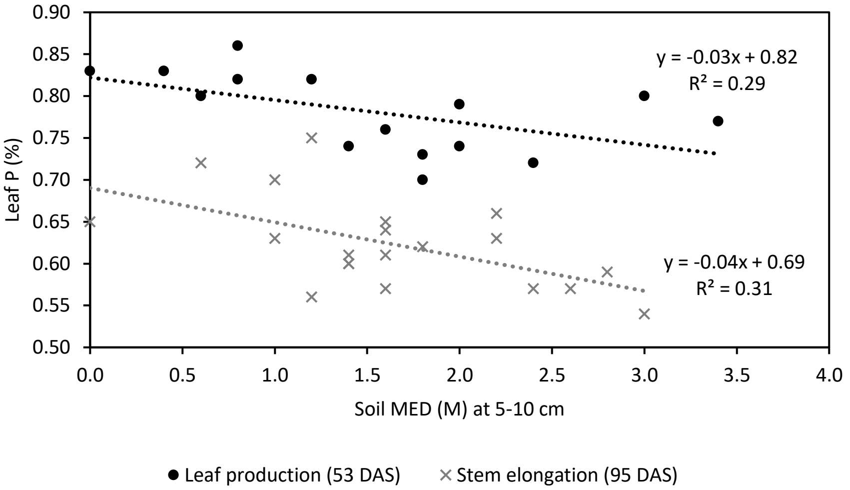

Figure 30. Relationship between soil water repellence severity (MED, M) at the 5-10 cm depth and canola leaf phosphorus concentration (P, %) during canola leaf production (53 DAS) and stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

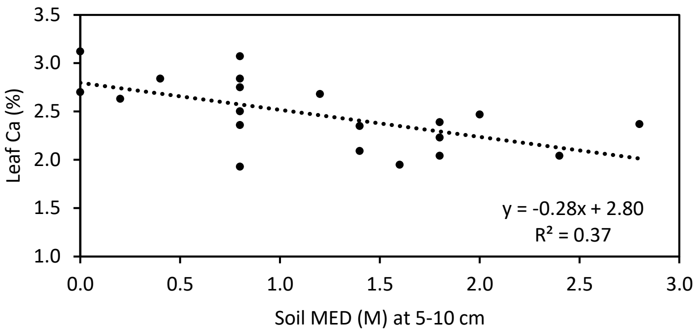

Figure 31. Relationship between soil water repellence severity (MED, M) at the 5-10 cm depth and canola leaf calcium concentration (Ca, %) during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

3.3.2 Meckering

Soil water repellence

Water repellence severity of the Grey Bleached-Ferric Kandosol at Meckering generally ranged from insignificant (MED 0.0) to severe levels (MED 2.4), with the median level being moderately repellent (MED 1.2) at the 0-5 cm depth and insignificant (MED 0.0) at the 5-10 cm depth. Soil water repellence severity was significantly affected by the two-way interaction of sampling depth × growth stage (*P* < 0.001; Table 12).

Table 12. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil water repellence severity (molarity of ethanol droplet, MED) at Meckering in 2016, with repeated measures for sampling depth and growth stage as within-subjects variables. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Source of variation	*F*
Growth stage	21****
Sampling depth	254****
Growth stage × Sampling depth	8****

Soil water repellence severity was significantly greater at the 0-5 cm depth (MED 0.7-1.6; slightly to moderately repellent) than at the 5-10 cm depth (MED 0.0-0.3; marginally repellent; Table 13) throughout the growing season, but soil water repellence severity in this Grey Bleached-Ferric Kandosol was relatively low in comparison to that at Kojonup. Soil water repellence severity at the 0-5 cm depth increased from winter to spring, peaking during wheat booting (MED 1.6; 100 DAS) before decreasing thereafter at crop maturity (MED 0.7; 161 DAS; Table 13), while soil water repellence severity at the 5-10 cm depth, albeit at low levels, also peaked during wheat anthesis (MED 0.3; 113 DAS).

Table 13. Soil water repellence severity (molarity of ethanol droplet, MED) in the furrow at the 0-5 and 5-10 cm depths during different growth stages in wheat at Meckering in 2016. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Depth	Emergence (22 DAS)	Tillering (64 DAS)	Booting (100 DAS)	Anthesis (113 DAS)	Grain development (134 DAS)	Maturity (161 DAS)
0-5 cm	$0.7^{a\dagger}$	$0.9^{ac\dagger}$	$1.6^{b\dagger}$	$1.5^{bd\dagger}$	$1.2^{cd\dagger}$	$0.7^{a\dagger}$
5-10 cm	0.0^{a}	0.0^{a}	0.1^{ab}	0.3^{b}	0.0^{a}	0.0^{a}

Different superscript letters denote significant differences between growth stages ($P < 0.05$).
† Significantly different from the 5-10 cm depth ($P < 0.05$).

Soil water content

Results showed that soil water content was significantly affected by the two-way interaction of sampling depth × growth stage ($P < 0.001$; Table 14) but was not affected by soil water repellence severity class (i.e., 3 classes: negligible/slight, moderate, and severe) in the Grey Bleached-Ferric Kandosol at Meckering. Soil water content was significantly greater at the 0-5 cm depth (5.0-8.0 %) than at the 5-10 cm depth (4.1-7.1 %) from wheat emergence to booting stages (Table 15), but thereafter was significantly greater at the 5-10 cm depth (0.2-1.8 %) than at the 0-5 cm depth (0.1-1.2 %) from wheat anthesis to maturity.

Table 14. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil water content at Meckering in 2016, with soil water repellence (SWR) severity class as a between-subjects variable and repeated measures for sampling depth and growth stage as within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ *(*),* $P \leq 0.01$ *(**),* $P \leq 0.005$ *(***), and* $P \leq 0.001$ *(****).*

Source of variation	*F*
Growth stage	672****
Sampling depth	14***
SWR severity class	4^{ns}
Growth stage × Sampling depth	29****
Growth stage × SWR severity class	2^{ns}
Sampling depth × SWR severity class	2^{ns}
Growth stage × Sampling depth × SWR severity class	0^{ns}

^{ns} Not significant ($P > 0.05$).

Soil water content significantly decreased over time from wheat tillering to crop maturity at the 0-5 (from 7.8 to 0.1 %) and 5-10 cm depths (from 6.8 to 0.2 %; Table

15). Bivariate analysis also showed no correlation between soil water repellence severity (MED) and soil water content in this Grey Bleached-Ferric Kandosol at Meckering (data not shown).

Table 15. Soil water content (%, w/w) in the furrow at the 0-5 and 5-10 cm depths during different growth stages in wheat at Meckering in 2016. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Emergence (22 DAS)	Tillering (64 DAS)	Booting (100 DAS)	Anthesis (113 DAS)	Grain development (134 DAS)	Maturity (161 DAS)
0-5 cm	$8.0^{a\dagger}$	$7.8^{a\dagger}$	$5.0^{b\dagger}$	$1.2^{c\dagger}$	$0.3^{d\dagger}$	$0.1^{e\dagger}$
5-10 cm	7.1^{a}	6.8^{a}	4.1^{b}	1.8^{c}	0.5^{d}	0.2^{e}

Different superscript letters denote significant differences between growth stages ($P < 0.05$).
† Significantly different from the 5-10 cm depth ($P < 0.05$).

Soil chemical properties

Soil Cu concentration, exchangeable Mg concentration, and exchangeable Mg percentage were significantly affected by the two-way interaction of growth stage × soil water repellence severity class ($P < 0.05$; Table 16).

Table 16. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between growth stage and soil water repellence (SWR) severity class on soil properties at the 0-10 cm depth at Meckering in 2016. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Soil properties	Growth stage	SWR severity class	Growth stage × SWR severity class
Organic carbon	1^{ns}	7***	1^{ns}
Electrical conductivity	39****	0^{ns}	0^{ns}
pH_{Ca}	14****	0^{ns}	2^{ns}
NH_4-N	20****	1^{ns}	0^{ns}
NO_3-N	55****	0^{ns}	1^{ns}
Colwell P	14****	0^{ns}	0^{ns}
Colwell K	4*	2^{ns}	1^{ns}
Extractable S	11****	2^{ns}	3^{ns}
Extractable B	1^{ns}	3^{ns}	0^{ns}
Extractable Cu	2^{ns}	1^{ns}	4*
Extractable Fe	6**	1^{ns}	1^{ns}
Extractable Mn	1^{ns}	1^{ns}	0^{ns}
Extractable Zn	0^{ns}	3^{ns}	2^{ns}
Exchangeable Ca concentration	1^{ns}	3^{ns}	1^{ns}
Exchangeable Mg concentration	1^{ns}	7***	4*
Exchangeable K concentration	4*	2^{ns}	1^{ns}
Exchangeable Na concentration	12****	0^{ns}	1^{ns}
Exchangeable Al concentration	2^{ns}	2^{ns}	1^{ns}
Effective cation exchange capacity	1^{ns}	3*	1^{ns}
Exchangeable Ca percentage	2^{ns}	1^{ns}	1^{ns}
Exchangeable Mg percentage	4*	4*	5*
Exchangeable K percentage	5*	2^{ns}	1^{ns}
Exchangeable Na percentage	17***	0^{ns}	1^{ns}
Exchangeable Al percentage	1^{ns}	2^{ns}	2^{ns}

^{ns} Not significant ($P > 0.05$).

During wheat emergence (22 DAS), soil Cu concentrations were significantly greater in Class 1 soils (negligible/slightly repellent; 0.49 mg/kg) than in Class 2 soils (moderately repellent; 0.32 mg/kg; Table 17). However, soil Cu concentrations were not different among soil water repellence severity classes during the booting (100 DAS) and grain development stages (134 DAS). By contrast, during wheat emergence, soil exchangeable Mg concentrations and percentages were significantly greater in Class 2 soils (moderately repellent; 0.39 cmol(+)/kg and 14.2 %, respectively) than in Class 1 soils (negligible/slightly repellent; 0.28 cmol(+)/kg and 12.1 %, respectively; Table 17). Furthermore, during grain production, soil exchangeable Mg concentrations and percentages were also significantly greater in Class 3 soils (severely repellent; 0.52 cmol(+)/kg and 15.0 %, respectively) than in Class 1 (negligible/slightly repellent; 0.31 cmol(+)/kg and 12.3 %, respectively) and Class 2 soils (moderately repellent; 0.29 cmol(+)/kg and 11.9 %, respectively; Table 17).

Table 17. Effect of soil water repellence (SWR) severity class on soil properties (0-10 cm) during different wheat growth stages at Meckering in 2016. Mean values based on an average sample size of 9 (unequal sample sizes). Significant differences based on the least significant difference (LSD) at P < 0.05.

Growth stage	SWR severity class	Soil Cu (mg/kg)	Soil exchangeable Mg concentration (cmol(+)/kg)	Soil exchangeable Mg percentage (%)
Emergence (22 DAS)	Class 1 (negligible/slight)	0.49^{a1}	0.28^{a1}	12.1^{a1}
	Class 2 (moderate)	0.32^{a1}	0.39^{a2}	14.2^{a2}
	Class 3 (severe)			
Booting (100 DAS)	Class 1 (negligible/slight)	0.33^{ab1}	0.32^{a1}	11.9^{a1}
	Class 2 (moderate)	0.44^{b2}	0.35^{a1}	12.3^{b1}
	Class 3 (severe)			
Grain development (134 DAS)	Class 1 (negligible/slight)	0.39^{b1}	0.31^{a1}	12.3^{a1}
	Class 2 (moderate)	0.30^{a1}	0.29^{b1}	11.9^{b1}
	Class 3 (severe)	0.24^{1}	0.52^{2}	15.0^{2}

Different superscript letters denote significant differences between growth stages within respective SWR severity class ($P < 0.05$).

Different superscript numbers denote significant differences between SWR severity class within respective growth stage ($P < 0.05$).

Likewise, bivariate correlation analysis also showed that soil Cu concentrations at the 0-10 cm depth were negatively correlated with soil water repellence severity at the 0-5 cm depth during wheat emergence ($R^2 = 0.59$; $P < 0.01$; 22 DAS) but not during booting and grain development stages. Soil exchangeable Mg concentrations and percentages at the 0-10 cm depth were positively correlated with soil water repellence severity at the 0-5 cm depth during wheat emergence ($R^2 = 0.53$ and 0.37, respectively;

$P < 0.05$; 22 DAS) and booting stages ($R^2 = 0.28$ and 0.25, respectively; $P < 0.05$; 100 DAS) but not during grain development stages.

Soil exchangeable Mg concentrations and percentages were also positively correlated with soil OC at the 0-10 cm depth during wheat emergence ($R^2 = 0.54$ and 0.34, respectively; $P < 0.05$; 22 DAS; Figure 32a and b, respectively).

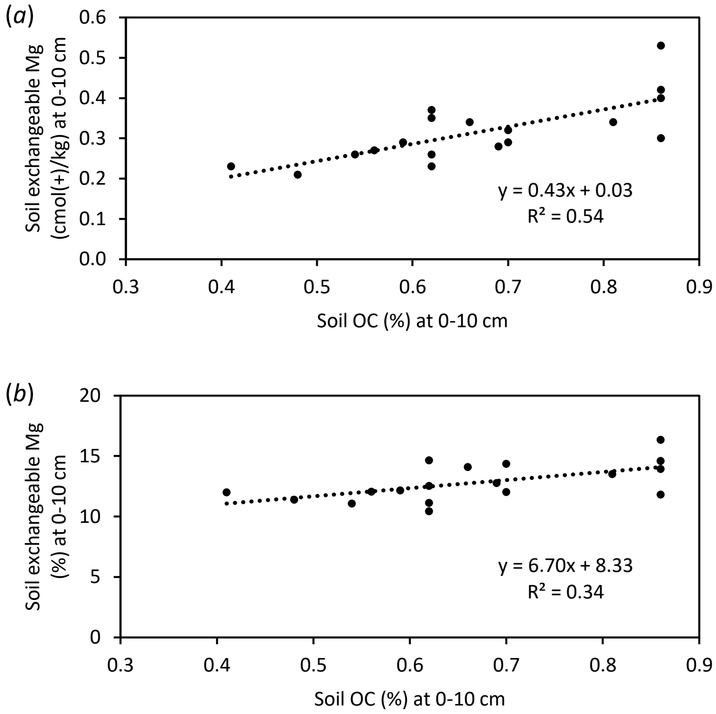

Figure 32. Relationship between soil organic carbon content (OC, %) and (a) soil exchangeable magnesium concentration (Mg, cmol(+)/kg) and (b) soil exchangeable magnesium percentage (Mg, %) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Soil OC and ECEC was also significantly greater ($P < 0.05$; Table 16) in Class 3 soils (severely repellent; 0.98 % and 3.47 cmol(+)/kg, respectively) than in Class 1 soils (negligible/slightly repellent; 0.59 % and 2.50 cmol(+)/kg, respectively; Table 18). Soil OC content was also significantly greater in Class 2 soils (moderately repellent; 0.74 %) than in Class 1 soils (negligible/slightly repellent; 0.59 %; Table 18).

Table 18. Effect of soil water repellence severity class on soil organic carbon content (OC, %) and effective cation exchange capacity (ECEC, cmol(+)/kg) at Meckering in 2016. Mean values based on an average sample size of 18 (unequal sample sizes). Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Soil properties	Class 1 (negligible/slight)	Class 2 (moderate)	Class 3 (severe)
Soil OC (%)	0.59^{a}	0.74^{b}	0.98^{b}
Soil ECEC (cmol(+)/kg)	2.50^{a}	2.67^{ab}	3.47^{b}

Likewise, bivariate correlation analysis also showed that soil OC content was positively correlated with soil water repellence severity at the 0-5 cm depth during wheat emergence ($R^2 = 0.53$; $P < 0.01$; 22 DAS), booting ($R^2 = 0.31$; $P < 0.05$; 100 DAS), and grain development stages ($R^2 = 0.36$; $P < 0.01$; 134 DAS; Figure 33). Soil ECEC was also positively correlated with soil water repellence severity at the 0-5 cm depth during wheat emergence ($R^2 = 0.39$; $P < 0.01$; 22 DAS; Figure 34) but not during booting or grain development stages. Soil OC and ECEC were, however, not correlated with soil water content, but soil OC and ECEC were positively correlated with one another during wheat emergence ($R^2 = 0.44$; $P < 0.01$; 22 DAS; Figure 35).

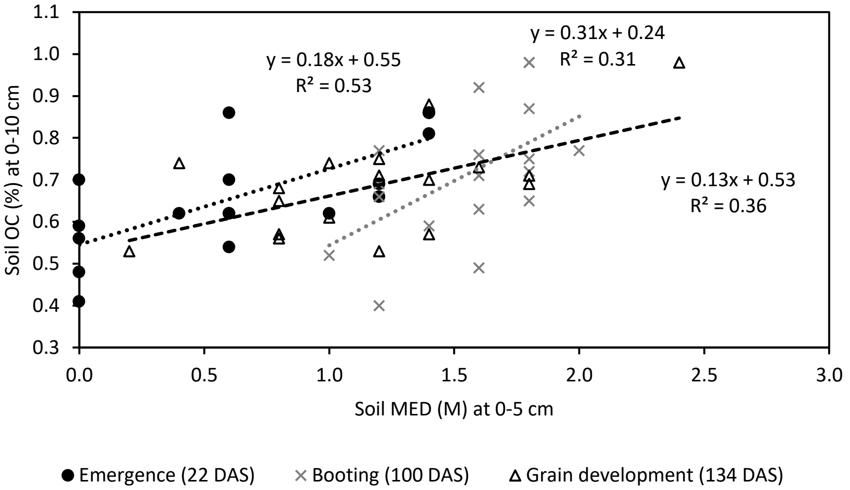

Figure 33. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and soil organic carbon content (OC, %) at the 0-10 cm depth during wheat emergence (22 DAS), booting (100 DAS), and grain development (134 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

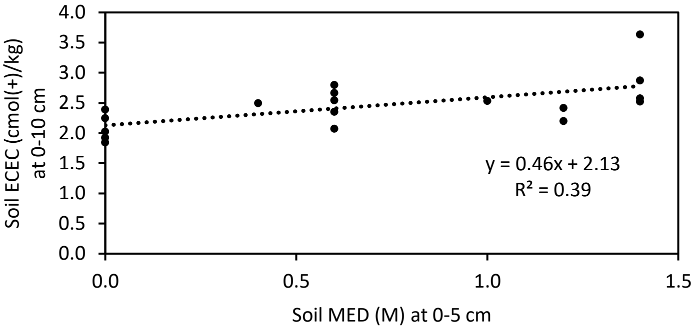

Figure 34. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and soil effective cation exchange capacity (ECEC, cmol(+)/kg) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

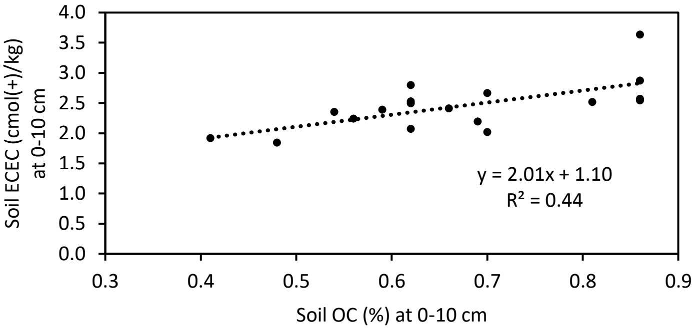

Figure 35. Relationship between soil organic carbon content (OC, %) and soil effective cation exchange capacity (ECEC, cmol(+)/kg) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Bivariate correlations also showed that soil S, exchangeable Ca, and exchangeable Na concentrations were positively correlated with soil water repellence severity during wheat emergence (R^2 = 0.55, 0.38, and 0.44, respectively; $P < 0.01$; 22 DAS; Figures 36a-c), despite no significant effect of soil water repellence severity class (Table 16). Likewise, during wheat emergence (22 DAS), soil S, exchangeable Ca, and exchangeable Na concentrations were positively correlated with soil OC (R^2 = 0.65, 0.41, and 0.53, respectively; $P < 0.01$; 22 DAS; Figures 37a-c). However, soil S, exchangeable Ca, and exchangeable Na concentrations were not correlated with soil water content (data not shown).

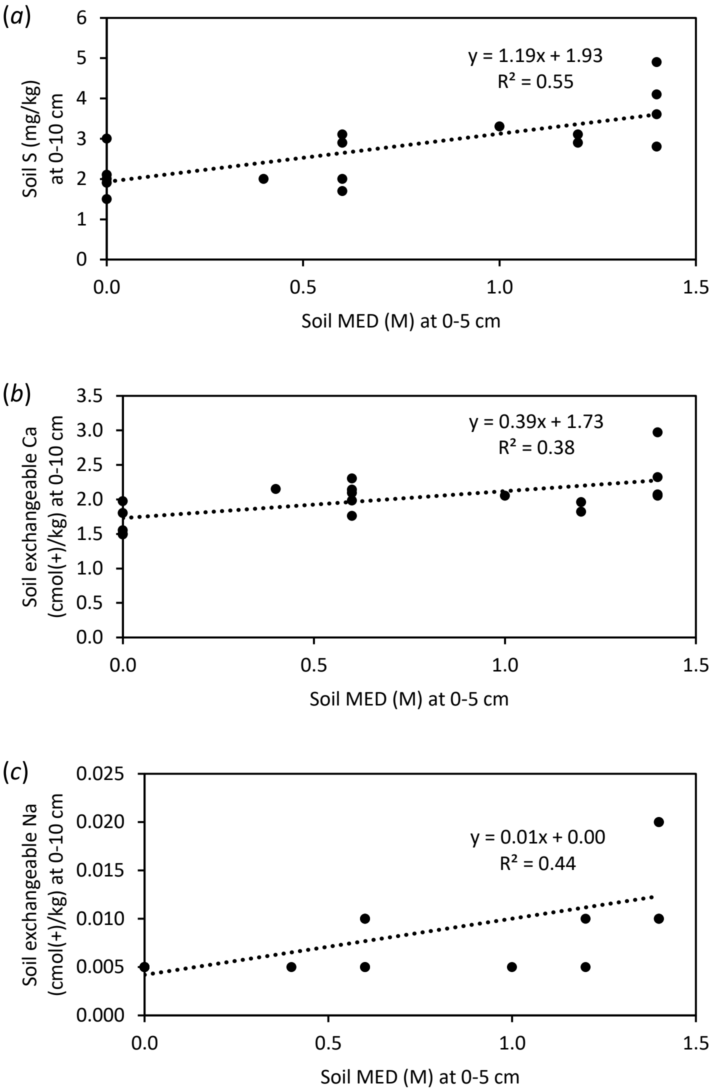

Figure 36. Relationship between soil water repellence severity (MED, M) and (a) soil sulphur concentration (S, mg/kg), (b) soil exchangeable calcium concentration (Ca, cmol(+)/kg), and (c) soil exchangeable sodium concentration (Na, cmol(+)/kg) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

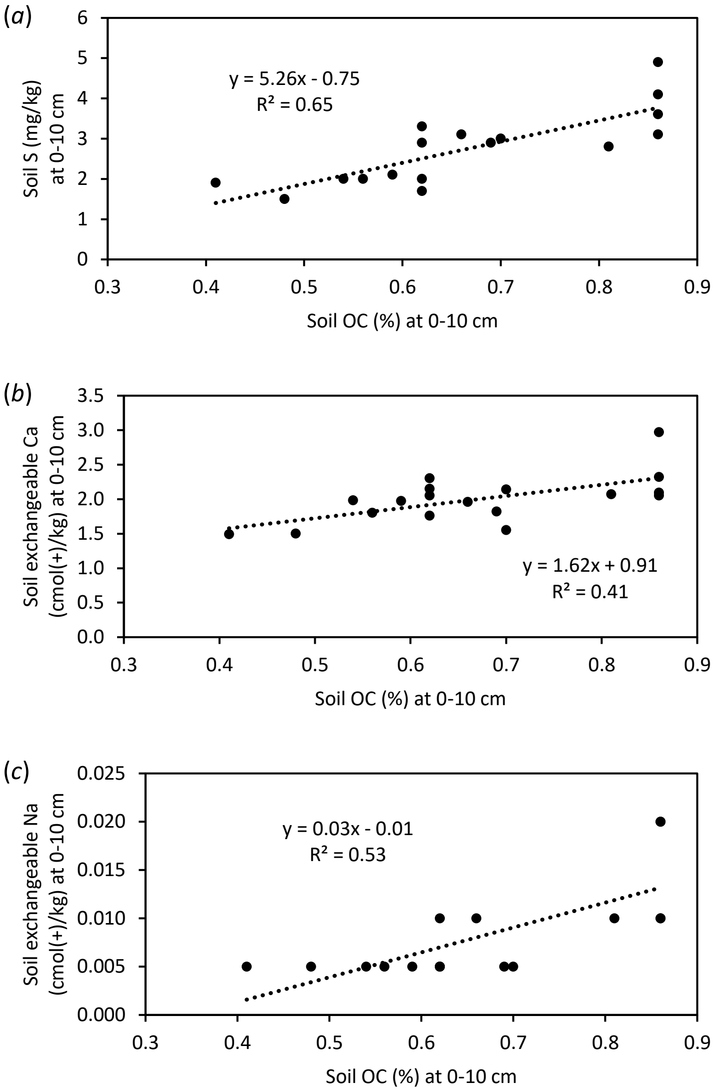

Figure 37. Relationship between soil organic carbon content (OC, %) and (a) soil sulphur concentration (S, mg/kg), (b) soil exchangeable calcium concentration (Ca, cmol(+)/kg), and (c) soil exchangeable sodium concentration (Na, cmol(+)/kg) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

By contrast, soil exchangeable K percentages were negatively correlated with soil water repellence severity during wheat emergence ($R^2 = 0.40$; $P < 0.01$; 22 DAS; Figure 38), but positively correlated with soil water content at the 0-5 and 5-10 cm depths during wheat emergence ($R^2 = 0.45$ and 0.39, respectively; $P < 0.01$; 22 DAS; Figure 39c). Soil Colwell K and exchangeable K concentrations were also positively correlated with soil water content at the 0-5 and 5-10 cm depths during wheat emergence ($0.37 \leq R^2 \leq 0.56$; 22 DAS; Figures 39a and b), while soil Colwell K was also positively correlated with soil water content at the 0-5 cm depth during wheat booting ($R^2 = 0.23$; $P < 0.05$; 100 DAS; data not shown) and grain development ($R^2 = 0.46$; $P < 0.01$; 134 DAS; data not shown). However, soil Colwell K and exchangeable K concentrations were not correlated with soil water repellence severity. Nevertheless, soil Colwell K concentration, exchangeable K concentration, and exchangeable K percentage were closely, positively correlated with one another throughout the season ($0.41 \le R^2 \le 0.80$; $P < 0.01$; data not shown).

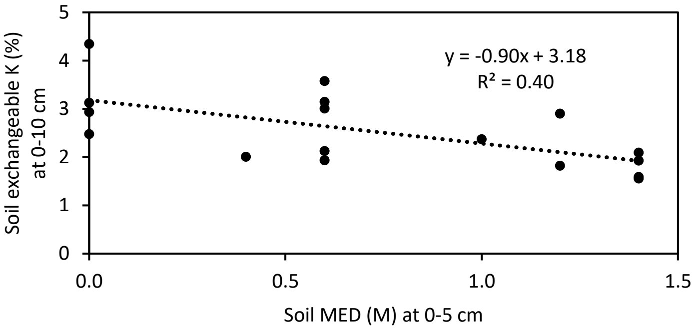

Figure 38. Relationship between soil water repellence severity (MED, M) and soil exchangeable potassium percentage (%) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

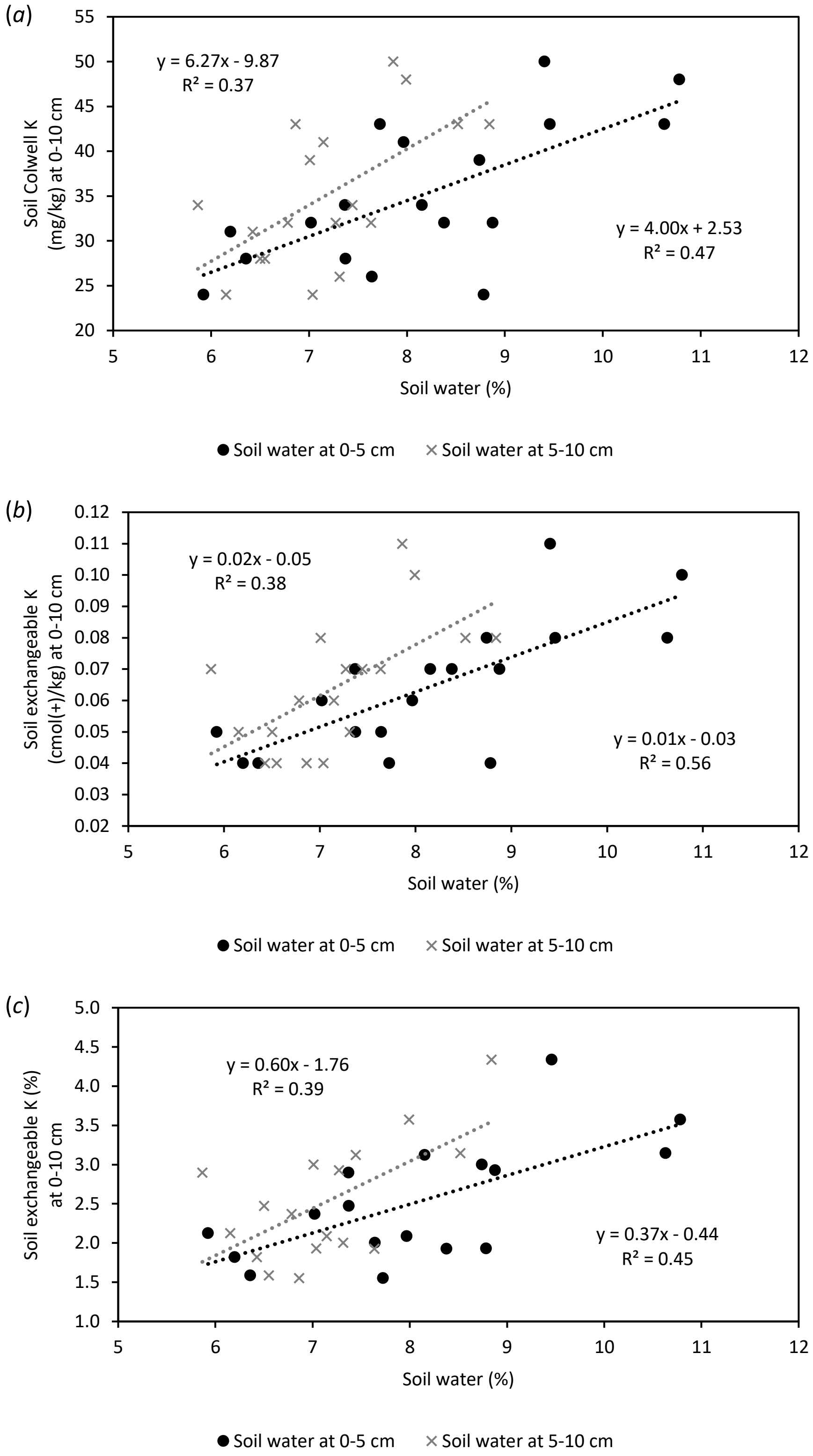

Figure 39. Relationship between soil water content (%, w/w) at the 0-5 and 5-10 cm depths and (a) soil Colwell potassium concentration (K, mg/kg), (b) soil exchangeable potassium concentration (K, cmol(+)/kg), and (c) soil exchangeable potassium percentage (K, %) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Soil Fe concentrations were also negatively correlated with soil water repellence severity at the 0-5 cm depth during wheat grain development ($R^2 = 0.45$; $P < 0.01$; 134 DAS; Figure 40).

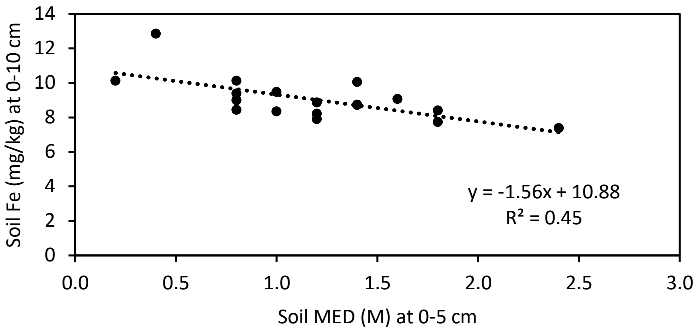

Figure 40. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and soil iron concentration (Fe, mg/kg) at the 0-10 cm depth during wheat grain development (134 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Soil water content at the 0-5 and 5-10 cm depths was also positively correlated with: (1) soil NH_4-N concentrations at the 0-10 cm depth during wheat booting ($R^2 = 0.24$ and 0.47, respectively; $P < 0.05$; 100 DAS; Figure 41); and, (2) soil NO_3-N concentrations at the 0-10 cm depth during wheat emergence ($R^2 = 0.41$ and 0.38, respectively; $P < 0.01$; 22 DAS; Figure 42).

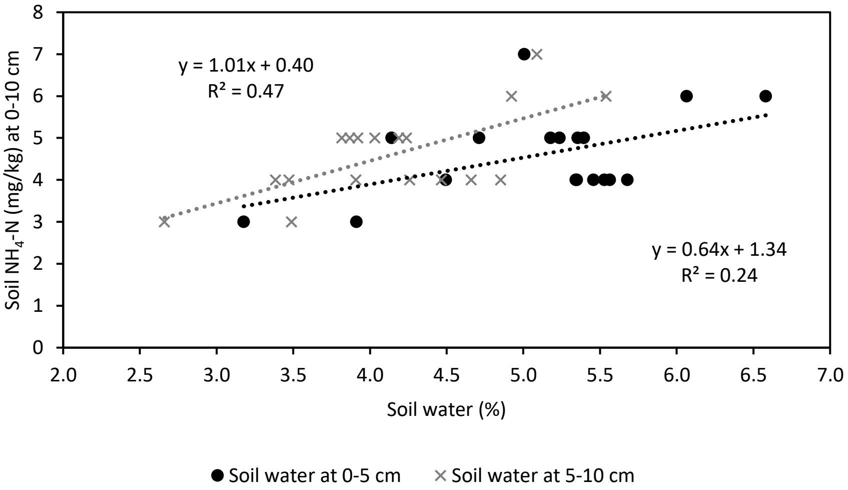

Figure 41. Relationship between soil water content (%, w/w) at the 0-5 and 5-10 cm depths and soil ammonium-nitrogen concentration (NH_4-N, mg/kg) at the 0-10 cm depth during wheat booting (100 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

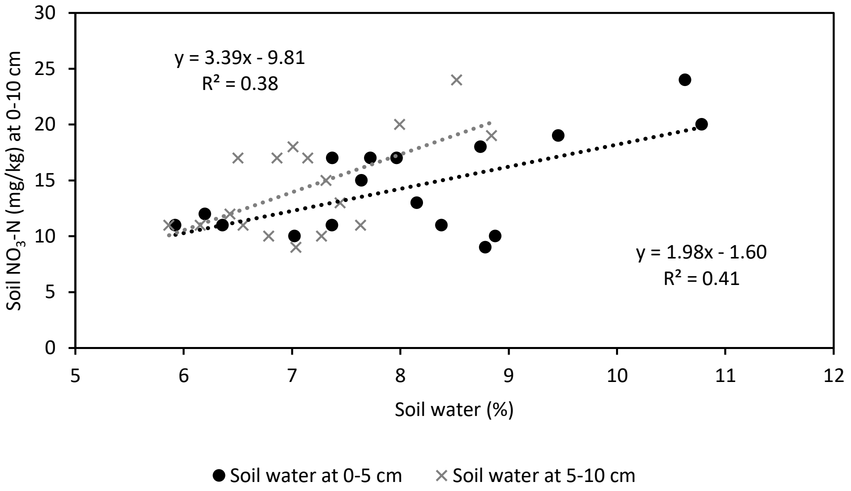

Figure 42. Relationship between soil water content (%, w/w) at the 0-5 and 5-10 cm depths and soil nitrate-nitrogen concentration (NO_3-N, mg/kg) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Crop growth and yield parameters

Wheat plant density, head density, shoot dry matter, and grain yield were significantly affected by soil water repellence severity class in the 0-5 cm depth ($P < 0.05$; Table 19), whereby wheat plant density (64 DAS), head density (161 DAS), shoot dry matter (161 DAS), and grain yield (161 DAS) were significantly greater in Class 1 (negligible/slightly repellent) soils (164 plants/m^2, 178 heads/m^2, 3.3 t/ha, and 1.68 t/ha, respectively) than in Class 2 (moderately repellent) soils (143 plants/m^2, 149 heads/m^2, 2.3 t/ha, and 1.13 t/ha, respectively; Figures 43a-d). Bivariate analysis showed that wheat plant density was negatively correlated with soil water repellence severity at the 0-5 cm depth during wheat emergence (22 DAS; $R^2 = 0.43$; $P < 0.05$; Figure 44). Wheat shoot dry matter and grain yield were also negatively correlated with soil water repellence severity at the 0-5 cm depth during crop maturity ($R^2 = 0.44$ and 0.46, respectively; $P < 0.05$; Figure 45), but were not correlated with soil water content (data not shown). Wheat leaf RWC (87-94 %) and 1000-grain weight (32.8-42.9 g) were not different among soil water repellence severity classes and were not correlated with either soil water repellence severity (MED) or soil water content (data not shown).

Table 19. Analysis of variance, ANOVA, test (F values with significance level) for the main effect of soil water repellence (SWR) severity class on wheat plant density, leaf RWC, head density, shoot dry matter, 1000-grain weight, and grain yield at Meckering in 2016. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Parameter	*F*
Plant density at tillering (64 DAS) [†]	9**
Leaf RWC at booting (100 DAS)	0 ^{ns}
Leaf RWC at anthesis (113 DAS)	0 ^{ns}
Head density at maturity (161 DAS)	6*
Shoot dry matter at maturity (161 DAS)	5*
1000-grain weight (161 DAS)	4 ^{ns}
Grain yield (161 DAS)	5*

[†] Based on soil water repellence severity during crop emergence.

^{ns} Not significant ($P > 0.05$).

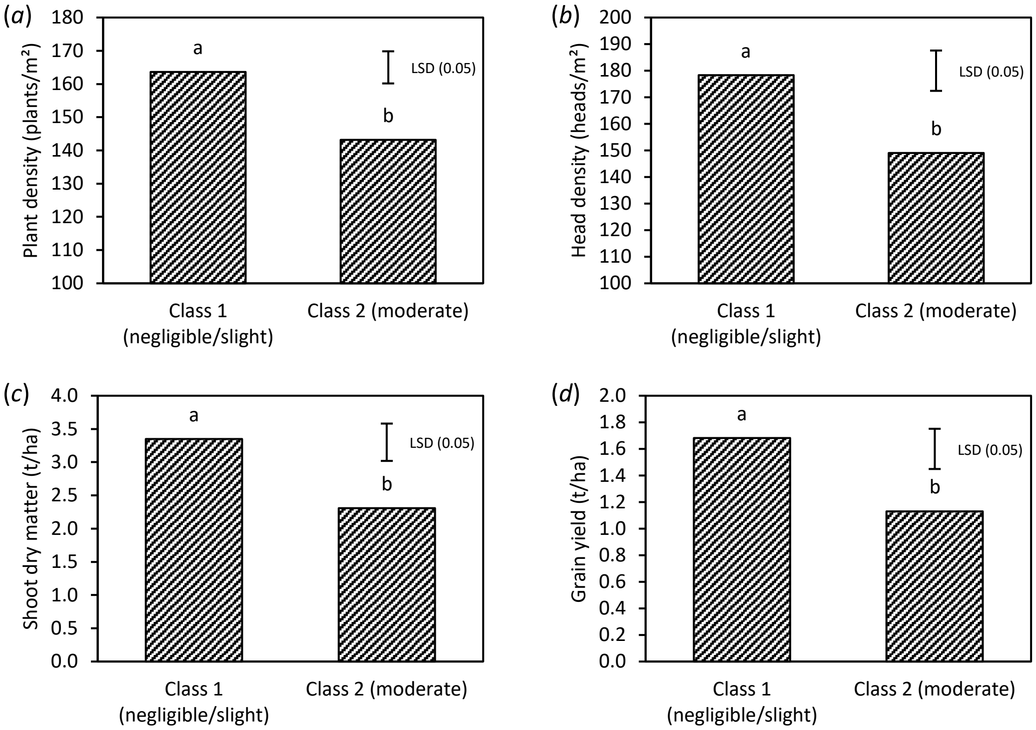

Figure 43. Effect of soil water repellence severity class on (a) wheat plant density (plants/m^2), (b) head density (heads/m^2), (c) shoot dry matter (t/ha), and (d) grain yield (t/ha) in a Grey Bleached-Ferric Kandosol at Meckering in 2016. Mean values based on an average sample size of 9 (unequal sample sizes). Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

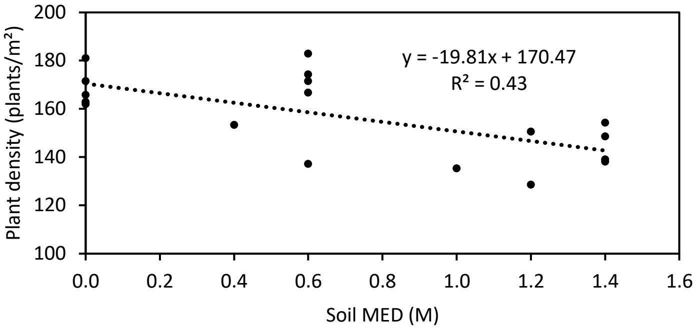

Figure 44. Correlation between soil water repellence severity (MED, M) at the 0-5 cm depth during wheat emergence (22 DAS) and wheat plant density (plants/m^2) during wheat tillering (64 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

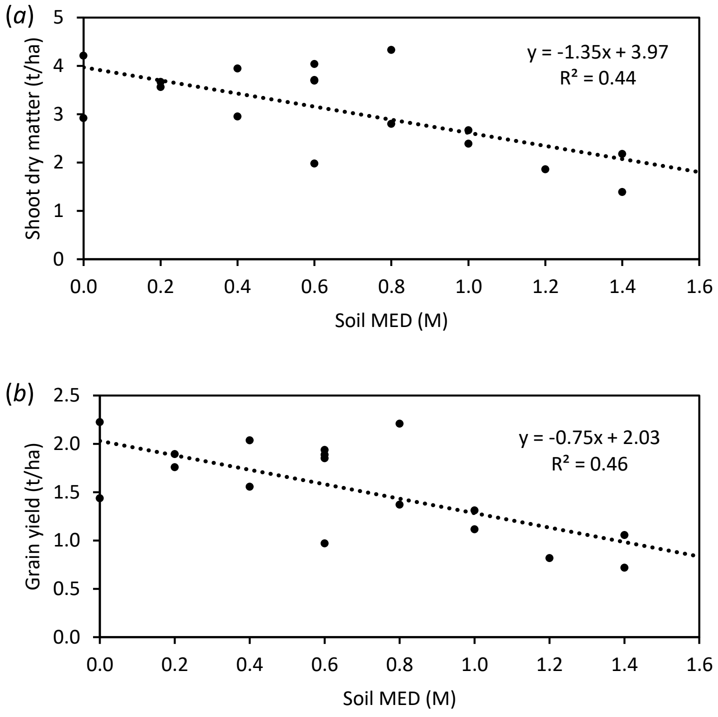

Figure 45. Correlation between soil water repellence severity (MED, M) at the 0-5 cm depth during wheat crop maturity and (a) wheat shoot dry matter (t/ha) and (b) grain yield (t/ha) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

By contrast, wheat head density, shoot dry matter, and grain yield were positively correlated with soil S concentrations at the 0-10 cm depth during wheat emergence ($R^2 = 0.22$, 0.30, and 0.31, respectively; $P < 0.05$; 22 DAS; Figures 46a-c), but not during wheat booting or grain development. Wheat shoot dry matter, 1000-grain weight, and grain yield were also positively correlated with soil exchangeable K concentration at the 0-10 cm depth during wheat grain development (R^2 = 0.30, 0.32, and 0.32, respectively; $P < 0.05$; 134 DAS; Figures 47a-c), but not during wheat emergence or booting. There were no correlations between wheat yield parameters and other soil nutrients (data not shown).

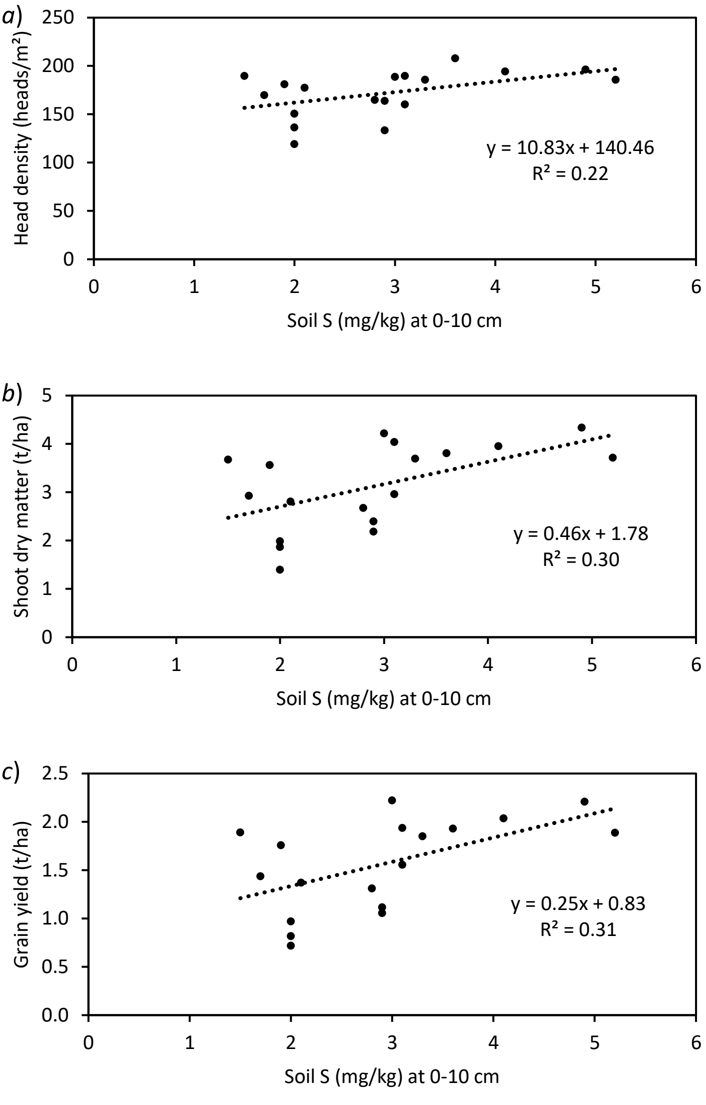

Figure 46. Correlation between soil sulphur concentration (S, mg/kg) at the 0-10 cm depth during wheat emergence (22 DAS) and (a) wheat head density (heads/m^2), (b) shoot dry matter (t/ha), and (c) grain yield (t/ha) at crop maturity (161 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

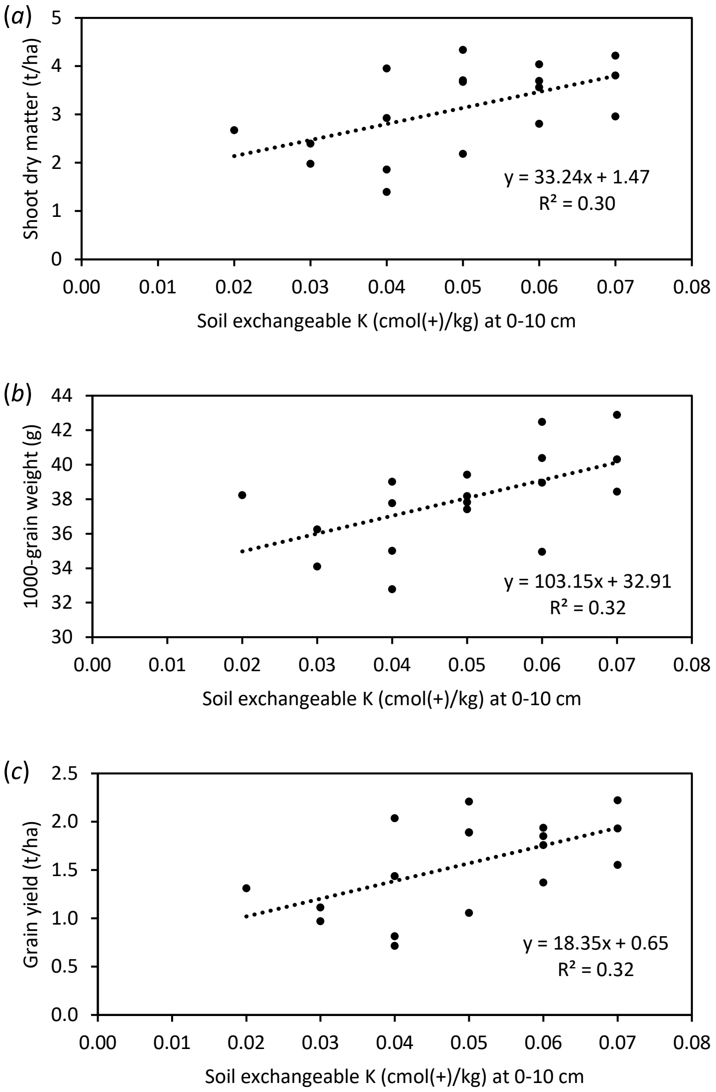

Figure 47. Correlation between soil exchangeable potassium concentration (K, cmol(+)/kg) at the 0-10 cm depth during wheat grain development (134 DAS) and (a) wheat head density (heads/m^2), (b) shoot dry matter (t/ha), and (c) grain yield (t/ha) at crop maturity (161 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Leaf nutrient concentrations

An assessment of nutrient concentrations in leaves found that wheat plants during tillering and anthesis were relatively deficient in K at Meckering (<2.8 and 2.0 %, respectively; Reuter and Robinson 1997; Appendix A.2), but were relatively adequate in other key nutrients. Notwithstanding the significant effect of soil water repellence severity class on leaf Cu, Mn, and Zn concentrations ($P < 0.05$; Table 20; see Appendix B.2.3), ANOVA tests showed no significant effect on leaf K concentrations. However, bivariate correlation analysis showed that leaf K concentrations were negatively correlated with soil water repellence at the 0-5 cm depth during wheat tillering ($R^2 = 0.30$; $P < 0.05$; 64 DAS; Figure 48).

Table 20. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between growth stage and soil water repellence (SWR) severity class on wheat leaf nutrient concentrations at Meckering in 2016. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Leaf nutrient concentration	Growth stage	SWR severity class	Growth stage × SWR severity class
N	91****	3 ^{ns}	1 ^{ns}
P	372****	0 ^{ns}	2 ^{ns}
K	1 ^{ns}	3 ^{ns}	1 ^{ns}
Ca	4*	2 ^{ns}	0 ^{ns}
Mg	6**	3 ^{ns}	0 ^{ns}
S	34****	0 ^{ns}	1 ^{ns}
Na	9****	0 ^{ns}	1 ^{ns}
Cl	14****	1 ^{ns}	1 ^{ns}
B	68****	3 ^{ns}	2 ^{ns}
Cu	16****	9**	1 ^{ns}
Fe	0 ^{ns}	1 ^{ns}	2 ^{ns}
Mn	4*	6*	0 ^{ns}
Zn	75****	5*	0 ^{ns}

^{ns} Not significant ($P > 0.05$).

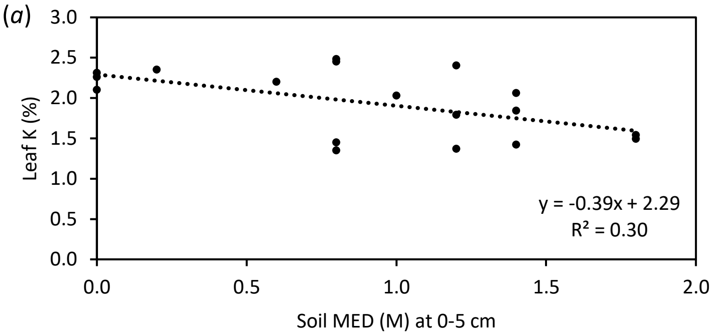

Figure 48. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and wheat leaf potassium concentration (K, %) during tillering (64 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

By contrast, leaf K concentrations were positively correlated with soil water content at the 0-5 cm depth during wheat tillering ($R^2 = 0.38$; $P < 0.01$; 64 DAS; Figure 49). Leaf K concentrations were also positively correlated with soil Colwell K ($0.30 \leq R^2 \leq 0.36$; $P < 0.05$; Figure 50a) and exchangeable K concentrations at the 0-10 cm depth during wheat emergence ($0.54 \leq R^2 \leq 0.64$; 22 DAS; $P < 0.01$; Figure 50b).

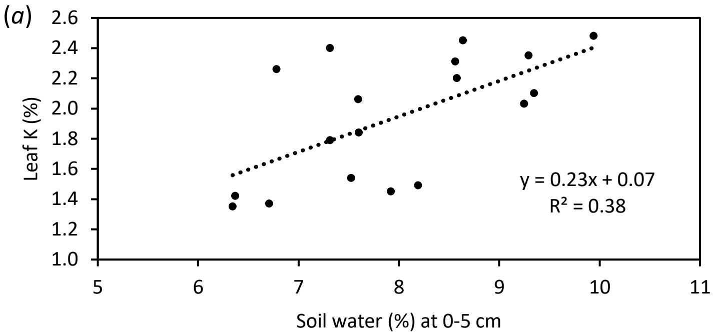

Figure 49. Relationship between soil water content (%, w/w) at the 0-5 cm depth and wheat leaf potassium concentration (K, %) during tillering (64 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Wheat leaf K concentrations during tillering were positively correlated with 1000-grain weight ($R^2 = 0.23$; $P < 0.05$; Figure 51), while leaf K concentrations during booting were positively correlated with shoot dry matter ($R^2 = 0.25$; $P < 0.05$; Figure 52a) and grain yield ($R^2 = 0.24$; $P < 0.05$; Figure 52b).

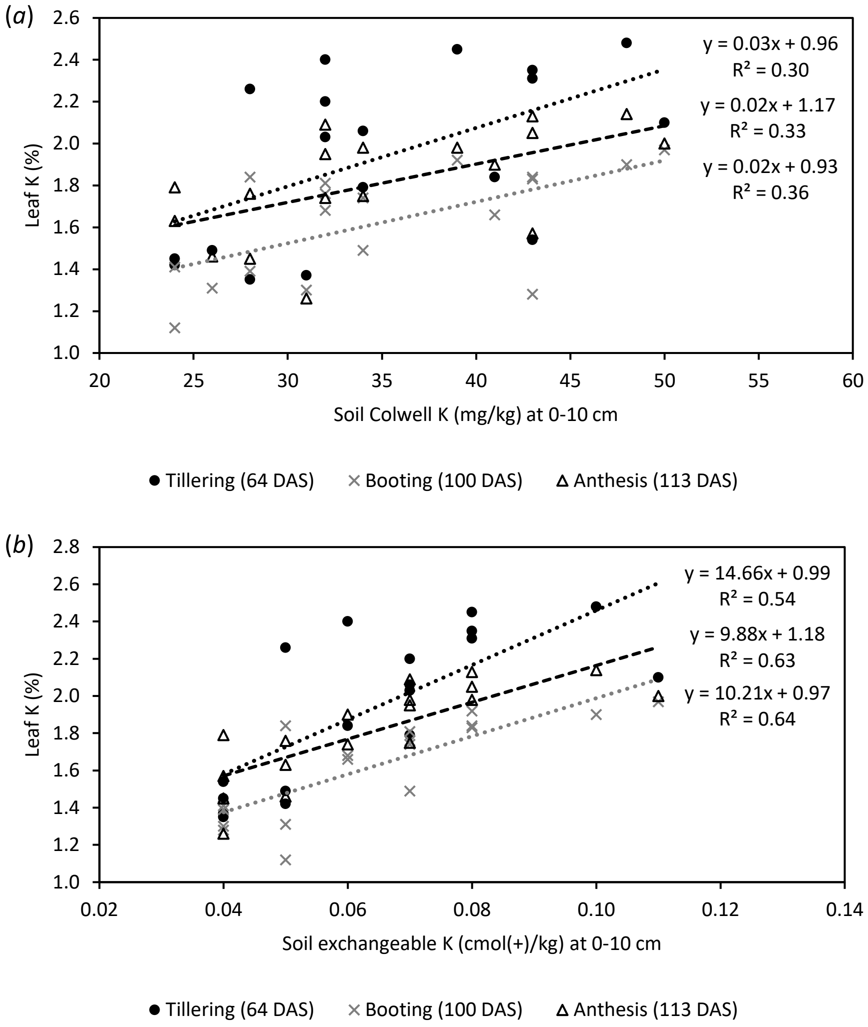

Figure 50. Relationship between wheat leaf potassium concentration (K, %) and (a) soil Colwell potassium concentration (K, mg/kg) and (b) soil exchangeable potassium concentration (K, cmol(+)/kg) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

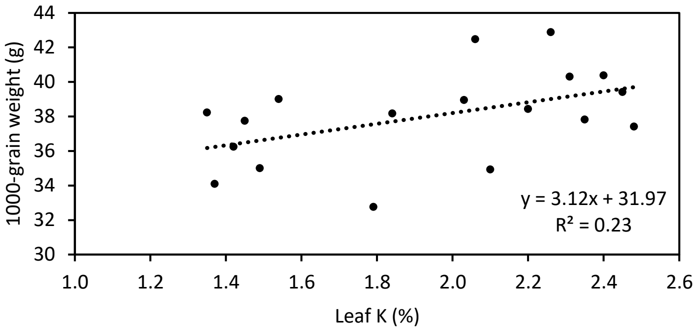

Figure 51. Relationship between wheat leaf potassium concentration (K, %) during tillering (64 DAS) and 1000-grain weight (g) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

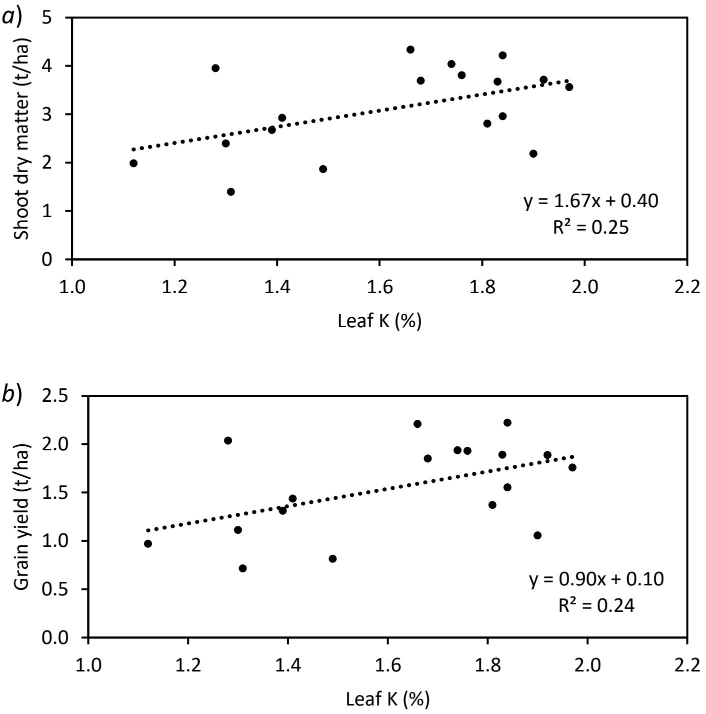

Figure 52. Relationship between wheat leaf potassium concentration (K, %) during wheat booting (100 DAS) and (a) shoot dry matter (t/ha) and (b) grain yield (t/ha) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

3.4 Discussion

Field studies were conducted to assess the spatial and temporal variability of soil water repellence severity in the crop row (0-5 and 5-10 cm depths) and to examine its possible relationships with: (a) soil nutrient availability (0-10 cm depth), (b) growth and nutrition of canola and wheat crops during key stages of phenological development, and (3) crop yield parameters on two representative sandy soils types in southwest WA – namely, a Ferric Chromosol at Kojonup and a Grey Bleached-Ferric Kandosol at Meckering. Based on current reports in literature, it was hypothesised that soil water repellence would adversely affect crop growth and nutrition, and consequently limit crop yields, due to a reduction in soil water and nutrient availability.

3.4.1 Soil water repellence

Soil water repellence can vary considerably over space and time (Harper and Gilkes 1994; Keizer *et al.* 2007; Wahl 2008; Müller *et al.* 2014a) but generally is most pronounced within the upper 10 cm of the soil profile due to the accumulation of decomposed plant residues and fungal matter (Doerr *et al.* 2000; Franco *et al.* 2000a), particularly after the dry season (Crockford *et al.* 1991; Rye and Smettem 2015, 2017).

In this field study, soil water repellence severity of a Ferric Chromosol at Kojonup was consistently and significantly greater at the 0-5 cm depth (MED 3.4; very severely repellent) than at the 5-10 cm depth (MED 1.3; moderately repellent) throughout the canola growth cycle. The Grey Bleached-Ferric Kandosol at Meckering was moderately repellent at the 0-5 cm depth (MED 0.7-1.6; slightly to moderately repellent) and virtually non-repellent at the 5-10 cm depth (MED 0.0-0.3) throughout the wheat growth cycle, with soil water repellence severity at the 0-5 cm depth increasing from winter to spring and peaking during the wheat booting stage (MED 1.6; 100 DAS). This is consistent with what has been reported previously (Rye and Smettem 2015).

Despite having a relatively high clay content (16-18 %), severe levels of water repellence in the Kojonup soil were thought to be attributed to its high gravel content (36-40 % w/w), presumably due to decreased specific soil surface area and increased concentration of hydrophobic organic compounds in the finer soil fraction (<2 mm; Bowden 2014). However, soil water repellence severity was not found to be correlated with soil gravel content at this site. Results, nevertheless, showed that increases in soil water repellence severity at the 5-10 cm depth were somewhat related to increases in soil OC at the 0-10 cm depth during the canola stem elongation ($R^2 = 0.38$; $P < 0.01$;

95 DAS) and pod development stages ($R^2 = 0.26$; $P < 0.05$; 143 DAS). Likewise, at Meckering, soil OC was found to be positively correlated with soil water repellence severity at the 0-5 cm depth throughout the growing season ($0.31 \leq R^2 \leq 0.53$; $P < 0.05$), and this could reflect an increased concentration of hydrophobic compounds in soils with higher soil OC content. Similar positive relationships have also been observed by Roper *et al.* (2013) and Leelamanie (2014). However, many other studies have shown soil water repellence to be poorly predicted by total soil OC (Teramura 1980; Harper and Gilkes 1994; Doerr *et al.* 2005; de Blas *et al.* 2010; Hallett *et al.* 2011), even among soils of similar textural characteristics (Doerr *et al.* 2006). Literature points to the critical importance of the composition or nature of the outermost layer of the organic coating on soil particles, particularly the long-chained amphipathic (or amphiphilic) compounds (Franco *et al.* 2000a; Horne and McIntosh 2000; Mainwaring *et al.* 2004; Morley *et al.* 2005). The high severity of soil water repellence at Kojonup could also be attributed to the type of hydrophobic organic compounds, possibly derived from natural *Eucalyptus* forest stands before agricultural land clearing (McGhie and Posner 1981), as severe soil water repellence has often been associated with *Eucalyptus* forests (Crockford *et al.* 1991; Doerr *et al.* 1996; Walden *et al.* 2015; Uddin *et al.* 2017).

Regardless of its origin, very severe water repellence at Kojonup and its relative persistence throughout the canola growth cycle (from autumn to spring) could have severe and sustained effects on canola growth and nutrition due to reduced soil water retention and prolonged soil dryness. By contrast, the ephemeral nature of soil water repellence at Meckering could suggest that its greatest impact on wheat growth and nutrition occurred at its peak expression during vegetative growth (<100 DAS). Nevertheless, inducing plant water and/or nutrient stress, especially during stem elongation or anthesis when growth and uptake are high (Edwards and Hertel 2011; Zheng *et al.* 2016), is known to have an injurious effect on crop growth and nutrition which can have serious yield penalties (Rezaei and Razzaghi 2015). The effects of soil water repellence severity on soil nutrient availability, crop growth, crop nutrition, and crop yield parameters were thus examined.

3.4.2 Effect of soil water repellence on soil water and nutrient availability

Topsoil water availability at Kojonup was decreased by soil water repellence severity but only during the canola leaf production stage whereby soil water content at the 0-5 cm depth was significantly lower in Class 4 soils (very severely repellent; 12.2 %) than in Class 2 (moderately repellent; 20.8 %) and 3 (severely repellent; 19.7 %) soils (Table 5). However, soil water repellence severity did not affect soil water content at Meckering. While no correlation between soil water repellence severity and soil water content were observed, the reduction in water content (by up to 8.6 % w/w) at the 0-5 cm depth in the very severely repellent soil relative to the moderately repellent soil during canola leaf production at Kojonup could probably be attributed to its greater resistance to water absorption (Roberts and Carbon 1971; Wang *et al.* 2000; Li *et al.* 2018). By contrast, other studies have suggested that soil water repellence can have a mulch effect that significantly reduces evaporative water loss from the soil surface (Bachmann *et al.* 2001; Gupta *et al.* 2015; Rye and Smettem 2017) by decreasing the upward capillary movement of water (DeBano 1981). Nonetheless, soil water content in the Kojonup soil was generally inversely related to the soil gravel content (>2 mm) at the 0-5 cm depth ($R^2 = 0.39$), given that soil water storage and hydraulic conductivity tend to decrease as the soil gravel content increases (Saxton and Rawls 2006).

Soil EC (solute concentration) at the 0-10 cm depth was, however, negatively correlated with soil water repellence severity ($0.43 \leq R^2 \leq 0.67$) and positively correlated with soil water content at Kojonup ($0.40 \leq R^2 \leq 0.49$), suggesting that increasing soil water repellence severity could adversely affect topsoil solute availability due to a reduction in soil water retention and enhanced solute transport from the 0-10 cm depth. As a result, accelerated leaching of water and solutes via preferential flow pathways in unsaturated water-repellent soils (Ritsema and Dekker 1994; Dekker and Ritsema 1996b; Bauters *et al.* 1998) can often be associated with an increased risk of groundwater contamination by surface-applied agrochemicals (van Dam *et al.* 1990; Blackwell 2000; Wang *et al.* 2000; Ritsema *et al.* 2002). Effects of soil water repellence on solute transport and leaching could consequently limit the availability of mobile soil nutrients, such as NO_3-N, K, and SO_4-S, in topsoil of which were found to be positively correlated with soil EC and soil water content at the 0-10 cm depth at Kojonup. Although soil NO_3-N and K concentrations were not directly correlated with soil water repellence severity, soil S concentrations were negatively correlated with soil water repellence severity at the 5-10 cm depth during canola pod development at Kojonup ($R^2 = 0.38$), but correlations were not observed during canola emergence or stem elongation. By contrast, other studies have observed that repellent soils can exhibit higher soil S concentrations in relative to wettable soils, presumably due to limited water flow in repellent soils (Hurraß and Schaumann 2006; Simpson *et al.* 2019). In view of these findings, future studies should also sample soils at 10-30 cm depth to determine whether nutrient availability in subsurface layers increases with soil water repellence on the Kojonup soil.

At Meckering, soil NO_3-N (during wheat emergence) and NH_4-N concentrations (during wheat booting) at the 0-10 cm depth were generally positively correlated with soil water content. Although soil NO_3-N and NH_4-N concentrations were not correlated with soil water repellence severity, these results likely reflect the influence of soil water availability on mineralisable N supply. Moreover, soil Cu concentrations were found to be negatively correlated with soil water repellence severity at the 0-5 cm depth during wheat emergence at Meckering ($R^2 = 0.59$) but were not correlated with soil water content (see Appendix B.2.1). Results could, therefore, suggest that the availability of soil N and Cu at Meckering and N, K, and S at Kojonup may be potentially reduced by soil water repellence, presumably due to enhanced water and solute leaching, and this could have adverse implications for plant uptake during critical growth stages. However, leaching of Cu in soils by preferential flow may not be as important compared to that of mobile nutrients (i.e., N, K, and S) due to its greater affinity for adsorption on clay and organic matter surfaces, and formation of insoluble metal-oxide minerals of Fe, Al, and Mn (Sipos 2010; Elbana and Selim 2011; Fosso-Kankeu and Waanders 2014).

Topsoil water repellence can increase the protection of organic matter from microbial decomposition which is known to favour aggregate stability (Piccolo *et al.* 1999; Goebel *et al.* 2005; Arcenegui *et al.* 2008) and this could probably explain the observed positive correlation between soil OC at the 0-10 cm depth and soil water repellence severity at the 5-10 cm depth at Kojonup and at the 0-5 cm depth at Meckering. Dry, repellent topsoils could, therefore, conserve a portion of the organic and inorganic nutrient supply by limiting their exposure to wetting events and hence mineralisation and dissolution processes (Goebel *et al.* 2011; Hoyle 2013). Such mechanisms would be important for the leaching of nutrient anions, especially NO_3^-, which are very mobile in the soil due to their negligible interaction with the negatively charged matrix (Lehmann and Schroth 2003). Soil organic matter can also contribute considerably to cation exchange due to its net negative charge (Schnitzer 1965; Mengel 1993) and thus improve the retention of nutrient cations (e.g., NH_4^+, Ca^{2+}, Mg^{2+}, K^+, and Na^+). This was consistent with an increase in soil S concentration, ECEC, exchangeable Ca, exchangeable Mg, and exchangeable Na concentrations at the 0-10 cm depth as both soil OC (from 0.41 to 0.86 %) and soil water repellence severity (from negligible/slight to moderate levels) increased at Meckering. Soil NH_4-N was also found to be positively correlated with soil OC at the 0-10 cm depth during canola emergence at Kojonup ($R^2 = 0.46$) but was not directly correlated with soil water repellence severity.

Alternatively, the positive correlations observed between soil water repellence and soil nutrient cations could also reflect a relationship between soil water repellence and soil surface charge characteristics by which soil water repellence severity may be enhanced by increasing the concentrations of soluble ions, such as Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, and SO_4^{2-} (Yang *et al.* 2013). This is because increasing the density of ions adsorbed at the solid-liquid interface decreases the surface-free energy of soil particle surfaces, resulting in an increase in the soil-water contact angle and hence soil water repellence severity (Chaudhuri and Paria 2009; Leelamanie and Karube 2013). The surface-free energy of a wettable soil (adhesive forces) must exceed the surface tension of water (cohesive forces between water molecules), such that the soil-water contact angle is less than or equal to 90^o (Doerr *et al.* 2000). By this convention, water-repellent soils with low-energy surfaces will have weak molecular attractions at the solid-liquid interface and hence result in a soil-water contact angle greater than or equal to 90^o (Roy and McHill 2002; Goebel *et al.* 2004). Other work has also demonstrated that an increase in the electrolyte concentration (ionic strength) of water by the dissolution of inorganic solutes (e.g., NaCl, KCl, Na_2SO_4, $CaCl_2$, etc) could also increase surface tension (Ralston and Healy 1973; Leroy *et al.* 2010; Lima *et al.* 2013) such that the soil-water contact angle increases non-linearly with electrolyte concentration, with a more pronounced increase in the soil-water contact angle at low electrolyte concentration (Leelamanie and Karube 2013). Relationships between soil water repellence severity and soil surface charge characteristics could, therefore, also explain why soil exchangeable Ca, Mg, and Na, and S concentrations increased with increasing soil water repellence severity (from slight to moderate levels) at Meckering.

Interestingly, soil pH_{Ca} at the 0-10 cm depth was found to be positively correlated with soil water repellence severity at the 0-5 cm depth during canola stem elongation at Kojonup. However, other studies indicate that soil water repellence severity decreases with increasing soil pH (Mataix-Solera *et al.* 2007; Martínez-Zavala and Jordán-López 2009; Diehl *et al.* 2010; Gautam and Ashwath 2012; Flores-Mangual *et al.* 2013; Mirbabaei *et al.* 2013; Yang *et al.* 2013). The inverse relationship between soil water repellence severity and soil pH could be explained by changes in the behaviour of pH active functional groups and negative surface charge density of the soil material caused by deprotonation – that is, the negative surface charge of soil is increased under increasing pH due to deprotonation and this decreases soil water repellence severity (Bayer and Schaumann 2007; Diehl *et al.* 2010). Soils with low pH and high ionic strength are, therefore, known to favour the expression of water repellence in comparison to soils with high pH and low ionic strength (Diehl 2009). Reduction in soil water repellence severity could also be attributed to the enhanced solubility of humic substances under alkaline conditions (Roberts and Carbon 1972; Lin *et al.* 2006) and indirectly by stimulating the growth and activity of wax-degrading microorganisms at more neutral-alkaline pH levels (Roper 2005; Roper 2006). However, soil water repellence has been observed in some calcareous soils (e.g., Arcenegui *et al.* 2008; Yang *et al.* 2013). Nevertheless, no apparent relationship between soil pH and soil water repellence severity was observed at Meckering (soil pH 5.9-6.3; see Appendix B.2.1) and this was also the case for Wallis *et al.* (1993; soil pH 5.6-6.9), possibly due to the small range in the pH values of the studied soils.

By and large, results from this experiment suggest that the availability of key plant nutrients (N, K, and S) in topsoil could be limited in more severely repellent sandy soils due to decreased soil water retention and increased leaching along preferential flow paths. However, the increased protection of topsoil nutrients from excessive in-season (or out-of-season) leaching losses could have potential benefits for fertiliser use efficiency (especially for nutrient cations such as Ca, Mg, and Na) and the productivity of the current or following crop. Potential to improve synchrony between soil nutrient release and plant nutrient demand could be possible by slowing or delaying mineralisation (attributed to early season rain) into the growing season when crops are sown and/or more developed (Myers *et al.* 1994). Results showed significant increases in soil NH_4-N concentrations at the 0-10 cm depth from canola stem elongation (6 mg/kg; 95 DAS) to pod development at Kojonup (9 mg/kg; 143 DAS), and from wheat emergence (2 mg/kg; 22 DAS) to booting at Meckering (4 mg/kg; 100 DAS), but such increases were relatively small and not related to canola or wheat yield parameters. However, the amount of nutrients conserved in repellent topsoil (especially the inter-row) and its contribution to crop growth and nutrition are not known but could be proportional to the volume of dry soil under relatively homogenous nutrient supply. Prolonged and severe soil water repellence could otherwise have different implications for the present crop if a large volume of soil remains dry and inaccessible to roots (e.g., poor nutrient use efficiency; Roper *et al.* 2015). The effects of soil water repellence on crop growth, nutrition, and yield are thus discussed.

3.4.3 Effect of soil water repellence on crop growth, nutrition, and yield

Meckering

Consistent with the study's hypothesis, results showed that wheat yield was adversely affected by an increase in soil water repellence severity at the 0-5 cm depth at Meckering, which can be attributed to decreases in plant density (64 DAS), head density (161 DAS), and shoot dry matter (161 DAS). In dryland agriculture, large variations in soil water content in the seeding row due to uneven wetting at the break of season frequently causes impaired and staggered crop germination and establishment on water-repellent soils (DeBano 1981; Roper *et al.* 2015), with prevalent dry repellent topsoil also leaving seeds ungerminated throughout the season (Hollamby and Davies 2012; GRDC 2014a). Crop yield per unit area of cultivated land would thus be directly limited on water-repellent soils (Bond 1972). In this study, the observed decreases in wheat grain yield could be explained by the reduction in plant establishment at Meckering. By contrast, soil water availability and leaf RWC (plant hydration) were not affected by soil water repellence severity in this study, and relationships between soil water availability and wheat shoot dry matter or seed yield parameters were also not apparent, suggesting that subsequent growth of wheat was not related to soil water availability. A recent study conducted by Li *et al.* (2019) did, however, find that increasing the water repellence severity of sandy loam soils (spiked with different concentrations of dichlorodimethylsilane) decreased the stem diameter, plant height, leaf area index, root length, dry matter, cob length, kernel weight, and water use efficiency of summer maize in comparison to plants grown in wettable soil under irrigation. They attributed the loss in summer maize growth to a reduction in soil water availability and root water uptake, presumably due to restricted water movement and the additional energy required to absorb water from repellent soils.

The same processes affecting soil water content are likely to affect soil nutrient availability in water-repellent soils, given that nutrient release (dissolution, desorption, and mineralisation; Barber 1995) and transport (mass flow and diffusion; Oliveira *et al.* 2010) are intrinsically dependent on the soil solution (Mengel 1995). Preferential flow can also result in the accelerated leaching of topsoil nutrients which bypasses the plant root zone (Blackwell 2000; Wang *et al.* 2000; Ritsema *et al.* 2002). Significant loss of water and plant-available nutrients could then limit crop nutrition and yield (van der Paauw 1962). Results showed that wheat grain yield were positively correlated with soil S concentration at the 0-10 cm depth during wheat emergence at Meckering ($0.22 \leq R^2 \leq 0.31$), while grain yield was also positively correlated with soil exchangeable K concentration at the 0-10 cm depth during wheat grain development ($0.30 \leq R^2 \leq 0.32$). These relationships were expected given that a majority of soils were below the critical S and Colwell K levels throughout the season for wheat (i.e., <4.5 mg KCl-40 extractable S/kg and <41 mg Colwell K/kg; Anderson *et al.* 2015). A reduction in soil K and S availability at the 0-10 cm depth would, therefore, limit wheat production on these water-repellent soils at Meckering. Interestingly, however, soil S concentrations were found to be higher in more severely repellent soils but were not correlated with wheat yield parameters, suggesting that the adverse effect of soil water repellence severity on wheat yield parameters was not simply related to low soil S availability at the 0-10 cm at Meckering. Indeed, Anderson *et al.* (2015) found that the 0-30 cm soil sampling depth was a better predictor of crop response to extractable S than the 0-10 cm depth. At the Meckering site, soil S concentration was positively correlated with soil OC at the 0-10 cm, suggesting that its availability was dependent on organic matter mineralisation.

Conversely, the observed decrease in soil exchangeable K percentage at the 0-10 cm depth during wheat emergence in more severely repellent soils could explain to some extent the decreases in wheat grain yield at Meckering. This was consistent with a negative correlation between wheat leaf K concentration and soil water repellence severity at the 0-5 cm depth during tillering and a positive correlation between leaf K concentration and soil water content at the 0-5 cm depth ($R^2 = 0.38$). Wheat leaf K concentrations during anthesis were also positively correlated with wheat shoot dry matter ($R^2 = 0.25$), 1000-grain weight ($R^2 = 0.23$), and grain yield ($R^2 = 0.24$), suggesting that wheat yield parameters were predominantly limited by decreased wheat K nutrition as soil water repellence severity increased, presumably due to a reduction in soil water content. This was confirmed by leaf tissue tests which showed that leaf K concentrations were indeed deficient during wheat tillering and anthesis (<2.8 and 2.0 %, respectively; Reuter and Robinson 1997). Based on these findings, the adverse effect of soil water repellence on wheat shoot dry matter production and grain yield at Meckering could, therefore, be attributed to: (1) a reduction in wheat plant establishment, and (2) a reduction in wheat K nutrition due to decreased soil water and K availability at the 0-10 cm depth.

Kojonup

In contrast to findings at Meckering, at Kojonup, unexpectedly, canola plant establishment, shoot dry matter, and seed yield at 191 DAS were positively correlated with soil water repellence severity at the 0-10 cm depth during canola emergence ($R^2 = 0.50$, 0.55, and 0.48, respectively). However, there was no relationship between canola seed yield and soil water content at 0-10 cm at Kojonup. Despite no apparent correlation between soil Cu concentration and soil water repellence severity, canola plant establishment, shoot dry matter, and seed yield were positively correlated with soil Cu concentration at the 0-10 cm depth during canola stem elongation. Leaf Cu concentrations were also positively correlated with increases in soil water repellence severity at the 5-10 cm depth during canola pod development, suggesting that soil water repellence may have had a positive effect on canola Cu uptake. Canola leaf Cu concentrations at anthesis (3-4 mg/kg) were also found to be below adequate in soils at Kojonup (<5-12 mg/kg; Reuter and Robinson 1997), despite relatively adequate pre-anthesis leaf Cu concentrations (4-25 mg/kg) and adequate soil Cu levels (>0.35 mg Cu/kg; Brennan *et al.* 2019). Copper is known to play important roles during the plant reproductive phase, especially for anther and pollen formation (microsporogenesis) and pollen viability such that severe Cu deficiencies can result in near complete sterility of pollen formed and inhibition of all grain production (Azouaou and Souvré 1993; Broadley *et al.* 2012). The observed increases in canola plant establishment, shoot dry matter, and seed yield at Kojonup could be related to an increase in canola Cu uptake at anthesis, although correlations between leaf Cu concentrations and yield parameters were not apparent. Canola leaf Mn concentrations were also positively correlated to soil water repellence severity at the 5-10 cm depth during pod development but were also not correlated with canola yield parameters. Moreover, leaf Mn concentrations were more than adequate for canola throughout the season (i.e., 30-100 mg Mn/kg; Reuter and Robinson 1997).

Canola leaf P and leaf Ca concentrations were negatively correlated with soil water repellence severity at the 5-10 cm depth, suggesting that canola P and Ca nutrition could potentially be limited in more severely repellent soils at Kojonup, presumably due to a reduction in soil water content and hence soil Ca and P availability at the 0-10 cm depth. Limited P nutrition, especially during early growth, can reduce plant growth and yield (Elliott *et al.* 1997; Grant *et al.* 2001) by restricting root development (Boatwright and Viets 1966) and tiller production, especially in cereals (Rodríguez *et al.* 1999). While canola is known to take up P later in its growth cycle (Rose *et al.* 2007), external P requirements are typically higher during early growth (Brennan *et al.* 2019), and P deficiencies can restrict root and shoot growth, branching, and pod number (Potash & Phosphate Institute 1999). Calcium deficiencies in canola can cause the top part of the raceme to wither due to decreased cell wall strength but calcium deficiencies are considered to be of little economic significance due to its patchy incidence within the paddock and plant recovery over time (Parker 2009). However, leaf P and Ca concentrations were not correlated with canola yield parameters and leaf tissue tests showed that pre-anthesis leaf P concentrations (0.54-0.86 %) and anthesis leaf Ca concentrations (1.0-1.6 %) were generally adequate (i.e., 0.35-0.60 % P and 1.0-2.0 % Ca; Reuter and Robinson 1997), despite somewhat borderline leaf P concentrations at anthesis (0.31-0.44 %).

The unexpected results at Kojonup suggest that other mechanisms were likely involved. These could include: (1) an increase in subsurface soil water and nutrient availability and hence plant uptake from deeper soil depths (>10 cm) due to increased solute redistribution into the subsoil in more severely repellent soils; and, (2) decreased water evaporation from water-repellent soils due to a reduction in the upward capillary movement of water (DeBano 1981). The fact that the farmer had banded 1 L of wetting agent in the furrow at sowing is noteworthy and could also contribute to the confounding effects of soil water repellence observed at Kojonup (see Chapters 5-7). Although banding wetting agent as a mitigation strategy does not completely ameliorate soil water repellence, it is designed to improve plant establishment by increasing water infiltration and promoting even wetting in the treated seed furrow (Blackwell 1993; Crabtree and Henderson 1999; Roper *et al.* 2015). The observed increase in canola plant establishment, shoot dry matter, Cu nutrition, and seed yield could, therefore, be explained by one or more of these mechanisms, despite the high severity of soil water repellence throughout the growing season. Nevertheless, the mechanisms contributing to the positive response of canola yield to increased soil water repellence require further study as outlined in Chapters 5-7.

3.5 Conclusion

This preliminary field study reveals that increased soil water repellence could have both adverse and favourable effects on dryland crop growth and nutrition on sandy soils in southwest WA, primarily due to its effect on soil water and nutrient availability and plant uptake. In agreement with the hypothesis that soil water repellence will be harmful to crop growth and nutrition, increases in soil water repellence severity (from negligible to moderate levels) at the 0-5 cm depth resulted in decreased wheat establishment, head density, shoot dry matter, K nutrition, and grain yield on a Grey Bleached-Ferric Kandosol at Meckering. While soil water repellence did not appear to affect soil water availability at the 0-10 cm depth, its adverse effect on soil K availability at the 0-10 cm depth and wheat K nutrition was evident, and this consequently contributed to some extent to the losses in wheat growth and yield. By contrast, canola establishment, shoot dry matter, Cu nutrition, and seed yield increased as soil water repellence severity increased (from moderate to very severe levels) at the 0-5 cm depth in a Ferric Chromosol at Kojonup, despite: (a) prolonged severe soil water repellence throughout the entire growing season, (b) a potential decrease in canola P and Ca nutrition, and (c) a decrease in soil solute availability, especially of NO_3-N, K, and SO_4-S, at the 0-10 cm depth. This contradiction could be attributable to the increased availability of soil water and nutrients in subsurface soil layers (i.e., below the 10 cm depth), which were not measured in this study, presumably due to leaching in the furrow of severely repellent soils. Nevertheless, the underlying mechanisms contributing to this positive response in canola are not well understood. Potential effects of soil water repellence on root growth and soil water and nutrient availability in the subsurface layer will, therefore, be examined in closer detail in the field (Chapter 4) and under controlled glasshouse conditions (Chapters 5-7).

Chapter 4: Effect of soil management practices on crop growth and nutrition on water-repellent sandy soils

4.1 Introduction

In Mediterranean-type climates, water is a major limiting factor for rainfed crop and pasture production as plant growth depends solely on stored soil water that is strongly influenced by seasonal rainfall which is often erratic and results in crop water deficits (Kronen 1994). The expression of soil water repellence in these water-limited environments can, therefore, cause major limitations to germination, establishment, growth, and yield of dryland crops and pastures on sandy agricultural soils (Bond 1972; DeBano 1981; Müller *et al.* 2014a; Roper *et al.* 2015), predominantly due to the increased spatial heterogeneity of plant-available water in the soil profile (Bond 1964), the prevalence of isolated dry soil zones even after rainfall (Blackwell 2000), and decreased soil water retention in comparison to that in wettable soils (Li *et al.* 1997; Doerr *et al.* 2006). The impact on Australian farming systems due to losses in crop and pasture production have been reviewed above (Chapter 1). Implementation of mitigation and/or amelioration strategies are thus critical for effective management of soil water repellence and grain production in these water-limited environments.

Various physical, chemical, and biological methods exist for managing soil water repellence (e.g., deep soil cultivation, clay spreading, wetting agent application, stimulation of wax-degrading microorganisms, furrow/on-row sowing and water harvesting, and no-tillage and stubble retention; Blackwell 2000; Hallett 2008; Müller and Deurer 2011; Roper *et al.* 2015). Of these methods, amelioration strategies employing claying and/or deep soil cultivation can produce substantial long-lasting benefits by masking hydrophobic compounds or altering surface soil properties to improve water infiltration (Ma'shum *et al.* 1989; Ward and Oades 1993; Cann 2000; Hall *et al.* 2010; Davies *et al.* 2011; Betti *et al.* 2015; Davies and Blackwell 2015; Roper *et al.* 2015). However, these practices are expensive for broadacre systems and may also carry a level of risk for crop growth, nutrition, and overall productivity if not applied correctly (Harper and Gilkes 2004; Davies *et al.* 2012a; Roper *et al.* 2015).

Risks due to claying concern the properties of subsoil clay applied (e.g., adverse pH, salinity, sodicity, and toxicity) and/or the method of application. While soils may no longer be repellent after claying, high application rates and/or inadequate incorporation of clay into topsoil can result in surface sealing, compaction, and decreased water use efficiency particularly from light rainfall events due to poor water infiltration, decreased wetting depth, and increased rate of evaporation of soil water from the surface soil layer (Davenport *et al.* 2011; Masters 2014). This would consequently limit plant root development into the subsoil (Davies *et al.* 2012a). High application rates (e.g., 150 t/ha) of high pH, calcareous clays can also lead to nutrient fixation relative to non-calcareous clays which can result in trace element deficiency, particularly in manganese (Davenport *et al.* 2011; Masters 2014). Fixation of P and K by clay and calcium carbonate could also have implications for plant P and K nutrition (Weil and Brady 2017). Sodic, alkaline subsoils can also contain high levels of Na and B which are potentially toxic to plants (Cartwright *et al.* 1984; Rengasamy 2002) and thus their incorporation in topsoil could have injurious effects on crop production in the short to medium term until they are leached deeper into the soil profile given sufficient rainfall (Davenport *et al.* 2011). Likewise, introduction of acidic subsoils could also adversely affect crop production due to Al and Mn phytotoxicity and nutrient imbalance, particularly of P (Rahman *et al.* 2018). By contrast, field trials have shown significant improvements in plant K nutrition by amending sandy soils with subsoil clay, predominantly of kaolinite, when the clay is high in exchangeable K, relative to untreated soils (Carter *et al.* 1998; Hall *et al.* 2010; Hall *et al.* 2015), but this response was generally limited to soils initially low in Colwell K (<60 mg/kg; Bell *et al.* 2018).

Spading or mouldboard ploughing may result in the dilution or redistribution of plant-available nutrients, especially immobile nutrients such as P which are stratified near the soil surface, and this could result in reduced topsoil P availability and consequently impact on crop P nutrition (Davies *et al.* 2010b; Scanlan *et al.* 2012; O'Callaghan 2017; Scanlan and Davies 2019). By contrast, topsoil burial from spading or mouldboard ploughing may also increase the availability of nutrients in the subsurface root zone which is less susceptible to soil drying compared to nutrients that are concentrated near the soil surface (Davies *et al.* 2012b; Davies and Johnston 2012). Loosening of soil due to spading or mouldboard ploughing may, however, result in poor seed-soil contact and reduced seeding depth control which consequently reduces crop emergence and establishment, despite the amelioration of soil water repellence and soil compaction (Davies *et al.* 2010a; Davies and Hollamby 2011). By contrast, significant increases in early plant biomass production could result in an increased risk of haying off due to depletion of plant-available water during the season and/or a dry finish to the season (Davies *et al.* 2010b; Hall *et al.* 2015; Roper *et al.* 2015), although this may also be negated by greater access of the crop to subsoil water supply (Kirkegaard *et al.* 2007).

Due to the adverse effect of soil water repellence on crop growth, nutrition, and grain yield as highlighted in Chapter 3, and the potential range of risks involved in claying and deep soil cultivation, especially given their long-term effects on soil properties and soil nutrient availability, there is an increasing need to better understand the outcomes for crop establishment, growth, nutrition, and overall productivity after the amelioration of soil water repellence, particularly in nutrient-deficient soils. In this chapter, the effects of deep soil cultivation (spading and one-way plough), subsoil clay spreading, wetting agent application, and supplementary fertiliser treatments on early season soil nutrient availability and the nutrition, dry matter production, and grain yield of wheat and canola crops grown on water-repellent sandy soils in southwest Western Australia were investigated. It was hypothesised that implementing these management practices would improve crop establishment, growth, nutrition, and grain yield by alleviating soil water repellence.

4.2 Materials and methods

4.2.1 Study site and climate

Research was conducted in 2017 on three farming properties (Figure 53) exhibiting water-repellent soil located in the wheatbelt of southwest Western Australia (climate classified by the Köppen-Geiger system as *Csa*) – namely, Badgingarra (30°14’17.74” S, 115°31’5.90” E), Moora (30°40’11.35” S, 115°54’54.65” E), and

Meckering (31°37’38.22” S, 116°52’16.53” E). Based on records from the Badgingarra research station (near the Badgingarra and Moora study sites; Figure 54a) and Mount Noddy weather station (near the Meckering study site; Figure 54b), both areas have a mean monthly temperature ranging from 17.4 (winter) to 34.5°C (summer) and a mean annual rainfall of 493 mm at Badgingarra (between 1985 to 2016) and 381 mm at Mount Noddy (between 1985 and 2016). During the study year (2017), records showed that the annual rainfall was 440 mm at Badgingarra which was 53 mm lower than average. However, rainfall in August 2017 was relatively higher (132 mm) than average (76 mm) which was also the highest on record since 1992 (Figure 54a). By contrast, annual rainfall at Mount Noddy in 2017 was 73 mm higher than the average, attributed to substantial rainfall in January (83 mm) and in February 2017 (110 mm) which was the highest on record over the past three decades (Figure 54b). It should be noted that substantial amounts of rainfall early in the season could compromise treatment effects by breaking down soil water repellence and increasing soil water storage.

Figure 53. Location of study sites at Badgingarra, Moora, and Meckering, Western Australia.

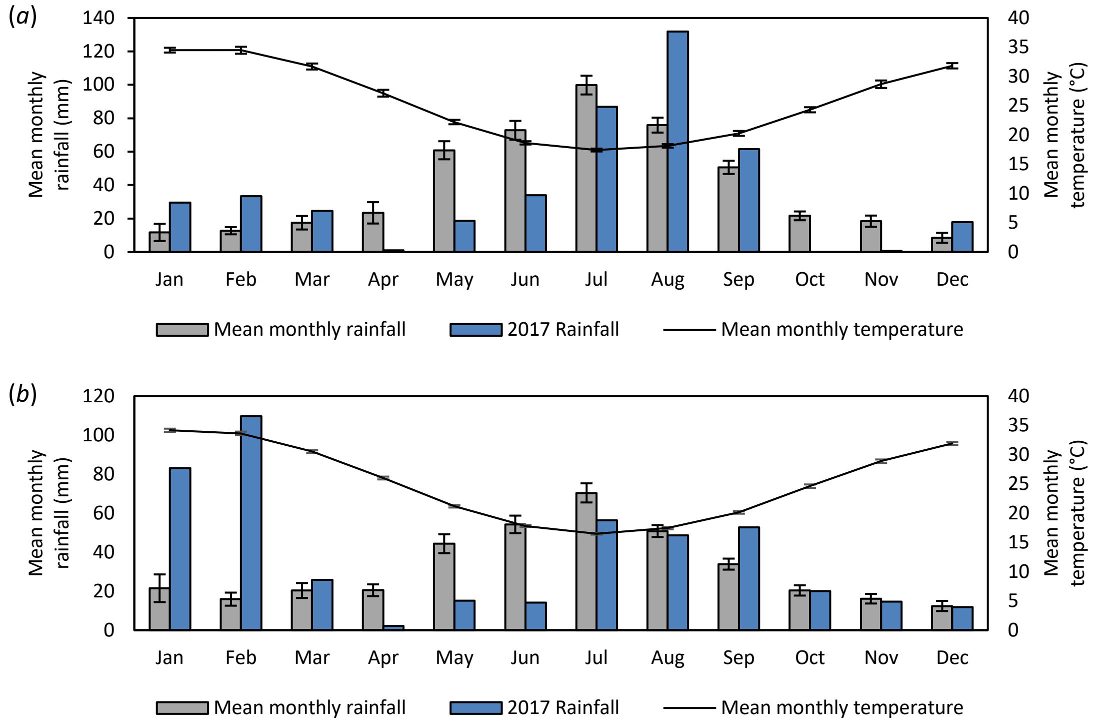

Figure 54. Mean monthly rainfall and temperature at (a) Badgingarra and (b) Meckering, Western Australia, with mean values (± standard error) based on records from 1985 to 2016 at the Badgingarra research station and Mount Noddy weather station, respectively.

4.2.2 Experimental design

Badgingarra

Wheat, *Triticum aestivum* cv. Scepter, was grown over 166 days, from 8 June to 21 November 2017, on a water-repellent pale deep sandy soil (Grey Tenosol, ASC) at Badgingarra to investigate the effects of: (a) spading (nil or one pass), (b) blanket-applied wetting agent (nil or one pass), (c) subsoil clay spreading (nil or 250 t/ha), and (d) supplementary potassium (K) fertiliser treatments (K0 = nil, K1 = 40 kg K/ha broadcast prior to sowing, and K2 = 40 kg K/ha broadcast at 54 DAS) on wheat growth and nutrition. Seventy-two microplots (5 × 2 m) consisting a full factorial of 24 treatment combinations and three replications were superimposed in a split-plot design (see Appendix C.1.1) on a pre-existing trial established by the Western Australian Department of Primary Industries and Regional Development (DPIRD; formerly the Department of Agriculture and Food WA) which had already applied spading and claying treatments in 2016. Microplot wetting agent (referred to as ‘wetter’) and fertiliser treatments were applied in 2017.

Preliminary assessments showed that subsoil clay aggregates (49.7 % clay) were inherently rich in K (159 mg Colwell K/kg) but had <2 mg NH_4-N/kg, 16 mg NO_3-N/kg, and <2 mg Colwell P/kg. As a result, 250 t/ha subsoil clay treatments will supply approximately 40 kg K/ha. Blanket wetting agent was applied post-sowing (1 DAS) using a backpack sprayer at a rate of 50 L of SE14® (SACOA Pty Ltd) /ha and 150 L water /ha. Basal fertiliser was applied by the farmer at sowing with 100 kg/ha of K-Till Extra, giving elemental application rates (kg/ha) of: 10.2 N, 12.0 P, 11.2 K, 6.0 S, 0.10 Cu, and 0.20 Zn. Two supplementary K fertiliser treatments were applied at a rate of 40 kg K/ha as muriate of potash (MOP, 49% K), with K1 treatments broadcast prior to sowing to allow for incorporation during seeding and K2 treatments broadcast at 54 days after sowing (DAS) without incorporation. Control (K0) treatments had only the basal K fertiliser applied by the farmer. Crop response to supplementary K fertiliser treatments were of interest since lupin leaf K concentrations in 2016 were found to be relatively low across the site (i.e., 1.0-1.4 %), even in areas where K-rich clay was applied. Potential effects of soil water repellence on wheat growth and K nutrition were, therefore, of interest at this site.

Moora

Canola, *Brassica napus* cv. Hyola 559TT, was grown over 181 days, from 9 May to 6 November 2017, in a water-repellent sandy ironstone gravel duplex soil (Ferric Chromosol, ASC) at Moora to investigate the effects of: (a) standard one-way plough, (b) blanket-applied wetter, and (c) supplementary nitrogen (N) and potassium (K) fertiliser treatments on canola growth and nutrition. Sixteen treatment combinations and three replications were applied over a total of 48 plots (20 × 1.8 m) in a full factorial split-plot design (see Appendix C.1.2). Standard one-way plough treatments were applied in 2015, while wetter and fertiliser treatments were applied in 2017. Soil wetter was blanket-applied immediately post-sowing (0 DAS) using a backpack sprayer at a rate of 50 L of SE14® (SACOA Pty Ltd) /ha and 150 L of water /ha. Basal fertiliser was applied at sowing using a cone seeder with 100 kg of Agstar Extra /ha, giving a rate (kg/ha) of: 14.1 N, 14.2 P, 9.2 S, 0.10 Cu, 0.20 Zn. As it was hypothesised that soil water repellence can limit soil mineralisation and crop nutrient uptake by increasing soil dryness and limiting soil moisture distribution, supplementary fertiliser treatments (nil, N, K, and NK) were broadcast ahead of seeding tines (to allow for incorporation at sowing) at a rate of 40 kg N/ha as urea (46% N) and 40 kg K/ha as muriate of potash (MOP, 49% K). Note, N and K fertiliser treatments were applied since the site was reported to respond well to N and K (Stephen Davies, personal communication). Given the effect of soil dryness on soil mineralisation and nutrient availability, the potential effects of soil water repellence on canola growth and N and K nutrition were thus assessed.

Meckering

Wheat cv. Scepter was grown over 168 days, from 30 May to 14 November 2017, on a water-repellent grey deep sandy duplex soil (Grey Bleached-Ferric Kandosol, ASC) at Meckering to assess the effect of supplementary nitrogen (N) and potassium (K) treatments on crop growth and nutrition. Four treatment combinations (nil, N, K, and NK treatments) and four replications were applied over a total of 16 plots (10 × 2 m) in a randomised block design (see Appendix C.1.3). Basal fertiliser was applied by the farmer with an elemental application rate of 24 kg N/ha, 25 kg K/ha, and 12 kg P/ha at sowing and additional 16 kg N/ha applied during tillering. Supplementary N and K fertiliser treatments were applied 22 days after sowing (DAS) at a rate of 40 kg N/ha as urea (46% N) and 40 kg K/ha as muriate of potash (MOP, 49% K). Since marginal K deficiencies were observed in 2016 soil tests (i.e., critical range of 39-45 mg/kg; Anderson *et al.* 2015) and in wheat leaf tissue tests (i.e., marginal range of 1.5-2.3 %; Reuter and Robinson 1997), it was hypothesised that supplementary fertilisers would be required to overcome limited crop nutrition on water-repellent soil. Note that this was conducted as a supplementary study with no treatments for managing soil water repellence.

4.2.3 Soil sampling and analysis

At all three study sites, soil cores were collected in each plot at 0-5 and 5-10 cm depths to assess for gravimetric soil water content and potential soil water repellence severity at three specific crop growth stages (Table 21).

Table 21. Sampling (days after sowing, DAS) at different crop growth stages in 2017. Decimal growth scales provided for canola (Edwards and Hertel 2011) and wheat (Zadoks et al. 1974).

Plant (study site)	Growth stage	DAS
Wheat (Badgingarra)	Z12: Emergence*	25
	Z21: Tillering	64
	Z65-67: Anthesis†$^{\Delta}$	113
Canola (Moora)	0.8: Emergence*	15
	1.10: Leaf production	53
	4.8: Anthesis†	106
Wheat (Meckering)	Z12: Emergence*	22
	Z21: Tillering	59
	Z65-67: Anthesis†	112

*Soil samples analysed for N, P, and K.
†Plant samples analysed for nutrient composition.
$^{\Delta}$Root samples analysed for root length density.

Gravimetric soil water contents (%) were determined in the laboratory (Rowell 1994). The 'potential' soil water repellence severity of all soil samples (air-dried at 40°C and sieved to <2mm) was assessed in the laboratory using the molarity of ethanol droplet, MED, test (King 1981). Soil water repellence severity was denoted by the MED concentration that penetrated the soil surface within 10 seconds.

Soil ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), Colwell phosphorus (P), and Colwell potassium (K) at the 0-10 cm depth were analysed on bulk samples collected during crop emergence using standard methods (Rayment and Lyons 2011) by the CSBP Soil and Plant Analysis Laboratory.

4.2.4 Plant sampling and analysis

At Badgingarra and Meckering, wheat emergence (two-leaf stage; 25 and 22 DAS, respectively) and stem density (anthesis; 113 and 112 DAS, respectively) were assessed within an area of 1 m × 3 rows (row spacing of 25.4 cm at Badgingarra and 31 cm at Meckering), with whole shoots harvested by hand cuts to determine shoot dry matter (anthesis). Nutrient concentrations in whole shoots (anthesis) were analysed using standard methods (Rayment and Lyons 2011) by the CSBP Soil and Plant Analysis Laboratory. Total nutrient uptake was also determined from shoot dry matter and are expressed in terms of mass per plant (data presented in Appendix C.3). At crop maturity, wheat was harvested with a plot harvester at Badgingarra (166 DAS) and by hand cutting quadrats at Meckering (168 DAS) to assess for grain yield, 1000-grain weight, grain protein, and grain moisture content. However, note that grain data at Badgingarra was only available for the control, spading, and clay treatments from the larger trial area due to the limited size for harvesting micro-plots therein. Based on hand harvest cuts, wheat head density was also assessed at Meckering (168 DAS) but not at Badgingarra.

At Moora, canola plant density, shoot dry matter, shoot nutrient concentrations, and total nutrient uptake were assessed during anthesis (106 DAS) within an area of 1 m × 3 rows (row spacing of 22 cm). Canola plants were harvested at maturity with a plot harvester (181 DAS) and assessed for seed yield, 1000-seed weight, seed protein, seed moisture, and seed oil content.

4.2.5 Root sampling and analysis

Roots were assessed in control, spading, and wetter treatments at Badgingarra, during anthesis (for maximum root development) to determine the effect of soil water repellence and other potential subsoil constraints on root growth. Wheat root length was quantified in the furrow and inter-row at four depths (0-5, 5-10, 10-15, and 15-20 cm). Roots were extracted using a 20 cm long and 6.2 cm diameter coring tube (i.e., 151 cm^3 sample volume) and a sharp knife to separate the four depths into plastic sealable bags. Three cores were collected from the furrow and inter-row of each treatment and across the three treatment replications. Root samples were rinsed in water, stored in vials containing 50% (v/v) ethanol, and refrigerated at 4°C. Root length (cm) was assessed by the WinRHIZO image analysis software (version 2005c; Regent Instruments Inc., Canada) with results presented as root length per cubic centimetre of soil (i.e., root length density, RLD, cm/cm^3).

4.2.6 Statistical analysis

Parametric statistical analyses were carried out using SPSS Statistics version 21.0 (IBM Corporation, Armonk, NY, USA) to determine the effect(s) of: (a) tillage (spading and one-way plough), (b) blanket-applied wetter, (c) clay spreading, and/or (d) supplementary fertiliser treatments on either wheat or canola growth, nutrition, and crop yield parameters. Assumptions of normality and homogeneity of variances were assessed and, where the assumptions were violated, data were transformed using a $\log_{10}$ transformation. Main effects and interactions for soil nutrient concentrations, crop shoot growth, crop nutrition, and crop yield parameters were analysed using the univariate analysis of variance, ANOVA (two-tail) test in SPSS. Soil water content and soil water repellence severity were analysed in a mixed model ANOVA in SPSS due to repeated measures for sampling depth and growth stage (within-subjects variable). Post hoc analysis was performed using Fisher's least significant difference (LSD) at $P < 0.05$ to determine significant differences among treatment factors.

4.3 Results

4.3.1 Badgingarra

Soil water repellence

Results from a mixed model ANOVA showed that soil water repellence severity (i.e., MED), was significantly affected by the four-way interaction of spading × blanket-applied wetter × clay spreading × growth stage ($P < 0.05$; see Appendix C.2.1). In control treatments (i.e., no spading, no wetter, and no clay), soil water repellence severity significantly decreased from emergence (MED 1.1; slight to moderately repellent; 25 DAS) to tillering (MED 0.6; slightly repellent; 64 DAS) and persisted at this level during anthesis (MED 0.6; slightly repellent; 113 DAS; Table 22). Spading treatments alone (no wetter and no clay) significantly decreased soil water repellence severity during emergence (from MED 1.1 to 0.2), tillering (from MED 0.6 to 0.0), and anthesis (from MED 0.6 to 0.1) relative to non-spaded treatments (Table 22). Blanket-applied wetter treatments alone (no spading and no clay) significantly decreased soil water repellence severity only during emergence (from MED 1.1 to 0.2; Table 22). Clay spreading treatments alone (no spading and no wetter) significantly decreased soil water repellence severity during emergence (from MED 1.1 to 0.5) and tillering (from MED 0.6 to 0.3; Table 22). However, no further reduction in soil water repellence severity was observed when treatments were applied in combination.

Soil water repellence severity was also significantly affected by the three-way interaction of spading × clay spreading × sampling depth ($P < 0.005$; see Appendix C.2.1). Clay spreading alone (no spading) significantly decreased soil water repellence severity at the 0-5 cm depth (from MED 0.6 to 0.1), but soil water repellence severity at the 5-10 cm depth was not affected by clay spreading unless applied in combination with spading (from MED 0.5 to 0.1; Table 23). Nevertheless, spading alone significantly decreased soil water repellence severity at the 0-5 and 5-10 cm depths (from MED 0.5-0.6 to 0.1; Table 23).

Table 22. Effect of spading, blanket-applied wetter, and clay spreading on soil water repellence severity (molarity of ethanol droplet, MED) in the furrow at the 0-10 cm depth during wheat emergence (25 DAS), tillering (64 DAS), and anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at P < 0.05.

Growth stage	Non-spaded				Spaded			
	Non-wetter		Wetter		Non-wetter		Wetter	
	Non-clayed	Clayed	Non-clayed	Clayed	Non-clayed	Clayed	Non-clayed	Clayed
Emergence	$1.1^{a\dagger\Delta*}$	0.5^{a}	0.2^{a}	0.3^{a}	0.2^{a}	0.2^{a}	0.2^{a}	0.1^{a}
Tillering	$0.6^{b\dagger*}$	0.3^{a}	$0.5^{a\dagger*}$	0.2^{a}	0.1^{a}	0.1^{a}	0.0^{a}	0.0^{a}
Anthesis	$0.6^{b\dagger}$	0.3^{a}	0.3^{a}	0.2^{a}	0.0^{a}	0.0^{a}	0.1^{a}	0.0^{a}

Different superscript letters denote significant differences within growth stages ($P < 0.05$).
† Significantly different from spaded treatments ($P < 0.05$).
$^{\Delta}$ Significantly different from wetter treatments ($P < 0.05$).
* Significantly different from clayed treatments ($P < 0.05$).

Table 23. Effect of spading and clay spreading on soil water repellence severity (molarity of ethanol droplet, MED) in the furrow at the 0-5 and 5-10 cm depths at Badgingarra in 2017. Mean values based on a sample size of 54. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Non-spaded		Spaded	
	Non-clayed	Clayed	Non-clayed	Clayed
0-5 cm	$0.6^{\dagger\Delta}$	0.1^{*}	0.1	0.0
5-10 cm	$0.5^{\dagger}$	$0.5^{\dagger}$	0.1	0.1

† Significantly different from spaded treatments ($P < 0.05$).
$^{\Delta}$ Significantly different from clayed treatments ($P < 0.05$).
* Significantly different from the 5-10 cm depth ($P < 0.05$).

Soil water content

Results from a mixed model ANOVA showed that gravimetric soil water content was significantly affected by the three-way interaction of spading × clay spreading × sampling depth ($P < 0.001$; see Appendix C.2.1). In general, soil water content was significantly greater at the 0-5 cm depth (7.8-9.1 %) than at the 5-10 cm depth (5.8-7.2 %; Table 24), regardless of spading or clay spreading. Either treatment of clay spreading or spading alone significantly increased soil water content at the 0-5 cm depth (from 7.8 to 8.6-8.7 %; Table 24), but soil water content at the 5-10 cm depth was not affected unless treatments were applied in combination (increased from 5.8 to 7.2 %). There was no effect of blanket-applied wetter or supplementary K fertiliser treatments on soil water content.

Table 24. Effect of spading and clay spreading on soil water content (%, w/w) in the furrow at the 0-5 and 5-10 cm depths at Badgingarra in 2017. Mean values based on a sample size of 54. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Non-spaded		Spaded	
	Non-clayed	Clayed	Non-clayed	Clayed
0-5 cm	$7.8^{*\dagger\Delta}$	8.7^{*}	8.6^{*}	9.1^{*}
5-10 cm	6.0	$5.8^{\dagger}$	6.5^{Δ}	7.2

† Significantly different from spaded treatments ($P < 0.05$).
$^{\Delta}$ Significantly different from clayed treatments ($P < 0.05$).
* Significantly different from the 5-10 cm depth ($P < 0.05$).

Soil water content was also significantly affected by the three-way interaction of clay spreading × sampling depth × growth stage ($P < 0.05$; see Appendix C.2.1). Soil water content was also significantly greater at the 0-5 cm depth (7.8-9.3 %) than at the 5-10 cm depth (5.6-7.6 %; Table 25), regardless of clay spreading and growth stage. In general, soil water content at the 0-5 and 5-10 cm depths was significantly greater during wheat tillering (7.3-8.9 %; 64 DAS) than during emergence (5.6-7.8 %; 25 DAS) or anthesis (5.9-8.0 %; 113 DAS; Table 25), except in clayed treatments whereby soil water content at the 0-5 cm depth was significantly greater during emergence (9.2 %) and tillering (9.3 %) than during anthesis (8.2 %). Clay spreading did not affect soil water content at the 0-5 and 5-10 cm depths (Table 25), except during wheat emergence (25 DAS) whereby soil water content at the 0-5 cm depth was significantly greater in clayed treatments (9.2 %) than in non-clayed treatments (7.8 %).

Table 25. Effect of clay spreading on soil water content (%, w/w) in the furrow at the 0-5 and 5-10 cm depths during wheat emergence (25 DAS), tillering (64 DAS), and anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 36. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Non-clayed			Clayed		
	Emergence	Tillering	Anthesis	Emergence	Tillering	Anthesis
0-5 cm	$7.82^{a\Delta}*$	$8.85^{b}*$	$7.95^{a}*$	$9.17^{a}*$	$9.34^{a}*$	$8.22^{b}*$
5-10 cm	5.57^{a}	7.31^{b}	5.90^{a}	5.77^{a}	7.57^{b}	6.12^{a}

Different superscript letters denote significant differences within growth stages ($P < 0.05$).
$^{\Delta}$ Significantly different from clayed treatments ($P < 0.05$).
* Significantly different from the 5-10 cm depth ($P < 0.05$).

Early season soil N, P, and K availability

Soil NH_4-N, NO_3-N, Colwell P, and Colwell K concentrations in the furrow at 0-10 cm were assessed during wheat emergence (25 DAS) at Badgingarra. Results showed that soil NH_4-N, Colwell P, and Colwell K concentrations were significantly affected by the two-way interaction of spading × clay spreading ($P < 0.05$; Table 26). Clay spreading alone significantly increased soil NH_4-N (from 8 to 15 mg NH_4-N/kg), Colwell P (from 15 to 19 mg P/kg), and Colwell K (from 22 to 34 mg K/kg; Table 27) concentrations at the 0-10 cm depth. However, in clayed treatments, spading significantly decreased soil NH_4-N (from 15 to 8 mg NH_4-N/kg) and Colwell P (from 19 to 14 mg P/kg; Table 27) concentrations at the 0-10 cm depth. Spading alone did not affect soil NH_4-N and Colwell P concentrations at the 0-10 cm. Soil Colwell K concentration in the furrow at the 0-10 cm depth was not affected by spading treatments, regardless of clay spreading.

Table 26. Analysis of variance test (F values with significance level) for main effects and interactions between spading, blanket-applied wetter, clay spreading, and supplementary K fertiliser treatments on soil ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), Colwell phosphorus (P), and Colwell potassium (K) concentrations in the furrow at the 0-10 depth during wheat emergence (25 DAS) at Badgingarra in 2017. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil NH_4-N	Soil NO_3-N	Soil Colwell P	Soil Colwell K
Spading	2 ^{ns}	6*	3 ^{ns}	0 ^{ns}
Wetter	0 ^{ns}	1 ^{ns}	2 ^{ns}	0 ^{ns}
Clay	1 ^{ns}	3 ^{ns}	0 ^{ns}	6*
Fertiliser	0 ^{ns}	0 ^{ns}	0 ^{ns}	5**
Spading × Wetter	4 ^{ns}	0 ^{ns}	9***	2 ^{ns}
Spading × Clay	10***	3 ^{ns}	8**	5*
Spading × Fertiliser	0 ^{ns}	1 ^{ns}	0 ^{ns}	1 ^{ns}
Wetter × Clay	0 ^{ns}	4 ^{ns}	1 ^{ns}	2 ^{ns}
Wetter × Fertiliser	0 ^{ns}	1 ^{ns}	2 ^{ns}	0 ^{ns}
Clay × Fertiliser	0 ^{ns}	0 ^{ns}	2 ^{ns}	0 ^{ns}
Spading × Wetter × Clay	3 ^{ns}	2 ^{ns}	3 ^{ns}	4 ^{ns}
Spading × Wetter × Fertiliser	2 ^{ns}	2 ^{ns}	0 ^{ns}	1 ^{ns}
Spading × Clay × Fertiliser	1 ^{ns}	0 ^{ns}	3 ^{ns}	1 ^{ns}
Wetter × Clay × Fertiliser	1 ^{ns}	0 ^{ns}	0 ^{ns}	1 ^{ns}
Spading × Wetter × Clay × Fertiliser	0 ^{ns}	0 ^{ns}	0 ^{ns}	2 ^{ns}

^{ns} Not significant ($P > 0.05$).

Soil Colwell P concentration in the furrow at the 0-10 cm depth was also significantly affected by the interaction of spading × blanket-applied wetter ($P < 0.005$; Table 26), whereby either spading or blanket-applied wetter treatment alone significantly decreased soil Colwell P concentration at the 0-10 cm depth (from 19 to

14 mg/kg; Table 28). Similarly, soil Colwell P concentration at the 0-10 cm depth also significantly decreased (from 19 to 16 mg/kg; Table 28) when both spading and blanket-applied wetter treatments were applied in combination relative to the control treatment.

Table 27. Effect of spading and clay spreading on soil ammonium-nitrogen (NH_4-N, mg/kg), Colwell phosphorus (P, mg/kg), and Colwell potassium (K, mg/kg) in the furrow at the 0-10 cm depth during wheat emergence (25 DAS) at Badgingarra in 2017. Mean values based on a sample size of 18. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Soil nutrients	Non-spaded		Spaded	
	Non-clayed	Clayed	Non-clayed	Clayed
Soil NH_4-N (mg/kg)	8.4^{a}	14.8^{b}	11.1^{ab}	7.6^{a}
Soil Colwell P (mg/kg)	14.7^{a}	18.7^{b}	16.1^{ab}	13.6^{a}
Soil Colwell K (mg/kg)	21.8^{a}	33.5^{b}	28.4^{ab}	28.7^{ab}

Table 28. Effect of spading and blanket-applied wetter on soil Colwell phosphorus (P, mg/kg) in the furrow at the 0-10 cm depth during wheat emergence (25 DAS) at Badgingarra in 2017. Mean values based on a sample size of 18. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Soil nutrients	Non-spaded		Spaded	
	Non-wetter	Wetter	Non-wetter	Wetter
Soil Colwell P (mg/kg)	19.1^{a}	14.3^{b}	13.9^{b}	15.8^{b}

Spading alone significantly ($P < 0.05$; Table 26) increased soil NO_3-N concentration in the furrow at the 0-10 cm depth (from 12 to 15 mg/kg; Figure 55). Supplementary K1 fertiliser treatment (K application prior to sowing) significantly ($P < 0.01$; Table 26) increased soil Colwell K concentration in the furrow at the 0-10 cm depth (from 26 to 34 mg/kg; Figure 56) relative to the control treatment (K0, no supplementary K). Note that supplementary K2 fertiliser treatment (delayed K application) was not applied until 54 DAS and hence soil Colwell K concentrations (25 DAS) were similar between K0 and K2 treatments.

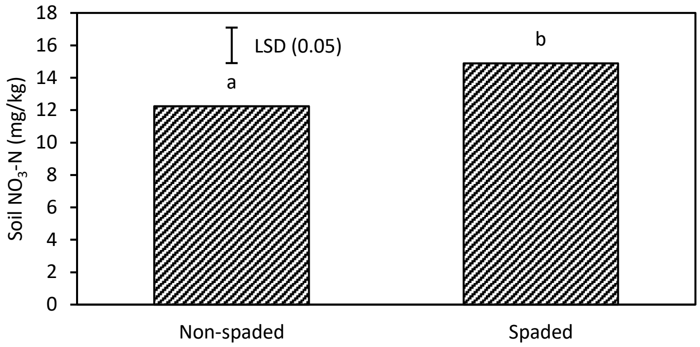

Figure 55. Effect of spading on soil nitrate-nitrogen (NO_3-N, mg/kg) during wheat emergence (25 DAS) at Badgingarra in 2017. Mean values based on a sample size of 36. Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

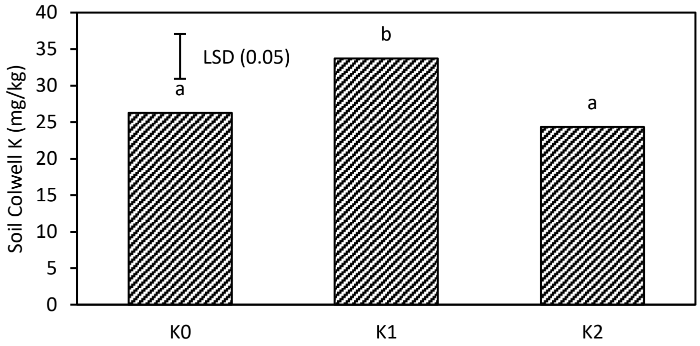

Figure 56. Effect of supplementary fertiliser potassium treatments (K0 = nil, K1 = 40 kg K/ha broadcast prior to sowing, and K2 = 40 kg K/ha broadcast at 54 DAS) on soil Colwell potassium (K, mg/kg) during wheat emergence (25 DAS) at Badgingarra in 2017. Mean values based on a sample size of 24. Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

Crop growth, yield, and quality

Wheat grain yield (166 DAS) was significantly affected by the interaction of spading × clay spreading ($P < 0.05$; Table 29), whereby spading significantly increased grain yield by an average of 47 % (from 1.80-2.11 to 2.73-2.96 t/ha; Table 30), with a more pronounced increase in non-clayed treatments (from 1.80 to 2.96 t/ha; by 64 %) than in clayed treatments (from 2.11 to 2.73 t/ha; by 29 %). However, post-hoc analysis indicated no effect of clay spreading on grain yield, regardless of spading.

Wheat emergence (25 DAS), stem density (113 DAS), and shoot dry matter (113 DAS) were also significantly improved by spading treatments ($P < 0.05$; Table 29; Figures 57a-c), while grain protein content significantly decreased (from 11.3 to 11.0 %; Figure 57d). There were no main treatment effects or interaction effects on wheat 1000-grain weight (37.7-42.9 g) and grain moisture content (12.0-12.5 %). Wetter treatments did not affect wheat emergence, stem density, or shoot dry matter. However, yield parameters were not assessed in wetter treatments due to limited plot size.

Table 29. Analysis of variance test (F values with significance level) for main effects and interactions between spading, blanket-applied wetter, clay spreading, and supplementary K fertiliser treatments on wheat emergence, stem density, shoot dry matter, grain yield, 1000-grain weight, grain protein content, and grain moisture content at Badgingarra in 2017. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Plant emergence	Stem density	Shoot dry matter	Grain yield	1000-grain weight	Grain protein	Grain moisture
Spading	8**	23****	19****	70****	0 ^{ns}	6*	0 ^{ns}
Wetter	3 ^{ns}	4 ^{ns}	0 ^{ns}				
Clay	1 ^{ns}	1 ^{ns}	0 ^{ns}	0 ^{ns}	0 ^{ns}	1 ^{ns}	0 ^{ns}
Fertiliser	0 ^{ns}	0 ^{ns}	0 ^{ns}				
Spading × Wetter	1 ^{ns}	0 ^{ns}	0 ^{ns}				
Spading × Clay	1 ^{ns}	0 ^{ns}	1 ^{ns}	7*	0 ^{ns}	0 ^{ns}	0 ^{ns}
Spading × Fertiliser	0 ^{ns}	1 ^{ns}	0 ^{ns}				
Wetter × Clay	3 ^{ns}	2 ^{ns}	1 ^{ns}				
Wetter × Fertiliser	2 ^{ns}	3 ^{ns}	2 ^{ns}				
Clay × Fertiliser	1 ^{ns}	0 ^{ns}	0 ^{ns}				
Spading × Wetter × Clay	0 ^{ns}	0 ^{ns}	0 ^{ns}				
Spading × Wetter × Fertiliser	2 ^{ns}	1 ^{ns}	1 ^{ns}				
Spading × Clay × Fertiliser	1 ^{ns}	1 ^{ns}	0 ^{ns}				
Wetter × Clay × Fertiliser	0 ^{ns}	0 ^{ns}	0 ^{ns}				
Spading × Wetter × Clay × Fertiliser	1 ^{ns}	1 ^{ns}	1 ^{ns}				

^{ns} Not significant ($P > 0.05$).

Table 30. Effect of spading and clay spreading on wheat grain yield (t/ha; 166 DAS) at Badgingarra in 2017. Mean values based on a sample size of 3. Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

Parameter	Non-spaded		Spaded	
	Non-clayed	Clayed	Non-clayed	Clayed
Grain yield (t/ha)	1.80^{a}	2.11^{a}	2.96^{b}	2.73^{b}

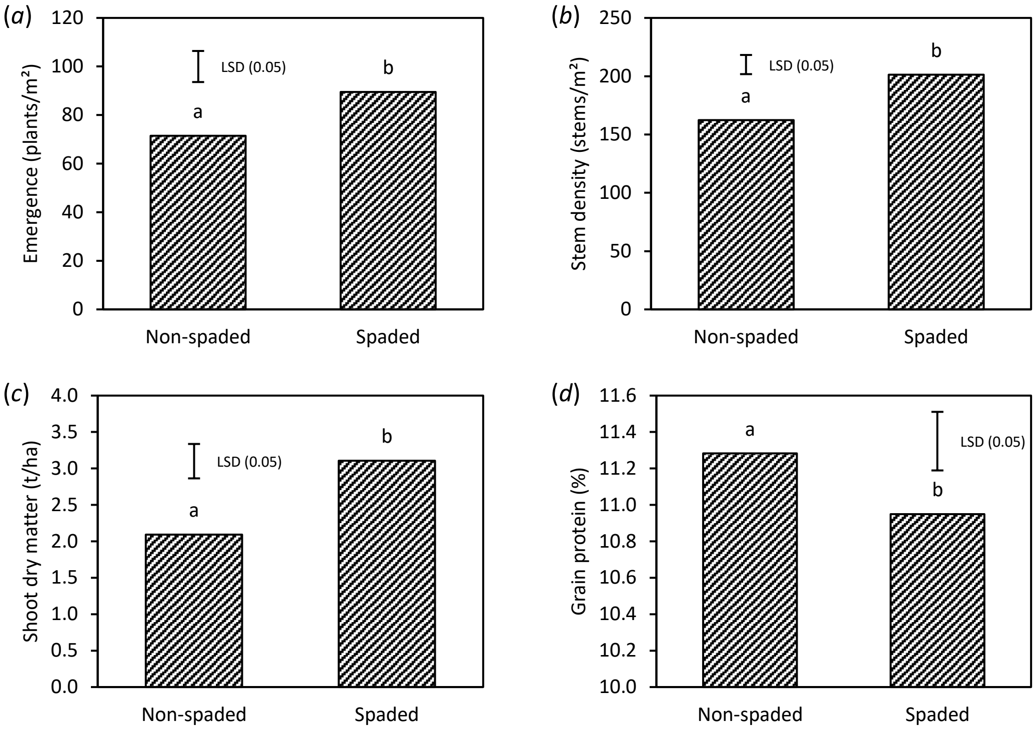

Figure 57. Effect of spading on (a) wheat emergence (25 DAS), (b) stem density (stems/m^2; 113 DAS), (c) shoot dry matter (t/ha; 113 DAS), and grain protein content (%; 166 DAS) at Badgingarra in 2017. Mean values based on a sample size of 36, except for grain protein where the sample size was 6. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Root length density

Wheat root length density (RLD) at the 0-5, 5-10, 10-15, and 15-20 cm at anthesis (113 DAS) was assessed in control, spading, and wetter treatments at Badgingarra. Results from a mixed model ANOVA showed that wheat RLD was significantly affected by the three-way interaction of spading × blanket-applied wetter × sampling row ($P < 0.05$; Table 31). Wheat RLD at the 0-20 cm depth was 66 % greater in the furrow (4.37-4.77 cm/cm^3) than in the inter-row (2.63-2.87 cm/cm^3; Table 32) but only when either spading or blanket wetter treatment was applied. Differences in wheat RLD between sampling rows were not observed in control treatments (no spading and no wetter) or when both treatments were applied in combination. Nevertheless, wheat RLD at the 0-20 cm depth was not significantly affected by either spading or wetter treatments (Table 32).

Table 31. Mixed model analysis of variance test (F values with significance level) for wheat root length density at anthesis (113 DAS) at Badgingarra in 2017, with spading and blanket-applied wetter treatments as between-subjects variables and a repeated measure for sampling row and sampling depth as the within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	*F*
Spading	0 ^{ns}
Wetter	1 ^{ns}
Row	42****
Depth	31****
Spading × Wetter	0 ^{ns}
Spading × Row	0 ^{ns}
Spading × Depth	2 ^{ns}
Wetter × Row	0 ^{ns}
Wetter × Depth	0 ^{ns}
Row × Depth	57****
Spading × Wetter × Row	5*
Spading × Wetter × Depth	0 ^{ns}
Spading × Row × Depth	3 ^{ns}
Wetter × Row × Depth	2 ^{ns}
Spading × Wetter × Row × Depth	1 ^{ns}

^{ns} Not significant ($P > 0.05$).

Wheat RLD was significantly affected by the two-way interaction of sampling row × sampling depth ($P < 0.05$; Table 31), whereby wheat RLD at the 0-5 and 5-10 cm depths was significantly greater in the furrow (4.89 and 6.48 cm/cm^3, respectively) than in the inter-row by 279 and 76 %, respectively (1.29 and 3.68 cm/cm^3, respectively; Table 33), while wheat RLD at the 15-20 cm depth was significantly greater in the inter-row (3.14 cm/cm^3) than in the furrow by 32 % (2.37 cm/cm^3). Wheat RLD at the 10-15 cm depth was not different between sampling rows (Table 33). Wheat RLD in the furrow was significantly greater at the 0-5 (4.89 cm/cm^3) and 5-10 cm depths (6.48 cm/cm^3) than at the 10-15 (3.89 cm/cm^3; by 26 and 67 %, respectively) and 15-20 cm depths (2.37 cm/cm^3; by 106 and 173 %, respectively; Table 33), but wheat RLD in the inter-row was significantly greater at the 10-15 (4.17 cm/cm^3) and 15-20 cm depths (3.14 cm/cm^3) than at the 0-5 cm depth (1.29 cm/cm^3; by 223 and 143 %, respectively).

Table 32. Effect of spading and blanket-applied wetter on wheat root length density (RLD, cm/cm^3) in the furrow and inter-row at the 0-20 cm depth during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 12. Significant differences based on the least significant difference (LSD) at P < 0.05.

Row	Non-spaded		Spaded	
	Non-wetter	Wetter	Non-wetter	Wetter
Furrow	3.99	4.77*	4.37*	4.50
Inter-row	3.18	2.87	2.63	3.59

† Significantly different from spaded treatments (P < 0.05).
$^\Delta$ Significantly different from wetter treatments (P < 0.05).
* Significantly different from the inter-row (P < 0.05).

Table 33. Wheat root length density (RLD, cm/cm^3) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 12. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Furrow	Inter-row
0-5 cm	4.89^{a†}	1.29^{a}
5-10 cm	6.48^{b†}	3.68^{bc}
10-15 cm	3.89^{c}	4.17^{b}
15-20 cm	2.37^{d†}	3.14^{c}

Different superscript letters denote significant differences within sampling depths (P < 0.05).
† Significantly different from the inter-row (P < 0.05).

Shoot nutrient concentrations

Nutrient concentrations in wheat whole shoots during anthesis (113 DAS) indicted that plants were relatively deficient in N (<1.8 %), K (<1.5 %), Mg (<0.15 %), B (<6 mg/kg), and Cu (<5 mg/kg; Reuter and Robinson 1997; Appendix A.2), with some plants also deficient in P (<0.15 %), S (<0.15 %), and Zn (<15 mg/kg). Shoot N concentrations were significantly affected by the three-way interaction of spading × blanket-applied wetter × supplementary K fertiliser treatments (*P* < 0.05; Table 34). Spading or blanket-applied wetter treatment alone significantly decreased shoot N concentrations (from 1.77 to 1.41-1.42 %; Table 35), but either treatment did not affect shoot N concentrations when supplementary K1 and K2 fertiliser treatments were applied. Supplementary K1 treatments alone also significantly decreased shoot N concentrations (from 1.77 to 1.52 %; Table 35) relative to control treatments, but supplementary K2 treatments (1.66 %) had no effect on shoot N concentrations.

Shoot N, S, B, and Zn concentrations were significantly affected by the two-way interaction of blanket-applied wetter × clay spreading (*P* < 0.05; Table 34). Blanket-applied wetter treatments alone significantly decreased shoot N (1.66 to 1.48 %), S (0.16 to 0.14 %), and Zn (16.0 to 13.4 mg/kg; Table 36) concentrations, but wetter treatments had no effect on shoot N, S, and Zn concentrations when clay was applied. Shoot B concentrations were not affected by wetter treatments, regardless of clay spreading. Likewise, clay spreading alone significantly decreased shoot N (1.66 to 1.45 %), S (0.16 to 0.14 %), B (3.31 to 3.04 mg/kg), and Zn (16.0 to 13.4 mg/kg; Table 36) concentrations, but clay spreading had no effect on shoot N, S, B, and Zn concentrations when wetter was applied.

Table 34. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between spading, blanket-applied wetter, clay spreading, and supplementary K fertiliser treatments on wheat whole shoot nutrient concentrations during wheat anthesis (113 DAS) at Badgingarra in 2017. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Whole shoot nutrient concentration					
	N	P	K	Ca	Mg	S
Spading	10***	4^{ns}	9***	9***	1^{ns}	12***
Wetter	4^{ns}	2^{ns}	4*	0^{ns}	0^{ns}	4^{ns}
Clay	8**	20****	3^{ns}	14****	1^{ns}	4*
Fertiliser	0^{ns}	0^{ns}	25****	8***	9****	2^{ns}
Spading × Wetter	3^{ns}	1^{ns}	1^{ns}	2^{ns}	2^{ns}	1^{ns}
Spading × Clay	1^{ns}	0^{ns}	1^{ns}	3^{ns}	1^{ns}	2^{ns}
Spading × Fertiliser	0^{ns}	0^{ns}	0^{ns}	0^{ns}	1^{ns}	0^{ns}
Wetter × Clay	7**	2^{ns}	4^{ns}	0^{ns}	1^{ns}	6*
Wetter × Fertiliser	2^{ns}	2^{ns}	0^{ns}	3^{ns}	2^{ns}	3*
Clay × Fertiliser	1^{ns}	1^{ns}	1^{ns}	0^{ns}	0^{ns}	2^{ns}
Spading × Wetter × Clay	0^{ns}	0^{ns}	0^{ns}	0^{ns}	0^{ns}	0^{ns}
Spading × Wetter × Fertiliser	4*	2^{ns}	1^{ns}	1^{ns}	1^{ns}	3^{ns}
Spading × Clay × Fertiliser	1^{ns}	0^{ns}	1^{ns}	0^{ns}	0^{ns}	0^{ns}
Wetter × Clay × Fertiliser	2^{ns}	1^{ns}	1^{ns}	0^{ns}	2^{ns}	0^{ns}
Spading × Wetter × Clay × Fertiliser	2^{ns}	1^{ns}	1^{ns}	3^{ns}	2^{ns}	2^{ns}

Source of variation	Whole shoot nutrient concentration					
	Na	B	Cu	Fe	Mn	Zn
Spading	35****	0^{ns}	42****	12***	18****	23****
Wetter	0^{ns}	0^{ns}	3^{ns}	0^{ns}	1^{ns}	8**
Clay	4*	4*	10***	24****	1^{ns}	7*
Fertiliser	0^{ns}	1^{ns}	0^{ns}	1^{ns}	1^{ns}	0^{ns}
Spading × Wetter	0^{ns}	4*	1^{ns}	0^{ns}	0^{ns}	0^{ns}
Spading × Clay	0^{ns}	0^{ns}	2^{ns}	9***	0^{ns}	0^{ns}
Spading × Fertiliser	2^{ns}	1^{ns}	0^{ns}	1^{ns}	0^{ns}	0^{ns}
Wetter × Clay	2^{ns}	5*	3^{ns}	1^{ns}	0^{ns}	9***
Wetter × Fertiliser	1^{ns}	0^{ns}	3^{ns}	3^{ns}	1^{ns}	7***
Clay × Fertiliser	0^{ns}	1^{ns}	2^{ns}	0^{ns}	0^{ns}	2^{ns}
Spading × Wetter × Clay	1^{ns}	1^{ns}	0^{ns}	0^{ns}	0^{ns}	0^{ns}
Spading × Wetter × Fertiliser	1^{ns}	2^{ns}	1^{ns}	1^{ns}	0^{ns}	1^{ns}
Spading × Clay × Fertiliser	0^{ns}	1^{ns}	0^{ns}	1^{ns}	0^{ns}	0^{ns}
Wetter × Clay × Fertiliser	0^{ns}	1^{ns}	1^{ns}	1^{ns}	1^{ns}	0^{ns}
Spading × Wetter × Clay × Fertiliser	0^{ns}	2^{ns}	3^{ns}	1^{ns}	0^{ns}	1^{ns}

^{ns} Not significant ($P > 0.05$).

Table 35. Effect of spading, blanket-applied wetter, and supplementary K fertiliser (K0 = nil, K1 = 40 kg K/ha broadcast prior to sowing, and K2 = 40 kg K/ha broadcast at 54 DAS) on whole shoot N concentrations (%) in wheat during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 6. Significant differences based on the least significant difference (LSD) at P < 0.05.

Supplementary fertiliser	Non-spaded		Spaded	
	Non-wetter	Wetter	Non-wetter	Wetter
K0	$1.77^{a\dagger\Delta}$	1.41^{a}	1.42^{a}	1.49^{a}
K1	1.52^{b}	1.59^{a}	1.46^{a}	1.46^{a}
K2	1.66^{ab}	1.52^{a}	1.51^{a}	1.41^{a}

Different superscript letters denote significant differences within fertiliser treatments ($P < 0.05$).

[†] Significantly different from spaded treatments ($P < 0.05$).

[Δ] Significantly different from wetter treatments ($P < 0.05$).

Table 36. Effect of blanket-applied wetter and clay spreading on whole shoot N, S, B, and Zn concentrations in wheat during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentrations	Non-wetter		Wetter	
	Non-clayed	Clayed	Non-clayed	Clayed
N (%)	$1.66^{\dagger\Delta}$	1.45	1.48	1.48
S (%)	$0.16^{\dagger\Delta}$	0.14	0.14	0.14
B (mg/kg)	3.31^{Δ}	3.04	3.15	3.16
Zn (mg/kg)	$16.0^{\dagger\Delta}$	13.4	13.4	13.5

[†] Significantly different from wetter treatments ($P < 0.05$).

[Δ] Significantly different from clayed treatments ($P < 0.05$).

Shoot Fe concentrations were significantly affected by the two-way interaction of spading × clay spreading ($P < 0.005$; Table 34), whereby clay spreading alone significantly increased shoot Fe concentrations (from 50.4 to 71.7 mg/kg; Table 37), but clay spreading had no effect in spaded treatments.

Table 37. Effect of spading and clay spreading on whole shoot Fe concentrations in wheat during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentrations	Non-spaded		Spaded	
	Non-clayed	Clayed	Non-clayed	Clayed
Fe (mg/kg)	50.4^{Δ}	$71.7^{\dagger}$	49.2	54.2

[†] Significantly different from spaded treatments ($P < 0.05$).

[Δ] Significantly different from clayed treatments ($P < 0.05$).

Shoot S and Zn concentrations were significantly affected by the two-way interaction of blanket-applied wetter × supplementary K fertiliser treatments ($P < 0.05$; Table 34). Wetter treatment alone significantly decreased shoot Zn concentrations (from 15.1 to 13.2 mg/kg; Table 38) but did not affect shoot S concentrations. In supplementary K1 treatments, shoot S and Zn concentrations were not affected by blanket-applied wetter treatments. However, in supplementary K2 treatments, wetter treatment significantly decreased shoot S (from 0.15 to 0.14 %) and Zn (from 15.6 to 12.6 mg/kg; Table 38) concentrations. Supplementary K1 treatment alone also significantly decreased shoot S (from 0.16 to 0.14 %) and Zn (from 15.1 to 13.4 mg/kg; Table 38) concentrations relative to the control treatment. However, when wetter was applied, there was generally no effect of supplementary K fertiliser on shoot S and Zn concentrations. Wetter treatments also significantly (*P* < 0.05; Table 34) decreased shoot K concentrations (from 1.08 to 1.01 %).

Table 38. Effect of blanket-applied wetter and supplementary K fertiliser (K0 = nil, K1 = 40 kg K/ha broadcast prior to sowing, and K2 = 40 kg K/ha broadcast at 54 DAS) on whole shoot N concentrations in wheat during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 12. Significant differences based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	Non-wetter			Wetter		
	K0	K1	K2	K0	K1	K2
S (%)	0.16^{a}	0.14^{b}	$0.15^{a\dagger}$	0.14^{a}	0.14^{a}	0.14^{a}
Zn (mg/kg)	$15.1^{a\dagger}$	13.4^{b}	$15.6^{a\dagger}$	13.2^{ab}	14.4^{a}	12.6^{b}

Different superscript letters denote significant differences within fertiliser treatments (*P* < 0.05).
† Significantly different from wetter treatments (*P* < 0.05).

In general, spading significantly (*P* < 0.005; Table 34) increased shoot K concentrations (from 0.99 to 1.09 %; Table 39) but decreased shoot Ca (from 0.32 to 0.28 %), S (from 0.15 to 0.14 %), Na (from 0.03 to 0.02 %), Cu (from 2.13 to 1.63 mg/kg), Mn (from 56.0 to 39.1 mg/kg), and Zn (from 15.2 to 13.0 mg/kg) concentrations. Clay spreading alone significantly (*P* < 0.05; Table 34) decreased shoot P (from 0.18 to 0.15 %), Ca (from 0.32 to 0.28 %), Na (from 0.03 to 0.02 %), and Cu (from 2.00 to 1.76 mg/kg; Table 40) concentrations. Supplementary K fertiliser treatments alone also significantly (*P* < 0.005; Table 34) increased shoot K concentrations (from 0.89 to 1.08-1.16 %; Table 41) but decreased shoot Ca (from 0.33 to 0.28-0.29 %) and Mg (from 0.13 to 0.12 %) concentrations.

Table 39. Effect of spading on whole shoot nutrient concentrations in wheat during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 36. Significant differences based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	Non-spaded	Spaded
K (%)	0.99[†]	1.09
Ca (%)	0.32[†]	0.28
S (%)	0.15[†]	0.14
Na (%)	0.03[†]	0.02
Cu (mg/kg)	2.13[†]	1.63
Mn (mg/kg)	56.0[†]	39.1
Zn (mg/kg)	15.2[†]	13.0

[†] Significantly different from spaded treatments (*P* < 0.05).

Table 40. Effect of spading on whole shoot nutrient concentrations in wheat during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 36. Significant differences based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	Non-clayed	Clayed
P (%)	0.18[†]	0.15
Ca (%)	0.32[†]	0.28
Na (%)	0.03[†]	0.02
Cu (mg/kg)	2.00[†]	1.76

[†] Significantly different from spaded treatments (*P* < 0.05).

Table 41. Effect of supplementary K fertiliser treatments (K0 = nil, K1 = 40 kg K/ha broadcast prior to sowing, and K2 = 40 kg K/ha broadcast at 54 DAS) on whole shoot nutrient concentrations in wheat during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 24. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	K0	K1	K2
K (%)	0.89^a	1.08^b	1.16^c
Ca (%)	0.33^a	0.29^b	0.28^b
Mg (%)	0.13^a	0.12^b	0.12^b

4.3.2 Moora

Soil water repellence

Results from a mixed model ANOVA showed that soil water repellence severity was significantly affected by the three-way interaction of blanket-applied wetter × sampling depth × growth stage (*P* < 0.001; see Appendix C.2.2). In soil untreated by wetter, soil water repellence severity in the furrow at the 0-5 cm depth significantly decreased from canola emergence (MED 2.8; severely repellent; 15 DAS) to leaf production (MED 2.2; moderate repellent; 53 DAS), with similar levels persisting during anthesis (MED 2.4; moderately repellent; 106 DAS; Table 42). Soil water repellence severity in the furrow was significantly lower at the 5-10 cm depth (MED

0.3-0.7; slightly repellent) than at the 0-5 cm depth (MED 1.0-2.8; slight to severely repellent; Table 42), regardless of wetter treatments and growth stage. However, soil water repellence severity in the furrow at the 5-10 cm depth was relatively similar between emergence and anthesis. Blanket-applied wetter treatments significantly decreased soil water repellence severity in the furrow at the 0-5 cm depth during emergence (from MED 2.8 to 1.0; 15 DAS) and leaf production (from MED 2.2 to 1.5; 53 DAS; Table 42) but had no effect during anthesis (106 DAS). At the 5-10 cm depth, however, wetter treatments only decreased soil water repellence severity during emergence (from MED 0.6 to 0.4; Table 42). In these wetter treatments, soil water repellence severity at the 0-5 and 5-10 cm depths significantly increased over time from emergence (MED 1.0 and 0.4, respectively) to anthesis (MED 2.2 and 0.7, respectively; Table 42).

Table 42. Effect of blanket-applied wetter on soil water repellence severity (molarity of ethanol droplet, MED) in the furrow at the 0-5 and 5-10 cm depths during canola emergence (15 DAS), leaf production (53 DAS), and anthesis (106 DAS) at Moora in 2017. Mean values based on a sample size of 24. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Non-wetter			Wetter		
	Emergence	Leaf production	Anthesis	Emergence	Leaf production	Anthesis
0-5 cm	$2.8^{a\dagger\Delta}$	$2.2^{b\dagger\Delta}$	$2.4^{b\Delta}$	$1.0^{a\Delta}$	$1.5^{b\Delta}$	$2.2^{c\Delta}$
5-10 cm	$0.6^{a\dagger}$	0.4^{b}	0.6^{ab}	0.4^{a}	0.3^{a}	0.7^{b}

Different superscript letters denote significant differences within growth stage ($P < 0.05$).

[†] Significantly different from wetter treatments ($P < 0.05$).

[Δ] Significantly different from the 5-10 cm depth ($P < 0.05$).

Soil water repellence severity was significantly affected by the two-way interaction of one-way plough × sampling depth ($P < 0.001$; see Appendix C.2.2). One-way ploughed treatments did not affect soil water repellence severity in the furrow at the 0-5 cm depth but significantly increased soil water repellence severity at the 5-10 cm depth (from MED 0.2 to 0.8; Table 43), albeit at low levels. Nevertheless, soil water repellence severity in the furrow was significantly greater at the 0-5 cm depth (MED 2.0-2.1; moderately repellent) than at the 5-10 cm depth (MED 0.2-0.8; slightly repellent; Table 43), regardless of one-way plough treatment.

Table 43. Effect of one-way plough on soil water repellence severity (molarity of ethanol droplet, MED) in the furrow at the 0-5 and 5-10 cm depths at Moora in 2017. Mean values based on a sample size of 72. Significant differences based on the least significant difference (LSD) at P < 0.05.

Parameter	Non-ploughed		One-way ploughed	
	0-5 cm	5-10 cm	0-5 cm	5-10 cm
Soil MED (M)	2.1^{Δ}	$0.2^{\dagger}$	2.0^{Δ}	0.8

[†] Significantly different from one-way ploughed treatments ($P < 0.05$).

[Δ] Significantly different from the 5-10 cm depth ($P < 0.05$).

Soil water content

Results from a mixed model ANOVA showed that gravimetric soil water content was significantly affected by the three-way interaction of blanket-applied wetter × sampling depth × growth stage ($P < 0.001$; see Appendix C.2.2). Blanket-applied wetter treatment significantly increased soil water content in the furrow at the 0-5 cm depth during canola emergence (from 6.7 to 7.6 %; 15 DAS) and leaf production (from 10.2 to 11.9 %; 53 DAS; Table 44) but did not affect soil water content at the 5-10 cm depth. However, soil water content in the furrow at the 0-5 and 5-10 cm depths significantly increased over time from emergence (6.7-7.6 and 7.1-7.3 %, respectively) to anthesis (12.5-12.7 and 9.1-9.4 %, respectively), regardless of wetter treatment.

Table 44. Effect of blanket-applied wetter on soil water content (%, w/w) in the furrow at the 0-5 and 5-10 cm depths during canola emergence (15 DAS), leaf production (53 DAS), and anthesis (106 DAS) at Moora in 2017. Mean values based on a sample size of 24. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Non-wetter			Wetter		
	Emergence	Leaf production	Anthesis	Emergence	Leaf production	Anthesis
0-5 cm	$6.69^{a\dagger}$	$10.23^{b\dagger\Delta}$	$12.71^{c\Delta}$	7.56^{a}	$11.88^{b\Delta}$	$12.49^{c\Delta}$
5-10 cm	7.05^{a}	8.19^{b}	9.10^{c}	7.26^{a}	8.67^{b}	9.44^{c}

Different superscript letters denote significant differences within growth stage ($P < 0.05$).

[†] Significantly different from wetter treatments ($P < 0.05$).

[Δ] Significantly different from the 5-10 cm depth ($P < 0.05$).

Soil water content was also significantly affected by the two-way interaction of one-way plough × sampling depth ($P < 0.001$; see Appendix C.2.2), whereby one-way plough significantly decreased soil water content at the 0-5 cm depth (from 11.2 to 9.3 %; Table 45) but did not affect soil water content at the 5-10 cm depth.

Table 45. Effect of one-way plough on soil water content (%, w/w) in the furrow at the 0-5 and 5-10 cm depths at Moora in 2017. Mean values based on a sample size of 72. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Parameter	Non-ploughed		One-way ploughed	
	0-5 cm	5-10 cm	0-5 cm	5-10 cm
Soil water (%)	$11.19^{\dagger\Delta}$	8.21	9.33^{Δ}	8.36

† Significantly different from one-way ploughed treatments ($P < 0.05$).
$^{\Delta}$ Significantly different from the 5-10 cm depth ($P < 0.05$).

Early season soil N, P, and K availability

Soil NH_4-N, NO_3-N, Colwell P, and Colwell K concentrations in the furrow at 0-10 cm were assessed during canola emergence (15 DAS) at Moora. Results showed that soil NO_3-N and Colwell K concentrations in the furrow at the 0-10 cm depth were significantly affected by supplementary N and K fertiliser treatments ($P < 0.05$; Table 46) but were not affected by one-way plough or blanket-applied wetter treatments. Soil NO_3-N concentration in the furrow at the 0-10 cm depth was significantly greater in supplementary N treatments (51 mg/kg) than in the control (37 mg/kg), K (34 mg/kg), and NK treatments (41 mg/kg; Table 47), with no differences between the control, K, and NK treatments. Soil Colwell K concentration in the furrow at the 0-10 cm depth was significantly greater in supplementary K (66 mg/kg) and NK treatments (66 mg/kg) than in the control (45 mg/kg) and N treatments (47 mg/kg; Table 47), with no differences between K and NK treatments or the control and N treatments. There were no main treatment effects or interaction effects on soil NH_4-N (5-24 mg/kg) and Colwell P concentration (25-87 mg/kg) in the furrow at the 0-10 cm depth.

Table 46. Analysis of variance test (F values with significance level) for main effects and interactions between one-way plough, blanket-applied wetter, and supplementary fertiliser treatments on soil ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), Colwell phosphorus (P), and Colwell potassium (K) concentrations in the furrow at the 0-10 depth during canola emergence (15 DAS) at Moora in 2017. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil NH_4-N	Soil NO_3-N	Soil Colwell P	Soil Colwell K
Plough	0^{ns}	2^{ns}	0^{ns}	0^{ns}
Wetter	3^{ns}	2^{ns}	1^{ns}	1^{ns}
Fertiliser	3^{ns}	5**	1^{ns}	11****
Plough × Wetter	2^{ns}	0^{ns}	0^{ns}	0^{ns}
Plough × Fertiliser	0^{ns}	1^{ns}	1^{ns}	1^{ns}
Wetter × Fertiliser	1^{ns}	0^{ns}	2^{ns}	1^{ns}
Plough × Wetter × Fertiliser	0^{ns}	1^{ns}	1^{ns}	1^{ns}

$^{\mathrm{ns}}$ Not significant ($P > 0.05$).

Table 47. Effect of supplementary fertiliser treatment on soil nitrate-nitrogen (NO_3-N, mg/kg) and Colwell potassium (K, mg/kg) in the furrow at the 0-10 cm depth during canola emergence (15 DAS) at Moora in 2017. Mean values based on a sample size of 12. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Parameter	Supplementary fertiliser			
	Nil	K	N	NK
Soil NO_3-N (mg/kg)	37.2^a	34.3^a	51.2^b	40.5^a
Soil Colwell K (mg/kg)	45.0^a	65.5^b	47.0^a	65.7^b

Crop growth, yield, and quality

One-way plough significantly (*P* < 0.001; Table 48) increased canola shoot dry matter (from 3.93 to 5.02 t/ha; Figure 58). However, there were no treatment effects or interaction effects on canola plant density (35-102 plants/m^2), seed yield (1.26-3.19 t/ha), 1000-seed weight (3.86-4.43 g), and seed moisture content (5.10-6.30 %).

Table 48. Analysis of variance test (F values with significance level) for main effects and interactions between one-way plough, blanket-applied wetter, and supplementary fertiliser treatments on canola plant density, shoot dry matter, seed yield, 1000-seed weight, seed protein content, seed moisture content, and seed oil content at Moora in 2017. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Source of variation	Plant density	Shoot dry matter	Seed yield	1000-seed weight	Seed protein	Seed moisture	Seed oil
Plough	1^{ns}	23****	0^{ns}	0^{ns}	2^{ns}	1^{ns}	2^{ns}
Wetter	0^{ns}	0^{ns}	1^{ns}	1^{ns}	2^{ns}	0^{ns}	1^{ns}
Fertiliser	1^{ns}	11****	1^{ns}	1^{ns}	5**	0^{ns}	4*
Plough × Wetter	3^{ns}	0^{ns}	0^{ns}	0^{ns}	0^{ns}	0^{ns}	1^{ns}
Plough × Fertiliser	2^{ns}	1^{ns}	1^{ns}	1^{ns}	0^{ns}	0^{ns}	0^{ns}
Wetter × Fertiliser	0^{ns}	2^{ns}	0^{ns}	0^{ns}	1^{ns}	0^{ns}	1^{ns}
Plough × Wetter × Fertiliser	1^{ns}	1^{ns}	3^{ns}	0^{ns}	1^{ns}	0^{ns}	1^{ns}

^{ns} Not significant (*P* > 0.05).

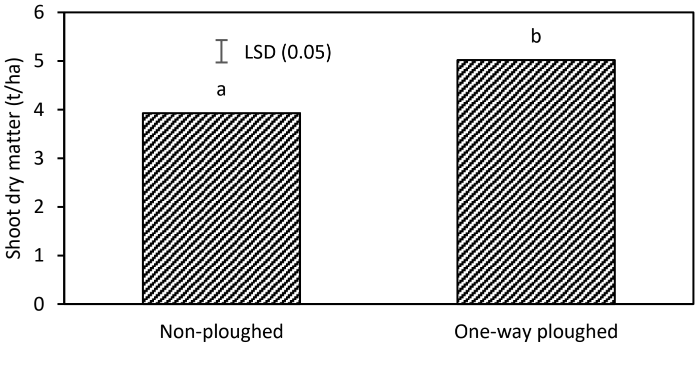

Figure 58. Effect of one-way plough on canola shoot dry matter (t/ha; 106 DAS) at Moora in 2017. Mean values based on a sample size of 24. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Canola shoot dry matter (106 DAS), seed protein content, and seed oil content (181 DAS) was significantly affected by supplementary N and K fertiliser treatments ($P < 0.05$; Table 48). Shoot dry matter was significantly greater in supplementary N (5.11 t/ha) and NK treatments (5.08 t/ha) than in the control (3.56 t/ha; by 44 and 43 %, respectively) and K treatments (4.14 t/ha; by 24 and 23 %, respectively; Table 49), with no differences between N and NK treatments or the control and K treatments. Seed protein content was significantly greater in supplementary N treatments (18.6 %) than in the control (17.4 %), K (17.7 %), and NK treatments (17.8 %; Table 49), with no differences between the control, K, and NK treatments. Seed oil content was significantly greater in the control (48.3 %) and NK treatments (48.2 %) than in N treatments (47.5 %; Table 49), with no differences between N and K treatments, or between the control, K and NK treatments.

Table 49. Effect of supplementary fertiliser treatment on canola shoot dry matter (t/ha; 106 DAS), seed protein content (%; 181 DAS), and seed oil content (%; 181 DAS) at Moora in 2017. Mean values based on a sample size of 12, except for seed protein and oil content where the sample size was 10. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Parameter	Supplementary fertiliser			
	Nil	K	N	NK
Shoot dry matter (t/ha)	3.56^{a}	4.14^{a}	5.11^{b}	5.08^{b}
Seed protein content (%)	17.4^{a}	17.7^{a}	18.6^{b}	17.8^{a}
Seed oil content (%)	48.3^{a}	47.8^{ab}	47.5^{b}	48.2^{a}

Shoot nutrient concentrations

An assessment of nutrient concentrations in canola whole shoots during anthesis (106 DAS) found that canola plants across the site at Moora were relatively deficient in N (<2.7 %), Mn (<30 mg/kg), and Zn (<25 mg/kg; Reuter and Robinson 1997; Appendix A.2), with some plants marginally deficient in P (<0.35 %), K (<2.8 %) and B (<30 mg/kg). In general, shoot N, P, K, Na, Cu, and Zn concentrations were significantly affected by supplementary N and K fertiliser treatments ($P < 0.01$; Table 50). Relative to the control treatment, supplementary N treatments significantly increased shoot N (from 2.01 to 2.16 %) and Na (from 0.16 to 0.30 %; Table 51) concentrations but decreased shoot P concentrations (from 0.38 to 0.34 %). However, supplementary K and NK treatments did not affect shoot N, P, or Na concentrations relative to the control treatment. Both supplementary N and NK treatments significantly increased shoot Cu (from 3.07 to 3.32 and 3.44 mg/kg, respectively) and Zn (from 18.1 to 20.5 and 21.3 mg/kg, respectively; Table 51) concentrations. Supplementary K and NK treatments also significantly increased shoot K concentrations (from 3.21 to 3.47 and 3.64 %, respectively; Table 51). Note, although shoot P concentrations were significantly affected by the three-way interaction of one-way plough × blanket-applied wetter × supplementary fertiliser treatments ($P < 0.05$; Table 50), post-hoc analyses showed no consistent response in shoot P and were thus not reported.

Table 50. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between one-way plough, blanket-applied wetter, and supplementary fertiliser treatments on canola whole shoot nutrient concentrations during anthesis (106 DAS) at Moora in 2017. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Source of variation	Shoot nutrient concentration					
	N	P	K	Ca	Mg	S
Plough	3^{ns}	1^{ns}	2^{ns}	20****	3^{ns}	5*
Wetter	0^{ns}	0^{ns}	0^{ns}	4*	1^{ns}	2^{ns}
Fertiliser	6***	6***	9****	2^{ns}	1^{ns}	0^{ns}
Plough × Wetter	0^{ns}	2^{ns}	0^{ns}	0^{ns}	0^{ns}	1^{ns}
Plough × Fertiliser	0^{ns}	2^{ns}	0^{ns}	0^{ns}	1^{ns}	0^{ns}
Wetter × Fertiliser	2^{ns}	1^{ns}	1^{ns}	3^{ns}	1^{ns}	1^{ns}
Plough × Wetter × Fertiliser	0^{ns}	4*	0^{ns}	1^{ns}	0^{ns}	1^{ns}
Source of variation	Shoot nutrient concentration					
	Na	B	Cu	Fe	Mn	Zn
Plough	3^{ns}	15****	9***	0^{ns}	3^{ns}	5*
Wetter	0^{ns}	0^{ns}	2^{ns}	0^{ns}	1^{ns}	3^{ns}
Fertiliser	15****	1^{ns}	5**	1^{ns}	1^{ns}	5***
Plough × Wetter	0^{ns}	0^{ns}	0^{ns}	0^{ns}	0^{ns}	0^{ns}
Plough × Fertiliser	2^{ns}	0^{ns}	0^{ns}	1^{ns}	1^{ns}	1^{ns}
Wetter × Fertiliser	1^{ns}	1^{ns}	0^{ns}	1^{ns}	0^{ns}	1^{ns}
Plough × Wetter × Fertiliser	0^{ns}	1^{ns}	1^{ns}	0^{ns}	0^{ns}	0^{ns}

^{ns} Not significant ($P > 0.05$).

Table 51. Effect of supplementary fertiliser treatments (nil, K = 40 kg K/ha, N = 40 kg N/ha, and NK = 40 kg N and K/ha broadcast at sowing) on whole shoot nutrient concentrations in canola during anthesis (106 DAS) at Moora in 2017. Mean values based on a sample size of 12. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Supplementary fertiliser	Shoot nutrient concentration					
	N (%)	P (%)	K (%)	Na (%)	Cu (mg/kg)	Zn (mg/kg)
Nil	2.01^{ac}	0.38^{ac}	3.21^{a}	0.16^{a}	3.07^{a}	18.1^{a}
K	1.99^{a}	0.39^{a}	3.47^{b}	0.16^{a}	3.24^{ab}	19.1^{ab}
N	2.16^{b}	0.34^{b}	3.10^{a}	0.30^{b}	3.32^{b}	20.5^{bc}
NK	2.10^{bc}	0.36^{bc}	3.64^{b}	0.20^{a}	3.44^{b}	21.3^{c}

One-way plough treatments significantly ($P < 0.05$; Table 50) increased shoot Ca (from 1.18 to 1.34 %), S (from 0.52 to 0.55 %), B (from 29.5 to 32.0 mg/kg), Cu (from 3.16 to 3.38 mg/kg), and Zn (from 19.1 to 20.4 mg/kg; Table 52) concentrations relative to non-ploughed treatments. However, blanket-wetter treatments significantly (*P* < 0.05; Table 50) decreased shoot Ca concentrations (from 1.30 to 1.22 %; Figure 59). There were no main treatment effects or interaction effects on shoot Mg (0.21-0.31 %), Fe (31.7-116.8 mg/kg), and Mn concentrations (13.1-30.5 mg/kg).

Table 52. Effect of one-way plough on whole shoot nutrient concentrations in canola during anthesis (106 DAS) at Moora in 2017. Mean values based on a sample size of 24. Significant differences based on the least significant difference (LSD) at P < 0.05.

Plough	Shoot nutrient concentration				
	Ca (%)	S (%)	B (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
Non-ploughed	1.18[†]	0.52[†]	29.5[†]	3.16[†]	19.1[†]
One-way ploughed	1.34	0.55	32.0	3.38	20.4

[†] Significantly different from one-way ploughed treatments (*P* < 0.05).

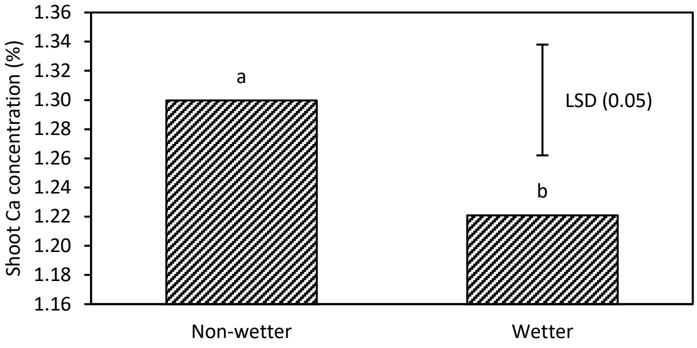

Figure 59. Effect of blanket-applied wetter on whole shoot Ca concentrations (%) in canola during anthesis (106 DAS) at Moora. Mean values based on a sample size of 24. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

4.3.3 Meckering

Soil water repellence

Results from a mixed model ANOVA showed that soil water repellence severity was significantly affected by sampling depth (*P* < 0.001; see Appendix C.2.3), whereby soil water repellence severity was significantly greater at the 0-5 cm depth (MED 0.7; slightly repellent) than at the 5-10 cm depth (MED 0.1; slight but marginally repellent). There was no effect of supplementary fertiliser treatment or growth stage on soil water repellence severity.

Soil water content

Results from a mixed model ANOVA showed that gravimetric soil water content was significantly affected by the two-way interaction of sampling depth × growth stage ($P < 0.001$; see Appendix C.2.3). Soil water content in the furrow at the 0-5 and 5-10 cm depths significantly increased over time from wheat emergence (2.25 and 3.81 %, respectively; 22 DAS) to tillering (7.61 and 5.18 %, respectively; 59 DAS; Table 53), but subsequently decreased during anthesis (0.78 and 1.16 %, respectively; 112 DAS). During wheat emergence and anthesis, soil water content in the furrow was significantly greater at the 5-10 cm depth (3.81 and 1.16 %, respectively) than at the 0-5 cm depth (2.25 and 0.78 %, respectively) but, during wheat tillering, soil water content in the furrow was significantly greater at the 0-5 cm depth (7.61 %) than at the 5-10 cm depth (5.18 %; Table 53).

Table 53. Soil water content (%, w/w) in the furrow at the 0-5 and 5-10 cm depths during canola emergence (15 DAS), leaf production (53 DAS), and anthesis (106 DAS) at Meckering in 2017. Mean values based on a sample size of 16. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Emergence	Tillering	Anthesis
0-5 cm	$2.25^{a\dagger}$	$7.61^{b\dagger}$	$0.78^{c\dagger}$
5-10 cm	3.81^{a}	5.18^{b}	1.16^{c}

Different superscript letters denote significant differences within growth stage ($P < 0.05$).

[†] Significantly different from the 5-10 cm depth ($P < 0.05$).

Early season soil N, P, and K availability

Soil NH_4-N, NO_3-N, Colwell P, and Colwell K concentrations in the furrow at 0-10 cm were assessed during wheat emergence (22 DAS) at Meckering. Results showed that soil NH_4-N and Colwell K concentrations in the furrow at the 0-10 cm depth were significantly affected by supplementary N and K fertiliser treatments ($P < 0.05$; Table 54). Soil NH_4-N concentration in the furrow at the 0-10 cm depth was significantly greater in supplementary N (91 mg/kg) and NK treatments (65 mg/kg) than in the control (21 mg/kg) and K treatments (26 mg/kg; Table 55). Soil Colwell K concentration in the furrow at the 0-10 cm depth was significantly greater in supplementary K (121 mg/kg) and NK treatments (105 mg/kg) than in the control (46 mg/kg) and N treatments (58 mg/kg; Table 55). Supplementary fertiliser treatments did not affect soil NO_3-N (10-29 mg/kg) and Colwell P concentrations (15-38 mg/kg) in the furrow at the 0-10 cm depth during wheat emergence.

Table 54. Analysis of variance test (F values with significance level) for the main effect of supplementary fertiliser treatment on soil ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), Colwell phosphorus (P), and Colwell potassium (K) concentrations in the furrow at the 0-10 depth during wheat emergence (22 DAS) at Meckering in 2017. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil NH_4-N	Soil NO_3-N	Soil Colwell P	Soil Colwell K
Fertiliser	19****	1 ^{ns}	0 ^{ns}	6*

^{ns} Not significant ($P > 0.05$).

Table 55. Effect of supplementary fertiliser treatments (nil, K = 40 kg K/ha, N = 40 kg N/ha, and NK = 40 kg N and K/ha broadcast at sowing) on soil ammonium-nitrogen (NH_4-N, mg/kg) and Colwell potassium (K, mg/kg) in the furrow at the 0-10 cm depth during wheat emergence (22 DAS) at Meckering in 2017. Mean values based on a sample size of 4. Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

Parameters	Nil	K	N	NK
Soil NH_4-N (mg/kg)	21.4^a	25.9^a	91.0^b	65.3^c
Soil Colwell K (mg/kg)	46.4^a	121.6^b	58.0^a	105.1^b

Crop growth, yield, and quality

Wheat stem density, head density, and shoot dry matter (112 DAS) were significantly affected by supplementary N and K fertiliser treatments ($P < 0.05$; Table 56). Wheat stem density was significantly greater in supplementary N (303 plants/m^2) and NK treatments (302 plants/m^2) than in the control (209 plants/m^2) and K treatments by an average of 45 and 35 %, respectively (223 plants/m^2; Table 57). Wheat head density was also significantly greater in supplementary N (268 heads/m^2) and NK treatments (278 heads/m^2) than in the control treatments by 29 and 34 %, respectively (208 heads/m^2; Table 57). Likewise, wheat shoot dry matter was significantly greater in supplementary NK treatments (5.83 t/ha) than in the control treatments by 52 % (3.84 t/ha; Table 57), but there were no differences in shoot dry matter elsewhere. Supplementary fertiliser treatments did not affect wheat emergence (127-184 plants/m^2; 22 DAS), grain yield (2.13-6.25 t/ha; 168 DAS), 1000-grain weight (36.3-48.3 g), grain protein content (5.6-10.9 %), and grain moisture content (10.2-11.1 %).

Table 56. Analysis of variance test (F values with significance level) for the main effect of supplementary fertiliser treatment on wheat plant density, head density, shoot dry matter, grain yield, 1000-seed weight, grain protein content, and grain moisture content at Meckering in 2017. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Plant emergence	Stem density	Head density	Shoot dry matter	Grain yield	1000-grain weight	Grain protein	Grain moisture
Fertiliser	1^{ns}	7***	4*	4*	1^{ns}	1^{ns}	2^{ns}	1^{ns}

^{ns} Not significant (P > 0.05).

Table 57. Effect of supplementary fertiliser treatments (nil, K = 40 kg K/ha, N = 40 kg N/ha, and NK = 40 kg N and K/ha broadcast at sowing) on wheat plant density (plants/m^{2}), head density (heads/m^{2}), and shoot dry matter (t/ha; 112 DAS) at Meckering in 2017. Mean values based on a sample size of 4. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Parameter	Nil	K	N	NK
Stem density (stems/m^{2})	209^{a}	223^{a}	303^{b}	302^{b}
Head density (heads/m^{2})	208^{a}	231^{ab}	268^{b}	278^{b}
Shoot dry matter (t/ha)	3.84^{a}	4.57^{ab}	5.23^{ab}	5.83^{b}

Shoot nutrient concentrations

An assessment of nutrient concentrations in wheat whole shoots during anthesis (112 DAS) found that wheat plants across the site at Meckering were relatively deficient in N (<1.8 %), K (<1.5 %), S (<0.15 %), B (<6 mg/kg), Cu (<5 mg/kg), and Zn (<15 mg/kg; Reuter and Robinson 1997; Appendix A.2), with some plants marginally deficient in Mg (<0.15 %) and Mn (<25 mg/kg). Shoot N, Ca, Mg, S, Cu, and Zn concentrations were significantly affected by supplementary N and K fertiliser treatments (P < 0.05; Table 58). Relative to the control treatment, supplementary N treatments significantly increased shoot N (from 1.27 to 1.54 %), Ca (from 0.38 to 0.48 %), Mg (from 0.14 to 0.17 %), and S (from 0.12 to 0.13 %; Table 59) concentrations but did not affect shoot Cu or Zn concentrations. Supplementary NK treatments also significantly increased shoot N (from 1.27 to 1.55 %) and Zn (from 11.7 to 15.5 mg/kg; Table 59) concentrations but did not affect shoot Ca, Mg, S, or Cu concentrations. However, supplementary K treatment significantly decreased shoot Ca (from 0.38 to 0.31 %), Mg (from 0.14 to 0.12 %), and Cu (from 2.64 to 2.22 mg/kg; Table 59) concentrations but did not affect shoot N, S, or Zn concentrations relative to the control treatment. Supplementary N and K fertiliser treatments did not affect wheat shoot P (0.21-0.30 %), K (0.73-1.37 %), Na (0.01-0.02 %), B (2.88-4.71 mg/kg), Fe (25.2-36.4 mg/kg) and Mn concentrations (20.1-54.5 mg/kg).

Table 58. Analysis of variance, ANOVA, test (F values with significance level) for the main effect of supplementary fertiliser treatments on wheat whole shoot nutrient concentrations during anthesis (112 DAS) at Meckering in 2017. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Shoot nutrient concentration	Fertiliser
N	6**
P	1^{ns}
K	1^{ns}
Ca	13****
Mg	11****
S	4*
Na	1^{ns}
B	1^{ns}
Cu	4*
Fe	1^{ns}
Mn	0^{ns}
Zn	6*

^{ns} Not significant (P > 0.05).

Table 59. Effect of supplementary fertiliser treatments (nil, K = 40 kg K/ha, N = 40 kg N/ha, and NK = 40 kg N and K/ha broadcast at sowing) on wheat whole shoot nutrient concentrations during anthesis (112 DAS) at Meckering in 2017. Mean values based on a sample size of 4. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	Supplementary fertiliser			
	Nil	K	N	NK
N (%)	1.27^{a}	1.22^{a}	1.54^{b}	1.55^{b}
Ca (%)	0.38^{a}	0.31^{b}	0.48^{c}	0.34^{ab}
Mg (%)	0.14^{a}	0.12^{b}	0.17^{c}	0.14^{ab}
S (%)	0.12^{ac}	0.11^{a}	0.13^{b}	0.13^{bc}
Cu (mg/kg)	2.64^{a}	2.22^{bc}	2.57^{ac}	2.77^{a}
Zn (mg/kg)	11.7^{a}	11.8^{a}	12.8^{a}	15.5^{b}

4.4 Discussion

4.4.1 Effects on soil water repellence and soil water availability

Due to crop production constraints on water-repellent soils, various strategies have been developed to ameliorate or mitigate soil water repellence in an attempt to improve plant establishment and overall yield (Roper *et al.* 2015). In this study, the effect(s) of some strategies, such as deep soil cultivation (spading and one-way plough), clay spreading, and the application of soil wetters (blanket-applied), on soil water repellence severity, soil water availability, soil nutrient availability, crop growth, crop nutrition, and crop yield parameters were assessed in a Grey Tenosol at Badgingarra and a Ferric Chromosol at Moora, Western Australia. Supplementary N and/or K treatments were also applied to these sites, in addition to another site at Meckering with a Grey Bleached-Ferric Kandosol, to assess plant nutrient uptake responses under observed N and K deficiencies in water-repellent soil.

Low to moderate soil water repellence severity in the furrow at the 0-10 cm depth was significantly decreased to marginal levels (from MED 0.6-1.1 to 0.0-0.2) by spading treatments throughout the 2017 growing season in a Grey Tenosol at Badgingarra. Soil cultivation by rotary spader or mouldboard plough is known to have significant long-term ameliorative results for soil water repellence on sandy soils (Davies and Lacey 2011; Hall *et al.* 2018). This is achieved when the repellent soil surface becomes diluted with wettable subsoil and/or buried partially or fully under wettable subsoil. Abrasion of the hydrophobic coatings on sand grains can also reduce the severity of water repellence. This increases the number of preferential flow pathways and soil hydraulic conductivity, thus improving the uniformity of soil wetting (Roper *et al.* 2015). Indirectly, soil cultivation would stimulate an increased activity of wax-degrading microorganisms which can result in the decomposition of hydrophobic organic matter, especially when lime can be incorporated to optimise soil pH levels (Roper 2005; Roper 2006).

By contrast, blanket-applied wetter treatments only reduced soil water repellence severity during wheat emergence (from MED 1.1 to 0.2; 25 DAS) at Badgingarra but did not affect SWR thereafter, suggesting that effects could have been weakened by later leaching or decomposition of wetting agent (e.g., Song *et al.* 2018) during the wheat tillering stage as a result of high August rainfall (Figure 54a). It may also be due to the nature of wetting agent which is designed to breakdown over time to reduce the risk of nutrient leaching (Roper *et al.* 2015). Surface spreading of 250 t clay-rich subsoil /ha alone (without incorporation by spading) also significantly reduced soil water repellence severity during wheat emergence (from MED 1.1 to 0.5) and tillering (from MED 0.6 to 0.3; 64 DAS). However, treated soils were still marginally repellent. Due to low clay content (<5 %), sandy soils are most severely affected by soil water repellence given that only <3 % of sand grains need to be coated with hydrophobic organic compounds for water repellence to be expressed (Bauters *et al.* 2000; Steenhuis *et al.* 2005; Unkovich *et al.* 2015). Consequently, increasing the specific soil surface area of repellent sandy soils by spreading and mixing 3-5 % clay would be enough to dilute the concentration of hydrophobic organic compounds and improve soil wettability (Ward and Oades 1993), with dispersible sodic clays being more effective than calcium saturated clays in reducing soil water repellence (Ma'shum *et al.* 1989).

However, due to the surface application of clay without incorporation by spading, its ameliorative effect on soil water repellence was limited to the 0-5 cm depth whereby soil water repellence severity at the 5-10 cm depth remained unaffected. Based on these results, spading alone has the potential to ameliorate soil water repellence at depth and over the long-term in comparison to blanket-applied wetter or clay treatments which appear to have relatively short-lived or limited depth effect. The ameliorative effect of clay spreading, however, is generally expected to provide a long-term solution for managing water repellence (Hall *et al.* 2010). Interestingly, applying either clay spreading or spading treatment alone only increased the soil water content in the furrow at the 0-5 cm depth by <1 % (w/w) but not at the 5-10 cm, unless both treatments were applied in combination which increased the soil water content at the 5-10 cm depth by 1.4 % (w/w). While these increases in soil water content are small, increased soil water retention at the soil surface could, however, be subjected to greater evaporative water losses, decreasing the depth of wetting and potentially reducing root development into the subsoil, particularly from light rainfall events (Davenport *et al.* 2011; Davies *et al.* 2012a; Bell and Sochacki 2016). By contrast, there was no significant effect of blanket-applied wetter treatments on soil water content in this Grey Tenosol at Badgingarra. From the present studies, applying either spading treatments or the combination of spading and claying treatments were the most effective method to ameliorate soil water repellence and increase soil water at depth. However, these results should be considered site-specific as the effects of blanket wetters, spading, and clay spreading are likely to differ in other soil types.

In the Ferric Chromosol at Moora, moderate to severe soil water repellence severity in the furrow at the 0-5 cm depth was significantly decreased to slight to moderate levels by blanket-applied wetter treatments during canola emergence (from MED 2.8 to 1.0; 15 DAS) and leaf production stages (from MED 2.2 to 1.5; 53 DAS). However, wetter treatments did not affect the moderate soil water repellence severity during canola anthesis (106 DAS). Likewise, blanket-applied wetter treatments also significantly increased soil water content in the furrow at the 0-5 cm depth during canola emergence (by 0.9 % w/w) and leaf production stages (by 1.7 % w/w), but not during anthesis, although the measured increases in soil water content were generally small. While soil water repellence severity in the furrow at the 5-10 cm depth also significantly decreased during emergence (from MED 0.6 to 0.4) in wetter treatments relative to non-wetter treatments, such decreases were only small and soil water content at the 5-10 cm depth remained unaffected. Blanket-applied wetter treatments only provided temporary relief as soil water repellence severity in wetter treatments as levels increased back to moderate levels during canola anthesis (106 DAS) at the 0-5 cm depth (from MED 1.0 to 2.2), with soil water repellence severity at the 5-10 cm depth also increasing (from MED 0.4 to 0.7). However, regardless of wetter treatment, soil water content in the furrow significantly increased over time from emergence to anthesis at the 0-5 (by up to 6 % w/w) and 5-10 cm depth (by up to 2 % w/w) due to increased seasonal rainfall.

Interestingly, one-way plough treatments at Moora did not affect soil water repellence severity at the 0-5 cm depth but resulted in a significant reduction in soil water content in the furrow at the 0-5 cm depth (by almost 2 % w/w) relative to non-ploughed treatments. However, the decreases in soil water were likely attributed to increased canola growth observed in one-way ploughed treatments (see discussion below). By contrast, one-way plough significantly increased soil water repellence severity in the furrow at the 5-10 cm depth (from MED 0.2 to 0.8), albeit at low levels, but one-way plough did not affect soil water content in the furrow at the 5-10 cm depth. Such increases in soil water repellence severity at depth were presumably due to the burial or mixing of repellent topsoil produced by the one-way plough. Nevertheless, soil water repellence severity in the furrow was significantly greater at the 0-5 cm depth (MED 2.0-2.1) than at the 5-10 cm depth (MED 0.2-0.8), regardless of one-way plough treatment. Therefore, blanket-applied wetter treatments were more effective in reducing soil water repellence and increasing soil water content in this Ferric Chromosol at Moora, despite being relatively short-lived and superficial in effect.

4.4.2 Effects on early season soil N, P, and K

In addition to the amelioration of soil water repellence, changes to soil properties and soil moisture conditions due to soil cultivation, blanket-applied wetters, and clay spreading are bound to have direct and indirect consequences for soil nutrient supply and root growth (Végh 1991), and therefore crop growth and nutrition (Mahler 1985; Seyfried and Rao 1987). In this study, spading treatment alone significantly increased soil NO_3-N concentrations in the furrow at 0-10 cm by 21 % during wheat emergence (25 DAS; to be referred to as 'early season') in a Grey Tenosol at Badgingarra. Such increases could likely be explained by the increases in soil water content in the furrow, resulting in increased soil respiration and N mineralisation (Kristensen *et al.* 2003), given that cultivation disrupts soil structure and aggregate stability which exposes protected soil organic matter to microbial degradation (Beare *et al.* 1994; Six *et al.* 1999). Reduced volatilisation of ammonia (NH_3) by topsoil incorporation (Sadeghpour *et al.* 2015) may have also contributed to increased soil N availability in spaded treatments relative to non-spaded soils, but this was not likely important since spading alone did not affect early season soil NH_4-N. These results were consistent with other field trials conducted in the Northern Agricultural Region of southwest Western Australia which showed both spading and mouldboard ploughing treatments to stimulate N mineralisation and increased NO_3-N concentration at depth, particularly after mouldboard ploughing whereby greater topsoil inversion occurred (Davies *et al.* 2010b). By contrast, the one-way plough treatment did not affect soil N, P, and K availability in the furrow at the 0-10 cm depth in the Ferric Chromosol at Moora. This may be because of: (1) the significant reduction in soil water content in the furrow at the 0-5 cm depth (by almost 2 % w/w) relative to non-ploughed treatments; and/or, (2) the comparatively shallow depth of soil incorporation by standard one-way ploughing (approximately 12 cm) relative to rotary spading treatments (approximately 40 cm), and hence nutrients were not as diluted within the sampled 0-10 cm depth.

Soil mineralisation can contribute to a substantial proportion of early season crop nutrition (Angus 2001; Masunga *et al.* 2016). However, the increase of 3 mg NO_3-N/kg in spaded treatments (equivalent to 4 kg NO_3-N/ha in 0-10 cm at a bulk density of 1.3 g/cm^3) may not be of practical importance to available soil N and crop N requirements. By contrast, stimulating mineralisation too early in the season may result in nutrients, particularly NO_3^-, being leached beyond the rooting depth of young plants

(Angus 2001), especially in cultivated soils (Sharma and Chaubey 2017). This may temporarily reduce early season N supply, although leached N can be recovered or captured later in the season as rooting depth increases (Lehmann and Schroth 2003). Permanent nutrient losses from leaching beyond the maximum rooting zone could, however, occur after heavy rainfall which may consequently limit their availability for crop uptake (Angus 2001), unless supplementary nutrients are supplied.

Clay spreading alone was also found to increase early season soil NH_4-N, Colwell P, and Colwell K concentrations in the furrow at the 0-10 cm depth by 76, 27, and 54 %, respectively, in the Grey Tenosol at Badgingarra. In addition to the inherent nutrient supply in clay aggregates (i.e., <2 mg NH_4-N/kg, 16 mg NO_3-N/kg, <2 mg Colwell P/kg, and 159 mg Colwell K/kg), clay spreading would also increase the absorptive surface area and exchange capacity of this Grey Tenosol, allowing more nutrients to be retained (Davenport *et al.* 2011). Nutrients bound to clay at the soil surface may, however, not be readily available to plant roots unless incorporated in the soil. However, in these clayed treatments, incorporation by spading significantly decreased early season soil NH_4-N and Colwell P concentrations in the furrow at 0-10 cm by 49 and 27 %, respectively, presumably due to the redistribution of clay and hence dilution of nutrients at depth. Redistribution of topsoil nutrients due to soil cultivation has also been reported by Davies *et al.* (2010b) who noted significant decreases in soil P at 0-10 cm (from 20 to 6 mg/kg) after mouldboard ploughing which were redistributed to the 10-30 cm as a result of topsoil inversion. Consequently, the effect of clay spreading on early season soil NH_4-N, Colwell P, and Colwell K concentrations in the furrow at the 0-10 cm depth was negligible in spaded treatments presumably due to dilution and redistribution of clay aggregates. Increased soil aeration and disturbance of ‘protected’ soil organic matter from spading would also result in increased microbial activity (Musarrat and Khan 2014) and hence increased microbial immobilisation of N and P could also contribute to a reduction in soil NH_4-N and Colwell P concentrations. Nevertheless, in this study, spading alone did not appear to affect early season soil NH_4-N, Colwell P, and Colwell K concentrations.

Interestingly, blanket-applied wetter treatments did not affect early season soil N, P, and K concentrations in the Ferric Chromosol at Moora. Likewise, blanket-applied wetter treatments also did not affect early season soil N and K concentrations in the Grey Tenosol at Badgingarra but did, however, significantly decrease soil Colwell P concentration in the furrow at the 0-10 cm depth by 25 %. This decrease in soil P availability in wetter treatments may perhaps be attributed to increased plant P uptake, P leaching, microbial P immobilisation due to increased wetting, and/or simply due to soil variability. Given no effect of wetter treatments on wheat growth (see discussion below), the observed decrease in early season soil P was unlikely due plant uptake. While soil P can be subject to leaching in pale sands with a low retention capacity (Weaver *et al.* 1988; Tischner 1999), the likelihood of P leaching during wheat emergence (25 DAS) was probably low given that soil water content at the 0-10 cm depth was relative low (<10 % w/w) in comparison to that expected at field capacity (15-25 %), and that rainfall from April to July 2017 was lower than average at Badgingarra (Figure 54a). Increased dissolution of P in wetter treatments could, however, result in rapid microbial immobilisation of P (Bünemann *et al.* 2012). However, results showed no significant effect of wetter treatment on soil water content in the furrow. Therefore, the observed decrease of 5 mg Colwell P/kg in wetter treatments relative to non-wetter treatments could likely be due to soil variability.

Regardless of soil spading, one-way plough, and/or blanket-applied wetter treatments, supplementary N and/or K treatments had a significant influence on early season soil N and K concentrations in the furrow at the 0-10 cm depth. For instance, in the Grey Tenosol at Badgingarra, application of supplementary K (40 kg K/ha) fertiliser treatments significantly increased soil Colwell K concentrations in the furrow at the 0-10 cm depth by 28 % relative to the control treatments. Clay spreading also increased soil Colwell K concentrations by 54 % due to a high K content in clay aggregate (159 mg/kg). In the Ferric Chromosol at Moora, supplementary N (40 kg N/ha) and K (40 kg K/ha) fertiliser treatments significantly increased soil NO_3-N concentrations (by 38 %) and Colwell K concentrations (by 46 %) relative to the control treatments. In a Grey Bleached-Ferric Kandosol, at Meckering, supplementary N (40 kg N/ha) and K (40 kg K/ha) fertiliser treatments also significantly increased soil NO_3-N concentrations (by 325 %) and Colwell K concentrations (by 161 %) relative to the control treatments. Due to the direct effect of supplementary N and K fertiliser treatments on soil N and K availability, supplementary fertilisers should thus be applied in addition to the management options for soil water repellence to overcome potential deficiencies in soil nutrients and crop nutrition (see discussion below).

4.4.3 Effects on crop growth, nutrient uptake, and yield

In a slightly water-repellent (MED 1.1) Grey Tenosol at Badgingarra, spading treatments alone significantly increased wheat emergence (from 71 to 90 plants/m^2; 25 DAS), stem density (from 162 to 201 stems/m^2; 113 DAS), shoot dry matter (from 2.09 to 3.11 t/ha; 113 DAS), whole shoot K concentrations (from 0.99 to 1.09 %; 113 DAS), total uptake of all nutrients (by an average of 41 %; except for Na, Cu, Fe, and Mn; 113 DAS; see Appendix C.3), and grain yield (from 1.80 to 2.96 t/ha; 166 DAS), but significantly decreased wheat whole shoot nutrient concentrations (N, Ca, S, Na, Cu, Mn, and Zn) and grain protein content (from 11.3 to 11.0 %). Alleviation of soil water repellence likely resulted in more even soil wetting and increased hydraulic conductivity due to the increasing number of preferred pathways (Roper *et al.* 2015) and this may explain the significant improvements in wheat establishment and yield on these spaded soils.

However, blanket-applied wetter and clay spreading treatments, which significantly reduced soil water repellence severity and increased soil water content in the furrow, had negligible effect on wheat emergence, stem density, shoot dry matter, and total nutrient uptake (except for Fe in clayed treatments; see Appendix C.3) at Badgingarra, despite significant reductions in shoot nutrient concentrations in blanket-applied wetter treatments (N, S, B, and Zn) and clay spreading treatments (N, P, Ca, S, Na, B, Cu, and Zn). Likewise, at Moora, the alleviation of soil water repellence by blanket-applied wetter treatments had no effect on canola plant density, shoot dry matter, shoot nutrient concentration (except for Ca which decreased from 1.30 to 1.22 %), total nutrient uptake (see Appendix C.3), seed yield, or seed quality on a severely water-repellent Ferric Chromosol. By contrast, standard one-way plough, which did not alleviate soil water repellence at 0-5 cm depth but increased its severity at the 5-10 cm depth (due to incorporation of the repellent upper layer), resulted in significantly increased canola shoot dry matter, shoot Ca, S, B, Cu, and Zn concentrations, and the total uptake of all nutrients (except for Fe and Mn; see Appendix C.3) at Moora. These results consequently suggest that the alleviation of soil water repellence alone was not important for either wheat or canola production on these sandy soil types.

Studies based on a collation of ten years of data also reported highly variable and unreliable responses to blanket-applied wetters on similar water-repellent sandy soil types in southwest WA (Davies *et al.* 2019). Dry sown cereal crops were generally more responsive to blanket-applied wetters than wet sown crops but positive yield responses appeared to be site-specific regardless of soil type (Davies *et al.* 2019). However, the underlying mechanisms for these responses to blanket-applied wetters are not well understood.

The lack of improvement in either wheat or canola production and their reduced nutrition at Badgingarra and Moora, respectively, due to either blanket-applied wetter and/or clay spreading could perhaps be due to the adverse effect of increasing absorptive soil surface area under limited soil moisture conditions, given that blanket-applied wetter and clay spreading treatments had only increased soil water content at the 0-5 cm depth but not at the 5-10 cm depth. Studies by Gupta *et al.* (2015) showed that reduced soil wetting depth and increased evaporative loss of water from a wettable (treated) soil surface relative to a repellent soil surface can cause marked differences in plant-available water in the root zone, which resulted in the growth impediment of chickpea (*Cicer arietinum*) seedlings and an overall reduction in plant water and nutrient use efficiency in wettable soils relative to repellent soils. The observed decrease in whole shoot nutrient concentrations in blanket-applied wetter and clay spreading treatments at Badgingarra could then be attributed to suboptimal plant water and nutrient uptake under dryland conditions.

While one-way ploughing did not affect canola plant density, seed yield, or seed quality, the mechanisms responsible for observed improvements in plant growth and nutrition in spaded and one-way ploughed soils at Badgingarra and Moora, respectively, could have been due to the marked effect of soil cultivation on soil physical properties, such as bulk density. The greater intensity and depth of cultivation achieved by the spader (approximately 40 cm) may also explain the significant improvements in wheat plant establishment and grain yield compared to that of one-way plough (approximately 12 cm). At Badgingarra, soil compaction which was known to co-occur at this site (Giacomo Betti, personal communication) and attempts to penetrate the soil profile using a metal rod had indicated the presence of a compacted soil layer at around the 15 to 20 cm depth. Similarly, difficulty in penetrating the soil profile of the Ferric Chromosol at Moora also increased sharply at the 10 cm depth, presumably due to a marked increase in gravel content (i.e., from 39 to 54 % w/w). However, soil strength measurements were not recorded at either site. The co-occurrence of soil water repellence and soil compaction is typical in many sandy agricultural soils of WA and thus soil cultivation techniques such as spading and mouldboard ploughing can be employed to simultaneously alleviate both constraints (Davies and Lacey 2011; Hall *et al.* 2018).

Decreased pore space, infiltration rate, and hydraulic conductivity in compacted soil (Singh *et al.* 2015) can strongly restrict plant root growth and soil water and air movement, leading to a reduction in plant water and nutrient uptake and consequently yield (Lipiec and Stpniewski 1995; Lipiec and Hatano 2003). Alleviation of the compacted soil layer would, therefore, improve root growth and allow plants to access deep-stored water and nutrients (Bennie and Botha 1986; Varsa *et al.* 1997). However, the assessment of wheat RLD during anthesis (113 DAS) at Badgingarra found no significant effect of spading on wheat RLD at the 0-20 cm depth, although wheat RLD was found to be significantly greater in the furrow than in the inter-row of spaded treatments (by 66 %) compared to that in non-spaded treatments where no differences were observed between sampling rows. While wheat root growth was not assessed below the 20 cm depth at Badgingarra, the observed increases in shoot K concentration in wheat may partly be due to increased plant access to subsoil K supplies (>30 cm depth) which can contribute to a large proportion of the total K uptake in spring wheat (i.e., from 9 to 70 %; Kuhlmann 1990). In semi-arid dryland cropping systems, access to deep-stored water and nutrients could also be pivotal for crop growth, nutrition, and production by evading stress during periods of drought (Varsa *et al.* 1997).

Unlike one-way plough which did not affect early season soil N, P, and K availability in the furrow at the 0-10 cm depth, the redistribution of topsoil nutrients from spading could have implications for the availability of plant nutrients due to increased dilution and/or redistribution of immobile nutrients due to its greater soil cultivation depth (Davies *et al.* 2010b). This was indeed the case for early season soil P which significantly decreased in the furrow at the 0-10 cm depth. Studies have shown that decreasing in early season P can restrict tiller production (Rodríguez *et al.* 1999), secondary root development (Boatwright and Viets 1966), and ultimately limit yields

(Elliott *et al.* 1997; Grant *et al.* 2001). However, spading did not significantly affect shoot P nutrition in this study.

Despite the various treatments to manage soil water repellence, a range of nutrients were found to be deficient or marginally deficient in plant whole shoots at Badgingarra (N, P, K, Mg, S, B, Cu, and Zn), Moora (N, K, B, Mn, and Zn), and Meckering (N, K, Mg, S, B, Cu, Mn, and Zn) and this would be largely attributed to the poor nutrient-holding capacity and low clay content in these sandy agricultural soils (McArthur 2004). Addition of supplementary fertilisers will, therefore, be required to improve crop growth and overall nutrition. At Badgingarra and Moora, supplementary K fertiliser treatments (40 kg K/ha broadcast at sowing) significantly increased shoot K concentrations in wheat and canola, respectively, relative to the control treatments. However, the supplementary K had no effect on the growth and total nutrient uptake of wheat and canola (see Appendix C.3). Moreover, surface spreading of K-rich clay aggregates (at 250 t/ha) at Badgingarra did not affect shoot K concentrations despite significantly increasing soil Colwell K concentrations in the furrow at the 0-10 cm depth.

Application of either spading or supplementary K fertiliser treatment alone also significantly reduced wheat shoot N concentration at Badgingarra. In spaded treatments, such reductions in shoot N concentration may be attributed to the increased leaching of early season NO_3-N as organic matter becomes exposed to mineralisation (Beare *et al.* 1994; Six *et al.* 1999; Kristensen *et al.* 2003). Although wheat plants were relatively deficient in both N and K, the observed increase in shoot K concentration in spaded treatments may have resulted in a decrease in shoot N concentration (in addition to other nutrients including Ca, S, Na, Cu, Mn, and Zn) presumably due to dilution of the nutrients in the increased shoot growth in response to improved K nutrition. As a result, nutrient concentrations in shoots may become diluted as a result of increasing dry matter accumulation and not necessarily due to their decreased concentration in the soil (Newbery *et al.* 1995). This would also imply that K was probably the most limiting nutrient in comparison to other nutrients in this Grey Tenosol. However, given the negligible effect of spreading K-rich clay or supplementary K fertiliser treatments on shoot dry matter despite increasing topsoil K availability, it is likely that spading may have increased plant access to subsoil K supply.

Addition of supplementary N and NK fertiliser treatments on a Ferric Chromosol at Moora significantly improved canola shoot dry matter, shoot Cu and Zn concentrations, and the total uptake of all nutrients (see Appendix C.3) relative to the control treatments, with supplementary N fertiliser treatments also significantly increasing shoot N concentration and seed protein content. While supplementary K fertiliser treatments did significantly increase canola shoot K concentration and total K uptake relative to the control treatments, there was no effect on shoot dry matter. Results indicate that canola growth was probably more limited by N than by K and this was due to prevalent N deficiency in canola plants with some plants only marginally K deficient. However, despite improvements in canola shoot dry matter, N nutrition, and seed protein content, supplementary N and NK fertiliser treatments did not result in noticeable yield gain on this water-repellent Ferric Chromosol. The same supplementary N and NK fertiliser treatments applied in a slightly water-repellent Grey Bleached-Ferric Kandosol at Meckering also had no noticeable effect on wheat grain yield, despite significantly increasing wheat stem density, head density, and shoot N concentrations relative to the control treatments. In dryland and terminal (end-season) water deficit environments, shoot dry matter and shoot nutrient increases often fail to increase final grain yield due to late season water limitations which prevent the yield response (e.g., decreased assimilate supply and/or shortened duration of the grain filling period; Abdoli *et al.* 2013; Mitchell *et al.* 2013; Farooq *et al.* 2014). During this present study, a period of drought was observed in October and November 2017 during the wheat grain and canola seed development stages, suggesting that terminal drought could have limited the yield response at the Badgingarra, Moora, and Meckering sites.

Influence of environmental factors such as rainfall may, however, dampen or mask the potential effects of soil water repellence (Unkovich *et al.* 2015) which may consequently explain why the effects of wetter and clay treatments on wheat growth and nutrition were marginal. At Badgingarra, the intense rainfall event (49.8 mm) that occurred during wheat tillering on August 9, 2017, was suspected to be a key factor and this was indicated by a significant decline in soil water repellence severity in untreated soils two days after the rainfall event including a significant increase in soil water content across the site. Due to the transient nature of soil water repellence (Keizer *et al.* 2007), the temporary expression of soil water repellence in this Grey Tenosol could also be due to its low to moderate severity at the 0-5 cm depth. This would also explain why amelioration of soil water repellence by either blanket-applied wetter or clay spreading treatments was not important for wheat production on these soils. Alternatively, the high plasticity of plant roots in response to soil heterogeneity and nutrient-enriched zones (Hodge 2004) could also result in compensatory adjustments in root:shoot ratio (Davidson 1969; Mackay and Barber 1985) which may also offset the adverse effects of soil water repellence and/or beneficial effects of applied treatments on soil water and nutrient uptake. Marginal changes could then be easily masked by environmental factors in field experiments.

4.5 Conclusion

In summary, spading alone has the potential to ameliorate soil water repellence at depth and over the growing season in comparison to either blanket-applied wetter or clay spreading treatments which appear to be relatively short-lived and/or have limited effect at depth if the mixing depth is only shallow. By contrast, one-way plough did not effectively manage soil water repellence on a Ferric Chromosol at Moora but instead increased it at the 5-10 cm depth due to topsoil inversion. Blanket-applied wetter treatments at the site in Moora also significantly reduced soil water repellence severity but were relatively short-lived and superficial in effect. Nevertheless, results suggest that the alleviation of soil water repellence alone was not important for either wheat or canola production on these sandy soils due to the negligible effect of blanket-applied wetter and clay spreading treatments on plant establishment, plant growth, and grain yield, and their negative effect on shoot nutrient concentrations. Findings indicate the resulting changes in soil physical properties, such as bulk density, due to soil cultivation treatments (spading and one-way plough) were largely responsible for the observed improvements in shoot dry matter, total nutrient uptake, and overall plant nutrition, presumably due to the alleviation of soil compaction within the cultivated depth. Spading was also found to significantly improve wheat plant establishment and grain yield, and this may be attributed to its greater working depth (approximately 40 cm) relative to one-way plough (approximately 12 cm). The resulting changes in soil properties due to soil spading were, nonetheless, found to have important implications for early season soil nutrient supply and plant uptake, which are attributed to: (1) the mechanical redistribution and dilution of topsoil nutrients, especially P which is relatively immobile in soil, (2) early release and potential leaching of mineral N as a result of increased soil wetting, mixing of organic residues, and increased mineralisation, and (3) increased plant root growth and potential access to subsoil resources such as K due to decreased soil strength within the cultivated depth. Due to widespread nutrient deficiencies, especially for N and/or K, observed in wheat and canola on this Ferric Chromosol, supplementary fertilisers will be required to maintain adequate crop nutrition. Given the variable nature of soil water repellence and the presence and complexity of multiple factors interacting in the soil-water environment, the present and previous field experiments had difficulty obtaining clear-cut conclusions. Therefore, the following chapters will evaluate glasshouse experiments designed to assess the effect of soil water repellence on early wheat growth and nutrition under variable conditions, including topsoil thickness, fertiliser placement, soil water supply, plant density, and surface micro-topography, which are relevant to dryland cropping systems in southwest WA.

Chapter 5: Effect of topsoil water repellence on early wheat growth and nutrition under variable topsoil thickness and fertiliser placement

5.1 Introduction

Adequate plant uptake of soil water and nutrients is critical for maximising plant growth and productivity (El-Ramady *et al.* 2014). However, in water-limited environments, impaired plant uptake of both water and nutrients can result in the suboptimal growth, nutrition, and yield of dryland crops and pastures (Alam 1999; Van Duivenbooden *et al.* 2000; Karim and Rahman 2015), even in fertilised fields (Amtmann and Blatt 2009; da Silva *et al.* 2011; Ahanger *et al.* 2016). Water-repellent soils which strongly resist water infiltration (Roberts and Carbon 1971; Wang *et al.* 2000; Li *et al.* 2018), increase surface runoff and soil erosion (Witter *et al.* 1991; Shakesby *et al.* 2000; Doerr *et al.* 2003), and cause unstable wetting and preferential flow patterns (Ritsema and Dekker 1994; Dekker and Ritsema 1996b; Bauters *et al.* 1998) are also likely to impair plant growth and yields, primarily by a reduction in soil water storage (Jordán *et al.* 2009), plant water uptake (Li *et al.* 2019), and the increased spatial heterogeneity in soil water content which constrains plant germination and establishment (Bond 1964; Bond 1972). The same processes are also likely to affect soil nutrient bioavailability, plant growth, and plant nutrition (Sunderman 1988; Doerr *et al.* 2000; Kramers *et al.* 2005; Jordán *et al.* 2013; Scanlan *et al.* 2013; Roper *et al.* 2015; Hewelke *et al.* 2018; Hermansen *et al.* 2019).

In Chapter 3, field investigations conducted on untreated water-repellent sandy soils at Meckering and Kojonup revealed that soil water repellence could have both adverse and favourable effects on dryland crop growth and nutrition. On a Grey Bleached-Ferric Kandosol at Meckering, increases in soil water repellence severity (from negligible to moderate levels) at the 0-5 cm depth resulted in decreased dryland wheat establishment, head density, shoot dry matter, K nutrition, and grain yield, despite no observable effect on soil water availability at the 0-10 cm depth. In contrast to these findings, similar investigations conducted on a Ferric Chromosol at Kojonup in the same year found that dryland canola establishment, shoot dry matter, Cu nutrition, and seed yield increased as soil water repellence severity increased (from moderate to very severe levels) at the 0-5 cm depth. These improvements were observed despite prolonged severe soil water repellence throughout the entire growing season and the possible decreases in canola P and Ca nutrition and soil solute availability (especially NO_3-N, K, and SO_4-S) at the 0-10 cm depth.

The contrasting crop growth and nutrition responses to increasing soil water repellence severity raises interesting questions. The differences could point to the importance of soil water and nutrients in deeper soil layers for plant uptake, presumably due to increased leaching in more severely repellent soils. The underlying mechanisms contributing to these responses in dryland crop growth and nutrition on water-repellent sandy soils are still not well understood. A glasshouse experiment was, therefore, conducted to examine more closely the effect of topsoil water repellence (nil and severe) on early wheat growth, root length density (RLD) and nutrition, under controlled environmental conditions and uniform plant density. Based on the consensus that soil water repellence constrains plant growth, it was hypothesised that early wheat growth and nutrition would be adversely affected in repellent soils relative to wettable soils. In addition, the experiment tested the effect of topsoil thickness (20 and 100 mm) because of its likely influence on depth of wetting, and fertiliser placement position (below or away from the seed in the inter-row) to determine the importance water availability in plant nutrient uptake between the furrow and inter-row.

5.2 Materials and methods

5.2.1 Treatment design

Wheat (*Triticum aestivum* cv. Mace) was grown over 51 days, from May to June 2017, in a glasshouse at Murdoch University, Western Australia (32°04’02.30” S 115°50’20.21” E), to investigate the effects of (a) topsoil water repellence (wettable or severely repellent topsoil), (b) topsoil thickness (20 or 100 mm), and (c) fertiliser placement position (50 mm below the seed or 100 mm away from the seed at the same depth) on early wheat growth and nutrition. The experiment involved a total of 8 treatment combinations with three replications which were arranged in a full factorial completely randomised design. Figure 60 illustrates the design of a plant-growth container.

Severely water-repellent topsoil (molarity of ethanol droplet, MED, value of 3.4; King 1981) from the 0-10 cm depth was collected from a gravelly sandy loam duplex soil (Ferric Chromosol, ASC) in Kojonup, Western Australia (33°41’08.83” S 117°01’54.01” E) and sieved to 2 mm to remove coarse gravel, with wettable subsoil (MED value of 0.0) from the 20-30 cm depth collected from a grey deep sandy duplex soil (Grey Bleached-Ferric Kandosol, ASC) at Meckering (31°37’38.22” S, 116°52’16.53” E). Properties of topsoil and subsoil (≤2 mm) are listed in Table 60. Note, subsoil from Kojonup was not collected due to high gravel and clay contents.

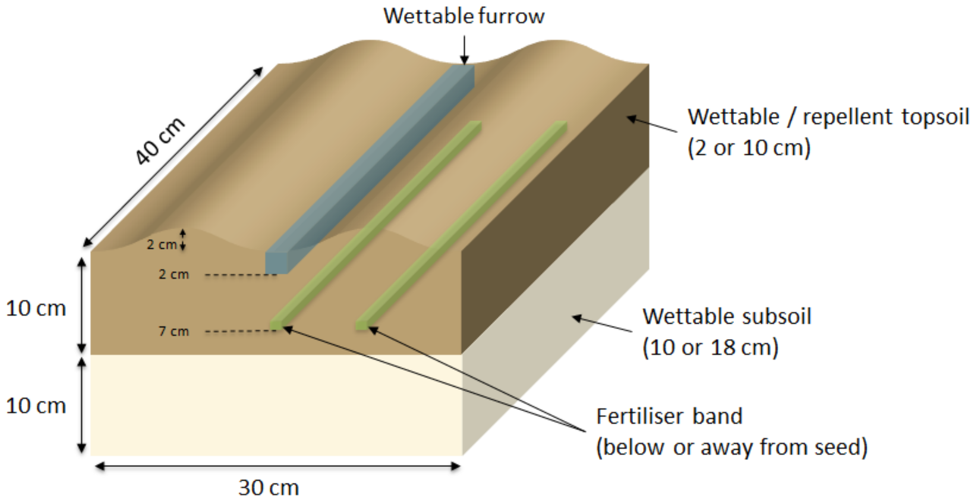

Figure 60. General design of a plant-growth container with wheat sown in a wettable furrow, in either wettable or severely repellent treatments with variable topsoil thickness (20 or 100 mm) and fertiliser placement (below or away from the seed).

To prepare wettable topsoil (MED 0.0), a bulk portion of repellent topsoil was treated with approximately 20 ml of 12.5 % v/v solution of SE14® (SACOA Pty Ltd) per kilogram of soil in a cement mixer. All soils were air-dried in the glasshouse, sieved (≤2 mm), and thoroughly mixed in a cement mixer prior to use. Holes were drilled in each container to allow for drainage, with shade cloth placed along the bottom to prevent soil spillage. Subsoil (100 or 180 mm) and topsoil (20 or 100 mm) were layered in each container to a total depth of 200 mm. At the 70 mm depth, fertiliser was banded either below or 100 mm to the side of the seeding row at the following rates (mg/kg): 60 N, 25 P, 70 K, 6 Mg, 49 S, 0.5 Zn, 0.1 B, 0.3 Mn, and 0.1 Cu. Ridges of approximately 20 mm high from the furrow base were created in the inter-row to model the ridge-furrow topography of agricultural cropping soils sown with knife tynes with a row spacing of 20 cm. Containers were tapped on the ground to re-compact the soil layers to a bulk density of 1.7 g/cm^3.

Table 60. Baseline properties of topsoil and subsoil used in treatment containers. Soils were analysed by the methods of Rayment and Lyons (2011).

Soil properties	Topsoil	Subsoil
pH_{Ca} ($CaCl_2$)	5.1	5.0
Organic carbon (g/kg)	35.3	2.1
Electrical conductivity (dS/m)	0.04	0.02
NH_4-N (mg/kg)	6.0	< 1.0
NO_3-N (mg/kg)	12.0	< 1.0
Colwell P (mg/kg)	65.0	14.0
Colwell K (mg/kg)	151.0	20.0
Effective cation exchange capacity (cmol(+)/kg)	5.82	1.09
Exchangeable Ca (cmol(+)/kg)	4.55	0.79
Exchangeable Mg (cmol(+)/kg)	0.61	0.15
Exchangeable K (cmol(+)/kg)	0.36	0.04
Exchangeable Na (cmol(+)/kg)	0.09	< 0.01
Exchangeable Al (cmol(+)/kg)	0.21	0.10
Extractable S (mg/kg)	7.1	1.7
Extractable B (mg/kg)	0.54	0.19
Extractable Cu (mg/kg)	0.37	0.30
Extractable Fe (mg/kg)	23.3	18.1
Extractable Mn (mg/kg)	4.01	0.96
Extractable Zn (mg/kg)	1.33	0.27
Sand (g/kg)	694.0	831.0
Silt (g/kg)	133.0	53.0
Clay (g/kg)	173.0	116.0

Sixteen wheat seeds were sown at the 20 mm depth in a wettable furrow, with approximately 300 g of wettable topsoil used for the seeding row in repellent treatments to ensure gemination. Plants were reduced to a uniform plant density of 15 plants per container (equivalent to 125 plants/m^2) and were hand watered every 2 days using a sprinkle bar over the whole container, with 500 ml (~ 4.2 mm) of tap water over a duration of 5 minutes (~50 mm/h). A total water supply of ~105 mm was applied over 51 days, but the watering did not cause drainage from the base of the container. The glasshouse had an average day air temperature of 19°C and relative humidity of 36 %. Growing containers were randomised weekly to eliminate possible bias from spatial variation in environmental conditions which may occur in the glasshouse (e.g., sunlight exposure and microclimate).

5.2.2 Wheat growth

Shoot growth

Treatment effects on wheat growth was investigated during early vegetative growth to avoid the breakdown of repellent treatments over time. Wheat seedling phenological development was assessed (23 days after sowing, DAS) according to Zadoks' (Z) growth scale (Zadoks *et al.* 1974; Anderson and Garlinge 2000). Average tiller number per plant was counted (46 DAS) and shoot biomass harvested (51 DAS) and oven-dried at 60°C to determine shoot dry matter per plant.

Root growth

Roots were extracted post-harvest (51 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths, using a 20 cm long and 6.2 cm diameter coring tube (i.e., 151 cm^3 sample volume). In each growing container, two cores were taken from the furrow and inter-row (where fertiliser was banded). Root samples were rinsed in water, stored in vials containing 50% (v/v) ethanol, and refrigerated at 4°C. Root length (cm) was assessed by the WinRHIZO image analysis software (version 2005c; Regent Instruments Inc., Canada) with results presented as root length per cubic centimetre of soil (i.e., root length density, RLD, cm/cm^3). Note, due to furrow infill from ridge erosion and soil compaction over time from watering, the height difference between the base of the furrow and tip of the ridge generally diminished from 20 mm (initial ridge construction at 0 DAS) to $\leq$5 mm (51 DAS). Slight differences in soil sampling depth between the furrow and inter-row were thus considered to have no significant confounding influence on the relative soil layers assessed for root length density.

5.2.3 Wheat hydration and soil water availability

Wheat hydration was assessed (51 DAS) by measuring the relative water content (RWC, %) or 'relative turgidity' in young fully expanded leaves (Barrs and Weatherley 1962; Mullan and Pietragalla 2012). Six leaves were collected from different plants in each container at solar noon (±2 hours). After the top and bottom sections of the leaves were cut off with secateurs, the leaf was sealed in pre-weighed plastic tubes, and stored in an insulated cooler. Samples were immediately measured for fresh weight in the laboratory and subsequently placed in the refrigerator for 24 hours, with 20 ml distilled water added to each sample tube for leaves to reach full turgor. Leaves were then removed from tubes, carefully dried with an adsorbent paper towel, and measured for turgid weight. Samples were oven-dried at 60°C and re-measured for dry weight. *In situ* volumetric soil water content (%) was also measured in each container, averaged from four sampling points in the furrow and inter-row at the 0-5 and 10-15 cm depths post-harvest (51 DAS) using the handheld MPM160 soil moisture meter (ICT International Pty Ltd, NSW, Australia).

5.2.4 Wheat shoot nutrient concentration and total nutrient uptake

Nutrient concentrations in wheat whole shoot samples were analysed using standard methods (Rayment and Lyons 2011) by the CSBP Soil and Plant Analysis Laboratory. Total nutrient uptake was also determined from shoot dry matter and was expressed in terms of mass per plant (mg or µg/container).

5.2.5 Statistical analysis

Parametric statistical analyses were carried out using SPSS Statistics version 21.0 (IBM Corporation, Armonk, NY, USA) to determine the effect(s) of (a) soil water repellence, (b) topsoil thickness, and (c) fertiliser placement position on wheat growth and nutrient uptake. Assumptions of normality and homogeneity of variances were assessed and, where the assumptions were violated, data were transformed using a $\log_{10}$ transformation. Main effects and interactions for wheat shoot growth and nutrient uptake were analysed using the univariate analysis of variance, ANOVA (two-tail) test in SPSS. Root length density and soil water post-harvest were analysed in a mixed model ANOVA in SPSS, using topsoil water repellence, topsoil thickness, and fertiliser placement as between-subjects variables and the repeated measures for sampling row and sampling depth as the within-subjects variable. A combined measurement of wheat RLD (referred here as 'total RLD') was also assessed using a univariate ANOVA to determine the overall response of RLD to treatments. Post hoc analysis was performed using Fisher's least significant difference (LSD) at $P < 0.05$ to determine significant differences among treatment factors. Bivariate correlation analysis was also conducted in SPSS to study key relationships between soil water post-harvest and wheat shoot growth and nutrition parameters in wettable and repellent treatments, with significant correlations (two-tailed) interpreted by the Coefficient of Determination (R^2) at the 95 and 99 % confidence intervals. The relative strength of correlation was classed as: weak ($R^2 \leq 0.39$), moderate ($0.40 \leq R^2 \leq 0.59$), strong ($0.60 \leq R^2 \leq 0.79$), and very strong ($0.80 \leq R^2 \leq 1.00$). Note that among a range of statistically significant observations, main treatment effects and interaction effects that help explain shoot dry matter responses will be the main focus in this chapter, while those that are generally unimportant or unrelated to growth responses will be provided in Appendix D: as supplementary data.

5.3 Results

5.3.1 Seedling development

Results showed that wheat seedling phenological development (23 DAS; Zadoks' growth scale) was significantly affected by the two-way interactions of topsoil water repellence × topsoil thickness ($P < 0.01$), and topsoil water repellence × fertiliser placement ($P < 0.001$; Table 61). Overall, seedling development was significantly advanced in repellent treatments (Z13.1-13.4) relative to wettable treatments (Z12.8-13.0; Figures 61 and 62), regardless of topsoil thickness and fertiliser placement. Seedling development was also significantly more advanced in wettable treatments with a 20 mm topsoil thickness (Z13.0) than a 100 mm topsoil thickness (Z12.8; Figure 61), but topsoil thickness did not affect seedling development in repellent treatments. By contrast, seedling development was significantly advanced in repellent treatments when fertiliser was banded below the seed (Z13.4) rather than away from the seed (Z13.1; Figure 62), but fertiliser placement did not affect seedling development in wettable treatments.

Table 61. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR), topsoil thickness (TT), and fertiliser placement (FP) on wheat seedling development (Zadoks' growth scale), tiller number, and dry matter, total root length density (RLD), and leaf relative water content (RWC). Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	SWR	TT	FP	SWR × TT	SWR × FP	TT × FP	SWR × TT × FP
Seedling stage	145****	13***	8*	10**	17****	1^{ns}	0^{ns}
Tiller number	35****	19****	26****	3^{ns}	0^{ns}	1^{ns}	0^{ns}
Shoot dry matter	102****	13***	12***	5*	3^{ns}	1^{ns}	1^{ns}
Total RLD	9**	17****	15***	8*	6*	0^{ns}	0^{ns}
Leaf RWC	2^{ns}	0^{ns}	8*	12***	1^{ns}	13***	0^{ns}

^{ns} Not significant ($P > 0.05$).

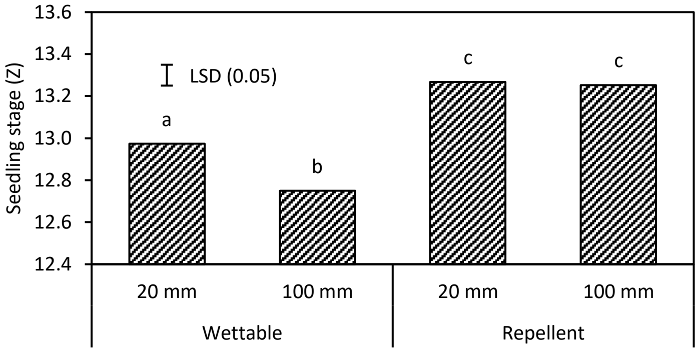

Figure 61. Effect of topsoil water repellence and topsoil thickness on wheat seedling development (Zadoks' growth scale, Z) at 23 DAS. Mean values based on a sample size of 6. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

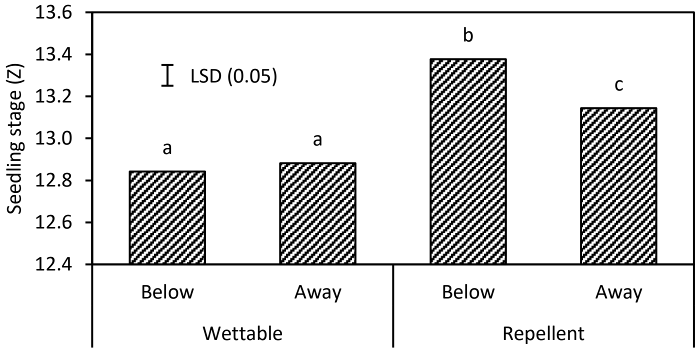

Figure 62. Effect of topsoil water repellence and fertiliser placement on wheat seedling stage (Z) at 23 DAS, according to Zadoks' growth scale. Mean values based on a sample size of 6. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

5.3.2 Tiller number

Only the main effects of topsoil water repellence, topsoil thickness, and fertiliser placement on wheat tiller number per plant were significant ($P < 0.001$; 46 DAS; Table 61). Tiller number was significantly greater in: (a) repellent treatments (1.7 tillers per plant) than in wettable treatments (1.0 tiller per plant; Figure 63a), (b) treatments with a 20 mm topsoil thickness (1.6 tillers per plant) than a 100 mm topsoil thickness (1.0 tiller per plant; Figure 63b), and (c) treatments with fertiliser banded below the seed (1.7 tillers per plant) than away from the seed (1.0 tiller per plant; Figure 63c).

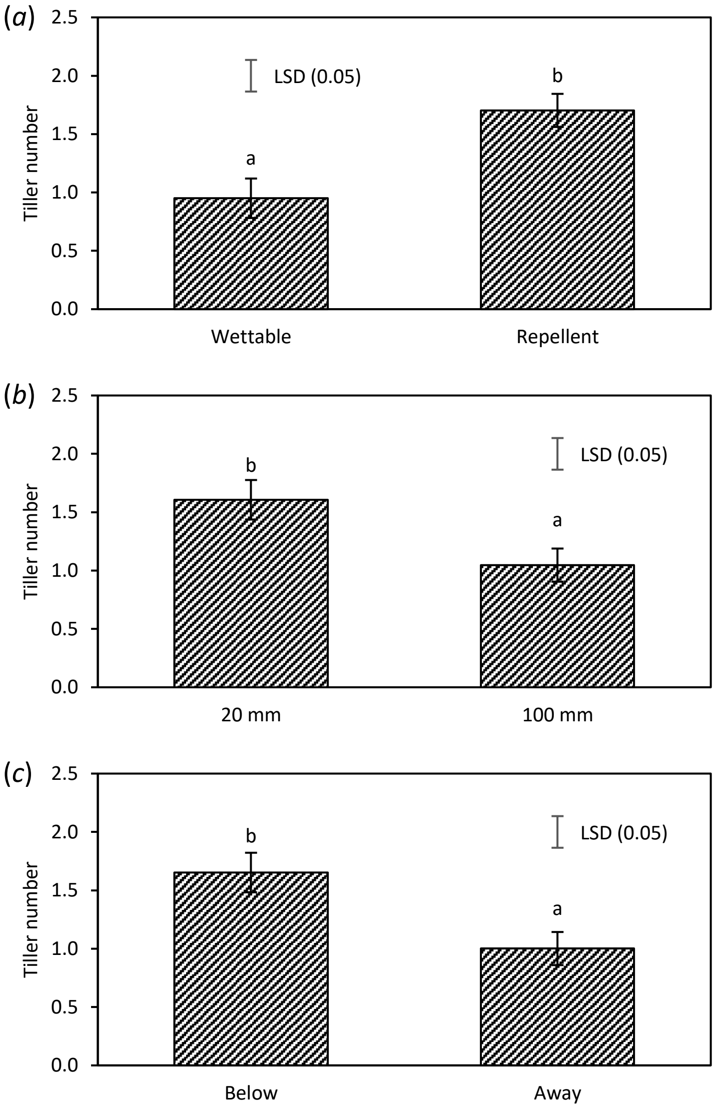

Figure 63. Effect of (a) topsoil water repellence (wettable or repellent), (b) topsoil thickness (20 or 100 mm), and (c) fertiliser placement (below or away from the seed) on wheat tiller number per plant

at 46 DAS. Mean values based on a sample size of 12. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

5.3.3 Shoot dry matter

Wheat shoot dry matter per plant (51 DAS) was significantly affected by the two-way interaction of topsoil water repellence × topsoil thickness (*P* < 0.05; Table 61). Shoot dry matter was significantly greater in repellent treatments (0.90-0.95 g/plant) than in wettable treatments (0.43-0.66 g/plant; Figure 64), but there was a more pronounced increase in shoot dry matter in treatments with a 100 mm topsoil thickness (by 109 %) than in treatments with a 20 mm topsoil thickness (by 44 %). Visible differences in shoot growth between treatments can also be observed in Figure 65. The main effect of fertiliser placement on shoot dry matter was also significant (*P* < 0.005; Table 61), whereby shoot dry matter was significantly greater when fertiliser was banded below the seed (0.80 g/plant) than away from the seed (0.67 g/plant; Figure 66).

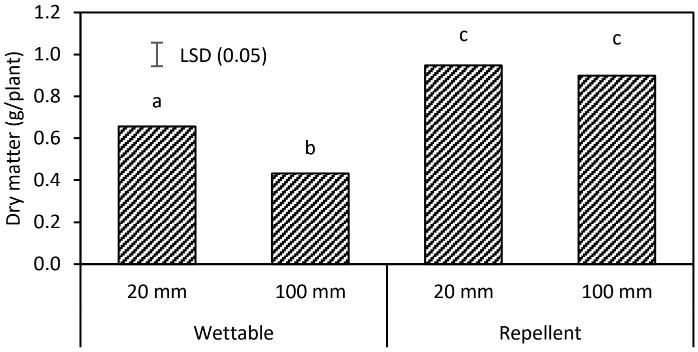

Figure 64. Effect of topsoil water repellence and topsoil thickness on wheat shoot dry matter (g/plant) at 51 DAS. Mean values based on a sample size of 6. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

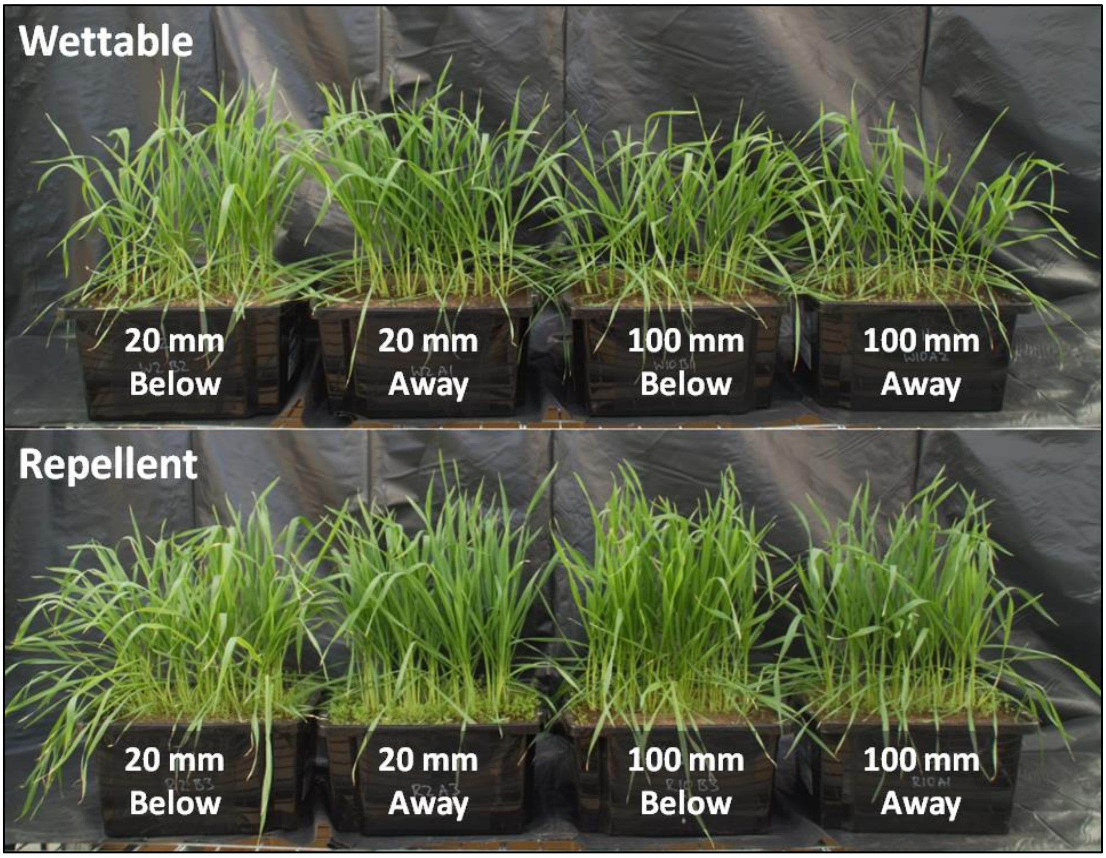

Figure 65. Wheat shoot growth at 51 DAS between wettable and repellent treatments, with variable topsoil thickness (20 or 100 mm) and fertiliser band placement (below or away from the seed).

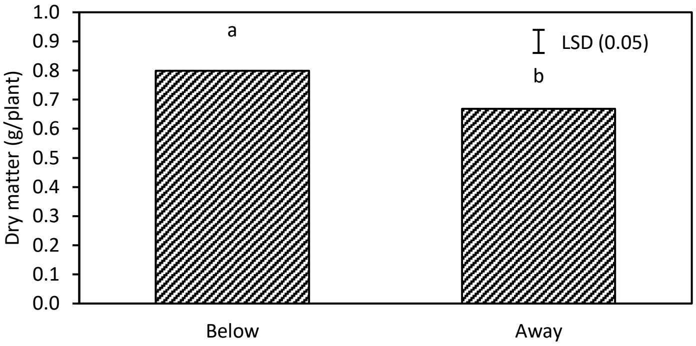

Figure 66. Effect of fertiliser placement on wheat shoot dry matter (g/plant) at 51 DAS. Mean values based on a sample size of 12. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

5.3.4 Root length density

The total root length density (RLD; 51 DAS) in the furrow and inter-row at the 0-20 cm depth of wheat was significantly affected by the two-way interaction of topsoil water repellence × topsoil thickness ($P < 0.05$; Table 61). In repellent treatments, total RLD was significantly greater in treatments with a 100 mm topsoil thickness (17.8 cm/cm^3) than a 20 mm topsoil thickness (14.2 cm/cm^3; Figure 67), but topsoil thickness did not affect total RLD in wettable treatments. The main effect of fertiliser placement on total RLD was also significant ($P < 0.005$; Table 61), but in contrast to the shoot dry matter response, total RLD was significantly greater when fertiliser was banded away from the seed (16.2 cm/cm^3) than below the seed (14.2 cm/cm^3; Figure 68).

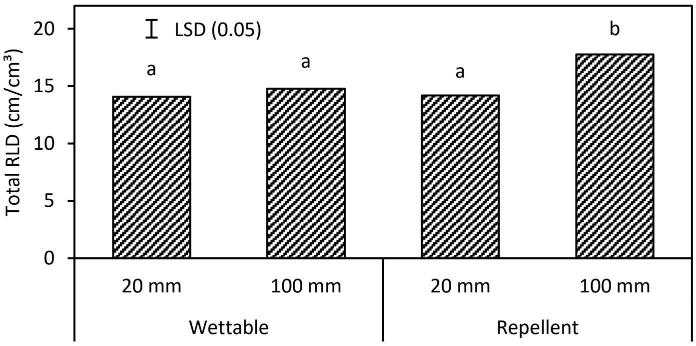

Figure 67. Effect of topsoil water repellence and topsoil thickness on total wheat root length density (RLD, cm/cm^3) at 51 DAS. Mean values based on a sample size of 6. Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

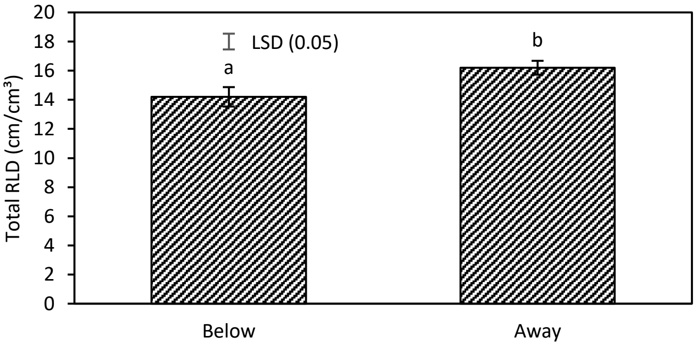

Figure 68. Effect of fertiliser placement on total wheat root length density (RLD, cm/cm^3) at 51 DAS. Mean values based on a sample size of 12. Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

The effects of topsoil water repellence, topsoil thickness, and fertiliser placement on wheat RLD in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths were also assessed in greater detail using a mixed model ANOVA (Table 62). Wheat RLD was significantly affected by the three-way interactions of topsoil water repellence × topsoil thickness × sampling depth ($P < 0.05$), and fertiliser placement × sampling row × sampling depth ($P < 0.001$; Table 62).

Table 62. Mixed model analysis of variance, ANOVA, test (F values with significance level) for wheat root length density (51 DAS), with topsoil water repellence (SWR), topsoil thickness (TT), and fertiliser placement (FP) as between-subjects variables and a repeated measure for sampling row and depth as the within-subjects variable. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	*F*
SWR	9**
TT	17****
FP	15***
Row	1016****
Depth	268****
SWR * TT	8*
SWR * FP	6*
SWR * Row	11***
SWR * Depth	12****
TT * FP	0^{ns}
TT * Row	9**
TT * Depth	30****
FP * Row	10***
FP * Depth	15****
Row * Depth	85****
SWR * TT * FP	0^{ns}
SWR * TT * Row	0^{ns}
SWR * TT * Depth	3*
SWR * FP * Row	43****
SWR * FP * Depth	9****
SWR * Row * Depth	2^{ns}
TT * FP * Row	49****
TT * FP * Depth	5***
TT * Row * Depth	16****
FP * Row * Depth	143****
SWR * TT * FP * Row	1^{ns}
SWR * TT * FP * Depth	2^{ns}
SWR * TT * Row * Depth	2^{ns}
SWR * FP * Row * Depth	4*
TT * FP * Row * Depth	26****
SWR * TT * FP * Row * Depth	2^{ns}

^{ns} Not significant ($P > 0.05$).

Wheat RLD at the 0-5 cm depth was significantly greater in repellent treatments (2.28-2.90 cm/cm^3) than in wettable treatments (1.72-1.76 cm/cm^3; Table 63), regardless of topsoil thickness, with RLD at the 10-15 cm depth also significantly greater in repellent treatments (1.42 cm/cm^3) than in wettable treatments (1.16 cm/cm^3) with a 20 mm topsoil thickness. However, topsoil water repellence did not affect RLD at the 5-10 and 15-20 cm depths in treatments with a 20 mm topsoil thickness, and

RLD at the 5-10, 10-15, and 15-20 cm depths in treatments with a 100 mm topsoil thickness. In repellent treatments, RLD at the 0-5 and 5-10 cm depths was significantly greater in treatments with a 100 mm topsoil thickness (2.28 and 2.42 cm/cm^3, respectively) than a 20 mm topsoil thickness (2.90 and 4.03 cm/cm^3, respectively; Table 63), respectively, but topsoil thickness did not affect RLD at the 10-15 and 15-20 cm depths. In wettable treatments, RLD at the 5-10 cm depth was also significantly greater in treatments with a 100 mm topsoil thickness (3.69 cm/cm^3) than a 20 mm topsoil thickness (2.87 cm/cm^3; Table 63), but RLD at the 15-20 cm depth was significantly greater in treatments with a 20 mm topsoil thickness (1.29 cm/cm^3) than a 100 mm topsoil thickness (0.73 cm/cm^3). There was no effect of topsoil water repellence on RLD at the 0-5 and 10-15 cm depths in wettable treatments.

Table 63. Effect of topsoil water repellence, topsoil thickness, and sampling depth on wheat root length density (cm/cm^3; 51 DAS). Mean values are averaged across fertiliser placements, based on a sample size of 12. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Depth	Wettable		Repellent	
	20 mm	100 mm	20 mm	100 mm
0-5 cm	1.72†	1.76†	2.28Δ	2.90
5-10 cm	2.87Δ	3.69	2.42Δ	4.03
10-15 cm	1.16†	1.21	1.42	1.17
15-20 cm	1.29Δ	0.73	0.99	0.77

† Significantly different from repellent treatments ($P < 0.05$).

Δ Significantly different from treatments with a 100 mm topsoil thickness ($P < 0.05$).

Wheat RLD in the furrow at the 5-10 cm depth was significantly greater when fertiliser was banded below the seed (5.70 cm/cm^3) than away from the seed (3.15 cm/cm^3; Table 64), but RLD in the furrow at the 0-5 cm depth was not affected by fertiliser placement. However, wheat RLD in the furrow at the 10-15 and 15-20 cm depths was significantly greater when fertiliser was banded away from the seed (2.40 and 2.34 cm/cm^3, respectively) than below the seed (1.19 and 0.52 cm/cm^3, respectively; Table 64), respectively.

In the inter-row, wheat RLD at the 0-5 and 5-10 cm depths was also significantly greater when fertiliser was banded away from the seed (0.81 and 2.94 cm/cm^3, respectively) than below the seed (0.17 and 1.21 cm/cm^3, respectively), respectively, but RLD in the inter-row at the 10-15 and 15-20 cm depths were significantly greater when fertiliser was banded below the seed (0.85 and 0.61 cm/cm^3, respectively) than away from the seed (0.52 and 0.32 cm/cm^3, respectively; Table 64). Nevertheless, these responses in wheat RLD do not appear to be related to shoot dry matter responses, presumably because root assessments at 51 DAS were too late to observe the primary differences in shoot dry matter attributed to topsoil water repellence.

Table 64. Effect of fertiliser placement on wheat root length density (cm/cm^3; 51 DAS). Mean values are averaged across topsoil water repellence and topsoil thickness, based on a sample size of 12. Significant differences denoted by an asterisk (*), based on the least significant difference (LSD) at P < 0.05.

Row	Depth	Fertiliser placement	
		Below	Away
Furrow	0-5 cm	3.95	3.73
	5-10 cm	5.70*	3.15
	10-15 cm	1.19	2.40*
	15-20 cm	0.52	2.34*
Inter-row	0-5 cm	0.17	0.81*
	5-10 cm	1.21	2.94*
	10-15 cm	0.85*	0.52
	15-20 cm	0.61*	0.32

5.3.5 Leaf relative water content

Overall, all wheat plants were relatively well hydrated (RWC > 90 %) and differences in leaf RWC were small. However, leaf RWC was significantly affected by the two-way interaction of soil water repellence × topsoil thickness ($P < 0.005$; Table 61). In wettable treatments, leaf RWC was significantly greater in treatments with a 20 mm topsoil thickness (94.5 %) than a 100 mm topsoil thickness (93.6 %; Figure 69), while leaf RWC was significantly greater in repellent treatments with a 100 mm topsoil thickness (94.8 %) than a 20 mm topsoil thickness (94.0 %).

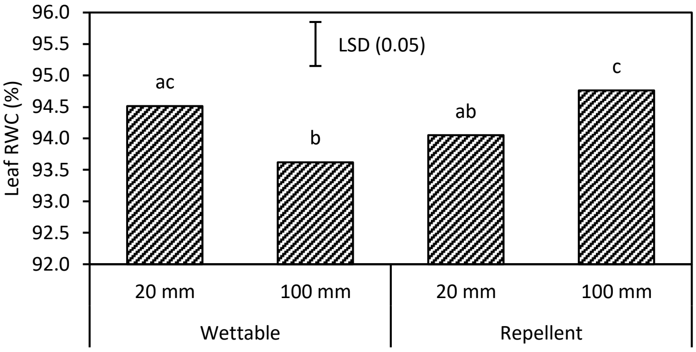

Figure 69. Effect of topsoil water repellence and topsoil thickness on relative water content (RWC, %) in young fully expanded wheat leaves at 51 DAS. Mean values based on a sample size of 6. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

5.3.6 Soil water post-harvest

Treatment effects on *in situ* soil water content post-harvest (51 DAS) were analysed using a mixed model ANOVA (Table 65), showing that soil water content was significantly affected by the three-way interaction of topsoil water repellence × sampling row × sampling depth ($P < 0.001$).

Table 65. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil water post-harvest (51 DAS), with topsoil water repellence (SWR), topsoil thickness (TT), and fertiliser placement (FP) as between-subjects variables and a repeated measure for sampling row and depth as the within-subjects variable. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Source of variation	*F*
SWR	49****
TT	0^{ns}
FP	2^{ns}
Row	2^{ns}
Depth	346****
SWR * TT	1^{ns}
SWR * FP	1^{ns}
SWR * Row	22****
SWR * Depth	31****
TT * FP	0^{ns}
TT * Row	86****
TT * Depth	42****
FP * Row	6*
FP * Depth	17****
Row * Depth	2^{ns}
SWR * TT * FP	1^{ns}
SWR * TT * Row	2^{ns}
SWR * TT * Depth	2^{ns}
SWR * FP * Row	0^{ns}
SWR * FP * Depth	1^{ns}
SWR * Row * Depth	64****
TT * FP * Row	3^{ns}
TT * FP * Depth	0^{ns}
TT * Row * Depth	38****
FP * Row * Depth	4^{ns}
SWR * TT * FP * Row	0^{ns}
SWR * TT * FP * Depth	0^{ns}
SWR * TT * Row * Depth	0^{ns}
SWR * FP * Row * Depth	1^{ns}
TT * Fertiliser * Row * Depth	4^{ns}
SWR * TT * FP * Row * Depth	0^{ns}

^{ns} Not significant ($P > 0.05$).

Soil water content was significantly greater in wettable treatments (15.7-29.9 %) than in repellent treatments (10.8-19.5 %; Table 66), regardless of sampling row and depth. Soil water content in the furrow was also significantly greater at the 0-5 cm depth (16.8-29.9 %) than at the 10-15 cm depth (10.8-16.4 %; Table 66), regardless of topsoil water repellence and sampling row. In repellent treatments, soil water content at the 0-5 cm depth was significantly greater in the furrow (19.5 %) than in the inter-row (16.8 %; Table 66), while soil water content at the 10-15 cm depth was significantly greater in the inter-row (11.6 %) than in the furrow (10.8 %). By contrast, in wettable treatments, soil water content at the 0-5 cm depth was significantly greater in the inter-row (29.9 %) than in the furrow (28.1 %; Table 66), while soil water content at the 10-15 cm depth was significantly greater in the furrow (16.4 %) than in the inter-row (15.7 %).

Table 66. Effect of topsoil water repellence, sampling row, and sampling depth on soil water content (%) post-harvest (51 DAS). Mean values based on a sample size of 12. Significant differences based on the least significant difference (LSD) at P < 0.05.

Row	Depth	Topsoil water repellence	
		Wettable	Repellent
Furrow	0-5 cm	$28.1^{a\dagger\Delta}$	$19.5^{a\Delta}$
	10-15 cm	$16.4^{b\dagger\Delta}$	$10.8^{b\Delta}$
Inter-row	0-5 cm	$29.9^{a\dagger}$	16.8^{a}
	10-15 cm	$15.7^{b\dagger}$	11.6^{b}

Different superscript letters denote significant differences within depth (*P* < 0.05).
† Significantly different from repellent treatments (*P* < 0.05).
$^{\Delta}$ Significantly different from the corresponding inter-row (*P* < 0.05).

5.3.7 Shoot nutrient concentrations

An assessment of nutrient concentrations in wheat whole shoots (51 DAS) found that in all treatments plants were relatively deficient in N (i.e., <6.7 %; Reuter and Robinson 1997; Appendix A.2) but were adequate in other key nutrients. Nevertheless, the shoot K and Mn concentrations were significantly affected by the two-way interaction of topsoil water repellence × topsoil thickness (*P* < 0.001; Table 67).

Table 67. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR), topsoil thickness (TT), and fertiliser placement (FP) on wheat shoot nutrient concentrations (51 DAS). Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Shoot nutrient concentration	Source of variation						
	SWR	TT	FP	SWR × TT	SWR × FP	TT × FP	SWR × TT × FP
N	34****	1^{ns}	2^{ns}	1^{ns}	2^{ns}	0^{ns}	0^{ns}
P	0^{ns}	80****	50****	1^{ns}	1^{ns}	0^{ns}	3^{ns}
K	89****	12***	46****	27****	3^{ns}	1^{ns}	0^{ns}
Ca	66****	4^{ns}	10**	1^{ns}	9**	7*	8*
Mg	1^{ns}	0^{ns}	38****	3^{ns}	8*	2^{ns}	0^{ns}
S	65****	10**	20****	3^{ns}	16****	0^{ns}	17****
B	0^{ns}	8*	22****	0^{ns}	0^{ns}	0^{ns}	0^{ns}
Cu	5*	23****	12***	1^{ns}	3^{ns}	15****	1^{ns}
Fe	4^{ns}	1^{ns}	10***	3^{ns}	0^{ns}	2^{ns}	8*
Mn	59****	89****	2^{ns}	22****	1^{ns}	1^{ns}	4^{ns}
Zn	0^{ns}	129****	64****	0^{ns}	4^{ns}	23****	8*

$^{\mathrm{ns}}$ Not significant (*P* > 0.05).

In repellent treatments, shoot K and Mn concentrations were significantly greater in treatments with a 100 mm topsoil thickness (7.22 % K and 147.3 mg Mn/kg, respectively) than a 20 mm topsoil thickness (6.53 % K and 101.6 mg Mn/kg, respectively; Table 68). Shoot Mn concentration was also significantly greater in wettable treatments with a 100 mm topsoil thickness (107.2 mg/kg) than a 20 mm topsoil thickness (91.9 mg/kg; Table 68), but topsoil thickness did not affect shoot K concentration in wettable treatments.

Table 68. Effect of topsoil water repellence and topsoil thickness on wheat shoot K and Mn concentration (51 DAS). Mean values based on a sample size of 6. Different letters denote significant differences across rows, based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	Wettable		Repellent	
	20 mm	100 mm	20 mm	100 mm
K (%)	6.20^{a}	6.06^{a}	6.53^{b}	7.22^{c}
Mn (mg/kg)	91.9^{a}	107.2^{b}	101.6^{ab}	147.3^{c}

A significant main effect of topsoil water repellence on wheat shoot N, Ca, S, and Cu was observed (*P* < 0.05; Table 67), whereby shoot N concentrations were significantly greater in repellent treatments (5.73 %) than in wettable treatments (5.43 %), but shoot Ca, S, and Cu concentrations were significantly greater in wettable treatments (0.53 % Ca, 0.49 % S, and 7.78 mg Cu/kg, respectively) than in repellent treatments (0.44 % Ca, 0.40 % S, and 7.38 mg Cu/kg, respectively; Table 69).

A significant main effect of topsoil thickness on shoot P, S, B, Cu, and Zn was observed (*P* < 0.05; Table 67), whereby shoot P, S, Ca, B, and Cu concentrations were significantly greater in treatments with a 20 mm topsoil thickness (0.82 % P, 0.46 % S, 45.0 mg B/ka, and 8.02 mg Cu/kg, respectively) than a 100 mm topsoil thickness (0.61 % P, 0.43 % S, 34.9 mg B/ka, and 7.14 mg Cu/kg, respectively), but shoot Zn concentrations were significantly greater in treatments with a 100 mm topsoil thickness (36.3 mg/kg) than a 20 mm topsoil thickness (29.9 mg/kg; Table 69).

Shoot P, K, S, B, and Fe concentrations were significantly greater (*P* < 0.01; Table 67) when fertiliser was banded below the seed (0.80 % P, 6.77 % K, 0.47 % S, 48.2 mg B/kg, and 75.0 mg Fe/kg, respectively) than away from the seed (0.64 % P, 6.24 % K, 0.42 % S, 31.7 mg B/kg, and 71.8 mg Fe/kg, respectively; Table 69). However, shoot Ca, Mg, Cu, and Zn concentrations were significantly greater (*P* < 0.01; Table 67) when fertiliser was banded away from the seed (0.50 % Ca, 0.27 %

Mg, 7.90 mg Cu/kg, and 35.4 mg Zn/kg, respectively) than below the seed (0.47 % Ca, 0.24 % Mg, 7.26 mg Cu/kg, and 30.8 mg Zn/kg, respectively; Table 69).

Table 69. Effect of topsoil water repellence, topsoil thickness, and fertiliser placement on wheat shoot nutrient concentrations (51 DAS). Mean values based on a sample size of 12. Significant differences between treatment levels denoted by an asterisk (*), based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	Topsoil water repellence	
	Wettable	Repellent
N (%)	5.43	5.73*
Ca (%)	0.53*	0.44
S (%)	0.49*	0.40
Cu (mg/kg)	7.78*	7.38
	Topsoil thickness	
	20 mm	100 mm
P (%)	0.82*	0.61
S (%)	0.46*	0.43
B (mg/kg)	45.0*	34.9
Cu (mg/kg)	8.02*	7.14
Zn (mg/kg)	29.9	36.3*
	Fertiliser placement	
	Below	Away
P (%)	0.80*	0.64
K (%)	6.77*	6.24
Ca (%)	0.47	0.50*
Mg (%)	0.24	0.27*
S (%)	0.47*	0.42
B (mg/kg)	48.2*	31.7
Cu (mg/kg)	7.26	7.90*
Fe (mg/kg)	75.0*	71.8
Zn (mg/kg)	30.8	35.4*

5.3.8 Total nutrient uptake

Treatment effects on total nutrient uptake in wheat plants at 51 DAS were assessed using a univariate ANOVA (Table 70). Differences in total nutrient uptake were strongly related to the wheat tiller number and shoot dry matter responses (see Section 5.3.9). Total uptake of N, K, Ca, Cu, Fe, Mn, and Zn was significantly affected by the two-way interaction of topsoil water repellence × topsoil thickness ($P < 0.05$; Table 70), whereby total uptake of N, K, Ca, Cu, Fe, Mn, and Zn was significantly greater in repellent treatments than in wettable treatments by an average of 83 % (Table 71), regardless of topsoil thickness.

Total uptake of N, K, Ca, Cu, Fe, and Mn was also significantly greater in wettable treatments with a 20 mm topsoil thickness than a 100 mm topsoil thickness by an average of 48 % (Table 71), with total Cu uptake also significantly greater in repellent treatments with a 20 mm topsoil thickness (7.30 µg/plant, respectively) than a 100 mm topsoil thickness (6.24 µg/plant). However, the effect of topsoil thickness on total N, K, Ca, and Fe was not observed in repellent treatments. By contrast, total Mn uptake was significantly greater in repellent treatments with a 100 mm topsoil thickness (132.3 µg/plant) than a 20 mm topsoil thickness (96.4 µg/plant; Table 71). Topsoil thickness did not affect total Zn uptake, regardless of topsoil water repellence.

Table 70. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR), topsoil thickness (TT), and fertiliser placement (FP) on wheat total nutrient uptake (51 DAS). Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Total nutrient uptake	Source of variation						
	SWR	TT	FP	SWR × TT	SWR × FP	TT × FP	SWR × TT × FP
N	108****	12***	10**	5*	3 ^{ns}	1 ^{ns}	1 ^{ns}
P	68****	58****	42****	0 ^{ns}	7*	0 ^{ns}	0 ^{ns}
K	146****	14***	21****	19****	1 ^{ns}	1 ^{ns}	0 ^{ns}
Ca	45****	14***	3 ^{ns}	9**	4 ^{ns}	5*	4 ^{ns}
Mg	78****	12***	2 ^{ns}	3 ^{ns}	3 ^{ns}	2 ^{ns}	1 ^{ns}
S	30****	30****	22****	2 ^{ns}	0 ^{ns}	0 ^{ns}	1 ^{ns}
B	16****	16****	26****	0 ^{ns}	1 ^{ns}	0 ^{ns}	0 ^{ns}
Cu	97****	45****	5*	6*	4 ^{ns}	2 ^{ns}	0 ^{ns}
Fe	110****	18****	15****	14***	1 ^{ns}	0 ^{ns}	2 ^{ns}
Mn	184****	0 ^{ns}	15****	27****	2 ^{ns}	0 ^{ns}	0 ^{ns}
Zn	78****	0 ^{ns}	1 ^{ns}	7*	0 ^{ns}	0 ^{ns}	0 ^{ns}

^{ns} Not significant ($P > 0.05$).

Table 71. Effect of topsoil water repellence and topsoil thickness on wheat total nutrient uptake (51 DAS). Mean values based on a sample size of 6. Different letters denote significant differences across rows, based on the least significant difference (LSD) at $P < 0.05$.

Total nutrient uptake	Wettable		Repellent	
	20 mm	100 mm	20 mm	100 mm
N (mg/plant)	35.9^{a}	23.3^{b}	54.3^{c}	51.4^{c}
K (mg/plant)	40.8^{a}	26.4^{b}	62.0^{c}	65.5^{c}
Ca (mg/plant)	3.36^{a}	2.35^{b}	4.10^{c}	4.06^{c}
Cu (µg/plant)	5.44^{a}	3.11^{b}	7.30^{c}	6.24^{d}
Fe (µg/plant)	47.9^{a}	31.1^{b}	69.3^{c}	68.5^{c}
Mn (µg/plant)	60.4^{a}	46.4^{b}	96.4^{c}	132.3^{d}
Zn (µg/plant)	19.5^{a}	15.7^{a}	28.4^{b}	31.9^{b}

The main effect of topsoil water repellence was, nevertheless, significant for the total uptake of all nutrients ($P < 0.001$; Table 70), whereby total uptake was significantly greater in repellent treatments than in wettable treatments by an average of 69 % (Table 72). The main effect of topsoil thickness was also significant for the total uptake of all nutrients ($P < 0.005$; Table 70), except for Mn and Zn which were not affected, whereby total uptake was significantly greater in treatments with a 20 mm topsoil thickness than a 100 mm topsoil thickness by an average of 38 % (Table 72). Moreover, the main effect of fertiliser placement was also significant for the total uptake of N, P, K, S, B, Cu, Fe, and Mn ($P < 0.05$; Table 70), whereby total uptake was significantly greater when fertiliser was banded below the seed than away from the seed by an average of 34 % (Table 72).

Table 72. Effect of topsoil water repellence, topsoil thickness, and fertiliser placement on wheat total nutrient uptake (51 DAS). Mean values based on a sample size of 12. Significant differences between treatment levels denoted by an asterisk (*), based on the least significant difference (LSD) at P < 0.05.

Total nutrient uptake	Topsoil water repellence	
	Wettable	Repellent
N (mg/plant)	29.6	52.9*
P (mg/plant)	4.04	6.71*
K (mg/plant)	33.6	63.7*
Ca (mg/plant)	2.86	4.08*
Mg (mg/plant)	1.37	2.30*
S (mg/plant)	2.71	3.66*
B (µg/plant)	23.4	36.7*
Cu (µg/plant)	4.27	6.77*
Fe (µg/plant)	39.5	68.9*
Mn (µg/plant)	53.4	114.4*
Zn (µg/plant)	17.6	30.2*
	Topsoil thickness	
	20 mm	100 mm
N (mg/plant)	45.1*	37.4
P (mg/plant)	6.61*	4.14
K (mg/plant)	51.4*	45.9
Ca (mg/plant)	3.73*	3.21
Mg (mg/plant)	2.01*	1.65
S (mg/plant)	3.66*	2.71
B (µg/plant)	36.7*	23.4
Cu (µg/plant)	6.37*	4.67
Fe (µg/plant)	58.6*	49.8
	Fertiliser placement	
	Below	Away
N (mg/plant)	44.7*	37.7
P (mg/plant)	6.42*	4.33
K (mg/plant)	55.2*	42.2
S (mg/plant)	3.59*	2.78
B (µg/plant)	38.6*	21.6
Cu (µg/plant)	5.81*	5.23
Fe (µg/plant)	60.4*	48.0
Mn (µg/plant)	93.9*	73.8

5.3.9 Bivariate correlation analysis

Bivariate correlation analysis showed that soil water content (51 DAS) at the 0-5 cm depth was strongly related to early wheat growth. However, soil water content in the furrow at the 0-5 cm depth of both wettable and repellent treatments was strongly negatively correlated with tiller number (R^2 = 0.75 and R^2 = 0.65, respectively) and very strongly negatively correlated with shoot dry matter (R^2 = 0.93 and R^2 = 0.83, respectively; Table 73). Likewise, in both wettable and repellent treatments, soil water content in the inter-row at the 0-5 cm depth was moderately negatively correlated with tiller number (R^2 = 0.59 and R^2 = 0.50, respectively) and strongly negatively correlated with shoot dry matter (R^2 = 0.62 and R^2 = 0.78, respectively; Table 73). However, soil water content at the 10-15 cm depth was not correlated with tiller number and shoot dry matter in either wettable or repellent treatments.

Table 73. Bivariate correlation (R^2 values) between soil water post-harvest and wheat shoot growth parameters in wettable and repellent treatments. Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Soil water							
	Wettable				Repellent			
	Furrow		Inter-row		Furrow		Inter-row	
	0-5 cm	10-15 cm	0-5 cm	10-15 cm	0-5 cm	10-15 cm	0-5 cm	10-15 cm
Tiller number	0.75**	0.34	0.59**	0.25	0.65**	0.07	0.50*	0.03
Shoot dry matter	0.93**	0.14	0.62**	0.21	0.83**	0.11	0.78**	0.12

In wettable treatments, soil water content in the furrow at the 0-5 cm depth was strongly negatively correlated with shoot P concentrations ($R^2 = 0.64$; Table 74) but was strongly positively correlated with Zn concentration ($R^2 = 0.73$). Soil water content in the inter-row at the 0-5 cm depth was also strongly negatively correlated with B concentration in wettable treatments ($R^2 = 0.66$; Table 74). In repellent treatments, soil water content in the furrow at the 0-5 cm depth was also moderately negatively correlated with shoot B nutrient concentration ($R^2 = 0.43$; Table 74), with soil water content in the inter-row at the 10-15 cm depth also moderately negatively correlated with shoot K and Mn concentrations ($R^2 = 0.42$ and 0.41, respectively). However, soil water content in the inter-row at the 10-15 cm depth was moderately positively correlated with shoot S concentration in repellent treatments ($R^2 = 0.40$; Table 74).

In wettable treatments, total uptake of all nutrients was strongly negatively correlated with soil water content in the furrow at the 0-5 cm depth ($0.60 \leq R^2 \leq 0.93$; Table 74) and, to a lesser extent, with soil water content in the inter-row at the 0-5 cm depth ($0.39 \leq R^2 \leq 0.84$). However, there was no correlation between total nutrient uptake and soil water content at 10-15 cm in wettable treatments. In repellent treatments, soil water content in the furrow at the 0-5 cm depth was strongly negatively correlated with total uptake of N, P, Ca, Mg, S, B, Cu, and Fe ($0.63 \leq R^2 \leq 0.95$; Table 74), and moderately negatively correlated with total K uptake ($R^2 = 0.58$) but was not correlated with total uptake of Mn or Zn. Soil water content in the inter-row at the 0-5 cm depth was also strongly negatively correlated with total uptake of N, K, Ca, Mg, S, Fe, Mn, and Zn in repellent treatments ($0.66 \leq R^2 \leq 0.83$; Table 74), and moderately negatively correlated with total B uptake in repellent treatments ($R^2 = 0.41$). Moreover, in repellent treatments, soil water content in the inter-row at the 10-15 cm depth was strongly negatively correlated with total uptake of Mn ($R^2 = 0.60$) and Zn ($R^2 = 0.62$; Table 74), with soil water content in the furrow at the 10-15 cm depth also moderately negatively correlated with total Zn uptake in repellent treatments ($0.86 \leq R^2 \leq 0.99$).

Table 74. Bivariate correlation (R^2 values) between soil water content (post-harvest) and wheat nutrient parameters (51 DAS) in wettable and repellent treatments. Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Nutrients		Soil water							
		Wettable				Repellent			
		Furrow		Inter-row		Furrow		Inter-row	
		0-5 cm	10-15 cm	0-5 cm	10-15 cm	0-5 cm	10-15 cm	0-5 cm	10-15 cm
Shoot nutrient concentration	N	0.08	0.03	0.03	0.00	0.06	0.00	0.06	0.02
	P	0.64**	0.30	0.34*	0.23	0.33	0.20	0.05	0.23
	K	0.29	0.10	0.33	0.01	0.01	0.18	0.27	0.42*
	Ca	0.26	0.22	0.12	0.10	0.09	0.11	0.07	0.17
	Mg	0.08	0.28	0.07	0.07	0.01	0.00	0.04	0.01
	S	0.19	0.07	0.26	0.00	0.02	0.29	0.03	0.40*
	B	0.32	0.05	0.66**	0.00	0.43*	0.08	0.17	0.09
	Cu	0.14	0.00	0.00	0.12	0.02	0.24	0.14	0.35*
	Fe	0.07	0.02	0.13	0.06	0.06	0.28	0.34*	0.37*
	Mn	0.41*	0.16	0.06	0.32	0.08	0.18	0.07	0.41*
	Zn	0.73**	0.50*	0.22	0.49*	0.33	0.10	0.05	0.13
Total nutrient uptake	N	0.93**	0.12	0.61**	0.19	0.84**	0.11	0.79**	0.12
	P	0.88**	0.21	0.58**	0.23	0.63**	0.03	0.31	0.04
	K	0.91**	0.15	0.65**	0.18	0.58**	0.19	0.81**	0.28
	Ca	0.82**	0.06	0.60**	0.15	0.72**	0.20	0.69**	0.24
	Mg	0.81**	0.04	0.50**	0.15	0.95**	0.12	0.70**	0.10
	S	0.81**	0.14	0.67**	0.12	0.71**	0.01	0.39*	0.02
	B	0.60**	0.08	0.84**	0.05	0.67**	0.01	0.41*	0.01
	Cu	0.85**	0.12	0.45*	0.26	0.64**	0.00	0.37*	0.01
	Fe	0.87**	0.11	0.65**	0.15	0.72**	0.17	0.83**	0.20
	Mn	0.79**	0.05	0.75**	0.07	0.17	0.35*	0.68**	0.60**
	Zn	0.68**	0.00	0.67**	0.03	0.25	0.56*	0.66**	0.62**

Despite N deficiency in wheat plants during early tillering (51 DAS), there was no correlation between shoot N concentration and shoot dry matter in either wettable or repellent treatments (Table 75). However, in wettable treatments, shoot P concentration was very strongly positively correlated with tiller number ($R^2 = 0.81$) and strongly positively correlated with dry matter ($R^2 = 0.69$; Table 75). Shoot K and B concentrations were also strongly positively correlated with tiller number ($R^2 = 0.62$). Shoot B concentrations were also moderately positively correlated with shoot dry matter in wettable treatments (R^2 0.42; Table 75). By contrast, shoot Zn concentration was strongly negatively correlated with tiller number ($R^2 = 0.74$) and shoot dry matter ($R^2 = 0.65$) in wettable treatments (Table 75). In repellent treatments, shoot P and B concentrations were also moderately positively correlated with tiller number (R^2 = 0.51 and 0.49, respectively; Table 75), while shoot Zn concentrations were moderately negatively correlated with tiller number (R^2 = 0.44).

Table 75. Bivariate correlation (R^2 values) between wheat shoot growth and nutrient parameters in wettable and repellent treatments. Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Nutrients		Wettable		Repellent	
		Tiller number	Dry matter	Tiller number	Dry matter
Shoot nutrient concentration	N	0.01	0.06	0.02	0.02
	P	0.81**	0.69**	0.51**	0.27
	K	0.62**	0.33*	0.07	0.14
	Ca	0.48*	0.30	0.00	0.05
	Mg	0.35*	0.10	0.06	0.06
	S	0.50*	0.22	0.01	0.01
	B	0.62**	0.42*	0.49*	0.33
	Cu	0.01	0.18	0.03	0.16
	Fe	0.15	0.12	0.27	0.22
	Mn	0.24	0.44*	0.11	0.02
	Zn	0.74**	0.65**	0.44*	0.33
Total nutrient uptake	N	0.75**	0.99**	0.80**	0.99**
	P	0.87**	0.96**	0.78**	0.66**
	K	0.85**	0.99**	0.61**	0.86**
	Ca	0.56**	0.87**	0.50*	0.77**
	Mg	0.48*	0.84**	0.69**	0.87**
	S	0.90**	0.90**	0.68**	0.57**
	B	0.79**	0.72**	0.69**	0.63**
	Cu	0.57**	0.92**	0.63**	0.51**
	Fe	0.81**	0.96**	0.78**	0.96**
	Mn	0.74**	0.86**	0.12	0.34*
	Zn	0.49*	0.82**	0.15	0.34*

In wettable treatments, shoot dry matter was very strongly positively correlated with total uptake of all nutrients ($0.82 \leq R^2 \leq 0.99$; Table 75), though to a lesser degree with total B uptake (R^2 = 0.72). Tiller number in wettable treatments was also very strongly positively correlated with total uptake of P, K, S, and Fe ($0.81 \leq R^2 \leq 0.90$; Table 75), strongly positively correlated with total uptake of N, B, and Mn ($0.74 \leq R^2 \leq 0.79$), and moderately positively correlated with total uptake of Ca, Mg, Cu and Zn ($0.48 \leq R^2 \leq 0.57$). In repellent treatments, shoot dry matter was also very strongly positively correlated with total uptake of N, K, Mg, and Fe ($0.86 \leq R^2 \leq 0.99$; Table 75), strongly positively correlated with total uptake of P, Ca, and B ($0.63 \leq R^2 \leq 0.77$), and moderately positively correlated with total uptake of S and Cu (R^2 = 0.57 and 0.51, respectively). Tiller number in repellent treatments was also very strongly positively correlated with total N uptake (R^2 = 0.80; Table 75), strongly positively correlated with total uptake of P, K, Mg, S, B, Cu, and Fe ($0.61 \leq R^2 \leq 0.78$), and moderately positively correlated with total Ca uptake (R^2 = 0.50). Total uptake of Mn and Zn was not correlated with tiller number or shoot dry matter in repellent treatments.

5.4 Discussion

Soil water repellence adversely affects crop growth and yield due to uneven soil wetting, reduced soil water storage, and the prevalence of dry soil patches (Doerr *et al.* 2000; Kramers *et al.* 2005; Roper *et al.* 2015; Li *et al.* 2019). The same processes are likely to affect the availability of nutrients from soil and fertiliser (Blackwell 1993). However, contrary to the hypothesis that plant growth and nutrient uptake would be impeded on water-repellent sandy soils, this glasshouse study demonstrated that severely repellent sandy loam topsoil significantly improved wheat tiller number (by up to 2 tillers; 46 DAS), shoot dry matter production (by 77 %; 51 DAS), and total nutrient uptake (by 69 %; 51 DAS) per plant relative to completely wettable topsoil treatments, under regular but low water supply (4.2 mm every two days; average day air temperature of 19°C and relative humidity of 36 %). Water infiltration did not cause drainage from the base of treatment containers even in the wettable furrow of repellent treatments, which was presumed to have resulted in preferential flow. Moreover, planting in the wettable furrow ensured that plant density was the same in all treatments and did confound responses to wettable topsoil, topsoil thickness, or fertiliser placement. The positive effects of severely repellent sandy loam topsoil on wheat seedling growth were evident by 23 DAS with the emergence of one additional leaf. Root data for this equivalent early growth period is not available. It is possible that the root data from 51 DAS was too late to reflect the early effects of soil wetting patterns on root growth and nutrient uptake, given the significant influence of fertiliser placement on localised root proliferation and lateral root elongation (see Section 5.3.4). Results, nevertheless, showed that water infiltration in the wettable furrow of repellent treatments with a 100 mm topsoil thickness significantly increased wheat RLD (51 DAS) at the 0-5 cm depth by 65 % and total RLD by 20 % relative to wettable treatments. Shoot N and K concentrations (51 DAS) were also significantly greater in repellent treatments than in wettable treatments, although wheat plants in all treatments were relatively deficient in N (<6.7 %) but adequate in K (i.e., >4.1 %; Reuter and Robinson 1997). These results suggest that potential increases in soil water availability at depth and mobilisation of nutrients from the fertiliser band in the furrow of repellent treatments were conducive to root growth and plant uptake under regular but low water supply. Consequently, the increase in plant growth and hence water uptake would then explain why soil water post-harvest (51 DAS) was significantly lower in repellent treatments than in wettable treatments, especially at the 0-5 cm depth, and this was supported by bivariate correlation analysis.

While all plants were well-hydrated (leaf RWC > 90 %), the same water applied in wettable treatments was presumably less efficiently utilised by plants due to the greater retention of water close to the surface which ultimately reduces wetting depth. This effect would be particularly pronounced during early establishment since root systems are small and plant uptake is constrained by limited soil-root contact (Andresen *et al.* 2016). Increased retention of soil water in the wettable upper soil layer would also result in increased evaporative losses of soil water (Bachmann *et al.* 2001; Rye and Smettem 2017) and this can adversely affect early plant growth due to an overall reduction in plant-available water (Gupta *et al.* 2015). By contrast, evaporation is lessened in water-repellent soils due to a reduction in upward capillary movement of water (DeBano 1981) and the diversion of water to the subsoil via preferential flow pathways (Ritsema and Dekker 1994). An overall decrease in soil water availability in wettable treatments would consequently reduce the root volume explored (Lobet *et al.* 2014) and hinder the flux of nutrients to the root, given that nutrient release (dissolution, desorption, and mineralisation; Barber 1995) and transport (mass flow and diffusion; Oliveira *et al.* 2010) are mechanisms intrinsically dependent on the soil solution (Mengel 1995). While soil water post-harvest at the 0-5 cm depth was comparably higher in wettable treatments (28.1-29.9 %) than in repellent treatments (16.8-19.5 %), differences could be explained by higher plant uptake in repellent treatments as a result of greater wheat shoot dry matter (by 77 %) and greater RLD at the 0-5 cm depth (by up to 65 %). These results suggest that, provided there was sufficient water and nutrient supply in the root zone, topsoil water repellence did not adversely affect early wheat root growth and nutrient uptake in the inter-row, despite a potential reduction in plant-accessible soil volume due to prolonged soil dryness (approximately 30 days). However, the increased prevalence of dry soil is likely to hinder plant nutrient use efficiency in water-repellent soils as roots are unable to forage therein (Roper *et al.* 2015).

Compared to the bulk volume of soil, preferential paths are potentially enriched zones of water, nutrients, and organic substrate (Bundt *et al.* 2001; Guggenberger and Kaiser 2003; Morales *et al.* 2010) and would, therefore, provide ‘hotspots’ for root foraging and nutrient acquisition in water-repellent soils. Under a heterogeneous nutrient supply, studies have shown that preferential root placement, root proliferation, and increased uptake kinetics in localised resource-enriched zones can result in increased plant nutrient use efficiency, early biomass, and nutrient accumulation in shoots (Day *et al.* 2003a; Rose *et al.* 2009; Ma *et al.* 2011), even if uptake is suppressed in deficient zones (Robinson 1994). Such positive responses to soil nutrient heterogeneity have been reported in various crops such as wheat (Trapeznikov *et al.* 2003; Ma *et al.* 2007; Ma and Rengel 2008), barley (Drew 1975; Drew and Saker 1978), maize (Li *et al.* 2012; Yu *et al.* 2014), canola (Rose *et al.* 2009), and lupin (Ma *et al.* 2011), and in perennial grasses (Day *et al.* 2003c). In this study, the observed increases in early growth and nutrient uptake in repellent treatments could also be explained by an overall increase in root growth (at the 0-5 cm depth) and root uptake kinetics in response to preferential flow in the furrow as opposed to that in wettable treatments. Follow up studies that investigate the early root growth responses in the water-repellent sands would help to verify this explanation, because in the present study root measurements at 51 DAS were apparently too late to reflect the growth responses that were already evident at 23 DAS.

Enhanced plant vigor in the early developmental stages of growth is desirable for the uptake of key macronutrients such as N (for canopy development and photosynthesis; Pang *et al.* 2014; Sarkar and Baishya 2017), P (for plant metabolism and root development; Grant *et al.* 2001; Fageria and Moreira 2011), K (for the regulation of various cellular processes; Mallarino *et al.* 1999; Kant *et al.* 2005), and S (for the formation of enzymes, amino acids, and protein structures in plants; Zhao *et al.* 1997; Naeem and MacRitchie 2003) which strongly determine crop yield, quality, and resistance to pests and environmental stress (Dordas 2008; Kumar and Sharma 2013). In this study, early wheat growth was presumably limited by N due to its relative deficiency in plant shoots. Increases in shoot N concentration were, therefore, expected to contribute greatly to the observed improvements in shoot growth and indirectly the uptake of other nutrients in repellent treatments relative to wettable treatments. However, results showed no correlation between shoot N concentration and shoot growth parameters. By contrast, shoot P concentration was found to be strongly positively correlated with tiller number (R^2 = 0.81) and dry matter (R^2 = 0.69) in wettable treatments, and moderately positively correlated with tiller number (R^2 =

0.51) in repellent treatments, suggesting that overall early P nutrition may have been more important than N nutrition. Although shoot Zn concentration was also found to be strongly negatively correlated with tiller number and dry matter in wettable treatments, this was likely due to a dilution effect on Zn in plant tissue (Imtiaz *et al.* 2003). The lack of correlation between shoot nutrient concentrations and shoot growth in repellent treatments may indicate that, with improved water availability at depth due to preferential flow, there was sufficient nutrient availability from fertiliser and soil reserves for early growth.

Increasing early root development and rooting depth during plant establishment will also enable greater exploitation of the soil matrix, increasing water and nutrient uptake which leads to more vigorous plant growth (Andresen *et al.* 2016) and consequently higher yields (Fageria and Moreira 2011). In arid and semi-arid dryland cropping systems, increasing early root development would also confer to plants greater tolerance to stress due to greater access to subsurface water and nutrient supplies (Shao *et al.* 2008; Fageria and Moreira 2011) and also enhance early uptake and use efficiency of fertiliser due to increased recovery of mobile nutrients, particularly N, in sandy soils (Liao *et al.* 2004; Liao *et al.* 2006). By contrast, soils with limited wetting depth may result in the development of shallow root systems that are prone to rapid drying (Weaver 1926; Dunbabin *et al.* 2003) and this may in part explain why seedling development, tiller number, shoot dry matter production, RLD at the 0-5 cm depth, and total nutrient uptake (particularly N and K nutrition) in wheat were significantly limited in wettable treatments compared to that in repellent treatments.

Reductions in seedling development (Z13.0 to Z12.8), shoot dry matter (by 35 %) and total uptake of N, K, Ca, Cu, Fe, and Mn per plant (by an average of 32 %) were also more pronounced in wettable treatments with a 100 mm topsoil thickness than a 20 mm topsoil thickness, suggesting that increased water retention in the upper topsoil layer due to thicker topsoil resulted in an overall reduction plant-available water and plant water use efficiency. This could also explain why RLD at the 15-20 cm depth was also found to be 43 % lower in wettable treatments with a 100 mm topsoil thickness than a 20 mm topsoil thickness, while RLD at the 5-10 cm depth was 29 % greater in wettable treatments with a 100 mm topsoil thickness than a 20 mm topsoil thickness, despite no effect on total RLD. In repellent treatments, a thicker (100 mm) topsoil also favoured wheat RLD at the 0-5 and 5-10 cm depths (by 27 and 67 %, respectively) and total RLD (by 25 %), but such increases did not result in further increases in early dry matter.

Regardless of topsoil water repellence and topsoil thickness, nutrient placement closer to the root zone can, nevertheless, stimulate early growth and plant vigour by increasing their accessibility to plant roots early in the growing season (Mahler 1985). This is particularly important for immobile nutrients such as P which tend to stratify within fertilised topsoil (Ma *et al.* 2009) and cannot be sufficiently transported by mass flow or diffusion (Marschner 2002; Jones and Jacobsen 2009). In this study, banding fertiliser below the seed significantly increased wheat shoot dry matter (by 19 %), shoot P, K, S, B, and Fe concentrations (by 25, 8, 12, 52, and 4 %, respectively), and the total uptake of N, P, K, S, B, Cu, Fe, and Mn per plant (by 34 % on average) relative to inter-row placement.

In summary, under limited water supply, preferential water flow in the wettable furrow of severely repellent topsoil treatments highly favoured early wheat growth and nutrient uptake compared to uniform wetting in completely wettable topsoil treatments, despite prolonged soil dryness in repellent inter-rows. However, treatment effects now need to be assessed under higher water supply, especially where excessive leaching of water and nutrients are likely to have adverse implications for plant growth (van der Paauw 1962). Nevertheless, field studies employing similar techniques involving furrow sowing and banded wetting agents in water-repellent soils have also reported that promoting more uniform and deeper wetting depths along the furrow can significantly increase germination and yield of various crops (wheat, barley, and lupin; Crabtree and Gilkes 1999a; Crabtree and Henderson 1999) and pastures (subterranean clover, dryland lucerne, tagasaste, phalaris, and perennial ryegrass; Crabtree and Gilkes 1999b) when used in combination with press-wheels for improved furrow definition and seed-soil contact. The potential to enhance rainfall and runoff capture (water harvesting) could, therefore, play an important role in early plant establishment on water-repellent soils, particularly in semi-arid and Mediterranean dryland cropping systems where seasonal water deficits are common (Blackwell 2000; DeBano 2000b; Roper *et al.* 2015). Additional studies should then be carried out under variable water supply and plant density to better understand the dynamic responses of early wheat growth and nutrition to topsoil water repellence, with added detail on soil water and nutrient availability. Assessments should also be conducted earlier (<50 days) to reduce compensatory effects of root and shoot growth recovery as the water repellence effects can dissipate in topsoil over time (Crockford *et al.* 1991).

5.5 Conclusions

Severely water-repellent sandy loam topsoil with a wettable furrow and uniform plant density significantly improved wheat seedling development, tiller number, shoot dry matter, shoot N and K concentrations, and total nutrient uptake per plant (51 DAS) relative to completely wettable topsoil treatments, under regular but low water supply, regardless of topsoil thickness (20 or 100 mm) and fertiliser band placement (below or away from the seed). Water infiltration in the wettable furrow of repellent treatments with a 100 mm topsoil thickness was also found to increase wheat RLD (51 DAS) at the 0-5 cm depth by 65 % and total RLD by 20 % relative to wettable treatments. Such increases in early growth and nutrient uptake in repellent treatments were attributed to preferential flow in the wettable furrow which increased soil water availability in the root zone without causing drainage from the base of treatment containers. While topsoil thickness was not important in repellent treatments, wettable treatments with a 100 mm topsoil thickness significantly reduced wheat growth and nutrient uptake relative to wettable treatments with a 20 mm topsoil thickness. This was presumably due to an overall decrease in plant-available water and plant water use efficiency during the early growth period. Results highlight the importance of water access by the roots for early wheat growth and nutrient uptake, under a limited water supply, in a water-repellent sand. Employing water harvesting techniques such as furrow sowing with banding wetting agents which also ensure uniform plant density can, therefore, play an important role in improving early crop establishment on water-repellent soils, particularly in water-limited dryland cropping systems. Validation studies should be conducted to assess in more detail the efficacy of *in situ* water harvesting on water-repellent soils and the effects on soil water and nutrient availability at depth. How early wheat growth and nutrition may respond to other factors such as water supply, surface topography, and plant density which should also be studied given their relevance for semi-arid and Mediterranean dryland crop production on water-repellent soils.

Chapter 6: **Effect of topsoil water repellence on early wheat growth and nutrition under variable low water supply**

6.1 Introduction

Dryland crop production in arid and semi-arid regions is strongly limited by erratic rainfall distribution and the occurrence of unpredictable droughts during the growing season (Kronen 1994). In water-repellent soils, impaired water infiltration (Roberts and Carbon 1971; Wang *et al.* 2000; Li *et al.* 2018), increased surface runoff and soil erosion (Witter *et al.* 1991; Shakesby *et al.* 2000; Doerr *et al.* 2003), and unstable wetting and preferential flow patterns (Ritsema and Dekker 1994; Bauters *et al.* 1998; Wallach 2010) could further constrain crop production due to increased spatial variability of stored soil moisture (Dekker and Ritsema 1996b) and an overall reduction in soil water storage capacity (Jordán *et al.* 2009) and plant water uptake (Li *et al.* 2019) that collectively decrease plant germination and growth (Bond 1964; Bond 1972; Unkovich *et al.* 2015). However, in contrast to the prediction that soil water repellence would adversely affect plant growth and nutrition (Doerr *et al.* 2000; Kramers *et al.* 2005; Roper *et al.* 2015; Li *et al.* 2019), earlier findings from a controlled glasshouse experiment (Chapter 5) showed that, under uniform plant density, severely water-repellent topsoil with a wettable furrow significantly increased early wheat growth and nutrient uptake by nearly 70 % in comparison to completely wettable topsoil. Given that watering did not cause leaching beyond treatment containers, preferential flow in the wettable furrow of repellent treatments was presumed to have contributed to the improved access to water and nutrient for plant growth.

Preferential flow in the furrow (planting zone) of water-repellent soils can be considered a mechanism for *in situ* water harvesting (Blackwell 1993) which is analogous to the ridge and furrow rainwater harvesting (RFRH) systems already implemented in many semi-arid dryland agricultural areas of the world, especially in

China (Boers and Ben-Asher 1982; Hatibu and Mahoo 1999; Li 2003; Turner 2004; Liu *et al.* 2005; Sturm *et al.* 2009; Gan *et al.* 2013; Liu and Jin 2016). For example, in central and northwest China, RFRH systems utilising surface mulches (e.g., plastic film, plant residue, gravel-sand materials to cover ridges and/or furrows) have been widely adopted to improve soil water, water use efficiency, nutrient uptake, and yield of corn (Li *et al.* 2000; Li *et al.* 2001; Ren *et al.* 2008; Wang *et al.* 2011), wheat (Li *et al.* 1999; Ren *et al.* 2016; Liu *et al.* 2018), canola (Gu *et al.* 2017; Gu *et al.* 2019), sweet sorghum (Wang *et al.* 2009b), foxtail millet (Lian *et al.* 2017), oats (Qi *et al.* 2015), alfalfa (Jia *et al.* 2006), sunflower (Pan *et al.* 2019), and potatoes (Wang *et al.* 2008). Likewise, El-Sadek and Salem (2015) has also demonstrated similar RFRH systems to improve faba bean production and water use efficiency in the arid North Western Coastal Zone of Egypt in comparison to conventional cultivation in flat bare soil. Other forms of *in situ* water harvesting using tied ridges and contour ridges have also been documented to improve crop production in semi-arid dryland cropping regions in Ethiopia (Araya and Stroosnijder 2010; Milkias *et al.* 2018) and Zimbabwe (Motsi *et al.* 2004).

Applying the same water harvesting principles in Australian agricultural systems can, therefore, be an effective method for capturing small rainfall events for dryland crop production on water-repellent soils (Blackwell 1993; Roper *et al.* 2015). Such water-repellent properties of the soil are also known to aid in soil water conservation by significantly reducing evaporative water loss from the soil surface (Bachmann *et al.* 2001; Rye and Smettem 2017) as a result of decreasing the upward capillary movement of water (DeBano 1981) and diverting water to subsurface layers via preferential flow pathways (Ritsema and Dekker 1994). Gupta *et al.* (2015) found that soils treated with a water-repellent surface layer saved up to 90 % water in comparison to wettable control soils, with water loss increasing as the relative area of wettable soil increases. They also found that the shoot and root growth of young chickpea (*Cicer arietinum*) plants significantly increased in repellent treatments relative to the control, with plant biomass increasing as much as 16.5 %. In another study, Salem *et al.* (2010) also reported an increase in plant height and root length of lettuce (*Lactuca sativa*) in soils treated with a subsurface layer of water-repellent sand in comparison to control soils. In this way, soil water in the root zone was retained for longer, favouring plant uptake and increasing plant resistance to water stress compared to the control.

The application of water-repellent soil for soil water conservation and crop production has, therefore, gained interest in recent times (Alazawi 2015; Kianmeher *et al.* 2016). However, despite these potential benefits for *in situ* water harvesting and soil water conservation, there is still more to be understood about the agronomy of naturally water-repellent agricultural soils in southwest Western Australia. To validate the efficacy of water-repellent soils for *in situ* water harvesting, a second controlled glasshouse experiment was conducted to examine the effect of topsoil water repellence (nil and severe) on early wheat growth and nutrition under variable but not excessive water supply (3.4, 4.4, and 5.4 mm every 2 days). It was hypothesised that plant growth and nutrient uptake will be higher in repellent treatments than in wettable treatments, regardless of water supply, so long as enough water can be harvested in the furrow from preferential flow. However, as the water supply increases, the effect of water harvesting on early wheat growth and nutrition will likely decrease due to a general increase in soil wetting depth and the attenuation of soil moisture differentials in the furrow and/or root zone.

6.2 Materials and methods

6.2.1 Treatment design

Wheat (*Triticum aestivum* cv. Mace) was grown over 40 days, from 2 October to 11 November 2018, under controlled glasshouse conditions at Murdoch University (32°04’02.30” S 115°50’20.21” E), Western Australia, to investigate the effects of (a) topsoil water repellence (wettable or severely repellent topsoil), and (b) water supply (3.4, 4.4, or 5.4 mm every 2 days) on early vegetative growth and nutrition. The same water-repellent topsoil (0-10 cm; a gravelly sandy loam duplex soil (Ferric Chromosol, ASC) in Kojonup (33°41’08.83” S, 117°01’54.01” E) and wettable subsoil (10-30 cm; a grey deep sandy duplex soil (Grey Bleached-Ferric Kandosol, ASC) at Meckering (31°37’38.22” S, 116°52’16.53” E) were used as in Chapter 5. Bulk soils were air-dried, sieved (≤2 mm) to remove gravel and coarse material, and thoroughly mixed in a cement mixer. Baseline soil properties of repellent topsoil, wettable topsoil, and wettable subsoil are detailed in Table 76. After processing, the repellent topsoil had a molarity of ethanol droplet (MED) value of 1.0 (i.e., low repellence; King 1981). The low severity of water repellence in these soils may be due to the soils already being wet when collected from the field before air-drying in the glasshouse. However, the same soils were found to develop severe water repellence by Day 12 (MED 3.0; see Section 6.3.1). Wettable topsoil was prepared by spraying and mixing approximately 50 ml of 3 % v/v solution of wetting agent (Everydrop Liquid Concentrate by Scotts Australia Pty Ltd) per kilogram of water-repellent topsoil in a cement mixer. Note, there were no added nutrients in this soil wetting agent. All soils were left to air-dry before being used to prepare treatments.

Table 76. Baseline properties of topsoil and subsoil used in treatment containers.

Soil properties	Topsoil*		Subsoil
	Wettable	Repellent	
pH_{Ca} ($CaCl_2$)	5.0	4.5	5.4
Organic carbon (g/kg)	32.6	32.8	0.5
Electrical conductivity (dS/m)	0.1	0.1	0.0
NH_4-N (mg/kg)	12.7	6.3	< 1.0
NO_3-N (mg/kg)	41.0	39.7	6.0
Colwell P (mg/kg)	58.7	129.3	11.0
Colwell K (mg/kg)	126.7	92.0	17.0
Effective cation exchange capacity (cmol(+)/kg)	6.65	4.14	0.70
Exchangeable Ca (cmol(+)/kg)	5.37	2.82	0.47
Exchangeable Mg (cmol(+)/kg)	0.66	0.30	0.08
Exchangeable K (cmol(+)/kg)	0.25	0.17	0.04
Exchangeable Na (cmol(+)/kg)	0.12	0.03	0.02
Exchangeable Al (cmol(+)/kg)	0.25	0.83	0.09
Extractable S (mg/kg)	36.8	13.3	2.0
Extractable B (mg/kg)	0.58	0.41	0.11
Extractable Cu (mg/kg)	0.72	1.01	0.21
Extractable Fe (mg/kg)	28.9	39.8	10.9
Extractable Mn (mg/kg)	3.68	5.62	0.26
Extractable Zn (mg/kg)	0.83	1.44	0.17
Sand (g/kg)	792.3	758.0	871.0
Silt (g/kg)	46.0	60.5	34.0
Clay (g/kg)	161.7	181.5	95.0

* Note, due to inadequate mixing of topsoil batches prior to the preparation of wettable topsoil, soil Colwell P concentration was different between wettable and repellent treatments.

Drainage holes were drilled in each container and shade cloth was placed along the bottom to prevent soil spillage. Subsoil (10 cm depth) and topsoil (10 cm depth) were layered in each container for a total depth of 20 cm, with ridges of approximately 2 cm high in the inter-rows and a row spacing of 20 cm. Containers were tapped on the ground to re-compact the soil layers to a bulk density of 1.7 g/cm^3. This bulk density was higher than that in the field (1.4-1.5 g/cm^3) due to the removal of coarse material (≤2 mm) and gravel. At the 7 cm depth, granular fertiliser (Growers Blue) was banded in the furrow at the following rate (mg/kg): 60 N, 25 P, 70 K, 6 Mg, 49 S, 0.5 Zn, 0.1 B, 0.3 Mn, and 0.1 Cu. Sixteen wheat seeds were sown at the 2 cm depth in a wettable furrow, equivalent to a rate of 125 seeds/m^2. Approximately 300 g of wettable topsoil was used for the furrow in repellent treatments to ensure uniform germination. Plants were reduced to a uniform plant density of 15 plants per container (equivalent to 125 plants/m^2). A total of 6 treatment combinations and three replications were arranged in a full factorial completely randomised design, with the general design of a plant-growth container illustrated in Figure 70.

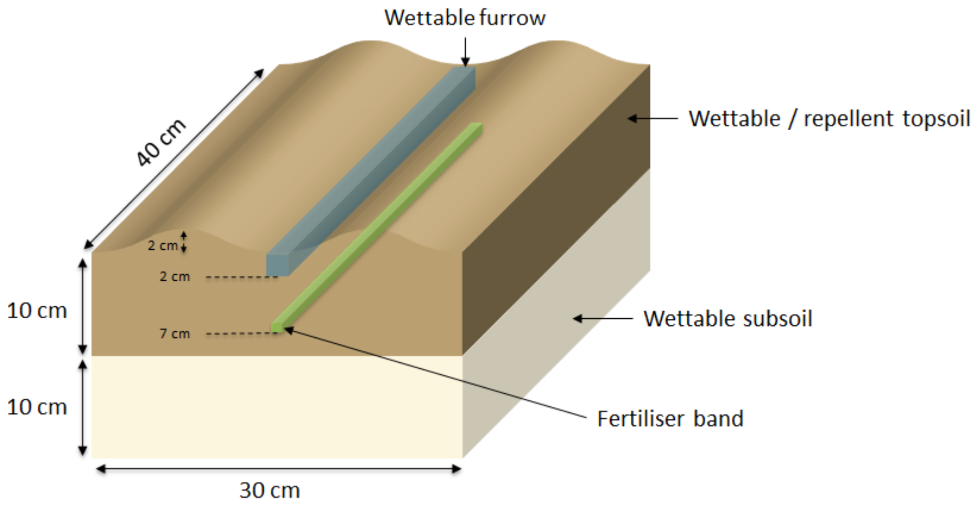

Figure 70. General design of a plant-growth container with wheat sown in a wettable furrow and fertiliser banded below the seed, in either wettable or severely repellent treatments.

In-situ soil volumetric water content (VWC, m^3/m^3) and soil electrical conductivity (EC, mS/cm) were measured over time in separate containers, with four Decagon 5TE sensors buried horizontally at the 5 and 15 cm depths in the furrow and inter-row. Four holes (1 cm diameter) were drilled in the side of the containers for the sensor cords and re-sealed with electrical tape. Containers were hand watered every 2 days using a sprinkle bar over the whole container, with three watering treatments: (i) 3.4 mm (415 ml), (ii) 4.4 mm (540 ml), and (iii) 5.4 mm (665 ml) over a duration of 5 minutes, whereby ~4.2 mm (520 ml) was the standard watering application used in Chapter 5, equivalent to a rainfall intensity of 52.3 mm/h with a 63.2 % annual exceedance probability (AEP) for the field site in Kojonup (Bureau of Meteorology 2018). Given a total of 20 separate wetting events, the total amount of water supplied to each treatment container was 68, 88, and 108 mm over 41 days, respectively, but none of the watering treatments caused drainage out of the container. The glasshouse had an average day air temperature of 18°C and relative humidity of 40 %. Treatment containers were re-positioned randomly every week to eliminate bias from environmental factors (e.g., sunlight exposure, microclimate, and microtopography).

Note, the studied watering regimes were generally related to dryland cropping systems in the medium (325-450 mm) to high (450-750 mm) rainfall zones of southwest WA, where crops are often sown on the first major rainfall between May and June in dryland regions of the wheatbelt of southwest WA (Liao *et al.* 2006). For crops sown at the beginning of June, the mean total amount of rainfall received over June to July could, therefore, be 147-173 mm (*ca*. 99-116 mm over 41 days) at Kojonup and Badgingarra (high rainfall zone; 450-750 mm; Table 77), 87-115 mm (*ca*. 58-77 mm over 41 days) at Meckering and Merredin (medium rainfall zone; 325-450 mm), or 63-81 mm (*ca*. 42-54 mm over 41 days) at Southern Cross and Dalwallinu (low rainfall zone; <325 mm). However, an equivalent water regimen for low rainfall areas was not included in this experiment.

Table 77. Mean monthly rainfall in Kojonup (1985-2016), Badgingarra (1985-2016), Meckering (Mount Noddy; 2008-2016), Merredin (1985-2016), Southern Cross (1997-2016), and Dalwallinu (1997-2016), Western Australia.

Location	Mean monthly rainfall (mm)												Mean annual rainfall (mm)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Kojonup	17.1	9.7	22.8	35.3	58.2	68.3	78.4	68.5	50.1	28.2	26.8	16.0	483.3
Badgingarra	11.7	12.7	17.5	23.4	60.8	72.8	99.8	75.9	50.6	21.6	18.4	8.5	493.4
Meckering	17.7	14.0	32.6	26.0	35.9	40.7	74.1	44.5	34.6	22.9	19.6	17.7	380.2
Merredin	23.4	17.1	22.5	23.3	38.8	40.0	46.8	38.5	26.2	16.2	16.9	17.5	327.2
Southern Cross	30.6	22.3	36.0	24.4	29.2	27.3	35.3	30.0	21.2	17.1	16.3	16.4	306.0
Dalwallinu	22.7	10.2	26.9	14.5	36.4	32.4	48.1	37.3	25.9	13.3	9.2	13.6	290.7

6.2.2 Soil and plant sampling and analysis

Soil was sampled post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths and analysed for ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), Colwell phosphorus (P), and Colwell potassium (K) according to standard methods (Rayment and Lyons 2011) by the CSBP Soil and Plant Analysis Laboratory. Note, due to furrow infill from ridge erosion and soil compaction over time from watering, the height difference between the base of the furrow and tip of the ridge generally diminished from 20 mm (initial ridge construction at 0 DAS) to ≤5 mm (41 DAS). Slight differences in soil sampling depth between the furrow and inter-row were thus considered to have no significant confounding influence on the relative soil layers assessed for soil nutrient availability.

In a separate treatment container, ‘actual’ soil water repellence severity was assessed *in situ* at the 2 cm depth in the inter-row using the molarity of ethanol droplet, MED, test (King 1981). Soil water repellence severity was denoted by the MED concentration that penetrated the soil surface within 10 seconds. Soil MED tests were conducted at solar noon (±2 hours) prior to watering every 2 days at different locations in the inter-row.

Wheat seedling growth stage (20 days after sowing, DAS) and tiller numbers (38 DAS) were assessed and aboveground biomass (40 DAS) was harvested and oven-dried at 60°C to determine shoot dry matter per plant. Wheat hydration was also assessed (40 DAS) by measuring the relative water content (RWC, %) or ‘relative turgidity’ in young fully expanded leaves (Barrs and Weatherley 1962; Mullan and Pietragalla 2012). Nutrient concentrations in wheat whole shoot samples were analysed using standard methods (Rayment and Lyons 2011) by the CSBP Soil and Plant Analysis Laboratory. Total nutrient uptake was also determined from shoot dry matter and are expressed in terms of mass per plant.

6.2.3 Statistical analysis

Parametric statistical analyses were carried out using SPSS Statistics version 21.0 (IBM Corporation, Armonk, NY, USA) to determine the effect(s) of (a) soil water repellence, and (b) water supply on early wheat growth and nutrient uptake (40 DAS). Assumptions of normality and homogeneity of variances were assessed and, where the assumptions were violated, data were transformed using a $\log_{10}$ transformation. Main effects and interactions for wheat shoot growth and nutrient uptake were analysed using the univariate analysis of variance, ANOVA (two-tail) test in SPSS. Soil nutrients post-harvest (41 DAS) were analysed in a mixed model ANOVA in SPSS, using topsoil water repellence and water supply as between-subjects variables with repeated measures for sampling row and depth as the within-subjects variable. Post hoc analysis was performed using Fisher’s least significant difference (LSD) at $P < 0.05$ to determine significant differences among treatment factors. Bivariate correlation analysis was also conducted in SPSS to study key relationships between soil water, nutrient availability, and wheat shoot growth and nutrition parameters, with significant correlations (two-tailed) interpreted by the Coefficient of Determination

(R^2) at the 95 and 99 % confidence intervals. The relative strength of correlation was classed as: weak ($R^2 \leq 0.39$), moderate ($0.40 \leq R^2 \leq 0.59$), strong ($0.60 \leq R^2 \leq 0.79$), and very strong ($0.80 \leq R^2 \leq 1.00$). Supplementary data will be provided in Appendix E:.

6.3 Results

6.3.1 Soil water repellence

Severity of topsoil water repellence at the 2 cm depth in the inter-row was measured at solar noon (±2 hours) prior to watering every 2 days over 41 days (Figure 71). Topsoil prior to the first watering event was slightly repellent (MED 1.0) on Day 1 but steadily became very severely repellent (MED 3.2) on Day 17. Topsoil water repellence severity thereafter remained relatively constant despite a slight decrease from Day 27 (MED 3.2) to Day 41 (MED 2.8).

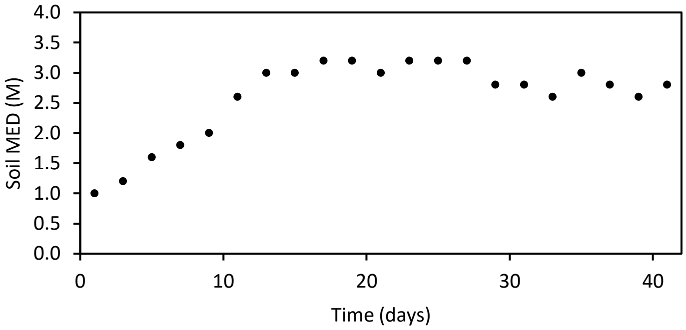

Figure 71. Severity of topsoil water repellence in the inter-row over 41 days, assessed by the molarity of ethanol droplet (MED) test every 2 days at solar noon (±2 hours) prior to watering.

6.3.2 Seedling development

Results showed that wheat seedling phenological development (20 DAS; Zadoks' growth scale) was significantly affected by the two-way interaction of topsoil water repellence × water supply ($P < 0.01$; Table 78). Seedling produced an extra leaf in repellent treatments (Z13.0-13.5) relative to wettable treatments (Z12.8-12.9; Figure 72a), regardless of water supply. In repellent treatments, seedling development significantly increased from Z13.0 to Z13.5 as the water supply increased from 3.4 to

5.4 mm. In wettable treatments, seedling development also significantly increased from Z12.8 to Z12.9 as the water supply increased from 3.4 to 4.4 mm but was not different to that in treatments with a 5.4 mm water supply.

Table 78. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR) and water supply (Water) on wheat seedling development (Zadoks' growth scale), tiller number, shoot dry matter, and leaf relative water content (RWC). Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Source of variation	Seedling stage	Tiller number	Dry matter	Leaf RWC
SWR	85****	693****	353****	18****
Water	16****	612****	199****	18****
SWR × Water	7**	127****	18****	1 ^{ns}

^{ns} Not significant ($P > 0.05$).

6.3.3 Tiller number

Wheat tiller number per plant (38 DAS) was significantly affected by the two-way interaction of topsoil water repellence × water supply ($P < 0.001$; Table 78). Tiller number was significantly greater in repellent treatments (0.2-2.8 tillers per plant) than in wettable treatments (0.0-1.2 tillers per plant; Figure 72b), regardless of water supply. Tiller number also significantly increased (from 0.0-0.2 to 1.2-2.8 tillers per plant) when the water supply increased from 3.4 to 5.4 mm, regardless of topsoil water repellence.

6.3.4 Shoot dry matter

Wheat shoot dry matter per plant (40 DAS) was significantly affected by the two-way interaction of topsoil water repellence × water supply ($P < 0.001$; Table 78). Shoot dry matter was significantly greater in repellent treatments (0.30-0.87 g/plant) than in wettable treatments by an average of 152 % (0.09-0.40 g/plant; Figure 72c), regardless of water supply, with a more pronounced increase in shoot dry matter in treatments with 3.4 mm water supply (by 220 %) than 4.4 (by 117 %) or 5.4 mm water supply (by 118 %). As the water supply increased from 3.4 to 5.4 mm, shoot dry matter also significantly increased by 328 % in wettable treatments (from 0.09 to 0.40 g/plant) and 191 % in repellent treatments (from 0.30 to 0.87 g/plant). The relative differences in shoot growth between treatments can also be observed in Figure 73.

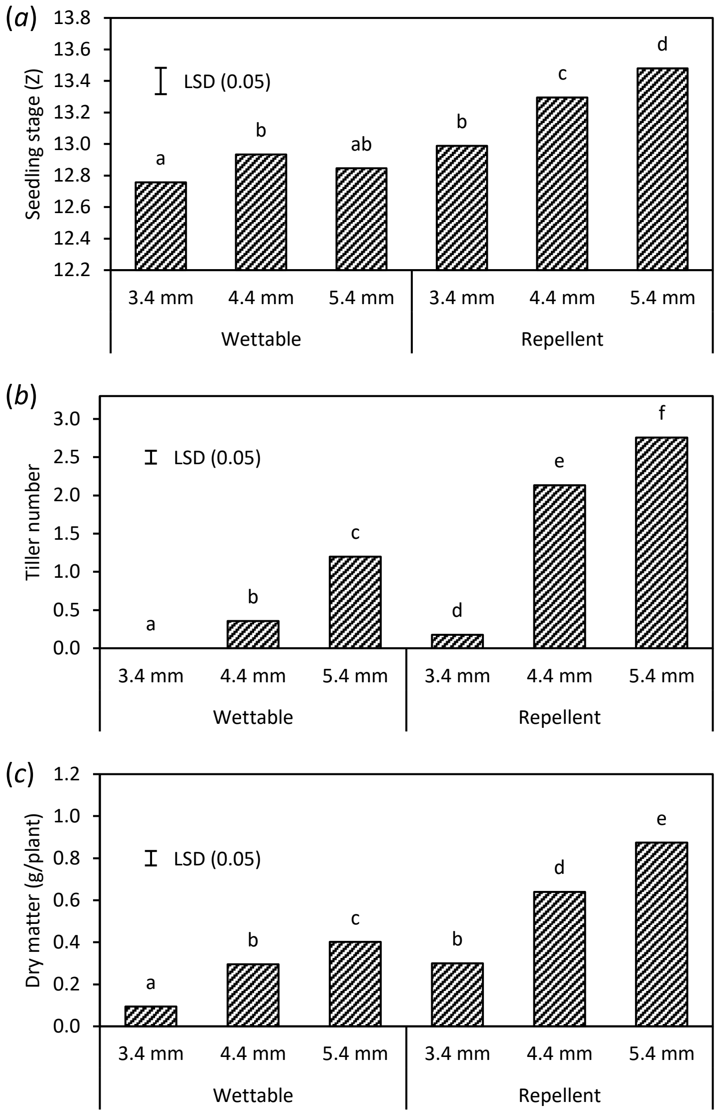

Figure 72. Effect of topsoil water repellence and water supply on (a) wheat seedling development (Zadoks' growth scale, Z) at 20 DAS, (b) tiller number per plant at 38 DAS, and (c) shoot dry matter (g/plant) at 40 DAS. Mean values based on a sample size of 3. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

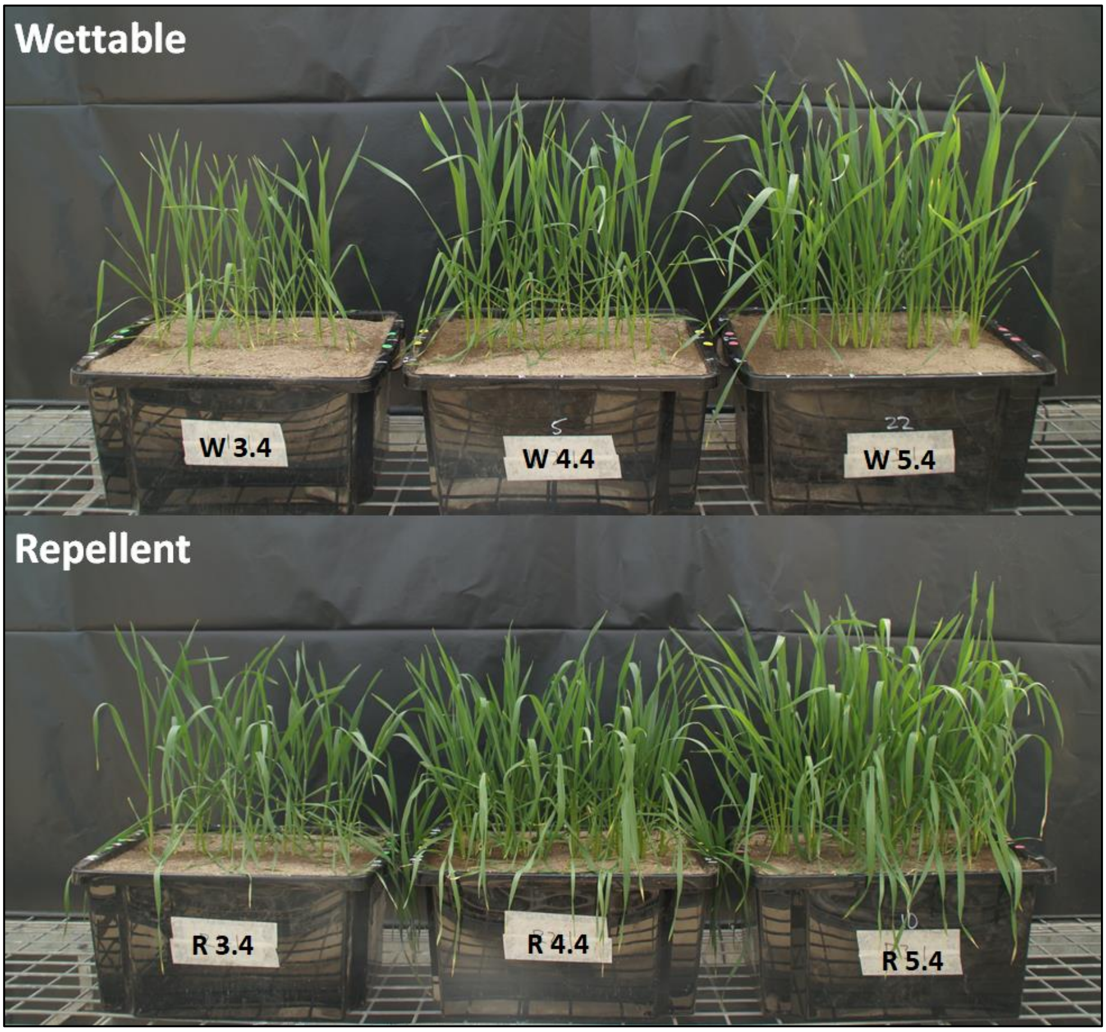

Figure 73. Comparison of wheat shoot growth at 40 DAS between wettable (W) and repellent (R) treatments, under varying watering treatments (3.4, 4.4, and 5.4 mm every 2 days).

Relationships between plant growth and nutrition

Tiller number and shoot dry matter per wheat plant were very strongly positively correlated with total uptake of all nutrients ($0.87 \leq R^2 \leq 1.00$; Table 79), and strongly positively correlated with shoot P ($R^2 = 0.89$; Figure 74a and b, respectively) and K concentrations ($R^2 = 0.82$ and 0.81, respectively; Figure 75a and b, respectively) but were not significantly correlated with shoot N and S concentrations.

Table 79. Bivariate correlation between wheat shoot growth and nutrient parameters using the coefficient of determination (R^2). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Tiller number	Shoot dry matter
Total N uptake	0.95**	1.00**
Total P uptake	0.97**	0.99**
Total K uptake	0.96**	1.00**
Total Ca uptake	0.91**	0.97**
Total Mg uptake	0.94**	0.98**
Total S uptake	0.96**	1.00**
Total B uptake	0.89**	0.95**
Total Cu uptake	0.93**	0.98**
Total Fe uptake	0.95**	1.00**
Total Mn uptake	0.87**	0.98**
Total Zn uptake	0.88**	0.98**
Shoot N concentration	0.44	0.55
Shoot P concentration	0.89**	0.89**
Shoot K concentration	0.82*	0.81*
Shoot Ca concentration	0.12	0.13
Shoot Mg concentration	0.15	0.23
Shoot S concentration	0.61	0.64
Shoot B concentration	0.18	0.22
Shoot Cu concentration	0.42	0.39
Shoot Fe concentration	0.73*	0.76*
Shoot Mn concentration	0.65	0.70*
Shoot Zn concentration	0.34	0.17

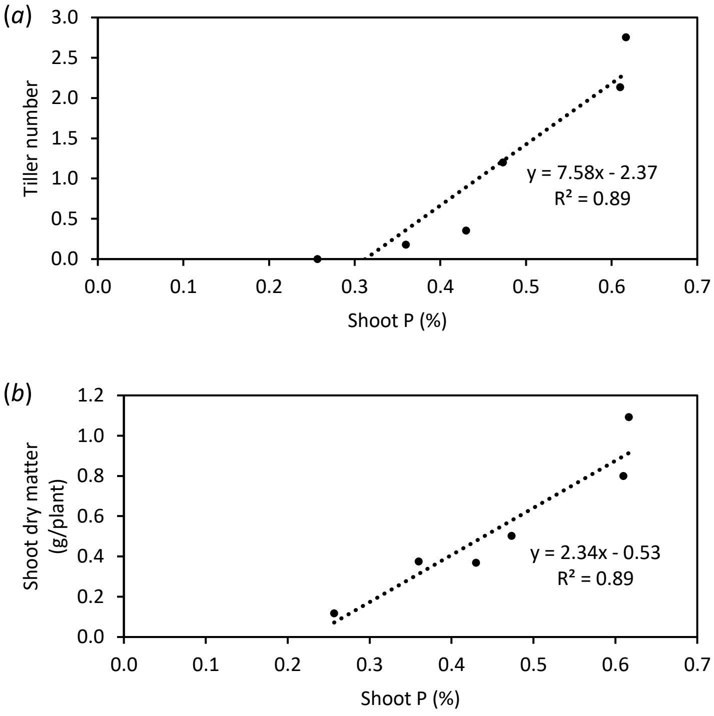

Figure 74. Relationship between wheat shoot phosphorus concentration (P, %) and (a) tiller number per plant at 38 DAS, and (b) shoot dry matter (g/plant) at 40 DAS.

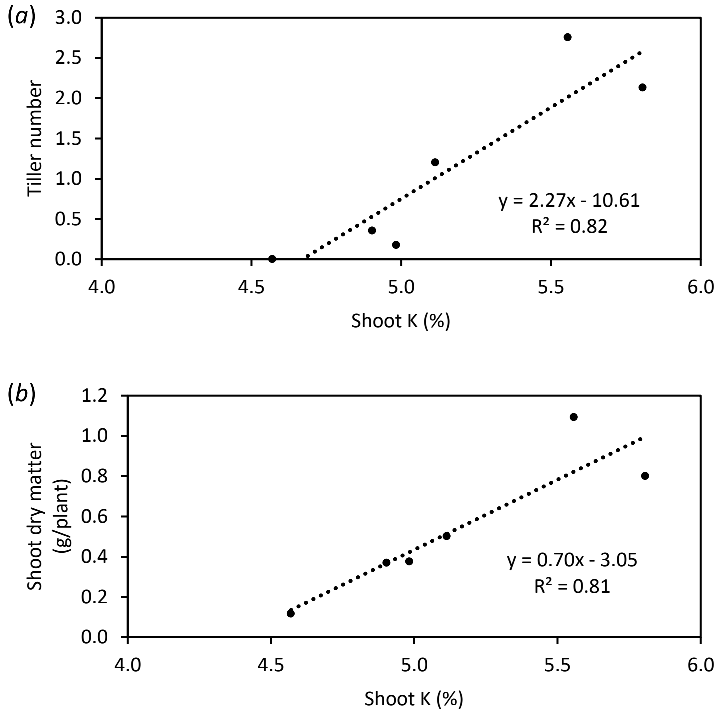

Figure 75. Relationship between wheat shoot potassium concentration (K, %) and (a) tiller number per plant at 38 DAS, and (b) shoot dry matter (g/plant) at 40 DAS.

6.3.5 Root growth observations

While root length was not assessed in this experiment, there were observable differences in root growth and rooting depth between wettable and repellent treatments, and between watering treatments (Figures 76 and 77). In general, rooting depth at final harvest was greater in repellent treatments than in wettable treatments and increased as the water supply increased from 3.4 to 5.4 mm. These observations were consistent with that of shoot dry matter. Note that, in wettable treatments with a 3.4 mm water supply, topsoil was dry below the 6 cm depth, resulting in no roots below this depth. However, under the same 3.4 mm water supply, root growth in repellent treatments reached the 10 cm depth, despite being relatively localised in the furrow. Even as the water supply increased to 5.4 mm, root growth in wettable treatments was still relatively limited to the 0-10 cm depth, which also coincides with the limited wetting depth.

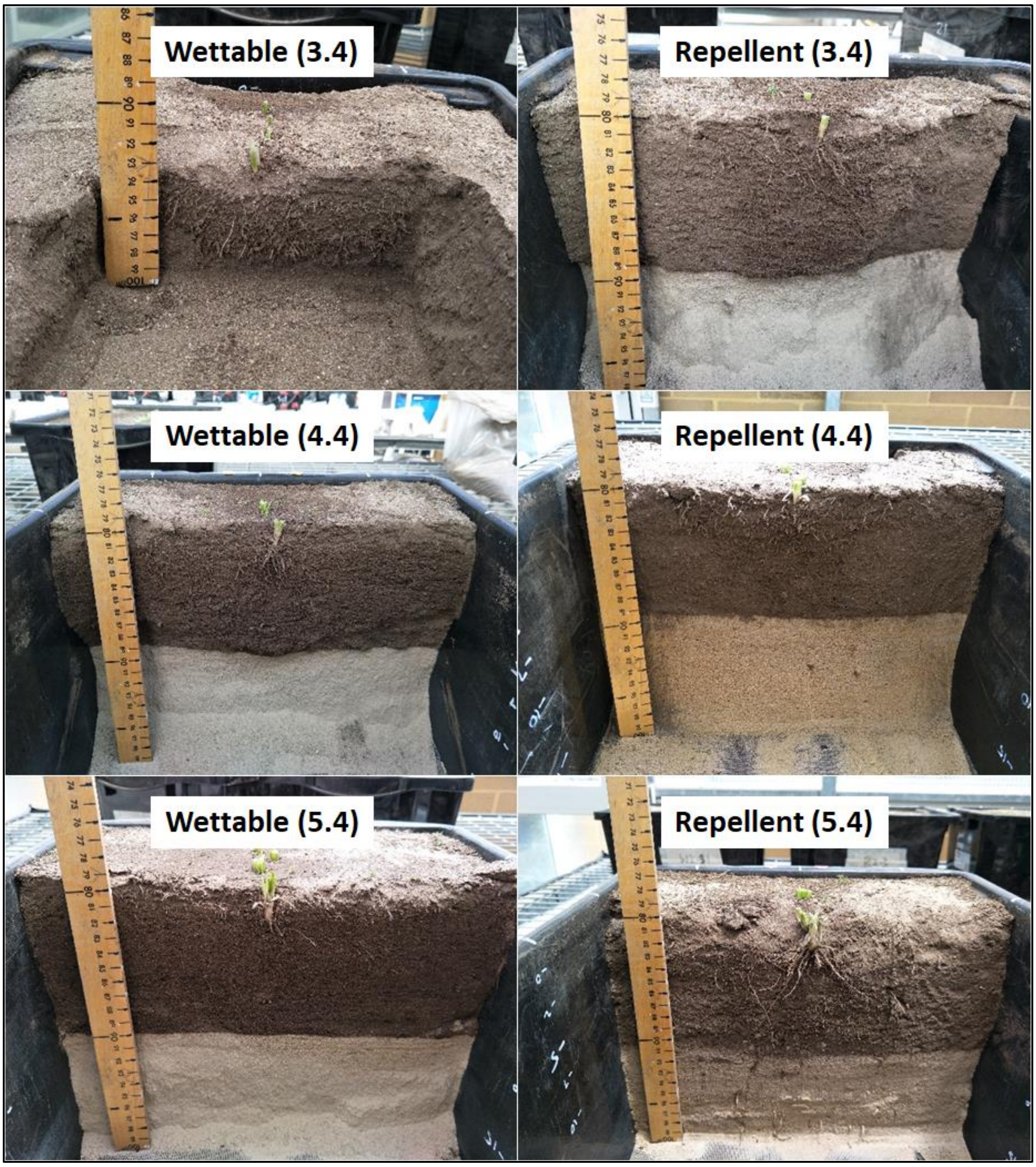

Figure 76. Observed differences in wheat root growth at 40 DAS between wettable (left) and repellent (right) treatments, under a 3.4, 4.4, and 5.4 mm water supply.

In repellent treatments, however, root growth reached the 20 cm depth and became bound by shade cloth (Figure 77), suggesting that topsoil water repellence greatly increased root growth at depth. Root growth was also relatively localised in the furrow of repellent treatments in comparison with that in wettable treatments where roots grew into the inter-rows. Dry zones in the inter-row of repellent topsoil were observed, particularly under a low water supply, due to preferential water flow in the wettable furrow.

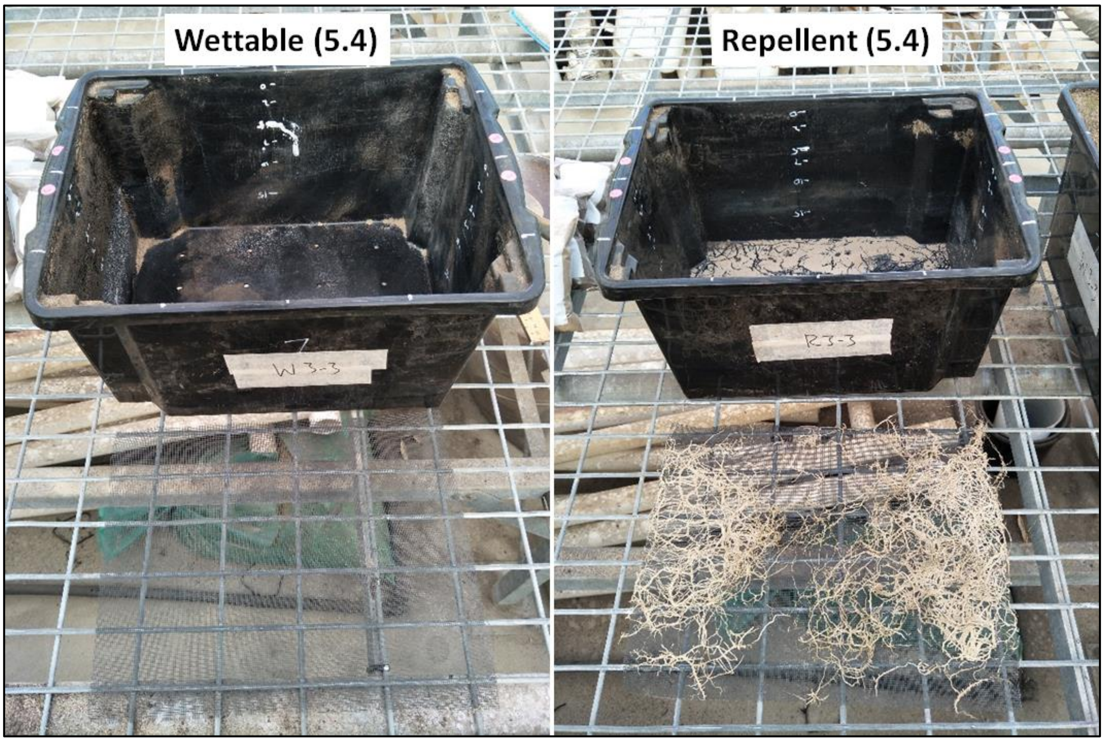

Figure 77. Matted root growth in repellent treatments (right) at the 20 cm depth compared to no roots in wettable treatments (left) under a 5.4 mm water supply.

6.3.6 Leaf relative water content

Only the main effects of topsoil water repellence and water supply on leaf RWC were significant (*P* < 0.001; Table 78), whereby: (1) leaf RWC was significantly greater in wettable treatments (88.5 %) than in repellent treatments (82.9 %; Figure 78a), and; (2) leaf RWC significantly increased (from 81.5 to 90.9 %) as the water supply increased from 3.4 to 5.4 mm (Figure 78b), but there was no difference between treatments with a 3.4 and 4.4 mm water supply.

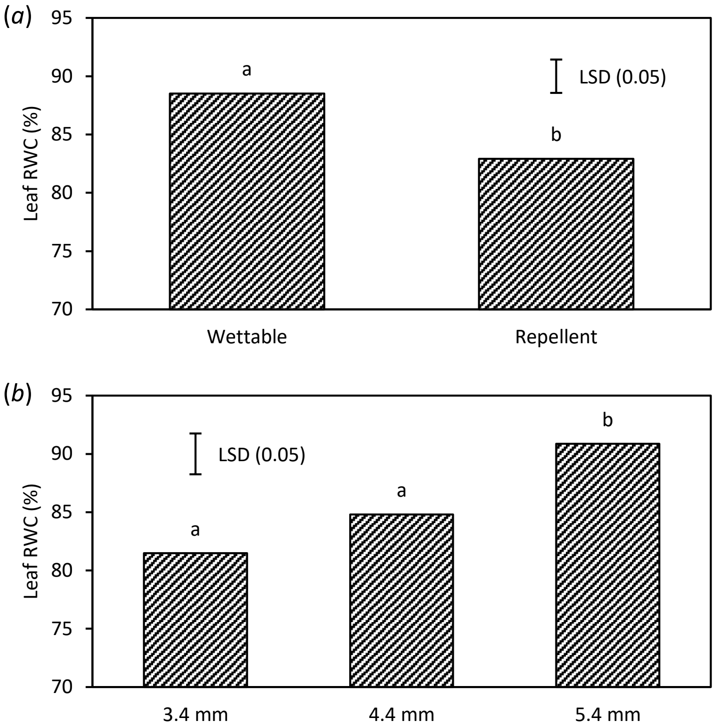

Figure 78. Effect of (a) topsoil water repellence and (b) water supply on relative water content (RWC, %) in wheat leaves at 40 DAS. Mean values based on a sample size of 9 and 6, respectively. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

6.3.7 Shoot nutrient concentrations

An assessment of nutrient concentrations in wheat whole shoots (40 DAS) found that wheat plants in all treatments were relatively deficient in N (i.e., <6.7 %; Reuter and Robinson 1997; Appendix A.2), with some plants marginally deficient in P (<0.3 %) and S (<0.3 %) in wettable treatments with a 3.4 mm water supply, but they were apparently adequate in other key nutrients. Bivariate correlation analysis showed that tiller number and shoot dry matter were very strongly positively correlated with shoot P (R^2 = 0.89) and K concentrations (R^2 = 0.81; see Section 6.3.4) but were not significantly correlated with shoot N and S concentrations.

Notwithstanding the treatment effects on other shoot nutrients, results showed that shoot N and K concentrations were significantly affected by the two-way interaction of topsoil water repellence × water supply ($P < 0.05$; Table 80). Shoot K concentrations were significantly greater in repellent treatments (4.98-5.81 %) than in wettable treatments (4.57-5.11 %; Table 81), regardless of water supply. Shoot N concentrations were also significantly greater in repellent treatments (4.90 %) than in wettable treatments (3.47 %; Table 81) but only in treatments with a 3.4 mm water supply. Regardless of topsoil water repellence, shoot N and K concentrations significantly increased as the water supply increased from 3.4 to 5.4 mm (from 3.47-4.90 to 5.32-5.37 % N and 4.57-4.98 to 5.11-5.56 % K, respectively; Table 81).

Table 80. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR) and water supply (Water) on wheat shoot nutrient concentrations (40 DAS). Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Shoot nutrient concentration	Source of variation		
	SWR	Water	SWR × Water
N	46****	65****	24****
P	62****	69****	2^{ns}
K	71****	30****	5*
Ca	16***	1^{ns}	3^{ns}
Mg	35****	1^{ns}	4*
S	11**	10***	3^{ns}
B	33****	8**	5*
Cu	12***	1^{ns}	5*
Fe	12***	15****	0^{ns}
Mn	83****	126****	17****
Zn	0^{ns}	5*	23****

^{ns} Not significant ($P > 0.05$).

Table 81. Effect of topsoil water repellence and water supply on wheat shoot nutrient concentrations (40 DAS). Mean values based on three replications. Different letters denote significant differences across rows, based on the least significant difference (LSD) at $P < 0.05$.

Shoot nutrient concentration	Wettable			Repellent		
	3.4 mm	4.4 mm	5.4 mm	3.4 mm	4.4 mm	5.4 mm
N (%)	3.47^{a}	4.92^{b}	5.32^{c}	4.90^{b}	5.19^{bc}	5.37^{c}
K (%)	4.57^{a}	4.90^{b}	5.11^{b}	4.98^{b}	5.81^{c}	5.56^{c}
Mg (%)	0.23^{ab}	0.24^{a}	0.21^{b}	0.17^{c}	0.19^{bc}	0.20^{bc}
B (mg/kg)	37.8^{a}	37.9^{a}	27.3^{b}	40.3^{a}	49.8^{c}	43.2^{ac}
Cu (mg/kg)	8.36^{acd}	9.56^{b}	9.27^{ab}	8.66^{abc}	8.03^{cd}	7.55^{d}
Mn (mg/kg)	306.9^{a}	212.1^{b}	161.8^{c}	217.5^{b}	157.8^{c}	152.8^{c}
Zn (mg/kg)	33.7^{a}	39.7^{b}	36.7^{ab}	44.6^{c}	34.0^{a}	33.2^{a}

The main effect of topsoil water repellence was significant for shoot P and S concentrations ($P < 0.01$; Table 80), whereby shoot P and S concentrations were significantly greater in repellent treatments (0.53 % P and 0.42 % S, respectively) than in wettable treatments (0.39 % P and 0.36 % S, respectively; Table 82). The main effect of water supply was also significant for shoot P and S concentrations ($P < 0.005$; Table 80), whereby shoot P and S concentrations significantly increased when the water supply increased from 3.4 to 5.4 mm (from 0.31 to 0.55 % P and 0.34 to 0.43 %

S, respectively; Table 83), despite no difference between a 4.4 and 5.4 mm water supply.

Table 82. Effect of topsoil water repellence on wheat shoot P, Ca, S, and Fe concentrations (40 DAS). Mean values based on a sample size of 9. Different letters denote significant differences across rows, based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	Wettable	Repellent
P (%)	0.39^a	0.53^b
Ca (%)	0.52^a	0.44^b
S (%)	0.36^a	0.42^b
Fe (mg/kg)	68.0^a	73.2^b

Table 83. Effect of water supply on wheat shoot P, S, and Fe concentrations (40 DAS). Mean values based on a sample size of 6. Different letters denote significant differences across rows, based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	3.4 mm	4.4 mm	5.4 mm
P (%)	0.31^a	0.52^b	0.55^b
S (%)	0.34^a	0.41^b	0.43^b
Fe (mg/kg)	64.8^a	73.7^b	73.3^b

6.3.8 Total nutrient uptake

Total uptake of all nutrients (except for Cu and Zn) was significantly affected by the two-way interaction of topsoil water repellence × water supply ($P < 0.01$; Table 84), whereby total uptake of N, P, K, Ca, Mg, S, B, Fe, and Mn was significantly greater in repellent treatments than in wettable treatments by an average of 172 % (Table 85), regardless of water supply. However, the increase in total nutrient uptake was more pronounced in treatments with a 3.4 mm water supply (by 246 %) than a 4.4 (by 133 %) or 5.4 mm water supply (by 138 %).

Total uptake of N, P, K, Ca, Mg, S, B, Fe, and Mn also significantly increased as the water supply increased from 3.4 to 5.4 mm by an average of 309 % (Table 85), regardless of topsoil water repellence. However, the increase in total nutrient uptake was more pronounced in wettable treatments (by 391 %) than in repellent treatments (by 228 %). In wettable treatments, total uptake of Ca, Mg, B, and Mn was not different between treatments with a 4.4 or 5.4 mm water supply.

Table 84. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR) and water supply (Water) on wheat total nutrient uptake (40 DAS). Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Total nutrient uptake	Source of variation		
	SWR	Water	SWR × Water
N	440****	271****	21****
P	457****	256****	51****
K	363****	184****	23****
Ca	120****	120****	11***
Mg	146****	133****	13****
S	167****	93****	8**
B	282****	85****	23****
Cu	147****	112****	2^{ns}
Fe	352****	198****	21****
Mn	144****	61****	7**
Zn	191****	91****	3^{ns}

^{ns} Not significant ($P > 0.05$).

Table 85. Effect of topsoil water repellence and water supply on wheat total nutrient uptake (40 DAS). Mean values based on three replications. Different letters denote significant differences across rows, based on the least significant difference (LSD) at $P < 0.05$.

Total nutrient uptake	Wettable			Repellent		
	3.4 mm	4.4 mm	5.4 mm	3.4 mm	4.4 mm	5.4 mm
N (mg/plant)	3.3^{a}	14.5^{b}	21.3^{c}	14.7^{b}	33.2^{d}	46.9^{e}
P (mg/plant)	0.24^{a}	1.27^{b}	1.90^{c}	1.09^{b}	3.90^{d}	5.37^{e}
K (mg/plant)	4.3^{a}	14.5^{b}	20.5^{c}	15.0^{b}	37.1^{d}	48.6^{e}
Ca (mg/plant)	0.46^{a}	1.68^{bc}	2.06^{b}	1.28^{c}	2.67^{d}	4.10^{e}
Mg (mg/plant)	0.22^{a}	0.70^{b}	0.84^{b}	0.51^{c}	1.22^{d}	1.72^{e}
S (mg/plant)	0.27^{a}	1.08^{b}	1.74^{c}	1.18^{b}	2.90^{d}	3.75^{e}
B (µg/plant)	3.6^{a}	11.3^{b}	11.1^{b}	12.1^{b}	31.9^{c}	37.7^{d}
Fe (µg/plant)	5.8^{a}	20.9^{b}	28.8^{c}	20.5^{b}	49.1^{d}	65.5^{e}
Mn (µg/plant)	28.8^{a}	62.7^{b}	65.2^{b}	64.6^{b}	100.9^{c}	133.5^{d}

6.3.9 Soil water and electrical conductivity

Soil volumetric water content and electrical conductivity (EC) was measured *in-situ* for 40 days using Decagon 5TE sensors in the furrow and inter-row at the 5 and 15 cm depths (Figures 79-82), with water first supplied on Day 1 until Day 39. The soil water content and EC in the furrow at the 5 cm depth increased rapidly in all repellent treatments but was considerably delayed in wettable treatments (by 1-3 weeks; Figures 79a and b, respectively), especially as the water supply decreased from 5.4 (after Day 9) to 4.4 mm (after Day 18 and Day 25 for soil water and EC, respectively). In wettable treatments with a 3.4 mm water supply, however, there was no observable change in soil water content in the furrow at the 5 cm depth over 40 days, suggesting that soil wetting was relatively shallow (<5 cm depth). As a result, soil water content and EC in the furrow at the 5 cm depth were relatively greater in repellent treatments than in wettable treatments (Figures 79a and b, respectively), regardless of water supply. Over time, soil water content in the furrow at the 5 cm depth in wettable treatments with a 5.4 mm water supply eventually exceeded that in repellent treatments with a 4.4 mm water supply (after Day 12) and a 3.4 mm water supply (after Day 18) but was still relatively lower than that in repellent treatments with a 5.4 mm water supply. After Day 33, soil EC in the furrow at the 5 cm depth in wettable treatments with a 5.4 mm water supply eventually exceeded that in repellent treatments.

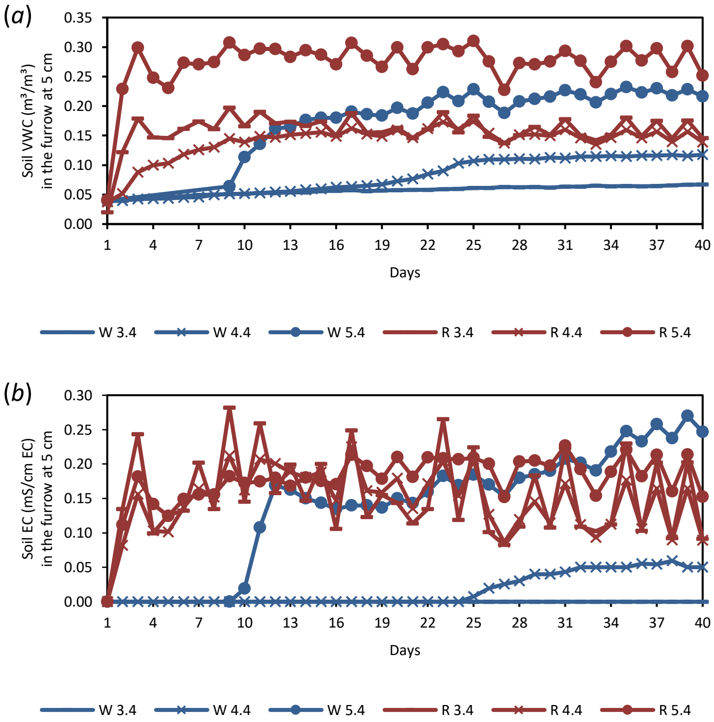

Figure 79. Soil (a) volumetric water content (VWC, m^3/m^3) and (b) electrical conductivity (EC, mS/cm) in the furrow at the 5 cm depth in wettable (W) and repellent (R) treatments, under variable water supply (3.4, 4.4, and 5.4 mm) over 40 days at solar noon (±2 hours).

Changes in soil water content and EC in the inter-row at the 5 cm depth were only detected in wettable treatments with a 5.4 mm water supply (Figures 80a and b, respectively), whereby soil water content and EC increased from Day 13 (0.07 m^3/m^3 and 0.00 mS/cm, respectively) to Day 17 (0.16 m^3/m^3 and 0.33 mS/cm, respectively) before plateauing thereafter. Soils in the inter-row at the 5 cm depth remained relatively dry (≤ 0.07 m^3/m^3) in all repellent treatments and in wettable treatments with a 3.4 or 4.4 mm water supply, although a constant increase in soil water content can be observed over time, presumably due to vapor diffusion (DeBano 1981).

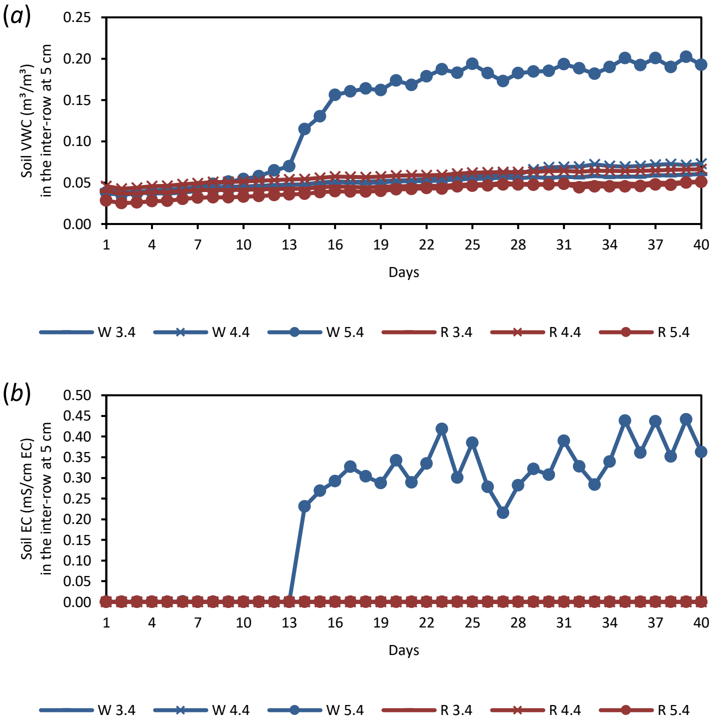

Figure 80. Soil (a) volumetric water content (VWC, m^3/m^3) and (b) electrical conductivity (EC, mS/cm) in the inter-row at the 5 cm depth in wettable (W) and repellent (R) treatments, under variable water supply (3.4, 4.4, and 5.4 mm) over 40 days at solar noon (±2 hours).

Changes in soil water content and EC in the furrow at the 15 cm depth were only detected in repellent treatments with either a 5.4 or 4.4 mm water supply (Figures 81a and b, respectively), with soil water content increasing from Day 7 (0.03 m^3/m^3) to Day 25 (0.12 m^3/m^3) in repellent treatments with a 5.4 mm water supply, before declining slightly thereafter to Day 40 (0.10 m^3/m^3). In repellent treatments with a 4.4 mm water supply, soil wetting gradually occurred over time from Day 1 (0.03 m^3/m^3) to Day 40 (0.06 m^3/m^3) and soil EC increased from Day 18 (0.0 mS/cm) to Day 21 (0.02 mS/cm) before plateauing, but such increases were relatively small. By contrast, soil wetting in the furrow at the 15 cm depth did not occur in repellent treatments with a 3.4 mm water supply or in wettable treatments, regardless of water supply (Figure 81), which hence resulted in no change in soil EC.

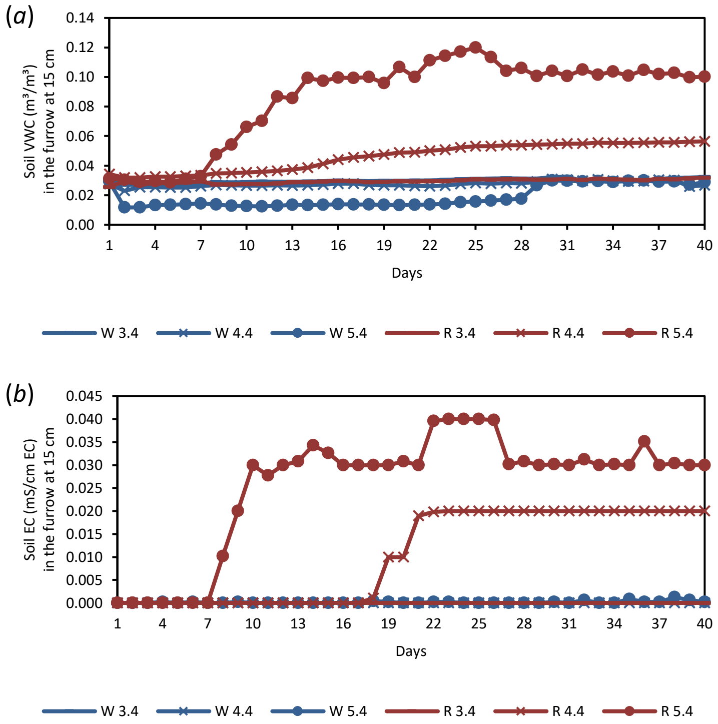

Figure 81. Soil (a) volumetric water content (VWC, m^3/m^3) and (b) electrical conductivity (EC, mS/cm) in the furrow at the 15 cm depth in wettable (W) and repellent (R) treatments, under variable water supply (3.4, 4.4, and 5.4 mm) over 40 days at solar noon (±2 hours).

Soil wetting in the inter-row at the 15 cm depth was only detected in repellent treatments with a 5.4 mm water supply (Figures 82a and b, respectively), whereby soil water content and EC increased from Day 13 (0.04 m^3/m^3 and 0.00 mS/cm, respectively) to Day 24 (0.10 m^3/m^3 and 0.03 mS/cm, respectively) before plateauing thereafter. Soils in the inter-row at the 15 cm depth remained relatively dry in all wettable treatments and in repellent treatments with a 3.4 or 4.4 mm water supply. Note, the observed decrease in soil water content (from Day 28 to 40) in repellent treatments with a 4.4 mm water supply was likely attributed to disturbance artefacts when retrieving data from the logger.

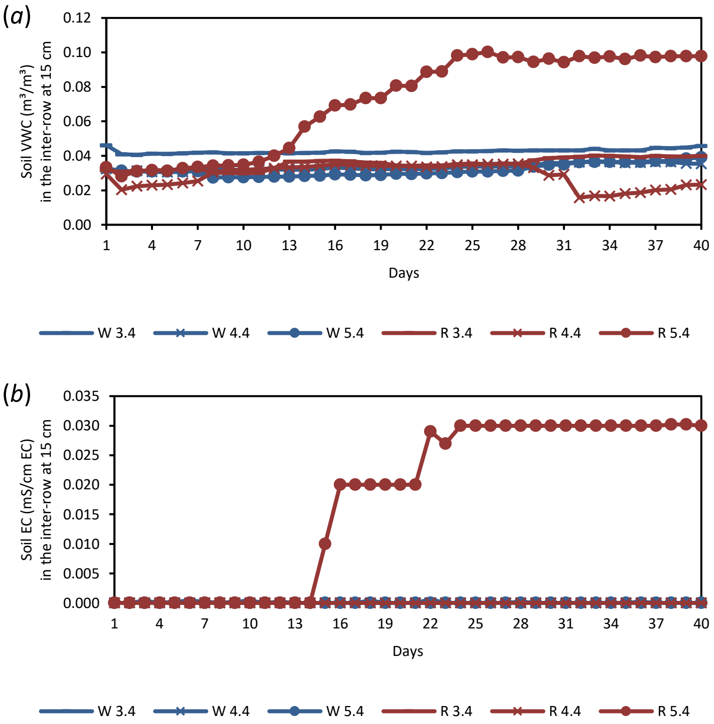

Figure 82. Soil (a) volumetric water content (VWC, m^3/m^3) and (b) electrical conductivity (EC, mS/cm) in the inter-row at the 15 cm depth in wettable (W) and repellent (R) treatments, under variable water supply (3.4, 4.4, and 5.4 mm) over 40 days at solar noon (±2 hours).

6.3.10 Soil ammonium-nitrogen

Results from a mixed model ANOVA showed that soil NH_4-N concentration post-harvest at 41 DAS was significantly affected by the three-way interaction of topsoil water repellence × sampling row × sampling depth ($P < 0.001$; Table 86). Soil NH_4-N concentration in the furrow at the 0-5 and 10-15 cm depths and inter-row at the 0-5 and 5-10 cm depths was not affected by topsoil water repellence. However, soil NH_4-N concentration in the furrow at the 5-10 cm depth was significantly greater in wettable treatments (659 mg/kg) than in repellent treatments (231 mg/kg; Table 87). By contrast, soil NH_4-N concentration in the furrow at the 15-20 cm depth was significantly greater in repellent treatments (21 mg/kg) than in wettable treatments (3 mg/kg; Table 87). Soil NH_4-N concentration in the inter-row at the 10-15 and 15-20 cm depths was also significantly greater in repellent treatments (15 and 9 mg/kg, respectively) than in wettable treatments (2 and 1 mg/kg, respectively; Table 87).

Table 86. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), Colwell phosphorus (P), and Colwell potassium (K) at 41 DAS, using topsoil water repellence (SWR) and water supply (Water) as between-subjects variables and repeated measures for sampling row and sampling depth as within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil NH_4-N	Soil NO_3-N	Soil Colwell P	Soil Colwell K
SWR	26****	61****	20****	19****
Water	2 ^{ns}	1 ^{ns}	0 ^{ns}	1 ^{ns}
Row	150****	28****	83****	120****
Depth	124****	92****	213****	160****
SWR × Water	2 ^{ns}	0 ^{ns}	0 ^{ns}	1 ^{ns}
SWR × Row	30****	21****	0 ^{ns}	17***
SWR × Depth	32****	30****	5*	27****
Water × Row	3 ^{ns}	5*	0 ^{ns}	2 ^{ns}
Water × Depth	4 ^{ns}	4 ^{ns}	0 ^{ns}	3 ^{ns}
Row × Depth	116****	52****	87****	119****
SWR × Water × Row	2 ^{ns}	0 ^{ns}	0 ^{ns}	1 ^{ns}
SWR × Water × Depth	2 ^{ns}	0 ^{ns}	0 ^{ns}	2 ^{ns}
SWR × Row × Depth	32****	17****	0 ^{ns}	20****
Water × Row × Depth	4*	7***	0 ^{ns}	3 ^{ns}
SWR × Water × Row × Depth	2 ^{ns}	2 ^{ns}	0 ^{ns}	1 ^{ns}

^{ns} Not significant ($P > 0.05$).

Table 87. Soil ammonium-nitrogen (NH_4-N) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in wettable and repellent treatments. Mean values based on a sample size of 9. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Depth	Wettable		Repellent	
	Furrow	Inter-row	Furrow	Inter-row
0-5 cm	21.4^{a}	14.3^{a}	$33.2^{a\Delta}$	13.4^{a}
5-10 cm	$659.1^{b\dagger\Delta}$	20.3^{b}	$231.0^{b\Delta}$	21.4^{b}
10-15 cm	10.9^{ac}	$2.3^{c\dagger}$	$25.3^{a\Delta}$	14.6^{a}
15-20 cm	$2.6^{c\dagger}$	$1.4^{c\dagger}$	$20.6^{a\Delta}$	8.5^{c}

Different superscript letters denote significant differences within depth ($P < 0.05$).
† Significantly different from repellent treatments ($P < 0.05$).
$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

Soil NH_4-N concentration post-harvest at 41 DAS was significantly affected by the three-way interaction of water supply × sampling row × sampling depth ($P < 0.05$; Table 86), whereby soil NH_4-N concentration in the furrow at the 5-10 cm depth significantly decreased (from 575 to 326 mg/kg) as the water supply increased from 3.4 to 5.4 mm (Table 88), while soil NH_4-N concentration in the furrow at the 10-15 and 15-20 cm depths significantly increased (from 1 to 34 and 21 mg/kg, respectively) as the water supply increased from 3.4 to 5.4 mm, despite no differences observed in treatments with a 4.4 mm water supply. Soil NH_4-N concentration in the furrow at the 0-5 cm depth was not affected by water supply. However, soil NH_4-N concentration in the inter-row at the 0-5 cm depth significantly decreased (from 16 to 12 mg/kg) as the water supply increased from 3.4 to 5.4 mm (Table 88). By contrast, soil NH_4-N concentration in the inter-row at the 5-10, 10-15, and 15-20 cm depths significantly increased as the water supply increased from 3.4 to 5.4 mm (from 13 to 29 mg/kg, 1 to 15 mg/kg, and 1 to 9 mg/kg, respectively; Table 88), despite no differences observed in treatments with a 4.4 mm water supply.

Table 88. Soil ammonium-nitrogen (NH_4-N) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in treatments with variable water supply (3.4, 4.4, and 5.4 mm). Mean values based on a sample size of 6. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	3.4 mm		4.4 mm		5.4 mm	
	Furrow	Inter-row	Furrow	Inter-row	Furrow	Inter-row
0-5 cm	$34.0^{1a\Delta}$	16.3^{1a}	17.5^{1a}	13.2^{2a}	$30.5^{1ac\Delta}$	12.2^{2ac}
5-10 cm	$574.5^{1b\Delta}$	12.7^{1a}	$435.0^{12b\Delta}$	20.7^{2b}	$325.7^{2b\Delta}$	29.3^{3b}
10-15 cm	1.3^{1c}	0.7^{1b}	18.8^{12c}	9.3^{12a}	$34.2^{2a\Delta}$	15.3^{2a}
15-20 cm	1.3^{1c}	1.1^{1b}	$12.3^{12c\Delta}$	4.5^{12c}	$21.2^{2c\Delta}$	9.3^{2c}

Different superscript letters denote significant differences within depth ($P < 0.05$).
Different superscript numbers denote significant differences within water supply ($P < 0.05$).
$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

6.3.11 Soil nitrate-nitrogen

Soil NO_3-N concentration post-harvest at 41 DAS was significantly affected by the three-way interaction of topsoil water repellence × sampling row × sampling depth ($P < 0.001$; Table 86). Soil NO_3-N concentration in the furrow and inter-row at the 5-10 cm depth was significantly greater in wettable treatments (283 and 73 mg/kg, respectively) than in repellent treatments (85 and 38 mg/kg, respectively; Table 89), but soil NO_3-N concentration in the furrow and inter-row at the 0-5, 10-15, and 15-20 cm depths was not affected by topsoil water repellence. Soil NO_3-N concentration at the 0-5 cm depth was significantly greater in the inter-row (52-53 mg/kg) than in the furrow (22-33 mg/kg; Table 89), regardless of topsoil water repellence. However, soil NO_3-N concentration at the 5-10 cm depth was significantly greater in the furrow (283 mg/kg) than in the inter-row (73 mg/kg; Table 89) in wettable treatments but not in repellent treatments. Soil NO_3-N concentration at the 10-15 and 15-20 cm depths was not different between sampling rows, regardless of topsoil water repellence.

Additionally, soil NO_3-N concentration post-harvest at 41 DAS was significantly affected by the three-way interaction of water supply × sampling row × sampling depth on soil NO_3-N concentration post-harvest at 41 DAS were observed ($P < 0.005$; Table

86). As the water supply increased from 3.4 to 5.4 mm, soil NO_3-N concentration in the furrow at the 5-10 cm depth significantly decreased (from 256 to 117 mg/kg; Table 90), while soil NO_3-N concentration in the inter-row at the 5-10 cm depth significantly increased (from 43 to 73 mg/kg). Likewise, soil NO_3-N concentration in the furrow and inter-row at the 10-15 and 15-20 cm depths also significantly increased as the water supply increased from 3.4 to 5.4 mm (from 5 to 19-26 mg/kg; Table 90). However, soil NO_3-N concentration in the furrow and inter-row at the 0-5 cm depth was not affected by water supply.

Table 89. Soil nitrate-nitrogen (NO_3-N) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in wettable and repellent treatments. Mean values based on a sample size of 9. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Depth	Wettable		Repellent	
	Furrow	Inter-row	Furrow	Inter-row
0-5 cm	$33.4^{a\Delta}$	53.3^{a}	$21.9^{a\Delta}$	52.3^{a}
5-10 cm	$283.0^{b\dagger\Delta}$	$72.7^{b\dagger}$	84.8^{b}	37.7^{b}
10-15 cm	15.8^{c}	11.7^{c}	11.2^{a}	13.7^{c}
15-20 cm	10.1^{c}	8.2^{c}	12.3^{a}	12.3^{c}

Different superscript letters denote significant differences within depth ($P < 0.05$).
† Significantly different from repellent treatments ($P < 0.05$).
$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

Table 90. Soil nitrate-nitrogen (NO_3-N) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in treatments with variable water supply (3.4, 4.4, and 5.4 mm). Mean values based on a sample size of 6. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Depth	3.4 mm		4.4 mm		5.4 mm	
	Furrow	Inter-row	Furrow	Inter-row	Furrow	Inter-row
0-5 cm	$25.0^{1a\Delta}$	51.8^{1a}	$18.3^{1a\Delta}$	59.7^{1a}	39.7^{1a}	47.0^{1a}
5-10 cm	$255.8^{1b\Delta}$	42.8^{1a}	$179.0^{12b\Delta}$	49.7^{1a}	116.8^{2b}	73.0^{2b}
10-15 cm	4.8^{1c}	5.0^{1b}	9.8^{1a}	10.2^{1b}	25.8^{2ac}	22.8^{2c}
15-20 cm	4.7^{1c}	4.5^{1b}	9.2^{1a}	7.8^{1b}	19.8^{2c}	18.5^{2c}

Different superscript letters denote significant differences within depth ($P < 0.05$).
Different superscript numbers denote significant differences within water supply ($P < 0.05$).
$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

6.3.12 Soil phosphorus

Soil Colwell P concentration post-harvest at 41 DAS was significantly affected by the two-way interaction of topsoil water repellence × sampling depth ($P < 0.05$; Table 86). Soil Colwell P concentration at the 0-5 and 5-10 cm depths was significantly greater in repellent treatments (103 and 203 mg/kg, respectively) than in wettable treatments (61 and 157 mg/kg, respectively; Table 91), but soil Colwell P concentration at the 10-15 and 15-20 cm depths was not affected by topsoil water repellence. Regardless of topsoil water repellence, soil Colwell P concentration was significantly greater at the 0-5 and 5-10 cm depths (61-103 and 157-203 mg/kg, respectively) than at the 10-15 and 15-20 cm depths (13-17 and 14-15 mg/kg, respectively; Table 91), with soil Colwell P concentration also significantly greater at the 5-10 cm depth than at the 0-5 cm depth. Soil Colwell P concentration was also significantly greater at the 10-15 cm depth (17 mg/kg) than at the 15-20 cm depth (15 mg/kg; Table 91) in repellent treatments but not in wettable treatments.

Table 91. Soil Colwell phosphorus (P) concentration (mg/kg) post-harvest (41 DAS) at the 0-5, 5-10, 10-15, and 15-20 cm depths in wettable and repellent treatments. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Depth	Wettable	Repellent
0-5 cm	$60.6^{a\dagger}$	102.8^{a}
5-10 cm	$156.6^{b\dagger}$	203.2^{b}
10-15 cm	12.8^{c}	17.2^{c}
15-20 cm	13.8^{c}	14.9^{d}

Different superscript letters denote significant differences within depth ($P < 0.05$).

[†] Significantly different from repellent treatments ($P < 0.05$).

Moreover, soil Colwell P concentration post-harvest at 41 DAS was also significantly affected by the two-way interaction of sampling row × sampling depth ($P < 0.001$; Table 86). Soil Colwell P concentration at the 0-5 cm depth was significantly greater in the inter-row (84 mg/kg) than in the furrow (80 mg/kg; Table 92), while soil Colwell P concentration at the 5-10 and 15-20 cm depths was significantly greater in the furrow (279 and 15 mg/kg, respectively) than in the inter-row (80 and 13 mg/kg, respectively). Soil Colwell P concentration at the 10-15 cm depth was not different between sampling rows. Soil Colwell P concentration was significantly greater at the 0-5 and 5-10 cm depths (80-84 and 80-279 mg/kg, respectively) than at the 10-15 and 15-20 cm depths (14-15 and 13-15 mg/kg, respectively; Table 92), with soil Colwell P concentration in the furrow also significantly greater at the 5-10 cm depth (279 mg/kg) than at the 0-5 cm depth (80 mg/kg). Soil Colwell P concentration in the inter-row was marginally greater at the 0-5 cm depth (84 mg/kg) than at the 5-10 cm depth (80 mg/kg; Table 92). Soil Colwell P concentration in the furrow and inter-row was not different between the 10-15 and 15-20 cm depths.

Table 92. Soil Colwell phosphorus (P) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Furrow	Inter-row
0-5 cm	$79.7^{a\Delta}$	83.7^{a}
5-10 cm	$279.4^{b\Delta}$	80.4^{b}
10-15 cm	15.7^{c}	14.2^{c}
15-20 cm	$15.3^{c\Delta}$	13.3^{c}

Different superscript letters denote significant differences within depth ($P < 0.05$).

$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

6.3.13 Soil potassium

Soil Colwell K concentration post-harvest at 41 DAS was significantly affected by the three-way interaction of topsoil water repellence × sampling row × sampling depth ($P < 0.001$; Table 86). Soil Colwell K concentration in the furrow and inter-row at the 5-10 cm depth was significantly greater in wettable treatments (1204 and 128 mg/kg, respectively) than in repellent treatments (556 and 97 mg/kg, respectively; Table 93). Soil Colwell K concentration in the inter-row at the 0-5 cm depth was also significantly greater in wettable treatments (119 mg/kg) than in repellent treatments (104 mg/kg; Table 93). However, soil Colwell K concentration in the furrow and inter-row at the 10-15 cm depth was significantly greater in repellent treatments (65 and 58 mg/kg, respectively) than in wettable treatments (28 and 16 mg/kg, respectively; Table 93), with soil Colwell K concentration in the furrow at the 15-20 cm depth also significantly greater in repellent treatments (59 mg/kg) than in wettable treatments (27 mg/kg; Table 93). Topsoil water repellence did not affect soil Colwell K concentration in the furrow at the 0-5 cm depth and inter-row at the 15-20 cm depth.

Table 93. Soil Colwell potassium (K) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in wettable and repellent treatments. Mean values based on a sample size of 9. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Wettable		Repellent	
	Furrow	Inter-row	Furrow	Inter-row
0-5 cm	$82.7^{a\Delta}$	$119.4^{a\dagger}$	99.9^{a}	103.6^{a}
5-10 cm	$1204.4^{b\dagger\Delta}$	$128.4^{a\dagger}$	$556.2^{b\Delta}$	96.9^{a}
10-15 cm	$28.0^{c\dagger}$	$15.9^{b\dagger}$	65.2^{c}	58.4^{b}
15-20 cm	$26.9^{c\dagger}$	27.8^{b}	$59.0^{c\Delta}$	38.7^{c}

Different superscript letters denote significant differences within depth ($P < 0.05$).

† Significantly different from repellent treatments ($P < 0.05$).

$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

6.3.14 Relationships between soil water, soil nutrients, plant growth, and plant nutrition

Effect of soil water availability on soil N, P, and K availability

Soil water content (40 DAS) in the furrow and inter-row was strongly positively correlated with soil EC at the 5 cm ($R^2 = 0.73$ and 0.97, respectively) and 15 cm depths ($R^2 = 0.93$ and 0.92, respectively; Table 94).

Table 94. Bivariate correlation (R^2 values) between soil water content and electrical conductivity (EC; 40 DAS). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Row	Depth	Soil water			
			Furrow		Inter-row	
			5 cm	15 cm	5 cm	15 cm
Soil EC	Furrow	5 cm	0.73*	0.01	0.66*	0.02
		15 cm	0.29	0.93**	0.10	0.38
	Inter-row	5 cm	0.25	0.08	0.97**	0.02
		15 cm	0.41	0.85**	0.09	0.92**

Soil water content in the furrow at the 5 cm depth was strongly positively correlated with soil NO_3-N in the furrow at the 15-20 cm depth ($R^2 = 0.77$) and in the inter-row at the 10-15 and 15-20 cm depths ($R^2 = 0.69$ and 0.81, respectively; Table 95). Soil water content in the inter-row at the 5 cm depth was also very strongly positively correlated with soil NO_3-N in the furrow at the 0-5 and 10-15 cm depths ($R^2 = 0.80$ and 0.81, respectively) and in the inter-row at the 5-10 cm depth ($R^2 = 0.86$; Table 95). Soil water content in the furrow at the 5 cm depth was strongly negatively correlated with soil NH_4-N in the inter-row at the 0-5 cm depth ($R^2 = 0.67$; Table 95), but also strongly positively correlated with soil NH_4-N in the inter-row at the 5-10 cm depth ($R^2 = 0.76$). Soil water content in the furrow at the 15 cm depth was strongly negatively correlated with soil NH_4-N ($R^2 = 0.77$) and Colwell K ($R^2 = 0.83$) in the furrow at the 5-10 cm depth, but also strongly positively correlated with soil NH_4-N and Colwell K in the furrow and inter-row at the 15-20 cm depths ($0.68 \leq R^2 \leq 0.98$; Table 95). Moreover, soil water content in the furrow at the 15 cm depth was also very strongly positively correlated with soil NH_4-N in the inter-row at the 10-15 cm depth ($R^2 = 0.90$) and strongly positively correlated with soil Colwell K in the furrow at the 10-15 cm depth ($R^2 = 0.74$; Table 95). Soil water content in the furrow at the 15 cm depth was also very strongly positively correlated with soil Colwell P in the furrow at the 5-10 cm depth ($R^2 = 0.92$; Table 95), with soil water content in the inter-row at the

15 cm depth strongly negatively correlated with soil Colwell P in the inter-row at the 15-20 cm depth ($R^2 = 0.74$; Table 95).

Table 95. Bivariate correlation between soil water content (40 DAS) and nutrients (ammonium-nitrogen, nitrate-nitrogen, Colwell phosphorus, and Colwell potassium) post-harvest (41 DAS), using the coefficient of determination (R^2). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Row	Depth	Soil water			
			Furrow		Inter-row	
			5 cm	15 cm	5 cm	15 cm
Soil NH$_4$-N	Furrow	0-5 cm	0.14	0.01	0.00	0.02
		5-10 cm	0.30	0.77*	0.09	0.21
		10-15 cm	0.55	0.58	0.06	0.16
		15-20 cm	0.35	0.96**	0.08	0.44
	Inter-row	0-5 cm	0.67*	0.12	0.18	0.03
		5-10 cm	0.76*	0.11	0.48	0.04
		10-15 cm	0.37	0.90**	0.04	0.35
		15-20 cm	0.38	0.98**	0.07	0.55
Soil NO$_3$-N	Furrow	0-5 cm	0.21	0.17	0.80*	0.04
		5-10 cm	0.51	0.52	0.01	0.12
		10-15 cm	0.49	0.01	0.81*	0.00
		15-20 cm	0.77*	0.29	0.34	0.15
	Inter-row	0-5 cm	0.10	0.08	0.49	0.14
		5-10 cm	0.09	0.12	0.86*	0.01
		10-15 cm	0.69*	0.27	0.36	0.13
		15-20 cm	0.81*	0.61	0.09	0.44
Soil Colwell P	Furrow	0-5 cm	0.08	0.32	0.24	0.04
		5-10 cm	0.21	0.92**	0.19	0.40
		10-15 cm	0.01	0.38	0.12	0.00
		15-20 cm	0.08	0.00	0.25	0.20
	Inter-row	0-5 cm	0.10	0.39	0.24	0.05
		5-10 cm	0.13	0.45	0.28	0.12
		10-15 cm	0.10	0.00	0.09	0.32
		15-20 cm	0.40	0.20	0.03	0.74*
Soil Colwell K	Furrow	0-5 cm	0.05	0.02	0.00	0.00
		5-10 cm	0.27	0.83*	0.14	0.26
		10-15 cm	0.42	0.74*	0.00	0.21
		15-20 cm	0.41	0.92**	0.05	0.38
	Inter-row	0-5 cm	0.66	0.44	0.01	0.10
		5-10 cm	0.00	0.16	0.30	0.02
		10-15 cm	0.22	0.64	0.11	0.10
		15-20 cm	0.62	0.68*	0.00	0.27

Soil N, P, and K availability

Soil NH$_4$-N and Colwell K concentrations (41 DAS) in the furrow at the 5-10 cm depth were strongly negatively correlated with their respective concentrations in the furrow and inter-row at the 10-15 and 15-20 cm depths ($0.79 \leq R^2 \leq 0.95$; Table 96). Similarly, soil K concentrations in the inter-row at the 0-5 cm depth were strongly negatively correlated with concentrations in the furrow and inter-row at the 10-15 and 15-20 cm depths ($0.67 \leq R^2 \leq 0.88$) but strongly positively correlated with soil Colwell K concentrations in the furrow at the 5-10 cm depth ($R^2 = 0.68$; Table 96). By contrast, soil NH$_4$-N, NO$_3$-N, and Colwell K concentrations in the furrow and inter-row at the 10-15 and 15-20 cm depths were strongly positively correlated with one another (0.69

≤ R^2 ≤ 0.99; Table 96). Soil Colwell P concentrations in the inter-row were also strongly positively correlated between the 10-15 and 15-20 cm depths (R^2 = 0.69; Table 96). Interestingly, soil Colwell P concentrations in the furrow at the 0-5 cm depth and in the inter-row at the 0-5 and 5-10 cm depths were very strongly positively correlated with one another (0.97 ≤ R^2 ≤ 0.99; Table 96).

Table 96. Bivariate correlation between soil nutrients (ammonium-nitrogen, nitrate-nitrogen, Colwell phosphorus, and Colwell potassium) post-harvest (41 DAS) in the furrow and inter-row at depth, using the coefficient of determination (R^2). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Row	Depth	Furrow				Inter-row			
			0-5 cm	5-10 cm	10-15 cm	15-20 cm	0-5 cm	5-10 cm	10-15 cm	15-20 cm
Soil NH_4-N	Furrow	0-5 cm								
		5-10 cm	0.01							
		10-15 cm	0.03	0.66						
		15-20 cm	0.02	0.84**	0.73*					
	Inter-row	0-5 cm	0.05	0.18	0.41	0.20				
		5-10 cm	0.01	0.16	0.62	0.19	0.76*			
		10-15 cm	0.03	0.86**	0.81*	0.99**	0.23	0.26		
		15-20 cm	0.02	0.79*	0.69*	0.99**	0.17	0.18	0.96**	
Soil NO_3-N	Furrow	0-5 cm								
		5-10 cm	0.00							
		10-15 cm	0.61	0.07						
		15-20 cm	0.21	0.36	0.77*					
	Inter-row	0-5 cm	0.65	0.05	0.47	0.21				
		5-10 cm	0.56	0.12	0.63	0.23	0.17			
		10-15 cm	0.20	0.31	0.79*	0.99**	0.22	0.26		
		15-20 cm	0.04	0.46	0.45	0.87**	0.03	0.07	0.84**	
Soil Colwell P	Furrow	0-5 cm								
		5-10 cm	0.53							
		10-15 cm	0.44	0.60						
		15-20 cm	0.54	0.03	0.25					
	Inter-row	0-5 cm	0.99**	0.60	0.53	0.50				
		5-10 cm	0.97**	0.64	0.42	0.40	0.97**			
		10-15 cm	0.42	0.04	0.42	0.83*	0.40	0.29		
		15-20 cm	0.03	0.05	0.16	0.55	0.03	0.00	0.69*	
Soil Colwell K	Furrow	0-5 cm								
		5-10 cm	0.00							
		10-15 cm	0.05	0.79*						
		15-20 cm	0.01	0.94**	0.91**					
	Inter-row	0-5 cm	0.09	0.68*	0.68*	0.68*				
		5-10 cm	0.02	0.50	0.23	0.29	0.27			
		10-15 cm	0.02	0.95**	0.73*	0.83*	0.74*	0.67*		
		15-20 cm	0.03	0.81*	0.84*	0.85**	0.88**	0.20	0.76*	

Effect of soil water and nutrient availability on plant growth and nutrition

Wheat tiller number ($R^2 = 0.75$), shoot dry matter ($R^2 = 0.81$), and total uptake of all nutrients ($0.71 \leq R^2 \leq 0.85$) were strongly positively correlated with soil water content in the furrow at the 15 cm depth (Table 97), but not with soil water content in the furrow at the 5 cm depth.

Table 97. Bivariate correlation between soil water content (40 DAS) and wheat shoot growth and nutrient parameters using the coefficient of determination (R^2). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Soil water			
	Furrow		Inter-row	
	5 cm	15 cm	5 cm	15 cm
Tiller number	0.58	0.75*	0.00	0.26
Shoot dry matter	0.56	0.81*	0.01	0.33
Total N uptake	0.59	0.81*	0.01	0.33
Total P uptake	0.48	0.85**	0.02	0.33
Total K uptake	0.51	0.82*	0.02	0.30
Total Ca uptake	0.64	0.78*	0.00	0.39
Total Mg uptake	0.58	0.79*	0.00	0.34
Total S uptake	0.55	0.79*	0.01	0.28
Total B uptake	0.34	0.82*	0.08	0.24
Total Cu uptake	0.62	0.71*	0.00	0.26
Total Fe uptake	0.53	0.81*	0.01	0.31
Total Mn uptake	0.52	0.80*	0.04	0.33
Total Zn uptake	0.61	0.74*	0.01	0.29

Wheat tiller number, shoot dry matter, and total nutrient uptake were strongly negatively correlated with soil NH_4-N, NO_3-N, and Colwell K concentrations in the furrow at the 5-10 cm depth ($0.66 \leq R^2 \leq 0.93$; Tables 98, 99, and 101, respectively), and also with soil Colwell K concentration in the inter-row at the 0-5 cm depth ($0.70 \leq R^2 \leq 0.85$; Table 101). However, tiller number and shoot dry matter were strongly positively correlated with soil NH_4-N and Colwell K in the furrow and inter-row at the 10-15 and 15-20 cm depths ($0.69 \leq R^2 \leq 0.98$; Tables 98 and 101, respectively).

Table 98. Bivariate correlation between soil ammonium-nitrogen (NH_4-N) post-harvest (41 DAS) and wheat shoot growth and nutrient parameters using the coefficient of determination (R^2). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Soil NH_4-N							
	Furrow				Inter-row			
	0-5 cm	5-10 cm	10-15 cm	15-20 cm	0-5 cm	5-10 cm	10-15 cm	15-20 cm
Tiller number	0.02	0.80*	0.93**	0.90**	0.40	0.45	0.95**	0.86**
Shoot dry matter	0.00	0.84*	0.80*	0.90**	0.47	0.40	0.92**	0.87**
Total N uptake	0.00	0.83*	0.81*	0.90**	0.48	0.42	0.92**	0.87**
Shoot N concentration	0.13	0.32	0.43	0.25	0.93**	0.67*	0.29	0.22

Tiller number and shoot dry matter were also strongly positively correlated to soil Colwell P concentration in the furrow at 5-10 cm ($0.66 \leq R^2 \leq 0.86$; Table 100) but were not correlated to soil Colwell P concentration elsewhere. Tiller number, dry matter, and total N uptake (except for B and Mn) were also strongly positively correlated with soil NO_3-N in the inter-row at the 15-20 cm ($0.72 \leq R^2 \leq 0.78$; Table 99).

Table 99. Bivariate correlation between soil nitrate-nitrogen (NO_3-N) post-harvest (41 DAS) and wheat shoot growth and nutrient parameters using the coefficient of determination (R^2). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Soil NO_3-N							
	Furrow				Inter-row			
	0-5 cm	5-10 cm	10-15 cm	15-20 cm	0-5 cm	5-10 cm	10-15 cm	15-20 cm
Tiller number	0.02	0.68*	0.17	0.62	0.00	0.01	0.60	0.78*
Shoot dry matter	0.03	0.80*	0.10	0.50	0.00	0.04	0.46	0.72*
Total N uptake	0.02	0.80*	0.11	0.53	0.00	0.03	0.48	0.75*
Shoot N concentration	0.11	0.65	0.27	0.46	0.07	0.01	0.38	0.41

Shoot K concentrations in wheat were strongly negatively correlated with soil Colwell K concentrations in the furrow at the 5-10 cm depth ($R^2 = 0.77$) and in the inter-row at the 0-5 cm depth ($R^2 = 0.81$; Tables 101). However, shoot K concentrations were strongly positively correlated with soil Colwell K concentrations in the furrow and inter-row at the 10-15 and 15-20 cm depths ($0.73 \leq R^2 \leq 0.87$). Shoot N concentrations were also strongly negatively correlated with soil NH_4-N concentrations in the inter-row at the 0-5 cm depth ($R^2 = 0.93$) but strongly positively correlated with soil NH_4-N concentration in the inter-row at the 5-10 cm depth ($R^2 = 0.67$; Table 98).

Table 100. Bivariate correlation between soil Colwell phosphorus (P) post-harvest (41 DAS) and wheat shoot growth and nutrient parameters using the coefficient of determination (R^2). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Soil Colwell P							
	Furrow				Inter-row			
	0-5 cm	5-10 cm	10-15 cm	15-20 cm	0-5 cm	5-10 cm	10-15 cm	15-20 cm
Tiller number	0.27	0.75*	0.53	0.00	0.35	0.33	0.00	0.07
Shoot dry matter	0.38	0.78*	0.45	0.00	0.47	0.46	0.00	0.09
Total P uptake	0.36	0.83*	0.52	0.00	0.45	0.44	0.01	0.07
Shoot P concentration	0.27	0.54	0.51	0.01	0.36	0.30	0.03	0.01

Table 101. Bivariate correlation between soil Colwell potassium (K) post-harvest (41 DAS) and wheat shoot growth and nutrient parameters using the coefficient of determination (R^2). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	Soil Colwell K							
	Furrow				Inter-row			
	0-5 cm	5-10 cm	10-15 cm	15-20 cm	0-5 cm	5-10 cm	10-15 cm	15-20 cm
Tiller number	0.04	0.79*	0.98**	0.93**	0.72*	0.21	0.72*	0.83*
Shoot dry matter	0.00	0.84**	0.88**	0.94**	0.79*	0.25	0.78*	0.84*
Total K uptake	0.01	0.87**	0.90**	0.95**	0.78*	0.29	0.81*	0.84*
Shoot K concentration	0.00	0.77*	0.82*	0.76*	0.81*	0.54	0.87*	0.73*

6.4 Discussion

Consistent with findings in Chapter 5, a wettable furrow that ensured uniform seedling emergence in a severely water-repellent (MED ~ 3.0) topsoil significantly increased wheat seedling growth (by an additional leaf stage; 20 DAS), tiller number (by up to an additional 2 tillers; 38 DAS), dry matter (by an average of 152 %; 40 DAS), and total uptake of all nutrients (by an average of 172 %; 40 DAS) relative to completely wettable (MED = 0.0) topsoil treatments under controlled glasshouse conditions and variable water supply (3.4, 4.4, or 5.4 mm every 2 days; average day air temperature of 18°C and relative humidity of 40 %). The relative increases in wheat shoot dry matter and total nutrient uptake due to topsoil water repellence were, however, more pronounced at the lowest water supply (3.4 mm) relative to a 4.4 or 5.4 mm water supply by almost 2-fold, thus highlighting the significance of water harvesting under low water supply.

Topsoil water repellence also increased shoot N, P, K, S, and Fe concentrations relative to wettable treatments, although the effect of topsoil water repellence on shoot N concentration was only observed in treatments with a 3.4 mm water supply. However, as the water supply increased from 3.4 to 5.4 mm, wheat seedling growth stage, tiller number, shoot dry matter, and total nutrient uptake also significantly increased, with a more pronounced increase in shoot dry matter and total nutrient uptake in repellent treatments than in wettable treatments. Shoot N, P, K, S, and Fe concentrations also significantly increased as the water supply increased from 3.4 to 5.4 mm, regardless of topsoil water repellence.

Such improvements in early wheat growth and nutrition in repellent treatments can be attributed to an increase in soil water and nutrient availability at depth in the root zone as a result of preferential flow in the wettable furrow. Indeed, soil sensors buried at depth showed that repellent treatments resulted in rapid vertical transport of water and solutes in the furrow at 5 cm depth, regardless of water supply (3.4, 4.4, or 5.4 mm) despite no drainage occurring below treatment containers during the 40-day experiment. By contrast, soil wetting at the 5 cm depth was considerably delayed in wettable treatments by 9 and 18 days under a 5.4 and 4.4 mm water supply, respectively, with no wetting observed in wettable treatments with a 3.4 mm water supply. These decreases in wetting depth in the furrow of wettable treatments would consequently explain why early wheat growth and nutrition (N, P, K, S, and Fe) were relatively poor in comparison to plants in repellent treatments receiving the same water supply. Although all plants were still relatively deficient in N (i.e., <6.7 %; Reuter and Robinson 1997), topsoil water repellence and water supply treatments were particularly important for early wheat P and S nutrition, given their marginal deficiency in some plants observed only in wettable treatments with a 3.4 mm water supply.

Shallow wetting (<5 cm depth) in wettable treatments would have impeded root access to fertiliser, which was banded at the 7 cm depth, and hence reduced nutrient uptake. Increasing the water supply from 3.4 to 4.4 mm did, however, at least result in soil wetting in the furrow at the 5 cm depth of wettable treatments which possibly allowed greater root access to fertiliser. This increase in plant-available water, wetting depth, and fertiliser access could then explain the observed improvements in wheat seedling growth, tiller number, dry matter, total nutrient uptake (except for Cu and Zn), and shoot N, K, Cu, and Zn concentrations in wettable treatments with a 4.4 mm water supply relative to a 3.4 mm water supply. However, compared to repellent treatments which exhibited preferential flow in the furrow, shallow wetting in the furrow and inter-row of wettable treatments was a significant limitation to the growth and nutrition of young wheat plants.

Evaporative water loss from the soil surface are reported to be higher in wettable treatments than in repellent treatments (Bachmann *et al.* 2001; Gupta *et al.* 2015; Rye and Smettem 2017) due to greater wet soil surface area exposed to air and stronger capillary forces which cause the upward movement of water (DeBano 1981). Increased soil surface drying in wettable treatments would consequently explain why the soil water content in the furrow at the 5 cm depth was constantly lower than that in repellent treatments, despite depressed plant growth and water uptake in wettable treatments. The total quantity of water available for plant uptake was, therefore, limited in wettable treatments and this would have led to the development of shallower root systems that are more vulnerable to drying (Weaver 1926; Dunbabin *et al.* 2003). Although no quantitative assessment on wheat root growth was undertaken in this experiment, visual differences at 40 DAS (Figures 76 and 77), indicated deeper roots in repellent treatments than in wettable treatments, especially as the water supply increased from 3.4 to 5.4 mm. Under a 5.4 mm water supply, roots were matted at the base (20 cm depth) of repellent treatments, while roots in wettable treatments remained relatively limited to the 0-10 cm depth. Such differences in root growth were consistent with that of shoot growth, reflecting the importance of soil water availability at depth for early root development and hence wheat growth and nutrition. Water ponding on the surface of water-repellent soil due to incomplete or delayed water infiltration can, however, be prone to evaporation and overland flow (Mao *et al.* 2019). Therefore, if enough rainfall can be captured in the furrow and transported to the root zone, preferential flow in water-repellent soils could have significant benefits for dryland cropping systems by conserving soil water and increasing subsurface water storage.

In semi-arid dryland cropping systems, plants with deeper root systems can access deep-stored water and nutrients, including leached nitrate (e.g., Dunbabin *et al.* 2003), allowing plants to evade water stress and potentially attain higher yields (Wasson *et al.* 2012). Increasing subsurface water storage and resource capture will, therefore, be critical for improving drought resistance (Hamblin and Hamblin 1985; Chloupek *et al.* 2010), and maximising crop production, particularly in regions where seasonal water deficits are common (Lobet *et al.* 2014; Thorup-Kristensen and Kirkegaard 2016). Studies by Kirkegaard *et al.* (2007) have also shown that, under moderate post-anthesis stress, even a relatively small supply of subsoil water (i.e., 10.5 mm in the 1.35-1.85 m layer) can be highly valuable for wheat grain development which increased grain yield by 0.62 t/ha. They attributed the additional yield to a period of higher assimilation 12-27 days after anthesis, demonstrating the high efficiency for subsoil water use (59 kg/ha per mm) by wheat plants during grain filling. Therefore, under a low water supply and moderate level of leaching, topsoil water repellence and preferential flow in the furrow may favour plant water use efficiency and hence early growth and nutrition in water-repellent soils by reducing evaporation, increasing subsurface water storage, and promoting deeper roots. In this way, adoption of water harvesting principles (e.g., furrow sowing and banding wetting agents; Blackwell 1993) that use water-repellent ridges in the inter-row may have a greater advantage over techniques that completely ameliorate soil water repellence and induce even wetting (e.g., blanket-applied wetting agents, clay spreading, or deep soil cultivation). However, compared to the relatively cheap and short-term effect of wetting agents on crop production, clay spreading and/or deep cultivation are expensive but can produce substantial and longer-lasting benefits (Roper *et al.* 2015), particularly due to the amelioration of multiple soil constraints (Hall *et al.* 2010).

In other circumstances, there may be risks from increased early plant growth in repellent treatments relative to wettable treatments that have adverse implications for crop yield under decreased water supply and/or terminal drought due to greater demand for water. Excessive vegetative biomass and plant water uptake may lead to post-anthesis water deficit, resulting in plants 'haying-off' and a yield that is disproportionately low in relation to total dry matter production (van Herwaarden *et al.* 1998; Nuttall *et al.* 2012). However, for such crops, shoot growth could provide useful livestock feed (Davies *et al.* 2012a). An assessment of plant hydration (40 DAS) showed that leaf RWC was significantly lower in repellent treatments (82.9 %) than in wettable treatments (88.5 %), with leaf RWC generally increasing from 81.5 to 90.9 % as the water supply increased from 3.4 to 5.4 mm. These results likely reflect the greater water use requirement by plants in repellent treatments due to their increased growth and transpiration rates relative to that in wettable treatments. While all plants remained well hydrated (RWC > 80 %), increased competition for water in repellent treatments may eventually lead to water stress if soil water is not replenished by rainfall. Nevertheless, rapid development of the rhizosphere and increased rooting depth early in the season could help lessen the impact of water stress and/or terminal drought on dryland crops due to a greater access to subsurface water and nutrient supplies (Shao *et al.* 2008; Fageria and Moreira 2011).

Despite the increased potential for leaching in repellent treatments, results highlight the importance of subsurface water and nutrient (N and K) supply at the 10-20 cm depth for early wheat growth and nutrition, whereby: (1) tiller number, shoot dry matter, and total nutrient uptake of all nutrients were positively correlated with post-harvest soil water content in the furrow at the 15 cm depth ($0.71 \leq R^2 \leq 0.85$); (2) tiller number and shoot dry matter were positively correlated with post-harvest soil NH_4-N and Colwell K concentrations in the furrow and inter-row at the 10-15 and 15-20 cm depths ($0.69 \leq R^2 \leq 0.98$); and (3) tiller number, dry matter, and total uptake of all nutrients (except for B and Mn) were positively correlated with post-harvest soil NO_3-N concentration in the inter-row at the 15-20 cm ($0.67 \leq R^2 \leq 0.80$). Increased soil wetting and nutrient (N and K) availability at the 10-20 cm depth in repellent treatments were, therefore, important mechanisms favouring early wheat growth and nutrition in repellent treatments relative to wettable treatments which had limited wetting at depth.

On the contrary, leaching of P was minimal since soil Colwell P concentration at the 15-20 cm depth was similar in repellent treatments (15 mg/kg) to that in wettable treatments (14 mg/kg). The negative correlation between soil water content in the inter-row at the 15 cm depth and soil Colwell P concentration in the inter-row at the 15-20 cm depth suggests that increasing water availability at depth may have enhanced P reactions with the solid phase (e.g., sorption by soil colloids, organic matter, and Fe/Al minerals; Menzies 2009), or due to increased plant P uptake from that layer due to greater root activity. Increases in soil water content in the furrow at the 15 cm depth were, however, positively correlated with increases in soil Colwell P concentration in the furrow at the 5-10 cm depth, reflecting an increase in soluble P from the fertiliser band. This increase in soil Colwell P concentration in the furrow at the 5-10 cm depth was consequently positively correlated to increases in wheat tiller number at 38 DAS and shoot dry matter at 40 DAS. Changes to soil Colwell P below the 10 cm depth did not appear to affect early growth. Based on these results, it can be concluded that increased soil P availability in the furrow at the 5-10 cm depth and soil N and K availability at the 10-20 cm depth due to preferential flow which increased soil water availability at depth were consequently important for early wheat growth and nutrition in repellent treatments.

However, significant differences in soil Colwell P concentration in the furrow at the 0-5 and 5-10 cm depths between wettable (61 and 157 mg/kg, respectively) and repellent treatments (103 and 203 mg/kg, respectively) were not only due to increased soil water availability and P dissolution but also due to differences in indigenous soil Colwell P concentrations (i.e., 59 and 129 mg/kg in wettable and repellent topsoil, respectively; Table 76) due to insufficient mixing of topsoil prior to the experiment. Furthermore, it could also be that the dissolution of P in wettable topsoil after the application of wetting agent may have resulted in rapid microbial immobilisation of P (Bünemann *et al.* 2012) relative to that in repellent topsoil which was untreated. Subsequent soil tests, however, suggest that soil Colwell P concentration was not directly affected by wetting agent treatment although soil mineralisation did result in increased soil N concentration (see Appendix E.2). Nevertheless, despite such difference in indigenous soil Colwell P (50-100 mg/kg), early wheat tillering, shoot dry matter, and total nutrient uptake were not correlated with soil Colwell P concentration in the furrow (0-5 cm) and inter-row (0-5 and 5-10 cm) but were found to be positively correlated with soil Colwell P concentration in the furrow at the 5-10 cm depth where fertiliser was banded at the 7 cm depth. Results, therefore, highlight the importance of soluble P fertiliser for early wheat growth and nutrient uptake, despite high indigenous Colwell P concentrations in topsoil.

Although the phosphorus buffering index (PBI) of these sandy loam soils was relatively low (PBI = 95) in comparison to other finer-textured loamy or clayey soil types (high PBI >280; Moody 2007; Wong *et al.* 2012), a supplementary experiment (see Appendix G:) showed that unfertilised (indigenous) topsoil resulted in negligible resin-extractable P over 30 days (<10 mg P/m^2), suggesting that starter P fertiliser was probably required to maintain adequate plant P uptake during the early growth stages in wheat. In comparison to other conventional chemical-based soil tests, many studies have also reported the superiority of resin-extractable P tests using ion exchange membranes in estimating soil P availability in relation to plant P response (Qian *et al.* 1992; Fernandes and Coutinho 1997; van Raij 1998; Turrión *et al.* 1999; Mallarino and Atia 2005; Sousa and Coutinho 2009), with their ability to even correctly assess P deficiencies in plants grown on heavily fertilised soils (e.g., soil Colwell P levels exceeding 100 mg/kg; Kusomo *et al.* 2001; Moody 2007).

Topsoil water repellence may have implications for the timing of soil mineralisation and the release of indigenous soil N supply due to the increased protection of aggregates from wetting and microbial degradation (Piccolo *et al.* 1999;

Goebel *et al.* 2005; Arcenegui *et al.* 2008). In this study, post-harvest NO_3-N concentrations in the inter-row at the 5-10 cm depth were almost 2-fold greater in wettable treatments (73 mg/kg) than in repellent treatments (38 mg/kg), indicating that limited wetting of the inter-row of repellent topsoil could have significantly reduced soil N mineralisation and hence NO_3-N availability. Depending on the synchrony between soil N mineralisation and plant N demand, mineralised N can contribute greatly to plant N requirements and N use efficiency (Myers *et al.* 1994). However, the observed changes in soil NO_3-N concentration in the inter-row at the 5-10 cm depth did not appear to be important for early wheat growth and nutrition, suggesting that early N mineralisation in wettable topsoil could be susceptible to N loss via NO_3-N leaching and/or gaseous NH_3 volatilisation (Cameron *et al.* 2013). Increased protection of early season N supply in the inter-row of dry, repellent topsoil may consequently have a 'slow-release' effect on mineralised N as the topsoil progressively wets up (e.g., >40 days) and plant roots explore a greater volume of topsoil. Prolonged soil dryness in water-repellent soil may, however, adversely affect plant uptake by restricting root placement and root volume (Lobet *et al.* 2014), and this may hinder plant nutrient use efficiency as roots are unable to forage therein (Roper *et al.* 2015). Nevertheless, results from this study clearly showed that increased plant-available water and nutrients near the fertiliser band or at the 10-20 cm depth had far greater benefits for early wheat growth and nutrition in repellent treatments relative to wettable treatments.

The studied watering regimes of 3.4, 4.4, and 5.4 mm every 2 days (i.e., 20 separate wetting events over 41 days) were generally related to dryland cropping systems in the medium (325-450 mm) to high (450-750 mm) rainfall zones of southwest WA, where the total amount of water supplied in each treatment container was 68, 88, and 108 mm, respectively. Under these watering regimes, results validated the high efficacy of topsoil water repellence for improving early wheat growth and nutrition via *in situ* water harvesting. This effect was most pronounced in treatments with the lowest water supply (3.4 mm), suggesting that *in situ* water harvesting could be more relevant for crops grown in lower rainfall areas. For arid and semi-arid dryland cropping systems that are strongly limited by low rainfall and seasonal water deficits, efforts to harvest rainfall and conserve soil water are indeed vital for crop production. Adoption of *in situ* water harvesting principles (e.g., furrow sowing and banding wetting agents) can, therefore, have their own advantages in capturing low rainfall events over other methods which completely ameliorate soil water repellence (e.g., claying and deep cultivation). However, the efficacy of water harvesting is likely to decline under high water supply and more severe leaching which could have different implications for early crop growth and nutrition. The efficacy of water harvesting in repellent soils under variable surface topography and plant density, however, also needs to be assessed given that ridge erosion, furrow in-fill, and uneven plant establishment are realities on water-repellent field soils. Future research should also study the efficacy of topsoil water repellence under variable surface topography, variable plant density, and higher water supply.

6.5 Conclusion

In a glasshouse experiment with uniform plant density, severe topsoil water repellence with a wettable furrow significantly increased early wheat growth and nutrient uptake (40 DAS) relative to completely wettable topsoil treatments, despite an increase in water supply from 3.4 to 5.4 mm every 2 days. These effects of topsoil water repellence were largely attributed to preferential flow in the furrow which significantly increased: (1) wetting depth and soil water availability in the furrow (15 cm) and hence increased plant water use efficiency in repellent treatments relative to wettable treatments which exhibited even but shallow wetting in the furrow and inter-row, and potentially greater evaporative water loss; and, (2) plant-available P in the furrow (5-15 cm) and subsurface N and K availability in the furrow and inter-row (10-20 cm). Such increases in soil water and nutrient availability strongly favoured early wheat growth and nutrient uptake in repellent treatments. Despite an increased potential for leaching in repellent treatments, increased water and nutrient transport favoured the development of deeper roots which, in turn, increased the recovery of subsoil N and K and probably stimulated the acquisition of additional subsurface water and nutrient supplies. Limited wetting of repellent topsoil in the inter-rows may also conserve early season N supply by delaying mineralisation and leaching which could be released later in the season when plant demand is higher and root systems are more extensive. By contrast, even wetting across the soil surface and the increased retention of water in the surface layer (0-10 cm) of wettable treatments greatly reduced the soil wetting depth and increased the risk of evaporative water loss, resulting in significantly lower wheat growth and nutrient uptake. In arid and semi-arid dryland cropping systems that are strongly limited by low rainfall and seasonal water deficits, adoption of *in situ* water harvesting principles (e.g., furrow sowing and banded wetting agents) that utilise preferential flow in the wettable furrows of severely repellent topsoil could benefit crop production by enhancing water and nutrient availability in the root zone and by preventing early season water and nutrient losses to the environment. Findings validate earlier work described in Chapter 5 and provide new insight on the efficacy of topsoil water repellence for *in situ* water harvesting to improve early wheat growth and nutrition under variable but not excessive water supply. Future research should also study the efficacy of topsoil water repellence under variable surface topography, variable plant density, and higher water supply and this is the focus of the next chapter.

Chapter 7: Effect of soil water repellence on early wheat growth and nutrition under variable surface topography and plant density

7.1 Introduction

Reducing unproductive water losses from runoff and evaporation, and making more soil water available for plant uptake and transpiration are key objectives for improving dryland crop production in arid and semi-arid regions (Rockström *et al.* 2010). One way is to capture and divert rainfall and runoff from a catchment area (e.g., on-/off-site micro-catchment, terraces, or ridges) to a cropped basin or reservoir (i.e., water harvesting; Boers and Ben-Asher 1982; Fink and Ehrler 1986; Hatibu and Mahoo 1999; Li 2003; Turner 2004; Liu *et al.* 2005; Sturm *et al.* 2009; Gan *et al.* 2013; Liu and Jin 2016). At this scale a portion of land needs to be sacrificed for water harvesting (Fink and Ehrler 1984). By contrast, approaches that modify microtopography (e.g., ridges and furrows) on a cropped area either alone or in combination with surface mulches (e.g., using plastic film, plant residue, and gravel-sand materials) can boost crop water use efficiency and crop yields by concentrating rainwater in the furrow or planting zone without the loss of planting area (e.g., ridge and furrow rainwater harvesting (RFRH) systems; Li *et al.* 1999; Li *et al.* 2000; Li *et al.* 2001; Jia *et al.* 2006; Ren *et al.* 2008; Wang *et al.* 2008; Wang *et al.* 2009b; Wang *et al.* 2011; Qi *et al.* 2015; Ren *et al.* 2016; Gu *et al.* 2017; Lian *et al.* 2017; Liu *et al.* 2018; Gu *et al.* 2019; Pan *et al.* 2019).

Unlike wettable cropping soils, rainfall partitioning in water-repellent soils is constrained by the soil's resistance to water absorption and infiltration (Roberts and Carbon 1971; Wang *et al.* 2000; Li *et al.* 2018) which causes increased surface runoff (Witter *et al.* 1991; Shakesby *et al.* 2000; Doerr *et al.* 2003) and unstable wetting and preferential flow patterns (Ritsema and Dekker 1994; Dekker and Ritsema 1996b; Bauters *et al.* 1998). As a result, seeds in the crop row are unable to germinate evenly on repellent soils, with the established plant also potentially limited in growth due to decreased water uptake (Li *et al.* 2019), resulting in non-uniform crop maturation and limited crop yields (Bond 1964; Bond 1972). Earlier findings from Chapters 5 and 6, however, suggested that *in situ* water harvesting can be far more effective on water-repellent soils than on completely wettable soils by facilitating deeper wetting depths, provided that water can be diverted to the furrow base (planting zone) of repellent soils. Other studies have also shown that water-repellent soils can act as a mulch and aid in soil water conservation by significantly reducing evaporative water loss from the soil surface (Bachmann *et al.* 2001; Gupta *et al.* 2015; Rye and Smettem 2017) by decreasing the upward capillary movement of water (DeBano 1981) and diverting water flow to subsurface layers via preferential pathways (Ritsema and Dekker 1994).

In dryland cropping systems, utilising soil water repellence for *in situ* water harvesting and soil water conservation is a counter-intuitive strategy for managing crop production on sandy soils. Further work to assess the role of surface topography (ridge-furrow or flat) and its interaction with topsoil water repellence is, therefore, needed to determine to what extent a ridge-furrow topography can contribute to water harvesting and to improved early plant growth. Given the reality that plant establishment is often constrained on water-repellent soils, the capacity of water harvesting to compensate for low plant densities during early plant growth should also be assessed. A glasshouse experiment was, therefore, conducted to examine the effect of topsoil water repellence (nil or severe) on early wheat growth and nutrition under variable surface topography (ridge-furrow or flat) and plant density (9, 12, or 15 plants/container). It was hypothesised that the efficacy of topsoil water repellence for *in situ* water harvesting to improve early wheat growth and nutrition would be lessened in: (a) treatments with a flat topography compared to a ridge-furrow topography due to the lack of water flow diverted to the seeded furrow, and (2) treatments with a higher plant density due to increased competition of water and nutrients.

7.2 Materials and methods

7.2.1 Treatment design

Wheat (*Triticum aestivum* cv. Mace) was grown over 40 days, from 5 April to 14 May 2019, under controlled glasshouse conditions at Murdoch University (32°04’02.30” S 115°50’20.21” E), Western Australia, to investigate the effects of (a) topsoil water repellence (wettable and severely repellent topsoil), (b) surface topography (ridge-furrow and flat), and (c) plant density (9, 12, and 15 plants/container) on early vegetative growth and nutrition of wheat plants. Water-repellent topsoil (0-10 cm) and wettable subsoil (10-30 cm) were collected from the same locations as for Chapter 5 and 6 experiments. Bulk soils were air-dried, sieved (≤2 mm) to remove gravel and coarse material, and thoroughly mixed in a cement mixer. Baseline soil properties are detailed in Table 102. Treatments in this experiment were prepared from the same batch of soil to avoid any differences in soil properties as observed in Chapter 6. After processing, the repellent topsoil had a molarity of ethanol droplet (MED) value of 2.2 (i.e., moderate repellence; King 1981). In contrast to the previous method for preparing wettable topsoil, wettable treatments were created by applying a 5 % v/v wetting agent solution (Everydrop Liquid Concentrate by Scotts Australia Pty Ltd) during the first hand watering event to prevent any confounding effects on N mineralisation prior to the experiment (see Appendix E.2). Prior to watering, 60 ml of 20 % v/v wetting agent solution was banded in the furrow of all treatments to ensure seed germination. Note, there were no added nutrients in this soil wetting agent.

Table 102. Baseline properties of topsoil and subsoil used in treatment containers. Soils were analysed by the methods of Rayment and Lyons (2011).

Soil properties	Topsoil	Subsoil
pH$_{Ca}$ (CaCl$_2$)	4.8	5.2
Organic carbon (g/kg)	37.1	1.8
Electrical conductivity (dS/m)	0.07	0.01
NH_4-N (mg/kg)	13.3	1.7
NO_3-N (mg/kg)	12.3	1.3
Colwell P (mg/kg)	116.7	14.3
Colwell K (mg/kg)	142.7	19.0
Effective cation exchange capacity (cmol(+)/kg)	5.01	0.68
Exchangeable Ca (cmol(+)/kg)	3.75	0.46
Exchangeable Mg (cmol(+)/kg)	0.44	0.07
Exchangeable K (cmol(+)/kg)	0.28	0.02
Exchangeable Na (cmol(+)/kg)	0.09	0.01
Exchangeable Al (cmol(+)/kg)	0.46	0.14
Extractable S (mg/kg)	14.7	1.3
Extractable B (mg/kg)	0.54	0.13
Extractable Cu (mg/kg)	0.84	0.46
Extractable Fe (mg/kg)	34.1	13.8
Extractable Mn (mg/kg)	4.59	0.33
Extractable Zn (mg/kg)	1.06	0.14
Sand (g/kg)	758.2	867.6
Silt (g/kg)	78.1	10.0
Clay (g/kg)	163.7	122.4

Drainage holes were drilled in each container and shade cloth was placed along the bottom to prevent soil spillage. Subsoil (10 cm depth) and topsoil (10 cm depth) were layered in each container for a total depth of 20 cm (i.e., treatments with a flat topography). To create treatments with a ridge-furrow topography, ridges were made in the inter-rows, approximately 4 cm high from the base of the furrow, using the same quantity of topsoil used in all treatments. Containers were tapped on the ground for every 4 cm of soil layered to create uniform bulk density. At the 7 cm depth (i.e., 5 cm below the seed in both ridge-furrow and flat treatments), granular fertiliser (Growers Blue) was banded in the furrow at the following rate (mg/kg): 60 N, 25 P, 70 K, 6 Mg, 49 S, 0.5 Zn, 0.1 B, 0.3 Mn, and 0.1 Cu. Nineteen wheat seeds were initially sown at the 1 cm depth along the furrow and later culled to the specific plant density treatment after emergence – that is, a plant density of 9, 12, and 15 plants/container which is equivalent to 75, 100, 125 plants/m^2, respectively. These rates were selected based on the range of wheat emergence observed in a water-repellent Grey Tenosol at Badgingarra in 2017 (see Chapter 4). In Western Australia, for an anticipated grain yield potential of 1, 2, or 3 t/ha, plant densities of 50, 100, or 150 plants/m^2, respectively, are generally regarded to be ideal to ensure that plant densities do not limit grain yield (Anderson and Garlinge 2000).

In separate containers, four Decagon 5TE sensors were buried horizontally in each container at the 5 and 15 cm depths in the furrow and inter-row for the *in-situ* measurement soil volumetric water content (VWC, m^3/m^3) and soil electrical conductivity (EC, mS/cm). Four holes (1 cm diameter) were drilled in the side of the containers for the sensor cords and re-sealed with electrical tape. All containers were hand watered every 2 days using a sprinkle bar over the whole container, with 540 ml (4.4 mm) of tap water over a duration of 1 minute (i.e., an equivalent intensity of 260 mm/h). Note, the water supplied was not sufficient to cause leaching at the base of the container. A total of 12 treatment combinations and three replications were arranged in a full factorial completely randomised design, with the general design of a plant-growth container illustrated in Figure 83. The glasshouse had an average day air temperature of 21°C and relative humidity of 38 %. Treatments were randomised weekly to eliminate bias from environmental factors (e.g., sunlight exposure and microclimate) affecting wheat growth.

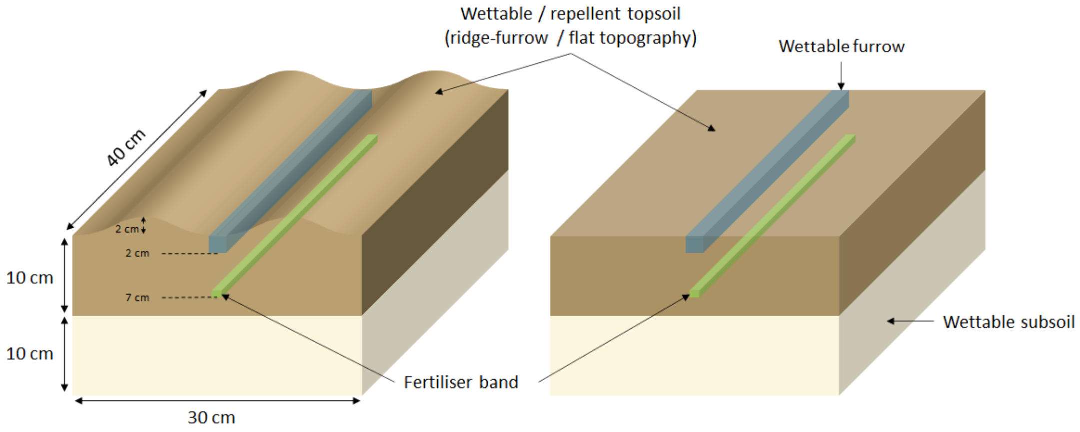

Figure 83. General treatment design of growing containers with a ridge-furrow and flat topography.

7.2.2 Soil and plant sampling and analysis

Soil was sampled post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths and analysed for ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), Colwell phosphorus (P), and Colwell potassium (K) according to standard methods (Rayment and Lyons 2011) by the CSBP Soil and Plant Analysis Laboratory. Note, due to furrow infill from ridge erosion and soil compaction over time from watering, the height difference between the base of the furrow and tip of the ridge generally diminished from 2 cm (initial ridge construction at 0 DAS) to ≤5 mm (41 DAS). Slight differences in soil sampling depth between the furrow and inter-row, and between the ridge-furrow and flat topography treatments were thus considered to have no significant confounding influence on the relative soil layers assessed for soil nutrient availability.

In a separate treatment container, ‘actual’ soil water repellence severity was assessed *in situ* at the 2 cm depth in the inter-row using the molarity of ethanol droplet, MED, test (King 1981). Soil water repellence severity was denoted by the MED concentration that penetrated the soil surface within 10 seconds. Soil MED tests were conducted at solar noon (±2 hours) prior to watering every 2 days at different locations in the inter-row.

Wheat seedling stage (20 DAS) and tiller numbers (39 DAS) were assessed and aboveground biomass (40 DAS) was harvested and oven-dried at 60°C for determining shoot dry matter per plant and total shoot dry matter per container. Wheat leaf hydration was also assessed (40 DAS) by measuring the relative water content (RWC, %) in young fully expanded leaves (Barrs and Weatherley 1962; Mullan and Pietragalla 2012). Nutrient concentrations in wheat whole shoot samples were analysed using standard methods (Rayment and Lyons 2011) by the CSBP Soil and Plant Analysis Laboratory. Total nutrient uptake was determined from shoot dry matter and was expressed in terms of mass per plant and total mass per container.

7.2.3 Statistical analysis

Parametric statistical analyses were carried out using SPSS Statistics version 21 (2012) to determine the effects of (a) topsoil water repellence, (b) surface topography, and (c) plant density on early wheat growth and total nutrient uptake. Assumptions of normality and homogeneity of variances were tested and, where the assumptions were violated, data were transformed using a $\log_{10}$ transformation. Main effects and interactions for wheat shoot growth and nutrient uptake parameters were analysed using the univariate analysis of variance, ANOVA (two-tail) test in SPSS. Note, however, that for seedling development, tiller number, and shoot boron (B) concentration, the Welch's one-way ANOVA test in SPSS was conducted to verify the significance of main effects, given that the assumption of homogeneity of variance was still violated despite $\log_{10}$ transformation. Soil nutrients post-harvest (41 DAS) were analysed in a mixed model ANOVA in SPSS, using topsoil water repellence, surface topography, and plant density as between-subjects variables with repeated measures for sampling row and depth as the within-subjects variable. Post hoc analysis was performed using Fisher's least significant difference (LSD) at $P < 0.05$ to determine significant differences among treatment factors.

7.3 Results

7.3.1 Soil water repellence

Severity of topsoil water repellence at the 2 cm depth in the inter-row was measured every 2 days at solar noon (±2 hours) prior to watering over 39 days (Figure 84). Topsoil prior to the first watering event was moderately repellent (MED 2.2) on Day 1, but steadily became very severely repellent over time (MED 3.8) by Day 37.

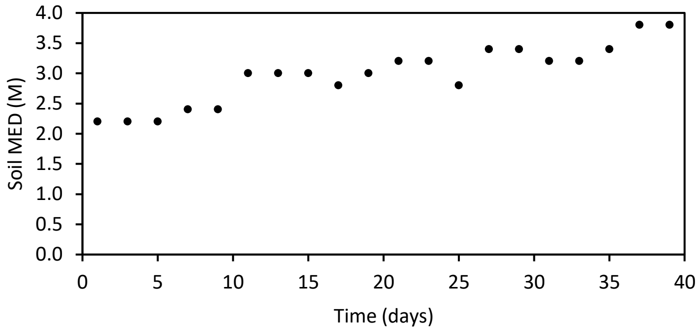

Figure 84. Severity of topsoil water repellence in the inter-row over 39 days, assessed by the molarity of ethanol droplet (MED) test every 2 days at solar noon (±2 hours) prior to watering.

7.3.2 Seedling development

Average wheat seedling phenological development (20 DAS; Zadoks' growth scale) was not affected by interactions between treatments, but the main effect of topsoil water repellence was significant (*P* < 0.001; Table 103). Wheat seedlings were significantly more advanced in repellent treatments (Z13.0) than in wettable treatments (Z12.9). There was no effect of surface topography or plant density on seedling stage.

Table 103. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR), surface topography (ST), and plant density (PD) on wheat seedling stage, tiller number, leaf relative water content (RWC), and dry matter. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Shoot parameters	Source of variation						
	SWR	ST	PD	SWR × ST	SWR × PD	ST × PD	SWR × ST × PD
Seedling stage^{W}	79****	2 ^{ns}	0 ^{ns}	1	0	0	1
Tiller number^{W}	371****	0 ^{ns}	0 ^{ns}	3	1	1	0
Shoot dry matter per plant	468****	9**	4*	0 ^{ns}	0 ^{ns}	2 ^{ns}	1 ^{ns}
Total shoot dry matter per container	423****	12***	29****	5*	6**	3 ^{ns}	2 ^{ns}
Leaf RWC	10***	14***	3 ^{ns}	0 ^{ns}	4*	5*	4*

^{W} Welch's one-way ANOVA test (for main effects only).
^{ns} Not significant (*P* > 0.05).

7.3.3 Tiller number

Only the main effect of topsoil water repellence on wheat tiller number per plant was significant (*P* < 0.001; Table 103), whereby tiller number was significantly greater in repellent treatments (1.9 tillers per plant) than in wettable treatments (0.3 tillers per plant). There was no effect of surface topography or plant density on tiller number per plant.

7.3.4 Shoot dry matter

At early tiller growth (40 DAS), there were no interactions between treatments for shoot dry matter per plant ($P < 0.001$; Table 103), but the main effects of topsoil water repellence ($P < 0.001$), surface topography ($P < 0.01$), and plant density were significant ($P < 0.05$). That is, shoot dry matter per plant was significantly greater in: (a) repellent treatments (0.57 g/plant) than in wettable treatments by 138 % (0.24 g/plant; Figure 85a); (b) treatments with a ridge-furrow topography (0.43 g/plant) than a flat topography by 13 % (0.38 g/plant; Figure 85b); and (c) treatments with a plant density of 9 plants/container (0.43 g/plant) than a plant density of 15 plants/container by 13 % (0.38 g/plant; Figure 85c). However, there were no differences in shoot dry matter per plant between treatments with a plant density of 9 and 12 plants/container, or 12 and 15 plants/container. Differences in shoot biomass between treatments can also be observed in Figure 86.

For total shoot dry matter per container, significant two-way interaction effects were observed between topsoil water repellence and surface topography ($P < 0.05$), and between topsoil water repellence and plant density ($P < 0.01$; Table 103). Total shoot dry matter was significantly greater in repellent treatments (5.41-8.02 g/container) than in wettable treatments (2.33-3.33 g/container) by an average of 141 %, regardless of surface topography (Figure 87) or plant density (Figure 88). Total shoot dry matter was significantly greater in repellent treatments with 9 plants/container (5.41 g/container) than in wettable treatments with 15 plants/container (3.33 g/container; Figure 88).

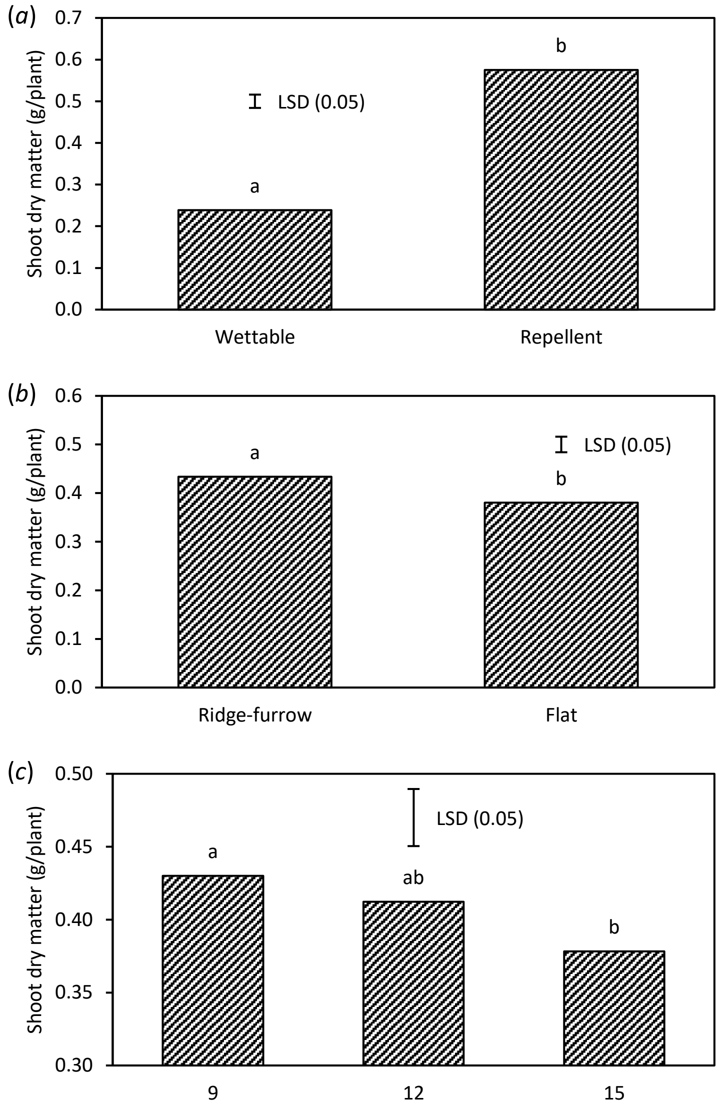

Figure 85. Effect of (a) topsoil water repellence (wettable and repellent), (b) surface topography (ridge-furrow and flat), and (c) plant density (9, 12, and 15 plants/container) on wheat dry matter (g/plant) at 40 DAS. Mean values based on a sample size of 18, 18, and 12, respectively. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

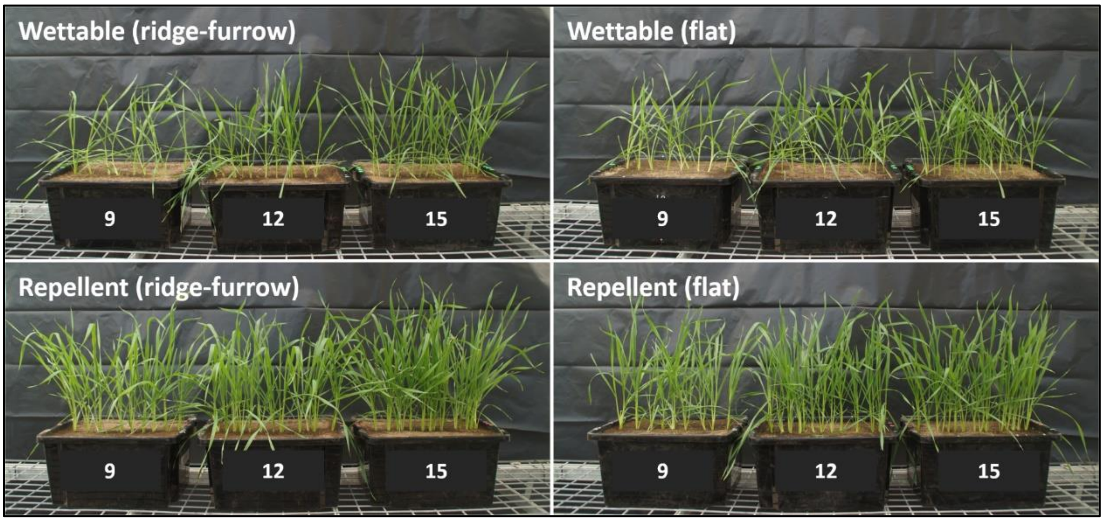

Figure 86. Comparison of wheat shoot growth at 40 DAS between wettable and repellent treatments, with either a ridge-furrow or flat topography, and variable plant density (9, 12, and 15 plants/container).

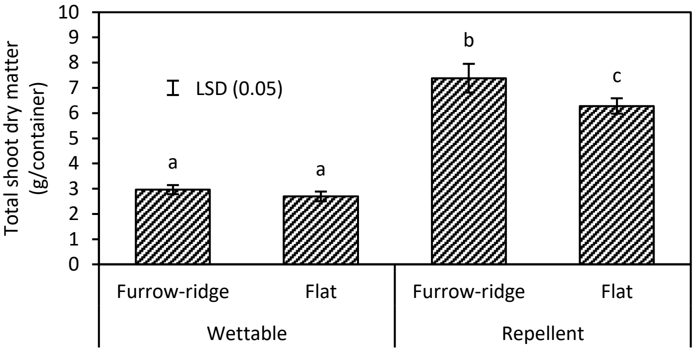

Figure 87. Effect of (a) topsoil water repellence (wettable and repellent) and (b) surface topography (ridge-furrow and flat) on wheat total shoot dry matter (g/container) at 40 DAS. Mean values based on a sample size of 9. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Total shoot dry matter was significantly greater in repellent treatments with a ridge-furrow topography (7.38 g/container) than a flat topography by 18 % (6.28 g/container; Figure 87), but total shoot dry matter was not affected by surface topography in wettable treatments. Total shoot dry matter also significantly increased as the plant density increased from 9 to 15 plants/container in both wettable (2.33 to 3.33 g/container) and repellent treatments (5.41 to 8.02 g/container; Figure 88).

However, in wettable treatments, total shoot dry matter was not different between 9 and 12 plants/container, or between 12 and 15 plants/container.

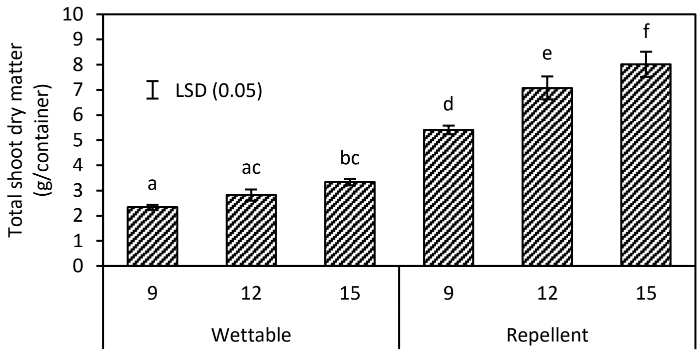

Figure 88. Effect of (a) topsoil water repellence (wettable and repellent) and (b) plant density (9, 12, and 15 plants/container) on wheat total shoot dry matter (g/container) at 40 DAS. Mean values based on a sample size of 6. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

7.3.5 Leaf relative water content

In general, results showed that all plants were relatively well hydrated (RWC > 90 %; 40 DAS; Figure 89). Leaf RWC was significantly affected by the three-way interaction of topsoil water repellence × surface topography × plant density ($P < 0.05$; Table 103), but there was no consistent effect of surface topography or plant density on leaf RWC. However, regardless of surface topography, leaf RWC was significantly greater in repellent treatments (96.4-97.1 %) than in wettable treatments with a plant density of 12 plants/container (95.2-96.0 %; Figure 89). Moreover, leaf RWC was also significantly greater in repellent treatments (96.9 %) than in wettable treatments a plant density of 15 plants/container (95.7 %; Figure 89) but only in treatments with a flat topography. In treatments with a plant density of 9 plants/container, there was no significant effect of topsoil water repellence on leaf RWC, regardless of surface topography.

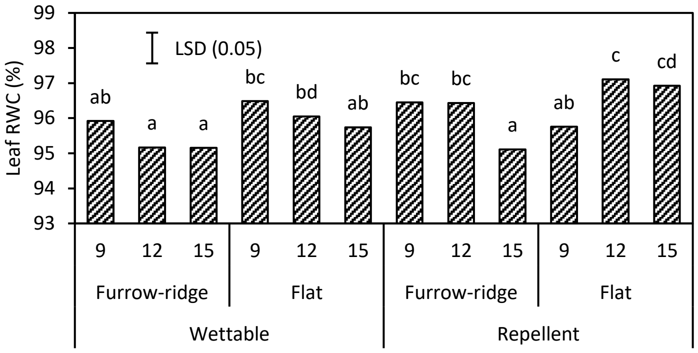

Figure 89. Effect of topsoil water repellence (wettable and repellent), surface topography (ridge-furrow and flat), and plant density (9, 12, and 15 plants/container) on relative water content (RWC, %) in young fully expanded wheat leaves at 40 DAS. Mean values based on three replications. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

7.3.6 Shoot nutrient concentrations

At 40 DAS, all wheat plants in all treatments were relatively deficient in N (i.e., < 6.7 %; Reuter and Robinson 1997; Appendix A.2) but were adequate in other key nutrients. Shoot N, Cu, and Mn concentrations were significantly affected by the two-way interaction of topsoil water repellence × plant density (*P* < 0.05; Table 104). Shoot N concentrations were significantly greater in repellent treatments (5.61-5.74 %) than in wettable treatments (5.24-5.28 %; Table 105), except in treatments with 9 plants/container where no differences were observed. By contrast, shoot Cu and Mn concentrations were significantly greater in wettable treatments (9.42-10.4 mg Cu/kg and190-209 mg Mn/kg, respectively) than in repellent treatments (7.32-7.64 mg Cu/kg and122-136 mg Mn/kg, respectively; Table 105), regardless of plant density. Shoot N concentrations were not affected by plant density in wettable treatments but were significantly greater in repellent treatments with 15 plants/container (5.74 %) than in treatments with 9 plants/container (5.52 %; Table 105). Shoot Cu concentrations also significantly greater in wettable treatments with 15 plants/container (10.4 mg/kg) than in treatments with either 9 (9.42 mg/kg) or 12 plants/container (9.61 mg/kg; Table 105), but no differences were observed in repellent treatments. In repellent treatments, shoot Mn concentrations were significantly greater in treatments with either 12 (136 mg/kg) or 15 plants/container (135 mg/kg) than in treatments with 9 plants/container (122 mg/kg; Table 105). Similarly, in wettable treatments, shoot Mn concentrations were also significantly greater in treatments with 15 plants/container (209 mg/kg) than in treatments with either 9 (190 mg/kg) or 12 plants/container (191 mg/kg; Table 105).

Table 104. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR), surface topography (ST), and plant density (PD) on wheat shoot nutrient concentration. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Shoot nutrient concentration	Source of variation						
	SWR	ST	PD	SWR × ST	SWR × PD	ST × PD	SWR × ST × PD
N	36****	0^{ns}	0^{ns}	4^{ns}	4*	1^{ns}	0^{ns}
P	710****	0^{ns}	7***	0^{ns}	2^{ns}	1^{ns}	5*
K	258****	0^{ns}	0^{ns}	10***	1^{ns}	1^{ns}	2^{ns}
Ca	1059****	124****	10****	16****	3^{ns}	2^{ns}	3^{ns}
Mg	121****	44****	3^{ns}	34****	3^{ns}	1^{ns}	1^{ns}
S	31****	0^{ns}	8***	50****	3^{ns}	6**	7***
B^{W}	101****	0^{ns}	1^{ns}	0^{ns}	1^{ns}	1^{ns}	1^{ns}
Cu	190****	7*	2^{ns}	4^{ns}	5*	5*	1^{ns}
Fe	20****	1^{ns}	4*	5*	12****	3^{ns}	5*
Mn	516****	79****	10****	14***	3*	3^{ns}	0^{ns}
Zn	5*	2^{ns}	2^{ns}	7*	3^{ns}	0^{ns}	2^{ns}

^{W} Welch's one-way ANOVA test (for main effects only).
^{ns} Not significant ($P > 0.05$).

Table 105. Effect of topsoil water repellence (wettable and repellent) and plant density (9, 12, and 15 plants/container) on wheat shoot N, Cu, and Mn concentration at 40 DAS. Mean values based on a sample size of 6. Different letters denote significant differences within columns, based on the least significant difference (LSD) at P < 0.05.

Topsoil water repellence	Plant density (plants/container)	N (%)	Cu (mg/kg)	Mn (mg/kg)
Wettable	9	5.38^{ab}	9.42^{a}	190.0^{a}
	12	5.28^{a}	9.61^{a}	191.2^{a}
	15	5.24^{a}	10.39^{b}	208.5^{b}
Repellent	9	5.52^{bc}	7.45^{c}	121.7^{c}
	12	5.61^{cd}	7.64^{c}	136.0^{d}
	15	5.74^{d}	7.32^{c}	135.1^{d}

Shoot P, S, and Fe concentrations were significantly affected by the three-way interaction of topsoil water repellence × surface topography × plant density ($P < 0.05$; Table 104). Shoot P concentrations were significantly greater in repellent treatments (0.72-0.80 %) than in wettable treatments (0.38-0.50 %; Table 106), regardless of surface topography and plant density. In treatments with a ridge-furrow topography, shoot Fe concentrations were also significantly greater in repellent treatments (97.1-99.0 mg/kg) than in wettable treatments (84.0-84.7 mg/kg; Table 106), except in treatments with a plant density of 9 plants/container where no differences were observed. Likewise, in treatments with a flat topography, shoot S and Fe concentrations were significantly greater in repellent treatments (0.54 % S and 94.2

mg Fe/kg, respectively) than in wettable treatments (0.51 % S and 82.9 mg Fe/kg, respectively; Table 106), but only in treatments with a plant density of 12 plants/container. By contrast, in treatments with a ridge-furrow topography, shoot S concentrations were significantly greater in wettable treatments (0.51-0.58 %) than in repellent treatments (0.47 %; Table 106), regardless of plant density.

Table 106. Effect of topsoil water repellence (wettable and repellent), surface topography (ridge-furrow and flat), and plant density (9, 12, and 15 plants/container) on wheat shoot P, S, and Fe concentration at 40 DAS. Mean values based on a sample size of 9. Different letters denote significant differences within columns, based on the least significant difference (LSD) at P < 0.05.

Topsoil water repellence	Surface topography	Plant density (plants/container)	P (%)	S (%)	Fe (mg/kg)
Wettable	Ridge-furrow	9	0.44^{abc}	0.55^{ae}	86.2^{abf}
		12	0.46^{ab}	0.58^{a}	84.7^{ab}
		15	0.40^{ac}	0.51^{bd}	84.0^{ae}
	Flat	9	0.50^{b}	0.50^{bc}	90.4^{bc}
		12	0.38^{c}	0.51^{bd}	82.9^{a}
		15	0.42^{ac}	0.51^{b}	92.8^{cd}
Repellent	Ridge-furrow	9	0.77^{de}	0.47^{c}	83.6^{ae}
		12	0.76^{de}	0.47^{c}	97.1^{dg}
		15	0.72^{d}	0.47^{c}	99.0^{d}
	Flat	9	0.76^{de}	0.48^{cd}	88.8^{bce}
		12	0.80^{e}	0.54^{ef}	94.2^{cd}
		15	0.73^{d}	0.52^{bf}	91.1^{cfg}

Shoot P concentrations were not affected by surface topography, except in wettable treatments with 12 plants/container whereby shoot P concentrations were significantly greater in treatments with a ridge-furrow topography (0.46 %) than a flat topography (0.38 %; Table 106). Shoot S concentrations were also significantly greater in wettable treatments with a ridge-furrow topography (0.55-0.58 %) than a flat topography (0.50-0.51 %; Table 106), except in treatments with a plant density of 15 plants/container where no differences were observed. By contrast, shoot S concentrations were significantly greater in repellent treatments with a flat topography (0.52-0.54) than a ridge-furrow topography (0.47 %; Table 106), except in treatments with a plant density of 9 plants/container where no differences were observed.

In treatments with a ridge-furrow topography, shoot P concentrations were not affected by plant density, regardless of topsoil water repellence. Shoot S concentrations were also unaffected by plant density in repellent treatments with a ridge-furrow topography but, in wettable treatments with a ridge-furrow topography, shoot S concentrations were significantly greater in treatments with a plant density of either 9 (0.55 %) or 12 plants/container (0.58 %) than in treatments with a plant density of 15 plants/container (0.51 %; Table 106). While there were treatment effects on shoot Fe concentrations the concentrations in plants were well above adequate and are not considered further as they are not likely related to growth responses (Table 106).

In repellent treatments with a flat topography, shoot P concentrations were significantly greater in treatments with a plant density of 12 plants/container (0.80 %) than with a plant density of 15 plants/container (0.73 %; Table 106), despite no differences between treatments with a plant density of 9 and 12 plants/container, or 9 and 15 plants/container. On the contrary, in repellent treatments with a flat topography, shoot S concentrations were significantly greater in treatments with a plant density of either 12 (0.54 %) or 15 plants/container (0.54 %) than in treatments with a plant density of 9 plants/container (0.48 %; Table 106). In wettable treatments with a flat topography, plant density did not affect shoot S concentrations, but shoot P concentrations were significantly greater in treatments with a plant density of 9 plants/container (0.50 %) than in treatments with a plant density of either 12 (0.38 %) or 15 plants/container (0.42 %; Table 106).

Shoot K, Ca, Mg, Mn, and Zn concentrations were significantly affected by the two-way interaction of topsoil water repellence × surface topography ($P < 0.05$; Table 104). Regardless of surface topography, shoot K concentrations were significantly greater in repellent treatments (6.43-6.63 %) than in wettable treatments (5.39-5.60 %; Table 107), but shoot Ca, Mg, and Mn concentrations were significantly greater in wettable treatments (0.55-0.69 % Ca, 0.19-0.22 % Mg, and 178.4-214.7 mg Mn/kg, respectively) than in repellent treatments (0.39-0.40 % Ca, 0.17-0.18 % Mg, and 123.4-138.4 mg Mn/kg, respectively; Table 107). Shoot Zn concentrations were also significantly greater in wettable treatments (30.6 mg/kg) than in repellent treatments (28.5 mg/kg; Table 107) but only in treatments with a flat topography. Shoot Ca and Mn concentrations were significantly greater in treatments with a flat topography (0.40-0.69 % Ca and 138-215 mg Mn/kg, respectively) than a ridge-furrow topography (0.36-0.55 % Ca and 123-178 mg Mn/kg, respectively; Table 107), regardless of topsoil water repellence. Shoot Mg and Zn concentrations were also significantly greater in wettable treatments with a flat topography (0.22 % Mg and 30.6 mg Zn/kg, respectively) than a ridge-furrow topography (0.19 % Mg and 28.9 mg Zn/kg, respectively; Table 107), but no differences were observed in repellent treatments. In repellent treatments, shoot K concentrations were also significantly greater in treatments with a flat topography (6.63 %) than a ridge-furrow topography (6.43 %; Table 107), but shoot K concentrations were significantly greater in wettable treatments with a ridge-furrow topography (5.60 %) than a flat topography (5.39 %).

Table 107. Effect of topsoil water repellence (wettable and repellent) and surface topography (ridge-furrow and flat) on wheat shoot K, Ca, Mg, Mn, and Zn concentration at 40 DAS. Mean values based on a sample size of 9. Different letters denote significant differences within columns, based on the least significant difference (LSD) at P < 0.05.

Topsoil water repellence	Surface topography	K (%)	Ca (%)	Mg (%)	Mn (mg/kg)	Zn (mg/kg)
Wettable	Ridge-furrow	5.60^{a}	0.55^{a}	0.19^{a}	178.4^{a}	28.9^{a}
	Flat	5.39^{b}	0.69^{b}	0.22^{b}	214.7^{b}	30.6^{b}
Repellent	Ridge-furrow	6.43^{c}	0.36^{c}	0.17^{c}	123.4^{c}	29.0^{a}
	Flat	6.63^{d}	0.40^{d}	0.18^{c}	138.4^{d}	28.5^{a}

Shoot Cu concentrations were also significantly affected by the two-way interaction of surface topography × plant density ($P < 0.05$; Table 104), whereby shoot Cu concentrations were significantly greater in treatments with either a 12 (8.94 mg/kg) or 15 plants/container (9.36 mg/kg) than in treatments with 9 plants/container (8.31 mg/kg; Figure 90), but only in treatments with a flat topography. Shoot Cu concentrations were also significantly greater in treatments with a flat topography (8.94-9.36 mg/kg) than a ridge-furrow topography (8.32-8.35 mg/kg; Figure 90), except in treatments with 9 plants/container where no differences were observed.

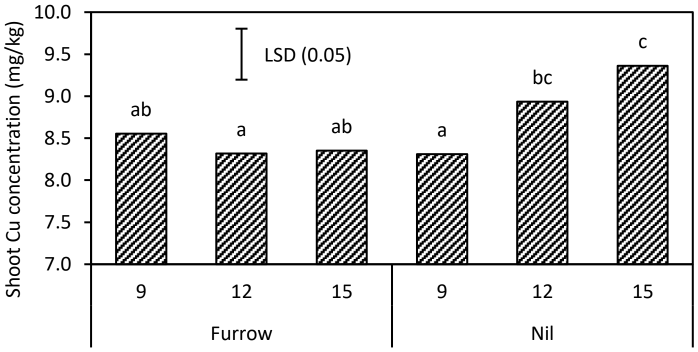

Figure 90. Effect of surface topography (ridge-furrow and flat) and plant density (9, 12, and 15 plants/container) on wheat shoot copper (Cu) concentration (mg/kg) at 40 DAS. Mean values based on a sample size of 6. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

For shoot B concentration, there were no significant interaction effects between treatments, but shoot B concentrations were significantly greater ($P < 0.001$; Table 104) in repellent treatments (31.3 mg/kg) than in wettable treatments (18.7 mg/kg; Figure 91). There was no effect of surface topography or plant density on shoot B concentration.

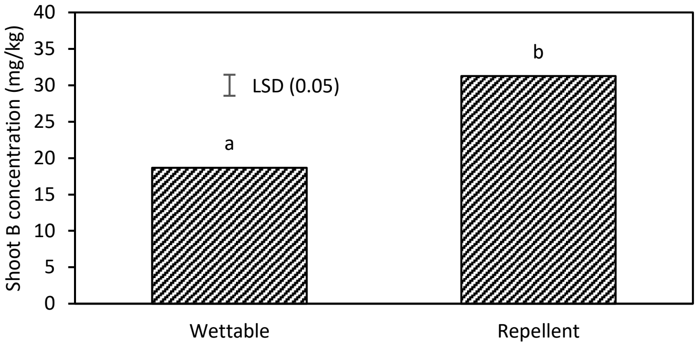

Figure 91. Effect of topsoil water repellence on wheat shoot boron (B) concentration (mg/kg) at 40 DAS. Mean values based on a sample size of 18. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Shoot Ca concentrations were significantly greater ($P < 0.001$; Table 104) in treatments with either 12 (0.50 %) or 15 plants/container (0.52 %) than in treatments with 9 plants/container (0.48 %; Figure 92).

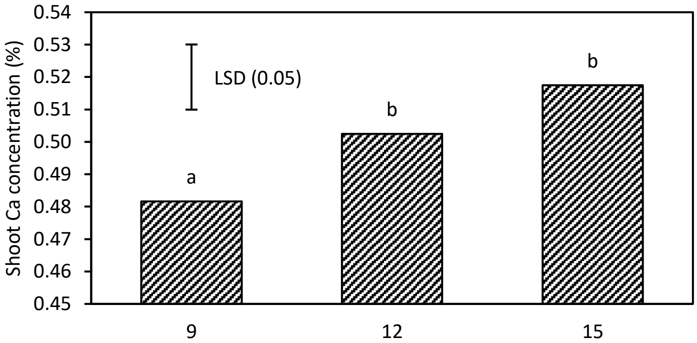

Figure 92. Effect of plant density (9, 12, and 15 plants/container) on wheat shoot calcium (Ca) concentration (mg/kg) at 40 DAS. Mean values based on a sample size of 12. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

7.3.7 Total nutrient uptake

Total nutrient uptake per plant in wheat (40 DAS) of N, P, K, S, B, Fe, Mn, and Zn was significantly greater ($P < 0.001$; Table 108) in repellent treatments than in wettable treatments by an average of 179 % (Table 109).

Table 108. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR), surface topography (ST), and plant density (PD) on wheat total nutrient uptake per plant. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Total nutrient uptake	Source of variation						
	SWR	ST	PD	SWR × ST	SWR × PD	ST × PD	SWR × ST × PD
N	489****	8****	3 ^{ns}	0 ^{ns}	1 ^{ns}	2 ^{ns}	1 ^{ns}
P	881****	5*	8***	0 ^{ns}	2 ^{ns}	3*	1 ^{ns}
K	638****	9**	4*	0 ^{ns}	1 ^{ns}	3 ^{ns}	0 ^{ns}
Ca	122****	0 ^{ns}	1 ^{ns}	4*	1 ^{ns}	1 ^{ns}	0 ^{ns}
Mg	267****	3 ^{ns}	2 ^{ns}	7*	1 ^{ns}	1 ^{ns}	0 ^{ns}
S	504****	9**	5*	0 ^{ns}	1 ^{ns}	2 ^{ns}	1 ^{ns}
B	390****	7*	1 ^{ns}	0 ^{ns}	1 ^{ns}	2 ^{ns}	1 ^{ns}
Cu	263****	6*	3 ^{ns}	5*	2 ^{ns}	1 ^{ns}	0 ^{ns}
Fe	446****	6*	1 ^{ns}	1 ^{ns}	2 ^{ns}	3 ^{ns}	2 ^{ns}
Mn	155****	0 ^{ns}	1 ^{ns}	2 ^{ns}	2 ^{ns}	1 ^{ns}	1 ^{ns}
Zn	399****	6*	2 ^{ns}	2 ^{ns}	1 ^{ns}	1 ^{ns}	1 ^{ns}

^{ns} Not significant ($P > 0.05$).

The total uptake per plant of N, K, S, B, Fe, and Zn was significantly greater ($P < 0.05$; Table 108) in treatments with a ridge-furrow topography than a flat topography by an average of 15 % (Table 110).

Table 109. Effect of topsoil water repellence on total uptake per plant of N, P, K, S, B, Fe, Mn, and Zn in wheat at 40 DAS. Mean values based on a sample size of 18. Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

Topsoil water repellence	N (mg/plant)	P (mg/plant)	K (mg/plant)	S (mg/plant)	B (µg/plant)	Fe (µg/plant)	Mn (µg/plant)	Zn (µg/plant)
Wettable	12.7^{a}	1.04^{a}	13.1^{a}	1.26^{a}	4.5^{a}	20.7^{a}	46.5^{a}	7.1^{a}
Repellent	32.3^{b}	4.35^{b}	37.5^{b}	2.81^{b}	18.1^{b}	53.2^{b}	74.7^{b}	16.6^{b}

Table 110. Effect of surface topography on total uptake per plant of N, K, S, B, Fe, and Zn in wheat at 40 DAS. Mean values based on a sample size of 18. Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

Surface topography	N (mg/plant)	K (mg/plant)	S (mg/plant)	B (µg/plant)	Fe (µg/plant)	Zn (µg/plant)
Ridge-furrow	23.8^{a}	26.8^{a}	2.14^{a}	12.5^{a}	39.5^{a}	12.6^{a}
Flat	21.1^{b}	23.8^{b}	1.93^{b}	10.1^{b}	34.5^{b}	11.1^{b}

Total uptake per plant of K and S was significantly greater ($P < 0.05$; Table 108) in treatments with a plant density of 9 plants/container (26.8 mg K/plant and 2.11 mg S/plant, respectively) than in treatments with a plant density of 15 plants/container by 14 and 12 %, respectively (23.5 mg K/plant and 1.88 mg S/plant, respectively; Table 111), but was not different to treatments with a plant density of 12 plants/container. Total S uptake per plant was, however, significantly greater in treatments with a plant density of 12 (2.12 mg/plant) than with a plant density of 15 plants/container by 13 % (1.88 mg/plant; Table 111), but this was not observed for total K uptake per plant.

Table 111. Effect of plant density on total uptake per plant of K and S in wheat at 40 DAS. Mean values based on a sample size of 12. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Plant density (plants/container)	K (mg/plant)	S (mg/plant)
9	26.8^{a}	2.11^{a}
12	25.7^{ab}	2.12^{a}
15	23.5^{b}	1.88^{b}

Total uptake per plant of Ca, Mg, and Cu was significantly affected by the two-way interaction of topsoil water repellence × surface topography ($P < 0.05$; Table 108), whereby total uptake per plant of Ca, Mg, and Cu was significantly greater in repellent treatments than in wettable treatments by an average of 80 % (Table 112), regardless of surface topography, but with a more pronounced increase in treatments with a ridge-furrow topography (by an average of 96 %) than a flat topography (by an average of 65 %). In repellent treatments, total uptake per plant of Mg and Cu was significantly greater in treatments with a ridge-furrow topography than a flat topography by an average of 15 % (Table 112).

Table 112. Effect of topsoil water repellence (wettable and repellent) and surface topography (ridge-furrow and flat) on total uptake per plant of Ca, Mg, and Cu in wheat at 40 DAS. Mean values based on a sample size of 9. Different letters denote significant differences within columns, based on the least significant difference (LSD) at P < 0.05.

Topsoil water repellence	Surface topography	Ca (mg/plant)	Mg (mg/plant)	Cu (µg/plant)
Wettable	Ridge-furrow	1.37^{a}	0.47^{a}	2.35^{a}
	Flat	1.55^{a}	0.51^{a}	2.31^{a}
Repellent	Ridge-furrow	2.23^{b}	1.08^{b}	4.56^{b}
	Flat	2.14^{b}	0.94^{c}	3.99^{c}

Total P uptake per plant was also significantly affected by the two-way interaction of surface topography × plant density ($P < 0.05$; Table 108). In treatments with a plant density of 9, total P uptake per plant was not affected by surface topography. In treatments with a plant density of 12, total P uptake per plant was significantly greater in treatments with a ridge-furrow topography (3.10 mg/plant) than a flat topography by 25 % (2.48 mg /plant; Table 113). In treatments with a plant density of 15 plants/container, total P uptake per plant was not affected by surface topography.

In treatments with a ridge-furrow topography, total P uptake per plant was significantly greater in treatments with a plant density of either 9 (2.91 mg/plant) or 12 plants/container (3.10 mg/plant) than in treatments with a plant density of 15 plants/container by 15 and 22 %, respectively (2.54 mg/plant; Table 113). In treatments with a flat topography, total P uptake per plant was significantly greater in treatments with a plant density of 9 plants/container (2.92 mg/plant) than in treatments with a plant density of either 12 plants/container by 18 % (2.48 mg/plant) or 15 plants/container by 32 % (2.21 mg/plant; Table 113).

Table 113. Effect of surface topography (ridge-furrow and flat) and plant density (9, 12, and 15 plants/container) on total P uptake per plant in wheat at 40 DAS. Mean values based on a sample size of 9. Different letters denote significant differences within columns, based on the least significant difference (LSD) at P < 0.05.

Surface topography	Plant density (plants/container)	P (mg/plant)
Ridge-furrow	9	2.91^{a}
	12	3.10^{a}
	15	2.54^{b}
Flat	9	2.92^{a}
	12	2.48^{b}
	15	2.21^{b}

For total nutrient uptake per container, significant two-way interaction effects were observed between topsoil water repellence and plant density ($P < 0.05$; Table 114). Total uptake per container of N, P, K, Ca, Mg, S, B, Fe, Mn, and Zn was significantly greater in repellent treatments than in wettable treatments by an average of 160 %, regardless of plant density (Table 115). Total uptake per container of N, P, K, Ca, Mg, S, B, Fe, Mn, and Zn significantly increased as the plant density increased from 9 to 15 plants/container by an average of 40 % (Table 115), regardless of topsoil water repellence, except for total uptake per container of P and B in wettable treatments which were not affected by plant density. Moreover, consistent with total dry matter per container, total uptake per container of N, P, K, Mg, S, B, Fe, and Zn was significantly greater in repellent treatments with 9 plants/container than in wettable treatments with 15 plants/container by an average of 88 % (Table 115).

Table 114. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between topsoil water repellence (SWR), surface topography (ST), and plant density (PD) on wheat total nutrient uptake per container. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Total nutrient uptake per container	Source of variation						
	SWR	ST	PD	SWR × ST	SWR × PD	ST × PD	SWR × ST × PD
N	411****	9**	27****	3 ^{ns}	8***	3 ^{ns}	1 ^{ns}
P	786****	8**	17****	4*	10****	2 ^{ns}	1 ^{ns}
K	511****	9***	25****	2 ^{ns}	8***	3 ^{ns}	1 ^{ns}
Ca	120****	0 ^{ns}	50****	5*	5*	1 ^{ns}	1 ^{ns}
Mg	258****	3 ^{ns}	32****	8**	6**	1 ^{ns}	1 ^{ns}
S	503****	9**	43****	0 ^{ns}	11****	2 ^{ns}	1 ^{ns}
B	149****	5*	10****	2 ^{ns}	5*	1 ^{ns}	0 ^{ns}
Cu	221****	5*	34****	5*	3 ^{ns}	1 ^{ns}	0 ^{ns}
Fe	281****	8**	24****	6*	8***	3 ^{ns}	3 ^{ns}
Mn	145****	0 ^{ns}	48****	3 ^{ns}	5*	0 ^{ns}	1 ^{ns}
Zn	308****	9**	25****	7*	4*	2 ^{ns}	2 ^{ns}

^{ns} Not significant ($P > 0.05$).

Table 115. Effect of topsoil water repellence (wettable and repellent) and plant density (9, 12, and 15 plants/container) on wheat total nutrient uptake per container at 40 DAS. Mean values based on a sample size of 6. Different letters denote significant differences within rows, based on the least significant difference (LSD) at $P < 0.05$.

Total nutrient uptake per container	Wettable			Repellent		
	9	12	15	9	12	15
N (mg/container)	125.4^{a}	149.5^{ab}	174.4^{b}	298.9^{c}	396.7^{d}	459.2^{e}
P (mg/container)	11.0^{a}	12.0^{a}	13.5^{a}	41.4^{b}	55.0^{c}	57.8^{c}
K (mg/container)	130.3^{a}	154.9^{ab}	180.7^{b}	351.7^{c}	462.5^{d}	523.6^{e}
Ca (mg/container)	14.0^{a}	17.1^{b}	21.1^{c}	19.3^{bc}	27.3^{d}	31.9^{e}
Mg (mg/container)	4.8^{a}	5.7^{ab}	7.0^{b}	9.0^{c}	12.8^{d}	14.3^{e}
S (mg/container)	12.3^{a}	15.5^{b}	16.9^{b}	25.7^{c}	35.5^{d}	39.4^{e}
B (µg/container)	41.5^{a}	56.5^{a}	62.1^{a}	146.9^{b}	248.3^{c}	258.4^{c}
Fe (µg/container)	205.5^{a}	236.4^{ab}	294.6^{b}	466.8^{c}	677.6^{d}	768.6^{e}
Mn (µg/container)	439.9^{a}	532.5^{a}	694.1^{b}	658.3^{b}	951.4^{c}	1076.5^{d}
Zn (µg/container)	68.2^{a}	81.3^{ab}	103.0^{b}	154.5^{c}	206.3^{d}	229.9^{e}

7.3.8 Soil water and electrical conductivity

Soil water content in the furrow at the 5 cm depth of repellent treatments increased immediately after the first watering event in repellent treatments from 0.03-0.04 m^3/m^3 (Day 1) to 0.13-0.15 m^3/m^3 (Day 5; Figure 93a), with overall soil wetting being relatively greater in repellent treatments with a ridge-furrow topography than with a flat topography. Soil EC in the furrow at the 5 cm depth in repellent treatments also increased shortly after the first watering event from 0.00 to 0.06-0.08 mS/cm (Day 5) and thereafter steadily increasing to 0.09 mS/cm (Day 40; Figure 93b). In wettable treatments, however, soil wetting in the furrow at the 5 cm depth was gradual and relatively delayed in comparison to repellent treatments (Figure 93a). Increases in soil water content did not occur until after Day 11 in wettable treatments with a ridge-furrow topography, or until Day 19 in wettable treatments with a flat topography. Likewise, changes in soil EC in the furrow at the 5 cm depth in wettable treatments were also relatively delayed (Figure 93b), increasing from 0.00 mS/cm (Day 15) to 0.06 mS/cm (Day 40) in wettable treatments with a ridge-furrow topography, and from 0.00 mS/cm (Day 21) to 0.14 mS/cm (Day 40) in wettable treatments with a flat topography. However, soil water content in the furrow at the 5 cm depth in wettable treatments with a ridge-furrow topography eventually exceeded that in repellent treatments with a flat topography after Day 30 (Figure 93a). While surface topography did not result in observable differences in soil EC in the furrow at the 5 cm depth in repellent treatments, soil EC in wettable treatments with a flat topography was comparatively greater than that in all other treatments from Day 26 onwards (i.e., presumably due to the accumulation of solutes under limited wetting depth; Figure 93b). The overall changes in soil EC nevertheless reflected changes in soil water content.

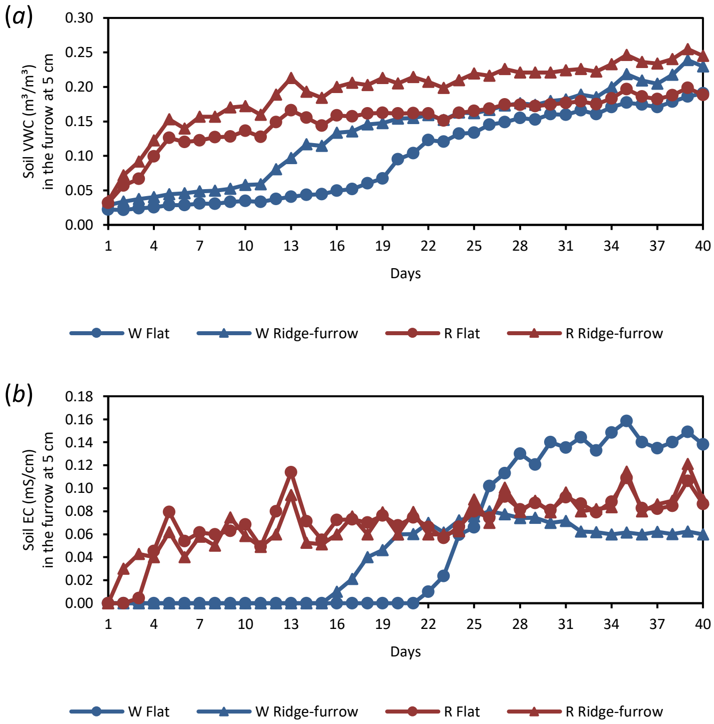

Figure 93. Soil (a) volumetric water content (VWC, m^3/m^3) and (b) electrical conductivity (EC, mS/cm) in the furrow at the 5 cm depth in wettable (W) and repellent (R) treatments, with either ridge-furrow or flat topography over 40 days at solar noon (±2 hours).

In the inter-row, soil water content and EC at the 5 cm depth increased more rapidly in repellent treatments with a ridge-furrow topography than in other treatments, whereby: (1) soil water content in the inter-row at the 5 cm depth increased from 0.04 m^3/m^3 (Day 3) to 0.17 m^3/m^3 (Day 13; Figure 94a), and subsequently increased to 0.23 m^3/m^3 (Day 40); and, (2) soil EC in the inter-row at the 5 cm depth increased in all treatments, particularly in repellent treatments with a ridge-furrow topography whereby soil EC increased from 0.00 mS/cm (Day 10) to 0.25 mS/cm (Day 40; Figure 94b). In wettable treatments, the initial increase in soil water content in the inter-row at the 5 cm depth was relatively delayed but occurred more rapidly in wettable treatments with a flat topography, increasing from 0.05 m^3/m^3 (Day 12) to 0.18 m^3/m^3 (Day 18) before steadily increasing to 0.26 m^3/m^3 (Day 40; Figure 94a). However, changes in soil EC were relatively similar between wettable treatments with a ridge-furrow and flat topography (Day 40; Figure 94b), although soil EC was slightly greater in wettable treatments with a flat topography than a ridge-furrow topography. Changes in soil water content at the 5 cm depth were also relatively similar between repellent treatments with a flat topography and wettable treatments with a ridge-furrow topography (Figure 94a). However, in repellent treatments with a flat topography, soil EC in the inter-row at the 5 cm depth increased rapidly from 0.00 mS/cm (Day 28) to 0.25 mS/cm (Day 40), despite being relatively delayed in comparison to other treatments.

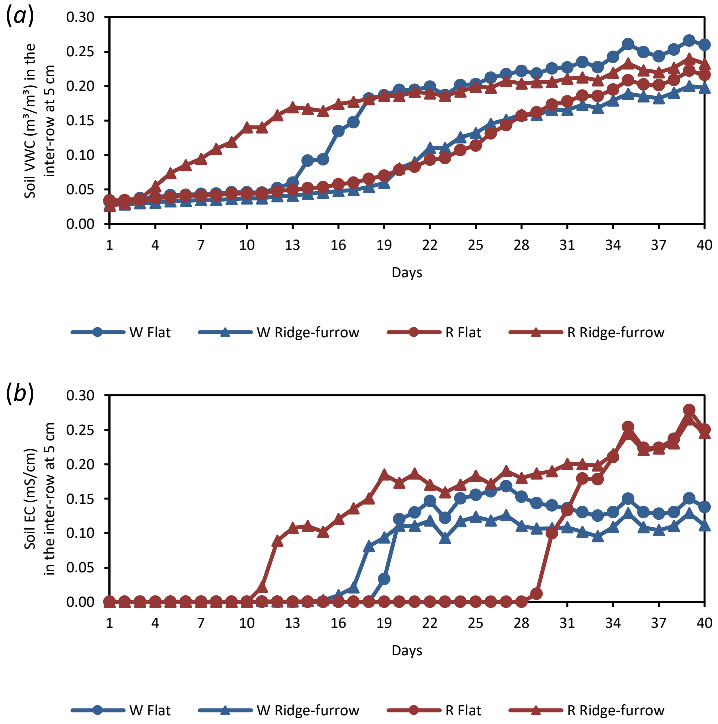

Figure 94. Soil (a) volumetric water content (VWC, m^3/m^3) and (b) electrical conductivity (EC, mS/cm) in the inter-row at the 5 cm depth in wettable (W) and repellent (R) treatments, with either ridge-furrow or flat topography over 40 days at solar noon (±2 hours).

Soil water content and EC in the furrow at 15 cm did not change over time in wettable treatments, regardless of surface topography (Figures 95a and b), due to limited wetting depth. By contrast, in repellent treatments with a ridge-furrow topography, soil water content in the furrow at 15 cm increased from 0.04 m^3/m^3 (Day 25) to 0.14 m^3/m^3 (Day 40; Figure 95a), and soil EC in the furrow at the 15 cm depth increased from 0.00 mS/cm (Day 27) to 0.06 mS/cm (Day 40; Figure 95b). In repellent treatments with a flat topography, slight increases in soil water content and EC in the furrow at 15 cm were observed from Day 35 (0.04 m^3/m^3 and 0.00 mS/cm, respectively) to Day 40 (0.06 m^3/m^3 and 0.05 mS/cm, respectively; Figures 95a and b).

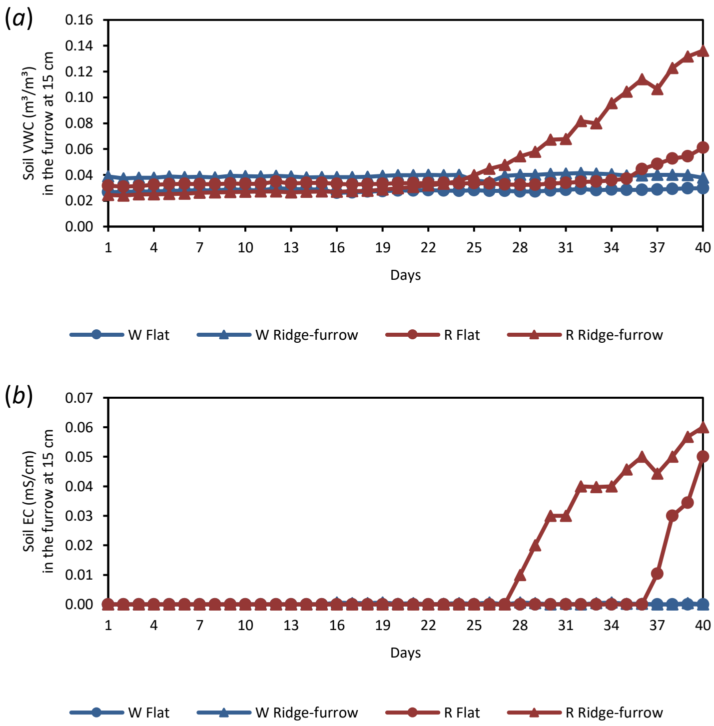

Figure 95. Soil (a) volumetric water content (VWC, m^3/m^3) and (b) electrical conductivity (EC, mS/cm) in the furrow at the 15 cm depth in wettable (W) and repellent (R) treatments, with either ridge-furrow or flat topography over 40 days at solar noon (±2 hours).

Soil water content and EC in the inter-row at the 15 cm depth increased only in repellent treatments with a ridge-furrow topography (Figures 96a and b), whereby: (1) soil moisture increased from 0.04 m^3/m^3 (Day 26) to 0.11 m^3/m^3 (Day 40); and, (2) soil EC increased from 0.00 mS/cm (Day 30) to 0.04 mS/cm (Day 40). Soils in the inter-row at the 15 cm depth remained relatively dry in all other treatments.

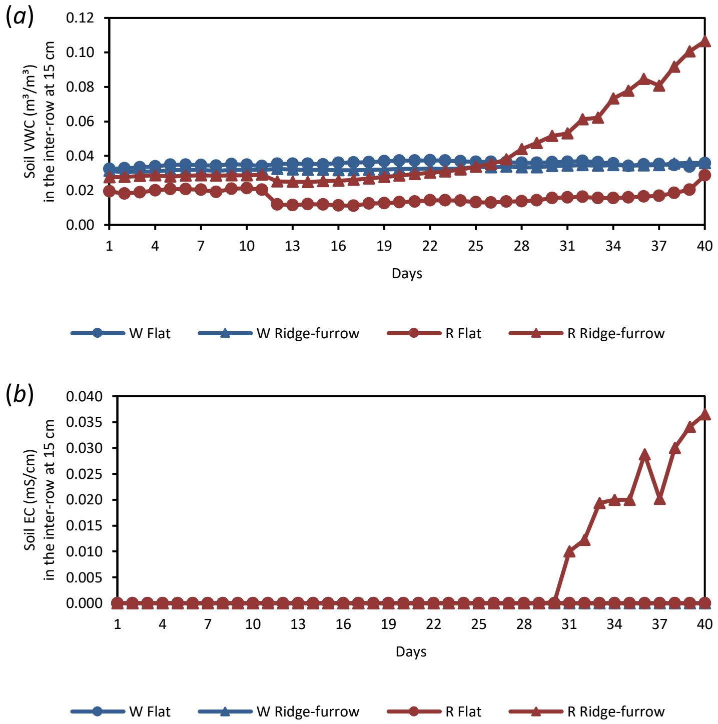

Figure 96. Soil (a) volumetric water content (VWC, m^3/m^3) and (b) electrical conductivity (EC, mS/cm) in the inter-row at the 15 cm depth in wettable (W) and repellent (R) treatments, with either ridge-furrow or flat topography over 40 days at solar noon (±2 hours).

7.3.9 Soil ammonium-nitrogen

Results from a mixed model ANOVA showed that soil NH_4-N concentration post-harvest at 41 DAS was significantly affected by the four-way interaction of topsoil water repellence × plant density × sampling row × sampling depth ($P < 0.05$; Table 116). Soil NH_4-N concentration in the furrow at the 0-5 and 15-20 cm depths and in the inter-row at the 0-5 and 5-10 cm depths was not affected by topsoil water repellence, regardless of plant density. However, soil NH_4-N concentration in the furrow at the 5-10 and 10-15 cm depths was significantly greater in wettable treatments (393-509 and 74-99 mg/kg, respectively) than in repellent treatments (92-126 and 48-59 mg/kg, respectively; Table 117), regardless of plant density. By contrast, soil NH_4-N concentration in the inter-row at the 10-15 cm depth was significantly greater in repellent treatments (8-17 mg/kg) than in wettable treatments (1-3 mg/kg; Table 117), regardless of plant density. Moreover, soil NH_4-N concentration in the inter-row at the 15-20 cm depth was also significantly greater in repellent treatments (9-21 mg/kg) than in wettable treatments (2-6 mg/kg; Table 117), except in treatments with a plant density of 15 plants/container where no difference was observed.

Table 116. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil ammonium-nitrogen (NH_4-N) at 41 DAS, using topsoil water repellence (SWR), surface topography (ST), and plant density (PD) as between-subjects variables and repeated measures for sampling row and depth as within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil NH_4-N
SWR	337****
ST	5*
PD	10****
Row	1866****
Depth	604****
SWR × ST	2 ^{ns}
SWR × PD	5*
SWR × Row	514****
SWR × Depth	268****
ST × PD	0 ^{ns}
ST × Row	10***
ST × Depth	7**
PD × Row	0 ^{ns}
PD × Depth	5*
Row × Depth	496****
SWR × ST × PD	1 ^{ns}
SWR × ST × Row	0 ^{ns}
SWR × ST × Depth	3 ^{ns}
SWR × PD × Row	4*
SWR × PD × Depth	5*
SWR × Row × Depth	279****
ST × PD × Row	1 ^{ns}
ST × PD × Depth	0 ^{ns}
ST × Row × Depth	5*
PD × Row × Depth	6***
SWR × ST × PD × Row	0 ^{ns}
SWR × ST × PD × Depth	0 ^{ns}
SWR × ST × Row × Depth	1 ^{ns}
SWR × PD × Row × Depth	6***
ST × PD × Row × Depth	0 ^{ns}
SWR × ST × PD × Row × Depth	0 ^{ns}

^{ns} Not significant ($P > 0.05$).

In general, soil NH_4-N concentration was significantly greater in treatments with a plant density of 9 plants/container than in treatments with 15 plants/container (Table 117), regardless of topsoil water repellence, sampling row, or sampling depth, except for: (1) soil NH_4-N concentration in the furrow at the 5-10 and 10-15 cm depths which was not affected by plant density in repellent treatments; (2) soil NH_4-N concentration in the furrow at the 5-10 cm depth which was significantly greater in wettable treatments with a plant density of 15 plants/container (509 mg/kg) than in treatments with 9 plants/container (393 mg/kg; Table 117); and, (3) soil NH_4-N concentration in the inter-row at the 10-15 and 15-20 cm depth was not affected by plant density in wettable treatments.

Table 117. Soil ammonium-nitrogen (NH_4-N) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in wettable and repellent treatments with variable plant density (9, 12, and 15 plants/container). Mean values based on a sample size of 6. Significant differences based on the least significant difference (LSD) at P < 0.05.

Plant density (plants/container)	Depth	Wettable		Repellent	
		Furrow	Inter-row	Furrow	Inter-row
9	0-5 cm	$33.8^{1a\Delta}$	16.5^{1a}	$46.2^{1a\Delta}$	15.8^{1ac}
	5-10 cm	$393.0^{1b\dagger\Delta}$	28.5^{1b}	$125.8^{1b\Delta}$	34.0^{1b}
	10-15 cm	$98.7^{1c\dagger\Delta}$	$3.3^{1c\dagger}$	$59.2^{1ac\Delta}$	17.0^{1a}
	15-20 cm	$71.2^{1d\Delta}$	$6.3^{1d\dagger}$	$66.2^{1c\Delta}$	20.8^{1c}
12	0-5 cm	27.5^{1a}	25.0^{2a}	$41.5^{1a\Delta}$	26.2^{2a}
	5-10 cm	$448.8^{1b\dagger\Delta}$	34.5^{1b}	$118.0^{1b\Delta}$	34.0^{1b}
	10-15 cm	$94.5^{12c\dagger\Delta}$	$1.7^{1c\dagger}$	$52.3^{1a\Delta}$	12.0^{12c}
	15-20 cm	$42.2^{2a\Delta}$	$2.1^{1c\dagger}$	$42.7^{2a\Delta}$	9.2^{2c}
15	0-5 cm	7.2^{2a}	5.8^{3a}	6.2^{2a}	5.5^{3a}
	5-10 cm	$509.0^{2b\dagger\Delta}$	11.5^{2b}	$91.5^{1b\Delta}$	18.2^{2b}
	10-15 cm	$74.2^{2c\dagger\Delta}$	$1.3^{1a\dagger}$	$47.7^{1cb\Delta}$	8.0^{2a}
	15-20 cm	$19.2^{2a\Delta}$	1.4^{1a}	$34.2^{2c\Delta}$	6.7^{2a}

Different superscript numbers denote significant differences within plant density ($P < 0.05$).
Different superscript letters denote significant differences within depth ($P < 0.05$).
† Significantly different from repellent treatments ($P < 0.05$).
$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

7.3.10 Soil nitrate-nitrogen

Results from a mixed model ANOVA showed that soil NO_3-N concentration post-harvest at 41 DAS was significantly affected by the four-way interaction of topsoil water repellence × surface topography × plant density × sampling row ($P <$ 0.05; Table 118). Regardless of surface topography and plant density, soil NO_3-N concentration in the furrow was significantly greater in wettable treatments (53-74 mg/kg) than in repellent treatments (36-55 mg/kg; Table 119), while soil NO_3-N concentration in the inter-row was significantly greater in repellent treatments (50-67 mg/kg) than in wettable treatments (28-39 mg/kg; Table 119).

In general, soil NO_3-N concentration was not affected by surface topography, regardless of topsoil water repellence and plant density (Table 119). Some effect of plant density was observed such that soil NO_3-N concentration in the furrow was significantly greater in treatments with a plant density of 15 plants/container (55-74 mg/kg) than in treatments with 9 plants/container (36-59 mg/kg; Table 119), regardless of topsoil water repellence and surface topography, except in repellent treatments with a ridge-furrow topography where no difference was observed. However, in repellent treatments with a ridge-furrow topography, soil NO_3-N concentration in the inter-row was significantly greater in treatments with a plant density of 12 plants/container (67 mg/kg) than in treatments with 15 plants/container (57 mg/kg; Table 119). Moreover, in repellent treatments with a flat topography, soil NO_3-N concentration in the inter-row was significantly greater in treatments with a plant density of 9 plants/container (65 mg/kg) than in treatments with 12 plants/container (50 mg/kg; Table 119). Nevertheless, the effect of plant density on soil NO_3-N concentration in the inter-row was not observed in wettable treatments, regardless of surface topography.

Table 118. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil nitrate-nitrogen (NO_3-N) at 41 DAS, using topsoil water repellence (SWR), surface topography (ST), and plant density (PD) as between-subjects variables and repeated measures for sampling row and depth as within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil NO_3-N
SWR	14****
ST	2 ^{ns}
PD	6*
Row	53****
Depth	400****
SWR × ST	0 ^{ns}
SWR × PD	0 ^{ns}
SWR × Row	293****
SWR × Depth	14****
ST × PD	3 ^{ns}
ST × Row	3 ^{ns}
ST × Depth	3 ^{ns}
PD × Row	19****
PD × Depth	15****
Row × Depth	14****
SWR × ST × PD	1 ^{ns}
SWR × ST × Row	1 ^{ns}
SWR × ST × Depth	1 ^{ns}
SWR × PD × Row	0 ^{ns}
SWR × PD × Depth	5***
SWR × Row × Depth	27****
ST × PD × Row	0 ^{ns}
ST × PD × Depth	2 ^{ns}
ST × Row × Depth	2 ^{ns}
PD × Row × Depth	5***
SWR × ST × PD × Row	4*
SWR × ST × PD × Depth	1 ^{ns}
SWR × ST × Row × Depth	2 ^{ns}
SWR × PD × Row × Depth	2 ^{ns}
ST × PD × Row × Depth	1 ^{ns}
SWR × ST × PD × Row × Depth	2 ^{ns}

^{ns} Not significant ($P > 0.05$).

Soil NO_3-N concentration was also significantly affected by the three-way interaction of topsoil water repellence × sampling row × sampling depth ($P < 0.001$; Table 118). Results showed that soil NO_3-N concentration in the furrow at the 0-5 cm depth was not affected by topsoil water repellence, but soil NO_3-N concentration in the furrow at the 5-20 cm depth was significantly greater in wettable treatments (51-111 mg/kg) than in repellent treatments (28-83 mg/kg, respectively; Table 120). By contrast, soil NO_3-N concentration in the inter-row was significantly greater in repellent treatments (35-111 mg/kg) than in wettable treatments (21-57 mg/kg; Table 120), regardless of depth.

Table 119. Soil nitrate-nitrogen (NO_3-N) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row in wettable and repellent treatments with variable surface topography (ridge-furrow or flat) and plant density (9, 12, and 15 plants/container). Mean values based on a sample size of 12. Significant differences based on the least significant difference (LSD) at P < 0.05.

Surface topography	Plant density (plants/container)	Wettable		Repellent	
		Furrow	Inter-row	Furrow	Inter-row
Ridge-furrow	9	$52.8^{a\dagger\Delta}$	$38.8^{a\dagger\S}$	$41.8^{a\Delta}$	61.9^{ab}
	12	$64.4^{b\dagger\Delta}$	$33.4^{a\dagger}$	$50.7^{a\Delta}$	$66.8^{a\S}$
	15	$71.4^{b\dagger\Delta}$	$30.8^{a\dagger}$	51.1^{a}	57.0^{b}
Flat	9	$58.8^{a\dagger\Delta}$	$28.1^{a\dagger}$	$35.8^{a\Delta}$	64.5^{a}
	12	$62.7^{a\dagger\Delta}$	$29.7^{a\dagger}$	47.8^{b}	50.1^{b}
	15	$73.8^{b\dagger\Delta}$	$31.5^{a\dagger}$	54.8^{b}	58.6^{ab}

Different superscript letters denote significant differences within plant density (*P* < 0.05).
† Significantly different from repellent treatments (*P* < 0.05).
§ Significantly different from flat topography treatments (*P* < 0.05).
$^{\Delta}$ Significantly different from the corresponding inter-row (*P* < 0.05).

Table 120. Soil nitrate-nitrogen (NO_3-N) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in wettable and repellent treatments. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Wettable		Repellent	
	Furrow	Inter-row	Furrow	Inter-row
0-5 cm	$39.7^{a\Delta}$	$26.8^{a\dagger}$	$36.8^{a\Delta}$	57.2^{a}
5-10 cm	$110.8^{b\dagger\Delta}$	$57.1^{b\dagger}$	$83.3^{b\Delta}$	111.4^{b}
10-15 cm	$54.2^{c\dagger\Delta}$	$23.4^{ac\dagger}$	$28.2^{c\Delta}$	35.8^{c}
15-20 cm	$51.2^{c\dagger\Delta}$	$20.9^{c\dagger}$	39.7^{a}	34.7^{c}

Different superscript letters denote significant differences within depth (*P* < 0.05).
† Significantly different from repellent treatments (*P* < 0.05).
$^{\Delta}$ Significantly different from the corresponding inter-row (*P* < 0.05).

7.3.11 Soil phosphorus

There was no significant treatment effect on soil Colwell P concentration post-harvest 41 DAS, but the soil Colwell P concentration was significantly affected by the two-way interaction of sampling row × sampling depth ($P < 0.001$; Table 121). At the 0-5 and 5-10 cm depths, soil Colwell P was significantly greater in the furrow (124 and 356 mg/kg, respectively) than in the inter-row (114 and 117 mg/kg, respectively; Table 122), but there was no difference in soil Colwell P between sampling rows at the 10-15 and 15-20 cm depths. Regardless of sampling row, soil Colwell P was significantly greater at the 0-5 (114-124 mg/kg) and 5-10 cm depths (117-356 mg/kg) than at the 10-15 (14-15 mg/kg) and 15-20 cm depths (14-15 mg/kg; Table 122), with soil Colwell P also significantly greater at the 5-10 cm depth than at the 0-5 cm depth.

There was no difference in soil Colwell P between the 10-15 and 15-20 cm depths, regardless of sampling row.

Table 121. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil Colwell phosphorus (P) at 41 DAS, using topsoil water repellence (SWR), surface topography (ST), and plant density (PD) as between-subjects variables and repeated measures for sampling row and depth as within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil Colwell P
SWR	1 ^{ns}
ST	2 ^{ns}
PD	2 ^{ns}
Row	739****
Depth	1825****
SWR × ST	0 ^{ns}
SWR × PD	0 ^{ns}
SWR × Row	0 ^{ns}
SWR × Depth	0 ^{ns}
ST × PD	2 ^{ns}
ST × Row	1 ^{ns}
ST × Depth	3 ^{ns}
PD × Row	2 ^{ns}
PD × Depth	2 ^{ns}
Row × Depth	657****
SWR × ST × PD	0 ^{ns}
SWR × ST × Row	2 ^{ns}
SWR × ST × Depth	1 ^{ns}
SWR × PD × Row	0 ^{ns}
SWR × PD × Depth	0 ^{ns}
SWR × Row × Depth	0 ^{ns}
ST × PD × Row	1 ^{ns}
ST × PD × Depth	1 ^{ns}
ST × Row × Depth	4 ^{ns}
PD × Row × Depth	3 ^{ns}
SWR × ST × PD × Row	0 ^{ns}
SWR × ST × PD × Depth	0 ^{ns}
SWR × ST × Row × Depth	1 ^{ns}
SWR × PD × Row × Depth	0 ^{ns}
ST × PD × Row × Depth	1 ^{ns}
SWR × ST × PD × Row × Depth	0 ^{ns}

^{ns} Not significant ($P > 0.05$).

Table 122. Soil Colwell phosphorus (P) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths. Mean values based on a sample size of 36. Significant differences based on the least significant difference (LSD) at P < 0.05.

Depth	Furrow	Inter-row
0-5 cm	124.2$^{a\Delta}$	113.9^{a}
5-10 cm	355.7$^{b\Delta}$	117.4^{b}
10-15 cm	14.3$^{c\Delta}$	14.5^{c}
15-20 cm	14.8$^{c\Delta}$	14.4^{c}

Different superscript letters denote significant differences within depth ($P < 0.05$).

$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

7.3.12 Soil potassium

Results from a mixed model ANOVA showed that soil Colwell K concentration post-harvest at 41 DAS was significantly affected by the four-way interaction of topsoil water repellence × surface topography × sampling row × sampling depth ($P < 0.05$; Table 123). Note, soil Colwell K concentration was also significantly affected by the four-way interaction of topsoil water repellence × plant density × sampling row × sampling depth ($P < 0.05$; Table 123) but will not be detailed here, despite some effect of plant density, given that the effects of topsoil water repellence, sampling row, and sampling depth are broadly similar (see Appendix F.2).

Table 123. Mixed model analysis of variance, ANOVA, test (F values with significance level) for soil Colwell potassium (K) at 41 DAS, using topsoil water repellence (SWR), surface topography (ST), and plant density (PD) as between-subjects variables and repeated measures for sampling row and depth as within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil Colwell K
SWR	104****
ST	0 ^{ns}
PD	0 ^{ns}
Row	1817****
Depth	1728****
SWR × ST	1 ^{ns}
SWR × PD	4*
SWR × Row	240****
SWR × Depth	146****
ST × PD	0 ^{ns}
ST × Row	2 ^{ns}
ST × Depth	1 ^{ns}
PD × Row	2 ^{ns}
PD × Depth	7***
Row × Depth	997****
SWR × ST × PD	0 ^{ns}
SWR × ST × Row	5*
SWR × ST × Depth	6*
SWR × PD × Row	2 ^{ns}
SWR × PD × Depth	4*
SWR × Row × Depth	187****
ST × PD × Row	1 ^{ns}
ST × PD × Depth	0 ^{ns}
ST × Row × Depth	1 ^{ns}
PD × Row × Depth	6***
SWR × ST × PD × Row	0 ^{ns}
SWR × ST × PD × Depth	0 ^{ns}
SWR × ST × Row × Depth	5*
SWR × PD × Row × Depth	5*
ST × PD × Row × Depth	1 ^{ns}
SWR × ST × PD × Row × Depth	0 ^{ns}

^{ns} Not significant ($P > 0.05$).

Soil Colwell K concentration in the furrow at the 0-5 and 15-20 cm depths was significantly greater in repellent treatments (154 and 92 mg/kg, respectively) than in wettable treatments with a ridge-furrow topography (131 and 64 mg/kg, respectively;

Table 124) but not with a flat topography. However, soil Colwell K concentration in the furrow at the 5-10 cm depth was significantly greater in wettable treatments (1103-1160 mg/kg) than in repellent treatments (537-661 mg/kg; Table 124), regardless of surface topography. Soil Colwell K concentration in the furrow at the 10-15 cm depth was also significantly greater in wettable treatments (157 mg/kg) than in repellent treatments (128 mg/kg; Table 124) but only in treatments with a flat topography. Nevertheless, soil Colwell K concentration in the inter-row was significantly greater in repellent treatments (40-193 mg/kg) than in wettable treatments (11-144 mg/kg; Table 124), regardless of surface topography or sampling depth, except for soil Colwell K concentration in the inter-row at the 0-5 and 15-20 cm depths which was also not affected by topsoil water repellence in treatments with a flat topography

Table 124. Soil Colwell potassium (K) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in wettable and repellent treatments with variable surface topography (ridge-furrow or flat). Mean values based on a sample size of 9. Significant differences based on the least significant difference (LSD) at P < 0.05.

Surface topography	Depth	Wettable		Repellent	
		Furrow	Inter-row	Furrow	Inter-row
Ridge-furrow	0-5 cm	$131.0^{a\dagger}$	$128.6^{a\dagger}$	$154.4^{a\S\Delta}$	$140.3^{a\S}$
	5-10 cm	$1160.3^{b\dagger\Delta}$	$144.4^{b\dagger}$	$537.4^{b\S\Delta}$	192.6^{b}
	10-15 cm	$139.6^{a\Delta}$	$19.2^{c\dagger}$	$112.7^{c\Delta}$	46.1^{c}
	15-20 cm	$64.1^{c\dagger\Delta}$	$11.4^{d\dagger}$	$92.7^{d\Delta}$	$39.9^{d\S}$
Flat	0-5 cm	132.6^{a}	125.9^{a}	125.7^{a}	130.2^{a}
	5-10 cm	$1103.1^{b\dagger\Delta}$	$140.7^{b\dagger}$	$661.3^{b\Delta}$	183.9^{b}
	10-15 cm	$156.9^{c\dagger\Delta}$	$19.4^{c\dagger}$	$128.4^{a\Delta}$	41.0^{c}
	15-20 cm	$70.8^{d\Delta}$	19.6^{c}	$77.2^{c\Delta}$	18.3^{d}

Different superscript letters denote significant differences within depth ($P < 0.05$).
† Significantly different from repellent treatments ($P < 0.05$).
§ Significantly different from flat topography treatments ($P < 0.05$).
$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

In wettable treatments, soil Colwell K concentration was not affected by surface topography, regardless of sampling row and depth. However, in repellent treatments, soil Colwell K concentration in the furrow at the 0-5 cm depth was significantly greater in treatments with a ridge-furrow topography (154 mg/kg) than a flat topography (126 mg/kg; Table 124). Likewise, soil Colwell K concentration in the inter-row at the 0-5 and 15-20 cm depths was also significantly greater in repellent treatments with a ridge-furrow topography (140 and 40 mg/kg, respectively) than a flat topography (130 and 18 mg/kg, respectively; Table 124). By contrast, soil Colwell K concentration in the furrow at the 5-10 cm depth was significantly greater in repellent treatments with a flat topography (661 mg/kg) than a ridge-furrow topography (537 mg/kg; Table 124). In repellent treatments, soil Colwell K concentration in the furrow at the 10-15 and 15-20 cm depths and inter-row at the 5-10 and 10-15 cm depths was not affected by surface topography.

7.4 Discussion

Soil water repellence can limit crop yield by impeding plant germination and establishment (Bond 1972) and plant growth and water uptake (Li *et al.* 2019) as a result of heterogenous soil wetting patterns (Ritsema *et al.* 1998) and an overall reduction in plant-available water (Hallett 2008). Previous reviews suggested that the same hydrologic processes are likely to limit soil nutrient availability and plant uptake due to large volumes of soil remaining dry (Roper *et al.* 2015) and the increased leaching potential along preferential flow pathways (Blackwell 2000). However, integration of water harvesting principles such as furrow sowing and banding wetting agents can improve semi-arid dryland crop production on water-repellent soils (Blackwell 1993; Crabtree and Henderson 1999; Roper *et al.* 2015). Earlier findings reported in Chapters 5 and 6 have also demonstrated the high efficacy of severe topsoil water repellence and preferential flow in a wettable furrow for *in situ* water harvesting relative to completely wettable soils, regardless of topsoil thickness (20 or 100 mm), fertiliser placement (below or away from the seed), or variable low water supply (3.4, 4.4, and 5.4 mm every 2 days). To complement these studies, the present study aimed to better understand the efficacy of water harvesting under variable surface topography and plant density, given that these parameters are often influenced by soil water repellence.

Findings showed that severely water-repellent sandy loam topsoil treatments with a wettable furrow significantly accelerated wheat seedling leaf emergence (from Z12.9 to Z13.0; 20 DAS), increased tiller number from 0.3 to 1.9 tillers per plant, increased shoot dry matter per plant by 138 % and total dry matter per container by 141 %, increased shoot N concentration (from 5.2 to 5.7 %), and total uptake of all nutrients by up to 179 % on average in comparison to completely wettable topsoil treatments, regardless of surface topography (ridge-furrow or flat) and plant density (9, 12, or 15 plants/container). Therefore, these results suggest that, despite an eroded ridge-furrow topography or constrained plant establishment due to soil water repellence, *in situ* water harvesting from furrow-sowing and banding wetting agents can still significantly improve the growth and nutrition of established plants compared to those in wettable soil.

Differences in early growth were not due to water stress given that plants in all treatments were relatively well-hydrated (RWC > 90 %), despite receiving a limited but regular water supply (total of 88 mm water over 40 days; average day air temperature of 21°C and relative humidity of 38 %). Preferential flow in the wettable furrow of repellent treatments also did not result in drainage from the base of treatment containers but increased soil water and solute availability in the furrow and inter-row at the 5 and 15 cm depths. This occurred much earlier in repellent treatments than in wettable treatments, especially in repellent treatments with a ridge-furrow topography. In comparison, soil wetting in the furrow at the 5 cm depth was relatively delayed in wettable treatments with a ridge-furrow topography (by 11 days) and flat topography (by 19 days), with wetting also limited at depth (<15 cm).

Compared to the sandy loam topsoil used in this experiment, the effect of preferential flow in the furrow of repellent treatments could well differ in lighter-textured soils with lower nutrient retention and water-holding capacity (Lehmann and Schroth 2003) and/or under a higher water supply where significant leaching can occur (Blackwell 2000). This is particularly true for NO_3^- and SO_4^{2-} which are repelled by the negative net charge of most soils (Hodges 2010) or B as boric acid, H_3BO_3, which has no charge and is weakly adsorbed in soil (Price 2006) and thus easily leached after heavy rainfall. Measurable leaching losses along preferential flow pathways, which were not evident in the present study or previous studies (Chapters 5 and 6), could limit crop uptake and reduce overall yield (van der Paauw 1962).

In dry repellent soil, however, stored nutrients may be conserved due to minimal exposure to wetting and mineralisation (Piccolo *et al.* 1999; Goebel *et al.* 2005; Arcenegui *et al.* 2008). Results showed relatively higher concentrations of NO_3-N and K in the inter-row at the 0-5 and 5-10 cm depths in repellent treatments relative to wettable treatments and this may suggest that: (1) repellent topsoil protected nutrients from leaching; (2) plant nutrient uptake from the inter-row at the 0-10 cm depth was relatively lower in repellent treatments than in wettable treatments; and/or, (3) lateral diffusion of banded wetting agent in the furrow following irrigation resulted in the redistribution of nutrients from the fertiliser band. Interestingly, the latter effect was found to coincide with soil sensor data which showed a relatively rapid increase in soil water and solute availability in the inter-row at the 5 cm depth in repellent treatments with a ridge-furrow topography in comparison to other treatments, although wetting in the inter-row was relatively delayed in repellent treatments with a flat topography. This difference in wetting pattern was presumably due to flow diversion towards the wettable furrow of repellent treatments with a ridge-furrow topography relative to treatments with a flat topography. Note that, in earlier experiments, repellent soil in the inter-row at the 5 cm depth remained relatively dry over 40 days (see Chapters 5 and 6), despite receiving the same water supply. However, in contrast to the previous method for establishing a wettable furrow (i.e., placement of dry, wettable topsoil that was pre-treated with wetting agent), the banding of wetting agent solution in the furrow at sowing in this experiment may have made it more mobile and possibly result in greater lateral movement of water and nutrients (N and K).

Possible movement and/or mineralisation of soil N may also perhaps explain the increased concentration of NO_3-N in the inter-row at the 10-15 and 15-20 cm depths of repellent treatments relative to wettable treatments, regardless of surface topography. However, it is more likely that such differences in soil NO_3-N were attributed to plant N uptake, given that soil NO_3-N in the furrow at the 5-20 cm depth was significantly lower in repellent treatments than in wettable treatments, which reflects the observed differences in shoot dry matter. Soil P availability was neither affected by topsoil water repellence nor surface topography and this could be due to its relative immobility in these sandy loam topsoils (see Chapters 5 and 6), although the phosphorus buffering index (PBI) of these sandy loam soils could be considered low (PBI = 95) in comparison to other in finer-textured loamy or clayey soil types (high PBI >280; Moody 2007; Wong *et al.* 2012). Moreover, it is also likely that the high concentration of P in topsoil may have masked differences in plant P uptake between treatments as concentrations more than adequate for plant uptake. Increases in soil K availability in the furrow and inter-row to the 15-20 cm depth was also evident but only in repellent treatments with a ridge-furrow topography, highlighting its greater potential for water harvesting and K redistribution relative to that in repellent treatments with a flat topography.

Increased soil NH_4-N and K availability in the furrow at the 15-20 cm depth was, nevertheless, observed in treatments with a lower plant density, regardless of topsoil water repellence. However, plant density did not affect soil P availability. Increases in soil Colwell K concentration in the inter-row at the 10-15 and 15-20 cm depths were also observed in repellent treatments with a lower plant density, but not in wettable treatments. Not surprisingly, the leaching potential would tend to be greater under reduced plant densities due to an overall reduction in root density and nutrient uptake (Dai *et al.* 2014; Jones and Olson-Rutz 2018) and even more so along preferential flow pathways in water-repellent soils (Blackwell 2000). By contrast, soil NO_3-N concentrations in the furrow were generally greater in treatments with a higher plant density, regardless of topsoil water repellence, but the reason for this remains unclear. Nevertheless, topsoil water repellence did not affect shoot N concentration in treatments with a lower plant density (9 plants/container) but did significantly increase shoot N concentration in treatments with a higher plant density (15 plants/container), suggesting that nutrient leaching and/or redistribution in the present study was not harmful but beneficial to early wheat N nutrition in repellent treatments, regardless of plant density.

The resulting effect of topsoil water repellence on water and nutrient availability in the root zone was, therefore, conducive to early wheat growth so much so that even the total amount of wheat shoot dry matter produced and nutrients (N, P, K, Mg, S, B, Fe, and Zn) assimilated in shoots were still significantly greater (by 62 and 88 %, respectively) in repellent treatments with low plant density (9 plants/container) than that produced in wettable treatments with high plant density (15 plants/container). It was also noted that while increasing the plant density from 9 to 15 plants/container can generally increase total shoot dry matter (by 46 %) and total nutrient uptake per container (by 40 %), topsoil water repellence resulted in a greater increase in total shoot dry matter (by 141 %) and total nutrient uptake per container (by 160 %), regardless of plant density. Findings, therefore, demonstrate the high efficacy of *in situ* water harvesting in repellent soils with a wettable furrow (e.g., furrow sowing and banded wetting agent in the furrow) to stimulate early wheat growth and nutrient uptake despite a 40 % reduction in plant density (i.e., from 15 to 9 plants/container which is equivalent to 125 to 75 plants/m^2).

Crop physiological responses are known to occur under reduced plant densities such as increased tiller number and grain-setting in cereals (e.g., *Triticum aestivum* L.; Li *et al.* 2016) or increased branching and pod development in canola (*Brassica napus* L.; Clarke and Simpson 1978; Angadi *et al.* 2003) due to decreased plant competition for light, water, and nutrients. In this study, although wheat tiller number per plant (39 DAS) was not affected by plant density, a reduction in plant density from 15 to 9 plants/container resulted in a significant increase in early wheat dry matter per plant (by 14 %; 40 DAS) and total uptake per plant of P (by 15-32 % depending on surface topography), K (by 14 %), and S (by 12 %; 40 DAS). However, such compensatory effects per se are relatively minor in comparison to that produced by increasing plant density or promoting water harvesting in repellent treatments.

Indeed, many water harvesting systems in semi-arid dryland cropping systems adopt a ridge and furrow topography (i.e., referred to as a ridge and furrow rainwater harvesting, RFRH, system), with the ridges often mulched with materials (e.g., plastic film, plant residue, and gravel-sand materials) to maximise the capture of rainfall and surface runoff in the furrow or planting zone (Liu *et al.* 2005; Gan *et al.* 2013). Compared to conventional flat planting methods, the ridge-furrow water harvesting system has been reported to improve water use efficiency and production of various crops under a limited water supply, including that of corn (Li *et al.* 2000; Li *et al.* 2001; Ren *et al.* 2008; Wang *et al.* 2011), wheat (Li *et al.* 1999; Ren *et al.* 2016; Liu *et al.* 2018), canola (Gu *et al.* 2017; Gu *et al.* 2019), sweet sorghum (Wang *et al.* 2009b), foxtail millet (Lian *et al.* 2017), oats (Qi *et al.* 2015), alfalfa (Jia *et al.* 2006), sunflower (Pan *et al.* 2019), potatoes (Wang *et al.* 2008; Zhao *et al.* 2014), and faba bean (El-Sadek and Salem 2015). Other forms of *in situ* water harvesting using tied ridges and contour ridges have also been documented to improve crop production in semi-arid dryland cropping regions in Ethiopia (Araya and Stroosnijder 2010; Milkias *et al.* 2018) and Zimbabwe (Motsi *et al.* 2004), but these effects are not related to water repellence.

In this study, the combination of topsoil water repellence and a ridge-furrow topography resulted in the greatest increase in soil water content at the 5 and 15 cm depths and was expected to provide the most favourable conditions for early root growth and uptake of wheat plants under low water supply. This was indeed true for total shoot dry matter per container (40 DAS) and total uptake of Mg and Cu per plant (40 DAS) which were found to be significantly greater in repellent treatments with a ridge-furrow topography than a flat topography by 18, 15, 20, and 14 %, respectively, but not in wettable treatments. In general, having a ridge-furrow topography also significantly increased wheat shoot dry matter per plant (by 13 %) and total uptake of N, K, S, B, Fe, and Zn per plant (by an average of 15 %; 40 DAS) relative to a flat topography, despite no effect on seedling stage and tiller number. While the effect of surface topography can be considered relatively minor in comparison to topsoil water repellence, per se, adopting a stable ridge-furrow system can indeed enhance the efficacy of water harvesting on water-repellent soils.

The efficacy of *in situ* water harvesting in field soils will diminish over time due to ridge erosion and furrow in-fill (from wind and rain), especially in coarser-textured soils which are less stable than finer-textured soils (Brouwer *et al.* 1988). This is also likely to occur following extended periods of rainfall which is also known to result in the breakdown of soil water repellence (Crockford *et al.* 1991), although in some cases soil water repellence may persist well into the winter season but potentially aid in soil moisture conservation (Rye and Smettem 2017). Benefits from *in situ* water harvesting (furrow sowing with banded wetting agent) for crop production on repellent soils can, therefore, be relatively short-lived (e.g., 2-3 months; Roper *et al.* 2015). Nonetheless, efforts to improve the stability of the ridge-furrow topography to maximise rainfall and runoff capture can play an important role in the early stages of crop growth and establishment on water-repellent soils.

Adoption of furrow sowing methods employing winged knife-points or boots are recommended for improving the efficacy of furrows due to the increased grading of repellent topsoil and creation of larger furrows and ridges relative to conventional knife points (Davies *et al.* 2012a; GRDC 2014a; Roper *et al.* 2015; Unkovich *et al.* 2015). Improvements in furrow stability by using press-wheels in combination with furrow sowing and banded wetting agents has also been reported to increase the germination and yield of various crops (wheat, barley, and lupin; Crabtree and Gilkes 1999a; Crabtree and Henderson 1999) and pastures (subterranean clover, dryland lucerne, tagasaste, phalaris, and perennial ryegrass; Crabtree and Gilkes 1999b). Decreased soil surface roughness due to compaction pressure from press-wheels could also reduce topsoil water repellence and consequently improve water entry in the furrow (Bryant *et al.* 2007). Furrow sowing on wide rows (more than 20 cm) could also allow for increased water harvesting and deeper sowing into moist soil (below the 7.5 cm depth) compared to the conventional 17 cm furrow width on water-repellent soils in southern Australia (Blackwell 1993).

Overall, despite variation in surface topography and plant density, severely water-repellent topsoil treatments with a wettable furrow greatly favoured the growth and nutrition of furrow-sown wheat (40 DAS) due to *in situ* water harvesting which increased plant-available water and soluble nutrients in subsurface layers relative to completely wettable topsoil treatments which exhibited an even but limited wetting at depth. Findings also highlight the high efficacy of *in situ* water harvesting in repellent treatments (9 plants/container) such that even a 40 % reduction in plant density (equivalent to a reduction of 50 plants/m^2) significantly improved total shoot dry matter (by 62 %) and total N, P, K, Mg, S, B, Fe, and Zn uptake per container (by 88 %) relative to wettable treatments with a high plant density (15 plants/container). Adopting a stable ridge-furrow system can also enhance the efficacy of *in situ* water harvesting in repellent treatments for shoot dry matter (by up to 18 %) and nutrient uptake (by up to 16 % on average) relative to a flat topography, but not in wettable treatments. *In situ* water harvesting could, therefore, be a practical strategy for enhancing the nutrition of early crop growth on water-repellent soils in semi-arid and Mediterranean low rainfall regions.

7.5 Conclusion

In agreement with earlier findings detailed in Chapters 5 and 6, severely water-repellent sandy loam topsoil with a wettable furrow significantly improved early growth (by up to 141 %) and nutrient uptake (by up to 179 % on average) of furrow-sown wheat (40 DAS) due to *in situ* water harvesting which increased plant-available water and soluble nutrients in subsurface soil relative to that in completely wettable topsoil treatments which exhibited an even but limited wetting at depth. These findings, which reflect a limited but regular water supply (total of 88 mm), were found regardless of surface topography (ridge-furrow and flat) and plant density (9, 12, and

15 plants/container). The high efficacy of *in situ* water harvesting enabled the low plant density (9 plants/container) in repellent treatments to not only compensate for but to significantly improve total shoot dry matter (by 62 %) and total N, P, K, Mg, S, B, Fe, and Zn uptake per container (by 88 %) relative to wettable treatments with a high plant density (15 plants/container). Adopting a stable ridge-furrow system can also enhance the efficacy of *in situ* water harvesting in repellent treatments for shoot dry matter (by up to 18 %) and nutrient uptake (by up to 16 % on average) relative to a flat topography, but not in wettable treatments. Future studies should assess the implications of topsoil water repellence and leaching under more intense irrigation, with attention to full-season dry matter production and grain yields to ascertain likely benefits in field production. Moreover, the efficacy of *in situ* water harvesting for early crop growth and nutrition should also be examined in the absence of banded wetting agent to mimic untreated water-repellent soils that exhibit uneven soil wetting and plant germination.

Chapter 8: **General discussion and conclusion**

8.1 Introduction

In water-limited environments, dryland crop and pasture production on water-repellent sandy agricultural soils is often considered to be constrained (Bond 1972; DeBano 1981; Müller *et al.* 2014a; Roper *et al.* 2015; Hewelke *et al.* 2018). This is due to reduced water infiltration (Roberts and Carbon 1971; Wang *et al.* 2000; Li *et al.* 2018), accentuated overland flow and soil erosion (Witter *et al.* 1991; Shakesby *et al.* 2000), and unstable wetting patterns and the development of preferential flow paths in the soil profile (Ritsema and Dekker 1994; Dekker and Ritsema 1996b; Bauters *et al.* 1998), which cause spatial heterogeneity in crop establishment, yield, and soil water content (with prevalent isolated dry zones; Bond 1964; Blackwell 2000), and decreased overall soil water retention (Li *et al.* 1997; Doerr *et al.* 2006). The same processes are also likely to affect soil nutrient bioavailability and plant nutrient uptake (Sunderman 1988; Doerr *et al.* 2000; Kramers *et al.* 2005; Jordán *et al.* 2013; Scanlan *et al.* 2013; Roper *et al.* 2015; Hermansen *et al.* 2019), and problems with crop nutrition on water-repellent sandy soils have also been reported by Australian growers (Unkovich *et al.* 2015). However, the role of soil water repellence in crop nutrition has not been assessed to date.

While various methods exist to manage soil water repellence for improving crop and pasture production (e.g., deep soil cultivation, clay spreading, wetting agent application, stimulation of wax-degrading microorganisms, furrow/on-row sowing and water harvesting, and no-tillage and stubble retention; Blackwell 2000; Roper *et al.* 2015), the outcomes for crop nutrition after amelioration are also not yet well understood with current research still in its early stages (O'Callaghan 2017). The present thesis has pursued a number of opportunities for better understanding the management of constraints to crop nutrition on water-repellent soils. Both field and glasshouse experiments were conducted to explore the implications of soil water repellence and its amelioration for crop growth and nutrition on several sandy soil types in the southwest region of Western Australia. The main new insight from this work is that provided that water can be diverted to the seeded furrow, soil water repellence stimulates early wheat growth due to improved water use efficiency and nutrient uptake. This is through the deep percolation of water into the soil where it is less susceptible to loss by evaporation. Hence, contrary to this thesis' hypotheses, soil water repellence need not inhibit nutrient availability to early growth of crops. Furrow sowing with banded wetting agent appears to be an agronomic approach for enhancing crop nutrition on water-repellent sands. This work supports a recent concept paper that argues for a re-thinking of soil water repellence from being an intractable problem to one that presents ecological and crop production opportunities (Ruthrof *et al.* 2019).

8.2 Role of soil water repellence in crop growth and nutrition

Preliminary field investigations (Chapter 3) showed that an increase in soil water repellence severity (from negligible to moderate levels) could account for a decrease in plant density, shoot dry matter production, K nutrition, and grain yield of wheat on an untreated Grey Bleached-Ferric Kandosol at Meckering, WA, supporting the hypothesis that soil water repellence can adversely affect crop growth, nutrition, and grain production. By contrast, it was also revealed at the Kojonup site that an increase in soil water repellence severity (from moderate to very severe levels) could also result in an increase in plant density, shoot dry matter, Cu nutrition, and seed yield of canola on a Ferric Chromosol. The apparent contradictory findings may be related to the treatment at sowing with 1 L/ha of banded wetting agent at Kojonup. Although the underlying mechanisms could not be established from this preliminary study, it was concluded that soil water repellence may have both adverse and beneficial implications, presumably due to its potential influence on soil water and nutrients in the root zone. However, the Kojonup findings, on the gravel soil with prolonged severe water repellence throughout the growing season, may provide some field validation for a positive role of soil water repellence for crop nutrition and growth, given that sufficient seedlings were established by the banded wetting agent treatment and the furrow sowing allowed water harvesting that enhances crop water use and nutrient uptake.

Additional field studies (Chapter 4) were conducted at Badgingarra and Moora to assess the effect of alleviating soil water repellence on crop growth and nutrition via the adoption of different amelioration and mitigation strategies, including spading, one-way plough, subsoil clay spreading, and blanket applications of wetting agent. While all treatments except for one-way plough alleviated soil water repellence, only spading resulted in significant improvements in plant emergence, shoot dry matter, K nutrition, and grain yield of wheat on a Grey Tenosol at Badgingarra. By contrast, the one-way plough treatments resulted in significant improvements in shoot dry matter and nutrition (Ca, S, B, Cu, and Zn) in canola on a severely water-repellent Ferric Chromosol at Moora. Given the negligible effect of alleviating soil water repellence via subsoil clay spreading (250 t/ha; 50 % clay; 159 mg K/kg) and blanket-applied wetting agent (50L/ha) on crop growth, nutrition, and grain production, it was concluded that the observed improvements due to spading and one-way plough were likely explained by their effect on soil physical properties within the cultivated soil depth, particularly the alleviation of subsoil compaction. Results from this study, therefore, indicated that the alleviation of soil water repellence may not be important for crop production at Badgingarra and Moora, presumably due to the presence of other soil constraints. Amelioration strategies, such as spading, which can treat multiple soil constraints (Hall *et al.* 2010; Davenport *et al.* 2011; Roper *et al.* 2015), could thus have greater agronomic opportunities for improving crop growth, nutrition, and grain production on these water-repellent soils. However, the implications of nutrient dilution and redistribution in the soil profile, particularly for immobile nutrients (e.g., P), due to topsoil inversion should be considered as the fertiliser regimen may need to be adjusted to account for nutrient deficits.

Due to confounding factors and multiple constraints in field environments which made it difficult to quantifying the effect of soil water repellence on crop growth and nutrition, a series of controlled glasshouse experiments (Chapters 5, 6, and 7) were conducted. These examined the effects of topsoil water repellence, topsoil thickness, fertiliser placement, variable water supply, plant density, and/or surface topography on soil water content, soil nutrient availability, and early wheat growth and nutrition in 27 L containers. Overall, all glasshouse experiments demonstrated that, under low but regular water supply, severely water-repellent topsoil with a wettable furrow (which ensured uniform seedling emergence) resulted in significant improvements in seedling development, tiller number, shoot dry matter production, and nutrition (especially N, P, and K) during the early vegetative stage in wheat (40-51 DAS) relative to completely wettable topsoil treatments, regardless of variable topsoil thickness (20 or 100 mm; Chapter 5), fertiliser band placement (below or away from the seed; Chapter 5), low water supply (3.4, 4.4, or 5.4 mm every 2 days; Chapter 6), surface topography (ridge-furrow or flat; Chapter 7), and/or plant density (9, 12, or 15 plants/container; Chapter 7).

Such increases in early wheat growth and nutrition in severely water-repellent topsoil treatments were found to be largely attributed to *in situ* water harvesting caused by preferential flow in the wettable furrow, which significantly increased: (1) the wetting depth and root depth and hence soil water availability in the furrow (15 cm); and, (2) plant-available P in the furrow (5-15 cm) and subsurface N and K availability in the furrow and inter-row (10-20 cm), without causing drainage from the base of treatment containers. These increases in soil water and nutrients at depth together with increased rooting depth were found to be closely related to increases in wheat shoot dry matter and nutrition (especially N and K; Chapter 6). However, the efficacy of *in situ* water harvesting for improving early wheat growth and nutrition will likely diminish with further increases in crop water supply due to an overall increase in soil wetting and rooting depth and a decrease in soil water differentials in the root zone.

Although dry soil zones in repellent treatments were initially hypothesised to limit plant nutrient uptake by restricting root placement and root foraging volume (Lobet *et al.* 2014), and potentially hindering the use efficiency of nutrients therein (Roper *et al.* 2015), the present findings underscore the high efficacy of *in situ* water harvesting for early wheat growth and nutrition in water-repellent soils. Even despite a 40 % reduction in plant density, severely repellent topsoil treatments with the lowest plant density (9 plants/container ≈ 75 plants/m²) still produced 62 % more shoot dry matter, with an 88 % increase in total N, P, K, Mg, S, B, Fe, and Zn uptake per container, relative to completely wettable topsoil treatments with the highest plant density (15 plants/container ≈ 125 plants/m²; Chapter 7). Indeed, compared to the bulk volume of soil, preferential paths can be considered as enriched zones of water, nutrients, and organic substrate (Bundt *et al.* 2001; Guggenberger and Kaiser 2003;

Morales *et al.* 2010) and would, therefore, provide ‘hotspots’ for foraging roots and nutrient acquisition in water-repellent soils.

By contrast, even soil wetting and increased water retention near the surface of completely wettable topsoil treatments generally resulted in shallow wetting depth and potentially greater evaporative water loss due to the greater surface area of wet soil. Other studies have also shown that water-repellent soils can act as a mulch and aid in soil water conservation by significantly reducing evaporative water loss from the soil surface (Bachmann *et al.* 2001; Gupta *et al.* 2015; Rye and Smettem 2017) by decreasing the upward capillary movement of water (DeBano 1981) in addition to diverting water flow to subsurface layers via preferential pathways (Ritsema and Dekker 1994). Even and shallow wetting patterns consequently led to an overall decrease in plant-available water and plant water use efficiency in completely wettable treatments, resulting in poor wheat growth and nutrition, under a low water supply. These differences in wetting effect would also explain why: (1) increasing the thickness of wettable topsoil from 20 to 100 mm had significantly reduced early wheat growth but not for repellent topsoil treatments (Chapter 5); and, (2) that a ridge-furrow topography had no effect on early wheat growth and nutrition in completely wettable topsoil treatments but could enhance the efficacy of *in situ* water harvesting in repellent treatments (Chapter 7).

Despite an increased leaching potential in severely repellent topsoil treatments, the observed increases in plant-available water and soluble nutrients at depth also favoured the development of deeper roots relative to that in completely wettable topsoil treatments. Increasing early root development and rooting depth during plant establishment is known to enable greater exploitation of the soil matrix which increases plant water and nutrient uptake, leading to more vigorous plant growth (Andresen *et al.* 2016) and consequently higher yields (Fageria and Moreira 2011). Increasing early root development of dryland crops would also confer to plants greater tolerance to drought stress due to greater access to deep-stored water and nutrient supplies (Dunbabin *et al.* 2003; Shao *et al.* 2008; Whitmore and Whalley 2009; Fageria and Moreira 2011) and enhance early uptake and use efficiency of fertiliser by increasing the recovery of mobile nutrients, particularly N, in sandy soils (Liao *et al.* 2004; Liao *et al.* 2006). By contrast, soils with limited wetting depth will have shallow root systems that are prone to rapid drying (Weaver 1926; Dunbabin *et al.* 2003). Increasing subsurface water storage and the rooting depth of crops due to preferential flow in water-repellent soils could, therefore, play a critical role in crop water use efficiency, drought stress resistance, and overall productivity in semi-arid dryland cropping systems that are strongly limited by low rainfall and seasonal water deficits (Kirkegaard *et al.* 2007; Chloupek *et al.* 2010; Comas *et al.* 2013; Lobet *et al.* 2014).

In hindsight, it is possible that the banded application of wetting agent by the farmer at Kojonup may have enhanced the water harvesting potential of more severely repellent soils in the paddock, resulting in a positive effect of soil water repellence on canola growth, Cu nutrition, and seed yield (Chapter 3), despite its prolonged expression throughout the growing season. Therefore, by maximising the capture of light rainfall events in wettable furrows and enhancing plant water and nutrient use efficiency, the adoption of *in situ* water harvesting principles (that utilise soil water repellence) as opposed to amelioration principles (that eliminate soil water repellence) could be an effective strategy for managing crop growth and nutrition on water-repellent dryland agricultural soils.

The ideal system for *in situ* water harvesting on water-repellent agricultural soils is, therefore, to furrow sow and to apply wetting agent in a band in the furrow base where seeds are placed to ensure uniform water entry and seedling emergence. Such systems may also be further improved by using wide furrows (wider than 20 cm) to increase the amount of water diverted to the planting zone and by using winged knife-points rather than conventional knife points to improve ridge-furrow stability and prevent backfilling of graded soil (Davies *et al.* 2012a; Unkovich *et al.* 2015). In addition, press-wheels tracking in the furrow can improve its definition and the seed-soil contact (Crabtree and Henderson 1999). The combination of these techniques could, therefore, be further tested and applied in crop and pasture systems affected by soil water repellence, particularly where soil amelioration strategies, such as spading and subsoil clay spreading, are not available or suitable.

8.3 Limitations and future research directions

Due to the variable nature of soil water repellence and the presence and complexity of biotic and abiotic factors interacting in the soil-water environment, the role of soil water repellence in crop growth and nutrition can be difficult to assess in the field. Empirical field research presented in this dissertation was able to establish a role of soil water repellence in crop nutrition. Further field research to validate the present findings in Chapters 5-7 would benefit from a larger number of samples to reduce the standard error, greater sampling area to improve field site representation, and sampling from both surface and subsurface depths to better assess the role of plant roots in nutrient uptake in water-repellent soils. Studies should also differentiate the effect of soil water repellence on mobile and immobile nutrients to provide valuable insight for fertiliser management on water-repellent soils.

While glasshouse studies offer greater control of treatments and conditions, relative to the real-world environments, the findings are often either limited to a specific scenario and/or overly simplified. To extrapolate the present findings, follow-up research needs to broaden the focus to include later phases of plant growth and extend the range of soil water regimes to both lower and higher supply and to examine the effects of less frequent water supply. In addition, the surface topography treatment (ridge-furrow or flat; Chapter 7) should be modified to remove surface runoff generated in severely repellent topsoil treatments so that it does not pond beside the walls of the treatment container, which promotes water infiltration under a positive hydraulic head, that would otherwise be lost in an uncontained area. The limited depth of treatment containers may also influence root growth (e.g., plants become root-bound), leaching, and soil nutrient distribution, which could potentially differ in deeper containers or field soils wherein root growth and nutrient leaching are not constrained at depth. Therefore, the effects of soil water repellence on root growth, leaching, and nutrient distribution should be validated in the field.

Although the benefits of *in situ* water harvesting were evident in water-repellent soils (with a wettable furrow) relative to completely wettable soils under the simulated conditions, the system assumed no losses in water via runoff or drainage (due to low water supply), except for evaporative water losses, which may misrepresent soil wetting patterns and plant responses under unconstrained field conditions with the same watering regimen. Soil water repellence can induce runoff and thus overall water loss from plots in field environments. At present, the studied watering regimes (3.4-5.4 mm every 2 days) were generally relevant for the dryland cropping systems in the medium (325-450 mm) to high (450-750 mm) rainfall zones of southwest WA. However, the outcomes for overall crop growth, nutrition, and/or grain production could also well differ under: (1) a higher water supply (e.g., high and/or intense rainfall or irrigation events), which could have other consequences due to excessive leaching; and/or, (2) under lower water supply or intermittent/terminal drought which could result in water stress and an increased risk of crops haying off prematurely. Simulating these conditions may provide useful information in future experiments.

Given the new insights garnered on the role of soil water repellence in *in situ* water harvesting and soil water conservation, next steps should include field trials to apply and validate present research findings on several water-repellent sandy agricultural soil types, over the entire crop growth cycle, and preferably over a wider range of rainfall environments to ascertain effects on crop production (i.e., final dry matter and grain yield). Outcomes may also vary under different nutrient regimes (i.e., adequate versus deficient). In the present field studies, it was hypothesised that plant responses to treatment effects would likely diminish under adequate nutrition and thus field sites with nutrient deficiencies were selected to lessen any confounding effects. Additional field studies could, therefore, be conducted under non-limiting nutrient levels to confirm the adverse effects of soil water repellence severity on crop growth, nutrition, and yield. The implications of soil water repellence should also be examined in the presence and absence of banded wetting agent to mimic the effects of uneven soil wetting in the planting row on plant establishment and density, and to determine whether *in situ* water harvesting without a wettable furrow could still be beneficial.

Due to the contrasting soil physical and hydraulic properties of water-repellent Chromosols, Kandosols, and Tenosols of southwest WA, studies should also assess the role of subsoil nutrient uptake (especially for N and K relative to P which differ greatly in mobility and distribution in the soil) and the mechanisms by which preferential flow wets up the subsurface soil layer. Compared to the layered soil profile (sandy loam topsoil over loamy sand subsoil) used in present glasshouse studies, the presence of a clay horizon at depth in a duplex soil (e.g., Chromosol) relative to a deep sand (e.g., Tenosol; with <5 % clay and no texture contrast) could have different consequences for soil water and nutrient redistribution in the root zone and plant root growth. Soil gravel content is also likely to play a significant role on the soil wetting depth and plant water and nutrient uptake by altering soil hydraulic conductivity and water-holding capacity. Examining the interactive effects between soil water repellence, soil type, soil gravel content on crop growth and nutrient uptake could, therefore, provide relevant and useful information for the effective management of crop production on different water-repellent soil types in the wheatbelt of southwest WA.

While the role of soil water repellence in soil mineralisation was not directly assessed in this dissertation, it can be hypothesised that limited wetting and prolonged dryness of repellent topsoil (especially the inter-rows) may help to conserve potentially mineralisable soil N by delaying mineralisation and leaching. Soil N released later in the season will be more efficiently used when plant demand is higher and root systems are more extensive. The implications of this delay in soil mineralisation for soil N availability, crop growth, N nutrition, and grain production on water-repellent soils could thus be examined in future research. Moreover, plant physiological and morphological responses to soil water repellence, particularly in relation to soil water and nutrient heterogeneity, could also be assessed to determine whether compensatory growth over time could overcome the adverse effects of soil water repellence, using a variety of crop species.

8.4 Final conclusions

Several field and glasshouse experiments were conducted to assess the effect of soil water repellence on crop growth and nutrition on several sandy agricultural soil types in the southwest region of Western Australia. Field results were not unequivocal but showed that soil water repellence, if left unmanaged, can adversely affect wheat shoot dry matter, K nutrition, and grain yield on a Grey Bleached-Ferric Kandosol at Meckering. Spading, as an amelioration strategy, alleviated soil water repellence and significantly improved wheat emergence, shoot dry matter, K nutrition, and grain yield on a Grey Tenosol at Badgingarra, but these improvements were likely attributed to the alleviation of soil compaction rather than alleviation of soil water repellence, given that the alleviation of soil water repellence by blanket-applied wetting agent (50 L/ha) and subsoil clay spreading treatments (250 t/ha; 50 % clay; 159 mg K/kg) had no effect on wheat production. By contrast, all glasshouse experiments demonstrated that, under low but regular water supply, severely water-repellent topsoil with a wettable furrow ensured uniform seedling emergence and increased early wheat growth and nutrition (especially N, P, and K; 40-51 DAS) due to *in situ* water harvesting and increased soil wetting and rooting depth relative to completely wettable topsoil treatments which exhibited an even but shallow wetting and rooting depth. Adopting *in situ* water harvesting principles (i.e., furrow sowing, banding wetting agent in the furrow, and using winged knife-points and/or press-wheels) can, therefore, be an effective strategy for managing crop growth and nutrition on water-repellent sandy soils by maximising the use efficiency of limited water supply on sandy soils.

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Appendix A: **General**

A.1 Effect of sieving on soil water repellence severity

The MED test was conducted in the laboratory to assess the effect of sieving on potential soil water repellence severity. Soils (0-10 cm) ranged from moderate (MED 2.0) to very severe (MED 3.6) potential water repellence, but results showed no significant differences between mean MED values before (MED 2.7) and after (MED 2.6) sieving (Figure 97). However, simple comparisons showed that, in 40% of samples, MED values generally decreased after sieving, suggesting that measuring potential soil water repellence after sieving may be underestimated. This can be explained by the abrasion of soil particles and hydrophobic coatings which reduces water repellence (King 1981; Ma'shum and Farmer 1985; Wallis *et al.* 1991). Therefore, to avoid any underestimation, tests for potential soil water repellence severity were conducted without sieving.

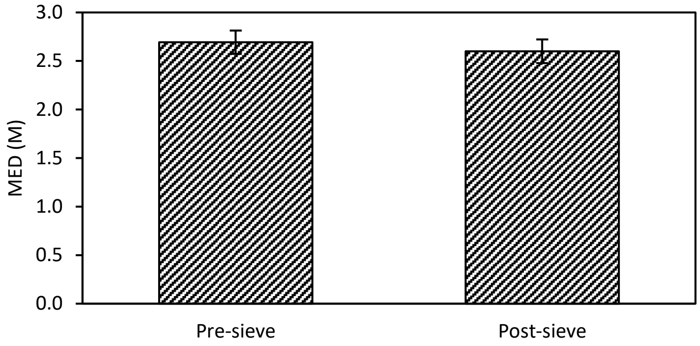


Figure 97. Soil water repellence before and after sieving assessed by the molarity of ethanol droplet (MED) test, based on fifteen Kojonup soil samples at 0-10 cm.

A.2 Plant nutrient thresholds

To assess the nutritional status of studied plants, nutrient concentrations in wheat and canola were benchmarked against thresholds described in Tables 125 and 126, respectively.

Table 125. Wheat (Triticum aestivum) nutrient concentration thresholds in leaves and whole shoots at different growth stages (Reuter and Robinson 1997).

Nutrient	Growth stage	Plant part	Deficient	Adequate
N (%)	Tillering	Leaf blade	<3.8	4.3-5.2
	Anthesis	Leaf blade	<2.4	2.7-3.0
	Tillering	Whole shoots	6.66	
	Anthesis	Whole shoots	<1.5	1.8-2.6
P (%)	Tillering	Leaf blade	<0.31	0.35-0.49
	Anthesis	Leaf blade	<0.22	0.25-0.34
	Stem elongation	Whole shoots		0.3-0.6
	Head emergence	Whole shoots		0.15-0.3
K (%)	Tillering	Leaf blade	<2.8	3.4-4.2
	Anthesis	Leaf blade	<2.0	2.3-3.2
	Tillering	Whole shoots	<3.5	>4.1
	Head emergence	Whole shoots		1.5-2.5
Ca (%)	Tillering	Youngest mature leaf blade	<0.18	0.21-0.4
	Stem elongation	Whole shoots		0.4-1.0
	Head emergence	Whole shoots	<0.2	0.2-0.5
Mg (%)	Tillering	Youngest mature leaf blade	<0.11	0.13-0.3
	Anthesis	Leaf blade	<0.1	>0.15
	Stem elongation	Whole shoots		0.12-0.25
	Head emergence	Whole shoots	<0.15	0.15-0.5
S (%)	Tillering	Youngest mature leaf blade	<0.15	0.15-0.4
	Anthesis	Green leaves	0.14	0.23
	Tillering	Whole shoots	0.3	
	Head emergence	Whole shoots	<0.15	0.15-0.4
Na (%)	Tillering	Youngest mature leaf blade		<0.5
	Anthesis	Whole shoots		~0.02
	Anthesis	Whole shoots		~0.02
B (mg/kg)	Tillering	Youngest mature leaf blade	<2	5-10
	Booting	Flag leaf	<3	7-24
	Stem elongation	Whole shoots		6-12
	Head emergence	Whole shoots	<6	6-10
Cu (mg/kg)	Tillering	Youngest mature leaf blade	<2	5-50
	Anthesis	Youngest emerged leaf blade	<1.6	>2.0
	Stem elongation	Whole shoots		7-15
	Head emergence	Whole shoots	<5	5-25
Fe (mg/kg)	Pre-heading	Leaf blade		25-100
	Head emergence	Whole shoots	<25	25-100
	Head emergence	Whole shoots	<25	25-100
Mn (mg/kg)	Tillering	Youngest mature leaf blade	<12	25-300
	Anthesis	Leaf blade	10	
	Stem elongation	Whole shoots		35-100
	Head emergence	Whole shoots	5-24	25-100
Zn (mg/kg)	Tillering	Youngest mature leaf blade	<14	15-70
	Anthesis	Youngest mature leaf blade		17-30
	Stem elongation	Whole shoots		25-70
	Head emergence	Whole shoots	<15	15-70

Table 126. Canola (Brassica napus) nutrient concentration thresholds in leaves and whole shoots at different growth stages (Reuter and Robinson 1997).

Nutrient	Growth stage	Plant part	Deficient	Adequate
N (%)	Vegetative	Mature leaf		3-4
	Pre-anthesis	Youngest mature leaf	0.8-2.7	3.5-5.5
	Anthesis	Youngest mature leaf		4.0-5.5
	Anthesis	Whole shoot	2.7-2.9	
P (%)	Pre-anthesis	Youngest mature leaf	0.09-0.20	0.35-0.60
	Anthesis	Youngest mature leaf		0.35-0.70
K (%)	Vegetative	Mature leaf		2.8-4.5
	Pre-anthesis	Youngest mature leaf	<1.6	2.8-5.5
	Anthesis	Youngest mature leaf		2.8-5.0
Ca (%)	Vegetative	Mature leaf		0.7-2.0
	Pre-anthesis	Youngest mature leaf	<0.8	1.4-3.0
	Anthesis	Youngest mature leaf		1-2
Mg (%)	Vegetative	Mature leaf		0.25-0.60
	Pre-anthesis	Youngest mature leaf	0.14	0.21-0.65
	Anthesis	Youngest mature leaf		0.25-0.40
	Anthesis	Whole shoot		>0.15
S (%)	Vegetative	Youngest mature leaf	0.11-0.21	0.26-0.93
	Pre-anthesis	Youngest mature leaf	<0.25	0.6-1.0
	Anthesis	Whole shoot	0.24	
Na (%)	Pre-anthesis	Youngest mature leaf		0.02-0.5
B (mg/kg)	Vegetative	Mature leaf		35-80
	Pre-anthesis	Youngest mature leaf	6-13	22-50
	Anthesis	Youngest mature leaf		30-60
Cu (mg/kg)	Vegetative	Mature leaf		6-12
	Pre-anthesis	Youngest mature leaf	<2	4-25
	Anthesis	Youngest mature leaf		5-12
	Anthesis	Whole shoot	2.8	2.7-6
Mn (mg/kg)	Vegetative	Mature leaf		40-100
	Pre-anthesis	Youngest mature leaf		30-250
	Anthesis	Youngest mature leaf		30-100
Zn (mg/kg)	Vegetative	Mature leaf		20-80
	Pre-anthesis	Youngest mature leaf	<12	21-55
	Anthesis	Youngest mature leaf		25-70

Appendix B: **Supplementary data for Chapter 3**

B.1 Kojonup

B.1.1 Soil chemical properties

Soil pH_{Ca} at the 0-10 cm depth was positively correlated with soil water content at the 0-5 and 5-10 cm depth during canola pod development ($R^2 = 0.39$ and 0.37, respectively; $P > 0.01$; 143 DAS; Figure 98), but there was no correlation during canola emergence or stem elongation (no data shown).

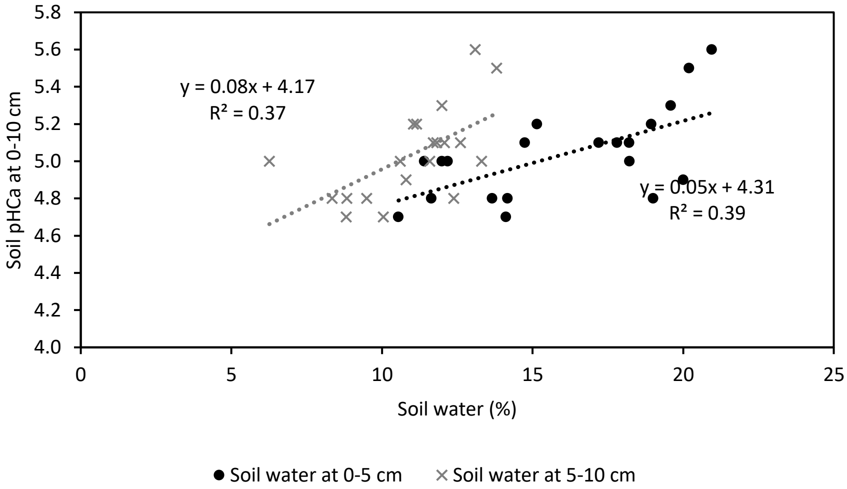


Figure 98. Relationship between soil pH_{Ca} ($CaCl_2$) at the 0-10 cm depth and soil water content (%, w/w) at the 0-5 and 5-10 cm depths during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

Soil Mn concentrations at the 0-10 cm depth were significantly greater in Class 3 soils (moderately repellent; 5.66 mg/kg) than in Class 5 soils during stem elongation (extremely repellent; 3.67 mg/kg; 95 DAS; Table 127). However, during pod development (143 DAS), soil Mn concentrations at the 0-10 cm depth were significantly lower in Class 2 soils (moderately repellent; 2.25 mg/kg) than in Class 4 (very severely repellent; 4.74 mg/kg) and Class 5 soils (extremely repellent; 4.97 mg/kg; Table 127). Interestingly, bivariate correlation analysis showed no correlation between soil Mn concentrations at the 0-10 cm depth and soil water repellence severity at the 0-5 cm depth, but soil Mn concentrations were positively correlated with soil water repellence severity at the 5-10 cm depth during pod development ($R^2 = 0.32$; $P < 0.05$; Figure 99). Results, however, indicate that such changes in soil Mn concentration were better explained by changes in soil pH_{Ca} at the 0-10 cm depth described by an inverse relationship ($0.39 \leq R^2 \leq 0.61$; $P < 0.05$; Figure 100).

Table 127. Effect of soil water repellence (SWR) severity class on soil manganese concentration (Mn, mg/kg), exchangeable aluminium percentage (Al, %), and exchangeable calcium percentage (Ca, %) at the 0-10 cm depth during different canola growth stages at Kojonup in 2016. Mean values based on an average sample size of 5 (unequal sample sizes). Significant differences based on the least significant difference (LSD) at P < 0.05.

Growth stage	SWR severity class	Soil Mn (mg/kg)	Soil exchangeable Al percentage (%)	Soil exchangeable Ca percentage (%)
Emergence (16 DAS)	Class 2 (moderate)	5.94^{a1}	2.42^{a1}	79.6^{a1}
	Class 3 (severe)	5.59^{a1}	3.55^{a1}	79.6^{a1}
	Class 4 (very severe)	6.55^{a1}	3.20^{a1}	78.7^{a1}
	Class 5 (extreme)			
Stem elongation (95 DAS)	Class 2 (moderate)			
	Class 3 (severe)	5.66^{ab1}	8.16^{b1}	76.6^{a1}
	Class 4 (very severe)	4.16^{b12}	4.25^{a2}	80.9^{a2}
	Class 5 (extreme)	3.67^{a2}	1.91^{a3}	83.3^{a2}
Pod development (143 DAS)	Class 2 (moderate)	2.25^{b1}	0.98^{a1}	84.8^{b1}
	Class 3 (severe)	3.96^{b12}	3.37^{a1}	83.1^{b1}
	Class 4 (very severe)	4.74^{b2}	3.26^{a1}	83.1^{b1}
	Class 5 (extreme)	4.97^{a2}	3.38^{a1}	81.3^{a1}

Different superscript letters denote significant differences between growth stages within respective SWR severity class (P < 0.05).

Different superscript numbers denote significant differences between SWR severity class within respective growth stage (P < 0.05).

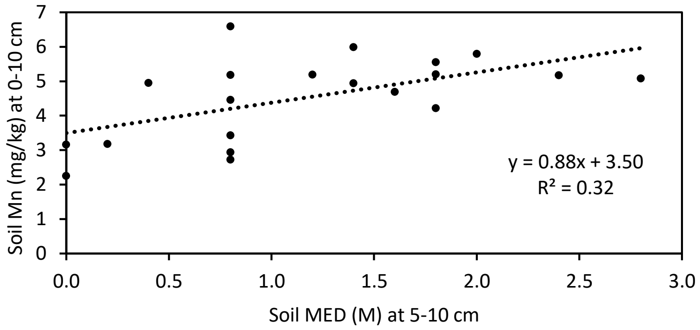


Figure 99. Relationship between soil water repellence severity (MED, M) at the 5-10 cm depth and soil manganese concentration (Mn, mg/kg) at the 0-10 cm depth during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

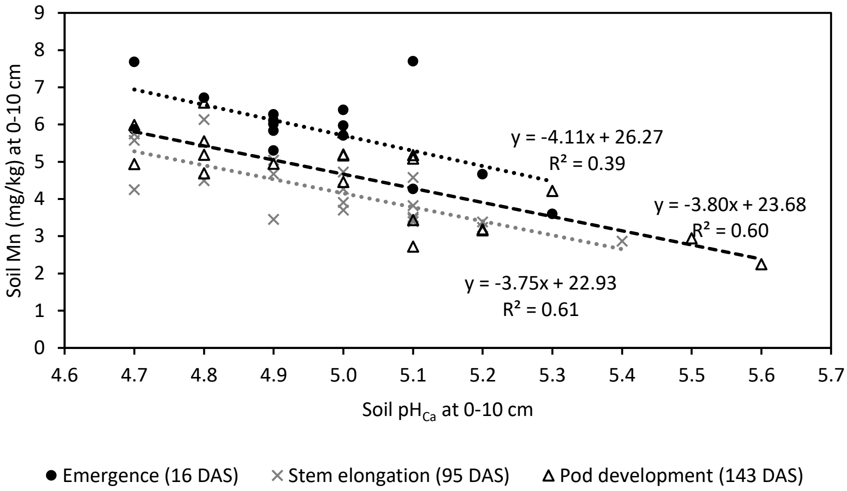


Figure 100. Relationship between soil pH$_{Ca}$ (CaCl$_2$) and soil manganese concentration (Mn, mg/kg) at the 0-10 cm depth during canola emergence (16 DAS), stem elongation (95 DAS) and pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

Soil Mn concentrations were also negatively correlated with soil water content at the 0-5 and 5-10 cm depths during pod development (R^2 = 0.51 and 0.29; $P < 0.05$; 143 DAS; Figure 101), but not during canola emergence or stem elongation (data not shown).

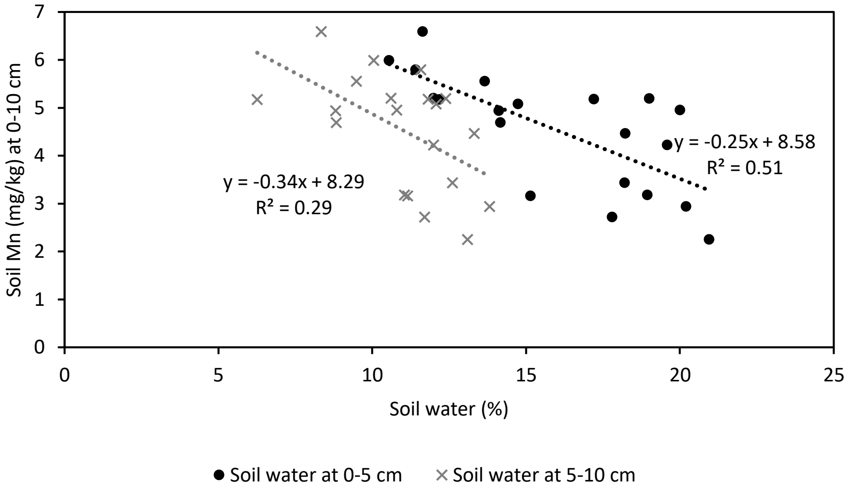


Figure 101. Relationship between soil manganese concentration (Mn, mg/kg) at the 0-10 cm depth and soil water content (%, w/w) at the 0-5 and 5-10 cm depths during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

During stem elongation (95 DAS), soil exchangeable Al percentage at the 0-10 cm depth was significantly greater in Class 3 soils (severely repellent; 8.16 %) than in Class 4 (very severely repellent; 4.25 %) and Class 5 soils (extremely repellent; 1.91 %; Table 127), whereas soil exchangeable Ca percentage at the 0-10 cm depth was significantly greater in Class 4 (very severely repellent; 80.9 %) and Class 5 soils (extremely repellent; 83.3 %) than in Class 3 soils (severely repellent; 76.6 %; Table 127). Bivariate correlation analysis also showed contrasting relationships of exchangeable Al and Ca percentages with soil water repellence severity, whereby soil exchangeable Al percentages at the 0-10 cm depth were negatively correlated with soil water repellence severity at the 0-5 cm depth during canola stem elongation ($R^2 = 0.44$; $P < 0.01$; Figure 102), while soil exchangeable Ca percentages at the 0-10 cm depth were positively correlated with soil water repellence severity at the 0-5 cm depth during stem elongation ($R^2 = 0.50$; $P < 0.01$; Figure 103).

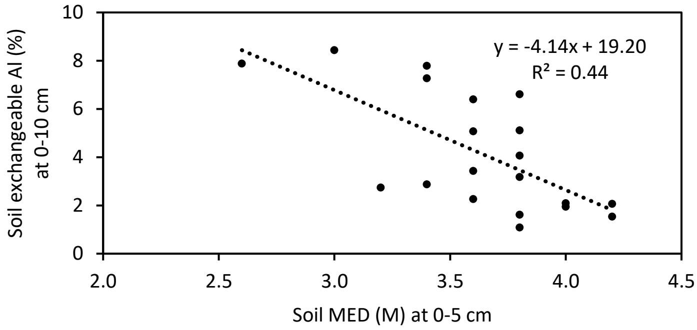


Figure 102. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and soil exchangeable aluminium concentration percentage (Al, %) at the 0-10 cm depth during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

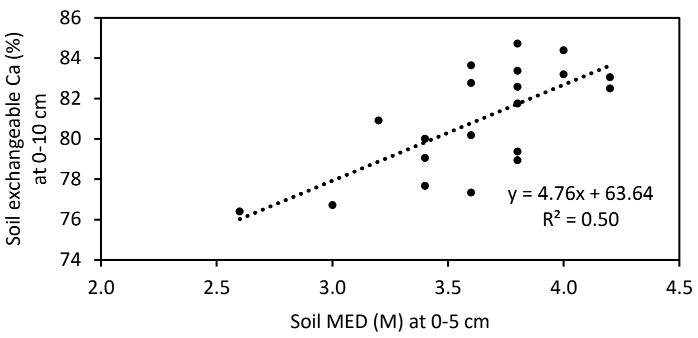


Figure 103. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and soil exchangeable calcium percentage (Ca, %) at the 0-10 cm depth during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

Such changes in soil exchangeable Al and Ca percentages were also significantly influenced by soil pH_{Ca} at the 0-10 cm depth, whereby: (1) soil exchangeable Al percentages were negatively correlated with soil pH_{Ca} ($0.64 \leq R^2 \leq 0.83$; $P < 0.01$; Figure 104), and (2) soil exchangeable Ca percentages were positively correlated with soil pH_{Ca} ($0.36 \leq R^2 \leq 0.67$; $P < 0.05$; Figure 105). A negative correlation between the percentage of soil exchangeable Ca and Al were also observed at the 0-10 cm depth during canola emergence ($R^2 = 0.49$; $P < 0.01$; 16 DAS), stem elongation ($R^2 = 0.84$; $P < 0.01$; 95 DAS), and pod development ($R^2 = 0.61$; $P < 0.01$; 143 DAS; Figure 106).

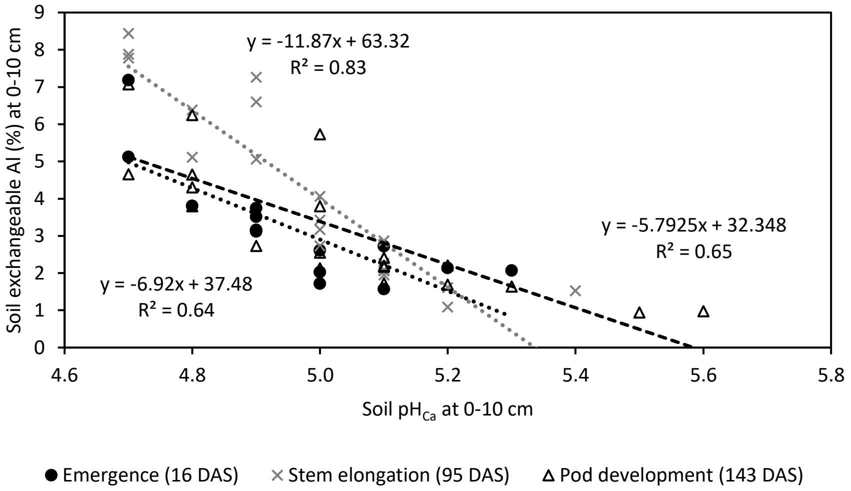


Figure 104. Relationship between soil pH_{Ca} ($CaCl_2$) and soil exchangeable aluminium percentage (Al, %) at the 0-10 cm depth in a Ferric Chromosol at Kojonup in 2016.

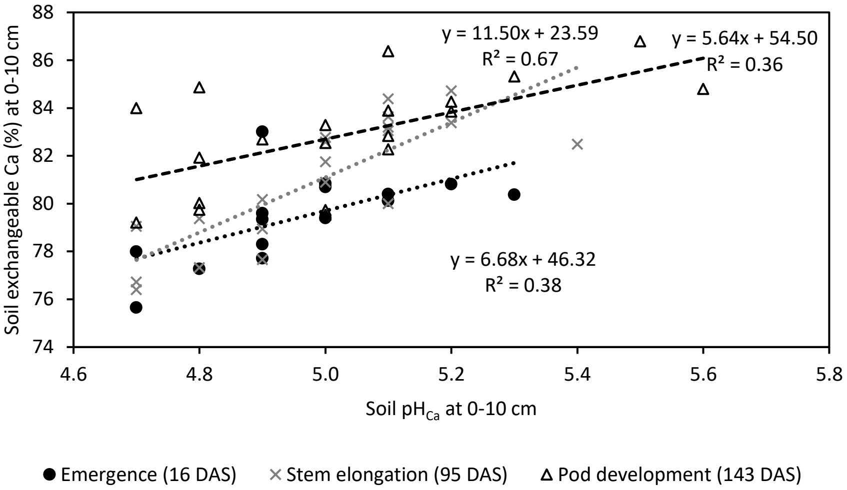


Figure 105. Relationship between soil pH$_{Ca}$ (CaCl$_2$) and soil exchangeable calcium percentage (Ca, %) at the 0-10 cm depth in a Ferric Chromosol at Kojonup in 2016.

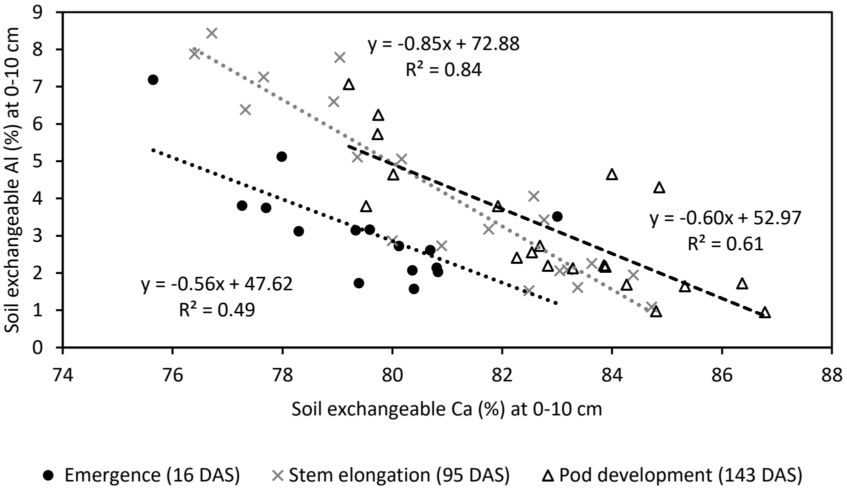


Figure 106. Relationship between soil exchangeable calcium percentage (Ca, %) and exchangeable aluminium percentage (Al, %) at the 0-10 cm depth during canola emergence (16 DAS), stem elongation (95 DAS), and pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

Likewise, during canola pod development (143 DAS), soil water content at the 0-5 and 5-10 cm depths was negatively correlated with soil exchangeable Al percentages (R^2 = 0.52 and 0.35, respectively; *P* < 0.01; Figure 107) and positively correlated with soil exchangeable Ca percentages (R^2 = 0.64 and 0.46, respectively; *P*

< 0.01; Figure 108), but correlations were not observed during canola emergence or stem elongation (data not shown).

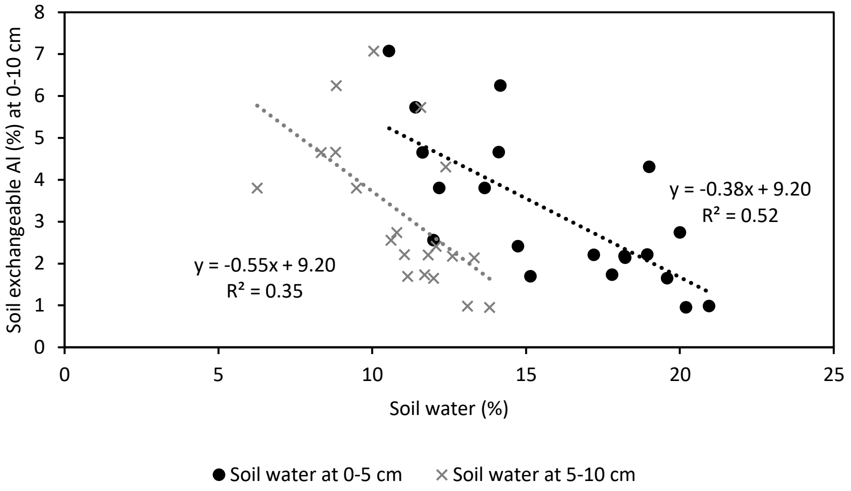


Figure 107. Relationship between soil exchangeable aluminium percentage (Al, %) at the 0-10 cm depth and soil water content (%, w/w) at the 0-5 and 5-10 cm depths during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

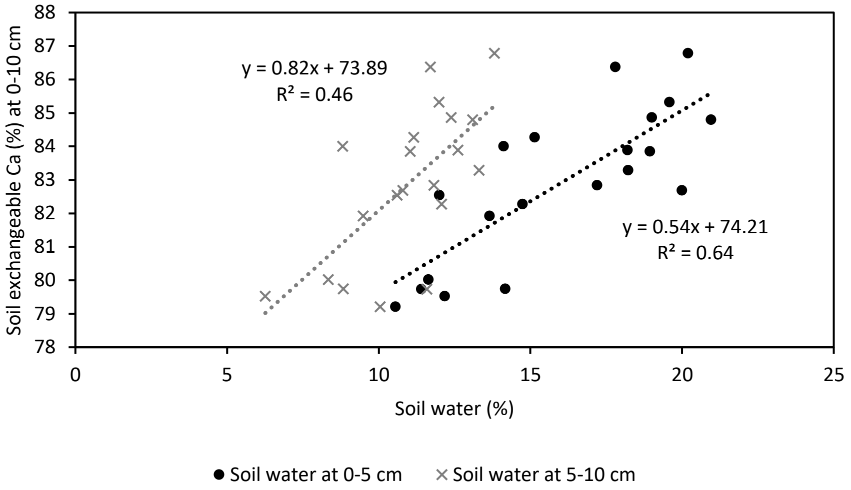


Figure 108. Relationship between soil exchangeable calcium percentage (Ca, %) at the 0-10 cm depth and soil water content (%, w/w) at the 0-5 and 5-10 cm depths during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

Soil exchangeable Al concentrations at the 0-10 cm depth were significantly affected by soil water repellence severity class ($P < 0.05$; see Table 7 in Section 3.3.1), whereby soil exchangeable Al concentrations at the 0-10 cm depth were significantly greater in Class 3 soils (severely repellent; 0.35 cmol(+)/kg) than in Class 2 (moderately repellent; 0.16 cml(+)/kg) and Class 5 soils (severely repellent; 0.20 cmol(+)/kg; Table 128). Bivariate correlations also showed that soil exchangeable Al concentrations at the 0-10 cm depth were negatively correlated with soil water repellence severity at the 0-5 cm depth during stem elongation ($R^2 = 0.43$; $P < 0.01$; Figures 109) but not during emergence or pod development (data not shown).

Table 128. Effect of soil water repellence severity class on soil exchangeable aluminium (Al, cmol(+)/kg) concentration at the 0-10 cm depth at Kojonup in 2016. Mean values based on an average sample size of 14 (unequal sample sizes). Significant differences based on the least significant difference (LSD) at P < 0.05.

Soil properties	Class 2 (moderate)	Class 3 (severe)	Class 4 (very severe)	Class 5 (extreme)
Soil exchangeable Al concentration (cmol(+)/kg)	0.16^{a}	0.35^{b}	0.29^{bc}	0.20^{ac}

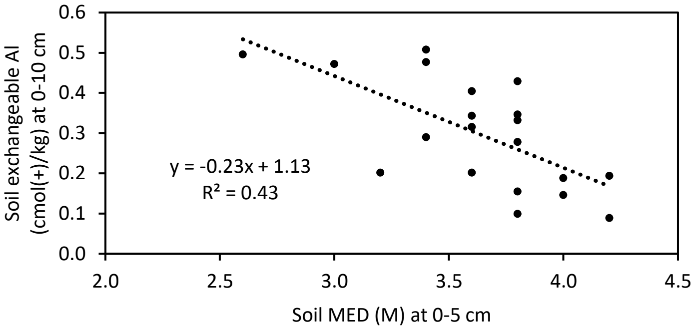


Figure 109. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and soil exchangeable aluminium concentration (cmol(+)/kg) at the 0-10 cm depth during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

Like soil Mn, changes in soil exchangeable Al concentrations were also strongly influenced by soil pH_{Ca} at the 0-10 cm depth, whereby soil exchangeable Al concentrations were negatively correlated with soil pH_{Ca} ($0.65 \leq R^2 \leq 0.83$; $P < 0.01$; Figure 110).

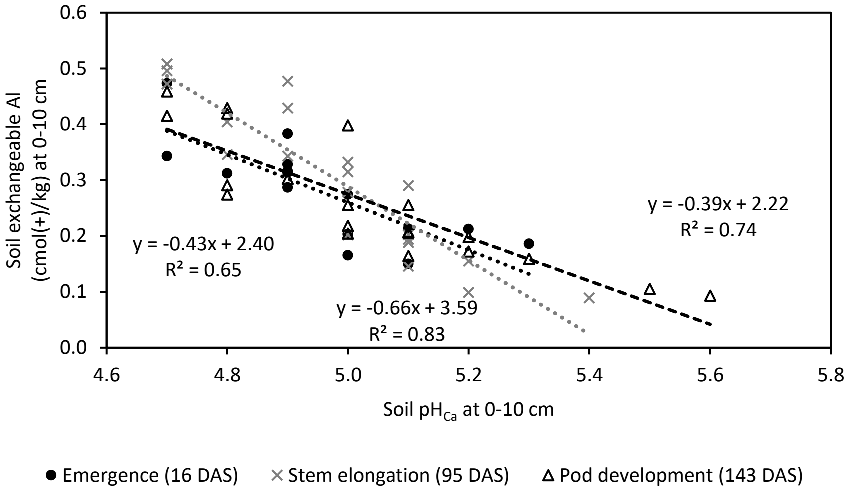


Figure 110. Relationship between soil pH$_{Ca}$ (CaCl$_2$) and soil exchangeable aluminium concentration (Al, cmol(+)/kg) at the 0-10 cm depth in a Ferric Chromosol at Kojonup in 2016.

Soil exchangeable Al concentrations at the 0-10 cm depth were also negatively correlated with soil water content at the 0-5 and 5-10 cm depths during canola pod development ($R^2 = 0.30$ and 0.21, respectively; $P < 0.05$; Figure 111), but correlations were not observed during canola emergence or stem elongation (data not shown).

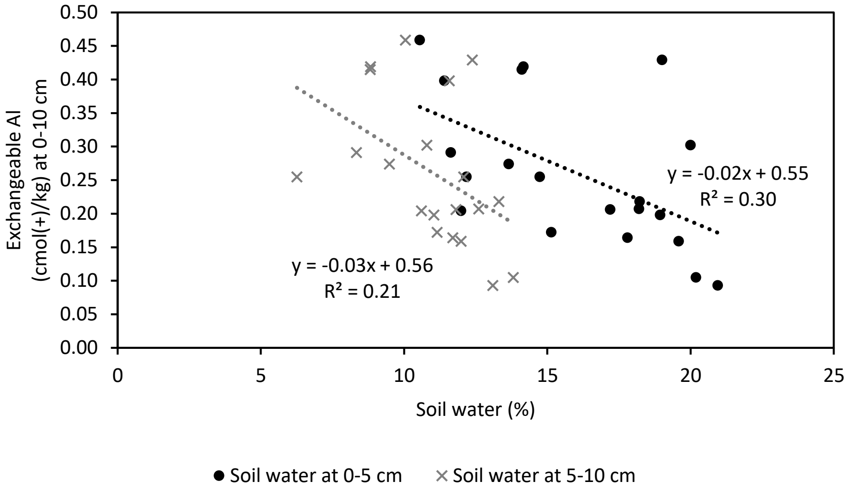


Figure 111. Relationship between soil exchangeable aluminium concentration (Al, cmol(+)/kg) at the 0-10 cm depth and soil water content (%, w/w) at the (a) 0-5 cm and (b) 5-10 cm depths during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

Soil exchangeable Ca concentrations at the 0-10 cm depth was positively correlated with soil EC at the 0-10 cm depth during pod development ($R^2 = 0.31$; $P < 0.05$; 143 DAS; Figure 112).

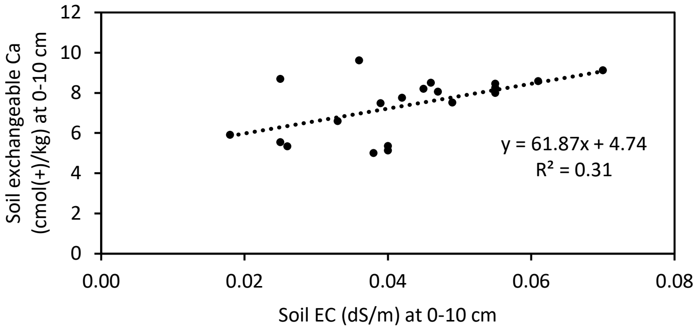


Figure 112. Relationship between soil electrical conductivity (dS/m) and soil exchangeable calcium concentration (Ca, cmol(+)/kg) at the 0-10 cm depth during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

Furthermore, soil exchangeable Ca and Mg concentrations were also positively correlated with soil pH_{Ca} at the 0-10 cm depth during canola stem elongation (R^2 = 0.34 and 0.23, respectively; $P < 0.01$) and pod development (R^2 = 0.31 and 0.47, respectively; $P < 0.05$; Figures 113 and 114, respectively).

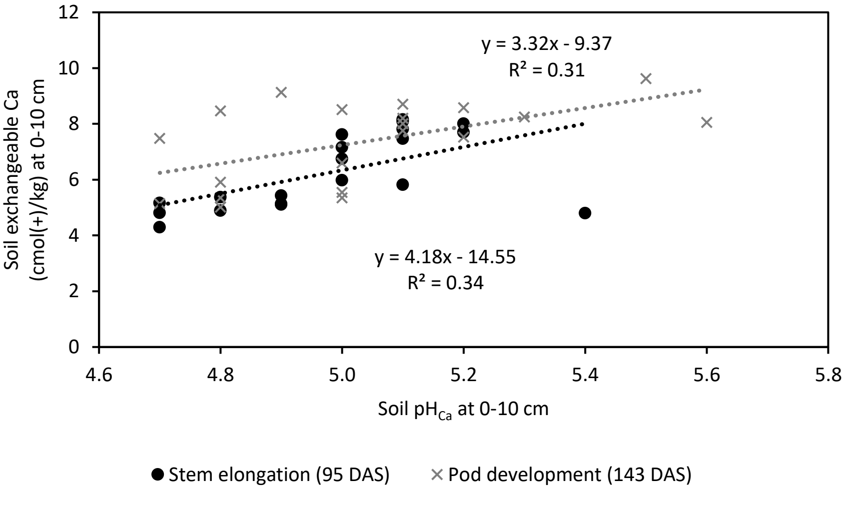


Figure 113. Relationship between soil pH_{Ca} ($CaCl_2$) and soil exchangeable calcium concentration (Ca, cmol(+)/kg) at the 0-10 cm depth in a Ferric Chromosol at Kojonup in 2016.

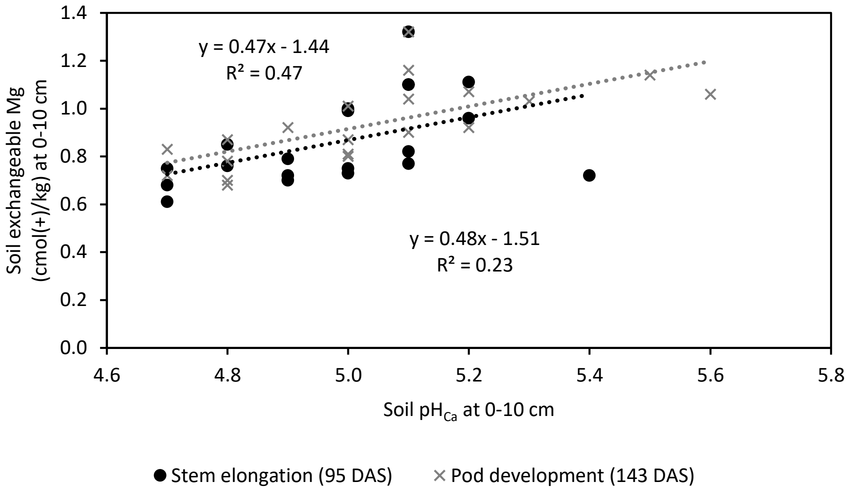


Figure 114. Relationship between soil pH$_{Ca}$ (CaCl$_2$) and soil exchangeable magnesium concentration (Mg, cmol(+)/kg) at the 0-10 cm depth in a Ferric Chromosol at Kojonup in 2016.

By contrast, soil NH$_4$-N concentrations were negatively correlated with soil pH$_{Ca}$ at the 0-10 cm depth during canola stem elongation ($R^2 = 0.33$; $P < 0.01$; 95 DAS; Figure 115), with soil Cu concentrations also negatively correlated with soil pH$_{Ca}$ at the 0-10 cm depth during canola pod development ($R^2 = 0.36$; $P < 0.01$; 143 DAS; Figure 116).

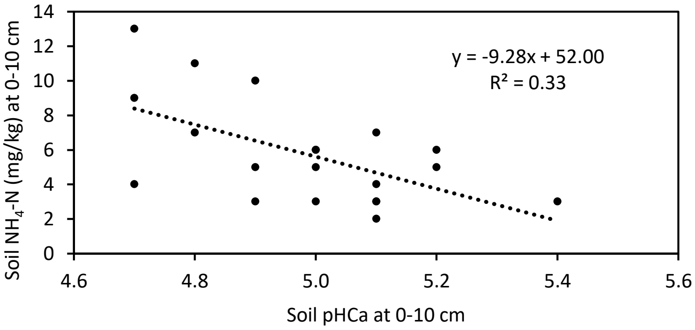


Figure 115. Relationship between soil pH$_{Ca}$ (CaCl$_2$) and soil ammonium-nitrogen concentration (NH$_4$-N, mg/kg) at the 0-10 cm depth during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

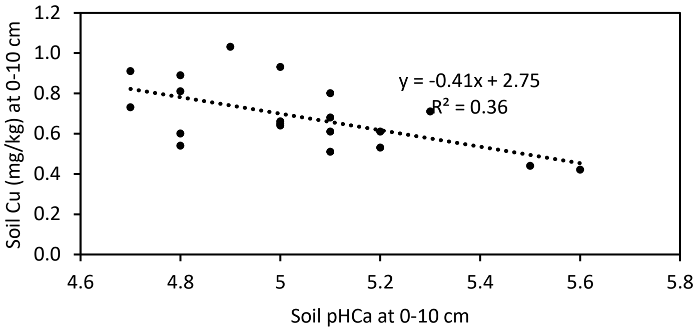


Figure 116. Relationship between soil pH_{Ca} ($CaCl_2$) and soil copper concentration (Cu, mg/kg) at the 0-10 cm depth during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

Soil NH_4-N, NO_3-N, Colwell K, S, OC, exchangeable K concentration, and exchangeable K percentage were also significantly affected by growth stage ($P < 0.05$; see Table 7 in Section 3.3.1). Soil NO_3-N, Colwell K, S, OC, exchangeable K concentration, and exchangeable K percentage significantly decreased from canola emergence (49.4 mg NO_3-N/kg, 187.0 mg K/kg, 11.2 mg S/kg, 3.98 % OC, 0.43 cmol(+) K/kg, and 4.70 % exchangeable K, respectively; 16 DAS) to stem elongation (11.0 mg NO_3-N/kg, 86.9 mg K/kg, 5.9 mg S/kg, 3.60 % OC, 0.18 cmol(+) K/kg, and 2.47 % exchangeable K, respectively; 95 DAS; Table 129), but remained relatively constant during pod development (143 DAS). Soil NH_4-N concentrations also significantly decreased from canola emergence (11.0 mg/kg; 16 DAS) to stem elongation (5.9 mg/kg; 95 DAS), but significantly increased again during pod development (9.4 mg/kg; 143 DAS; Table 129).

Table 129. Soil properties during different canola growth stages at Kojonup in 2016. Mean values based on a sample size of 20, except during the canola emergence where the sample size was 15. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Soil properties	Emergence (16 DAS)	Stem elongation (95 DAS)	Pod development (143 DAS)
Soil OC (%)	3.98^{a}	3.60^{b}	3.50^{b}
Soil NH_4-N (mg/kg)	11.0^{a}	5.9^{b}	9.4^{ab}
Soil NO_3-N (mg/kg)	49.4^{a}	11.0^{b}	10.5^{b}
Soil Colwell K (mg/kg)	187.0^{a}	86.9^{b}	106.9^{b}
Soil S (mg/kg)	11.2^{a}	5.9^{b}	6.2^{b}
Soil exchangeable K concentration (cmol(+)/kg)	0.43^{a}	0.18^{b}	0.22^{b}
Soil exchangeable K percentage (%)	4.70^{a}	2.47^{b}	2.48^{b}

B.1.2 Crop growth and yield parameters

Canola plant density at leaf production (53 DAS) was positively correlated with leaf RWC during stem elongation ($R^2 = 0.49$; $P < 0.01$; 95 DAS; Figure 117). Canola 1000-seed weight was also positively correlated with leaf RWC during canola anthesis ($R^2 = 0.42$; $P < 0.01$; 116 DAS) and pod development ($R^2 = 0.44$; $P < 0.01$; 143 DAS; Figure 118). By contrast, canola shoot dry matter and seed yield were negatively correlated with leaf RWC during canola anthesis ($R^2 = 0.27$ and 0.25, respectively; $P < 0.05$; 116 DAS; Figures 119a and b, respectively), with shoot dry matter and seed yield being closely, positively correlated ($R^2 = 0.98$; $P < 0.01$; 191 DAS; Figure 120).

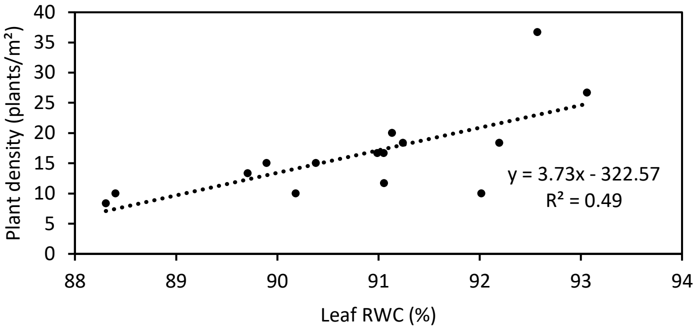


Figure 117. Relationship between canola leaf relative water content (RWC, %) during stem elongation (95 DAS) and plant density (plants/m^2) during leaf production (53 DAS) in a Ferric Chromosol at Kojonup in 2016.

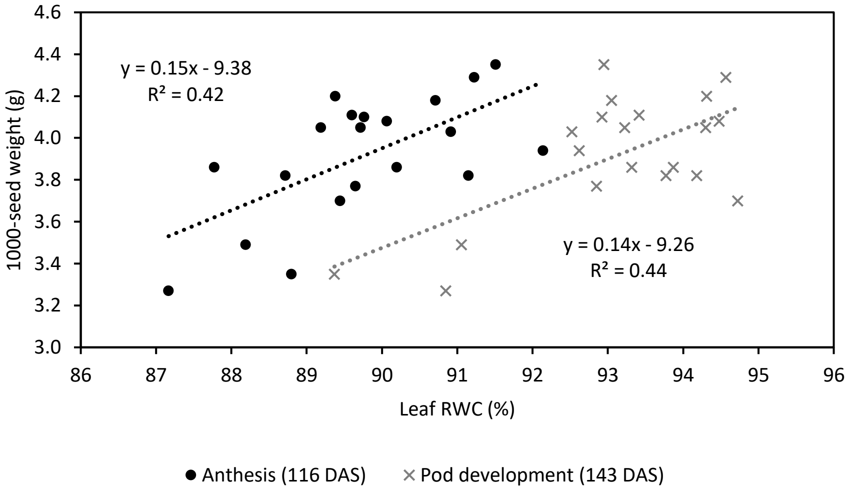


Figure 118. Relationship between canola 1000-seed weight (g) and leaf relative water content (RWC, %) during anthesis (116 DAS) and pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

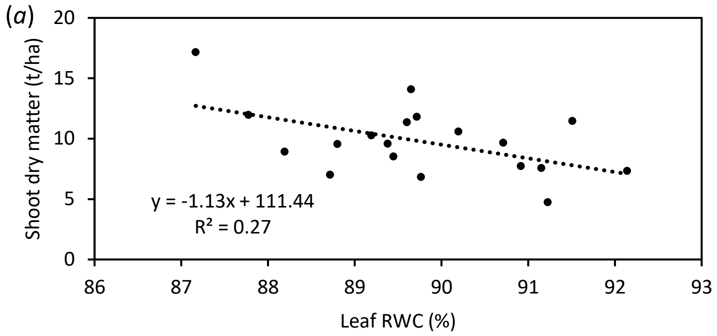


Figure 119. Relationship between canola leaf relative water content (RWC, %) during anthesis (116 DAS) and (a) shoot dry matter (t/ha) and (b) 1000-seed weight (g) at crop maturity (191 DAS) in a Ferric Chromosol at Kojonup in 2016.

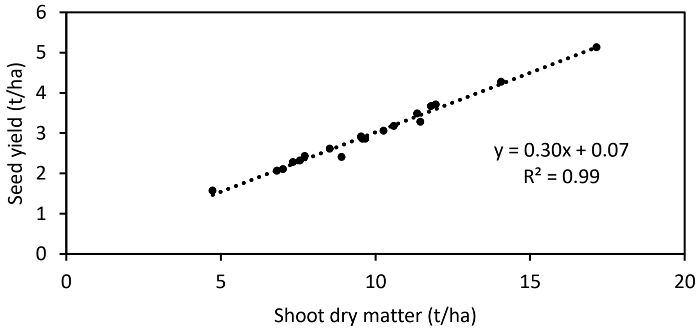


Figure 120. Correlation between canola shoot dry matter (t/ha) and seed yield (t/ha) at crop maturity (191 DAS) in a Ferric Chromosol at Kojonup in 2016.

B.1.3 Leaf nutrient concentrations

Leaf P concentrations were not correlated with soil water or gravel content (data not shown), but leaf P concentrations were positively correlated with soil Colwell P concentrations at the 0-10 cm depth during canola emergence ($R^2 = 0.22$; $P < 0.05$; 95 DAS; Figure 121) and stem elongation ($R^2 = 0.30$; $P < 0.05$; 95 DAS; Figure 122).

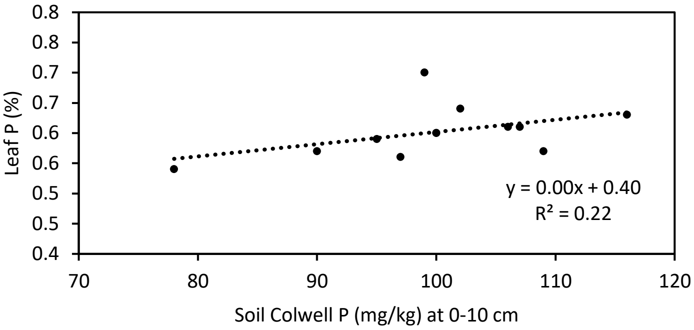


Figure 121. Relationship between soil Colwell phosphorus concentration (P, mg/kg) at the 0-10 cm depth during canola emergence (16 DAS) and canola leaf phosphorus concentration (P, %) during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

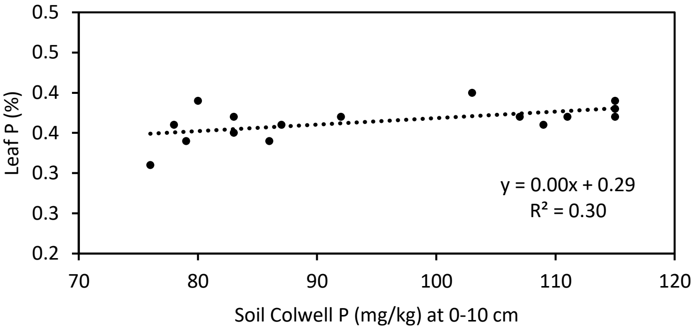


Figure 122. Relationship between soil Colwell phosphorus concentration (P, mg/kg) at the 0-10 cm depth during canola stem elongation (95 DAS) and canola leaf phosphorus concentration (P, %) during canola anthesis (116 DAS) in a Ferric Chromosol at Kojonup in 2016.

Likewise, leaf Ca concentrations were also negatively correlated with soil gravel content at the 0-5 cm depth ($R^2 = 0.31$; $P < 0.05$; 143 DAS; Figure 123) but positively correlated with soil water content at the 0-5 ($R^2 = 0.61$; $P < 0.01$) and 5-10 cm depths during canola pod development ($R^2 = 0.63$; $P < 0.01$; 143 DAS; Figure 124). Leaf Ca concentrations were also positively correlated with soil pH_{Ca} ($R^2 = 0.37$; $P < 0.01$; Figure 125) and soil exchangeable Ca concentrations and percentages at the 0-10 cm depth during canola pod development ($R^2 = 0.62$ and 0.40, respectively; $P < 0.01$; 143 DAS; Figure 126a and b, respectively).

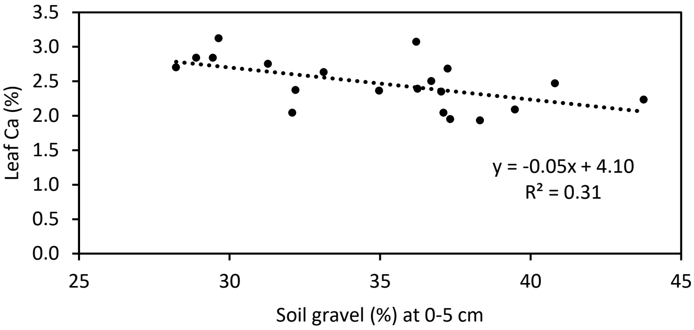


Figure 123. Relationship between soil gravel content (%, w/w) at the 0-5 cm depth and canola leaf calcium concentration (Ca, %) during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

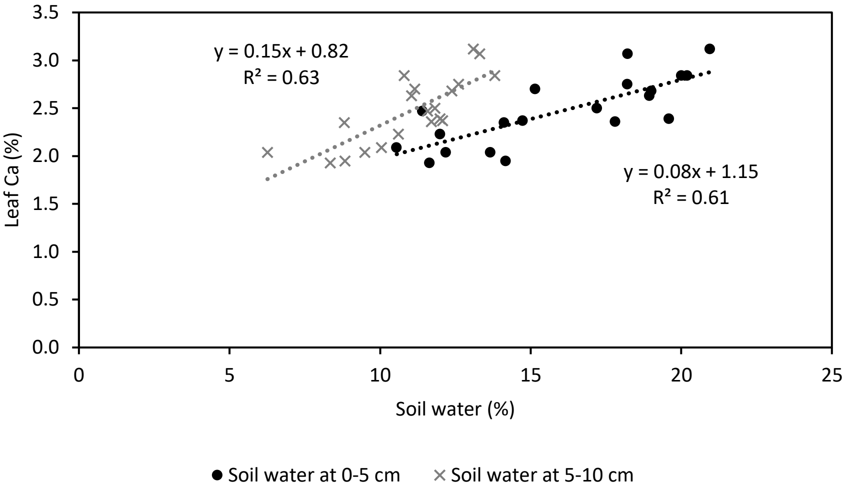


Figure 124. Relationship between canola leaf calcium concentration (Ca, %) and soil water content (%, w/w) at the 0-5 and 5-10 cm depths during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

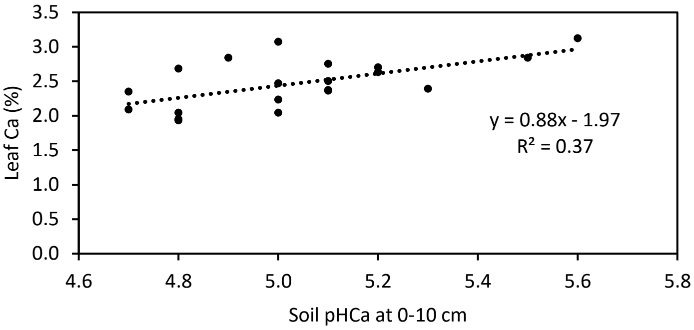


Figure 125. Relationship between canola leaf calcium concentration (Ca, %) and soil pH$_{Ca}$ (CaCl$_2$) at the 0-10 cm depth during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

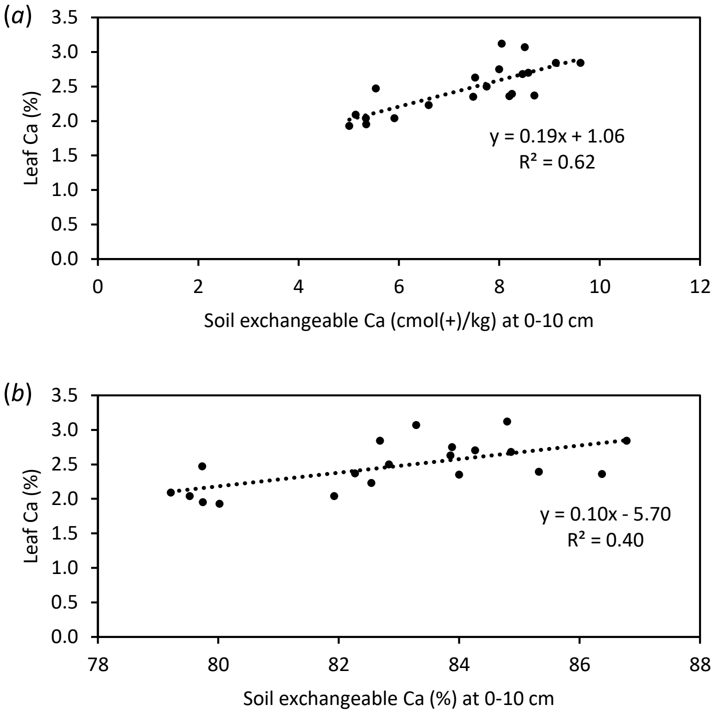


Figure 126. Relationship between canola leaf calcium concentration (Ca, %) and (a) soil exchangeable calcium concentration (Ca, cmol(+)/kg) and (b) soil exchangeable calcium percentage (Ca, %) at the 0-10 cm depth during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

Leaf Cu and Mn concentrations were also positively correlated with soil gravel content at the 0-5 cm depth during pod development (R^2 = 0.42 and 0.50, respectively;

$P < 0.01$; 143 DAS; Figures 127a and b, respectively), with leaf Fe and Mn concentrations also positively correlated with soil gravel content at the 0-5 cm depth during stem elongation ($R^2 = 0.32$ and 0.27, respectively; $P < 0.05$; 95 DAS; Figures 128a and b, respectively).

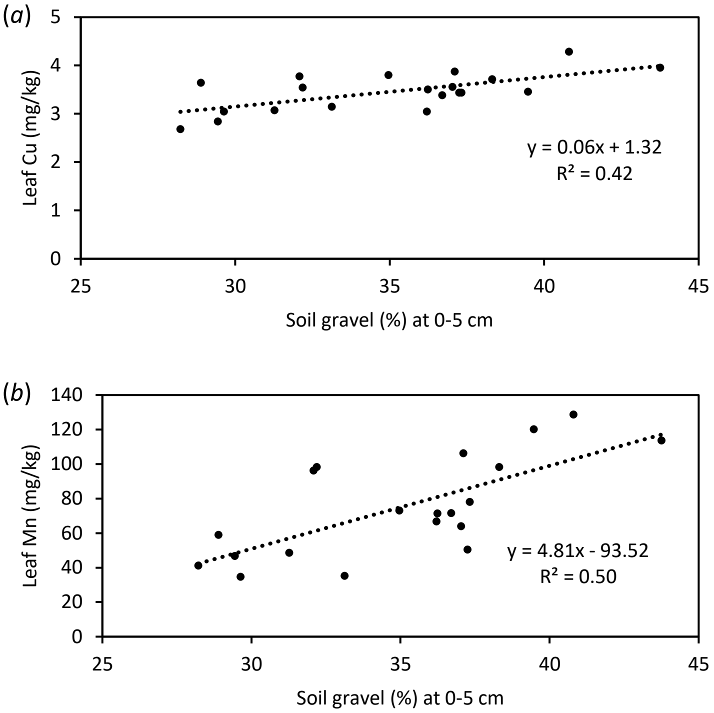


Figure 127. Relationship between soil gravel content (%, w/w) at the 0-5 cm depth and (a) canola leaf copper concentration (Cu, mg/kg) and (b) leaf manganese concentration (Mn, mg/kg) during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

By contrast, leaf Cu concentrations were negatively correlated with soil water content at the 0-5 ($R^2 = 0.32$; $P < 0.01$) and 5-10 cm depths during pod development ($R^2 = 0.22$; $P < 0.05$; 143 DAS; Figure 129). Leaf Fe concentrations were also negatively correlated with soil water content at the 0-5 ($R^2 = 0.44$; $P < 0.01$) and 5-10 cm depths during stem elongation ($R^2 = 0.34$; $P < 0.01$; 95 DAS; Figure 130) and to a lesser extent with soil water content at the 0-5 cm depth during anthesis ($R^2 = 0.23$; $P < 0.05$; 116 DAS; Figure 131). Leaf Mn concentrations were also negatively correlated with soil water content at the 0-5 cm depths during canola leaf production ($R^2 = 0.31$; $P < 0.05$; 53 DAS), stem elongation ($R^2 = 0.25$; $P < 0.05$; 95 DAS), anthesis ($R^2 = 0.29$; $P < 0.05$; 116 DAS), and pod development ($R^2 = 0.70$; $P < 0.01$; 143 DAS; Figure

132). Nevertheless, canola leaf Cu, Fe, and Mn concentrations were not correlated with canola yield parameters (data not shown).

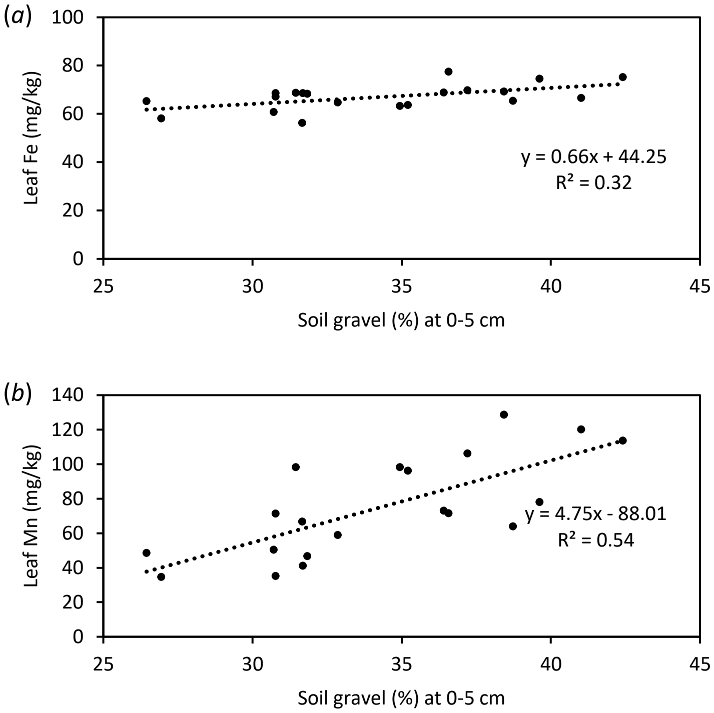


Figure 128. Relationship between soil gravel content (%, w/w) at the 0-5 cm depth and (a) canola leaf iron concentration (Fe, mg/kg) and (b) leaf manganese concentration (Mn, mg/kg) during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

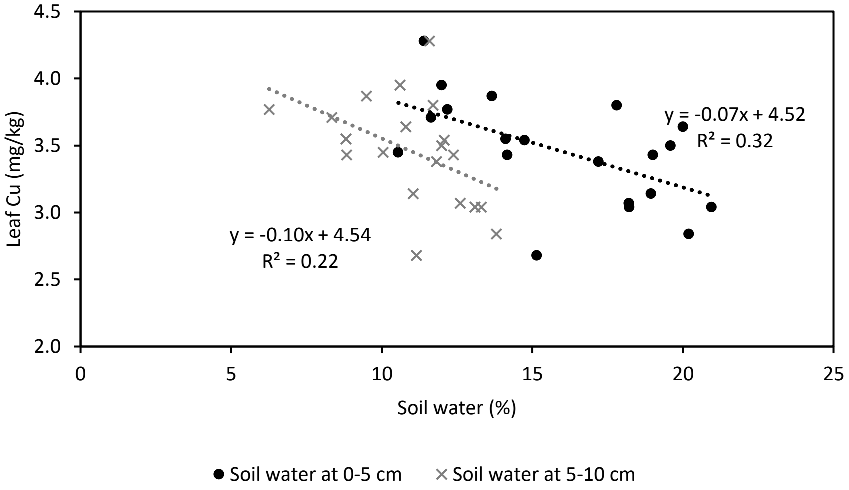


Figure 129. Relationship between canola leaf copper concentration (Cu, mg/kg) and soil water content (%, w/w) at the 0-5 and 5-10 cm depths during canola pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

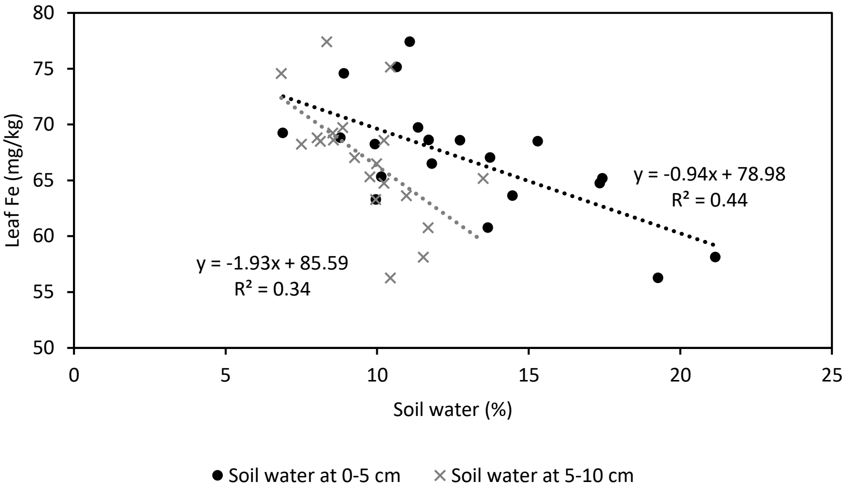


Figure 130. Relationship between canola leaf iron concentration (Fe, mg/kg) and soil water content (%, w/w) at the 0-5 and 5-10 cm depths during canola stem elongation (95 DAS) in a Ferric Chromosol at Kojonup in 2016.

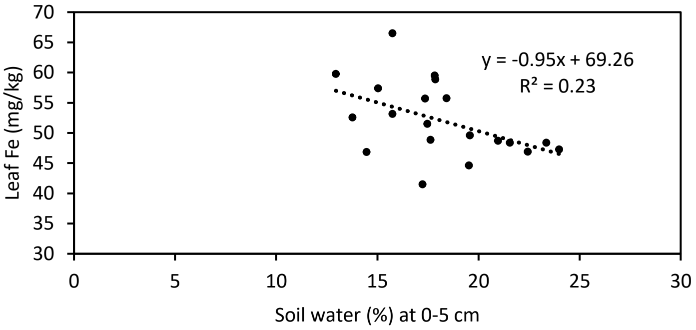


Figure 131. Relationship between canola leaf iron concentration (Fe, mg/kg) and soil water content (%, w/w) at the 0-5 cm depth during canola anthesis (116 DAS) in a Ferric Chromosol at Kojonup in 2016.

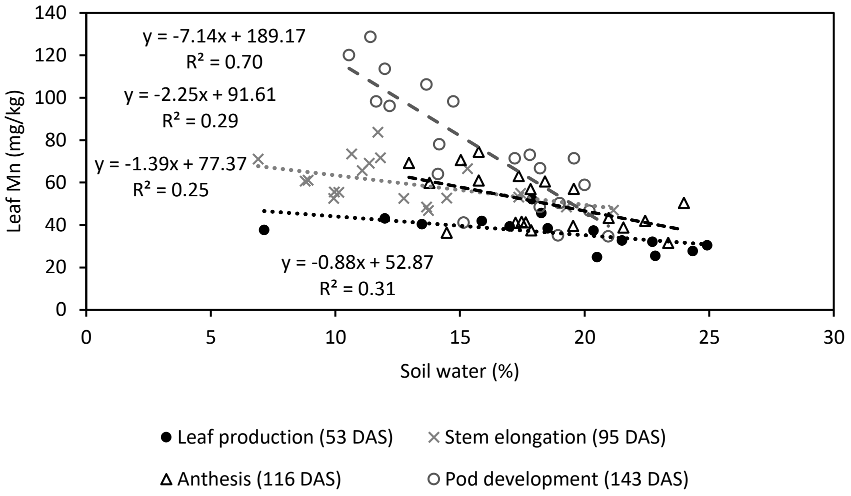


Figure 132. Relationship between canola leaf manganese concentration (Mn, mg/kg) and soil water content (%, w/w) at the 0-5 cm depth during canola leaf production (53 DAS), stem elongation (95 DAS), anthesis (116 DAS), and pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

By contrast, leaf Cu and Mn concentrations were negatively correlated with soil pH during canola stem elongation ($R^2 = 0.23$ and 0.56, respectively; $P < 0.05$; 95 DAS) and pod development ($R^2 = 0.25$ and 0.27, respectively; $P < 0.05$; 143 DAS; Figures 133a and b).

Leaf Mn concentrations were positively correlated with soil Mn concentrations during canola stem elongation ($R^2 = 0.49$; $P < 0.01$; 95 DAS) and pod development ($R^2 = 0.59$; $P < 0.01$; 143 DAS; Figure 134). However, leaf Cu and Fe concentrations were not correlated with soil Cu and Fe concentrations (data not shown).

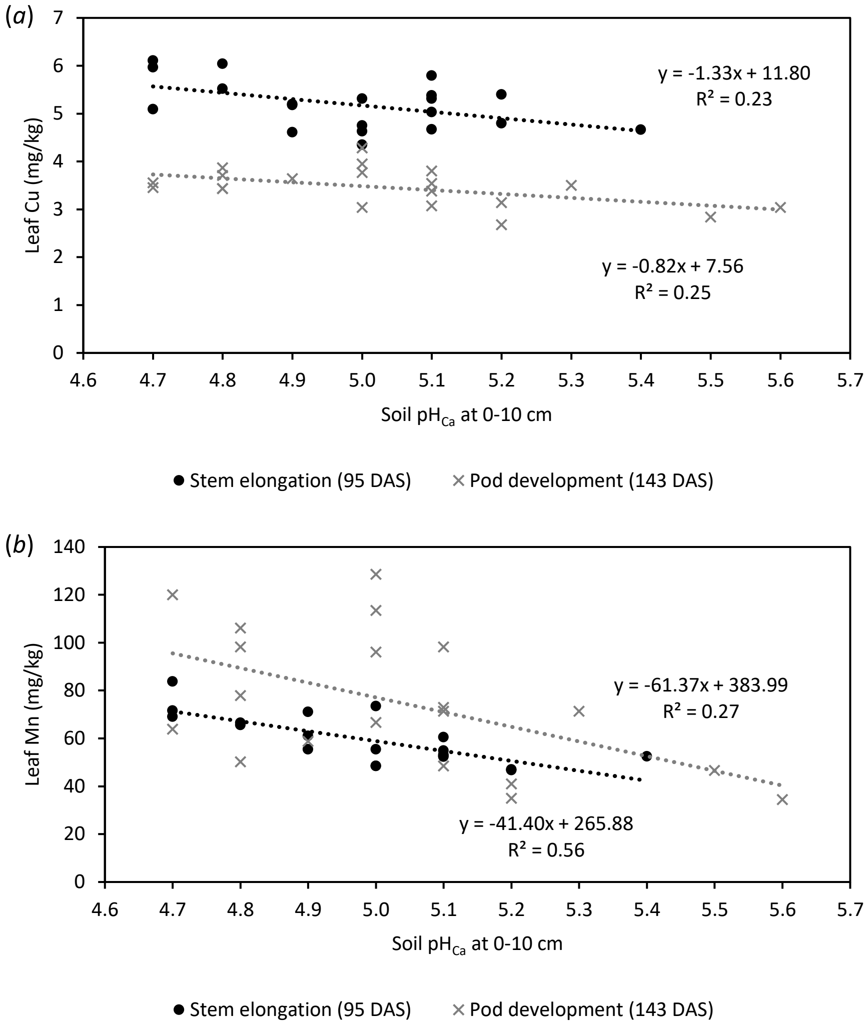


Figure 133. Relationship between soil pH_{Ca} ($CaCl_2$) at the 0-10 cm depth and (a) canola leaf copper concentration (Cu, mg/kg) and (b) leaf manganese concentration (Mn, mg/kg) during canola stem elongation (95 DAS) and pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

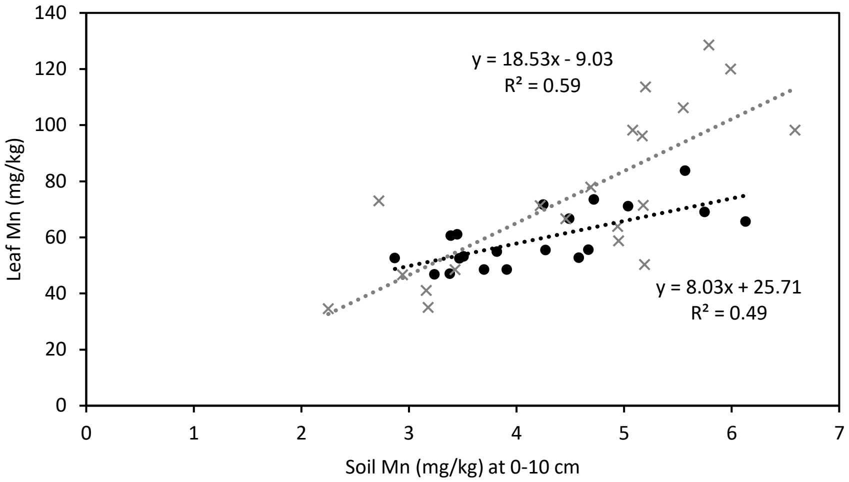


Figure 134. Relationship between soil manganese concentration (Mn, mg/kg) at the 0-10 cm and canola leaf \manganese concentration (Mn, mg/kg) during canola stem elongation (95 DAS) and pod development (143 DAS) in a Ferric Chromosol at Kojonup in 2016.

Canola leaf nutrient concentrations were significantly affected by growth stage ($P < 0.001$; see Table 11 in Section 3.3.1). Results showed that leaf N, P, Fe, and Zn concentrations significantly decreased from canola leaf production (5.87 % N, 0.79 % P, 84.8 mg Fe/kg, and 47.0 mg Zn/kg, respectively; 53 DAS) to anthesis (3.07 % N, 0.37 % P, 51.6 mg Fe/kg, and 17.4 mg Zn/kg, respectively; 116 DAS) and remained relatively constant thereafter (Table 130). Leaf K concentrations also significantly decreased from leaf production (4.64 %; 53 DAS) to stem elongation (2.98 %; 95 DAS) but significantly increased during anthesis (3.33 %; 116 DAS) before decreasing again during pod development (2.97 %; 143 DAS; Table 130). Leaf Ca concentrations significantly decreased from canola leaf production (1.27 % Ca; 53 DAS) to stem elongation (1.08 %; 95 DAS) but significantly increased thereafter to pod development (2.57 %; 143 DAS; Table 130). Leaf Mg concentrations were relatively constant from canola leaf production (0.31 %; 53 DAS) to anthesis (0.26 %; 116 DAS) but significantly increased thereafter during pod development (0.53 %; 143 DAS; Table 130). Leaf S and B concentrations significantly increased from leaf production (0.70 % S and 22.2 mg B/kg, respectively; 53 DAS) to pod development (1.41 % S and 56.8 mg B/kg, respectively; 143 DAS; Table 130). Leaf Na concentrations significantly decreased from leaf production (0.17 %; 53 DAS) to stem elongation (0.05 %; 95 DAS) and remained relatively constant thereafter (Table 130). Leaf Cl concentrations also significantly decreased from leaf production (0.79 %; 53 DAS) to stem elongation (0.52 %; 95 DAS) before significantly increasing during anthesis (0.96 %; 116 DAS) and remaining constant thereafter (Table 130). Leaf Cu concentrations significantly increased from canola leaf production (4.76 mg Cu/kg; 53 DAS) to stem elongation (5.37 mg Cu/kg; 95 DAS) before decreasing during anthesis (3.53 mg Cu/kg; 116 DAS) and remaining relatively constant thereafter (Table 130). Leaf Mn concentrations also significantly increased from canola leaf production (39.0 mg Mn/kg; 53 DAS) to stem elongation (63.3 mg Mn/kg; 95 DAS) and remained relatively constant thereafter (Table 130).

Table 130. Leaf nutrient concentrations during different growth stages in canola at Kojonup. Mean values based on a sample size of 20, except during the canola emergence and leaf production stages where the sample size was 15. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Leaf nutrient concentration	Leaf production (53 DAS)	Stem elongation (95 DAS)	Anthesis (116 DAS)	Pod development (143 DAS)
N (%)	5.87^{a}	4.74^{b}	3.07^{c}	3.09^{c}
P (%)	0.79^{a}	0.63^{b}	0.37^{c}	0.40^{c}
K (%)	4.64^{a}	2.98^{b}	3.33^{c}	2.97^{b}
Ca (%)	1.27^{ab}	1.08^{b}	1.27^{a}	2.57^{c}
Mg (%)	0.31^{a}	0.30^{a}	0.26^{a}	0.53^{b}
S (%)	0.70^{a}	0.81^{b}	0.86^{b}	1.41^{c}
Na (%)	0.17^{a}	0.05^{b}	0.04^{b}	0.05^{b}
Cl (%)	0.79^{a}	0.52^{b}	0.96^{a}	0.88^{a}
B (mg/kg)	22.2^{a}	28.5^{b}	36.8^{c}	56.8^{d}
Cu (mg/kg)	4.76^{a}	5.37^{b}	3.53^{c}	3.34^{c}
Fe (mg/kg)	84.8^{a}	67.5^{b}	51.6^{c}	55.8^{c}
Mn (mg/kg)	39.0^{a}	63.3^{bc}	47.7^{ac}	65.8^{b}
Zn (mg/kg)	47.0^{a}	32.8^{b}	17.4^{c}	19.3^{c}

B.2 Meckering

B.2.1 Soil chemical properties

Soil Cu and exchangeable Mg concentrations and percentages were not correlated with soil water content (data not shown). However, soil Cu concentrations were positively correlated with soil OC at the 0-10 cm depth during wheat booting ($R^2 = 0.27$; $P < 0.05$; 100 DAS; Figure 135).

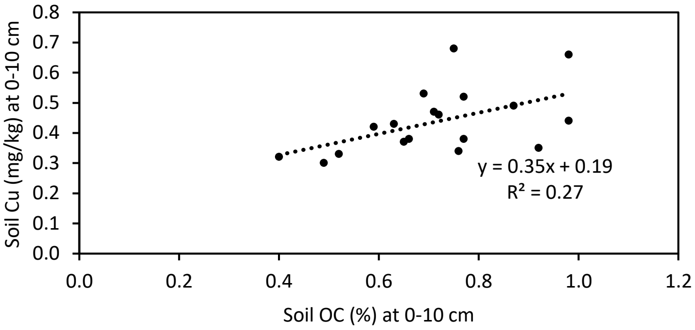


Figure 135. Relationship between soil organic carbon content (OC, %) and soil copper concentration (Cu, mg/kg) at the 0-10 cm depth during wheat booting (100 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Soil S, exchangeable Ca, and exchangeable Na concentrations were positively correlated with soil ECEC during wheat emergence (R^2 = 0.40, 0.98, and 0.69, respectively; $P < 0.01$; 22 DAS; Figures 136a-c).

Soil Fe concentrations were positively correlated with soil water content at the 0-5 and 5-10 cm depths during wheat emergence ($R^2 = 0.45$; $P < 0.01$; 22 DAS; Figure 137).

Soil NH_4-N, NO_3-N, Colwell P, Colwell K, S, EC, pH_{Ca}, Fe, exchangeable K and Na concentrations, and exchangeable K and Na percentages were significantly affected by growth stage ($P < 0.05$; see Table 16 Section 3.3.2). Soil EC, NO_3-N, Colwell P, S, and Fe concentrations significantly decreased from wheat emergence (0.05 dS/m, 15.0 mg NO_3-N/kg, 21.0 mg P/kg, 3.06 mg S/kg, and 10.6 mg Fe/kg, respectively; 22 DAS) to booting (0.03 dS/m, 2.0 mg NO_3-N/kg, 14.9 mg P/kg, 2.02 mg S/kg, and 9.1 mg Fe/kg, respectively; 100 DAS; Table 131) but remained relatively constant during grain development (134 DAS). Soil Colwell K and exchangeable K also significantly decreased from wheat emergence (35.0 mg K/kg, 0.06 cmol(+) K/kg, and 2.52 % K, respectively; 22 DAS) to booting (24.5 mg K/kg, 0.04 cmol(+) K/kg, and 1.50 % K, respectively; 100 DAS; Table 131), with soil Colwell K concentrations also significantly increasing again during grain development (35.9 mg/kg; 134 DAS). By contrast, soil pH_{Ca}, exchangeable Na concentration, and exchangeable Na percentage significantly increased from wheat emergence (pH_{Ca} 5.9, 0.01 cmol(+) Na/kg, and 0.37 % Na, respectively; 22 DAS) to booting (pH_{Ca} 6.3, 0.02 cmol(+)

Na/kg, and 0.70 % Na, respectively; 22 DAS; Table 131) but remained relatively constant during grain development (134 DAS). Soil NH_4-N concentrations also significantly increased from wheat emergence (2.08 mg/kg; 22 DAS) to booting (4.32 mg/kg; 100 DAS) but significantly decreased thereafter during grain development (1.05 mg/kg; 134 DAS; Table 131).

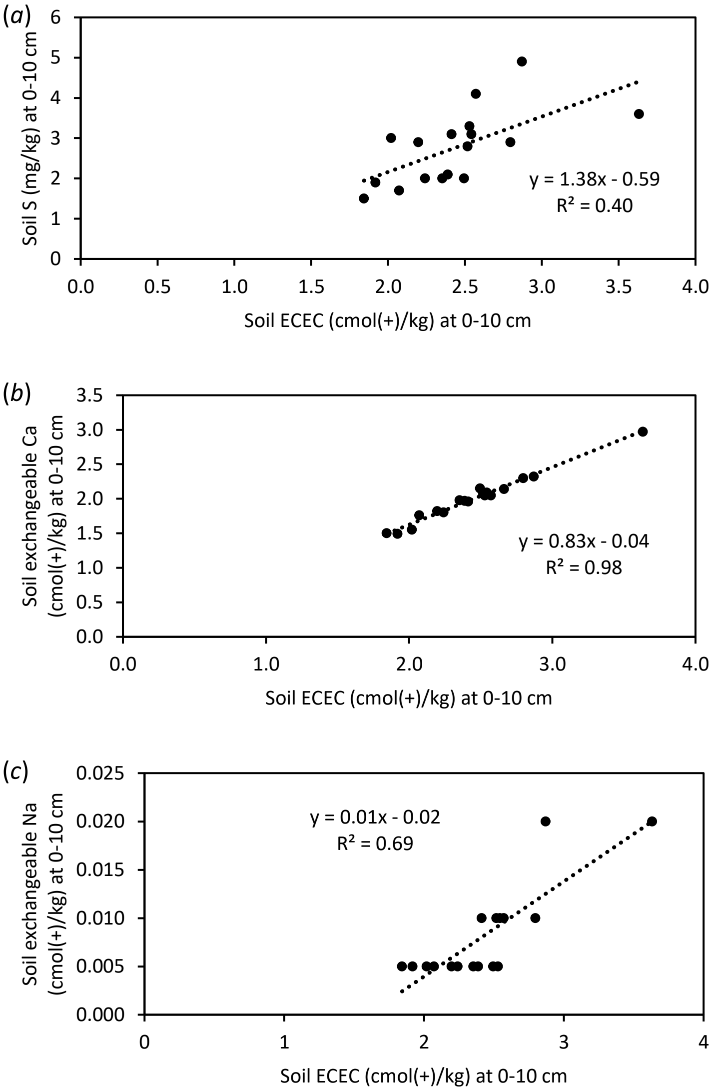


Figure 136. Relationship between soil effective cation exchange capacity (ECEC, cmol(+)/kg) and (a) soil sulphur concentration (S, mg/kg), (b) soil exchangeable calcium concentration (Ca, cmol(+)/kg), and (c) soil exchangeable sodium concentration (Na, cmol(+)/kg) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

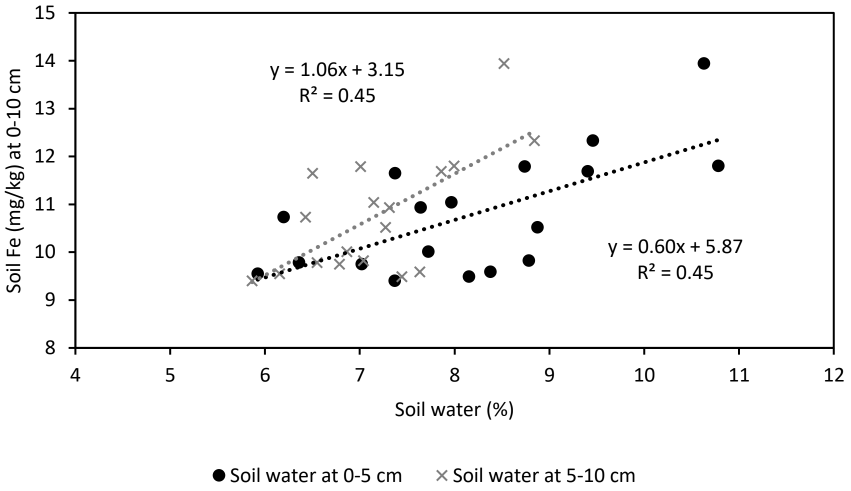


Figure 137. Relationship between soil water content (%, w/w) at the 0-5 and 5-10 cm depths and soil iron concentration (Fe, mg/kg) at the 0-10 cm depth during wheat emergence (22 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Table 131. Soil properties during different wheat growth stages at Meckering. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at P < 0.05.

Soil properties	Emergence (22 DAS)	Booting (100 DAS)	Grain development (134 DAS)
Soil EC (dS/m)	0.05^a	0.03^b	0.02^b
Soil pH_{Ca}	5.9^a	6.3^b	6.1^b
Soil NH_4-N (mg/kg)	2.08^a	4.32^b	1.05^c
Soil NO_3-N (mg/kg)	15.0^a	2.0^b	1.2^b
Soil Colwell P (mg/kg)	21.0^a	14.9^b	15.3^b
Soil Colwell K (mg/kg)*	35.0^a	24.5^b	35.9^a
Soil S (mg/kg)*	3.06^a	2.02^b	2.42^b
Soil Fe (mg/kg)	10.6^a	9.1^b	8.6^b
Soil exchangeable K concentration (cmol(+)/kg)	0.06^a	0.04^b	0.06^{ab}
Soil exchangeable Na concentration (cmol(+)/kg)	0.01^a	0.02^b	0.02^b
Soil exchangeable K percentage (%)	2.52^a	1.50^b	1.98^{ab}
Soil exchangeable Na percentage (%)	0.37^a	0.70^b	0.72^b

* Below critical levels (GRDC 2014b).

B.2.2 Crop growth and yield parameters

In general, wheat growth and yield parameters were positively correlated with one another, especially between wheat head density, shoot dry matter, and grain yield ($0.36 \leq R^2 \leq 0.99$; $P < 0.05$; Figures 138a-f).

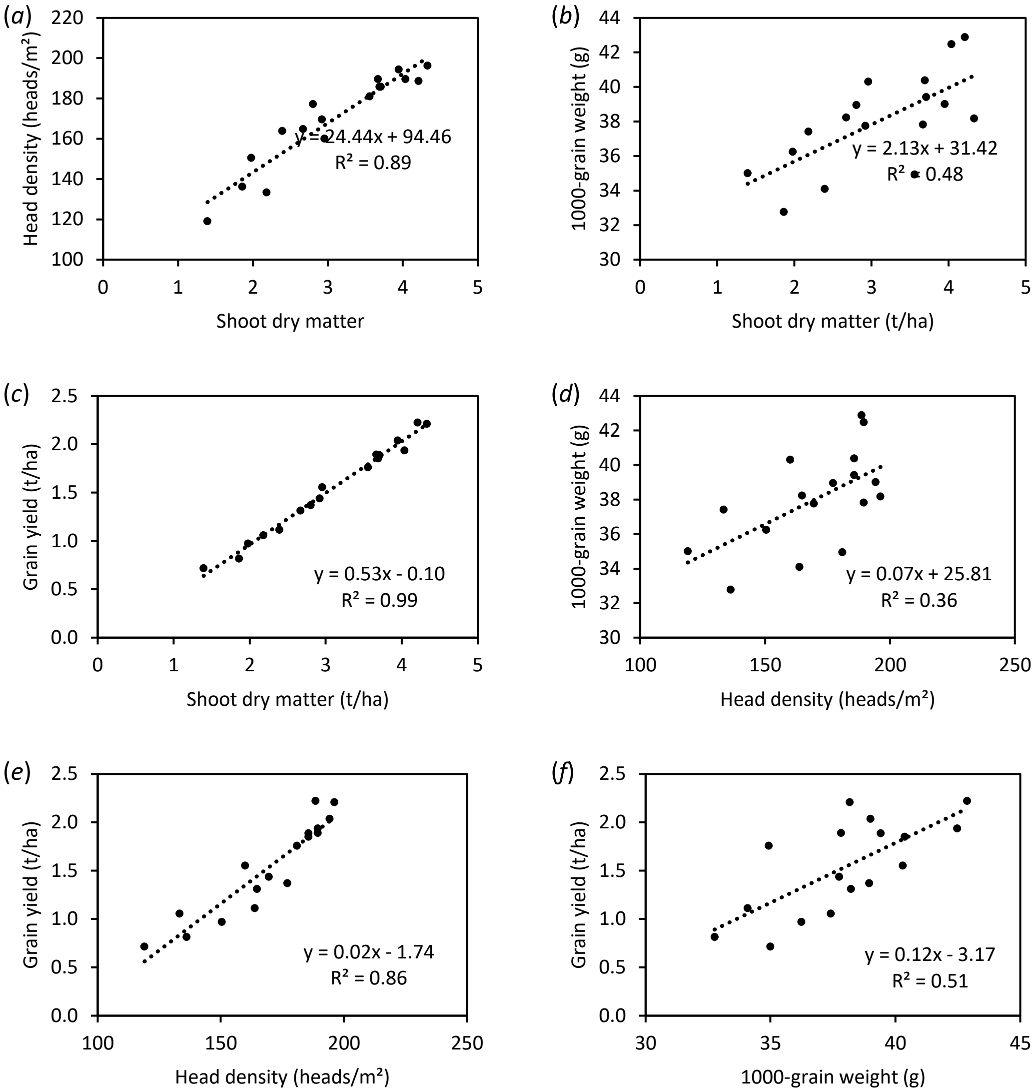


Figure 138. Correlation between wheat head density (heads/m^2), shoot dry matter (t/ha), 1000-grain weight (g), and grain yield (t/ha) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

B.2.3 Leaf nutrient concentrations

Wheat leaf Cu, Mn, and Zn concentrations were significantly affected by soil water repellence severity class ($P < 0.05$; see Table 20 Section 3.3.2), whereby leaf Cu, Mn, and Zn concentrations were significantly greater in Class 2 (moderately repellent) soils (5.34 mg Cu/kg, 87.6 mg Mn/kg, and 20.6 mg Zn/kg, respectively) than in Class 1 (negligible/slightly repellent) soils (4.31 mg Cu/kg, 69.2 mg Mn/kg, and 19.2 mg Zn/kg, respectively; Table 132). However, there was no significant interaction of growth stage × soil water repellence severity class.

Table 132. Effect of soil water repellence severity class on leaf Cu, Mn, and Zn concentrations in wheat at Meckering. Mean values based on an average sample size of 27 (unequal sample sizes). Significant differences based on the least significant difference (LSD) at P < 0.05.

Leaf nutrient concentration	Class 1 (negligible/slight)	Class 2 (moderate)
Leaf Cu (mg/kg)	4.31^a	5.34^b
Leaf Mn (mg/kg)	69.2^a	87.6^b
Leaf Zn (mg/kg)	19.2^a	20.6^b

Bivariate correlation analysis also showed that leaf Cu and Zn concentrations were positively correlated with soil water repellence severity at the 0-5 cm depth during wheat tillering ($R^2 = 0.35$ and 0.25, respectively; $P < 0.05$; Figures 139a and b, respectively), but correlations between leaf Mn and soil water repellence severity were not observed (data not shown). Leaf Cu, Mn, and Zn concentrations were, however, negatively correlated with soil water content at the 0-5 cm depth during wheat tillering ($R^2 = 0.44$, 0.40, and 0.27, respectively; $P < 0.05$; 64 DAS) and booting stages ($R^2 = 0.36$, 0.31, and 0.36, respectively; $P < 0.05$; 100 DAS; Figures 140a-c), with leaf Mn concentrations also negatively correlated with soil water content at the 0-5 cm depth during wheat anthesis ($R^2 = 0.41$; $P < 0.01$; 113 DAS). Leaf Cu concentrations during wheat tillering (64 DAS) were also negatively correlated with soil Cu concentrations at the 0-10 cm depth during wheat emergence ($R^2 = 0.36$; $P < 0.05$; 22 DAS; Figure 141), while leaf Mn concentrations were positively correlated with soil Mn concentrations during wheat booting ($R^2 = 0.68$; $P < 0.01$; 100 DAS; Figure 142). However, leaf Zn concentrations were not correlated with soil Zn concentrations (data not shown).

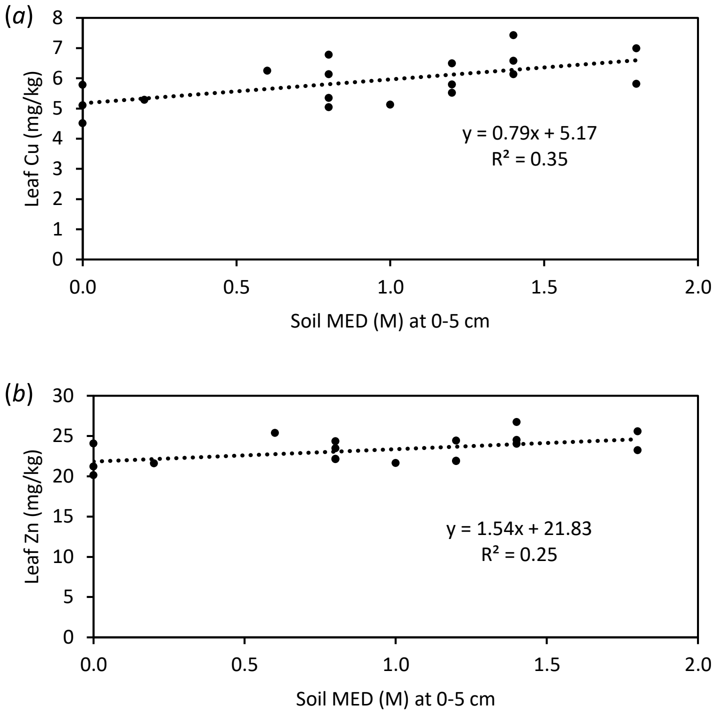


Figure 139. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and (a) wheat leaf copper concentration (Cu, mg/kg) and (b) leaf zinc concentration (Zn, mg/kg) during wheat tillering (64 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

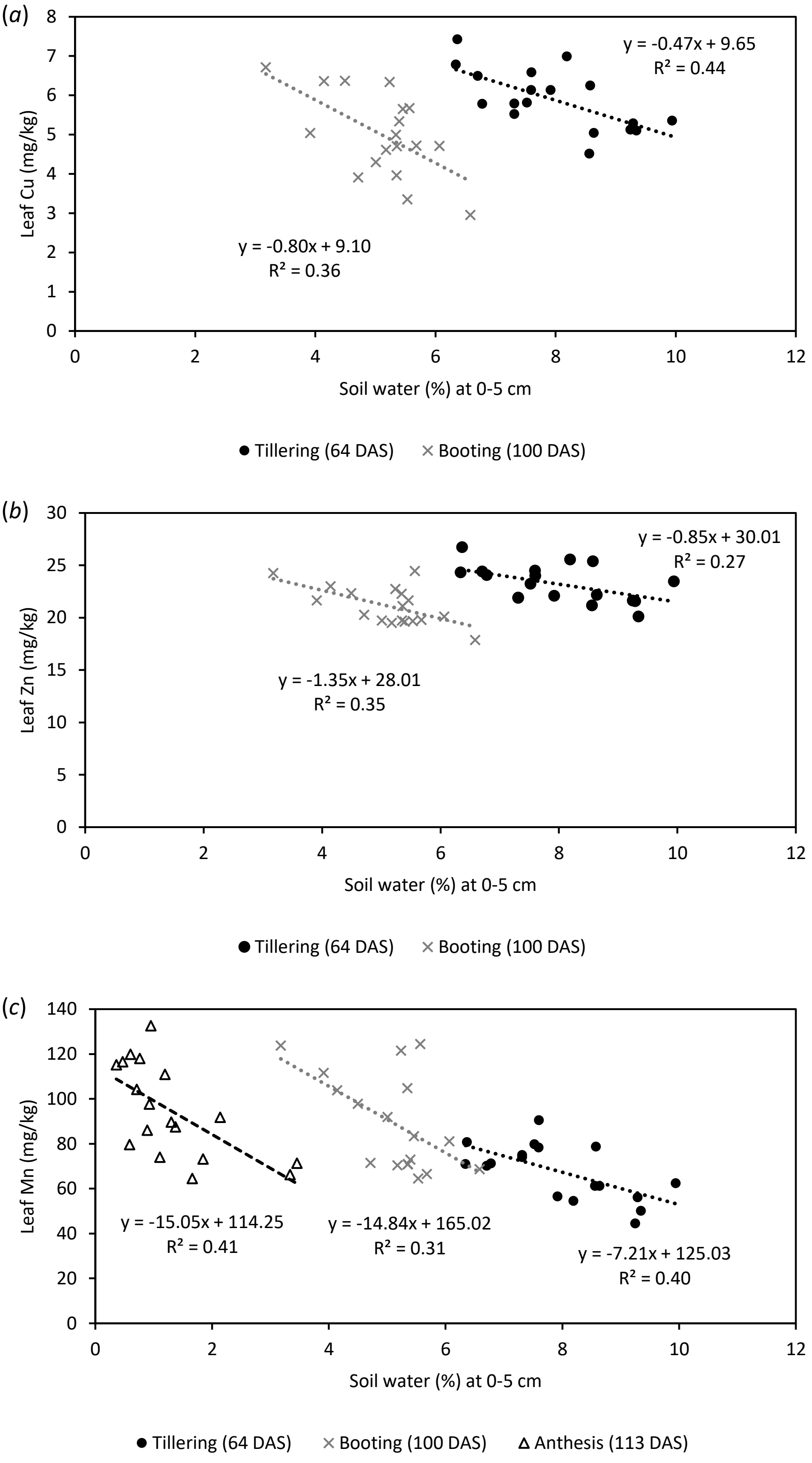


Figure 140. Relationship between soil water content (%, w/w) at the 0-5 cm depth and (a) wheat leaf copper concentration (Cu, mg/kg), (b) leaf zinc concentration (Zn, mg/kg), and (c) leaf manganese concentration (Mn, mg/kg) during wheat tillering (64 DAS), booting (100 DAS), and/or anthesis (113 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

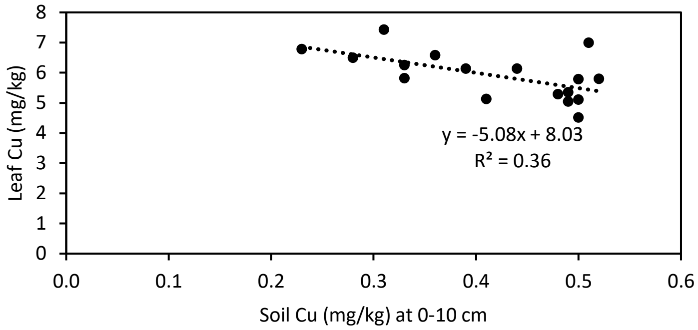


Figure 141. Relationship between soil copper concentration (Cu, mg/kg) at the 0-10 cm depth during wheat emergence (22 DAS) and wheat leaf copper concentration (Cu, mg/kg) wheat tillering (64 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

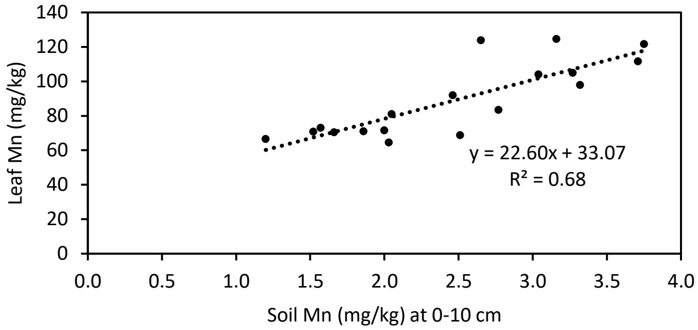


Figure 142. Relationship between soil manganese concentration (Mn, mg/kg) at the 0-10 cm depth and wheat leaf manganese concentration (Mn, mg/kg) during wheat booting (100 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Leaf Ca and Mg concentrations were positively correlated with soil water repellence severity at the 0-5 cm depth during wheat tillering (R^2 = 0.29 and 0.48, respectively; $P < 0.05$; 64 DAS; Figures 143b and c, respectively).

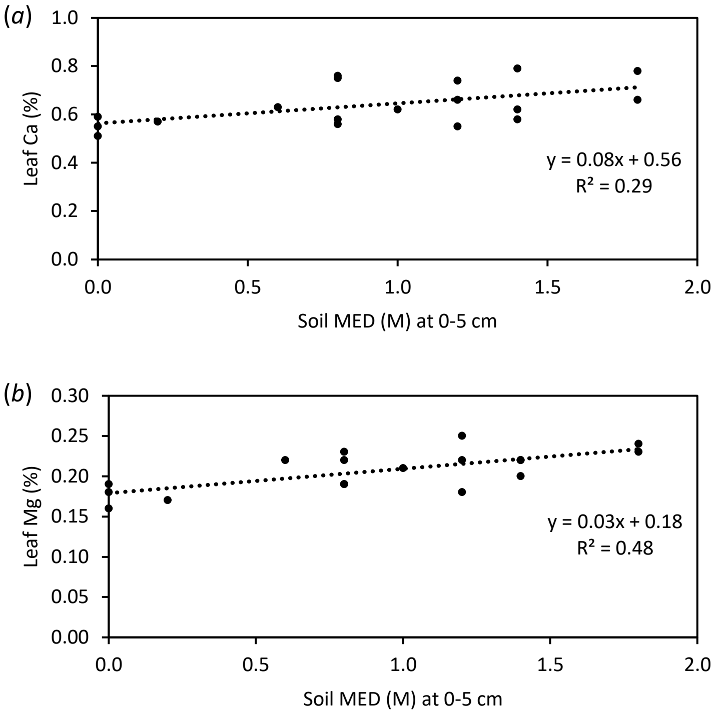


Figure 143. Relationship between soil water repellence severity (MED, M) at the 0-5 cm depth and (a) wheat calcium concentration (Ca, %) and (b) leaf magnesium concentration (Mg, %) during wheat tillering (64 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Leaf Ca and Mg concentrations were negatively correlated with soil water content at the 0-5 cm depth during wheat tillering (R^2 = 0.25 and 0.27, respectively; $P < 0.05$; 64 DAS; Figures 144b and c, respectively). However, leaf Ca and Mg concentrations were not correlated with soil exchangeable Ca and Mg concentrations at the 0-10 cm depth, respectively (data not shown). Concentrations of other nutrients in wheat leaf tissue were not correlated with soil water content or their respective soil nutrient concentrations at the 0-10 cm depth (data not shown).

Leaf Ca concentrations during wheat tillering and anthesis were negatively correlated with wheat shoot dry matter (R^2 = 0.35; $P < 0.05$; Figure 145a), 1000-grain weight (R^2 = 0.31 and 0.27, respectively; $P < 0.05$; Figure 145b), and grain yield (R^2 = 0.34 and 0.36, respectively; $P < 0.05$; Figure 145c). Leaf Cu concentrations during wheat anthesis were also negatively correlated with shoot dry matter (R^2 = 0.30; $P < 0.05$; Figure 146a), 1000-grain weight (R^2 = 0.30; $P < 0.05$; Figure 146b), and grain yield (R^2 = 0.31; $P < 0.05$; Figure 146c). Wheat leaf Mg, Mn, and Zn concentrations were not correlated with wheat yield parameters (data not shown). Interestingly, wheat leaf K concentrations were found to be negatively correlated with leaf Ca ($0.78 \leq R^2 \leq 0.88$; $P < 0.01$; no data shown), Mg ($0.71 \leq R^2 \leq 0.82$; $P < 0.01$; no data shown), and Cu concentrations throughout the tillering, booting, and anthesis stages ($0.57 \leq R^2 \leq 0.68$; $P < 0.01$; 64-113 DAS; no data shown), and also negatively correlated with leaf Mn ($R^2 = 0.34$; $P < 0.05$; no data shown) and Zn concentrations during wheat booting ($R^2 = 0.34$; $P < 0.05$; 100 DAS; no data shown). Note, these correlations suggest that changes in leaf Ca, Mg, Cu, Mn, and Zn concentrations were likely attributed to growth dilution as a result of increasing leaf K.

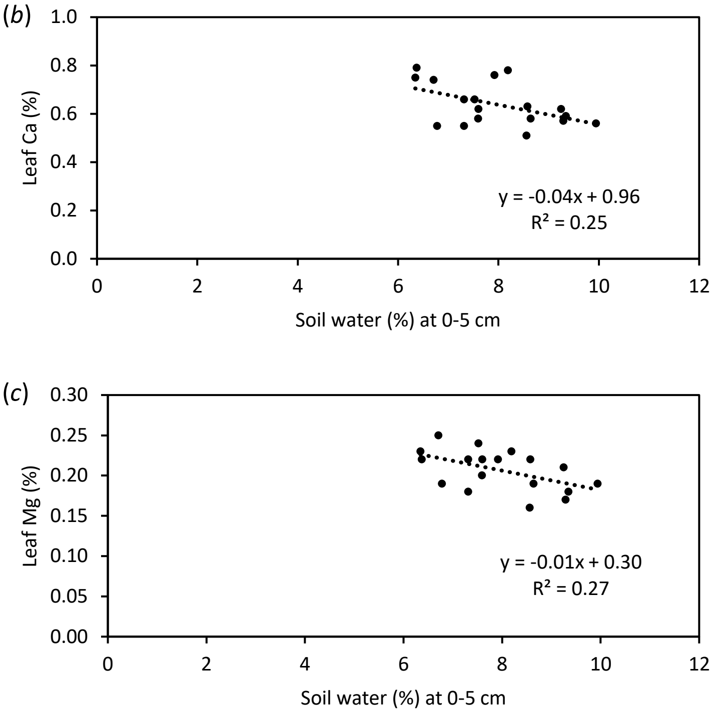


Figure 144. Relationship between soil water content (%, w/w) at the 0-5 cm depth and (a) wheat leaf calcium concentration (Ca, %) and (b) leaf magnesium concentration (Mg, %) during wheat tillering (64 DAS) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

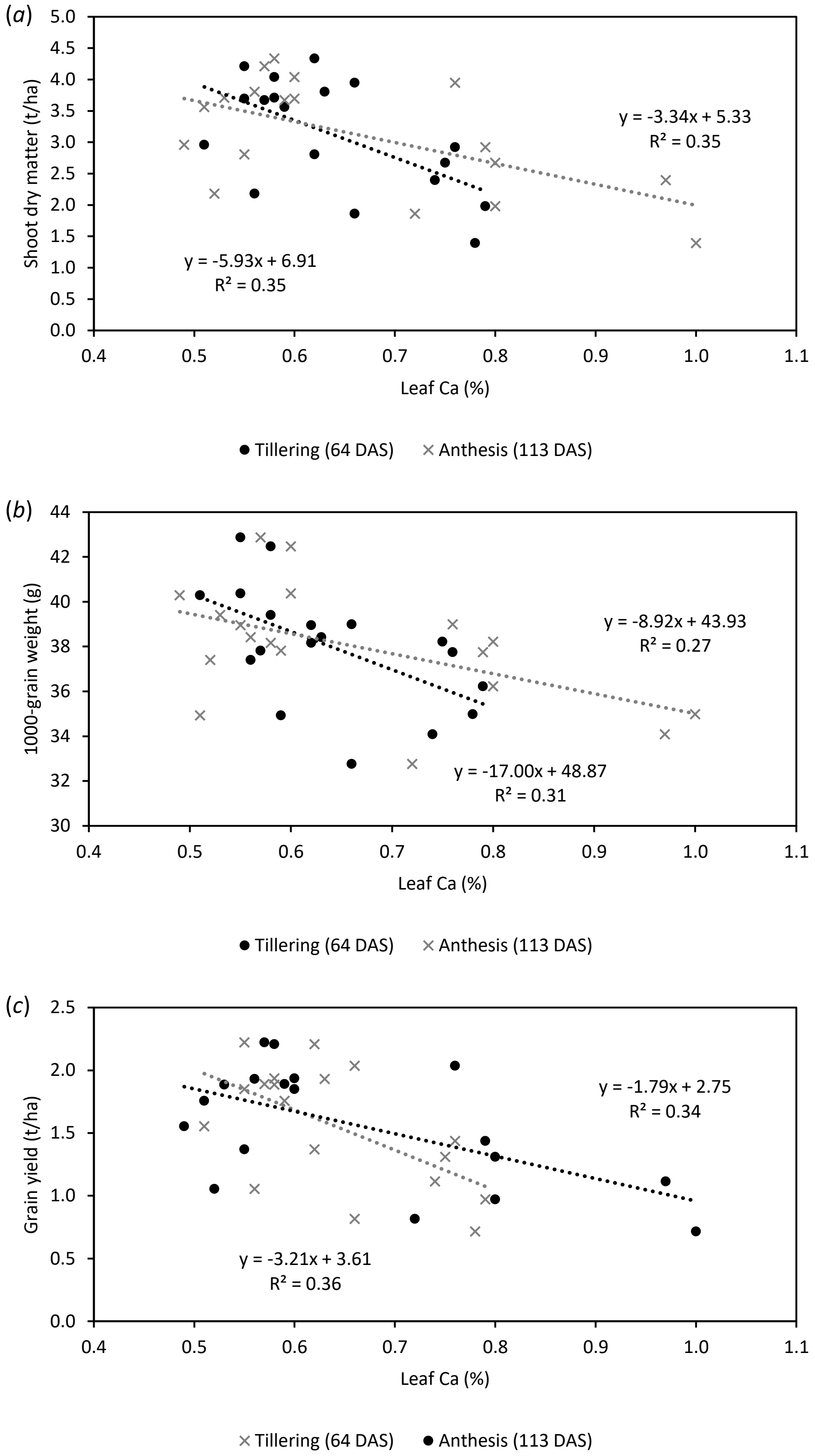


Figure 145. Relationship between wheat leaf calcium concentration (Ca, %) during wheat tillering (64 DAS) and anthesis (113 DAS) and (a) wheat shoot dry matter (t/ha), (b) 1000-grain weight (g), and (c) grain yield (t/ha) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

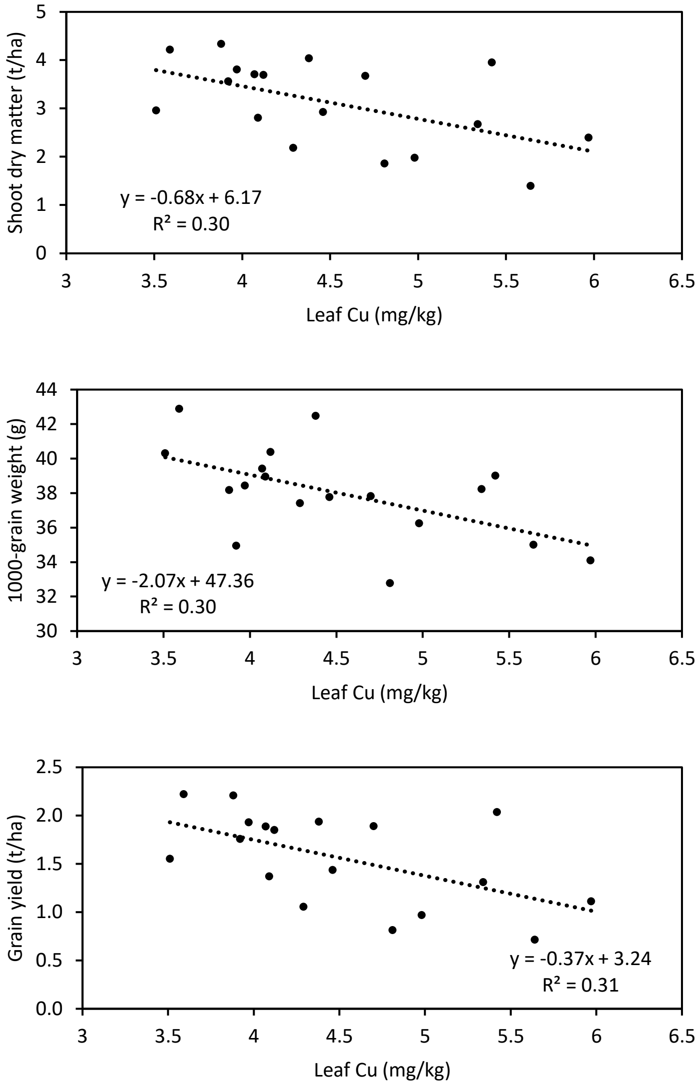


Figure 146. Relationship between wheat leaf copper concentration (Cu, mg/kg) during wheat anthesis (113 DAS) and (a) wheat shoot dry matter (t/ha), (b) 1000-grain weight (g), and (c) grain yield (t/ha) in a Grey Bleached-Ferric Kandosol at Meckering in 2016.

Concentrations of all nutrients (except K and Fe) in young, fully matured wheat leaves were significantly affected by growth stage ($P < 0.05$; see Table 20 in Section 3.3.2). Results showed that leaf N and Zn concentrations significantly decreased from wheat emergence (4.43 % N and 23.3 mg Zn/kg, respectively; 22 DAS) to anthesis (3.59 % N and 16.0 mg Zn/kg, respectively; 113 DAS; Table 133), while leaf Mg, B, and Mn concentrations significantly increased from wheat emergence (0.21 % Mg, 3.18 mg B/kg, and 68.4 mg Mn/kg, respectively; 22 DAS) to anthesis (0.26 % Mg, 5.85 mg B/kg, and 89.4 mg Mn/kg, respectively; 113 DAS). Leaf P, S, and Cu concentrations also significantly decreased from wheat emergence (0.50 % P, 0.34 % S, and 5.94 mg Cu/kg, respectively; 22 DAS) to booting (0.33 % P, 0.31 % S, and 4.21 mg Cu/kg, respectively; 100 DAS) and remained constant during anthesis (Table 133). Leaf Ca and Cl concentrations significantly decreased from wheat emergence (0.64 % Ca and 0.57 % Cl, respectively; 22 DAS) to booting (0.44 % Ca and 0.41 % Cl, respectively; 100 DAS; Table 133), but increased during anthesis (0.65 % Ca and 0.55 % Cl, respectively; 113 DAS). Leaf Na concentrations slightly but significantly increased from wheat emergence (0.02 % Na; 22 DAS) to booting (0.03 %; 100 DAS; Table 133) and remained constant during anthesis.

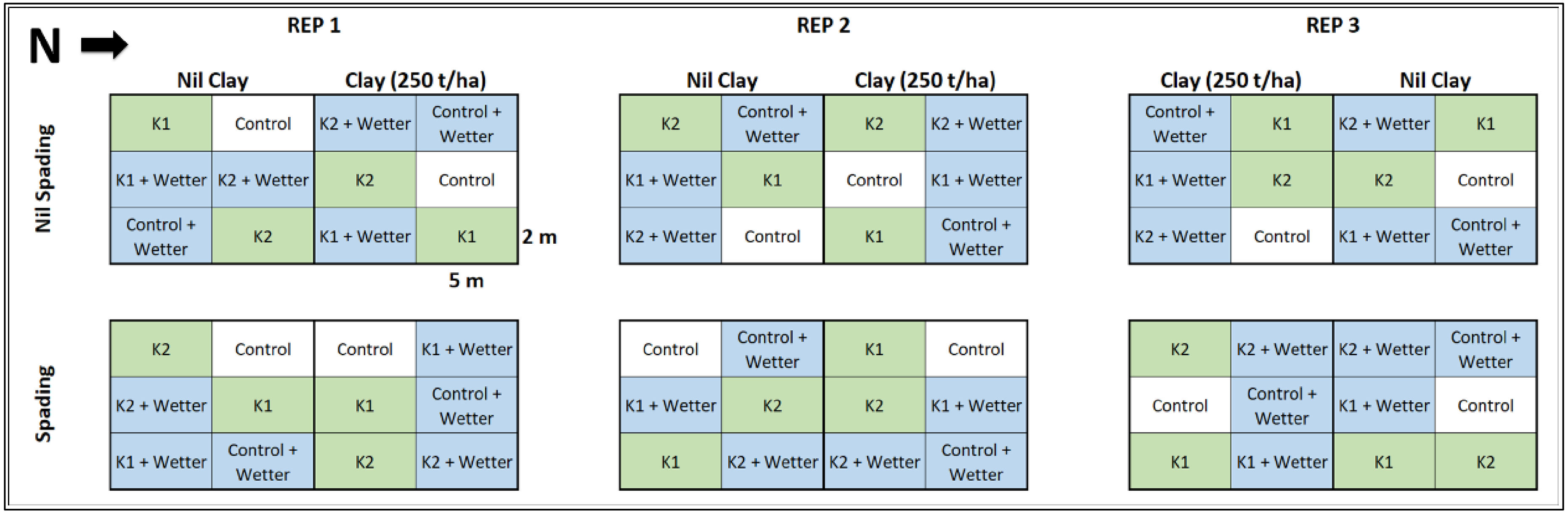
Table 133. Leaf nutrient concentrations during different growth stages in wheat at Meckering. Mean values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Leaf nutrient concentration	Emergence (22 DAS)	Booting (100 DAS)	Anthesis (113 DAS)
Leaf N (%)	4.43^{a}	4.12^{b}	3.59^{c}
Leaf P (%)	0.50^{a}	0.33^{b}	0.31^{b}
Leaf K (%)	1.92^{a}	1.76^{a}	1.82^{a}
Leaf Ca (%)	0.64^{a}	0.44^{b}	0.65^{a}
Leaf Mg (%)	0.21^{a}	0.18^{a}	0.26^{b}
Leaf S (%)	0.34^{a}	0.31^{b}	0.30^{b}
Leaf Na (%)	0.02^{a}	0.03^{b}	0.03^{b}
Leaf Cl (%)	0.57^{a}	0.41^{b}	0.55^{a}
Leaf B (mg/kg)	3.18^{a}	4.15^{b}	5.85^{c}
Leaf Cu (mg/kg)	5.94^{a}	4.21^{b}	4.32^{b}
Leaf Fe (mg/kg)	72.0^{a}	70.2^{a}	71.3^{a}
Leaf Mn (mg/kg)	68.4^{a}	77.5^{ab}	89.4^{b}
Leaf Zn (mg/kg)	23.3^{a}	20.4^{b}	16.0^{c}

Appendix C: **Supplementary data for Chapter 4**

C.1 Experimental design

C.1.1 Badgingarra



REP 1

	Nil Clay		Clay (250 t/ha)	
Nil Spading	K1	Control	K2 + Wetter	Control + Wetter
	K1 + Wetter	K2 + Wetter	K2	Control
	Control + Wetter	K2	K1 + Wetter	K1
Spading	K2	Control	Control	K1 + Wetter
	K2 + Wetter	K1	K1	Control + Wetter
	K1 + Wetter	Control + Wetter	K2	K2 + Wetter

REP 2

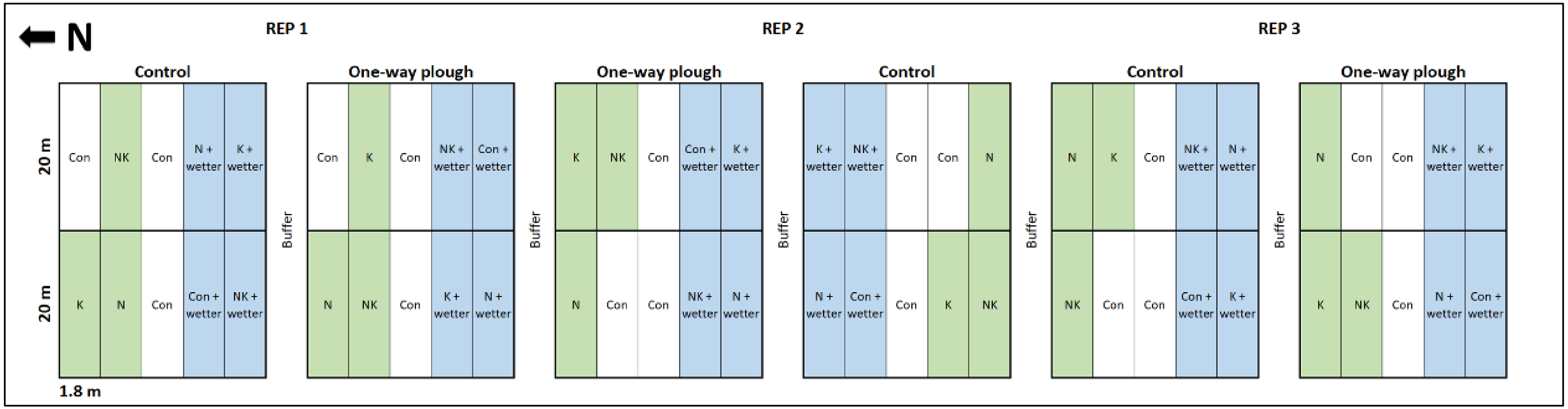
	Nil Clay		Clay (250 t/ha)	
Nil Spading	K2	Control + Wetter	K2	K2 + Wetter
	K1 + Wetter	K1	Control	K1 + Wetter
	K2 + Wetter	Control	K1	Control + Wetter
Spading	Control	Control + Wetter	K1	Control
	K1 + Wetter	K2	K2	K1 + Wetter
	K1	K2 + Wetter	K2 + Wetter	Control + Wetter

REP 3

	Clay (250 t/ha)		Nil Clay	
Nil Spading	Control + Wetter	K1	K2 + Wetter	K1
	K1 + Wetter	K2	K2	Control
	K2 + Wetter	Control	K1 + Wetter	Control + Wetter
Spading	K2	K2 + Wetter	K2 + Wetter	Control + Wetter
	Control	Control + Wetter	K1 + Wetter	Control
	K1	K1 + Wetter	K1	K2

Figure 147. Seventy-two microplots (5 × 2 m), consisting of spading, blanket-applied wetter (50 L of SE14® /ha and 150 L water /ha), subsoil clay spreading (250 t/ha), and supplementary potassium (K) fertiliser treatments (K1 = 40 kg K/ha broadcast prior to sowing, and K2 = 40 kg K/ha broadcast at 54 DAS) on a water-repellent pale deep sandy soil at Badgingarra in 2017.

C.1.2 Moora



REP 1

Control						One-way plough				
Con	NK	Con	N + wetter	K + wetter	Buffer	Con	K	Con	NK + wetter	Con + wetter
K	N	Con	Con + wetter	NK + wetter		N	NK	Con	K + wetter	N + wetter

REP 2

One-way plough						Control				
K	NK	Con	Con + wetter	K + wetter	Buffer	K + wetter	NK + wetter	Con	Con	N
N	Con	Con	NK + wetter	N + wetter		N + wetter	Con + wetter	Con	K	NK

REP 3

Control						One-way plough				
N	K	Con	NK + wetter	N + wetter	Buffer	N	Con	Con	NK + wetter	K + wetter
NK	Con	Con	Con + wetter	K + wetter		K	NK	Con	N + wetter	Con + wetter

Figure 148. Forty-eight plots (20 × 1.8 m), consisting of standard one-way plough, blanket-applied wetter (50 L of SE14® /ha and 150 L of water /ha), and supplementary nitrogen (N = 40 kg N/ha) and potassium (K = 40 kg K/ha) fertiliser treatments on a water-repellent sandy ironstone gravel duplex soil at Moora in 2017.

C.1.3 Meckering

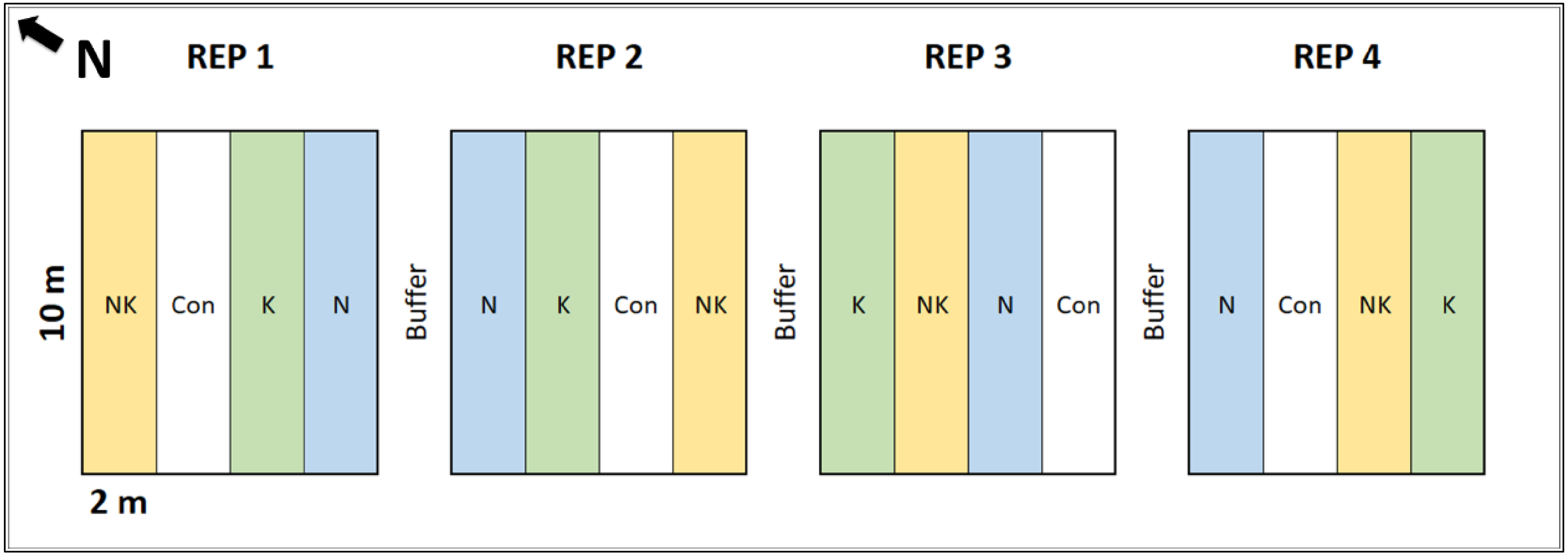


Figure 149. Sixteen plots (10 × 2 m), consisting of supplementary nitrogen (N = 40 kg N/ha) and potassium (K = 40 kg K/ha) fertiliser treatments on a water-repellent grey deep sandy duplex soil at Meckering in 2017.

C.2 Soil water repellence and soil water content

C.2.1 Badgingarra

Table 134. Mixed model analysis of variance test (F values with significance level) for soil water content and soil water repellence severity (molarity of ethanol droplet, MED) at Badgingarra in 2017, with spading, blanket-applied wetter, clay spreading, and supplementary K fertiliser treatments as between-subjects variables and a repeated measure for sampling depth and growth stage as the within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil water content	Soil water repellence severity
Spading	18****	46****
Wetter	1	6*
Clay	7*	11***
Fertiliser	0	1
Depth	585****	15****
Growth Stage	39****	5****
Spading × Wetter	3	6*
Spading × Clay	0	5*
Spading × Fertiliser	1	2
Spading × Depth	6*	2
Spading × Growth Stage	1	0
Wetter × Clay	1	1
Wetter × Fertiliser	0	2
Wetter × Depth	3	1
Wetter × Growth Stage	2	4*
Clay × Fertiliser	0	0
Clay × Depth	7*	14****
Clay × Growth Stage	2	0
Fertiliser × Depth	1	0
Fertiliser × Growth Stage	1	1
Depth × Growth Stage	18*	1
Spading × Wetter × Clay	1	3
Spading × Wetter × Fertiliser	0	2
Spading × Wetter × Depth	0	1
Spading × Wetter × Growth Stage	0	3*
Spading × Clay × Fertiliser	2	2
Spading × Clay × Depth	14****	9***
Spading × Clay × Growth Stage	2	0
Spading × Fertiliser × Depth	2	0
Spading × Fertiliser × Growth Stage	0	1
Spading × Depth × Growth Stage	2	2
Wetter × Clay × Fertiliser	0	1
Wetter × Clay × Depth	0	2
Wetter × Clay × Growth Stage	2	1
Wetter × Fertiliser × Depth	1	1
Wetter × Fertiliser × Growth Stage	1	1
Wetter × Depth × Growth Stage	0	0
Clay × Fertiliser × Depth	1	0
Clay × Fertiliser × Growth Stage	2	0
Clay × Depth * Growth Stage	4*	1
Fertiliser × Depth × Growth Stage	1	2
Spading × Wetter × Clay × Fertiliser	1	1
Spading × Wetter × Clay × Depth	2	0
Spading × Wetter × Clay × Growth Stage	1	3*
Spading × Wetter × Fertiliser × Depth	2	1
Spading × Wetter × Fertiliser × Growth Stage	0	1
Spading × Wetter × Depth × Growth Stage	0	0
Spading × Clay × Fertiliser × Depth	4*	1
Spading × Clay × Fertiliser × Growth Stage	0	0
Spading × Clay × Depth × Growth Stage	1	1
Spading × Fertiliser × Depth × Growth Stage	1	1
Wetter × Clay × Fertiliser × Depth	1	0
Wetter × Clay × Fertiliser × Growth Stage	2	0
Wetter × Clay × Depth × Growth Stage	1	1

Wetter × Fertiliser × Depth × Growth Stage	1	1
Clay × Fertiliser × Depth × Growth Stage	2	1
Spading × Wetter × Clay × Fertiliser × Depth	1	1
Spading × Wetter × Clay × Fertiliser × Growth Stage	1	0
Spading × Wetter × Clay × Depth × Growth Stage	1	0
Spading × Wetter × Fertiliser × Depth × Growth Stage	1	1
Spading × Clay × Fertiliser × Depth × Growth Stage	0	0
Wetter × Clay × Fertiliser × Depth × Growth Stage	2	0
Spading × Wetter × Clay × Fertiliser × Depth × Growth Stage	1	0

C.2.2 Moora

Table 135. Mixed model analysis of variance test (F values with significance level) for soil water content and soil water repellence severity (molarity of ethanol droplet, MED) at Moora in 2017, with one-way plough, blanket-applied wetter, and supplementary fertiliser treatments as between-subjects variables and a repeated measure for sampling depth and growth stage as the within-subjects variables. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Soil water content	Soil water repellence severity
Plough	14****	12***
Wetter	6*	49****
Fertiliser	1	2
Depth	204****	1628****
Growth Stage	301****	15****
Plough × Wetter	3	0
Plough × Fertiliser	0	3*
Plough × Depth	53****	93****
Plough × Growth Stage	1	1
Wetter × Fertiliser	1	1
Wetter × Depth	2	115****
Wetter × Growth Stage	5**	28****
Fertiliser × Depth	1	0
Fertiliser × Growth Stage	0	1
Depth × Growth Stage	165****	6***
Plough × Wetter × Fertiliser	0	0
Plough × Wetter × Depth	0	1
Plough × Wetter × Growth Stage	0	1
Plough × Fertiliser × Depth	2	1
Plough × Fertiliser × Growth Stage	1	1
Plough × Depth × Growth Stage	0	2
Wetter × Fertiliser × Depth	0	0
Wetter × Fertiliser × Growth Stage	0	1
Wetter × Depth × Growth Stage	10****	29****
Fertiliser × Depth × Growth Stage	1	1
Plough × Wetter × Fertiliser × Depth	1	1
Plough × Wetter × Fertiliser × Growth Stage	1	2
Plough × Wetter × Depth × Growth Stage	0	2
Plough × Fertiliser × Depth × Growth Stage	1	0
Wetter × Fertiliser × Depth × Growth Stage	1	1
Plough × Wetter × Fertiliser × Depth × Growth Stage	1	1

C.2.3 Meckering

Table 136. Mixed model analysis of variance test (F values with significance level) for soil water content and soil water repellence severity (molarity of ethanol droplet, MED) at Meckering in 2017, with supplementary fertiliser treatment as the between-subjects variable and a repeated measure for

sampling depth and growth stage as the within-subjects variables. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Source of variation	Soil water content	Soil water repellence severity
Fertiliser	0	1
Depth	3	33****
Growth stage	436****	3
Fertiliser × Depth	2	1
Fertiliser × Growth stage	1	1
Depth × Growth stage	100****	1
Fertiliser × Depth × Growth stage	0	1

C.3 Total nutrient uptake

C.3.1 Badgingarra

Total uptake of all nutrients (except for Na, Cu, Fe, and Mn) was significantly affected by spading ($P < 0.005$; Table 137), whereby total uptake of N, P, K, Ca, Mg, S, B, and Zn were significantly greater in spaded treatments than in non-spaded treatments by an average of 41 % (Table 138). Total uptake of Na, Cu, and Mn were not affected by treatments, but total Fe uptake was significantly affected by clay spreading ($P < 0.05$; Table 138), whereby total Fe uptake was significantly greater in clayed treatments (162.6 µg/plant) than in non-clayed treatments by 31 % (124.5 µg/plant; Figure 150).

Table 137. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between spading, blanket-applied wetter, clay spreading, and supplementary K fertiliser treatments on wheat total nutrient uptake during wheat anthesis (113 DAS) at Badgingarra in 2017. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Source of variation	Total nutrient uptake					
	N	P	K	Ca	Mg	S

Spading	11***	14****	20****	10***	17****	12***
Wetter	0	0	0	1	1	0
Clay	0	2	0	1	0	0
Fertiliser	0	0	3	0	0	0
Spading × Wetter	0	0	0	0	0	0
Spading × Clay	1	2	1	0	1	0
Spading × Fertiliser	0	0	0	1	1	0
Wetter × Clay	0	0	0	1	1	0
Wetter × Fertiliser	1	1	1	1	1	1
Clay × Fertiliser	0	0	0	1	0	0
Spading × Wetter × Clay	0	0	0	0	0	0
Spading × Wetter × Fertiliser	1	1	1	1	1	1
Spading × Clay × Fertiliser	0	0	0	0	0	0
Wetter × Clay × Fertiliser	0	0	0	1	0	1
Spading × Wetter × Clay × Fertiliser	0	0	0	0	0	0

Source of variation	Total nutrient uptake					
	Na	B	Cu	Fe	Mn	Zn
Spading	4	20****	3	4	0	6*
Wetter	1	1	0	0	0	0
Clay	0	0	0	7*	0	0
Fertiliser	0	0	0	0	1	0
Spading × Wetter	1	0	0	0	0	1
Spading × Clay	1	1	0	3	1	1
Spading × Fertiliser	1	0	0	0	0	1
Wetter × Clay	0	0	0	0	1	0
Wetter × Fertiliser	2	2	1	0	0	0
Clay × Fertiliser	0	1	0	0	0	0
Spading × Wetter × Clay	0	0	0	0	0	0
Spading × Wetter × Fertiliser	1	1	2	1	0	0
Spading × Clay × Fertiliser	0	0	0	0	0	0
Wetter × Clay × Fertiliser	1	1	0	0	2	1
Spading × Wetter × Clay × Fertiliser	0	0	0	0	0	0

Table 138. Effect of spading on total nutrient uptake in wheat during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 36. Significant differences based on the least significant difference (LSD) at P < 0.05.

Total nutrient uptake	Non-spaded	Spaded
N (mg/plant)	32.6†	45.1
P (mg/plant)	3.42†	4.76
K (mg/plant)	21.2†	34.3
Ca (mg/plant)	6.41†	8.66
Mg (mg/plant)	2.52†	3.68
S (mg/plant)	3.10†	4.26
Na (µg/plant)	0.58	0.70
B (µg/plant)	6.53†	9.78
Cu (µg/plant)	4.26	4.91
Fe (µg/plant)	129.3	157.7
Mn (µg/plant)	117.9	113.2
Zn (µg/plant)	31.2†	38.8

† Significantly different from spaded treatments ($P < 0.05$).

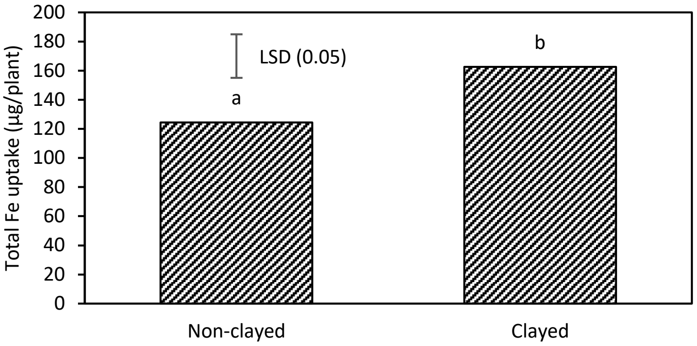


Figure 150. Effect of clay spreading on total Fe uptake (µg/plant) in wheat during anthesis (113 DAS) at Badgingarra in 2017. Mean values based on a sample size of 36. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

C.3.2 Moora

Total Na uptake was also significantly affected by the two-way interaction of one-way plough × supplementary fertiliser treatments ($P < 0.05$; Table 139). Total Na uptake was not affected by one-way plough treatments, except when supplementary N fertiliser was applied whereby total Na uptake was significantly greater in one-way ploughed treatments (20.9 µg/plant) than in non-ploughed treatments by 90 % (11.0 µg/plant; Table 140). In non-ploughed treatments, total Na uptake was significantly greater in N (11.0 µg/plant) and NK treatments (9.6 µg/plant) than in the control treatments by 150 and 118 %, respectively (4.4 µg/plant; Table 140), with total Na uptake also greater in N treatments (11.0 µg/plant) than in K treatments by 112 % (5.2 µg/plant). In non-ploughed treatments, there were no differences in total Na uptake between the control and K treatments, N and NK treatments, or K and NK treatments. In one-way ploughed treatments, total Na uptake was significantly greater in N treatments (20.9 µg/plant) than in the control (6.7 µg/plant; by 212 %), K (8.1 µg/plant; by 158 %), and NK treatments (10.1 µg/plant; by 107 %; Table 140), with no differences between the control, K, and NK treatments.

Nevertheless, total uptake of all nutrients (except for Na, Fe, and Mn) was significantly affected by one-way plough treatments ($P < 0.001$; Table 139), whereby total uptake of N, P, K, Ca, Mg, S, B, Cu, and Zn was significantly greater in one-way ploughed treatments than in non-ploughed treatments by an average of 36 % (Table 141).

Table 139. Analysis of variance, ANOVA, test (F values with significance level) for main effects and interactions between one-way plough, blanket-applied wetter, and supplementary fertiliser treatments on canola total nutrient uptake during anthesis (106 DAS) at Moora in 2017. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Source of variation	Total nutrient uptake					
	N	P	K	Ca	Mg	S
Plough	27****	21****	25****	33****	25****	27****
Wetter	0	0	0	0	0	0
Fertiliser	15****	5***	12****	10****	11****	10****
Plough × Wetter	0	0	1	0	1	0
Plough × Fertiliser	2	1	1	2	2	2
Wetter × Fertiliser	1	1	2	1	1	1
Plough × Wetter × Fertiliser	1	0	0	0	0	0
Source of variation	**Total nutrient uptake**					
	Na	B	Cu	Fe	Mn	Zn
Plough	13****	33****	33****	1	4	26****
Wetter	0	0	0	0	0	0
Fertiliser	19****	11****	15****	3*	8****	14****
Plough × Wetter	0	0	0	1	0	0
Plough × Fertiliser	4*	2	2	1	2	2
Wetter × Fertiliser	1	1	2	1	1	2
Plough × Wetter × Fertiliser	0	0	0	0	0	0

Table 140. Effect of one-way plough and supplementary fertiliser treatments (nil, K = 40 kg K/ha, N = 40 kg N/ha, and NK = 40 kg N and K/ha broadcast at sowing) on total Na uptake (μg/plant) in canola during anthesis (106 DAS) at Moora in 2017. Mean values based on a sample size of 6. Significant differences based on the least significant difference (LSD) at P < 0.05.

Total nutrient uptake	Non-ploughed				One-way ploughed			
	Nil	K	N	NK	Nil	K	N	NK
Na (μg/plant)	4.4^{a}	5.2^{ac}	$11.0^{b\dagger}$	9.6^{bc}	6.7^{a}	8.1^{a}	20.9^{b}	10.1^{a}

Different superscript letters denote significant differences within supplementary fertiliser treatments ($P < 0.05$).
† Significantly different from one-way ploughed treatments ($P < 0.05$).

Total uptake of all nutrients was also significantly affected by supplementary fertiliser treatments ($P < 0.05$; Table 139). Total uptake of N, Ca, Mg, S, B, Mn, and Zn was significantly greater in N and NK treatments than in the control treatments (by an average of 54 %) and K treatments (by an average of 29 %; Table 142), with no differences between N and NK treatments or the control and K treatments. Total Cu uptake was also significantly greater in N (17.1 μg/plant) and NK treatments (17.5 μg/plant) than in the control (11.0 μg/plant; by 55 and 59 %, respectively) and K treatments (13.4 μg/plant; by 28 and 31 %, respectively; Table 142), with total Cu uptake also significantly greater in K treatments than in the control treatments by 22 % but with no differences between N and NK treatments. Total P and Fe uptake was significantly greater in N (17.7 mg P/plant and 283.1 μg Fe/plant, respectively) and NK treatments (18.3 mg P/plant and 248.3 μg Fe/plant) than in the control treatments by an average of 33 (P) and 85 % (Fe), respectively (13.5 mg P/plant and 143.6 µg Fe/plant; Table 142), but there were no differences in total P and Fe uptake between the control and K treatments, or N, K, and NK treatments. Total K uptake was significantly greater in N (158.4 mg/plant), K (144.0 mg/plant), and NK treatments (185.1 mg/plant) than in the control treatments by 38, 26, and 61 %, respectively (114.7 mg/plant; Table 142), with total K uptake significantly greater in NK treatments than in N (by 17 %) and K treatments (by 29 %) but with no difference between N and K treatments.

Table 141. Effect of one-way plough on total nutrient uptake in canola during anthesis (106 DAS) at Moora in 2017. Mean values based on a sample size of 24. Significant differences based on the least significant difference (LSD) at P < 0.05.

Total nutrient uptake	Non-ploughed	One-way ploughed
N (mg/plant)	80.1†	105.9
P (mg/plant)	14.1†	18.6
K (mg/plant)	129.7†	171.4
Ca (mg/plant)	46.5†	68.0
Mg (mg/plant)	9.3†	12.6
S (mg/plant)	20.4†	27.6
B (µg/plant)	116.1†	161.2
Cu (µg/plant)	12.5†	17.1
Zn (µg/plant)	75.5†	103.9

† Significantly different from one-way ploughed treatments ($P < 0.05$).

Table 142. Effect of supplementary fertiliser treatments (nil, K = 40 kg K/ha, N = 40 kg N/ha, and NK = 40 kg N and K/ha broadcast at sowing) on total nutrient uptake in canola during anthesis (106 DAS) at Moora in 2017. Mean values based on a sample size of 12. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Total nutrient uptake	Nil	K	N	NK
N (mg/plant)	71.5^{a}	82.5^{a}	111.2^{b}	106.8^{b}
P (mg/plant)	13.5^{a}	15.8^{ab}	17.7^{b}	18.3^{b}
K (mg/plant)	114.7^{a}	144.0^{b}	158.4^{b}	185.1^{c}
Ca (mg/plant)	42.9^{a}	52.8^{a}	66.5^{b}	66.9^{b}
Mg (mg/plant)	8.3^{a}	9.9^{a}	13.0^{b}	12.7^{b}
S (mg/plant)	18.6^{a}	22.4^{a}	27.5^{b}	27.4^{b}
B (µg/plant)	106.3^{a}	128.6^{a}	158.7^{b}	161.0^{b}
Cu (µg/plant)	11.0^{a}	13.4^{b}	17.1^{c}	17.5^{c}
Fe (µg/plant)	143.6^{a}	212.3^{ab}	283.1^{b}	248.3^{b}
Mn (µg/plant)	68.0^{a}	76.9^{a}	103.0^{b}	106.7^{b}
Zn (µg/plant)	64.8^{a}	79.5^{a}	106.1^{b}	108.4^{b}

C.3.3 Meckering

Total uptake of all nutrients (except K, Na, and Mn) was significantly affected by supplementary N and K fertiliser treatments ($P < 0.05$; Table 143). Total uptake of N, Ca, and Mg was significantly greater in N (80.6 mg N/plant, 24.8 mg Ca/plant, 8.92 mg Mg/plant, respectively) and NK treatments (90.4 mg N/plant, 19.9 mg Ca/plant, 7.94 mg Mg/plant, respectively) than in the control (49.0 mg/plant, 14.4 mg Ca/plant, 5.38 mg Mg/plant, respectively; by an average of 62 %) and K treatments (55.5 mg/plant, 14.0 mg Ca/plant, 5.38 mg Mg/plant, respectively; by an average of 57 %; Table 144), with no differences in total uptake of N, Ca, and Mg between the control and K treatments, or N and NK treatments. Total uptake of S and B was also significantly greater in N (6.94 mg S/plant and 21.8 µg B/plant, respectively) and NK treatments (7.66 mg S/plant and 23.0 µg B/plant, respectively) than in the control treatments by an average of 60 % (4.44 mg S/plant and 14.3 µg B/plant, respectively; Table 144), with total uptake of S and B also significantly greater in NK treatments (7.66 mg S/plant and 23.0 µg B/plant, respectively) than in K treatments by an average of 45 % (5.02 mg S/plant and 16.7 µg B/plant, respectively), but with no differences in total uptake of S and B between the control and K treatments, N and K treatments, or N and NK treatments.

Table 143. Analysis of variance, ANOVA, test (F values with significance level) for the main effect of supplementary fertiliser treatments on wheat total nutrient uptake during anthesis (112 DAS) at Meckering in 2017. Significance level (two-tailed): P ≤ 0.05 (*), P ≤ 0.01 (**), P ≤ 0.005 (***), and P ≤ 0.001 (****).

Total nutrient uptake	Fertiliser
N	6**
P	4*
K	2
Ca	10***
Mg	5*
S	4*
Na	2
B	4*
Cu	5*
Fe	4*
Mn	3
Zn	7**

Total uptake of P, Cu, and Fe was significantly greater in NK treatments (15.1 mg P/plant, 16.3 µg Cu/plant, and 193.8 µg Fe/plant, respectively) than in the control (9.5 mg P/plant, 10.1 µg Cu/plant, and 120.9 µg Fe/plant, respectively; by an average of 61 %) and K treatments (10.7 mg P/plant, 10.1 µg Cu/plant, and 132.8 µg Fe/plant, respectively; by an average of 49 %; Table 144), but with no differences in total uptake of P, Cu, and Fe between the control, N, and K treatments, or N and NK treatments. Total Zn uptake was also significantly greater in NK treatments (91.4 µg Zn/plant) than in the control (44.6 µg Zn/plant; by 105 %), N (66.5 µg Zn/plant; by 37 %), and K treatments (53.4 µg Zn/plant; by 71 %; Table 144), but there were no differences in total Zn uptake between the control, N, and K treatments. Supplementary N and K treatments did not affect wheat total uptake of K (24.5-94.7 mg/plant), Na (0.27-1.43 µg/plant), and Mn (74.5-278.4 µg/plant).

Table 144. Effect of supplementary fertiliser treatments (nil, K = 40 kg K/ha, N = 40 kg N/ha, and NK = 40 kg N and K/ha broadcast at sowing) on wheat total nutrient uptake during anthesis (112 DAS) at Meckering in 2017. Mean values based on a sample size of 4. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

Total nutrient uptake	Supplementary fertiliser			
	Nil	K	N	NK
N (mg/plant)	49.0^{a}	55.5^{a}	80.6^{b}	90.4^{b}
P (mg/plant)	9.5^{a}	10.7^{a}	12.7^{ab}	15.1^{b}
Ca (mg/plant)	14.4^{a}	14.0^{a}	24.8^{b}	19.9^{b}
Mg (mg/plant)	5.38^{a}	5.38^{a}	8.92^{b}	7.94^{b}
S (mg/plant)	4.44^{a}	5.02^{ab}	6.94^{bc}	7.66^{c}
B (µg/plant)	14.3^{a}	16.7^{ab}	21.8^{bc}	23.0^{c}
Cu (µg/plant)	10.1^{a}	10.1^{a}	13.4^{ab}	16.3^{b}
Fe (µg/plant)	120.9^{a}	132.8^{a}	170.4^{ab}	193.8^{b}
Zn (µg/plant)	44.6^{a}	53.4^{a}	66.5^{a}	91.4^{b}

Appendix D: **Supplementary data for Chapter 5**

D.1 Root length density

Total RLD of wheat was significantly affected by the two-way interaction of topsoil water repellence × fertiliser placement ($P < 0.05$; see Table 61 in Section 5.3.1), whereby total RLD was significantly greater in repellent treatments (15.6 cm/cm^3) than in wettable treatments by 22 % (12.8 cm/cm^3; Figure 151) when fertiliser was banded below the seed. However, topsoil water repellence did not affect total RLD when fertiliser was banded away from the seed.

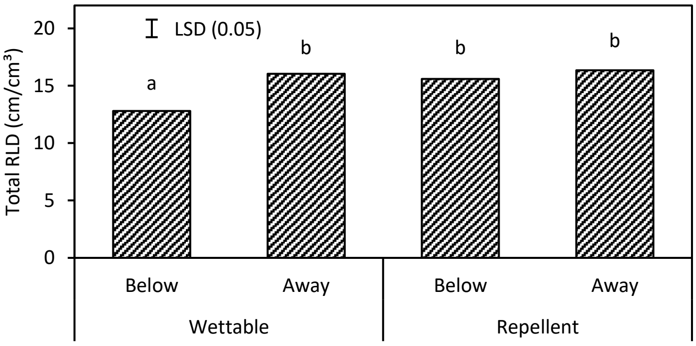


Figure 151. Effect of topsoil water repellence and fertiliser placement on total wheat root length density (RLD, cm/cm^3) at 51 DAS. Mean values based on a sample size of 6. Different letters denote significant differences, based on the least significant difference (LSD) at $P < 0.05$.

Results showed that wheat RLD was significantly affected by the four-way interactions of topsoil water repellence × fertiliser placement × sampling row × sampling depth ($P < 0.05$), and topsoil thickness × fertiliser placement × sampling row × sampling depth ($P < 0.001$; see Table 62 in Section 5.3.4). When fertiliser was banded below the seed, RLD in the furrow at the 0-5 and 10-15 cm depths was significantly greater in repellent treatments (4.40 and 2.02 cm/cm^3, respectively) than in wettable treatments (3.51 and 0.35 cm/cm^3, respectively; Table 145), respectively, but RLD in the inter-row at the 10-15 cm depth was significantly greater in wettable treatments (1.05 cm/cm^3) than in repellent treatments (0.65 cm/cm^3). Topsoil water repellence did not affect RLD in the furrow at the 5-10 and 15-20 cm depths or in the inter-row at the 0-5, 5-10, and 15-20 cm depths when fertiliser was banded below the seed. When fertiliser was banded away from the seed, RLD in the furrow and inter-row at the 0-5 cm depth was significantly greater in repellent treatments (4.40 and 1.34 cm/cm^3, respectively) than in wettable treatments (3.05 and 0.28 cm/cm^3, respectively; Table 145), respectively, but RLD in the furrow at the 10-15 and 15-20 cm depths was significantly greater in wettable treatments (2.78 and 2.77 cm/cm^3, respectively) than in repellent treatments by 38 and 46 % (2.02 and 1.90 cm/cm^3, respectively), respectively. Topsoil water repellence did not affect RLD in the furrow at the 5-10 cm depth or in the inter-row at the 5-10, 10-15, and 15-20 cm depths when fertiliser was banded away from the seed.

Table 145. Effect of topsoil water repellence and fertiliser placement on wheat root length density (cm/cm^3; 51 DAS). Mean values based on a sample size of 6. Significant differences based on the least significant difference (LSD) at P < 0.05.

Row	Depth	Wettable		Repellent	
		Below	Away	Below	Away
Furrow	0-5 cm	3.51^{a†}	3.05^{a†}	4.40^{a}	4.40^{a}
	5-10 cm	5.45^{a}	3.31^{b}	5.95^{a}	2.98^{b}
	10-15 cm	0.35^{a†}	2.78^{b†}	2.02^{a}	2.02^{a}
	15-20 cm	0.20^{a}	2.77^{b†}	0.83^{a}	1.90^{b}
Inter-row	0-5 cm	0.13^{a}	0.28^{a†}	0.21^{a}	1.34^{b}
	5-10 cm	1.43^{a}	2.92^{b}	1.00^{a}	2.96^{b}
	10-15 cm	1.05^{a†}	0.55^{b}	0.65^{a}	0.48^{a}
	15-20 cm	0.69^{a}	0.38^{b}	0.53^{a}	0.26^{b}

Different superscript letters denote significant differences within fertiliser placement (P < 0.05).

† Significantly different from repellent treatments (P < 0.05).

When fertiliser was banded below the seed, RLD in the furrow at the 5-10 cm depth was significantly greater in treatments with a 100 mm topsoil thickness (7.52 cm/cm^3) than a 20 mm topsoil thickness (3.90 cm/cm^3; Table 146), but RLD in the inter-row at the 10-15 cm depths was significantly greater in treatments with a 20 mm topsoil thickness (1.12 cm/cm^3) than a 100 mm topsoil thickness (0.58 cm/cm^3). Topsoil thickness did not affect RLD in the furrow at the 0-5, 10-15, and 15-20 cm depths or in the inter-row at the 0-5, 5-10, and 15-20 cm depths when fertiliser was banded below the seed. When fertiliser was banded away from the seed, RLD in the furrow at the 0-5 cm depth was significantly greater in treatments with a 100 mm topsoil thickness (4.05 cm/cm^3) than a 20 mm topsoil thickness (3.40 cm/cm^3; Table 146), but RLD in the furrow at the 15-20 cm depth was significantly greater in treatments with a 20 mm topsoil thickness (2.97 cm/cm^3) than a 100 mm topsoil thickness (1.70 cm/cm^3). Root length density in the inter-row at the 5-10 cm depth was also significantly greater in treatments with a 100 mm topsoil thickness (3.65 cm/cm^3) than a 20 mm topsoil thickness (2.24 cm/cm^3; Table 146) when fertiliser was banded away from the seed. However, topsoil thickness did not affect RLD in the furrow at the 5-10 and 10-15 cm depths and in the inter-row at the 0-5, 10-15, and 15-20 cm depth when fertiliser was banded away from the seed.

Table 146. Effect of topsoil thickness and fertiliser placement on wheat root length density (cm/cm^3; 51 DAS). Mean values based on a sample size of 6. Significant differences based on the least significant difference (LSD) at P < 0.05.

Row	Depth	20 mm		100 mm	
		Below	Away	Below	Away
Furrow	0-5 cm	3.76^{a}	3.40^{a†}	4.15^{a}	4.05^{a}
	5-10 cm	3.89^{a†}	2.97^{b}	7.52^{a}	3.33^{b}
	10-15 cm	1.34^{a}	2.21^{b}	1.03^{a}	2.60^{b}
	15-20 cm	0.67^{a}	2.97^{b†}	0.36^{a}	1.70^{b}
Inter-row	0-5 cm	0.20^{a}	0.65^{b}	0.14^{a}	0.97^{b}
	5-10 cm	1.49^{a}	2.24^{b†}	0.94^{a}	3.65^{b}
	10-15 cm	1.11^{a†}	0.48^{b}	0.58^{a}	0.56^{a}
	15-20 cm	0.68^{a}	0.24^{b}	0.54^{a}	0.40^{a}

Different superscript letters denote significant differences within fertiliser placement ($P < 0.05$).
† Significantly different from treatments with a 100 mm topsoil thickness ($P < 0.05$).

Regardless of topsoil water repellence and topsoil thickness, RLD in the furrow at the 0-5 cm depth was not affected by fertiliser placement. However, RLD in the inter-row at the 0-5 cm depth was significantly greater in repellent treatments with fertiliser banded away from the seed (1.34 cm/cm^3) than below the seed by 538 % (0.21 cm/cm^3; Table 145), but this was not observed in wettable treatments. Likewise, RLD in the inter-row at the 0-5 cm depth was also significantly greater when fertiliser was banded away from the seed (0.65-0.97 cm/cm^3) than below the seed by up to 579 % (0.14-0.20 cm/cm^3; Table 146), regardless of topsoil thickness. Regardless of topsoil water repellence and topsoil thickness, RLD in the furrow at the 5-10 cm depth was significantly greater when fertiliser was banded below the seed (3.89-7.52 cm/cm^3) than away from the seed by up to 126 % (2.97-3.33 cm/cm^3; Tables 145 and 146), while RLD in the inter-row at the 5-10 cm depth was significantly greater when fertiliser was banded away from the seed (2.24-3.65 cm/cm^3) than below the seed by up to 288 % (0.94-1.49 cm/cm^3; Tables 145 and 146). In wettable treatments, RLD in the furrow at the 10-15 cm depth was also significantly greater when fertiliser was banded away from the seed (2.78 cm/cm^3) than below the seed by 694 % (0.35 cm/cm^3; Table 145), while RLD in the inter-row at the 10-15 cm depth was significantly greater when fertiliser was banded below the seed (1.05 cm/cm^3) than away from the seed by

91 % (0.55 cm/cm^3). However, fertiliser placement did not affect RLD in the furrow and inter-row at the 10-15 cm depth in repellent treatments. Regardless of topsoil thickness, RLD in the furrow at the 10-15 cm depth was also significantly greater when fertiliser was banded away from the seed (2.21-2.60 cm/cm^3) than below the seed by up to 151 % (1.03-1.34 cm/cm^3; Table 146). By contrast, in treatments with a 20 mm topsoil thickness, RLD in the inter-row at the 10-15 cm depth was significantly greater when fertiliser was banded below the seed (1.11 cm/cm^3) than away from the seed by 131 % (0.48 cm/cm^3), but this was not observed in treatments with a 100 mm topsoil thickness. Regardless of topsoil water repellence and topsoil thickness, RLD in the furrow at the 15-20 cm depth was significantly greater when fertiliser was banded away from the seed (1.70-2.97 cm/cm^3) than below the seed by up to 1258 % (0.20-0.83 cm/cm^3; Tables 145 and 146), while RLD in the inter-row at the 15-20 cm depth was significantly greater when fertiliser was banded below the seed (0.53-0.69 cm/cm^3) than away from the seed by up to 182 % (0.24-0.38 cm/cm^3), except in treatments with a 100 mm topsoil thickness whereby RLD in the inter-row at the 15-20 cm depth was not affected by fertiliser placement.

D.2 Leaf relative water content

Wheat leaf RWC was significantly affected by the two-way interaction of topsoil thickness × fertiliser placement ($P < 0.005$; see Table 61 in Section 5.3.1). When fertiliser was banded below the seed, leaf RWC was significantly greater in treatments with a 100 mm topsoil thickness (94.3 %) than a 20 mm topsoil thickness (93.5 %; Figure 152), but leaf RWC was significantly greater in treatments with a 20 mm topsoil thickness (95.0 %) than a 100 mm topsoil thickness (94.1 %) when fertiliser was banded away from the seed. In treatments with a 20 mm topsoil thickness, leaf RWC was significantly greater when fertiliser was banded away from the seed (95.0 %) than below the seed (93.5 %; Figure 152), but fertiliser placement did not affect leaf RWC in treatments with a 100 mm topsoil thickness.

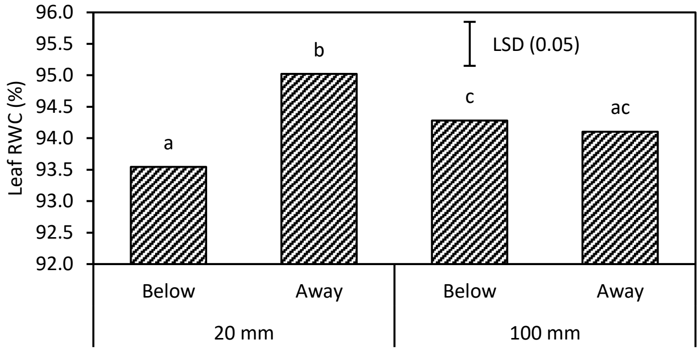


Figure 152. Effect of topsoil thickness and fertiliser placement on relative water content (RWC, %) in young fully expanded wheat leaves at 51 DAS. Mean values based on a sample size of 6. Different letters denote significant differences, based on the least significant difference (LSD) at P < 0.05.

D.3 Soil water post-harvest

Soil water content post-harvest at 51 DAS was significantly affected by the three-way interaction of topsoil thickness × sampling row × sampling depth (*P* < 0.005; see Table 65 in Section 5.3.6), whereby soil water content in the furrow at the 0-5 cm depth was significantly greater in treatments with a 100 mm topsoil thickness (26.6 %) than a 20 mm topsoil thickness (20.9 %; Table 147), but topsoil thickness did not affect soil water content in the inter-row at the 0-5 cm depth. However, soil water content at the 10-15 cm depth was significantly greater in treatments with a 20 mm topsoil thickness (15.4-15.7 %) than a 100 mm topsoil thickness (11.6-11.8 %; Table 147), regardless of sampling row. In treatments with a 20 mm topsoil thickness, soil water content at the 0-5 cm depth was significantly greater in the inter-row (23.1 %) than in the furrow (20.9 %; Table 147) but, in treatments with a 100 mm topsoil thickness, soil water content at the 0-5 cm depth was significantly greater in the furrow (26.6 %) than in the inter-row (23.6 %). Soil water content at the 10-15 cm depth was not different between sampling row, regardless of topsoil thickness. Soil water content was significantly greater at the 0-5 cm depth (20.9-26.6 %) than at the 10-15 cm depth (11.6-15.7 %; Table 147), regardless of topsoil thickness and sampling row.

Soil water content was also significantly affected by the two-way interaction of fertiliser placement × sampling depth (*P* < 0.001; see Table 65 in Section 5.3.6), whereby soil water content at the 0-5 cm depth was significantly greater when fertiliser was banded away from the seed (25.5 %) than below the seed (21.7 %; Table 148), but soil water content at the 10-15 cm depth was not affected by fertiliser placement. Soil water content was also significantly greater at the 0-5 cm depth (21.7-25.5 %) than at the 10-15 cm depth (13.3-13.9 %), regardless of fertiliser placement.

Table 147. Effect of topsoil thickness, sampling row, and sampling depth on soil water content (%) post-harvest (51 DAS). Mean values based on a sample size of 12. Significant differences based on the least significant difference (LSD) at P < 0.05.

Row	Depth	Topsoil thickness	
		20 mm	100 mm
Furrow	0-5 cm	$20.9^{a\dagger\Delta}$	$26.6^{a\Delta}$
	10-15 cm	$15.4^{b\dagger}$	11.8^{b}
Inter-row	0-5 cm	23.1^{a}	23.6^{a}
	10-15 cm	$15.7^{b\dagger}$	11.6^{b}

Different superscript letters denote significant differences within depth ($P < 0.05$).

[†] Significantly different from treatments with a 100 mm topsoil thickness ($P < 0.05$).

[Δ] Significantly different from the corresponding inter-row ($P < 0.05$).

Table 148. Effect of fertiliser placement and sampling depth on soil water content (%) post-harvest (51 DAS). Mean values based on a sample size of 24.

Depth	Fertiliser placement	
	Below	Away
0-5 cm	$21.7^{a\dagger}$	25.5^{a}
10-15 cm	13.9^{b}	13.3^{b}

Different superscript letters denote significant differences within depth ($P < 0.05$).

[†] Significantly different from treatments with fertiliser banded away from the seed ($P < 0.05$).

Soil water content was also significantly affected by the two-way interaction of fertiliser placement × sampling row ($P < 0.05$; see Table 65 in Section 5.3.6), whereby soil water content was significantly greater in the furrow (18.1 %) than in the inter-row (17.5 %) when fertiliser was banded below the seed, but not when fertiliser was banded away from the seed. Nevertheless, such differences were relatively small despite being statistically significant. There was also no effect of fertiliser placement on soil water content, regardless of sampling row (data not shown).

D.4 Shoot nutrient concentrations

Shoot Ca, S, Fe, and Zn concentrations were significantly affected by the three-way interaction of topsoil water repellence × topsoil thickness × fertiliser placement ($P < 0.05$; see Table 67 in Section 5.3.7). In treatments with a 20 mm topsoil thickness and fertiliser banded either below or away from the seed, shoot Ca and S concentrations were significantly greater in wettable treatments (0.48 and 0.55 % Ca, and 0.53 and 0.47 % S, respectively) than in repellent treatments (0.40 and 0.47 % Ca, and 0.45 and 0.40 % S, respectively; Table 149). Similarly, in treatments with a 100 mm topsoil thickness, shoot Ca concentration was significantly greater in wettable treatments (0.58 %) than in repellent treatments (0.42 %; Table 149), but only when fertiliser was banded away from the seed. In treatments with a 100 mm topsoil thickness and fertiliser banded below the seed, shoot S and Zn concentration was also significantly greater in wettable treatments (0.55 % S and 34.1 mg Zn/kg, respectively) than in repellent treatments (0.35 % S and 31.3 mg Zn/kg, respectively; Table 149), but shoot Fe concentration was significantly greater in repellent treatments (78.6 mg/kg) than in wettable treatments (71.0 mg/kg; Table 149). In treatments with a 100 mm topsoil thickness and fertiliser banded away from the seed, shoot Zn concentration was also significantly greater in repellent treatments (41.2 mg/kg) than in wettable treatments (38.7 mg/kg; Table 149). There was no effect of topsoil water repellence on shoot Fe and Zn concentration in treatments with a 20 mm topsoil thickness, regardless of fertiliser placement.

In wettable treatments, topsoil thickness did not affect shoot Ca concentration, regardless of fertiliser placement. However, shoot S concentration was significantly greater in wettable treatments with a 20 mm topsoil thickness (0.47 %) than a 100 mm topsoil thickness (0.41 %; Table 149), but only when fertiliser was banded away from the seed. By contrast, when fertiliser was banded either below or away from the seed, shoot Zn concentration was significantly greater in wettable treatments with a 100 mm topsoil thickness (34.1 and 38.7 mg/kg, respectively) than in treatments with a 20 mm topsoil thickness (28.5 and 30.9 mg/kg, respectively; Table 149). Shoot Fe concentration was also significantly greater in wettable treatments with a 100 mm topsoil thickness (76.2 mg/kg) than a 20 mm topsoil thickness (71.0 mg/kg; Table 149), but only when fertiliser was banded below the seed. In repellent treatments with fertiliser banded below the seed, shoot Ca and Fe concentrations were significantly greater in treatments with a 100 mm topsoil thickness (0.48 % Ca and 78.6 mg Fe/kg, respectively) than a 20 mm topsoil thickness (0.40 % Ca and 74.2 mg Fe/kg, respectively; Table 149), while shoot S concentration was significantly greater in treatments with a 20 mm topsoil thickness (0.45 %) than a 100 mm topsoil thickness (0.35 %; Table 149). When fertiliser was banded away from the seed, shoot Ca concentration was also significantly greater in repellent treatments with a 20 mm topsoil thickness (0.47 %) than a 100 mm topsoil thickness (0.42 %; Table 149), but shoot Zn concentration was significantly greater in repellent treatments with a 100 mm topsoil thickness (41.2 mg/kg) than a 20 mm topsoil thickness (30.7 mg/kg; Table 149).

Table 149. Effect of topsoil water repellence, topsoil thickness, and fertiliser placement on wheat shoot Ca, S, Fe, and Zn concentration (51 DAS). Mean values based on three replications. Different letters denote significant differences across rows, based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	Wettable				Repellent			
	20 mm		100 mm		20 mm		100 mm	
	Below	Away	Below	Away	Below	Away	Below	Away
Ca (%)	0.48^{a}	0.55^{bc}	0.51^{ab}	0.58^{c}	0.40^{d}	0.47^{a}	0.48^{a}	0.42^{d}
S (%)	0.53^{a}	0.47^{b}	0.55^{a}	0.41^{cd}	0.45^{bc}	0.40^{d}	0.35^{e}	0.39^{de}
Fe (mg/kg)	76.2^{ad}	69.4^{b}	71.0^{bc}	72.5^{ab}	74.2^{ac}	71.9^{ab}	78.6^{d}	73.1^{ab}
Zn (mg/kg)	28.5^{a}	30.9^{ad}	34.1^{b}	38.7^{c}	29.4^{ad}	30.7^{ad}	31.3^{d}	41.2^{e}

In wettable treatments with either a 20 or 100 mm topsoil thickness, shoot Ca concentration was significantly greater when fertiliser was banded away from the seed (0.55 and 0.58 %, respectively) than below the seed (0.48 and 0.51 %, respectively; Table 149). Shoot Zn concentration was also significantly greater in wettable treatments with fertiliser banded away from the seed (38.7 mg/kg) than below the seed (34.1 mg/kg; Table 149), but only in treatments with a 100 mm topsoil thickness. However, in wettable treatments with either a 20 or 100 mm topsoil thickness, shoot S concentration was significantly greater when fertiliser was banded below the seed (0.53 and 0.55 %, respectively) than away from the seed (0.47 and 0.41 %, respectively; Table 149). Shoot Fe concentration was also significantly greater in wettable treatments with fertiliser banded below the seed (76.2 mg/kg) than away from the seed (69.4 mg/kg; Table 149), but only in treatments with a 20 mm topsoil thickness. In repellent treatments with a 100 mm topsoil thickness, shoot Zn concentration was significantly greater when fertiliser was banded away from the seed (41.2 mg/kg) than below the seed (31.3 mg/kg; Table 149). Likewise, in repellent treatments with a 20 mm topsoil thickness, shoot Ca concentration was significantly greater when fertiliser was banded away from the seed (0.47 %) than below the seed (0.40 %; Table 149). By contrast, in repellent treatments with a 100 mm topsoil thickness, shoot Ca and Fe concentrations were significantly greater when fertiliser was banded below the seed (0.48 % Ca and 78.6 mg Fe/kg, respectively) than away from the seed (0.42 % Ca and 73.1 mg Fe/kg, respectively; Table 149), but the effect of fertiliser placement on shoot Fe concentration was not observed in repellent treatments with a 20 mm topsoil thickness. Likewise, in repellent treatments with a 20 mm topsoil thickness, shoot S concentration was also significantly greater when fertiliser was banded below the seed (0.45 %) than away from the seed (0.40 %; Table 149), but the effect of fertiliser placement on shoot S concentration was not observed in repellent treatments with a 100 mm topsoil thickness.

Shoot Mg concentrations were significantly affected by the two-way interaction of topsoil water repellence × fertiliser placement ($P < 0.05$; see Table 67 in Section 5.3.7). In both wettable and repellent treatments, shoot Mg concentration was significantly greater when fertiliser was banded away from the seed (0.27 and 0.26 %, respectively) than below the seed (0.23 and 0.24 %, respectively; Table 150). When fertiliser was banded away from the seed, shoot Mg concentration was also significantly greater in wettable treatments (0.27 %) than in repellent treatments (0.26 %; Table 150), but topsoil water repellence did not affect shoot Mg concentration when fertiliser was banded below the seed. Topsoil thickness did not affect shoot Mg concentration.

Table 150. Effect of topsoil water repellence and fertiliser placement on wheat shoot Mg concentration (51 DAS). Mean values based on a sample size of 6. Different letters denote significant differences across rows, based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	Wettable		Repellent	
	Below	Away	Below	Away
Mg (%)	0.23^{a}	0.27^{b}	0.24^{a}	0.26^{c}

Shoot Cu concentrations were significantly affected by the two-way interaction of topsoil thickness × fertiliser placement ($P < 0.001$; see Table 67 in Section 5.3.7). Shoot Cu concentration was significantly greater in treatments with a 20 mm topsoil thickness (8.06 mg/kg) than a 100 mm topsoil thickness (6.46 mg/kg; Table 151), but only in treatments with fertiliser banded below the seed. Shoot Cu concentration was also significantly greater when fertiliser was banded away from the seed (7.82 mg/kg) than below the seed (6.46 mg/kg; Table 151), but only in treatments with a 100 mm topsoil thickness.

Table 151. Effect of topsoil thickness and fertiliser placement on wheat shoot Cu concentration (51 DAS). Mean values based on a sample size of 6. Different letters denote significant differences across rows, based on the least significant difference (LSD) at P < 0.05.

Shoot nutrient concentration	20 mm		100 mm	
	Below	Away	Below	Away
Cu (mg/kg)	8.06^{a}	7.98^{a}	6.46^{b}	7.82^{a}

D.5 Total nutrient uptake

Total P uptake was significantly affected by the two-way interaction of topsoil water repellence × fertiliser placement (P < 0.05; see Table 70 in Section 5.3.8), whereby total P uptake was significantly greater in repellent treatments (5.23-8.19 mg/plant) than in wettable treatments by up to 76 % (3.43-4.65 mg/plant; Table 152), regardless of fertiliser placement. Total P uptake was also significantly greater when fertiliser was banded below the seed (4.65-8.19 mg/plant) than away from the seed by up to 57 % (3.43-5.23 mg/plant; Table 152), regardless of topsoil water repellence.

Table 152. Effect of topsoil water repellence and fertiliser placement on wheat total P uptake (51 DAS). Mean values based on a sample size of 6. Different letters denote significant differences across rows, based on the least significant difference (LSD) at P < 0.05.

Total nutrient uptake	Wettable		Repellent	
	Below	Away	Below	Away
P (mg/plant)	4.65^{a}	3.43^{b}	8.19^{c}	5.23^{a}

Total Ca uptake were significantly affected by the two-way interaction of topsoil thickness × fertiliser placement (P < 0.05; see Table 70 in Section 5.3.8). Total Ca uptake was also significantly greater in treatments with a 20 mm topsoil thickness (3.76 mg/plant) than a 100 mm topsoil thickness by 36 % (2.77 mg/plant; Table 153), but only when fertiliser was banded away from the seed. There was no effect of topsoil thickness on total Ca uptake when fertiliser was banded below the seed. In treatments with a 100 mm topsoil thickness, total Ca uptake was significantly greater when fertiliser was banded below the seed (3.65 mg/plant) than away from the seed by 32 % (2.77 mg/plant; Table 153), but the effect of fertiliser placement on total Ca uptake was not observed in treatments with a 20 mm topsoil thickness.

Table 153. Effect of topsoil thickness and fertiliser placement on wheat total Ca uptake (51 DAS). Mean values based on a sample size of 6. Different letters denote significant differences across rows, based on the least significant difference (LSD) at $P < 0.05$.

Total nutrient uptake	20 mm		100 mm	
	Below	Away	Below	Away
Ca (mg/plant)	3.70[a]	3.76[a]	3.65[a]	2.77[b]

Appendix E: **Supplementary data for Chapter 6**

E.1 Weed emergence

In separate containers, weed emergence was assessed in both wettable and repellent treatments (Figures 153 and 154). Weed emergence was significantly greater in wettable treatments (176 ± 18 weeds per container) than in repellent treatments (35 ± 11 weeds per container; *P* < 0.005), with a general increase in weed emergence as the water supply increased. Note, weeds were non-existent in wettable treatments with a 3.4 mm water supply, probably due to low soil water availability and high evaporation rate at the soil surface.

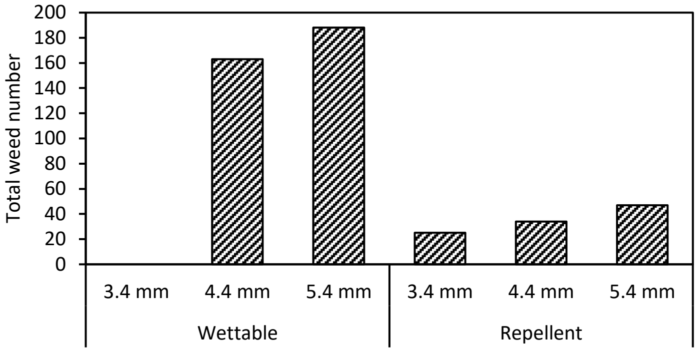


Figure 153. Average wheat seedling growth between wettable and repellent treatments, under varying watering treatments (3.4, 4.4, and 5.4 mm). Mean (± standard error) values based on three replications.

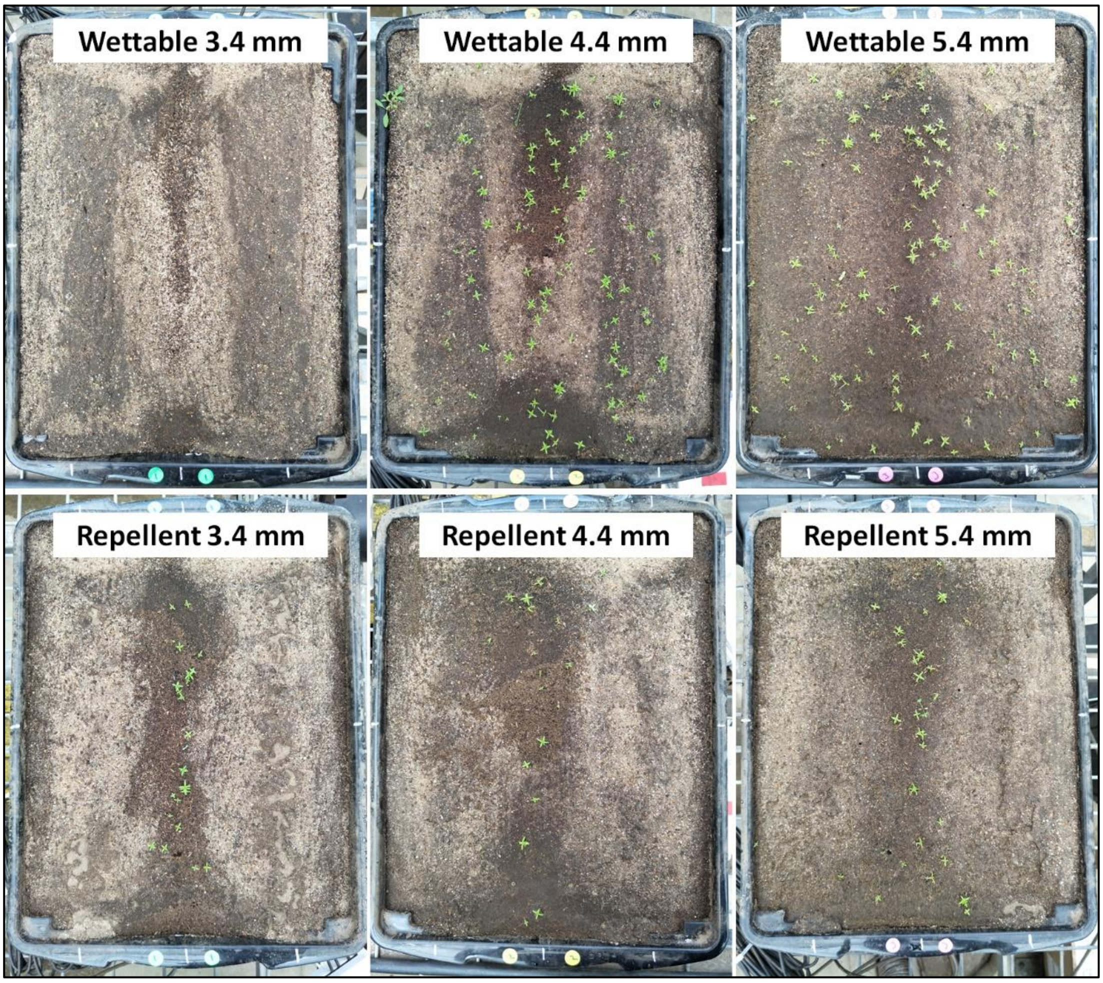


Figure 154. Weed emergence in wettable and repellent treatments, with a 3.4, 4.4, and 5.4 mm water supply.

E.2 Effect of wetting on soil nutrient availability when preparing wettable topsoil

In glasshouse experiments detailed in Chapters 5 and 6, wettable topsoil was prepared by treating water-repellent topsoil with wetting agent (Everydrop Liquid Concentrate by Scotts Australia Pty Ltd). However, this method of preparing wettable topsoil may result in confounding effects on soil nutrient availability due to soil mineralisation. Therefore, the effect of wetting agent treatment on soil NH_4-N, NO_3-N, Colwell P, and Colwell K concentration was assessed (Table 154). In this assessment, wettable topsoil was prepared by spraying and mixing 50 ml of 3 % v/v solution of wetting agent (Everydrop Liquid Concentrate by Scotts Australia Pty Ltd) per kilogram of water-repellent topsoil in a cement mixer. Wettable topsoil was left to air-dry for a week in the glasshouse and then sampled for analysis by the CSBP Soil and Plant Analysis Laboratory.

Results showed that soil Colwell P and K were not affected by wetting agent treatment, but soil NH_4-N and NO_3-N were significantly greater in wettable treatments (19 and 21 mg/kg, respectively) than in repellent treatments (14 and 13 mg/kg, respectively; $P < 0.01$), presumably due to stimulated N mineralisation. As such, N mineralisation prior to the experiment can have confounding effects on experimental treatments and the method of applying wetting agent solution to create wettable treatments, therefore, needs changing to prevent pre-experiment N mineralisation. This can be achieved by applying wetting agent solution during hand watering events.

Table 154. Effect of wetting agent treatment on soil nutrient concentrations. Mean (± standard error) values based on two replications.

	Wettable (treated)	Repellent (untreated)
NH_4-N (mg/kg)	19 ± 1	14 ± 1
NO_3-N (mg/kg)	21 ± 0	13 ± 0
Colwell P (mg/kg)	128 ± 1	121 ± 8
Colwell K (mg/kg)	154 ± 3	154 ± 11

Nevertheless, it is interesting to note that topsoil water repellence ultimately favoured early wheat growth and nutrient uptake relative to wettable topsoil treatments (see Chapters 5, 6, and 7), suggesting that increased soil NH_4-N and NO_3-N concentrations in wettable topsoils due to pre-treatment N mineralisation was not important in comparison to the benefits of water harvesting in repellent treatments.

E.3 Total nutrient uptake

The main effects of topsoil water repellence and water supply on wheat total Cu and Zn uptake were also significant ($P < 0.001$; see Table 84 in Section 6.3.8), whereby total Cu and Zn uptake was: (a) significantly greater in repellent treatments (4.77 µg Cu/plant and 21.4 µg Zn/plant, respectively) than in wettable treatments by 95 and 117 % (2.44 µg Cu/plant and 9.9 µg Zn/plant, respectively; Table 155), respectively, and (b) significantly increased as the water supply increased from 3.4 to 5.4 mm by 205 % (from 1.69 to 5.15 µg Cu/plant) and 165 % (from 8.3 to 21.9 µg Zn/plant; Table 156), respectively.

Table 155. Effect of topsoil water repellence on wheat total Cu and Zn uptake (40 DAS). Mean values based on a sample size of 9. Different letters denote significant differences across rows, based on the least significant difference (LSD) at P < 0.05.

Total nutrient uptake	Repellent	Wettable
Cu (ug/plant)	4.77^{a}	2.44^{b}
Zn (ug/plant)	21.4^{a}	9.9^{b}

Table 156. Effect of water supply on wheat total Cu and Zn uptake (40 DAS). Mean values based on a sample size of 6. Different letters denote significant differences across rows, based on the least significant difference (LSD) at P < 0.05.

Total nutrient uptake	3.4 mm	4.4 mm	5.4 mm
Cu (ug/plant)	1.69^{a}	3.97^{b}	5.15^{c}
Zn (ug/plant)	8.3^{a}	16.7^{b}	21.9^{c}

E.4 Correlations between shoot nutrient concentrations

In general, wheat shoot N, P, K, S, and Fe concentrations were strongly positively correlated with one another ($0.68 \leq R^2 \leq 0.91$; Table 157), while shoot Mn concentrations were strongly negatively correlated with shoot N, P, K, S, and Fe concentrations ($0.73 \leq R^2 \leq 0.96$).

Table 157. Bivariate correlation between wheat shoot nutrient concentrations using the coefficient of determination (R^2). Significance level (two-tailed): $P \leq 0.05$ (*) and $P \leq 0.01$ (**).

Parameter	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn
P	0.68*									
K	0.55	0.91**								
Ca	0.01	0.07	0.28							
Mg	0.27	0.16	0.33	0.71*						
S	0.87**	0.80*	0.79*	0.13	0.37					
B	0.01	0.19	0.35	0.39	0.16	0.05				
Cu	0.00	0.18	0.30	0.48	0.21	0.04	0.46			
Fe	0.79*	0.95**	0.88**	0.06	0.18	0.87**	0.16	0.07		
Mn	0.94**	0.84*	0.73*	0.04	0.25	0.96**	0.02	0.03	0.90**	
Zn	0.02	0.15	0.12	0.00	0.10	0.01	0.04	0.31	0.05	0.01

E.5 Estimating potential evaporative water loss

Soil volumetric water contents (VWC, m^3/m^3) in the furrow and inter-row at the 5 and 15 cm depths at 40 DAS (Section 6.3.9) were used to estimate the potential total evaporative water loss in wettable and repellent treatment containers, under variable water supply (3.4, 4.4, and 5.4 mm every 2 days). Given the absence of plant growth and no drainage loss below containers, the total volume of water lost from containers over the 40-day period could be attributed to evaporative water loss and was equal to the total volume of water supplied minus the estimated residual volume of water in soil on Day 40 (Table 158). The residual volume of water was estimated from the soil VWC (m³/m³) multiplied by the soil volume (m³). Table 158 reports the calculations and the estimated total volume (L) of water lost via evaporation.

Note, for the calculation, each container was divided into 8 equal parts, consisting of a primary furrow (at the centre of the container), two secondary half furrows (at both edges of the container) which is assumed to form an additional furrow, and two inter-row regions below the ridge, at the 0-10 and 10-20 cm depths (Figure 155).

Table 158. Calculating potential water loss (L) in wettable and repellent treatments with variable water supply (3.4, 4.4, and 5.4 mm every 2 days) over 40 days, based on soil volumetric water contents (VWC, m³/m³).

Calculations	Wettable			Repellent		
	3.4 mm	4.4 mm	5.4 mm	3.4 mm	4.4 mm	5.4 mm
Soil VWC (m³/m³) per soil section						
Furrow (0-10 cm)	0.07	0.12	0.22	0.15	0.14	0.25
Furrow (10-20 cm)	0.03	0.03	0.03	0.03	0.06	0.10
Inter-row (0-10 cm)	0.06	0.07	0.19	0.05	0.07	0.05
Inter-row (10-20 cm)	0.05	0.04	0.04	0.04	0.02	0.10
Water volume (m³) per soil section						
Furrow (0-10 cm)	0.00083	0.00146	0.00269	0.00181	0.00172	0.00312
Furrow (10-20 cm)	0.00040	0.00033	0.00036	0.00039	0.00070	0.00124
Inter-row (0-10 cm)	0.00075	0.00090	0.00239	0.00064	0.00082	0.00063
Inter-row (10-20 cm)	0.00057	0.00044	0.00048	0.00050	0.00029	0.00121
Water volume (L) per soil section						
Furrow (0-10 cm)	0.83	1.46	2.69	1.81	1.72	3.12
Furrow (10-20 cm)	0.40	0.33	0.36	0.39	0.70	1.24
Inter-row (0-10 cm)	0.75	0.90	2.39	0.64	0.82	0.63
Inter-row (10-20 cm)	0.57	0.44	0.48	0.50	0.29	1.21
Total water volume in containers (L)	2.55	3.13	5.91	3.33	3.53	6.20
Total volume of water supplied (L)	8.30	10.80	13.30	8.30	10.80	13.30
Total volume of water lost (L)*	5.75	7.67	7.39	4.97	7.27	7.10
Percentage of water lost (%)*	69.3	71.0	55.5	59.8	67.3	53.3

* Water lost via evaporation given the absence of plant growth and no drainage loss below containers.

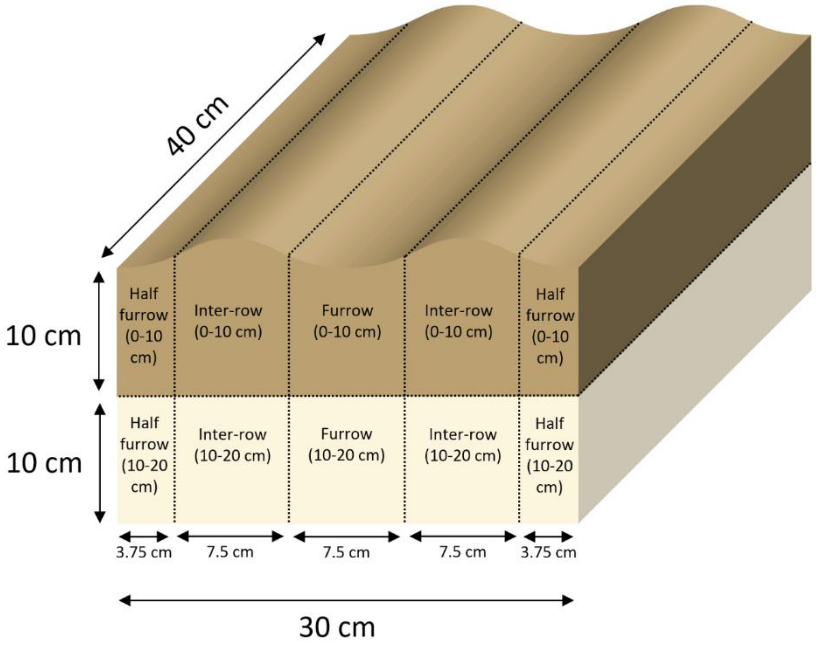


Figure 155. Estimating potential water loss in the furrows and inter-rows at the 0-10 and 10-20 cm depths of a treatment container.

Due to the positive hydraulic head of ponded water along the walls of repellent treatment containers, water infiltration resulted in soil wetting below the secondary furrows relative to the inter-row regions below the ridge which remained relatively dry. Hence, secondary furrows were included in these calculations to account for differences in soil wetting pattern between wettable and repellent treatments. Soil volumetric water contents at the 5 and 15 cm depths at Day 40 were assumed to be constant for the 0-10 and 10-20 cm depths, respectively, given the lack of data for other specific depths. The soil surface was also assumed to be relatively flat due to furrow infill and ridge erosion over time which resulted in the loss of the original ridge-furrow topography.

Results from a univariate ANOVA showed that the estimated percentage of water lost via evaporation over 40 days was not significantly affected by either topsoil water repellence or water supply (Table 159). Other studies have, however, demonstrated that water-repellent soils can act as a mulch and aid in soil water conservation by significantly reducing evaporative water loss from the soil surface (Bachmann *et al.* 2001; Gupta *et al.* 2015; Rye and Smettem 2017) by decreasing the upward capillary movement of water (DeBano 1981) and diverting water flow to subsurface layers via preferential pathways (Ritsema and Dekker 1994).

Table 159. Analysis of variance test (F values with significance level) for main effects of topsoil water repellence (SWR) and water supply (Water) on the percentage of evaporative water loss from treatment containers. Significance level (two-tailed): $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.005$ (***), and $P \leq 0.001$ (****).

Source of variation	Water loss
SWR	1^{ns}
Water	6^{ns}

^{ns} Not significant ($P > 0.05$).

In the present study, the negligible difference in evaporative water loss between wettable and repellent treatments was likely due to the lack of specific soil VWC data near the soil surface (especially in the upper 5 cm depth) where water loss differentials are likely to be greatest. Evaporative water loss at the soil surface (or the uppermost soil layer) would also be expected to be higher than that for the entire 0-10 cm depth. As a result of using soil VWC measurements from the 5 and 15 cm depths, current estimations likely underestimated the potential water loss in wettable treatments and overestimated that in repellent treatments.

Appendix F: **Supplementary data for Chapter 7**

F.1 Soil ammonium-nitrogen

Three-way interaction effects between surface topography, sampling row, and depth on soil NH_4-N concentration were also significant ($P < 0.05$; see Table 116 in Section 7.3.9), whereby soil NH_4-N concentration in the furrow and inter-row at the 0-5 cm depth was significantly greater in treatments with a ridge-furrow topography (32 and 18 mg/kg, respectively) than a flat topography (22 and 14 mg/kg; Table 160). However, soil NH_4-N concentration in the furrow at the 5-10 cm depth was significantly greater in treatments with a flat topography (305 mg/kg) than a ridge-furrow topography (257 mg/kg; Table 160). There was no effect of surface topography on soil NH_4-N concentration in the furrow at the 10-15 and 15-20 cm depths and in the inter-row at the 5-10, 10-15, and 15-20 cm depths.

Table 160. Soil ammonium-nitrogen (NH_4-N) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in treatments with either a ridge-furrow or flat topography. Mean (± standard error) values based on a sample size of 18. Significant differences based on the least significant difference (LSD) at $P < 0.05$.

Depth	Ridge-furrow		Flat	
	Furrow	Inter-row	Furrow	Inter-row
0-5 cm	$32.3^{a\dagger\Delta}$	$17.8^{a\dagger}$	$21.8^{a\Delta}$	13.8^{a}
5-10 cm	$257.2^{b\dagger\Delta}$	25.7^{b}	$304.8^{b\Delta}$	27.9^{b}
10-15 cm	$66.6^{c\Delta}$	7.6^{c}	$75.6^{c\Delta}$	6.8^{c}
15-20 cm	$45.3^{d\Delta}$	9.4^{d}	$46.5^{d\Delta}$	6.1^{c}

Different superscript letters denote significant differences within depth ($P < 0.05$).

† Significantly different from flat topography treatments ($P < 0.05$).

$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

Soil NH_4-N concentration was significantly greater in the furrow than in the inter-row, regardless of surface topography and depth (Table 160). Regardless of surface topography, soil NH_4-N concentration in the furrow and inter-row was significantly greater at the 5-10 cm depth (257-304 and 26-28 mg/kg, respectively) than at the 0-5, 10-15, and 15-20 cm depths (Table 160). Soil NH_4-N concentration in the furrow was significantly greater at the 10-15 (67-76 mg/kg) and 15-20 cm depths (45-47 mg/kg) than at the 0-5 cm depth (22-32 mg/kg; Table 160), regardless of surface topography. However, soil NH_4-N concentration in the inter-row was significantly greater at the 0-5 cm depth (14-18 mg/kg) than at the 10-15 (7-8 mg/kg) and 15-20 cm depths (6-9 mg/kg; Table 160), regardless of surface topography. Moreover, soil NH_4-N concentration in the furrow was significantly greater at the 10-15 cm depth (67-76 mg/kg) than at the 15-20 cm depth (45-47 mg/kg; Table 160), regardless of surface topography. However, soil NH_4-N concentration in the inter-row was significantly greater at the 15-20 cm depth (9 mg/kg) than at the 10-15 cm depth (8 mg/kg; Table 160) but only in treatments with a ridge-furrow topography.

F.2 Soil potassium

Results also showed significant four-way interaction effects between topsoil water repellence, plant density, sampling row, and depth on soil Colwell K concentration post-harvest at 40 DAS ($P < 0.05$; see Table 123 in Section 7.3.12). Note that the following effects of topsoil water repellence, sampling row, and depth on soil Colwell K concentration in relation to their interaction with plant density are similar to that discussed above in relation to their interaction with surface topography. Soil Colwell K concentration in the furrow at the 0-5 and 15-20 cm depths was not affected by topsoil water repellence, regardless of plant density. However, soil Colwell K concentration in the furrow at the 5-10 and 10-15 cm depths was significantly greater in wettable treatments (989-1262 and 156-170 mg/kg, respectively) than in repellent treatments (572-650 and 117-134 mg/kg, respectively; Table 161), regardless of plant density, except in treatments with a plant density of 15 plants/container whereby soil Colwell K concentration in the furrow at the 10-15 cm depth was not affected by topsoil water repellence. By contrast, soil Colwell K concentration in the inter-row was significantly greater in repellent treatments (36-196 mg/kg) than in wettable treatments (16-145 mg/kg; Table 161), regardless of plant density and depth, except in (1) treatments with a plant density of 12 plants/container whereby soil Colwell K concentration in the inter-row at the 15-20 cm depth was not affected by topsoil water repellence; and, (2) treatments with a plant density of 15 plants/container whereby soil Colwell K concentration in the inter-row at the 0-5 and 15-20 cm depths was not affected by topsoil water repellence.

Table 161. Soil Colwell potassium (K) concentration (mg/kg) post-harvest (41 DAS) in the furrow and inter-row at the 0-5, 5-10, 10-15, and 15-20 cm depths in wettable and repellent treatments with variable plant density (9, 12, and 15 plants/container). Mean values based on a sample size of 6. Significant differences based on the least significant difference (LSD) at P < 0.05.

Plant density (plants/container)	Depth	Wettable		Repellent	
		Furrow	Inter-row	Furrow	Inter-row
9	0-5 cm	126.8^{1a}	$123.8^{1a\dagger}$	139.0^{1a}	135.5^{12a}
	5-10 cm	$988.5^{1b\dagger\Delta}$	$145.3^{1b\dagger}$	$576.8^{1b\Delta}$	195.8^{1b}
	10-15 cm	$170.3^{1c\dagger\Delta}$	$21.2^{1c\dagger}$	$134.3^{1a\Delta}$	53.5^{1c}
	15-20 cm	$101.3^{1d\Delta}$	$17.1^{1c\dagger}$	$117.7^{1a\Delta}$	41.2^{1d}
12	0-5 cm	134.2^{1a}	$127.7^{1a\dagger}$	147.0^{1a}	141.0^{1a}
	5-10 cm	$1144.8^{2b\dagger\Delta}$	$143.0^{1b\dagger}$	$649.7^{1b\Delta}$	184.3^{2b}
	10-15 cm	$155.7^{1a\dagger\Delta}$	$21.2^{1c\dagger}$	$116.7^{1c\Delta}$	41.7^{12c}
	15-20 cm	$62.2^{2c\Delta}$	13.8^{1d}	$73.8^{2d\Delta}$	24.2^{2d}
15	0-5 cm	134.3^{1a}	130.2^{1a}	134.2^{1a}	129.3^{2a}
	5-10 cm	$1261.8^{2b\dagger\Delta}$	$139.3^{1a\dagger}$	$571.7^{1b\Delta}$	184.5^{2b}
	10-15 cm	$118.7^{2a\Delta}$	$15.7^{1b\dagger}$	$110.7^{1c\Delta}$	35.5^{2c}
	15-20 cm	38.8^{2c}	15.7^{1b}	$63.3^{2d\Delta}$	22.0^{2d}

Different superscript numbers denote significant differences within plant density ($P < 0.05$).
Different superscript letters denote significant differences within depth ($P < 0.05$).
† Significantly different from repellent treatments ($P < 0.05$).
$^{\Delta}$ Significantly different from the corresponding inter-row ($P < 0.05$).

Soil Colwell K concentration in the furrow and inter-row at the 0-5 cm depth was not affected by plant density, regardless of topsoil water repellence, except where soil Colwell K concentration in the inter-row at the 0-5 cm depth was significantly greater in repellent treatments with a plant density of 12 plants/container (141 mg/kg) than in treatments with 15 plants/container (129 mg/kg; Table 161). Soil Colwell K concentration in the furrow at the 5-10 cm depth was also not affected by plant density in repellent treatments, but soil Colwell K concentration in the furrow at the 5-10 cm depth was significantly greater in wettable treatments with a plant density of either 12 (1145 mg/kg) or 15 plants/container (1262 mg/kg) than in wettable treatments with 9 plants/container (989 mg/kg; Table 161), with no difference between wettable treatments with a plant density of 12 and 15 plants/container. Nevertheless, soil Colwell K concentration in the inter-row at the 5-10 cm depth was not affected by plant density, regardless of topsoil water repellence.

In repellent treatments, soil Colwell K concentration in the furrow at the 10-15 cm depth was not affected by plant density, but soil Colwell K concentration in the inter-row at the 10-15 cm depth was significantly greater in treatments with a plant density of 9 plants/container (54 mg/kg) than in treatments with 15 plants/container (36 mg/kg; Table 161). In wettable treatments, soil Colwell K concentration in the furrow at the 10-15 cm depth was also significantly greater in treatments with a plant density of either 9 (170 mg/kg) or 12 plants/container (156 mg/kg) than in treatments with 15 plants/container (119 mg/kg; Table 161), but soil Colwell K concentration in the inter-row at the 10-15 cm depth was not affected by plant density.

In repellent treatments, soil Colwell K concentration in the furrow and inter-row at the 15-20 cm depth was significantly greater in treatments with a plant density of 9 plants/container (118 and 41 mg/kg, respectively) than in treatments with either 12 (74 and 24 mg/kg, respectively) or 15 plants/container (63 and 22 mg/kg, respectively; Table 161), with no difference between treatments with a plant density of 12 and 15 plants/container. Likewise, in wettable treatments, soil Colwell K concentration in the furrow at the 15-20 cm depth was significantly greater in treatments with a plant density of 9 plants/container (101 mg/kg) than in treatments with either 12 (62 mg/kg) or 15 plants/container (39 mg/kg; Table 161), but soil Colwell K concentration in the inter-row at the 15-20 cm depth was not affected by plant density.

Soil Colwell K concentration at the 0-5 cm depth was not different between sampling rows, regardless of topsoil water repellence and plant density. However, soil Colwell K concentration at the 5-10, 10-15, and 15-20 cm depths was significantly greater in the furrow than in the inter-row (Table 161), regardless of topsoil water repellence and plant density, except in wettable treatments with a plant density of 15 plants/container whereby soil Colwell K concentration at the 15-20 cm depth was not different between sampling rows.

Soil Colwell K concentration in the furrow and inter-row was significantly greater at the 5-10 cm depth (572-1262 and 139-196 mg/kg, respectively) than at the 0-5, 10-15, and 15-20 cm depths (Table 161), regardless of topsoil water repellence and plant density, except in wettable treatments with a plant density of 15 plants/container whereby soil Colwell K concentration in the inter-row was not different between the 0-5 and 5-10 cm depths. Soil Colwell K concentration in the furrow and inter-row was also significantly greater at the 0-5 cm depth than at the 10-15 and 15-20 cm depths (Table 161), regardless of topsoil water repellence and plant density, except in (1) repellent treatments with a plant density of 9 plants/container whereby soil Colwell K concentration in the furrow was not different between the 0-5, 10-15, and 15-20 cm depths; (2) wettable treatments with a plant density of 9 plants/container whereby soil Colwell K concentration in the furrow was significantly greater at the 10-15 cm depth (170 mg/kg) than at the 0-5 cm depth (127 mg/kg); and, (3) wettable treatments with a plant density of either 12 or 15 plants/container whereby soil Colwell K concentration in the furrow was not different between the 0-5 and 10-15 cm depths. Moreover, soil Colwell K concentration in the furrow and inter-row was significantly greater at the 10-15 cm depth than at the 15-20 cm depth, regardless of topsoil water repellence and plant density, except in (1) repellent treatments with a plant density of 9 plants/container whereby soil Colwell K concentration in the furrow was not different between the 10-15 and 15-20 cm depths; and, (2) wettable treatments with a plant density of 15 plants/container whereby soil Colwell K concentration in the inter-row was not different between the 10-15 and 15-20 cm depths.

Appendix G: **Effect of topsoil water repellence on soil phosphorus availability**

G.1 Introduction

Soil water repellence can limit crop yield by impeding plant germination and establishment (Bond 1972) and plant growth and uptake (Li *et al.* 2019) as a result of heterogenous soil wetting patterns (Ritsema *et al.* 1998) and an overall reduction in plant-available water (Hallett 2008). The same hydrologic processes are likely to limit soil nutrient availability and plant uptake due to large volumes of soil remaining dry (Roper *et al.* 2015) and increased leaching potential along preferential flow pathways (Blackwell 2000). However, contrary to this hypothesis, glasshouse studies (see Chapters 5, 6, and 7) showed that preferential flow in the wettable furrow of severely water-repellent topsoil treatments significantly increased early wheat growth and nutrition relative to completely wettable topsoil treatments which exhibited even but shallow wetting. Despite preferential flow in the wettable furrow of repellent treatments, the water supplied (≤5.4 mm every two days) was not enough to cause drainage below treatment containers (≤51 DAS) but the increased wetting depths favoured deeper root growth. The resulting increase in soil water content, dissolution of the fertiliser band in the furrow at the 7 cm depth, and redistribution of soluble N and K concentrations at depth (10-20 cm) were consequently found to be correlated with early wheat growth and nutrition, while soil water and nutrient availability in the inter-row of topsoil (0-10 cm depth) were not important. Consequently, the prolonged (>30 days) dryness of repellent topsoil in the inter-rows did not adversely affect wheat growth and nutrition.

To assess more closely the dynamics of plant-available nutrients in these treatments, a supplementary glasshouse study was conducted to assess the effect of topsoil water repellence on resin-extractable (plant-available) phosphorus (P) over 31 days using identical treatment containers, under the same glasshouse conditions but in the absence of plant growth. The rationale for assessing soil P dynamics is due to its relatively higher stability in the soil compared to other key nutrients, such as N and K, which are more mobile and prone to leaching (Hodges 2010). It could, therefore, be presumed that any effects on soil P are likely to be similar, if not more pronounced, for other nutrients. It was hypothesised that: (1) soil water and phosphorus availability will increase in the furrow at depth of repellent treatments due to preferential flow and accelerated leaching relative to wettable treatments; and, (2) prolonged dryness of repellent topsoil in the inter-rows will delay the release of P by inhibiting soil mineralisation until the onset of soil wetting.

G.1.1 Using ion exchange resins for assessing soil P availability

Ion exchange resins, which act as nutrient ion sinks analogous to the mechanism of plant uptake, have been used to extract plant-available nutrients in the soil solution (Onn 1982; Qian *et al.* 1992; Dobermann *et al.* 1994; Qian *et al.* 1996; Qian and Schoenau 2005). In comparison to conventional soil test procedures that require the dissolution of chemical constituents, ion exchange extractions do not exert a destructive influence on soil constituents (van Raij *et al.* 1986; Fernandes and Coutinho 1997). Studies have also reported the superiority of ion exchange membranes over existing chemical-based soil tests in estimating relative nutrient availability in relation to plant response, especially for P (Qian *et al.* 1992; Fernandes and Coutinho 1997; van Raij 1998; Turrión *et al.* 1999; Mallarino and Atia 2005; Sousa and Coutinho 2009).

Anion exchange resins, impregnated on membrane sheets, have been employed to study soil P dynamics (Saunders 1964) and for predicting plant uptake and yield responses (Qian *et al.* 1992; Fernandes and Coutinho 1997; Mallarino and Atia 2005). Accuracy of such predictions has also been observed to increase by the addition of cation exchange resins which helps to regulate calcium ion, Ca^{2+}, activity (Curtin *et al.* 1987; Saggar *et al.* 1990; Fernandes and Coutinho 1997; Turrión *et al.* 1999). To increase the analytical speed of extractions, P extraction and elution times can also be considerably reduced (i.e., from 16 to 2 hours) without sacrificing significant predictive power (Qian *et al.* 1992; Sousa and Coutinho 2009). Therefore, ion exchange resin membrane technology can provide a more pragmatic and accurate index of P absorption under rhizospheric conditions in comparison to conventional methods of soil sampling and testing.

While a majority of studies have widely adopted ion exchange membranes for laboratory batch extractions (Saggar *et al.* 1990; Qian *et al.* 1992; McLaughlin *et al.* 1994; Kouno *et al.* 1995; Fernandes and Coutinho 1997; Turrión *et al.* 1999; Mallarino and Atia 2005; Sousa and Coutinho 2009; Cheesman *et al.* 2010; Mason *et al.* 2010; Bortolon *et al.* 2011; Butterly *et al.* 2011), the *in situ* extraction of soil nutrients can also be conducted by the direct burial of ion exchange membranes in the soil (Saunders 1964; Qian and Schoenau 1995; Subler *et al.* 1995; Qian *et al.* 1996; Cain *et al.* 1999; Ziadi *et al.* 1999; Bowatte *et al.* 2008; Meason and Idol 2008; Vandecar *et al.* 2011). As a diffusive-sensitive approach, the latter provides a useful index of soil nutrient bioavailability that enables the study of nutrient supply rates and long-term dynamics (Skogley and Dobermann 1996; Qian and Schoenau 2002).

Simultaneous extractions of other nutrients (i.e., N, K, S, Ca, and Mg) can also be achieved by using ion exchange resins (van Raij *et al.* 1986; McLaughlin *et al.* 1994; Bortolon *et al.* 2011). However, due to the complexity of such extractions and their requirement of expensive equipment, single nutrient extractions employing the cation-anion exchange resin membrane (CAERM) system (Fernandes and Coutinho 1997) will be conducted in this study to assess soil P dynamics in water-repellent soils.

G.2 Materials and methods

G.2.1 Treatment design

Soil water content, soil electrical conductivity, and soil plant-available P (soluble) were measured in a pot experiment over 31 days, from 12 August to 11 September 2018, under controlled glasshouse conditions and in the absence of plant growth at Murdoch University, Western Australia (32°04’02.30” S 115°50’20.21” E). Water-repellent topsoil (0-10 cm) was collected from a gravelly sandy loam duplex soil (Ferric Chromosol, ASC) in Kojonup (33°41’08.83” S, 117°01’54.01” E) and wettable subsoil (10-30 cm) was collected from a grey deep sandy duplex soil (Grey Bleached-Ferric Kandosol, ASC) at Meckering (31°37’31.12” S, 116°52’32.47” E). Note, subsoil from Kojonup was not used due to high gravel and clay content. Bulk soils were air-dried, sieved (≤2 mm) to remove gravel and coarse material, and thoroughly mixed in a cement mixer. Baseline properties of topsoil and subsoil are detailed in Table 162. After processing, topsoil was moderately repellent (molarity of ethanol droplet, MED, value of 2.2; King 1981). Wettable topsoil was prepared by spraying and mixing approximately 50 ml of 3 % v/v solution of wetting agent (Everydrop Liquid Concentrate by Scotts Australia Pty Ltd) per kilogram of water-repellent topsoil in a cement mixer. Note, there were no added nutrients in this soil wetting agent. All soils were left to air-dry before being used to prepare treatments.

Table 162. Baseline properties of topsoil and subsoil used in treatment containers. Soils were analysed by the methods of Rayment and Lyons (2011).

Soil properties	Topsoil	Subsoil
pH ($CaCl_2$)	5.1	5.4
Organic carbon (g/kg)	33.5	0.5
Electrical conductivity (dS/m)	0.1	0.0
NH_4-N (mg/kg)	32.0	< 1.0
NO_3-N (mg/kg)	16.0	6.0
Colwell P (mg/kg)	51.0	11.0
Colwell K (mg/kg)	113.0	17.0
Effective cation exchange capacity (cmol(+)/kg)	6.24	0.70
Exchangeable Ca (cmol(+)/kg)	5.09	0.47
Exchangeable Mg (cmol(+)/kg)	0.65	0.08
Exchangeable K (cmol(+)/kg)	0.25	0.04
Exchangeable Na (cmol(+)/kg)	0.08	0.02
Exchangeable Al (cmol(+)/kg)	0.17	0.09
S (mg/kg)	13.3	2.0
B (mg/kg)	0.54	0.11
Cu (mg/kg)	0.42	0.21
Fe (mg/kg)	22.8	10.9
Mn (mg/kg)	2.78	0.26
Zn (mg/kg)	0.71	0.17
Sand (g/kg)	722.0	871.0
Silt (g/kg)	112.0	34.0
Clay (g/kg)	166.0	95.0

Drainage holes were drilled in each container and shade cloth was placed along the bottom to prevent soil spillage. Subsoil (10 cm depth) and topsoil (10 cm depth) were layered in each container for a total depth of 20 cm. Slight ridges of approximately 2 cm high were created in the inter-row to model the ridge-furrow topography of agricultural cropping soils. Containers were tapped on the ground for every 4 cm of soil layered to re-compact the soil and create uniform bulk density. At the 7 cm depth, granular fertiliser (Growers Blue) was banded in one half of each container in the furrow and inter-rows at the following rate (mg/kg): 60 N, 25 P, 70 K, 6 Mg, 49 S, 0.5 Zn, 0.1 B, 0.3 Mn, and 0.1 Cu.

At the 4-5 and 14-15 cm soil depths, in both halves of each container, plant-available P was measured by burying 12.5 x 40 mm strips of strong acid cation (1.6±0.1 meq/g, CMI-7000S) and 10 x 50 mm strips of strong base anion (1.3±0.1 meq/g, AMI-7001S) exchange membranes supplied by Membranes International Inc., New Jersey, USA. Cation and anion strips were buried in pairs in the furrow and inter-row (i.e., 10 cm away from the furrow), with the length of strips positioned horizontally and the width vertically. A 1 cm distance was kept between the cation and anion strip faces. Note, paired cation and anion strips were placed in both halves of each container, giving a total of 12 cation and 12 anion strips per container. Approximately 300 g of wettable topsoil was used for the furrow in repellent treatments. A total of 4 treatment combinations and three replications were arranged in a completely randomised design, with the general treatment design illustrated in Figure 156.

In separate containers, soil volumetric water content (VWC, m^3/m^3) and soil electrical conductivity (EC, mS/cm) were measured *in-situ* over time using Decagon 5TE sensors. Four sensors were buried horizontally flat through the side of each container at the 5 and 15 cm depths in the furrow and inter-row. Placement of soil moisture sensors in this manner prevents interference with soil surface hydrology and surrounding bulk density as opposed to installing the sensors vertically from the soil surface. All containers were hand watered every 2 days with 540 ml (4.4 mm) of tap water over a duration of 5 minutes, equivalent to a rainfall intensity of 52.3 mm/h with a 63.2 % annual exceedance probability for the field site in Kojonup (AEP; Bureau of Meteorology 2018). Given a total of 15 separate wetting events, the total amount of water applied over 31 days was approximately 66 mm (8.1 L) per container but did not result in drainage below treatment containers. Treatments were randomised weekly to eliminate bias from environmental factors (e.g., sunlight exposure, microclimate, and microtopography).

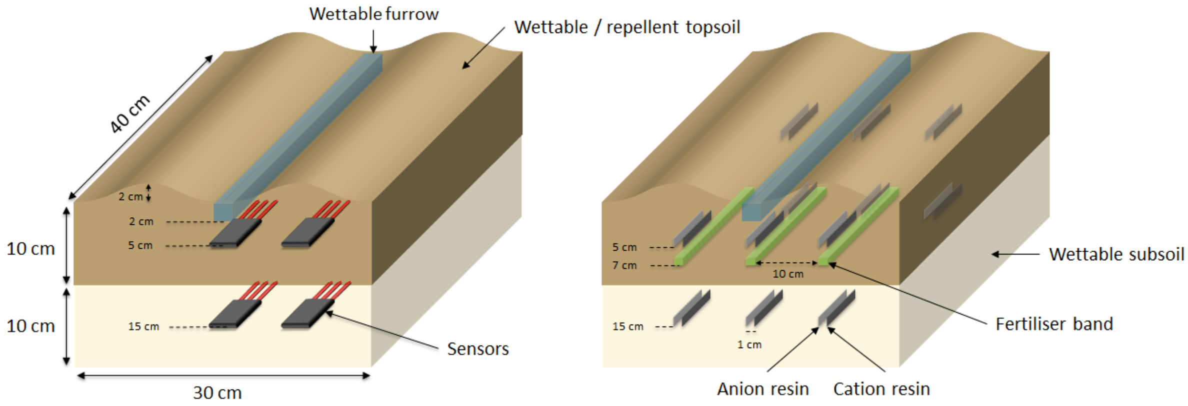


Figure 156. In-situ measurement of soil water, solute, and phosphorus (P) availability in wettable and severely repellent treatments, with and without fertiliser bands.

G.2.2 Soil measurements and extraction periods

Over 31 days, topsoil water repellence severity was determined in a separate container by the molarity of ethanol droplet, MED, test (King 1981; Crabtree and Henderson 1999). The MED test was conducted every 2 days at solar noon (±2 hours) prior to watering. Soil moisture at the 5 and 10 cm depths in the furrow and inter-row were recorded continuously using Decagon 5TE sensors equipped with an EM50 data logger.

To assess temporal changes in plant-available P, membrane strips were retrieved at various times: (i) 1 day, (ii) 5 days, (iii) 10 days, (iv) 20 days, and (v) 30 days after the first watering event. Separate containers were used for different extraction times and replicated thrice, giving a total of 30 containers (i.e., wettable and repellent topsoil, 5 extraction times, and 3 replications). Cation and anion strips were placed in separate 50 ml polypropylene centrifuge tubes and immediately rinsed thrice with deionised water to remove soil particles from the membrane. Elution of P from the anion strip was conducted immediately after rinsing. Cations were not analysed in this experiment but were kept in cold storage for future analysis. Anion strips were regenerated for future use.

G.2.3 Membrane pre-treatment and regeneration

Prior to use, cation and anion strips were converted to Na^+ form and HCO_3^- form, respectively, according to the procedure by Saggar *et al.* (1990). Cation and anion strips were placed into 500 ml beakers containing 0.5 M NaCl and 0.5 M $NaHCO_3$ solutions, respectively, and stirred occasionally for 1 hour. This step was repeated using fresh solutions for another hour and then washed with deionised water. Strips were oven-dried at 40°C prior to placement in the soil. The same procedure was used for the regeneration of resin membrane strips after usage.

G.2.4 Elution and colorimetric determination of phosphorus

Phosphorus was eluted from anion strips by adding 50 ml of 0.5 M hydrochloric acid, HCl, solution to each tube and shaking for 2 hours in an end-over-end shaker. The strips were subsequently removed from the eluent and regenerated for future use. The eluted P in the HCl solution was analysed colorimetrically by the molybdate-ascorbic acid blue method (Murphy and Riley 1962), using a Shimadzu Recording Spectrophotometer UV-1601 at 882 μm (Shimadzu Europa GmbH, Duisburg, Germany). A calibration curve was created using standard solutions of 0.0 to 1.0 mg P/L (Figure 157), prepared from the dilution of a 4 mg P/L stock solution. Note, P concentrations determined from anion strips are expressed as mg P/m^2. A detection limit of 10 mg P/m^2 was calculated (i.e., 9.3 ± 0.7 mg P/m^2), using eight blank solutions of deionised water and reagent (Murphy and Riley 1962), to allow for variability and/or error in absorbance values and prevent the over-estimation of soluble P concentrations (Table 163).

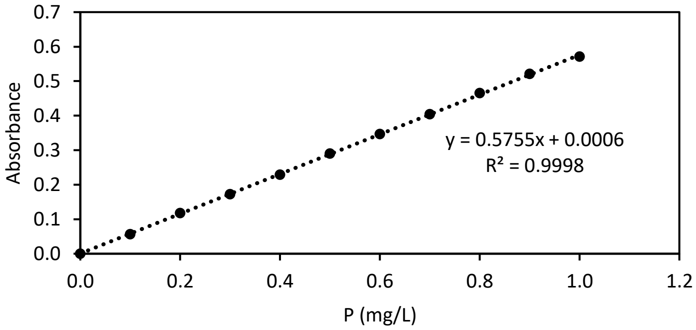


Figure 157. Calibration curve for the determination of phosphorus (P) at 882 μm, using standard solutions of 0.0 to 1.0 mg P/L.

Table 163. Determination of phosphorus (P) detection limit (mg P/m^2) using blank solutions and linear equation from the calibration curve.

Blank sample	Absorbance	P (mg/L)	P (mg/m²)
1	0.0062	0.010	9.7
2	0.0055	0.009	8.5
3	0.0060	0.009	9.4
4	0.0052	0.008	8.0
5	0.0085	0.014	13.7
6	0.0055	0.009	8.5
7	0.0055	0.009	8.5
8	0.0054	0.008	8.3
Mean	0.0060	0.009	9.3
Standard error	0.0004	0.001	0.7

G.2.5 Statistical analysis

The effect of topsoil water repellence on *in situ* soil water content, electrical conductivity (solute concentration), and soil P concentration (as resin-extractable P) were assessed in the furrow and inter-row at the 5 and 10 cm depths over 30 days. However, the effects of topsoil water repellence, fertiliser placement, and extraction time on soil P concentration could not be analysed statistically given that more than 90 % of measured soil P concentrations were below the detection limit of 10 mg P/m^2. Mean (± standard error) values of three replicates were, nonetheless, plotted for a visual comparison between treatments.

G.3 Results

G.3.1 Soil water repellence

Severity of topsoil water repellence was measured every 2 days at solar noon (±2 hours) prior to watering over 31 days (Figure 158). Topsoil prior to the first watering event was moderately repellent (MED 2.2) on Day 1 but thereafter steadily became severely repellent (MED 2.8) on Day 7. Topsoil water repellence severity remained constant until Day 17 where it reached a very severe level (MED 4.8) on Day 23 before plateauing. Note, while the soil surface of repellent soils in the inter-row became noticeably wettable on Day 19 (Figure 159), the soil immediately beneath the surface was still dry. Subsequent MED tests were, therefore, conducted below this depth, thus coinciding with the increased MED values.

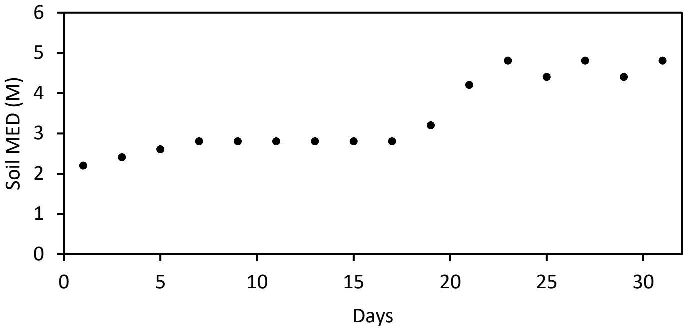


Figure 158. Severity of topsoil water repellence over 31 days, assessed by the molarity of ethanol droplet (MED) test every 2 days at solar noon (±2 hours) prior to watering.

Figure 159. Surface soil of repellent treatments on Day 19 prior to watering.

G.3.2 Soil water availability

Soil volumetric water content was measured *in-situ* over 31 days using Decagon 5TE sensors in the furrow and inter-row at the 5 and 15 cm depths, with mean values from three replicates illustrated in Figures 160a-d. Results showed immediate wetting of the soil in the furrow at the 5 cm depth in repellent treatments compared to gradual wetting in wettable treatments (Figure 160a), with greater soil water contents in repellent treatments than in wettable treatments. On Day 31, the soil water content in the furrow at the 5 cm depth was almost 2-fold greater in repellent treatments than in wettable treatments. However, soil wetting in the inter-row at the 5 cm depth was greater in wettable treatments than in repellent treatments (Figure 160b), whereby soil water content gradually increased from 0.04 m^3/m^3 (Day 1) to 0.08 m^3/m^3 (Day 19), before further increasing to 0.14 m^3/m^3 in wettable treatments (Day 31). In repellent treatments, soils remained relatively dry but small gradual increases in soil water content in the inter-row at the 5 cm depth were observed from 0.04 m^3/m^3 (Day 1) to 0.06 m^3/m^3 (Day 31; Figure 160b). By contrast, soil wetting in the furrow and inter-row at the 15 cm depth was not observed in wettable treatments (Figures 160c and d) but were observed to increase from 0.03 m^3/m^3 (Day 3) to 0.15 m^3/m^3 (Day 13), before slightly dropping to 0.12 m^3/m^3 in repellent treatments (Day 31).

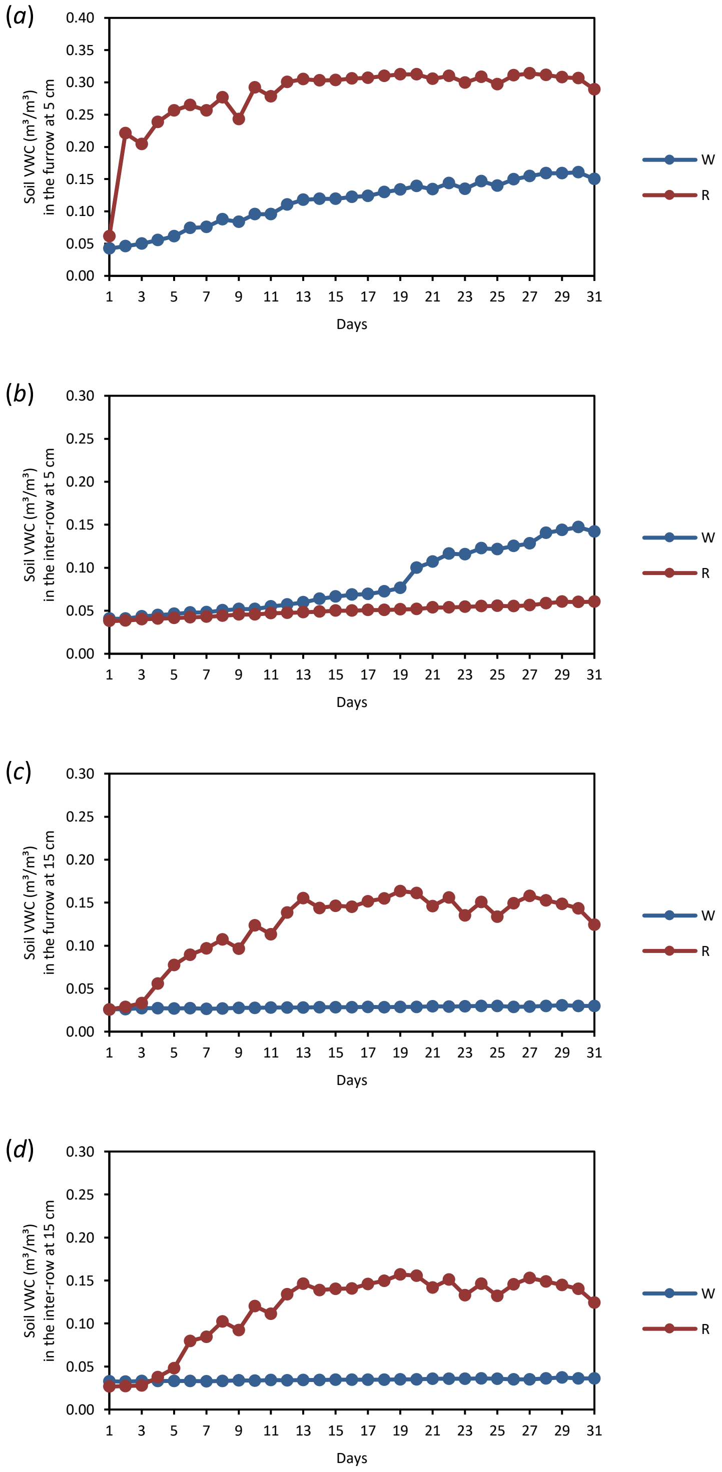


Figure 160. Soil volumetric water content (VWC, m^3/m^3) in wettable (W) and repellent (R) treatments in the furrow at (a) 5 cm and (b) 15 cm, and in the inter-row at (c) 5 cm and (d) 15 cm, over 31 days at solar noon (±2 hours).

G.3.3 Soil electrical conductivity

Soil EC, as a measure of soil solute concentration and a function of the soil water content (Brevik *et al.* 2006), was similarly affected by topsoil water repellence (Figures 161a-d). Soil EC in the furrow at the 5 cm depth of repellent treatments rapidly increased from Day 1 (0.02 mS/cm) to Day 31 (0.34 mS/cm), resulting in a 4-fold increase in soil EC relative to that in wettable treatments on Day 31 (Figure 161a). The overall rate of increase in solute concentration over time (i.e., dissolution) was, therefore, greater in repellent treatments (0.0085 mS/cm/day) that in wettable treatments (0.0031 mS/cm/day). By contrast, changes in soil EC in the inter-row at the 5 cm depth were not observed in repellent treatments as soil wetting did not occur but, in wettable treatments, soil EC increased from 0.01 mS/cm (Day 20) to 0.15 mS/cm (Day 31; Figure 161b). Nevertheless, there were no changes in soil EC at the 15 cm depth in wettable treatments (Figures 161c and d) due to limited wetting (<15 cm; Figures 161c and d). In repellent treatments, however, soil EC in the furrow and inter-row at the 15 cm depth increased from 0.00 mS/cm (Day 3) to 0.06 mS/cm (Day 27), before slighting dropping to 0.03 mS/cm (Day 31; Figures 161c and d), but such increases in soil EC were relatively minor in comparison to that at the 5 cm depth.

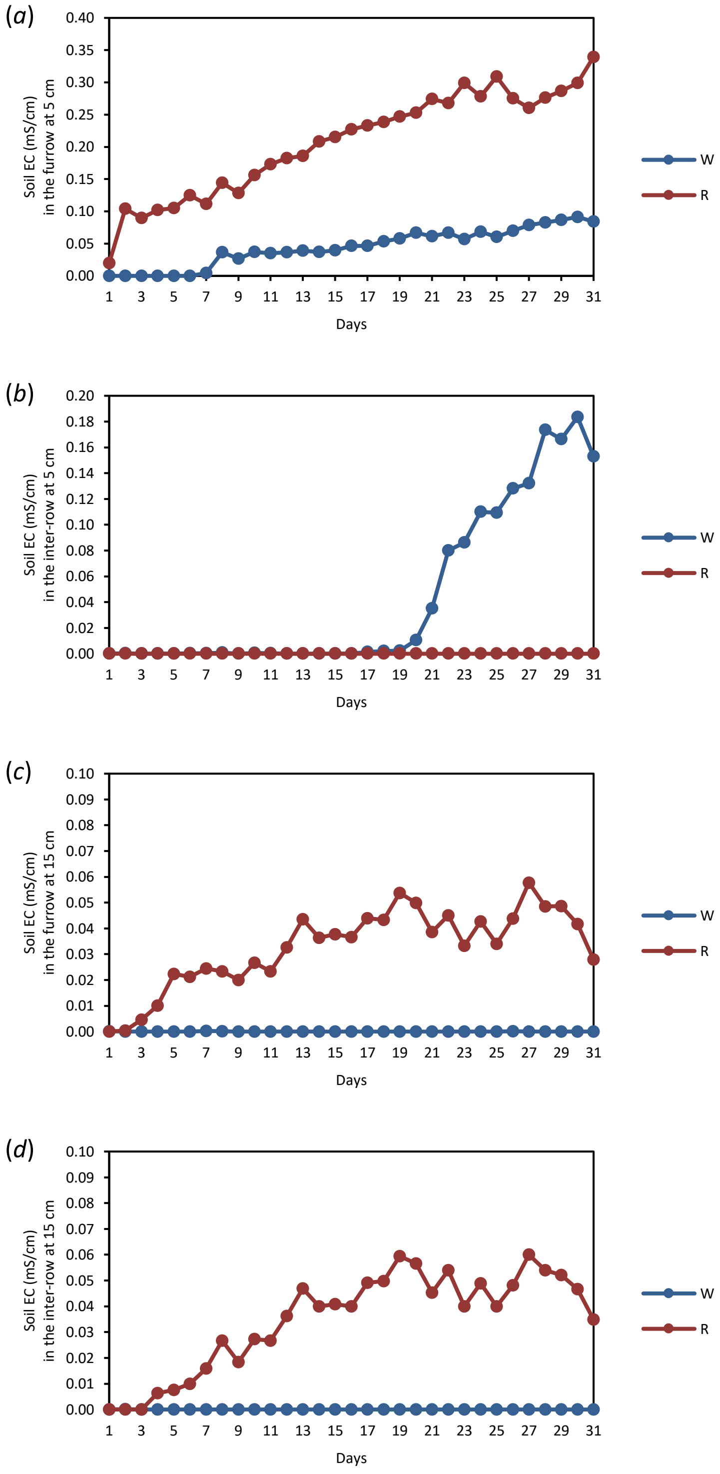


Figure 161. Soil electrical conductivity (EC, mS/cm) in wettable (W) and repellent (R) treatments in the (a) furrow at 5 cm, (b) inter-row at 5 cm, (c) furrow at 15 cm, and (d) inter-row at 15 cm, over 31 days at solar noon (±2 hours).

G.3.4 Soil phosphorus availability

Soil P concentrations (as resin-extractable P) were measured from anion strips buried in the furrow and inter-row at the 5 and 15 cm depths in wettable and repellent treatments on Day(s) 1, 5, 10, 20, and 30. However, more than 90 % of measured soil P concentrations fell below the detection limit of 10 mg P/m^2 (Figures 162 and 163) which included those in: (1) wettable treatments, regardless of fertiliser placement and extraction time, and (2) repellent treatments at the 5 cm depth, regardless of fertiliser placement and extraction time. However, in repellent treatments with fertiliser banded at the 7 cm depth, soil P concentrations were found to increase in the furrow at the 15 cm depth from Day 1 (<10 mg P/m^2; Figure 162 a) to Day 5 (103 mg P/m^2; Figure 162 b) and then to Day 10 (349 mg P/m^2; Figure 162 c), before dropping to borderline levels on Day 20 (12 mg P/m^2; Figure 162 d) and disappearing on Day 30 (<10 mg P/m^2; Figure 162 e). On Day 20, borderline soil P concentrations were also observed in the inter-row at the 15 cm depth in repellent treatments with banded fertiliser (12 mg P/m^2; Figure 163d) but soil P concentrations elsewhere in the inter-row were nonetheless below the detection limit.

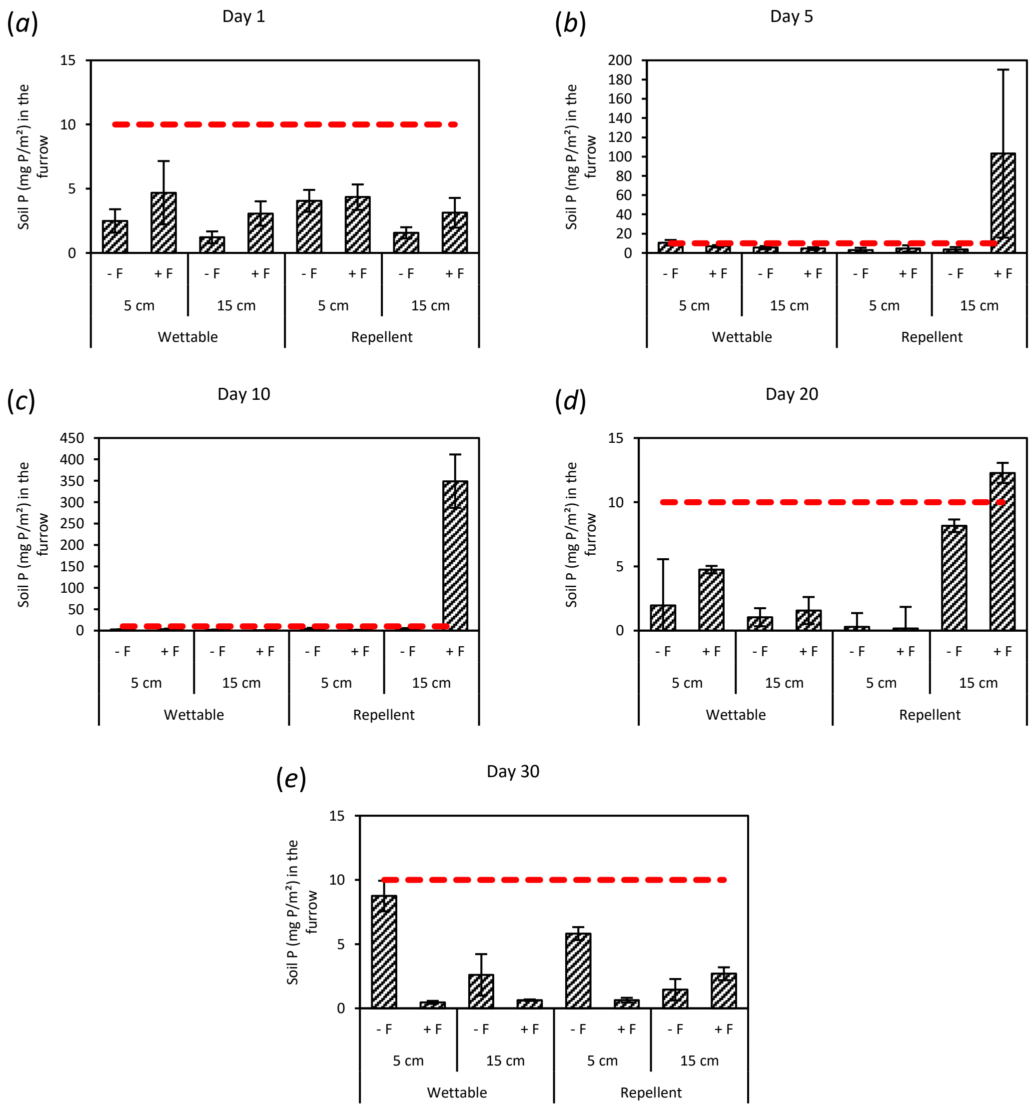


Figure 162. Soil phosphorus concentration (mg P/m^2) in the furrow at the 5 and 15 cm depths in wettable and repellent treatments, with (+ F) and without (- F) banded fertiliser on (a) Day 1, (b) Day 5, (c) Day 10, (d) Day 20, and (e) Day 30. Detection limit of 10 mg P/m^2 denoted by red line.

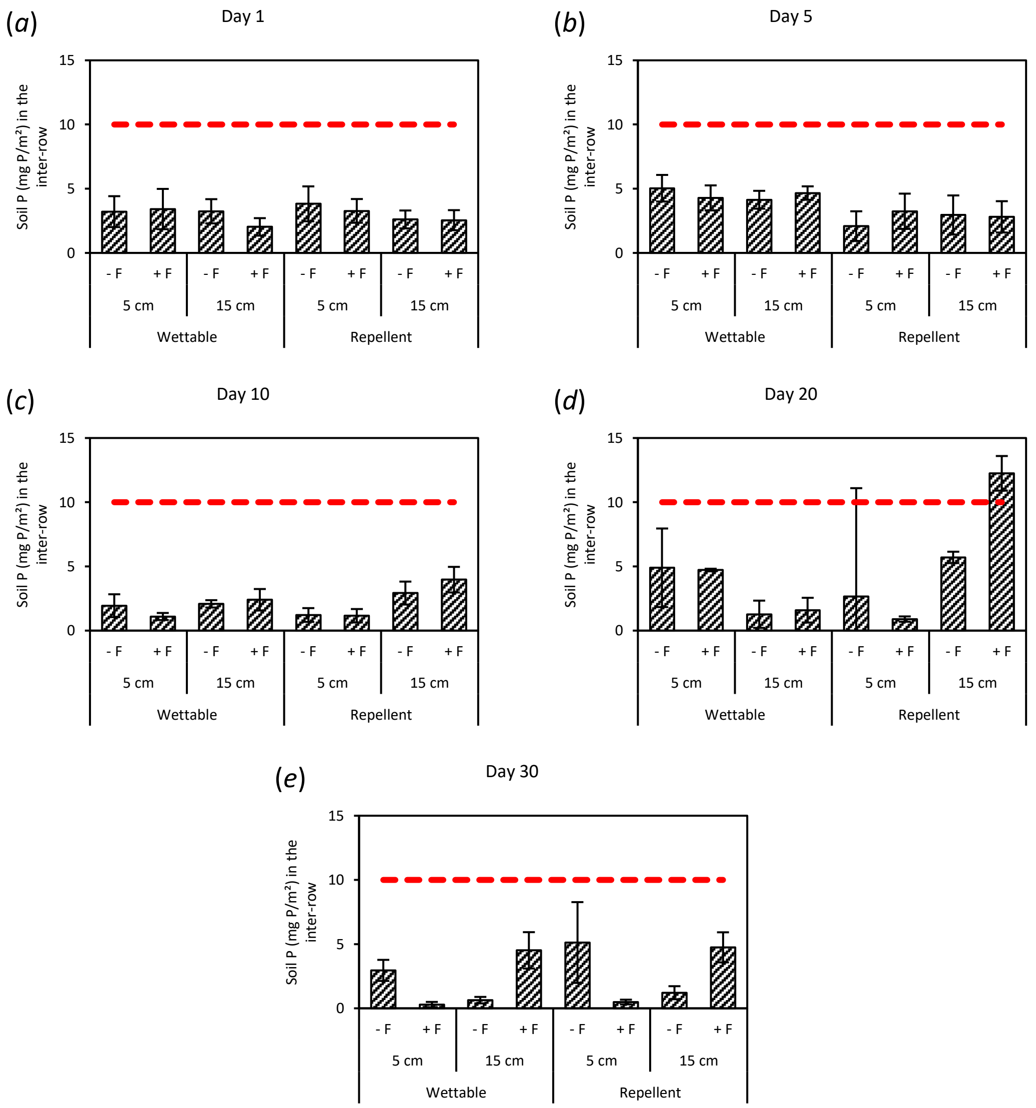


Figure 163. Soil phosphorus concentration (mg P/m^2) in the inter-row at the 5 and 15 cm depths in wettable and repellent treatments, with (+ F) and without (- F) banded fertiliser on (a) Day 1, (b) Day 5, (c) Day 10, (d) Day 20, and (e) Day 30. Detection limit of 10 mg P/m^2 denoted by red line.

G.4 Discussion

The effect of severe topsoil water repellence on soil water content, solute concentration (EC), and soil P concentration (as resin-extractable P) in the furrow and inter-row at the 5 and 15 cm depths was assessed over 31 days, under controlled glasshouse conditions in the absence of plant growth. In repellent treatments, severe topsoil water repellence persisted throughout the experiment despite supply of 4.4 mm every two days (total of 66 mm), which induced preferential flow in the wettable furrow of repellent treatments. This resulted in the rapid increase in soil water content and solute concentration in the furrow at the 5 and 15 cm depths and in the inter-row at the 15 cm within the first week but did not result in drainage below treatment containers, despite the absence of plants. By contrast, uniform wetting and retention of water in wettable treatments effectively decreased the overall wetting rate and water content at the 5 cm depth, resulting in a limited wetting depth (<15 cm). Repellent topsoil in the inter-row at the 5 cm depth remained relatively dry throughout the experiment and, therefore, the release of mineralised nutrients could not be assessed.

In-situ measurements using anion resin strips confirmed the rapid movement of soluble P in the furrow at the 15 cm depth from Day 5 which peaked on Day 10 before declining to borderline levels on Day 20. Soluble P in the inter-row at the 15 cm depth also increased on Day 20 which can be attributed to the lateral diffusion of the wetting front after bypassing the water-repellent topsoil layer (0-10 cm). This flush in soluble P, however, only occurred below the fertiliser band (7 cm depth), suggesting that fertiliser P will be a key source of plant-available P early in the growing season. Note, soluble P was not detected at the 15 cm depth in wettable treatments due to limited wetting depth (<15 cm). Negligible detection of soluble P at the 5 cm depth could be due to phosphate being strongly bound to organic matter, clay, and Fe/Al/Mn oxides in this sandy loam topsoil (Lehmann and Schroth 2003) in comparison to pale sandy soils (e.g., Tenosols) which have a low sorption capacity and high permeability (Weaver *et al.* 1988; Tischner 1999). Although the phosphorus buffering index (PBI) of these sandy loam soils could be considered low (PBI = 95) in comparison to other in finer-textured loamy or clayey soil types (high PBI >280; Moody 2007; Wong *et al.* 2012), results suggests that starter P fertiliser would probably be required to maintain adequate plant P uptake during early growth stages, despite seemingly adequate soil Colwell P concentrations of 51 mg/kg. In comparison to other conventional chemical-based soil tests, many studies have also reported the superiority of using ion exchange membranes in estimating soil P availability in relation to plant P response (Qian et al. 1992; Fernandes and Coutinho 1997; van Raij 1998; Turrión et al. 1999; Mallarino and Atia 2005; Sousa and Coutinho 2009), with their ability to even correctly assess P deficiencies in plants grown on heavily fertilised soils (e.g., soil Colwell P levels exceeding 100 mg/kg; Kusomo *et al.* 2001; Moody 2007).

At the onset of the early season rain, however, excessive leaching of nutrients and other solutes may occur before crops are sown and bypass the rooting zone (Lehmann and Schroth 2003), and this can limit crop nutrient uptake and reduce overall yield (van der Paauw 1962). Many studies also indicate the increased risk of groundwater contamination by agrochemical leaching along preferential pathways in water-repellent topsoils (Hendrickx *et al.* 1993; Nguyen *et al.* 1999; Blackwell 2000). However, given that deep leaching to the base of treatment containers did not occur after the application of 15 separate 4.4 mm wetting events over 30 days, this would suggest that frequent, small rainfall events during early crop growth may not result in substantial leaching, at least from sandy loam topsoils. Under the same water regime, excessive leaching of water and nutrients could well occur in pale sandy soils (e.g., Tenosols) due to the a comparatively lower clay content (<5 %) and hence lower absorptive surface area and cation exchange capacity (Davenport *et al.* 2011). The degree of leaching would also be greatly reduced in the presence of plants and roots due to continuous water uptake and transpiration, including root adaptations for capturing leached nutrients such as nitrate (Liao *et al.* 2006; Wang *et al.* 2016). Arbuscular mycorrhizal fungi can also significantly reduce nutrient leaching due to the enhanced foraging capacity of plant-mycorrhizal root systems (Asghari and Cavagnaro 2011). Alternatively, deep percolation of water may in turn promote deeper rooting depths (Whitmore and Whalley 2009) and allow roots to access deep-stored water and nutrient supplies (Dunbabin *et al.* 2003). In semi-arid dryland cropping systems where seasonal water deficits are common, increased subsurface water storage and rooting depth due to preferential flow could, therefore, improve crop water use efficiency, drought stress resistance, and overall productivity (Kirkegaard *et al.* 2007; Chloupek *et al.* 2010; Comas *et al.* 2013; Lobet *et al.* 2014).

In wettable treatments, limited wetting depths and slow wetting rates may result in the development of shallow root systems that may also be prone to drying (Weaver 1926; Dunbabin *et al.* 2003). Evaporative water loss from the soil surface would also be considerably higher in wettable treatments than in repellent treatments due to: (1) a greater exposure of moisture in the wettable surface layer, and (2) decreased capillary forces in repellent soils which are necessary to move water to the soil surface (DeBano 1981). This would also explain why soil water content in the furrow at the 5 cm depth was consistently low in wettable treatments relative to repellent treatments throughout the experiment despite frequent watering. The ability of water-repellent topsoil to reduce net evaporative water losses has also been observed in other studies by up to 90 % (Gupta *et al.* 2015; Rye and Smettem 2017). Therefore, assuming negligible leaching losses, topsoil water repellence could help conserve plant-available water by reducing evaporative losses.

Inter-row soils of dry water-repellent topsoil may limit the release and transport of key plant nutrients by delaying rewetting events and by protecting organic matter from microbial degradation (Piccolo *et al.* 1999; Goebel *et al.* 2005; Arcenegui *et al.* 2008). This could consequently have implications for the timing of mineralisation and early season plant nutrient uptake. Wetting of topsoil in the inter-row (5 cm) of wettable treatments resulted in a spike in solute concentration from Day 19 to 29, presumably due to the dissolution of salts and mineralisation of organic matter. By contrast, this was not observed in the inter-row at the 5 cm depth in repellent treatments due to prolonged soil dryness over 30 days. In particular, large quantities of nutrients, such as nitrate (NO_3^-), can be released by a flush in mineralisation after the rewetting of dry soil and this would consequently expose nitrate to leaching and biological immobilisation (Lehmann and Schroth 2003). Protection of topsoil N from an early season flush in mineralisation after high rainfall events (~50 mm) could, therefore, prevent excessive N leaching and conserve N supply for when crops are sown and/or more developed. Additional losses in soil N may also be attributed to the volatilisation of gaseous ammonia (NH_3) under warm, moist, and/or alkaline conditions, particularly after urea fertiliser (Cameron *et al.* 2013), and/or the denitrification of soil NO_3^- which produces gaseous nitrous oxide (N_2O), nitric oxide (NO), and di-nitrogen (N_2) under wet, anaerobic conditions (Giles *et al.* 2012). While microbial denitrification is unlikely to occur in free-draining sandy soils, texture-contrast soil types (i.e., Chromosol) that have a sandy topsoil over clayey subsoil are more prone to waterlogging and consequently denitrification (McFarlane and Wheaton 1990; Bronson and Fillery 1998). By contrast, stored nutrients could be released and made available to plants later in the season when soil water repellence breaks down and soils wet up after winter rain (Crockford *et al.* 1991; Rye and Smettem 2015) and when soils are warmer and mineralisation increases during spring in the Mediterranean climate (Lawson 2015). Increasing synchrony between nutrient release in inter-row and plant nutrient demand is key for improving fertiliser use efficiency and crop productivity (Myers *et al.* 1994). However, the short duration of this experiment precludes testing this hypothesis.

While preferential flow and leaching are unavoidable consequences of soil water repellence, results of this study indicate that, under a frequent low water supply and no permanent leaching loss, topsoil water repellence can have a positive effect on early season soil water availability, by: (1) increasing the amount of water harvested in a wettable furrow and at depth via preferential flow, and (2) decreasing net evaporative water losses from the soil surface layer. By contrast, heavy rainfall and preferential flow events early in the growing season may result in rapid mobilisation and leaching of nutrients beyond the root zone in sandy soils, including the accelerated leaching of fertiliser P, which could have adverse implications for plant growth. However, increased protection of organic nutrients (especially N) in repellent topsoil from early season mineralisation and leaching losses could be beneficial for plants when mineralised nutrients are released at a time when crops have a high nutrient demand. Nevertheless, the effect of topsoil water repellence on soil mineralisation dynamics could not be directly assessed in this experiment due to prolonged soil dryness throughout the 31-day experiment.

G.5 Conclusion

Preferential flow in the wettable furrow of severely water-repellent topsoil treatments significantly increased soil water content in the furrow at the 5 and 15 cm depth, leaving topsoil in the inter-row at the 5 cm depth relatively dry over 31 days. By contrast, uniform distribution and increased retention of applied water in the surface layer of wettable treatments effectively decreased overall soil water contents at the 5 cm depth and wetting rates (i.e., time taken for water to penetrate at depth) which ultimately limited wetting depths to <15 cm. The enhanced wetting patterns under furrow observed in repellent treatments also resulted in the rapid mobilisation and leaching of soluble P from the fertiliser band which peaked on day 10 at the 15 cm depth. Results also suggest the importance of fertiliser to supply plant-available P at the start of the growing season due to the negligible soluble P levels extracted from the unfertilised bulk soil. Although leaching did not occur beyond treatment containers in the present study, higher rainfall and preferential flow events early in the season may deplete the supply of plant-available nutrients in the furrow or fertiliser band and this may have consequences for crop growth and nutrition. A portion of organic nutrients in the intervening regions of dry water-repellent topsoil may, however, be protected from early season rewetting events and their later release into the season (> 31 days) may benefit plant growth and nutrition. Nevertheless, soil water availability will be the main driver limiting crop growth and yield in semi-arid dryland cropping systems. Therefore, efforts to limit evaporative water losses and increase subsurface water storage via preferential flow in soils with topsoil water repellence could potentially improve crop water use efficiency, drought stress resistance, and overall productivity.

Appendix H: **Effect of wetting agent concentration on soil phosphorus availability**

H.1 Introduction

The effect of wetting agent concentration on soil phosphorus (P) availability in treated (wettable) topsoil was assessed as a supplementary experiment to glasshouse studies conducted. The aim of this study was to ensure that the effect topsoil water repellence (or soil wettability) on soil phosphorus was independent of wetter concentration. It was hypothesised that differences in wetting agent concentration in soil will have no significant effect on soil P availability so long as the soil is completely wettable.

H.2 Materials and methods

H.2.1 Treatment design

Soil P concentrations in topsoils treated with three rates of wetting agent were assessed using strong base anion membrane strips (10 x 50 mm; Membranes International Inc., New Jersey, USA) in 2 L pots incubated over 2, 5, and 10 days, under controlled glasshouse conditions and in the absence of plant growth at Murdoch University, WA (32°04’02.30” S 115°50’20.21” E; (Figure 164). To prepare treatments, water-repellent topsoil (≤2 mm) derived from a gravelly sandy loam duplex soil (Ferric Chromosol, ASC) in Kojonup (33°41’08.83” S, 117°01’54.01” E) was treated with three rates of wetting agent – that is, 50 ml of either 3, 6, or 15 % v/v of wetting agent (Everydrop Liquid Concentrate by Scotts Australia Pty Ltd) per kilogram of soil. Note, the wettable topsoil used in Chapter 6 was prepared from 50 ml of 3 % v/v of the same wetting agent per kilogram of soil, with exception to SE14® that was used in Chapter 5. Soils were left to air-dry before being used to prepare treatments.

Granular fertiliser (Growers Blue) was evenly spread at the 1 cm depth at the following rate (mg/kg): 480 N, 200 P, 560 K, 48 Mg, 392 S, 4 Zn, 0.8 B, 2.4 Mn, and 0.8 Cu (i.e., 8 times the application rate in previous experiments to create uniform spread). Four anion membrane strips were placed at the 6 and 11 cm depths (i.e., 5 and 10 cm below the fertiliser layer), with the length of membrane strips positioned horizontally and the width vertically. Resins at each layer were placed 90° relative to the other to form a criss-cross (lattice) pattern to avoid disrupting the vertical flow of leachate. Treatments were replicated trice, giving a total of 27 pots. To generate sufficient leaching, pots were hand watered every two days with 40 mm (620 ml) of tap water.

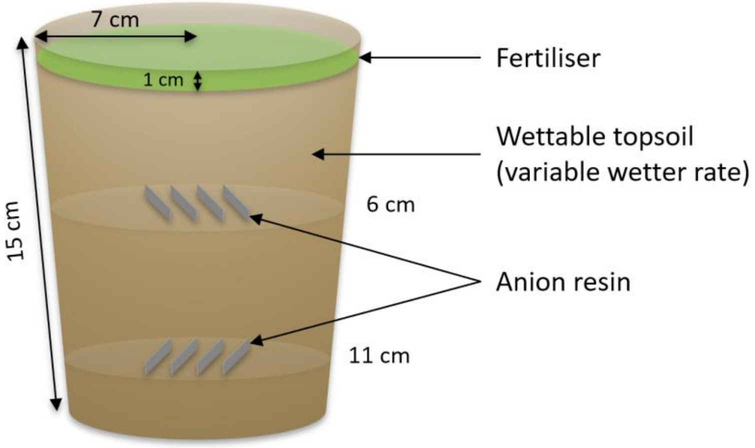


Figure 164. Wetting agent treatment design with fertiliser evenly spread at the 1 cm depth and anion membrane resins at the 6 and 11 cm depth.

H.2.2 Sampling and extraction times

Membrane strips were retrieved at three times: (i) 2 days, (ii) 5 days, and (iii) 10 days after the first watering event. Anion membrane strips were placed in separate 50 ml polypropylene centrifuge tubes and rinsed thrice with deionised water to remove soil particles from the membrane. Phosphorus was eluted from anion strips by adding 50 ml of 0.5 M hydrochloric acid, HCl, solution to each tube and shaking for 2 hours in an end-over-end shaker. The strips were subsequently removed from the eluent and regenerated for future use. The eluted P in the HCl solution was analysed colorimetrically by the molybdate-ascorbic acid blue method (Murphy and Riley 1962), using a Shimadzu Recording Spectrophotometer UV-1601 at 882 μm

(Shimadzu Europa GmbH, Duisburg, Germany). A calibration curve was created using standard solutions of 0.0 to 1.0 mg P/L (see Figure 157 in Appendix G.2.4), prepared from the dilution of a 4 mg P/L stock solution. Note, P concentrations determined from anion strips are expressed as mg P/m^2. A detection limit of 10 mg P/m^2 was calculated (i.e., 9.3 ± 0.7 mg P/m^2), using eight blank solutions of deionised water and reagent (Murphy and Riley 1962), to allow for variability and/or error in absorbance values and prevent the over-estimation of soluble P concentrations (see Table 163 in Appendix G.2.4).

H.2.3 Statistical analysis

Significant differences in resin-extractable P concentration between wetter treatments and different extraction times were determined from the two-sample t-test (one-tail) in Microsoft Excel (2016).

H.3 Results and discussion

The effect of wetting agent concentration on resin-extractable soil P concentration at the 6 and 11 cm depth was assessed over 2, 5, and 10 days (Figure 165). Given a detection limit of 10 mg P/m^2, changes in P were not detected at the 11 cm depth. However, at the 6 cm depth, P was detected but effects of wetting agent concentration (1X, 2X, or 5X where X is the standard application rate of 3 % v/v) on resin-extractable P after Day 2, 5, or 10 were not significant. These results were consistent with the hypothesis that wetting agent concentration in soil will have no significant effect on soil P availability so long as the soil is completely wettable.

Due to the high variability of resin-extractable P in treatment replicates, there was also no significant change in P over time, between Day 2, 5, and 10, despite an increasing trend in P due to fertiliser leaching.

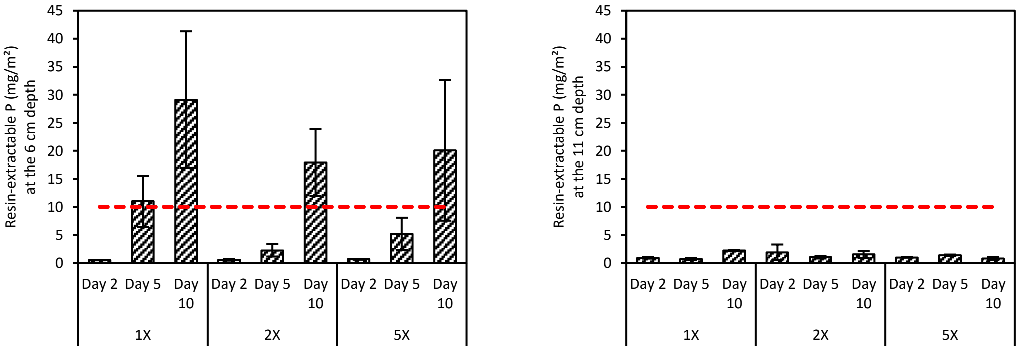


Figure 165. Effect of wetting agent concentration (1X, 2X, and 5X) on resin-extractable phosphorus (P, mg/m^2) at the 6 and 11 cm depth over 2, 5, and 10 days. Mean (± standard error) values based on three replications. Detection limit of 10 mg P/m^2 indicated by red line.

H.4 Conclusion

Increasing the wetting agent concentration in treated soils by 2 or 5-fold the standard application rate (3 % v/v) did not significantly affect resin-extractable P concentration at the 6 or 11 cm depth in sandy loam soil. However, leaching of P from surface-applied fertiliser was observed at the 6 cm depth over the 10-day glasshouse experiment. Differences in the rate of wetting agent application would, therefore, be unimportant for soil P availability so long as treated soils are completely wettable. relation to earlier glasshouse experiments, the effect of topsoil water repellence (i.e., soils untreated by wetting agent) on soil P availability and early plant growth and nutrition can then be attributed to soil water availability rather than to an effect of the wetting agent concentration on P availability.