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The nature of highly calcareous soils and their impact on crop productivity. *A literature review.*

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- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2018), and provided constructive feedback which was considered and addressed by the author(s).

Keywords

Calcareous soils, soil constraints, phosphorus, iron deficiency, cropping

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Contents

1 Introduction

Calcareous soils are those where calcium carbonate (either soft carbonate fractions or limestone) is an important part of the soil composition within at least some layers of the soil profile. These soils are widespread in south-eastern Australia but within the agricultural zone are most common in low rainfall areas. The upper Eyre Peninsula (EP) is an agricultural region where calcareous soils, including some that are extremely high in carbonate throughout the profile, dominate the landscape. Despite calcareous soils being most common in drier environments, they are also important soils in areas such as the South-East and Yorke Peninsula (YP) of South Australia (SA) as well as other parts of Australia.

The nature of calcareous soils results in many constraints to agricultural productivity and while these constraints may not be unique to calcareous soils, they are often most extreme in these soils. Rhizoctonia root rot, boron toxicity and phosphorus deficiency are just three issues that can be both severe and widespread in crops and pastures grown in calcareous soils, especially in highly calcareous soils.

The purpose of this review is to summarise the following:

- Where calcareous soils occur within the agricultural zone of southern Australia with emphasis on the upper EP and South-East regions of SA.
- The types of farming systems practised on them, how their productivity rates in terms of their water-limited potential, and how much of any productivity gaps are due to the properties of their calcareous soils. The major focus will be on highly calcareous soils because they tend to manifest these constraints most severely.
- Local research already conducted into constraints posed by calcareous soils.
- Gaps that exist in that knowledge, and opportunities for improved productivity for farming systems on calcareous soils.

This document is an early step in the delivery of a research initiative that will identify the impacts of topsoil and subsoil chemical conditions of highly calcareous soils on crop productivity on the upper Eyre Peninsula and in the South-East of South Australia. Integrated solutions to reduce the impact of these multiple constraints to cropping will then be developed.

2 Where do calcareous soils occur?

Author: B Masters

Calcareous soils (Calcarosols) are those where calcium carbonate is an important part of the soil composition within at least some layers of the soil profile. They are widespread across southern Australia. In the agricultural zone they are most common within the low rainfall zone (mean rainfall between 200 and 350 mm) where "the presence of carbonates in the soil profile derives from low rainfall and a general lack of strong leaching" (McKenzie et al. 2004).

Calcareous soils can contain variable amounts and forms of calcium carbonate throughout the profile and lack a clear or abrupt texture change (McKenzie et al. 2004; Hall et al. 2009) with field texture (and often carbonate content) increasing with depth. Carbonates can either be present as 'soft' finely divided fractions <2 mm in diameter or hard carbonate (rubbly) segregations. In South Australia these soils are commonly used for broadacre cropping, pasture, and in some cases irrigated horticulture. Key sub-regions within South Australia that have a high proportion of highly calcareous soils include upper and western EP and lower YP, while moderately calcareous soils are prevalent in the crop-producing areas of central EP, upper YP, the Murray Mallee and the lower South-East (Figure 1).

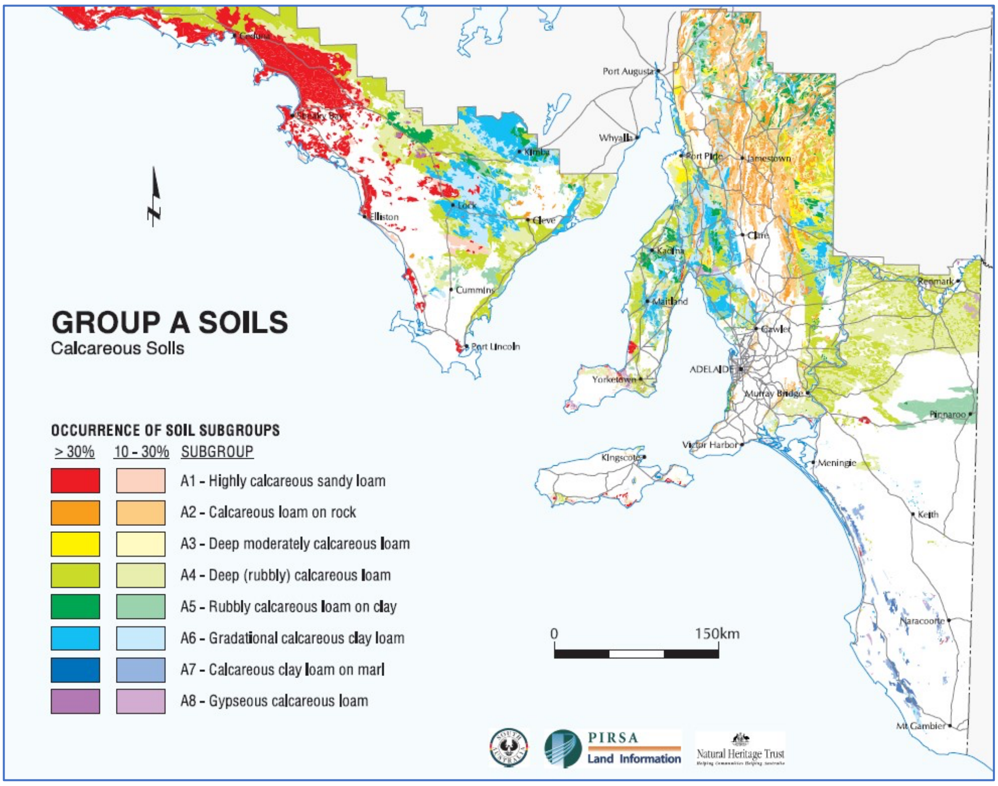


Figure 1. Distribution of Group A calcareous soils in South Australia. *Map Sourced from DWBLC Soil and Land Information Unit 'Soils of South Australian Agricultural Lands' (2002).*

Calcareous soils can be broadly categorised based on the amount of carbonate present within the soil profile:

- ***Very highly calcareous soils*** – sands to loams where carbonate is greater than 20% throughout the profile (and sometimes greater than 50%).
- ***Highly calcareous soils –*** carbonate content is greater than 8% throughout the profile but increasing with depth.
- ***Calcareous soils*** – calcareous layers are evident throughout most of the profile, with variable carbonate content (mostly less than 20%).

2.1 Calcareous soils in South Australia

Very highly calcareous soils occur on about 1 M ha (10%) of the total land in South Australia cleared for agriculture, with a significant concentration on the EP (Figure 2) where 29% of the land cleared for agriculture in this region falls into this category (DWLBC 2007). Where the carbonate content is more than 40% (by analysis) in the top 10 cm, these soils are classified as Supravescent Calcarosols (Isbell 2016). These soils are represented by soil groups A1 (highly calcareous sandy loam), B1 (shallow highly calcareous sandy loam on calcrete) and H1 (carbonate sands).

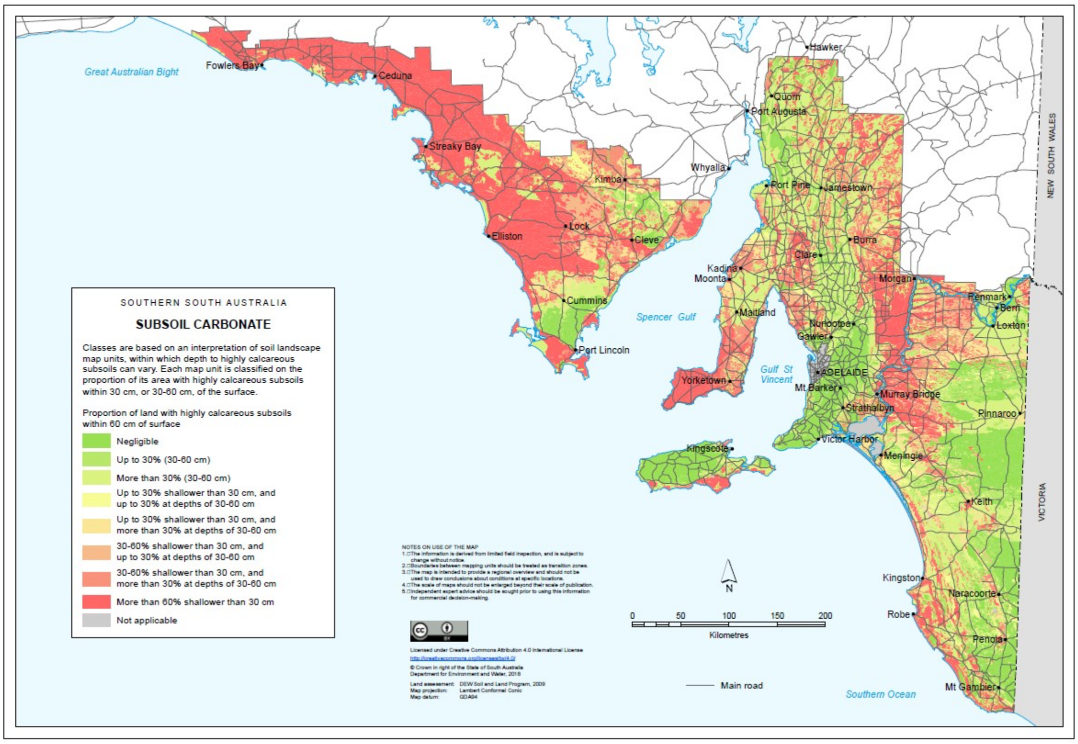


Figure 2. Extent and proportion of subsoil carbonate on Eyre Peninsula soils. *Map sourced from* https://data.environment.sa.gov.au/Content/Downloads/SoilAttrib_SA_SubsoilCarbonate.pdf *(28/01/2020).*

Highly calcareous soils are soils where carbonate is present throughout the profile and is greater than 8% in the subsoil, increasing to >20% with depth. Where these soils contain between 8 and 40% carbonate in the top 10 cm they are classified as Hypervescent Calcarosols (Isbell 2016). These soils occur on around 2.5 M ha (25%) of land cleared for agriculture in South Australia with significant concentrations in the EP, Northern and Yorke and South Australian Murray Darling Basin regions (>30% of the region's agricultural lands). These soils are represented by soil groups A2 (calcareous loam on rock), A4 (deep rubbly calcareous loam), A5 (calcareous loam on clay), A6 (gradational calcareous clay loam), and B2 (shallow calcareous loam on calcrete). In the South-East region, in addition to the shallow calcareous loams (B2 soils), this category is also represented by a large area (23,000 ha) of A7 soils (calcareous clay loam on marl) which, within South Australia, are largely unique to this region (Figure 3).

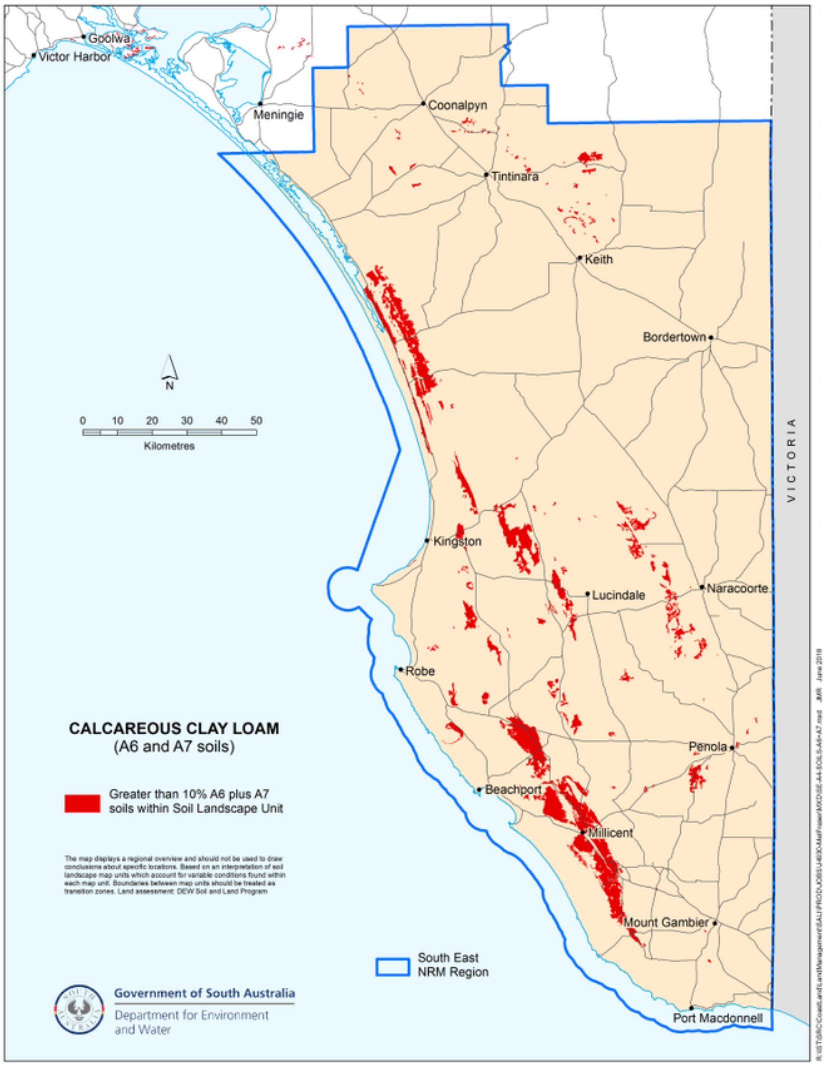


Figure 3. Distribution of Soil Groups A6 and A7 in the South-East region of South Australia. *Map Sourced from Maschmedt (2011).*

Calcareous soils are those that have calcareous layers evident throughout most of the profile and have variable carbonate content that is mostly less than 20% but is detectable through the application of dilute hydrochloric acid solution. These soils comprise about 800,000 ha (7%) of South Australia's agricultural land and are represented by soil groups A3 (deep moderately calcareous loam), A8 (gypseous calcareous loam), E2 (red cracking clay), H2 (calcareous versions of siliceous sands) and B5 (shallow dark clay loam on limestone). In most regions these soils are largely represented by the calcareous versions of siliceous sands. However, there are significant areas (32,000 ha) of the Northern and Yorke regions where calcareous soils are represented by soil group A3 (deep moderately calcareous loams) and a further 32,000 ha of E2 (red cracking clays) and, uniquely to the South-East, these soils are represented by group B5 (shallow dark clay loam on limestone).

Calcareous subsoils

Other soil types across south-eastern Australia often have carbonate layers concentrated in the subsoils. These can include both soils with abrupt texture changes within the profile (i.e., Chromosols and Sodosols as represented by soil groups B, D, F, G and J) as well as those soils that lack this abrupt texture change (i.e., Vertosols, Dermosols and Kandosols, as represented by soil groups C and E).

In addition to impacts on nutrition, wind erosion risk, herbicide breakdown and soil biological function caused by the presence of high amounts of carbonates at the soil surface, calcareous subsoils can further limit production. These soils often have very low organic carbon, high alkalinity, sodicity and salinity (particularly where heavier textured subsoil layers are present resulting in an accumulation of salts). While non-sodic variants generally have good drainage, they have reduced water holding capacity due to reduced soil volume caused by a high volume of coarse carbonate fragments (Hall et al. 2009). Carbonates in the subsoils are classified by type: Class I (fine soil carbonate in clay with few calcrete fragments), Class II (sheet or boulder calcrete) and Class III (compact mixture of loamy sand to light sandy clay loam and fine soil carbonate), with this class further subdivided depending on the quantities of calcrete fragments (Wetherby 2003).

2.1.1 Example soil profiles of South Australia

Eyre Peninsula

On EP the highly calcareous soils are largely represented by the highly calcareous sandy loams and sandy clay loams (with varying depth to substrate) with smaller areas of deep carbonate sand often containing shell fragments (soil subgroup H1). Additionally, there are large areas of loamy textured surface soils over highly calcareous subsoil clays.

Very Highly Calcareous Sandy Loam (Wookata) (EW060)

General Profile Description
Very highly calcareous sandy loam over rubbly carbonate becoming less rubbly and slightly more clayey with depth

		Soil Chemistry[A]						
Depth (cm)	**Layer Description**	**pH (H_2O)**	**$CaCO_3$ (%)**	**ECe (dS/m)**	**OC (%)**	**ESP (%)**	**CEC**	**Boron (mg/kg)**
0-30	Brown massive highly calcareous sandy loam	8.3	70	1.2	0.95	1.5	12	2.8-4.8
30-43	Rubbly class IIIc carbonate	N/A	N/A	N/A	N/A	N/A	N/A	N/A
43-100	Light yellow brown massive very highly calcareous sandy loam (abrupt calcrete)	9.0	78	0.9	0.25	6.3	5	2.3
132-170	Yellow massive very highly calcareous light sandy clay loam	9.2	85	1.3	0.13	12.3	8	3.9
Desired value		**6.0-7.0**	**<3.0%**	**<2.0 dS/m**	**>1.5 % in 0-10 cm**	**<6%**	**>10**	**<15 mg/kg**

Very Highly Calcareous Sandy Clay Loam (Magarey/Cungena) (EW075)

		Soil Chemistry[A]						
Depth (cm)	**Layer Description**	**pH (H_2O)**	**$CaCO_3$ (%)**	**ECe (dS/m)**	**OC (%)**	**ESP (%)**	**CEC**	**Boron (mg/kg)**
0-15	Brown friable highly calcareous light sandy clay loam with minor carbonate concretions	8.4	36	1.28	1.1	<1	12	2
15-28	Brown friable highly calcareous light sandy clay loam with 10-20% carbonate concretions	9.0	40	0.68	0.7	2	11	3

General Profile Description
Very highly calcareous sandy clay loam with variable rubble content at depth

28-52	Pink friable very highly calcareous sandy clay loam with more than 50% carbonate concretions	9.7	54	1.88	0.3	19	8	11
52-150	Class IIIC rubbly carbonate to sheet calcrete	9.7	69	9.1	N/A	40	5	13
Desired value		**6.0-7.0**	**<3.0%**	**<2.0 dS/m**	**>1.5 % in 0-10 cm**	**<6%**	**>10**	**<15 mg/kg**

Deep Carbonate Sand (Haslam soil) (EF024)

General Profile Description
Very thick yellowish-brown sand to loamy sand, dominantly carbonate

		Soil Chemistry[A]						
Depth (cm)	**Layer Description**	**pH (H_2O)**	**$CaCO_3$ (%)**	**ECe (dS/m)**	**OC (%)**	**ESP (%)**	**CEC**	**Boron (mg/kg)**
0-8	Brown loose highly calcareous loamy sand	8.4	86	2.4	1.2	2.4	5	3
8-80	Yellowish brown soft highly calcareous loamy sand	8.7-9.4	87	1.2-1.8	0.1-0.6	3.9	2	3-5
80-150	Yellowish brown soft highly calcareous loamy sand (some Class IV Carbonate)	9.5	91	0.9	<0.1	N/A	1	2-3
150-180	Very pale brown friable very highly calcareous light sandy loam with more than 50% calcrete concretions on rubbly calcrete pan.	9.7	88	2.4	<0.1	N/A	2	6
Desired value		**6.0-7.0**	**<3.0%**	**<2.0 dS/m**	**>1.5 % in 0-10 cm**	**<6%**	**>10**	**<15 mg/kg**

Calcareous Sandy Loam Over Clay (Minnipa/Wiabuna) (EC054)

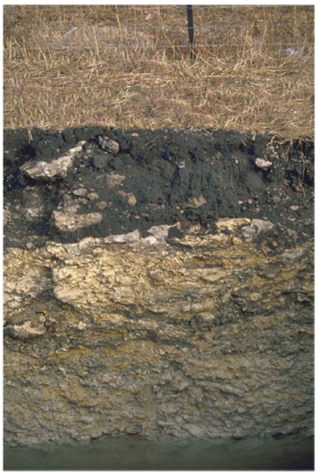
		Soil Chemistry[A]						
Depth (cm)	**Layer Description**	**pH (H_2O)**	**$CaCO_3$ (%)**	**ECe (dS/m)**	**OC (%)**	**ESP (%)**	**CEC**	**Boron (mg/kg)**
0-25	Dark brown soft slightly calcareous sandy loam	8.0	1-4	1.1-1.4	0.9	1	15	3
25-42	Yellowish red very highly calcareous light sandy clay loam	8.3	14	3.4	0.4	3	14	4
42-70	Orange very highly calcareous light sandy clay loam with 20-50% Class IIIB carbonate nodules into hard laminar carbonate	8.7	54	11.6	0.3	7	9	31

	90-200	Reddish yellow highly calcareous light clay	9.5	37-52	10.5	<0.1	38-53	9	40
General Description Calcareous sandy loam grading to a very highly calcareous sandy clay loam over rubbly carbonate with clayey substrate within 120 cm	**Desired value**		**6.0-7.0**	**<3.0%**	**<2.0 dS/m**	**>1.5 % in 0-10 cm**	**<6%**	**>10**	**<15 mg/kg**

[A] From SALI 2007 (State Soil Characterisation pit data sheets)
ECe (electrical conductivity of saturated soil extract), OC (organic carbon), ESP (exchangeable sodium percent), CEC (cation exchange capacity)

South East

In the higher rainfall zone of the South East, Calcarosols are represented by heavier textured clay loams to clays, often with shallow surface soils on highly calcareous subsoil layers (calcrete or marl). Due to the clayey textures and the fact that these soils are usually found in low-lying situations in the landscape, drainage is poor and can result in waterlogging and increased salinity levels in the lower subsoils (DWLBC 2002).

			Soil Chemistry[A]						
Black Cracking Clay on Calcrete (SE031)	**Depth (cm)**	**Layer Description**	**pH (H_2O)**	**$CaCO_3$ (%)**	**ECe (dS/m)**	**OC (%)**	**ESP (%)**	**CEC**	**Boron (mg/kg)**
	0-20	Black firm light – medium calcareous clay	8.0	6-15	1.3	5.0	1.0	33	2.0
	20-25	Very strong cemented massive calcrete pan	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	25-55	Dark grey firm highly calcareous medium clay (>50% hard carbonate nodules	8.5	33	0.51	0.8	1.4	23	2.5
	55+	Pale yellow hard calcareous light medium clay (marl)	8.6	58	0.84	0.1	3.5	15	1.2
General Profile Description Black calcareous clay loam to clay over calcrete limestone at shallow depth	**Desired value**		**6.0-7.0**	**<3.0%**	**<2.0 dS/m**	**>1.5 % in 0-10 cm**	**<6%**	**>10**	**<15 mg/kg**

Calcareous Clay on Marl

(SE054)
General Profile Description
Calcareous dark coloured clay loam to clay becoming more clayey and calcareous at depth with variable rubble over marl

		Soil Chemistry[A]						
Depth (cm)	**Layer Description**	**pH (H_2O)**	**$CaCO_3$ (%)**	**ECe (dS/m)**	**OC (%)**	**ESP (%)**	**CEC**	**Boron (mg/kg)**
0-17	Black firm calcareous medium heavy clay (2-10% carbonate concretions)	7.9	16	1.12	6.8	1.1	48	2.7
17-26	Dark firm moderately calcareous medium heavy clay	8.2	37	0.64	2.3	2.1	25	2.1
26-81	Dark grey firm highly calcareous light medium clay (10-50% carbonate nodules)	8.6-8.9	45-55	0.5-0.8	<0.7	3.9-8.0	9-17	0.6-1.2
81-160	Grey friable (wet) highly calcareous light clay (2-20% carbonate nodules)	8.6	24-42	0.9-1.1	<0.3	6.4-8.0	14-24	0.8
Desired value		**6.0-7.0**	**<3.0%**	**<2.0 dS/m**	**>1.5 % in 0-10 cm**	**<6%**	**>10**	**<15 mg/kg**

[A] From SALI 2007 (State Soil Characterisation pit data sheets)
ECe (electrical conductivity of saturated soil extract), OC (organic carbon), ESP (exchangeable sodium percent), CEC (cation exchange capacity)

2.2 Calcareous soils in Western Australia

Several soils in Western Australia have calcareous soil layers. In the South West agricultural region, the main cropping zone within the state, it is estimated that there is around 1.25 M ha of soils that are calcareous throughout the soil profile. These include calcareous deep sands close to the coast (344,000 ha) and calcareous loamy earths (Morrel, Merredin, Salmon Gums and Kopi soils comprising around 880,000 ha (van Gool et al. 2018; D. van Gool pers comm, 8 Dec 2020)). Additionally, there is an estimated 2.5 M ha (10%) of alkaline grey sandy duplex soils (Mallee, Scadden and Moort soils) that can, but do not always, contain calcareous soil layers (van Gool et al. 2018). Crop and pasture production can be constrained by a number of factors in these soils.

There are also a number of soil groups in Western Australia's cropping zone that have potentially calcareous subsoil layers, but which are minor in terms of area, including shallow soils on rock and self-mulching clays (D. van Gool pers comm, 8 December 2020).

2.3 Calcareous soils in other states and territories

2.3.1 NSW

Soils that are calcareous throughout (Calcarosols) are generally confined to the lower rainfall areas of south-western NSW. However, soils containing calcareous subsoils (Chromosols, Sodosols) are common throughout the Riverine Plain and Mallee regions bordering Victoria and South Australia.

2.3.2 **Victoria**

The majority of Calcarosols in Victoria are in the Mallee and northern Wimmera regions, with minor areas near the coast around Portland in the South West and in the East Gippsland region (D. Rees pers comm, 14 December 2020) (Figure 4).

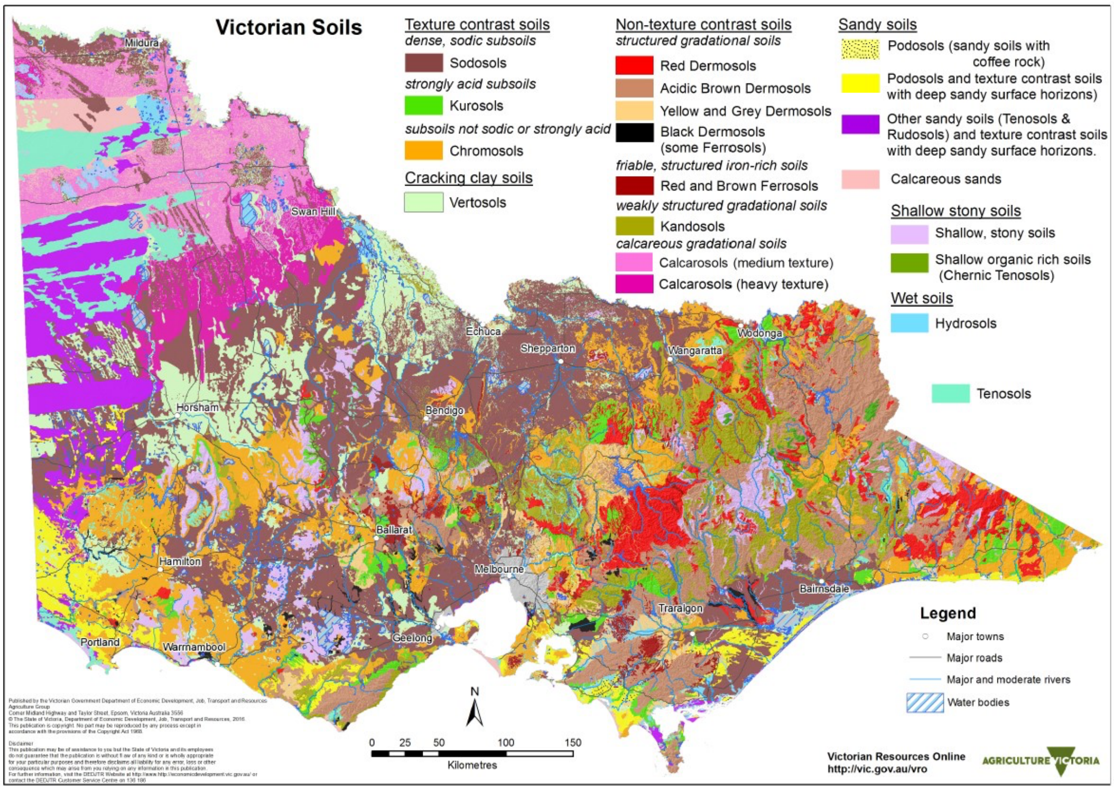


Figure 4. Distribution of key soil types in Victoria. *Map sourced from Agriculture Victoria (2014), Victorian Resources Online. Archived at https://web.archive.org/web/2021/http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/victorian_soils_map_2014 (accessed 28/01/2021)*

In Victoria, there is estimated to be around 2.3 M ha of soils with calcareous layers throughout the profile (0.5 M ha of calcareous sands and 1.7 M ha with loamy surface soils or heavier), with perhaps another 0.5 to 1.0 M ha of soils with calcareous subsoil layers (Sodosols or Vertosols) (M. Cann pers comm, 14 December 2020).

2.3.3 **Queensland, Northern Territory and Tasmania**

Calcarosols only make up very small proportions of the agricultural soils in Queensland, the Northern Territory and Tasmania. In the Northern Territory these soils are mostly restricted to small pockets in Central Australia, the Victoria River District, and the Katherine and Mataranka Districts (DENR 2020), whilst in Queensland and Tasmania they cover less than 0.5% of the state. In Queensland these soils are mainly present in the western areas and are formed on calcium-rich rocks from windborne sediments and limestone (Qld Govt 2020). Calcarosols are the least abundant soil in Tasmania (0.3%), occurring predominantly on Flinders Island with a small area on the coast in the south (Cotching 2009).

2.4 Distribution of calcareous soils globally

Calcareous soils (World Reference Soil Group: Calcisol) are widely distributed across the globe, mostly in the arid to semi-arid regions. Whilst difficult to quantify, the Food and Agriculture Organisation of the United Nations (FAO) estimates up to 1 billion ha of land fits into this classification (Driessen et al. 2001). These soils represent the dominant soil group, or can be found in association with the dominant soil groups, in much of North Africa, the Middle East, South-Western USA/Northern Mexico, and in the southern semi-arid regions of the Australian, South American and African continents (Figure 5).

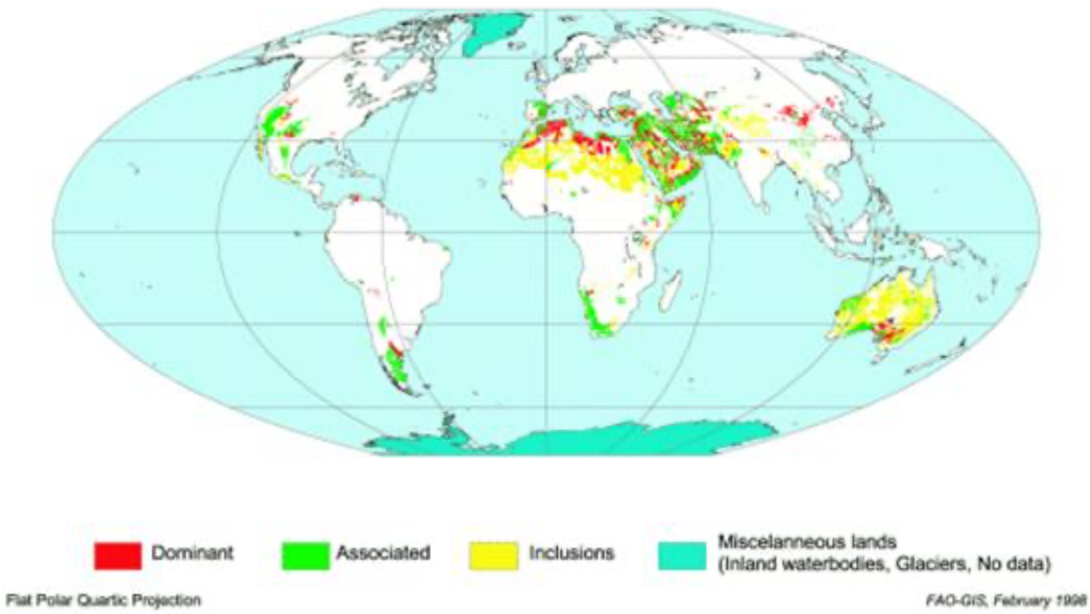


Figure 5. Distribution of Calcisols world-wide. *Map sourced from http://www.fao.org/soils-portal/soil-management/management-of-some-problem-soils/calcareous-soils/en/ (28/01/2021).*

3 Farming systems on highly calcareous soils on the upper Eyre Peninsula and South East of South Australia

Authors: B Dzoma, M Evans

3.1 Upper Eyre Peninsula (EP)

The development of farming systems in this semi-arid Mediterranean region of Australia has evolved from a very low external input system to a system including legume nitrogen (N) inputs, short rotations and improved crop varieties (Adcock 2005). The introduction of break crops such as canola, lentils and vetch, combined with the strategic application of N fertilisers, has facilitated a shift to an “improved efficiency of inputs” (Gregory et al. 2002). Before the adoption of more intensive cropping and conservation tillage practices, the dominant form of agricultural land use was rotational cropping of cereals and pasture legumes for grazing. With intensification, this region has adopted alternative cropping sequences that are primarily dependent on local climate and soil types. Cropping sequences are currently limited to winter crops, mainly cereals (wheat, barley, oats), oilseeds (canola), and grain legumes (lupins, field peas, lentils, chickpeas, vetch), and rarely extend to summer crops like sorghum and millet grown as cover crops. In this semi-arid environment, moisture limitation is a major source of variability for dry matter and grain production. The effects of limited water supply are very evident on the upper EP because wheat yields have not improved at the same rate as in other wheat growing regions in Australia. Estimates of crop water use efficiency (WUE) are low, ranging from 8–12 kg ha^{-1} mm^{-1} (Coventry et al. 1998). A more recent WUE survey on the EP by the Low Rainfall Collaboration Group (LRCG), conducted between 2010 and 2013, reported that WUE was still below 40% based on the French/Schultz model (GRDC 2013). According to the surveys, the main ways growers have tried to increase WUE of crops in recent years have been to seed early (before mid-May), keep the ground free of weeds over summer to store moisture, keep up fertiliser use and use no-till methods.

Upper Eyre Peninsula is characterised by large areas of coarse-textured highly calcareous soils. On these soils with low water holding capacity and highly variable low rainfall, early cereal growth is slow, tillering is poor, and grain yields are low – often less than 1 t ha^{-1} (Holloway et al. 2001a).

3.1.1 **Cereals**

Cereal crops are the most reliable crop type for the highly calcareous soils of the upper EP, which results in them being grown at a higher intensity than is desirable from a disease and weed pressure perspective (Sadras and Roget 2004). The cereals are highly demanding for inputs of N and moderately demanding for inputs of phosphorus (P). Some alternative crop types have been explored, but the remoteness and associated freight costs can be a key issue, especially for the Western EP environment.

3.1.2 **Legumes**

There is a lack of adapted grain legume options for the upper EP, and annual *Medicago* species, which are a key component of annual pastures in this region, do not always fix adequate N, apparent via nodule checks and subsequent pre-sowing N tests. Improved legume performance is critical to reducing the intensity of inputs required for cereal production (McLaughlin et al. 1988).

3.1.3 **Canola**

Canola is a break crop known to offer a significant disease break and some nutritional benefits for subsequent crops (McBeath et al. 2015). However, it is prone to both establishment and yield failure under dry conditions, which limits the area that is sown to canola on upper EP. Recent work focussed on low-rainfall canola production shows that canola can bring significant value to profit potential if sown only on a genuine establishment opportunity within the optimal window, if the cultivar cost and required performance gain is understood and if N supply is maintained (McBeath et al. 2020).

3.2 South East

Information obtained from a cross section of growers across the South East (SE) of SA indicates that cropping and livestock are both important components of the current farming systems. In a 2015 survey, 86% of farmers were practising mixed farming, while only 12% were exclusively livestock producers and 4% were exclusively cropping (Turner and Pearce 2015). Zhang et al. (2006) highlighted the poor adaptation of crop cultivars in this environment, due to higher rainfall, longer and cooler growing seasons and a longer period of high frost risk. Most growers in this region identify soils such as Calcarosols and grey Vertosols as the most challenging soils for growing legume crops. Therefore, yield gaps exist because of a lack of knowledge around the behaviour and management of calcareous soils and legume species adapted to these high rainfall environments.

3.3 Yield gaps

Potential production is rarely achieved in broadacre crops in semi-arid Mediterranean-type environments (Hamblin and Kyneur, 1993). While Australian wheat producers are closing the yield gap at a rate of about 1% per annum, actual wheat yields have stagnated since 1990 (Hochman et al. 2016). A recent analysis of Australia's wheat yields (Hochman et al. 2016) has shown that over the 17 years from 1996–2012, the average Australian annual yield of 1.73 t ha^{-1} was 50% of the average water limited yield of 3.45 t ha^{-1}. Factors including biotic stresses (plant diseases, insects and other pests, in-crop weeds) and abiotic stresses (extreme alkalinity and acidity, subsoil compaction, sodicity and high calcium carbonate in the top and subsoils) contribute to the yield gap. Knowing the yield gap to address is important to maximise on returns. Hunt et al. (2019) described the "technical efficiency yield gap" as the distance from the production frontier at a given level of inputs, and the "technology yield gap" as the gap between "feasible yields" and the potential (water-limited) yields, which can only be achieved using advanced technologies and the latest varieties. The estimated technical and technology yield gaps provide important information when developing an amelioration plan, helping to highlight the limits of productivity within the context of rainfall, and local knowledge of gains that can be achieved through targeted strategies.

Increasing intensification and crop production can be difficult to achieve until the causes of the unrealised yield potential are identified and quantified so that appropriate management practices can be identified and implemented by farmers at a justifiable cost. One promising strategy to increase grain production is to close the gap between yields currently achieved on farms and those that can be achieved by addressing multiple soil constraints that limit crop productivity and rotation options. On highly calcareous soils, constraints, including high levels of alkalinity and carbonate in the surface layer, and boron toxicity, salinity, sodicity in the subsoil layer, interact to limit crop and pasture growth. Therefore, addressing these constraints and providing practical soil management solutions for farmers and advisers, including the specific soil type targets for this management, will facilitate improved crop productivity and profitability.

3.3.1 Upper Eyre Peninsula

Current estimates for common rotation crops on the upper EP (Table 1) indicate that yield gaps are up to 60% for cereal crops and 70% for canola. However, it is important to note that the accuracy of these estimates could be improved through better characterisation of the water supply characteristics of the key soil types in these environments.

Table 1. Yield and yield gap data for wheat, barley and canola, for sites on upper Eyre Peninsula.

Site *(soil type)*	**Crop**	**Actual yield (t ha^{-1})**	**Water-limited yield (t ha^{-1})**	**Yield gap (t ha^{-1})**	**Relative yield (%)**
Le Hunte - Elliston *(Calcarosol)*	Wheat	1.6	3.6	2.1	43
	Barley	1.6	4.2	2.6	38
	Canola	0.8	1.6	0.8	50
West coast (*Calcarosol*)	Wheat	1	2.5	1.5	41
	Barley	1.1	2.5	1.4	43
	Canola	0.6	1.9	1.3	30

Actual farmer yields (t ha^{-1}) extracted from www.yieldgapaustralia.com.au

3.3.2 **South East**

Current estimates for common rotation crops in the SE of SA (Table 2) indicate that yield gaps are approximately 30% for wheat in the Wattle Range where Calcarosols are a major soil type, around 50% for pulses (www.yieldgapaustralia.com.au), and as high as 65% for canola.

Table 2. Yield and yield gap data for common rotational crops in the South East region of SA.

Site	**Crop**	**Actual yield (t ha^{-1})**	**Water-limited yield (t ha^{-1})**	**Yield gap (t ha^{-1})**	**Relative yield (%)**
Naracoorte	Wheat	2.4	6.5	4.1	37
	Barley	2.4	6.5	4.1	37
	All pulses*	2	3.9	1.8	53
	Canola	1.2	3.4	2.2	35
Wattle Range	Wheat	3.2	4.2	1	76
	Barley	2.8	6.1	3.3	46
	All pulses*	2	3.8	1.8	54
	Canola	1.5	4.1	2.6	36

Source: www.yieldgapaustralia.com.au. *Data collected and presented are sourced from ABARES (http://www.agriculture.gov.au/abares). There are gaps in the data over the 15-year reporting period.

On-farm grain yields in the Southern Region high rainfall zone (HRZ) are typically only half to a third of the potential yield, which is estimated at 4.5–11 t ha^{-1} for wheat, depending on location (McCaskill et al. 2016). McCaskill et al. (2016) consider this difference to be related largely to insufficient fertiliser application and further suggest that the lack of evidence for economic returns from investment in fertiliser is a barrier to applying enough fertiliser to fulfil yield potential. Constraints to production on alkaline soils in the SE identified at a MacKillop Farm Management Group workshop held at Reedy Creek in 2017 are consistent with this being the case, as they included the following:

- Nitrogen use
- Forms, rates and timing of P fertiliser
- P tie-up in the soil
- Trace elements and foliar fertilisers

- Shallow limestone rock – how to break it without bringing it to the surface, and
- Gypsum – how, when, where, rates.

The 26 farmers and consultants who participated in this workshop came from Keith, Conmurra, Avenue, Millicent, Naracoorte, Kingston and Reedy Creek, providing representation for many of the localities with alkaline inter-dunal plains.

3.3.3 Other districts in South Australia

Calcarosols, while mostly found throughout the upper EP and SE of SA, also occur in other regions in southern Australia. In SA, the YP is a gently undulating plain with central rises and low hills. Soils are largely loam over clay, shallow calcrete or calcareous loams. Subsoil salinity, alkalinity, sodicity and boron are widespread, restricting root growth and water use efficiency. The Lower YP (e.g., Yorketown) has a high proportion of highly calcareous soils while the upper YP (Kadina, Moonta, Maitland) is characterised by moderately calcareous soils. Calcareous soils are also found in the mid-North region of South Australia. This region has a diverse agricultural sector.

Table 3. Yield and yield gap data for common rotational crops in the mid-North and Yorke Peninsula regions of SA.

Region	Site	Crop	Actual yield (t ha^{-1})	Water-limited yield (t ha^{-1})	Yield gap (t ha^{-1})	Relative yield (%)
Mid North	**Goyder**	Wheat	2	4.5	2.5	44
		Barley	2.1	5.9	3.9	35
		Canola	1.3	2.3	1	55
	Wakefield - Barunga West	Wheat	2.4	4.7	2.3	52
		Barley	2.4	6.2	3.8	38
		Canola	1.3	2.3	1	56
Yorke Peninsula	**Kadina**	Wheat	2.5	4.7	2.2	54
		Barley	2.5	6	3.5	42
		Canola	1	2.3	1.3	42
	Moonta	Wheat	2.6	4.7	2.1	54
		Barley	2.5	5.8	3.4	42
		Canola	1	2.3	1.3	43
	Wallaroo	Wheat	2.5	4.4	1.9	57
		Barley	2.5	5.3	2.8	47
	Yorke Peninsula - North	Wheat	2.9	4.9	2.1	58
		Barley	2.7	6.4	3.7	42
		Canola	1.1	2.8	1.7	41
	Yorke Peninsula - South	Wheat	2.5	5.1	2.6	49
		Barley	2.3	6.6	4.3	35
		Canola	1.3	3.5	2.2	36

Source: www.yieldgapaustralia.com.au

Estimates of the yield gap (Table 3) in the mid-North cropping region are approximately 50% for wheat, 63% for barley and 45% for canola. In the YP cropping region, the estimates for yield gap vary from 42–51% for wheat and 53–65% for barley and canola. These estimates are important to know so that sound decisions can be made about how much of the yield gap can be closed by adopting different treatment options, both agronomically and through soil remediation. In these environments, some of this gap can be attributed to agronomic inputs, disease, pests and frost, but research results show that substantial yield improvements can be obtained when underlying soil constraints are addressed (Fraser 2020).

4 Constraints in highly calcareous soils that affect agricultural production, and attempts to overcome them

There are several key constraints to crop growth on highly calcareous soils that interact to limit crop and pasture productivity (Figure 6). In surface layers, high levels of alkalinity and carbonate inhibit the cycling and supply of nutrients such as phosphorus (P), nitrogen (N), sulfur (S), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn). The negative effects of this environment on the cycling and survival of biota in turn allow disease inoculum and infection to proliferate. In the subsoil a range of constraints are common, including boron toxicity, salinity, chloride toxicity and in some cases sodicity (Adcock et al. 2007; Hall et al. 2009; Rengasamy 2010). Calcareous soils have a highly buffered alkaline pH in water, which varies from pH 8.0–9.5, depending on carbonate chemistry. High concentrations of bicarbonate and aluminium present in alkaline soil solution may be phytotoxic (Rengasamy 2010; Brautigan et al. 2014). The chemical constraints to root proliferation all act to limit access to water. Additionally, highly calcareous soils possess unique water holding capacity characteristics that mean higher amounts of rainfall are required before water becomes plant-available. In the low productivity environment of the upper EP, inputs of carbon into the system are low and of low quality, reinforcing a low nutrient supply system (Figure 6).

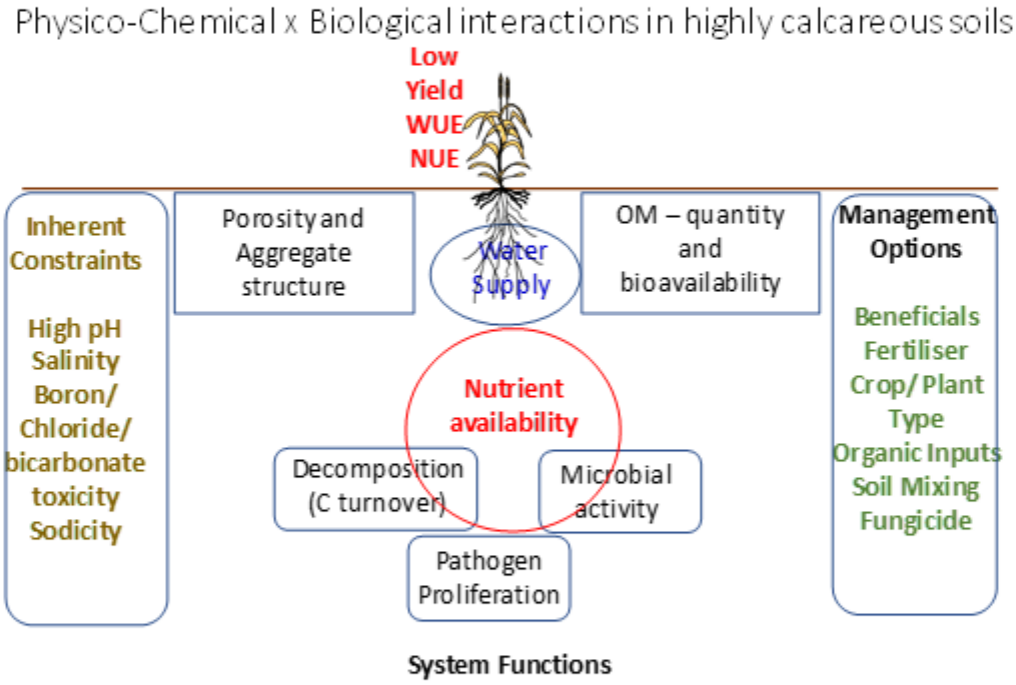


Figure 6. A schematic representation of the inherent constraints, system functions and potential management options in highly calcareous soils.

4.1 Topsoil constraints

4.1.1 Pathogens and Diseases (V Gupta)

Soil-borne pathogens are one of the critical bottlenecks to plant growth and production in cereal crops grown in calcareous soils. Most of the information that follows relates to the upper EP because there is little equivalent information for the SE. Previous research demonstrated the major impact of disease and nutrient deficiencies on cereal crop yields on calcareous soils at Streaky Bay on EP. Using fumigation in combination with extra fertilisers showed that suppression of pathogens combined with optimised nutrient supply could produce crops at water-limited yield potential, removing the 44% yield gap (Gupta et al. 2011). Although improved P nutrition and fumigation on alkaline soils at Minnipa and Franklin also increased yields (by 16–22%), grain yields still only reached 53–73% of water-limited yield potential, suggesting that other constraints had not been addressed (Roget et al. 2004). However, these studies highlight that addressing biological constraints is a key requirement to improving crop yields on highly calcareous soils.

Some of the soil-borne fungal and nematode pathogens commonly observed include rhizoctonia root rot (*Rhizoctonia solani* AG8), take-all (*Gaeumannomyces graminis var. tritici*), fusarium crown rot (*Fusarium pseudograminearum*), *Fusarium culmorum*, pythium root rot (*Pythium* species), common root rot (*Bipolaris sorokiniana*), and *Pratylenchus* species. However, under conservation cropping systems rhizoctonia root rot caused by *R. solani* AG8 has been found to be the most dominant disease (see Figures 7 and 8). The use of resistant varieties during the last two decades has generally reduced the incidence and impact by cereal cyst nematode disease. During the 1970s and 80s, take-all was one of the major diseases in cereal crops in the southern Australian cropping regions with calcareous soils. However, rotation with non-host crops and adoption of summer management practices such as (i) the control of green bridges with good summer weed control, (ii) delayed planting to reduce the level of pathogen inoculum by prolonging the saprophytic phase prior to sowing, and (iii) the use of seed-treatment and foliar fungicides (e.g., flutriafol (Impact®), silthiofam, fluquinconazole) have reduced the incidence of take-all disease (Roget 2003). Changes in the pattern of in-season rainfall during the last two decades have also contributed to lower build-up of *Ggt* inoculum. Development of agronomically significant biological disease suppression through long-term adoption of conservative agricultural practices may have also contributed to lessening the impact from take-all in other soil types across southern Australia, but it is less likely in calcareous soils (Roget et al. 1999).

Figure 7. Typical rhizoctonia damage in a cereal crop on a highly calcareous soil of the upper Eyre Peninsula (N Wilhelm, SARDI).

Rhizoctonia root rot continues to be a severe, extensive and frequent soil-borne disease in calcareous soils across southern and western Australian cropping regions, especially in highly calcareous soils (Figure 8). Knowledge of rhizoctonia root rot has increased considerably over the past eight years and includes a better understanding of the role of non-cereal crops in rotation, inoculum dynamics over the year, new fungicides and methods of application and the importance of summer weed control. For example, canola and other grass-free break crops can lower inoculum levels provided they remain grass-free, although the effect is only evident for a single following season (Gupta et al. 2010; Cook 2014). Current farming systems have moved to earlier sowing windows when soils are warmer and early crop growth is rapid, which normally reduces rhizoctonia damage. However, rhizoctonia is still a major problem with early sowing on calcareous soils, for which the reasons are not fully understood. Tillage will break up the fungal networks of rhizoctonia and can reduce disease but leaves these fragile soils highly vulnerable to wind erosion, and hence cultivation is rarely practised in current systems on calcareous soils. In addition, the effectiveness of many of these practices has been found to be unreliable and only provide partial control of disease impacts. High pathogen inoculum levels after cereal crops are a feature of highly calcareous soils and they can be 2–3 times higher than in the Mallee soils (Gupta et al. 2010). It has been found that in addition to high pathogen load, in the highly calcareous soils the infection potential seems to be higher, probably due to reduced microbial activity (biological buffering capacity) and nutrient limitations which exacerbate the pathogen impacts (Davey et al. 2021). Research in non-calcareous soils indicated that application of N may alleviate effects of rhizoctonia disease, but such effects have not been investigated in calcareous soils (Wall et al. 1994). Phosphorus concentration in shoot tissue has been shown to fall below critical ranges in rhizoctonia-diseased plants and since P availability is generally low in calcareous soils, rhizoctonia impacts may be exacerbated in calcareous soils without adequate P supply (Wall et al. 1994). Similarly, Zn fertilisation was found to increase tolerance to rhizoctonia disease in *Medicago truncatula* and may play a role in alleviating rhizoctonia impacts in calcareous soils (Streeter et al. 2001). Overall, damage from rhizoctonia is greater in poorly nourished crops, and hence is common on highly calcareous soils. The longer residual presence of sulfonyl urea herbicides in high pH calcareous soils has been shown to increase rhizoctonia root disease and reduce yields by up to 1 t ha^{-1} (Neate 1994). Increased leakage and alteration of root exudates from roots in the presence of sulfonyl urea herbicides, and reduced metabolic status of the rhizosphere microbial community, have been suggested to contribute to this effect (Neate 1994). Fungicides recently released for reducing rhizoctonia on cereals are proving less effective on highly calcareous soils. Also, potential effects of fungicides on soil biological functions are not well understood.

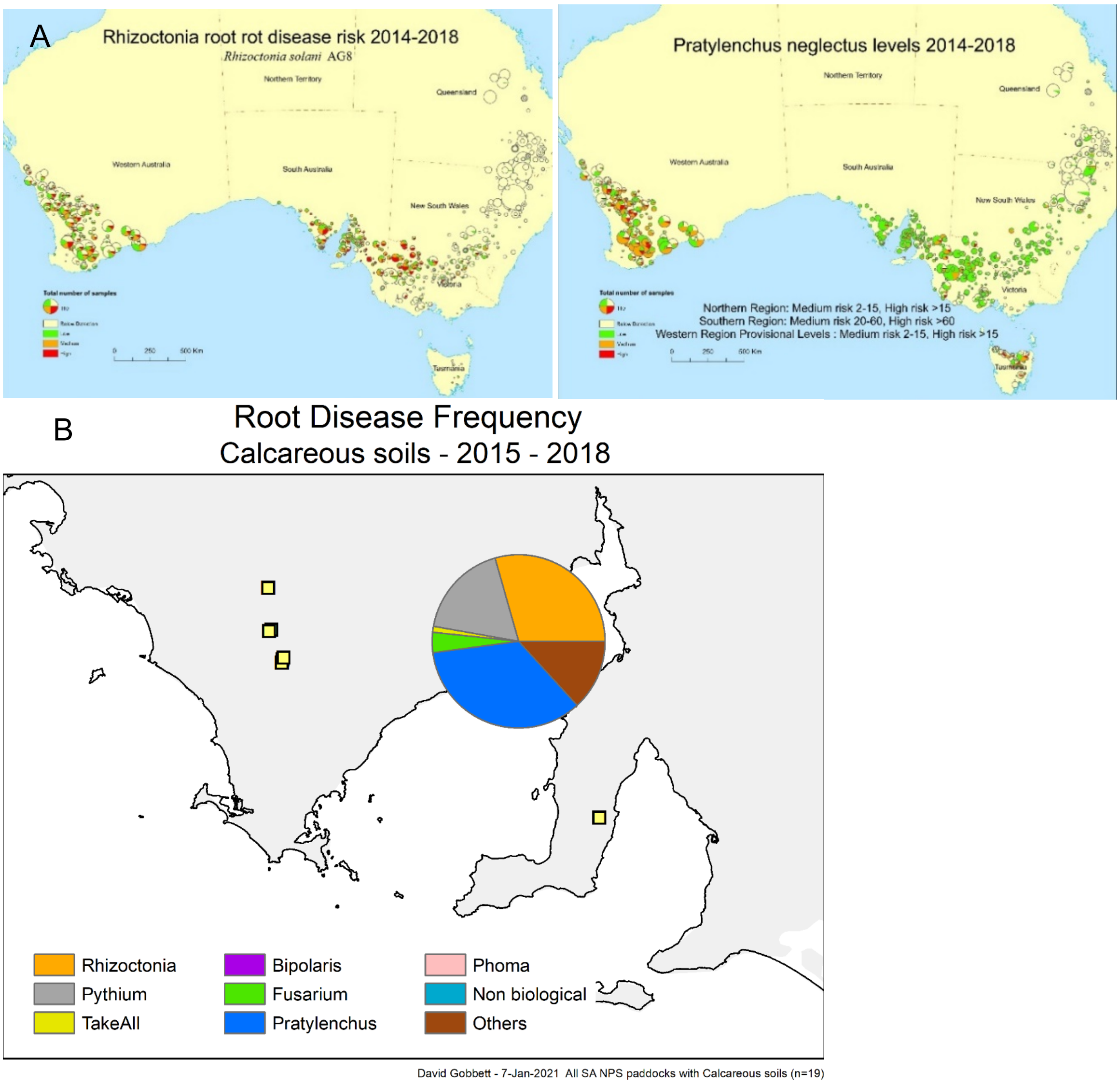


Figure 8. (A) Maps showing the distribution of soil-borne pathogenic fungus R. solani AG8, and plant parasitic nematode Pratylenchus neglectus in agricultural soils across Australia. *Each pie chart depicts the proportion of soil samples received by the SARDI Root Disease diagnostic labs (Predicta®B maps; https://pir.sa.gov.au/research/services/molecular_diagnostics/predicta_b). (B) Frequency of occurrence of different root diseases from calcareous soil fields across South Australia during the 2015–2018 seasons (Gupta et al. 2019a).*

Effective management of rhizoctonia disease in rainfed cropping systems requires both the management of *Rhizoctonia solani* AG8 inoculum and the infection process through the off-season and in-crop periods (Figure 9). As *R. solani* AG8 is an integral member of the soil microbial community in calcareous soils, its abundance during the non-crop season is influenced through interactions with soil conditions and microbial community. Soil conditions such as optimal moisture promoting general microbial activity would cause significant decline in the inoculum levels (Gupta et al. 2008; Gupta et al. 2012); however, the presence of a volunteer or weed host would negate the inoculum decline. In-crop management of rhizoctonia inoculum levels is critical to reduce rhizoctonia disease impacts on grain crops in a cropping system, as inoculum build-up in one year's crop is the major determinant of disease risk in the following year. A significant variation in rhizoctonia inoculum build-up exists between cereal crops wheat, barley, triticale and rye and their varieties. Inoculum build-up was generally higher in barley varieties compared to that in other crops. Results are in general agreement with observations in other experiments in the Mallee and on calcareous soils on the EP (Gupta et al. 2017). However, the effectiveness of the varietal-based variation in inoculum level in reducing disease impacts in following crops has not been investigated in the Calcarosols on the EP.

In addition to keeping pathogen inoculum levels low (both during crop and pasture phases) the other key to long term rhizoctonia disease control is to reduce infection by the pathogen and increase the ability of crops to tolerate the infection, i.e., by creating environments where plant infection is reduced and plant immunity or tolerance to infection is improved (Figure 9). A variety of microbial (bacterial and fungal) inoculants that have been tested for controlling rhizoctonia disease have shown positive responses in controlled environment conditions but failed to produce consistent and reliable results under field conditions (Franco et al. 2007; Ellis 2017; Barnett et al. 2019). The successful control of soil-borne plant pathogens involves management of the pathogen at the inoculum source and in the rhizosphere, and across time (pre-season and in the presence of the susceptible plant). Hence, in situ enhancement of natural disease suppression may be more effective than adding inoculants. The low level of field-based success with added inoculants for controlling soil-borne diseases such as rhizoctonia, particularly in Calcarosols, may be attributed to a lack of understanding of the inoculant survival under chemically constrained soil conditions along with factors that promote rhizoctonia growth in high pH soils. Preliminary results have indicated that bacterial groups that generally respond to C inputs (e.g., proteobacteria) don't seem to show a similar response in calcareous soils. As many of these bacteria have capacity to control fungal pathogens, it is important to identify management practices that can promote beneficial bacterial groups and/or other microbes with similar capabilities (Gupta et al. 2019b). Other avenues for reducing the impact of soil-borne root diseases could be through (i) enhancement of root growth through modifying soil physical and chemical conditions, (ii) biological promotion of root growth, and/or (iii) inducing resistance against pathogen attack (Figure 9). For example, previous research has shown that although canola in rotation does not eliminate rhizoctonia incidence, root growth after canola was better compared to that after cereal crops or pastures (Gupta 2011). This would contribute to enhanced plant health and nutrition. Such efforts to improve root growth to compensate for the impact of root diseases such as rhizoctonia have not been investigated.

Microbial community composition varies significantly between rhizosphere and endosphere of plant roots and is also influenced by plant and varietal type (Compant et al. 2019). However, plant-based effects are primarily modulated by soil habitat and its microbiome composition and management impacts (Gupta and Sharma 2021). For example, changes in the soil microbiome with adoption of different crop management practices could influence plant-associated microbiomes either beneficially (i.e., development of a disease-suppressive community) or otherwise (e.g., reduced microbial diversity due to intensive tillage and specific agrochemicals) (Hartman et al. 2018). Currently there is no information on management effects on rhizosphere microbial communities in calcareous soils.

Root lesion nematode *P. neglectus* is the more common plant parasitic nematode found in the South Australian agricultural fields, including in the calcareous soils in EP, although the level of occurrence was lower than that for rhizoctonia disease (Figure 8). Field evaluation of different wheat and barley varieties for resistance rankings at different sites across South Australia indicated high correlations between resistance rankings at each site and good connectivity of varieties in common between sites (Linsell et al. 2015). There was a strong crop-type effect, with bread wheat generally more susceptible to *P. neglectus* than barley, which was more susceptible than durum. Additionally, many bread wheat varieties showed useful levels of resistance. However, there was common occurrence of rhizoctonia in calcareous soils, thus separation of the effects of the two diseases and true resistance ranking was found to be difficult. Soil-borne diseases in cereals do not occur in isolation. Typically, as one disease is managed the next most-abundant disease may occupy the niche, contributing to losses in crop productivity.

Biological disease suppression against rhizoctonia disease has been shown to develop in some soil types across southern and Western Australia. Biological disease suppression can reduce disease sufficiently to reduce yield losses (Roget 1995; Gupta et al. 2009; Gupta et al. 2019b). In these studies, disease suppression was found to improve through the addition of higher levels of biologically available C over longer periods (>5–7 years) to change the composition of microbial communities (Gupta et al. 2011). Suppression is a microbial community-based function and suppressive microbial (bacteria and fungi) community signatures and biomarkers have been identified using next generation molecular and biochemical tools (Hayden et al. 2018; Gupta et al. 2019b). However, field-based experiments conducted by Cook et al. (2012) failed to show development of agronomically useful levels of disease suppression against rhizoctonia disease. Changing the rotation, retention of stubble and nutrient supply across eight years altered microbial population activity and diversity, but disease suppression to rhizoctonia and take-all did not develop. Also, in the higher rainfall seasons, cereal crops were limited by low nutrition in several rotations (Cook et al. 2012). Other research indicated that even though microbial activity increases with added C inputs on highly calcareous soils (Gupta and Reddy 2010; Davey et al. 2021), root disease suppression rarely develops, suggesting nutrition may play a role in disease suppression/incidence in calcareous soils. This supports observations from controlled environment experiments that nutrient (e.g., P) limitations may not only increase disease impact but also restrict the development of suppressive communities. Davey et al. (2021) found that N application alone did not improve the potential for suppression of disease, as evident by the absence of any reduction in root infection relative to unfertilised plants in the inoculated bioassay. In highly calcareous soils, application of P fertiliser significantly altered the microbial catabolic activity and diversity indicating that P availability may be constraining microbial activity (Davey et al. 2021). It was also reported that application of P without enough labile C is likely to increase root infection and the amount of *R. solani* AG8 (Davey et al. 2021). Preliminary observations of the response of general soil bacterial and fungal communities to the addition of crop residues in calcareous soils indicated the lack of response of bacterial groups containing genera with plant growth promoting abilities. This response has been shown to be required for the development of disease suppression in other soils (Gupta et al. 2019b). Other research suggests that soil carbonate- and alkalinity-induced nutrient deficiencies in the alkaline calcareous soils are likely to interact to modify the development of biological disease suppression and the expression of disease (Roget et al. 1999; Davey et al. 2019a). The differences found between soils from EP in terms of plant and soil organism responses to different organic matter (OM) inputs (e.g., roots or wheat stubble) suggest that abiotic factors modify the development of biological disease suppression and the expression of the disease (Davey et al. 2019a). The role that chemical and nutritional constraints in the highly calcareous soils play in the differential response in microbial communities relative to the growth and infectivity by *R. solani* AG8 is not known. Similarly, soil factors that promote or inhibit the preferential growth of *R. solani* AG8 fungus in these soils are not well understood. Previous research indicated that the presence of large quantities of mineral N in the surface soil during early autumn may inhibit the expression of suppression (Gupta 2011). Our understanding of seasonal mineral N accumulation in calcareous soils under different cropping systems is limited and it may be this pattern that is constraining the development or expression of a disease suppressive community.

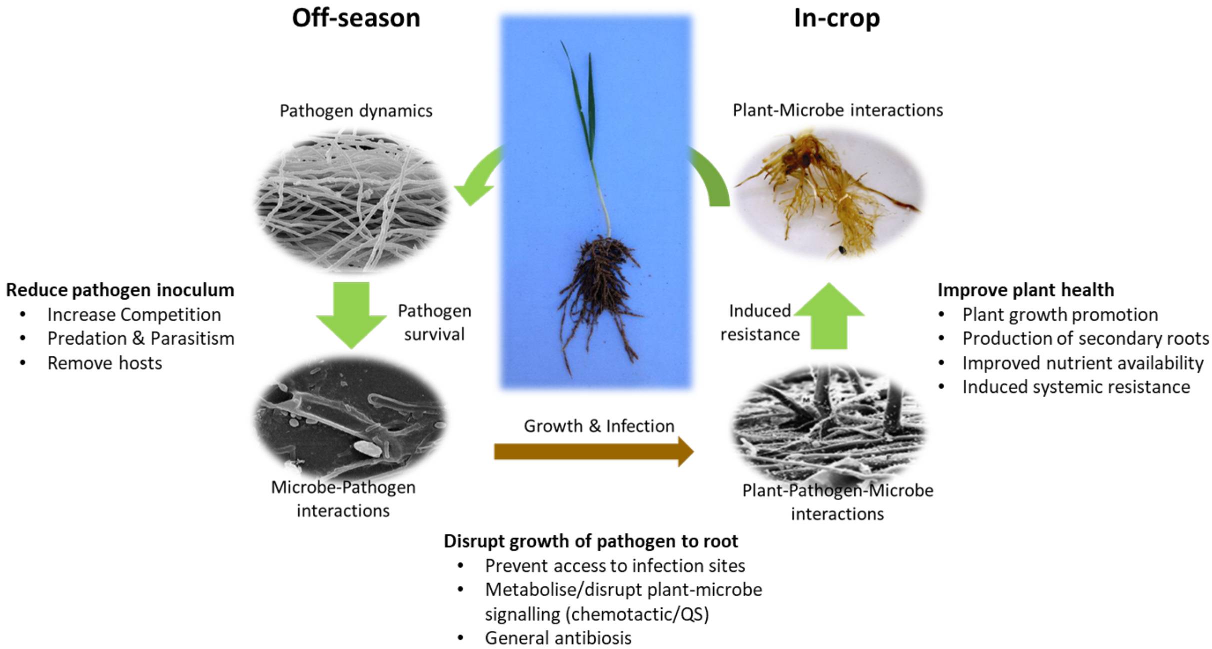


Figure 9. Conceptual diagram showing the different interactions between soil-borne pathogens and soil biota, and plant-microbe interactions that can influence disease incidence and impact on cereal plant growth and production (Gupta 2011).

Overall, the lack of a mechanistic understanding of the influence of soil abiotic and biotic factors on the growth of the pathogen and its ability to infect the seedlings in the presence of an active and diverse microbial community during different phases of plant-pathogen-microbe interactions (i.e., in-fallow and in-crop) in nutrient-constrained calcareous soils, makes it difficult to truly evaluate management influences on disease incidence and impact. Experiments across South Australia and Western Australia indicated that liquid streaming of fungicides (e.g., Uniform®, EverGol® Prime) were more effective in reducing yield losses from rhizoctonia in wheat and barley crops compared to seed treatments (McKay et al. 2014). Dual banding of fungicides generally worked best with knife point and triple disc systems that disturb the soil 3–4 cm below the seed. In field trials at Minnipa, in-furrow application of fungicide products was more effective than seed application, with yield responses in both wheat and barley. However, application of appropriate tillage, starter N and Zn produced similar yields to many fungicide treatments (Cook 2014). Also, farmer field demonstrations showed variable responses to the fungicides, depending on the product and application method, in second year cereal paddocks with high rhizoctonia inoculum (Cook 2014). However, large-scale demonstrations by growers across the EP with in-furrow fungicide applications at seeding did not reduce rhizoctonia or produce yield benefits over three seasons (Cook 2017). Research evaluating liquid streaming methods has shown a strong effect of growing season rainfall on the magnitude of yield response to fungicide application, suggesting that crops with healthy root systems are better at exploiting soil moisture during the season and accessing stored soil moisture from summer rainfall (McKay et al. 2018). Research in the Mallee region has indicated that the effects of fungicides on different microbial communities are variable, and the interaction between fungicide effects on rhizoctonia and other biological processes would determine their efficacy and any benefits on final crop yield. Lack of knowledge about potential effects of fungicides on key groups of microbial communities as part of an integrated management system restricts development of management options that can enhance their effectiveness (Gupta 2015).

Another pressure for farming systems on calcareous soils is the presence of exotic snails (Anon 2003). Four introduced species of snails have become major pests of grain crops and pastures in southern agricultural systems: the white Italian, the common white, the small conical and the conical. Snails cause damage by grazing emerging seedlings of crops and pastures and causing harvesting and grain delivery issues. Canola and other break crops are most vulnerable to predation from these exotic snails. These snails are most fecund and widespread on calcareous soils (Anon 2003). A wide range of control and mitigation strategies have been developed (Smith 2013), but they continue to be an issue for farming systems on calcareous soils.

4.1.2 **Water holding characteristics**

Author: T McBeath

Calcareous soils retain more water at high levels of suction or drying when compared to a sand with equivalent particle size. This is due to the structure of intra-particle voids (as observed using scanning electron microscopy) and means that the crop lower limit of a calcareous sand will be higher than for other sands (Shahnazari et al. 2020). This in turn means that more rainfall is required to fulfil the crop lower limit before soil water becomes available to plants. This unique structure means that great care needs to be taken in the evaluation of soil conditioners because products that increase the soil water holding capacity may in fact reduce the amount of plant-available water. By contrast, the inter-particle pores dominate soil water behaviour at low levels of suction and wet calcareous soils behave similarly to wet sands (Kouzegaran et al. 2019; Shahnazari et al. 2020). This means that the range of soil water contents over which water is available to growing crop roots is quite narrow. There are techniques available to allow sampling specifically from soil pore water. Sampling soil water using hollow-fibre tubes is thought to generate a sample that more closely represents the pore water that a plant would have access to compared with centrifuge-based methods (Menzies and Guppy 2000).

Carbonates promote stable macro-aggregate structure with very low rates of turnover of the organic matter within due to low internal porosity (Muneer and Oades 1989; Fernandez-Ugalde et al. 2014). The low internal porosity is thought to be due to accumulation of calcite microcrystals (Fernandez-Ugalde et al. 2014). These different macro-aggregate structures are thought to be proportionally large enough to affect the processes of organic matter protection and water storage in calcareous soils. Understanding the soil water content and supply in soils that contain significant quantities of rocks or gravel requires a more considered approach to the characterisation of water holding capacity (Cousin et al. 2003). This often involves characterising the bulk density and water holding characteristics of the fine and the gravel fractions, which then need to be combined in a representative ratio (Wong et al. 2016; Gu et al. 2017). This is relevant to assumptions about both water and nutrient storage and supply in these soils.

4.1.3 **Organic matter quantity and turnover**

Author: V Gupta

Soil microbial activity and biological processes are influenced by chemical (pH, carbonate associated toxicity, salinity) and physical (aggregation, pore structure and water holding capacity) properties (Figure 10). It has been suggested that in calcareous soils edaphic factors such as high pH and salt/carbonate toxicities will influence diversity and function of organisms (Wakelin et al. 2008; Rath et al. 2019). Results from a survey of surface soils from more than 25 properties on upper EP over two years indicated that microbial biomass (MB) levels ranged between <100 and 1000 mg C g^{-1} soil, with a trend of higher MB under pasture-wheat rotation compared to continuous crop systems or remnant vegetation. There was also a positive relationship between soil organic C (SOC) and MB C (McNeill and Day 2001). An investigation of soil biology diversity and abundance in EP soils indicated that in the alkaline calcareous soils at Port Kenny, MB accounted for only 1.4–1.52% of SOC (Masters 2018). These and other findings for calcareous soils indicate that MB levels expressed as a ratio of SOC (microbial quotient) are generally less than 5%, which is suggested to be a threshold or estimate of the attainable level (Gonzalez-Quinones et al. 2011; Gupta et al. 2019b). The inability to accurately measure SOC levels in carbonate-rich calcareous soils also makes it difficult to reliably estimate the true status of MB and its responses to management in these soils. Microbial biomass levels were marginally higher after a well-grown canola crop (Gupta 2011). Microbial activity per unit MB or SOC in calcareous soils was generally low, probably due to one or more abiotic and/or nutritional constraints. For example, in general in alkaline soils, MB and activity levels in surface soils show significant negative correlation with electrical conductivity and soil pH (Garcia et al. 1994; Gonzalez-Quinones et al. 2011). In controlled-environment experiments using alkaline highly calcareous soils, application of P fertiliser significantly altered the microbial catabolic activity and diversity indicating that P availability may be constraining microbial activity (Davey et al. 2021).

The level of microbial activity and microbial responses to management in calcareous soils can be linked to the composition of soil microbial community, as composition in calcareous surface soils was found to be significantly different to that in non-calcareous alkaline and Mallee soils. For example, calcareous soils in general seem to harbour a higher proportion of fungi relative to bacteria compared to other agricultural soils. Calcareous soils from EP showed lower genetic diversity of bacterial community compared to non-calcareous and Mallee soils (Gupta 2015). Relative abundance of the Proteobacteria group was significantly lower, whereas Actinobacteria and Bacteroides were higher, in the calcareous surface soils.

Available C is a key driver of soil biological activity and nutrient cycling, especially in the low organic matter agricultural soils in Australia. There are regional differences in the composition of SOC, and farm practices can influence dissolved organic C (DOC) levels. McDonald et al. (2017) reported that DOC concentrations in the alkaline soils of the EP and mid-North regions of SA were high relative to the amount of SOC, and that high amounts of charcoal were present in the EP soils. Additionally, alkaline soils from EP generally showed higher C:N ratios (e.g., >14.5) (Tavakkoli et al. 2015; McDonald et al. 2017). The alkaline pH and carbonate chemistry both promote dissolution of DOC, resulting in a poor ability to retain DOC (Tavakkoli et al. 2015). It has been suggested that some calcareous soils occlude SOC (Rowley et al. 2018). Therefore, although the total organic C content of highly calcareous soils may be high for a semi-arid environment, it is likely that much of that C may not be readily available (Demoling et al. 2007; Schmidt et al. 2012; Tavakkoli et al. 2015). Since high pH is one of the abiotic constraints in highly calcareous soils for biological activity, amelioration practices that can reduce soil pH (Brautigan et al. 2014) could increase microbial activity and even modify microbial community to promote beneficial biological processes related to nutrient cycling and plant health.

Although the general effects of some of these soil properties on soil biological activity are known, there is limited understanding of the activity, composition and diversity of soil bacterial and fungal communities in calcareous soils. The effects of these properties on microbial activity and biological processes can be direct effects of physico-chemical constraints on microbial communities, or indirect, through their effects on plant growth and plant-microbe interactions (Figure 10). Soil moisture, temperature and C availability need to be synchronised for optimal performance of a range of key biological functions including those related to soil organic matter turnover and nutrient mineralisation (Gupta et al. 2019b).

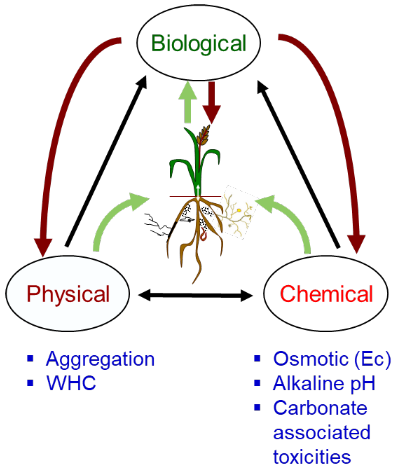


Figure 10. A conceptual diagram showing the direct effects and indirect effects through growing plants of soil physical and chemical factors and biological functions.

4.1.4 Nutrient Availability and Supply

Authors: T McBeath, V Gupta, M Evans, E Tavakkoli

Nitrogen availability is one of the key factors influencing cereal crop production in rain-fed cropping regions of the EP, including in calcareous soils (Adcock 2005). N mineralised from soil organic matter and crop residues has been shown to make a large contribution (~50%) to cereal crop uptake in rain-fed systems in many agricultural regions of Australia, and is expected to be similar in calcareous soils (Angus and Grace 2017). In a controlled environment experiment, Hancock et al. (2011) showed that while N fertiliser recovery (measured using ^{15}N tracing) was greater in average (decile 5) compared with dry (decile 2) conditions, losses of N fertiliser were lower in these calcareous soils than might be expected, by 13–24%. It is generally accepted that plant-available P is critically deficient in highly calcareous soils. However, it was also found that maximum benefit from fluid P fertilisers could only be realised with the addition of adequate fertiliser N (J. Hancock, Univ of Adel. pers comm). Also, stream bar applications of N post-seeding (as urea ammonium nitrate [UAN]) did not seem to provide an advantage over application of N at seeding (Hancock 2002). A mechanistic knowledge of the soil N cycle and the various biological processes involved, especially seasonal changes and in relation to plant requirements, is critical to understand the N supply and loss potential of soils and how they could be managed to improve N use efficiency (NUE) including more efficient fertiliser application methods.

In the SE, where the calcareous soils are also often rich in organic matter (3–7% organic C) and many farmers are trying to achieve hyper-yielding crops, current N calculators seem to be over-predicting N mineralisation and hence estimating low fertiliser N rates to apply. Timing and forms of N to apply are also concerns for cropping farmers in the SE, especially because soils are frequently waterlogged during winter and spring.

Carbon availability is the most limiting constraint to microbial functions in low fertility calcareous soils and management of biologically available C is the key to improving biological functions, including those involved in N mineralisation (Gupta et al. 2019b). In soils, water-soluble organic C is not only an immediate source of C for microbes, but its production is microbially mediated and the flow of C through water-soluble components supplies substrate for MB turnover. In Australian agricultural soils, MB-C accounts for 1.5–3.0% of soil organic C and MB N is 2–5% of total N. The amount of MB varies with soil type and agro-ecological region, and is influenced by crop rotation, tillage and stubble management practices that influence microbial populations and the quantity and quality of residues.

The amount of plant-available N in any soil is a balance between mineralisation and immobilisation functions, which are mediated by a variety of microbial processes (i.e., decomposition of crop residues, release of organic N, nitrification), all of which can be affected by the physico-chemical characteristics of calcareous soils (alkaline pH, carbonate concentration, biologically available C, pore-water relations). For example, Adcock (2005) indicated that the length of wetting and drying cycles (moisture supply) regulated crop residue decomposition and N mineralisation. Net N mineralisation was higher with legume residues and fortnightly or monthly rewetting events compared to more frequent wetting. However, the mechanisms for changes in the various biological processes underlying the N supply potential and N immobilisation capacity of calcareous soils have not been adequately quantified, and management effects are not known.

Nitrification is the process of conversion of ammonium N to nitrate N, with nitrate N being the form of N most readily available for plant uptake. Nitrification is considered as one of the critical steps in N mineralisation. Currently, little is known about the populations and responses of different groups of nitrifying organisms, or of the nitrification process, to varying soil-water conditions and management practices in calcareous soils. In soils, nitrification is generally associated with autotrophic nitrifying microorganisms (bacteria and archaea), but nitrification by heterotrophic microorganisms has been shown to contribute a significant proportion of total nitrification, especially under conditions that may not favour autotrophic nitrifying organisms (Killham 1986; Jia and Conrad 2009). Culture-based analysis for the abundance of nitrifying bacteria indicated a lower abundance of ammonia oxidizing bacteria (AOB) in highly calcareous soil from EP compared to Mallee sand, red brown earth and other alkaline soils (Gupta et al. 2008). Using culture-independent methods, Tao et al. (2017) found that in calcareous soils of pH 8.1–8.6, AOB were the dominant nitrifying microorganisms and most responsive to organic manure and inorganic fertiliser additions compared to ammonia oxidising archaea (AOA). However, AOA are suggested to be better adapted to nutrient-poor environments (Schauss et al. 2009) such as in calcareous soils. It is suggested that changes in AOB community structure and abundance under different crop management systems in unconstrained soils may be associated with combined effects of a range of edaphic and environmental factors including soil pH, availability of organic C and N availability (Muema et al. 2015; Ouyang et al. 2018). Also, as nitrification is an aerobic process, pore structure and soil conditions that facilitate oxygen diffusion (e.g., high bulk density) could influence nitrification and overall N mineralisation. Little is known about the responses of different nitrifying organisms and the nitrification process in alkaline calcareous soils with physical and chemical constraints and unique water availability properties. Currently, models such as the Agricultural Production Systems sIMulator (APSIM) do not predict nitrification to occur in high pH soils.

Field-based measurements for denitrification in an alkaline calcareous red sandy loam at Minnipa indicated that under a canola-wheat high input treatment, N_2O emissions were on average 6 g N_2O-N ha^{-1} day^{-1} (2.2 kg N_2O-N ha^{-1} year^{-1}) and were lower than emissions observed in the lower EP (Wanilla) (Harris 2015). N_2O emissions were higher under canola-wheat rotation than in the pea-wheat rotation. Additionally, high pre-seeding soil mineral N levels resulted in higher N_2O fluxes, especially after a significant rainfall event (Harris 2015). In the alkaline calcareous soils, modified N fertilisers such as nitrification and urease inhibitors, which have been shown to reduce rates of nitrification and consequently N_2O emissions, may increase N loss via NH_3 volatilisation (Mahmood et al. 2011). A better understanding of the factors that regulate nitrification and other N cycling processes would help design management practices that promote timely mineralisation of N from soil organic matter and fertilisers.

Microbial and N dynamics are largely unresearched in the SE cropping environments, which have shallow water tables, long springs and very alkaline calcareous soils with high organic matter levels as common features.

A key consideration in highly calcareous soils, especially when soil moisture is low, is the risk of fertiliser toxicity. The risk is highest for fertilisers that will release ammonia when added to soil. For example, 23 kg N ha^{-1} as urea placed with the seed reduced plant establishment in three trials on Upper EP, whether the crop was dry sown or sown on the break (Cook et al. 2019). A recent study demonstrated that the minimum critical distance at which fertiliser should be separated from seed in order to avoid fertiliser toxicity was higher in calcareous soils for commonly used fertilisers including diammonium phosphate (DAP) and urea (Dockerill 2019). Current seed bed utilisation charts do not adequately cover this extra risk in calcareous soils.

Reactions of nutrients in calcareous soil strongly favour fixation (or precipitation) type reactions, which are very difficult to reverse. P sorption curves from field-collected soil samples suggest that on EP, 80–90% of applied P on grey calcareous soils and 50% of applied P on red calcareous soils is rapidly fixed and unavailable to plants (Bertrand et al. 2000). The sorption values found in this survey confirm that soils on EP are among the most highly P-fixing soils found in Australia (Bertrand et al. 2000). In calcareous soils with high concentrations of calcium, calcium forms precipitates with P, which reduces the diffusion of P and other nutrients away from fertiliser granules.

The fixation reactions in calcareous soils lead to issues of low concentrations or poor supply of P, Cu, Mn and Zn and very low fertiliser nutrient recovery (Figure 11).

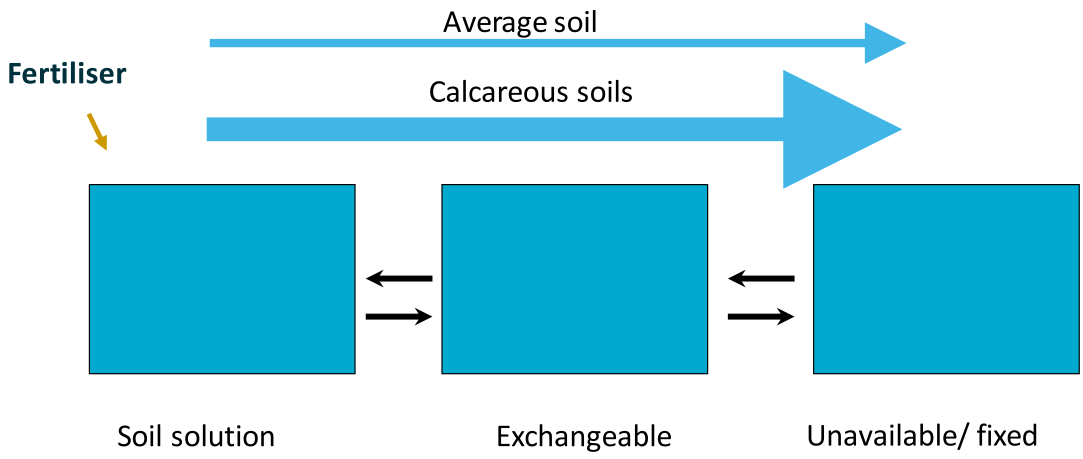


Figure 11. A schematic representation of the reactions of phosphorus and zinc in highly calcareous soils representing that precipitation reactions (unavailable/fixed) are more strongly favoured.

Plant P nutrition is a challenge in highly calcareous soils due to strong sorption and slow dissolution processes, which reduce P availability to crops (Lombi et al. 2004). Addressing P access and availability in these soils is one way of increasing crop productivity and thus reducing the yield gap in moisture-limited environments like the upper EP. A study was conducted on upper EP comparing a range of fluid fertiliser products compared with granular products in field experiments with spring wheat on highly calcareous grey sandy loams (>50% carbonate) and a calcareous red brown sandy loam (5–10% carbonate). Grain yield was increased by 23% by applying fluid compared with granular fertiliser on the grey calcareous soil and by 19% on the calcareous red brown sandy loam (Holloway et al. 2001*a*). Liquid sources of P fertiliser were shown to be of significant benefit to fertiliser P recovery and crop yield of grey highly calcareous soils (90% of tests) in the late 1990s and early 2000s (Holloway et al. 2001a; Holloway et al. 2007). Under controlled conditions, plants grown in a grey highly calcareous soil from EP, when provided with P in different forms, took 50% of their P from fluid fertiliser but only 30% of their P from granular fertiliser, indicating the efficiency of fluid fertiliser was at least 20% better than the granular product (Bertrand et al. 2000).

The relative difference in yield gains for fluid P compared to granular P appears to increase with increasing $CaCO_3$ content of the soil (Figure 12; Holloway et al. 2000a). Also, the rate of increase in yield with increasing P application appears to be greater for fluid P than for granular P on highly calcareous soils (Holloway et al. 2000b). Quantifying these relationships might make it easier to identify the paddocks most likely to have significant yield gains from fluid P application. Combinations of fluid and granular fertiliser applied together produced variable results in terms of dry matter production and yield gains, with the simplest and most effective method being to apply all nutrients in fluid form (Frischke et al. 2000).

Application methods also influence yield responses to fluid fertilisers. A water rate of no less than 120 L ha^{-1} (Holloway et al. 2000c; Frischke 2002) and pressure of at least 10 psi gives good results in a range of situations (Frischke 2002). Keeping water rates up assists in dilution and distribution in the soil profile (Frischke et al. 2001). Although higher water rates might be advantageous in some circumstances, this is unlikely to be practical or economic on a paddock scale. If water rates are too low, it will be hard to maintain a continuous stream and even distribution between lines and blockages will be a problem (Frischke 2002). Although responses might be improved by applying fluid fertiliser as a wide spray rather than as thin stream (Brace et al. 2001), farmers do consider it important to apply fluid fertilisers in an unbroken band for best results (Frischke et al. 2001).

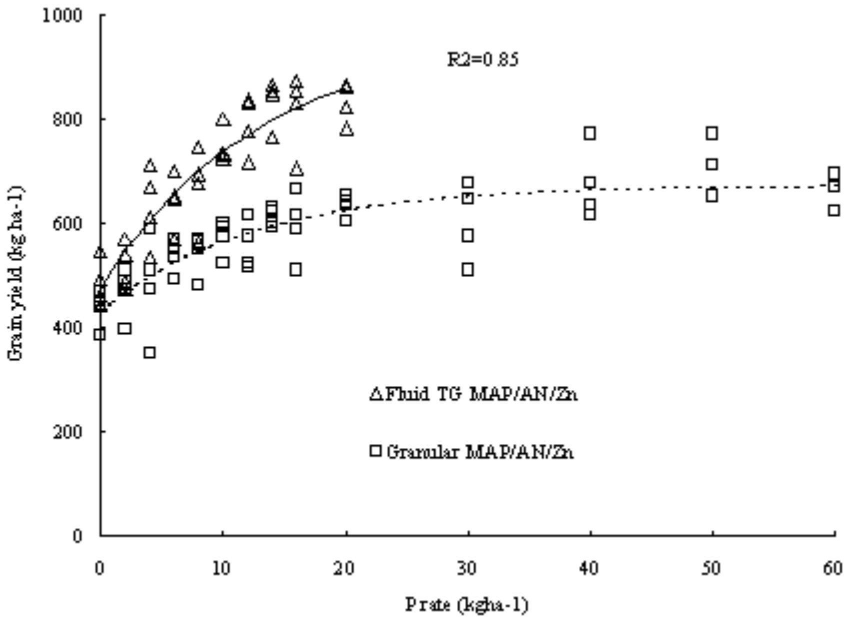


Figure 12. Response of grain yield of Frame wheat on a highly calcareous soil on upper EP to rates of P applied as fluid technical grade MAP in solution with ammonium nitrate and zinc sulphate, or granular MAP with ammonium nitrate and zinc sulphate. From Holloway et al. (2001).

The carryover effect of fluid nutrients on yield of subsequent cereal crops has been small and variable on EP Calcarosols (Bertrand et al. 2001; Brace et al. 2001; Holloway et al. 2001b; Holloway et al. 2001; Cordon 2003; Holloway et al. 2003), although there are reports of increases in early dry matter production resulting from fluid fertiliser carryover (Bertrand et al. 2001; Holloway et al. 2003; Cook et al. 2006). The main exception to this is the finding that fluid fertiliser carryover increased barley yields as well as early and late dry matter production on calcareous soils where high rhizoctonia levels were present (Cook et al. 2010). The residual value of fluid fertiliser and granular fertiliser appears to be similar, but that is dependent on factors such as soil type, crop type grown in the previous season and the form and amount of fertiliser applied in the current year (Holloway et al. 2001b). In general, the previous crop type is more important than the form of fertiliser used in that crop (Holloway et al. 2001b).

P management is also an issue for SE farmers on calcareous soils who are concerned about balancing rates of P fertilisers that allow very high yielding crops but also minimise losses into water tables and waterways. Appropriate soil P reserves, rates and types of P fertilisers are all uncertainties for growers on calcareous soils, which have only relatively short cropping histories.

Significant responses to liquid sources of Zn fertiliser have also been recorded in these soil types (Hettiarachchi et al. 2008). A key outcome of this work was the identification that liquid sources of P and Zn offered superior mobility and lability to crop plants in highly calcareous soils (Lombi et al. 2004; McBeath et al. 2007). The interaction between fertiliser reactions in calcareous soil and soil water has been examined under controlled conditions, and while fertiliser diffusion was limited by dryness, the amount of P that is potentially plant-available (or exchangeable, Figure 11) was not (McBeath et al. 2012b). However, under field conditions a significant effect of soil dryness reducing P fertiliser recovery has been demonstrated (McBeath et al. 2012a).

While there has been some adoption of liquid sources of P within and beyond Australia (Akhtar et al. 2015), most uses of liquid fertilisers are for the application of micronutrients (Zn, Cu, Mn) due to the substantial price premium for liquid P. Liquid P costs in Australia, per unit P, are approximately double that of granular fertiliser P. However, when the differences in fertiliser efficiency and N required are considered, growers who are set up for liquid P delivery can make the system work at a similar cost.

In 2014, only 19% of 50 EP and 24 Mallee broadacre crop growers surveyed were using fluid delivery systems for fertilisers and micronutrients (Scholz and Cook 2014). While cost is a likely contributor to the relatively low adoption of fluid delivery systems for P, there are also other factors in play on EP. Firstly, moisture stress is often present during grain filling, meaning that significant yield responses to liquid sources of P are unlikely in many seasons. Secondly, farmer experience suggests the yield gains at a paddock level are less than those seen in trials (Doudle et al. 2002) and paddock demonstrations indicate that yield improvements are often small (Cordon 2005). Paddocks are likely to have large spatial variations in soil responses to fluid P, and it is possible this is contributing to the differences in yield gains seen at a trial and at a paddock level. Some farmers are using liquid P on crops in the SE, but this is based on little local information.

Figure 13. Mn deficiency in wheat on a calcareous soil of the upper Eyre Peninsula (N Wilhelm, SARDI).

Micronutrient supply (Zn, Cu, Mn) remains a key limiting factor in highly calcareous soils (e.g., Figure 13; Rashid and Ryan, 2004) but can be resolved through frequent applications of small doses, with liquid sources more effective than granular (Hettiarachchi et al. 2010a; Hettiarachchi et al. 2010b). An additional micronutrient worthy of consideration is iron, particularly in legumes. Local rhetoric is that legumes perform poorly in calcareous soils. While this can in part be related to the supply of P, Fe deficiency is a commonly cited issue for legume production in calcareous soils globally (Liesch et al. 2011a; Liesch et al. 2011b). It has not been recognised as a widespread problem on upper EP. However, patches of stunted and yellowing break crops are common on the calcareous soils of the SE. These patches respond to foliar applications of Mn and Fe but never fully recover (Figure 14).

Figure 14. Poorly growing faba beans on calcareous soils in the SE of SA (M Fraser, DEPIR, Naracoorte SA).

Arbuscular mycorrhizal fungi (AMF), which form symbiotic relationships with plants, are widespread in soils, including in highly calcareous soils, and can provide benefits in nutrient supply, especially P in P-deficient soils (Smith and Read 1997). Unlike medic and clover, which are well colonised by AMF (>70% of root length colonised), the finely-branched root system of wheat tends to be poorly colonised (10–30%) (Graham and Abbott 2000). However, Li et al. (2005) showed that wheat was highly colonised in a calcareous soil from EP. It was suggested that interactions between wheat and AMF in calcareous soil are strongly influenced by P supply. A considerable amount of ^{32}P (50–80%) was delivered into wheat via the AMF pathway even with no growth responses, suggesting that AMF colonisation provides a conduit for P uptake by wheat plants in calcareous soils. Also, observations of growth depression in plants due to C demand from AMF colonisation in early seedling stages had disappeared at maturity (Li et al. 2006). AMF benefits to P nutrition varied with the type of P fertiliser (granular compared to liquid forms) and the benefits were greater with fertiliser P application compared to low available P situations, in particular in the P-fixing Calcarosols. It was suggested that plant-AMF interactions could provide other benefits to plant health through AMF-microbe interactions. The role of AMF colonisation, in terms of plant health under high soil-borne disease conditions that occur in calcareous soils, has not been investigated.

There are still some formulations left to experiment with in calcareous soils, including acidifying agents, dilution-based approaches and saturation reactions (Weeks Jr and Hettiarachchi 2020). Recent work on moderately calcareous soils in the US has shown that the proportion of fertiliser applied that is labile (potentially plant-available) is higher in formulations with a higher water volume and where polyphosphate fertilisers are blended with MAP (Weeks Jr and Hettiarachchi 2020). Previous work that examined polyphosphate in isolation did not find it to be significantly more labile than other sources of liquid P (McBeath et al. 2007), so this new work blending combinations of products offers new insight.

When fertiliser is banded, the fertilised volume is a small proportion of the total soil profile and creates an increased proportion of soil nutrient load that is exposed to topsoil drying.

Experiments have generated yield increases when fertiliser was applied 8–15 cm below the seed (Scott 1973; Jarvis and Bolland 1991; Helyar 1998; Holloway et al. 2004). One option might be to band nutrient near the seed for starter nutrition and modify the fertility of the remaining soil volume to provide nutrients later in the season. This approach has been tested in Northern Australia (Angus et al. 2019) and is now being evaluated on other soil types in southern Australia through the Deep P project (GRDC project, DAN2001-033RTX).

Synergy between N and P when supplied together is known (Officer et al. 2008; Armstrong et al. 2015; Duncan et al. 2018), and while partially evaluated in highly calcareous soils (Holloway et al. 2002), it has not been fully explored. Preliminary work in the Mallee suggests that P supplied near the seed combined with N banded below the seed can offer improved early vigour and in some cases yield benefits (McBeath et al. 2017).

While some Australian soil types are responsive to S fertiliser (Anderson et al. 2013), detection of a significant yield response on highly calcareous soils is limited. There are, however, examples where gypsum has been used to lower pH in very high pH (>9.0) calcareous soils (Brautigan et al. 2014), which may supply plant-available S as well.

There are several options for applying Fe to legume crops including foliar application, seed coating and soil banding at the time of seeding. Work based in the US suggested that seed coating with subsequent drying prior to the seed being sown was the most effective option (Liesch et al. 2011a). Seed priming with zinc has also shown to be of significant benefit in highly calcareous soils, providing additional benefit on top of that achieved with seed priming with water alone (Harris et al. 2007). A re-examination of seed priming with custom blends of trace elements for the purpose of establishment of good early vigour and disease tolerance could be worthy. Custom blends of trace elements delivered via the foliar pathway may also be a viable option (Yaseen et al. 2013).

Soil mixing may be used to address stratification of nutrient in layers prone to drying and their subsequent low solubility, a significant issue in highly fixing soils. Mixing may also have a dilution effect, which could overcome some of the issues that arise when nutrients prone to precipitation reactions are applied at high concentrations in a band. An example of this is an evaluation of different sources of Zn, where the solubility of the Zn product became less of an impediment to lability when the nutrient was mixed throughout the soil volume (McBeath and McLaughlin 2014). The strategies to deliver soil mixing might be those used for mixing of repellent and constrained sands, including ploughing, spading and ripping with inclusion.

4.1.5 **Stabilisation of soil organic carbon with iron oxide minerals and biochar**

Authors: E Tavakkoli, L van Zwieten

Soil organic carbon (SOC) plays a vital role in maintaining soil quality and ecosystem functions, supporting agronomic productivity and resilience to induced stresses including drought and climate change. Human activities and land use change have, however, reduced SOC in agricultural land by an average (globally) of 0.5–2 Mg C ha^{-1} yr^{-1} (Ogle et al. 2005). Between 40–60% of C photosynthesised by plants is released through roots as rhizodeposits (i.e., exudates, soluble lysates, mucilage, sloughed-off root cells and tissues) and contributes to up to 1% of the SOC pool per year (Kuzyakov and Schneckenberger 2004). Because rhizodeposits are labile (e.g., sugars, amino acids, organic acids), they can be rapidly mineralised (to CO_2) by microorganisms (Kuzyakov and Larionova 2005). Further, the labile C inputs tend to stimulate R-strategist microorganisms, resulting in the priming of SOC (i.e., when the microorganisms run out of labile C from rhizodeposits, they seek SOC as a nutrient and energy source and lower SOC stocks) (Zhu et al. 2014). There are several factors that control how much of the rhizodeposits are either stabilised as SOC, or mineralised. Factors including soil physical characteristics (e.g., aggregation), chemical characteristics (e.g., pH, SOC content), mineralogy and biological properties (Blagodatskaya and Kuzyakov 2008; Philippot et al. 2013) can all influence the fate of rhizodeposits.

By increasing the stabilisation of rhizodeposits, it should be possible to build SOC stocks and potentially shift the soil microbial community to a more structured community with improved carbon use efficiency (CUE) (Fang et al. 2018). Several processes have been suggested as targets to improve CUE and stabilisation of rhizodeposits:

- physical protection in aggregates (organo-mineral protection of rhizodeposits by biochar-induced microaggregates) (Weng et al. 2018)
- physical protection via sorption to short range-ordered Fe oxides, such as ferrihydrite, (Rasmussen et al. 2010)
- physical protection via co-precipitation with the iron mineral goethite (FeOOH) (Kaiser and Guggenberger 2007; Jeewani et al. 2020)
- manipulating soil mycorrhizae (AMF) that contribute to terrestrial C sequestration by acting as a conduit to transfer rhizodeposits from roots to the soil (Wright et al. 1998; Řezáčová et al. 2018)
- balancing the microbial nutrient stoichiometry requirements of inputs (Kirkby et al. 2016; Fang et al. 2020) to obtain optimal ratios of C: N: P.

While there is still uncertainty around the exact value to production from improving SOC stocks, estimates have shown that wheat yield can increase by 20–70 kg ha^{-1} for every 1 t ha^{-1} increase in the SOC pool in the root zone (Lal 2006). There is, however, a paucity of knowledge on the role of improved SOC stocks in highly calcareous soils. Constraints to production in calcareous soils that could be addressed through increasing SOC content could include the following:

- reducing N volatilisation (via NH_3 and denitrification) by storing more N in the microbial and SOC pools, and through providing adequate protons in soil to enhance ammonium content;
- increasing available P content by intercepting available P before it is locked up as calcium phosphate, concomitantly increasing the microbial cycling of P;
- modification of soil eH through biochar application, thus lowering the free energy required for plant nutrient uptake (Chew et al. 2020); and
- modification of the soil microbial community through biochar application. This should directly influence soil organic matter content and improve soil available N, P, and K (Zhou et al. 2019; Joseph et al. 2021).

Biochar is a carbon-rich material that is produced in oxygen-limited conditions, generally between 400–700 °C, and has been proposed as a geoengineering solution that has potential to actively reduce the atmospheric concentrations of greenhouse gases and enhance the sustainability of agriculture through improving soil conditions. In a detailed meta-analysis comparing biochar amendments to fertilised controls using over 100 published studies, Ye et al. (2019) showed that biochar resulted in an average increase in crop production of 15%. Most biochars are alkaline due to their ash content (Macdonald et al. 2014) and have been shown to impart significant improvements in yield in acidic soils. However, their high EC and alkaline properties can cause yield penalties in Australian calcareous soil (Macdonald et al. 2014). Indeed, another meta-analysis of published international studies showed that biochar is most effective in highly acidic soil with little benefit in alkaline soils (Dai et al. 2020). However, recent advancements in material sciences engineering have allowed biochars to be substantially modified to become ‘fit for purpose’. Biochar derived from wheat straw was post-treated with phosphoric acid (Yao et al. 2015) to produce an acidic biochar with greater surface area and high nutrient (especially P) content. This modified biochar was shown to significantly improve yields in a moderately acid soil, but data on alkaline or highly alkaline Calcarosols is still lacking.

Biochar has also been shown to improve soil water retention and reduce soil compaction. A meta-analysis showed an average reduction in soil bulk density of 9% (Razzaghi 2020), which has been suggested as an important factor in developing agroecosystem resilience (Edeh et al. 2020). These soil physical property changes may further explain the positive effects of biochars, particularly in sandy soil. Importantly, Edeh et al. (2020) showed that biochar decreased saturated hydraulic conductivity (Ksat) in sandy soils (by up to 64.6%), and increased plant-available soil water by 47% for the coarse-textured soils and by 9% for medium textured soils. Using x-ray µ-tomography, Quin et al. (2014) explained these findings by quantifying the increase in total soil porosity, connectivity of pore space and number of pores as affected by biochar application across soils of different texture.

4.1.6 Dispersion and Alkalinity

Author: E Tavakkoli

The presence of dispersed clay particles in the soil solution can result from the abundance of Na^+ ions, and to K^+ ions to a lesser extent (Rengasamy and Marchuk 2011), that are adsorbed on the exchange surfaces of clay particles. Clay dispersion increases the severity of physical constraints in dense clay subsoils. The fine dispersed particles of clay diffuse into soil pores and block them, and then remain in the pores when the soil dries (Rengasamy et al. 2016). The dispersed clay reduces the hydraulic conductivity in the clay subsoil, and this reduction increases with high bulk densities. Both McNeal et al. (1968) and Frenkel et al. (1978) report a marked decline in the hydraulic conductivity in soil columns in the presence of percolating Na solutions with low salt concentrations. Hydraulic conductivity declined as the clay percent increased. The measure that is frequently used to indicate whether clays might disperse is the exchangeable sodium percentage (ESP) when it exceeds a critical value, nominally 6% for Australian sodic soils. The ESP is the ratio of exchangeable Na to the sum of exchangeable cations (Sumner 1993). Another measure is the sodium adsorption ratio (SAR), which involves measuring exchangeable calcium, magnesium and sodium. The reason why Na promotes dispersion is because large hydrated Na^+ ions form loose ionic bonds of attraction to negative sites on clay surfaces, forming a swarm of ions that extend out to form an expansive diffuse layer (Shainberg and Letey 1984). The overlap between diffuse layers of Na^+ ions around clay particles creates repulsion forces, causing the clay particles to swell and separate to the point where forces of attraction between the clay particles disappear (Sumner 1993), and the particles disperse through the soil solution.

In calcareous soils, high ESP and high pH are always linked together and it is difficult to apportion their effects on the resulting poor soil physico-chemical conditions and consequently on crop growth. An excess of exchangeable sodium and high pH caused by the presence of sodium carbonate or bicarbonate impart poor physical conditions to these soils. In many saline sodic soils that do not contain sodium carbonate, the pH is around 8.2–8.3. Gupta and Khosla (1982) indicated that pH, with its intimate relationship with sodicity of calcareous soils, is likely to affect the whole range of physico-chemical and surface properties of soils. Variations in pH have been found to affect dispersion in pure clay minerals (Schofield and Samson 1954) and in soils (Tavakkoli et al. 2015). Depending on clay mineralogy and oxide contents, soils may exhibit a net negative charge or positive charge at high or low pH respectively. For example, Suarez et al. (1984) showed that at constant SAR and electrolyte levels, clay dispersion increased with increasing pH. Changes in pH affect the edge charge on clays and the surface charge of oxide minerals such as iron and aluminium. At low pH, soil minerals are positively charged and bonded to the negatively charged faces of the phyllosilicates. At high pH, however, they undergo charge reversal, and thereby increased dispersion.

For surface soils, the zero point of charge (ZPC) and charge reversal usually occurs around pH 7–9 but may vary depending on the structural composition and degree of crystallinity of the variable charge components. At low pH values (below ZPC), the positive charge on edge surface leads to edge-to-face association, which inhibits dispersion. When pH exceeds the ZPC, the increase in negative charge results in increased dispersion. Adsorption of various anions can increase the net negative charge in the clay system and hence its dispersion (Shanmuganathan and Oades 1983).

When Na accumulates in calcareous layers, soluble $NaHCO_3$ and Na_2CO_3 salts form, which increase alkalinity considerably to pH(H_2O) values greater than 9 (Rengasamy and Olsson 1991; Tavakkoli et al. 2015). Several chemical constraints can develop in these highly alkaline subsurface layers. Toxic concentrations of carbonate and bicarbonate anions can be present in highly alkaline subsoils. Gao et al. (2012) found that Na forms of carbonate were more toxic than bicarbonate forms, for oat plants in a glasshouse pot trial. They attributed the greater toxicity to the increased energy demands in sequestering Na^+ ions, to making osmotic adjustments in cells, and to reductions in photosynthesis. However, dicot calcifuge plants such as peas and beans suffer more intense root inhibition from HCO_3 ions compared to the monocots barley and oats. In addition to these anion toxicities, toxic concentrations of aluminate ($Al(OH)_4$) anions as well as boron (B) can also occur in these soils (Cartwright et al. 1984, 1986). Boron toxicity tends to occur in seasons with dry finishes during grain filling when the roots need to explore deeper soil layers to absorb water (Bell, 1999). The nutritional status of crops growing in highly alkaline subsoils is poor, with the high pH affecting cation and anion uptake (Gao et al. 2012). The high alkalinity also increases negative charges on the surfaces of clay particles, which increases clay dispersion. A consequence of the combination of chemical toxicities, nutrient deficiencies and increased clay dispersion, is that highly alkaline subsoils represent a hostile environment for crop roots (Chorom and Rengasamy 1997; Rengasamy et al. 2016).

4.1.7 **Vulnerability to erosion**

Author: B Masters

In South Australia, the soil formation process of aeolian deposition leading to the formation of many of the calcareous soils is also responsible for some of the production constraints associated with these soils. The calcareous sands and sand loams common to the EP and YP regions have moderate inherent susceptibility to wind erosion (Figure 15).

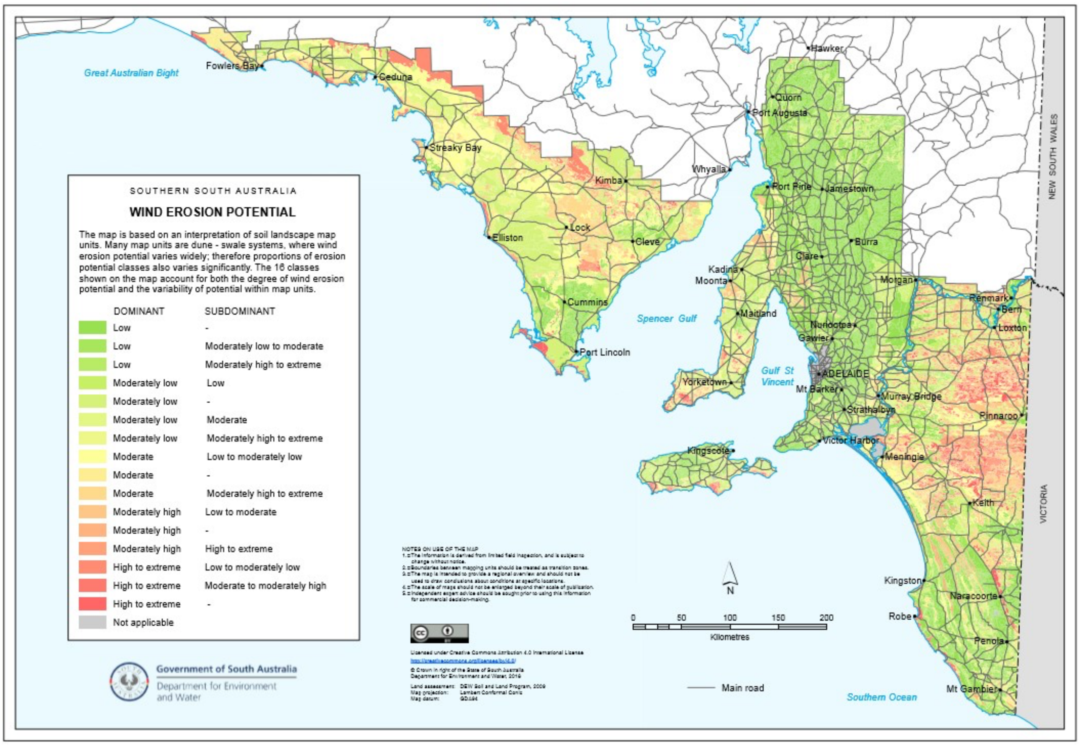


Figure 15. Inherent wind erosion potential of soils across South Australia. *Map sourced from https://data.environment.sa.gov.au/Content/Downloads/SoilAttrib_SA_WindErosion.pdf (28/01/2021).*

4.2 Subsoil constraints

Authors: B Masters, M Evans

Because leaching of salts from the profile is, and has historically been, limited by rainfall, there can often be an accumulation of salts in association with calcareous layers in the soil profile. Such salts include boron, and sodium and potassium chloride, as well as bicarbonate salts resulting in high alkalinity, sodicity and salinity. Boron toxicity can be an issue in association with many of the calcareous soils of EP and YP. In lower rainfall environments where marine sediments (which are high in B) have influenced soil formation, an accumulation of B can be present within the soils (Figure 16). Because B is slightly soluble, it tends to be leached out of the root zone in higher rainfall areas (Department of Environment and Water Soil and Land Information, accessed 22/12/2020).

Work from the EP shows that many of the highly calcareous sandy loams (Cungena and Nunjikompita) can contain quantities of B that present a low hazard to wheat production whilst the redder variants (Minnipa and Poochera soils) can contain much higher levels in the subsoil, presenting a significant constraint to crop production. This work showed that whilst high levels of salt could be found in many of the subsoils assessed, the distribution of salt was much more variable than for B (Holloway 1991).

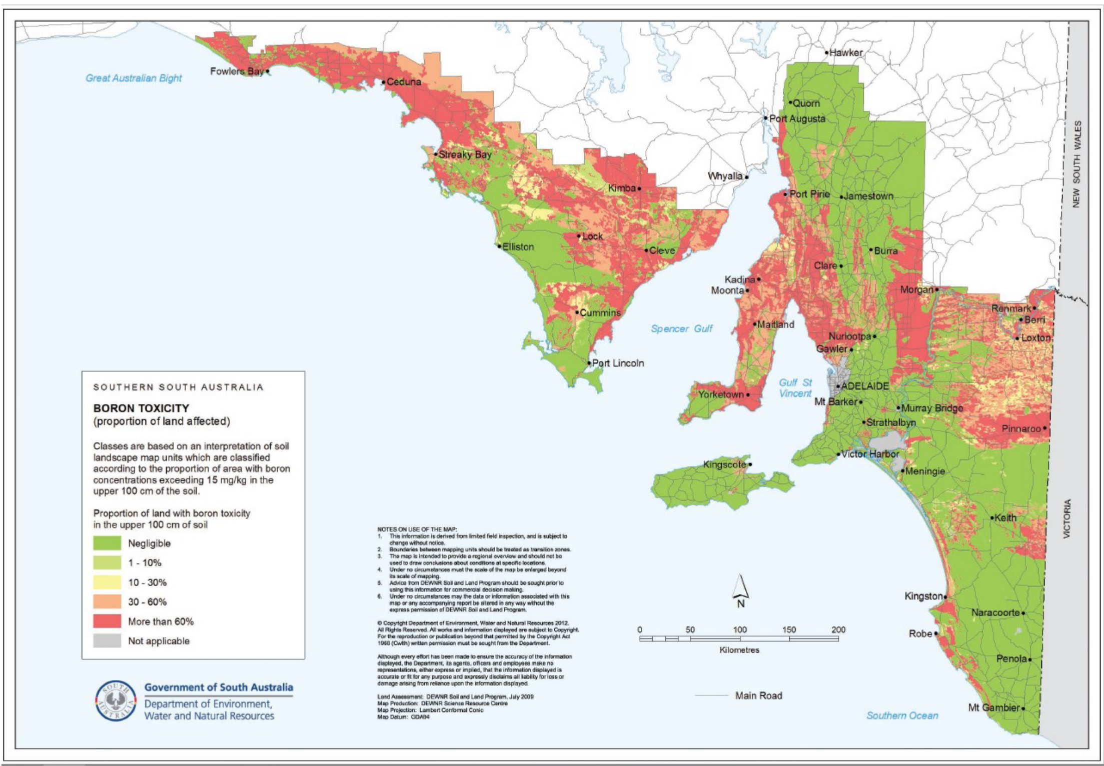


Figure 16. Distribution of land affected by boron toxicity (boron concentrations exceeding 15 mg kg^{-1} within 100 cm of the surface). *Map sourced from https://data.environment.sa.gov.au/Content/Downloads/SoilAttrib_SA_ToxicBoron-Proportion.pdf (28/01/2021).*

Physical disturbance of subsoils and incorporating nutrients or organic matter are two ways of ameliorating poor subsoils and improving crop performance. However, trials on the EP indicated that there was no economic advantage in mechanical intervention to ameliorate compacted subsoil layers. Although limited benefits were seen at some sites (mostly sandy soils but not Calcarosols), these did not last longer than two seasons (Doudle 2004). Another trial reported that fluid fertiliser applied into the subsoil using a deep ripper increased yield but was not economic (Hancock 2003). Wind erosion risk is very high when deep ripping legume stubbles or cereal paddocks with very low stubble levels (Dzoma et al. 2019a). Ripping to 40 cm with inclusion plates and wide rows (60 cm) does not leave the ground as vulnerable to wind erosion as spading and is also proving competitive in terms of economic returns (Wilhelm et al. 2019). Furthermore, if mechanical interventions and ameliorants applied deep in the soil profile stimulate early biomass production, they can increase the risk of haying off when soil water reserves are low and the finish to the season is harsh and dry (Dzoma et al. 2019a). This can be a problem on the shallow crests of sandhills in very dry seasons (Dzoma et al. 2019b). As good early dry matter production is often noted with these treatments (Doudle 2002; Masters and Davenport 2015), it is probable that soil moisture is depleted prior to grain filling in dry seasons, causing haying off. These conditions are common on upper EP.

In the high rainfall cropping areas of the SE, there has been almost no assessment of deep soil disturbance using mechanical interventions (e.g., ripping, spading), either alone or in combination with amelioration options (e.g., fluid fertiliser at depth, incorporating organic material) for managing production constraints on calcareous soils. At Frances in the year of ripping (Potter and McFarlane 2010) and the year after ripping and spading (Potter and Bailey 2009), there were limited yield gains for barley, but it is unclear whether the trial sites were on alkaline soils. Bailey (2010) found ripping, spading and delving increased early dry matter production at Kybybolite, but this did not result in improved yields (possibly because of the sharp finish). Again, it is unclear whether the site was on alkaline soils. McCaskill et al. (2016) found that in a decile 1 year across the Southern Region HRZ, there were early biomass responses to N and P at most sites but that this did not carry through to improved yield. Evidence suggested that treatments with higher fertiliser inputs hayed off due to moisture stress during grain filling – just as is seen in the low rainfall environment on EP. Heavy soils and early waterlogging can reduce rooting depth in the HRZ and, when combined with low plant-available water in heavy soils, this can mean there is limited soil water available to plants during grain filling.

In summary, mechanical interventions and soil ameliorants can increase biomass and grain yield but results are highly variable and it can take some time following modification to see benefits (Masters 2019). Responses to the interventions and ameliorants depend on season, site and treatment selected, indicating the management strategy needs to be tailored to the characteristics of the soil profile at depth (Masters and Davenport 2016). If a holistic approach of managing more than just one subsoil constraint is used, that may improve the longevity of benefits and of overall returns on investment (Dzoma et al. 2019a).

As the responses to these interventions and ameliorations are dependent on the characteristics of the soil profile at depth, treatment efficacy could be affected by within-paddock soil variability to such an extent it will not be economic. One recent demonstration supports this contention, where deep ripping increased grain yield of wheat on the mid-slope of a sand hill, but not on the crest (Dzoma et al. 2019b). If this is commonly the case, then using proximal sensing technologies (Arsego et al. 2018 and 2019) or other methods to map subsoil characteristics and match treatments to the needs of different areas within a paddock might improve the economic outcome. Affordable, practical machinery is needed for delivery of ameliorants into constrained soil layers (Masters and Davenport 2016).

Exploring the experiences of other regions and states not only provides ideas for new research programs but can also indicate how applicable findings from one area are likely to be to other areas with highly calcareous soils. Yorke Peninsula (YP) in SA and Salmon Gums in Western Australia (WA) also have areas with highly calcareous soils and have examined options for managing the constraints imposed by those soils.

Field trials at Salmon Gums provided similar results to those seen on EP when comparing fluid P with granular P application – fluid fertiliser increased tissue P concentrations and plant growth, responses were greater in soils with higher calcium carbonate content, addition of N improved response to the fluid P, and grain yield responses only occurred on soils responsive to P. Pot experiments using soils from WA, Vic and SA concluded that as soil pH and calcium carbonate content increase, cereal responses to fluid P application increase when compared with granular P, regardless of soil source (Lombi et al. 2003).

On YP, mechanical interventions improved crop growth but did not always improve yield and were considered expensive as large equipment is required (Hignett 2001; Hignett and Gierke 2002). Fluid P increased tissue P concentrations, vegetative growth and yield of wheat and barley when compared to granular P on a very P deficient sand with 80–85% $CaCO_3$, but not on a less P deficient loam with 12–14% $CaCO_3$ (Wilhelm 2002). After three years of field assessment, fluid P fertilisers were considered to be more effective on coastal calcareous sandy loams with low rainfall and 5–10% $CaCO_3$ than on similar soils with higher rainfall and >80% $CaCO_3$ (Wilhelm 2004). This suggests that higher rainfall can improve the efficacy of granular fertiliser and reduce the advantages of fluid fertilisers on highly calcareous soils.

The high cost of fluid fertiliser was considered to be a barrier to adoption of this technology (Wilhelm 2002; Long 2004).

The responses to treatments on the calcareous soils of YP and WA are similar to those seen when managing production constraints on calcareous soils on EP. This indicates that findings and recommendations from research in one area should have wide applicability. The importance of treatment economics and of rainfall effects on efficacy of granular fertilisers relative to fluid fertilisers should be considered when planning and interpreting research results and making management recommendations.

5 Opportunities and Research Gaps

While grain cropping on fragile soils is common on upper EP, several significant soil constraints to using the available soil water, optimising crop nutrition and growth and achieving target grain yields in this strongly water-limited environment exist. The weight of evidence from low rainfall south-eastern Australia is that productivity on these soils is well below potential and that opportunities for improving productivity in the region are likely to be greater on sands than finer textured soils (Unkovich et al. 2020). The costs of available amelioration and mitigation techniques need to be weighed against the achievable crop yield and system benefits. These will to a large extent be determined by the water-limited crop yield potential. Therefore, an assessment of the gap between actual crop yields, the current water-limited crop yield potential, and the yield potential of reformed soils in the region is required to close the large yield gap. Hochman and Horan (2018) estimated that half of the average yield gap of wheat in Australia (i.e., 1.71 t ha^{-1}) can be attributed to low N fertiliser inputs applied to replace the N extracted from the soil by crops. While this is true in many low rainfall cropping systems, opportunities do exist that can close the large yield gap on upper EP using multiple strategies.

The constraints to production identified for alkaline soils in the SE are similar to those identified for alkaline soils on EP, which suggests that similar approaches and a basic suite of treatments can be used in both regions to assess similarity of responses and to strengthen conclusions from the overall field trials program. The similarity of constraints to production identified in both regions also implies that findings from one region may have some direct applicability to the other region despite differences in farming systems and agroclimatic conditions. However, the strategies to overcome or minimise these constraints may be quite different between the two regions, given the vastly different production and input profiles for their farming businesses.

Many studies in low and high rainfall regions show that reducing soil constraints to production and providing good early nutrition (including fluid fertiliser) often results in improved early dry matter production that does not lead to yield gains due to haying off after moisture stress during grain filling. Several authors (McBeath et al. 2005; McBeath et al. 2007; Armstrong et al. 2008) have noted that a “challenge to the wider scale adoption of fluid fertilisers is our current inability to identify under what circumstances fluid fertilisers out-perform granular forms”. McCaskill et al. (2016) suggest that in the Southern Region HRZ most N be applied in-crop, both to allow some control of excessive canopy development in dry seasons and to achieve higher N efficiency. These findings all imply that quantifying treatment effects on production of dry matter, tillers, heads and time to crop maturity (combined with soil and weather data) will assist in gaining a better understanding of when and why treatments are most likely to increase yield. To assist in interpretation, the amount and timing of dry matter production could be manipulated using fertiliser formulations (e.g., granular or fluid), plant growth regulants and rates and timing (e.g., at seeding or in-crop) of fertiliser application.

McCaskill et al. (2016) consider on-farm grain yields in the Southern Region HRZ are typically only half to a third of the potential yield, and they consider this to be related largely to insufficient fertiliser application. They further suggest that the lack of evidence for economic returns from investment in fertiliser is a barrier to applying sufficient fertiliser to fulfil yield potential. Conyers and Holland (2013) undertook P rate research at Keith and stress the importance of knowing soil P levels and where the P curve flattens for a given locality. However, findings from these research programs do not include specific recommendations for alkaline soils in the SE, which makes it clear that any future research on these soils should consider fertiliser rates (granular and fluid) and the economic returns of those fertiliser treatments over a range of sites and seasons.

The impact of very high pH, especially in the presence of limestone, on some basic and important soil cycles is poorly understood. On the upper EP, this cycling is affected by frequent and extended periods of low soil moisture and in the SE by extended periods of waterlogging. It is a priority to better understand cycling of N in these extreme soils and how soil biology functions and can be better managed. Improved understanding should lead to crops with better and more targeted nutrition, and to specifically reduce the impact of a major disease on upper EP, rhizoctonia.

More specifically, gaps in our knowledge of cropping on very calcareous soils and opportunities for improvement include the following:

- Addressing biological constraints is a key requirement to improving crop yields on highly calcareous soils.
- Rhizoctonia is still a major constraint:
    - Fungicides recently released for reducing rhizoctonia on cereals are proving less effective on highly calcareous soils.
    - Potential effects of fungicides on soil biological function are not well understood.
    - Effectiveness of cereal variety-based variation in inoculum levels for reducing disease impacts in the following crops has not been investigated in the Calcarosols on Eyre Peninsula.
    - There is no information on management effects on rhizosphere microbial communities in calcareous soils.
    - Soil factors that promote or inhibit the preferential growth of *R. solani* AG8 fungus in these soils are not well understood.
    - Our understanding of seasonal mineral N accumulation in the calcareous soils under different cropping systems is limited and it may be this pattern that is constraining the development or expression of a disease suppressive community.
- Understanding and quantifying water holding characteristics of these highly calcareous soils is important to manage water supply more effectively.
- Amelioration practices that can reduce soil pH could increase microbial activity and even modify microbial community to promote beneficial biological processes related to nutrient cycling and plant health.

- There is limited understanding of the activity, composition and diversity of soil bacterial and fungal communities in calcareous soils.
- There is a paucity of knowledge on the role of improved SOC stocks in highly calcareous soils.
- Biochars are soil conditioners which have been successful in other soils and environments but have been rarely tested on calcareous soils.
- A mechanistic knowledge of the soil N cycle and the various biological processes involved, especially seasonal changes and in relation to plant requirements, is critical to understand the mechanisms for changes in the various biological processes underlying the N supply potential.
- N immobilisation capacity of calcareous soils has not been adequately quantified and management effects are not known.
- Optimal soil P reserves, rates and types of P fertilisers are all uncertainties for SE farmers on calcareous soils.
- The impacts of physical interventions with or without ameliorants in calcareous soils are uncertain.

The following strategies have merit for investigation.

5.1 Using gypsum to ameliorate the alkalinity of calcareous soils

In the highly alkaline soils that dominate crop production throughout south-eastern Australia, high pH limits the accumulation and retention of organic C and thus the availability of nutrients. The use of gypsum and increasing legume production have been shown to reduce pH and improve soil chemical and physical properties in highly alkaline soils, but this technique has not been explored in broadacre dryland cropping systems. The low productivity of crops and pastures on alkaline soils, and especially in low rainfall environments, restricts biomass production and limits the input of organic C into the soil. Moreover, the stability of the organic C is reduced at high pH because the dissolution of the organic matter (measured as the concentration of dissolved organic C) increases with pH (Bolan et al. 2011; Tavakkoli et al. 2015; McDonald et al. 2017). Consequently, the retention of organic C in alkaline soils may be low. A survey of Australian soils found that pH was the second most important factor after rainfall in explaining variation in soil organic C (Spain et al. 1983). Reducing pH in alkaline soils to pH 8 or less has the potential to improve crop production and enhance soil fertility, but currently there are no commercial practices recommended to lower pH. Many alkaline soils are calcareous, although the concentrations of calcium carbonate vary considerably. In alkaline soils the concentrations of carbonate ions is critical to the pH. In soils with carbonate alkalinity, the pH is determined by the activity of HCO_3 and the partial pressure of CO_2 (PCO_2) (Sposito 2016):

$$pH = 7.86 - \log(HCO_3) - \log(PCO_2)$$

Therefore, pH can be reduced by reducing the concentration of HCO_3 or by increasing PCO_2. Numerous studies have examined the reclamation of alkaline sodic and alkaline sodic-saline soils via the application of gypsum and incorporation of organic amendments. Gypsum reduces the pH of alkaline soils via the formation of calcium carbonate which reduces the concentration of soluble carbonates (Chorom and Rengasamy 1997; Wong et al. 2009). The effectiveness of gypsum may be enhanced by the leaching of soluble salts from the root zone, which is aided by irrigation or high rainfall (Qadir et al. 2003; Chi et al. 2012). Increasing plant root growth and microbial activity, both of which will generate CO_2 will also help to lower pH by increasing PCO_2. Another potential approach is phytoremediation, which relies on the release of protons by roots to acidify the soil (Yan et al. 1992; Yan et al. 1996; Mubarak and Nortcliff 2010; Ryan et al. 2022). This increases the dissolution of calcium carbonate, releasing Ca^{2+} and displacing Na^{+} on the exchange complex of the clays (Qadir et al. 2007). Legumes may be particularly effective with regard to phytoremediation due to the acidifying effect of N_2 fixation (Qadir et al. 2007; Brautigan et al. 2014), which is thought to be proportional to biomass production (Unkovich et al. 2010; Peoples et al. 2012). Thus, high sowing and fertiliser rates may enhance growth, and similarly N_2 fixation, thereby increasing the acidifying effects. The greatest benefit of these practices is achieved by lowering soil pH from very high values (≥9.0) to approximately 8.5. Further reductions in pH are unlikely due to the high buffering capacity of soils.

Despite a considerable body of work that has demonstrated the capacity of gypsum and organic amendments to lower soil pH and improve crop productivity, effects have largely been studied under controlled conditions using moist soil or frequent watering, in irrigated field trials, or in high rainfall environments, and often with high rates of gypsum (10–15 t ha^{-1} up to 36 t ha^{-1}) and large inputs of biomass (Chorom and Rengasamy 1997; Qadir et al. 2003; Wong et al. 2009; Chi et al. 2012; Li-ping et al. 2015). Hence, the effectiveness of these treatments to reduce pH on alkaline soils in semi-arid rainfed systems, in which biomass production and leaching are low, is not known. Recently, Tavakkoli et al. (2022) conducted five short-term rotation experiments in Victoria and South Australia to investigate the potential of gypsum application and legume-based rotations to reduce the pH of highly alkaline soils, improve soil organic carbon, and increase crop production. The topsoils at these sites were alkaline but most were not sodic and none were saline. While boosting of legume biomass via an increase in sowing and fertiliser rates had a negligible effect on soil properties, applications of gypsum at 2.5 t ha^{-1} consistently reduced soil pH and dissolved organic C up to a depth of 20–30 cm, both in the first and subsequent year after application. There was little further change when gypsum was applied at 5 t ha^{-1}. The concentration of water-soluble aluminium was high when pH >9.0 and concentrations fell after gypsum was applied. In soils with high concentrations of carbonate, however, these changes were less. Low rates of gypsum application may be effective in reducing pH and improving crop production in regions with alkaline soils low in calcium carbonate.

5.2 Improving the reliability of dry seeding

Dry sowing can speed the seeding process and ensure timely sowing of all paddocks on broadacre farming enterprises, but achieving consistently good yields in the highly calcareous and low rainfall environment can be problematic. Dry sowing does not appear to reduce plant establishment in cereal crops when compared with sowing on the season break, but it does decrease early dry matter production (Cook et al. 2019) and good early dry matter production is associated with increased yield potential. Increasing early dry matter production would appear to be the way to resolve this issue. However, increasing early dry matter production on the highly calcareous soils in the low rainfall environment on EP can also reduce grain yield (Cook et al. 2019) if soil moisture is depleted prior to grain filling in a dry finish to the season (Frischke et al. 2000; Holloway et al. 2000a; Holloway et al. 2000c).

Maintaining good early dry matter production to improve yield potential while not depleting soil moisture needed for grain filling is not a simple proposition. As a result of research programs on EP, there are several directions to pursue in order to quantify and manage early dry matter production relationships with yield. One interesting option might be the quality of the seed (size, source and nutrient content) used for dry sowing. Sowing after the break of the season at Minnipa, seed size was generally considered to be most important in giving good establishment, vigour and yield (Cordon et al. 2004; Hussein and McDonald 2012, 2013 and 2014). Yield benefits ascribed to seed source were inconsistent (Hussein and McDonald 2012), but yield improvements were associated with higher seed concentrations of P and K (Hussein and McDonald 2013 and 2014) and Zn (Hussein and McDonald 2014). Assessing the influence of seed quality on yield of dry sown wheat and barley should be considered. Given that fluid fertilisers can increase in planta concentrations of P, K and Zn, it is interesting to speculate whether fluid fertiliser application to areas being harvested for seed for the next year and grading the seed after harvest to ensure good seed size might assist with improving the reliability of dry seeding.

Early dry matter production in dry sown situations can be increased by increasing seeding rates or by providing N below the seed (Cook et al. 2019). Toxicity of granular fertiliser reduces emergence of dry sown wheat on grey calcareous soils when applied with, rather than below, the seed, and might reduce emergence even at quite low application rates (e.g., DAP at 30 kg ha^{-1}; Cook and Wilhelm 2019). This finding is problematic as preliminary calibration of the Colwell P soil test for wheat suggests the critical level of P for Mallee-type soils is higher than the current standard (Davey et al. 2019b), implying that higher P application rates might be required, which will add to fertiliser toxicity issues at seeding. Fluid N can increase emergence and early dry matter production and in a dry season, plants supplied with fluid fertiliser are more effective at converting soil moisture into grain yield than plants supplied with granular fertiliser (Baldock and Martin 2014). Additionally, the efficiency of fluid fertiliser compared with that of granular fertiliser increases in lower rainfall seasons with dry openings or early finishes (Holloway et al. 2001b). Although herbicides were not found to affect wheat plant establishment when dry sown (Cook et al. 2019), it appears that quite low herbicide residues may cause crop productivity issues on alkaline sandy soils, particularly where low rainfall occurs between application and the next crop (Dzoma et al. 2019c).

All of these findings suggest that further research is needed in calcareous soils to compare the impact of fertiliser types, application methods, rates and placement as well as herbicide residues on dry sown wheat and barley emergence, early/mid dry matter production, maturity and yield. One specific question to address is, if fluid N were to be placed well below the seed, would it delay early dry matter production so that soil moisture depletion did not affect grain filling in a dry season, but still increase dry matter production enough to improve potential yield in a good season?

5.3 Seeder strategies – Water harvesting and wetters

There is some evidence that highly calcareous soils have some water repellent characteristics (Aelamanesh et al. 2014). When combined with the low range in water contents over the plant-available water range, extracting maximum value out of every rainfall event is critical. There has been considerable effort in recent years to identify strategies that improve the retention and availability of water in repellent sands (Roper et al. 2015; Unkovich et al. 2020). The exploration of strategies like on- or near-row sowing, moisture delving and the use of some banded wetters that have shown value in water repellent sands is also worth evaluation in calcareous sands (Desbiolles et al. 2020). The most consistent effect extracted from these techniques is the presence of small but significant amounts of surface soil-water around the planted seed and subsequent benefits to crop establishment, which in turn lead to benefits for weed management through crop competition and significant yield benefits in some seasons. Recent work from WA suggests that furrow sowing techniques that increase water in the seed row (e.g., near-row sowing with banded wetters) can improve early crop nutrition and vigour compared with other sowing strategies (Yeap 2020). By concentrating water in a smaller part of the paddock, efficiencies in water use can be gained through increased water infiltration in the seed row, reduced evaporative losses, and increased crop rooting depth (Yeap 2020).

5.4 Fungicides

The use of fungicides for the control of take-all has been practised for more than a decade and its application combined with other management-based practices (e.g., rotation) when required has been found to be essential to minimise the impact of this disease on cereal crop yields. For rhizoctonia disease control, research conducted across SA and WA indicated that liquid streaming of fungicides was more effective in reducing yield losses in wheat and barley crops compared to seed treatments. However, similar effectiveness of fungicide applications was not seen in the calcareous soils in EP and the variable success of new fungicide application methods could be attributed to the strong influence of soil abiotic and biotic factors, including (i) nutrient constraints on the microbial community reducing effects on pathogen growth, (ii) non-target fungicide effects, and (iii) seasonal rainfall effects on crop responses. These observations suggest that improving the effectiveness of fungicides in the chemical and biologically constrained calcareous soils may require their use as part of a system-based approach. For example, strategies that combine fungicide use to reduce disease effects with practices that improve nutrient and water availability should be evaluated for overall benefit in plant health and crop productivity.

5.5 Biologicals

As the infection of crops with the pathogen *R. solani* AG8 occurs over a long period (i.e., seedling to physiological maturity), its successful control involves management of the pathogen inoculum and plant’s response to infection in terms of growth and immunity development (Figure 9). Until now, all potential biocontrol agents have been applied with the seed, either as single inoculants or mixtures, and have generally targeted initial infection during the seedling stage only, resulting in a low level of success under field conditions. This is attributed to the lack of understanding of the inoculant survival under chemically constrained soil conditions, inability of the inoculants to survive and be effective over long periods, and little knowledge of the factors that promote rhizoctonia growth in high pH soils. Similarly, the lack of in situ enhancement of natural disease suppression, which is generally considered as more effective than adding inoculants, can be linked to not targeting the combined chemical, nutritional and biological constraints to cause a change in microbial communities (Gupta et al. 2019b).

In view of these findings, further research to investigate microbial solutions (i) for promotion of root growth, (ii) to induce resistance against pathogen attack, and (iii) control rhizoctonia growth is suggested. Also, management practices that can enhance root growth through modifying soil physical and chemical conditions could be explored. Such efforts to improve root growth to compensate for the impact of root diseases including rhizoctonia have not been investigated.

5.6 Herbicide use

Herbicide use is an important part of conservation agriculture systems, including in the pasture-crop systems in calcareous soils. In view of the potential herbicide effects, both direct and indirect, on general microbial community, plant-pathogen interactions, soil-borne disease impacts, and a longer than usual persistence of some types of herbicides in high pH calcareous soils, it is essential to evaluate potential effects of new herbicides on disease incidence and overall crop health.

5.7 Organic Inputs

Given the C-based limitations in highly calcareous environments, the evaluation of inputs that allow for co-applications of nutrients and C may offer nutrient supply and cycling benefits. It seems that the application of organic inputs to calcareous soils can generate mixed effects. In a study by Lentz and Ippolito (2012), biochar and animal manures were able to increase the concentration of available nutrients (except Fe) and total and organic C, and while animal manure offered a yield benefit, biochar did not. Similarly, animal manure showed sustained crop yield benefit in a 25-year experiment, while a more stable input (as stubble manure) did not increase yield to the same degree (Zhao et al. 2009). However, the stubble manure offered more substantive benefits to the soil through increased respiration, water retention, microbial biomass and soil porosity. Hemmat et al. (2010) demonstrated that several manures (biosolids, composts and animal manure) invoked some significant changes in soil organic C with flow-on benefits for water holding capacity and CEC. It is critical to recognise that many organic inputs have the potential to influence water and nutrient storage and supply simultaneously, and targeted experiments need to be designed to capture both of these factors.

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8 Glossary

Aggregation	Occurs when multiple soil particles bind together to form larger units (an aggregate)
Arbuscular Mycorrhizal Fungi (AMF)	A type of soil-borne fungus which penetrates the cortical cells of the roots of host plants forming arbuscules and develops a symbiotic relationship. The fungus gains energy (e.g., C) from the host plant and the fungus aids in nutrient uptake for the host plant
Autotrophic	An autotroph is an organism that can produce its own food using light, water, carbon dioxide, or other chemicals.
Biochar	A charcoal that is produced by pyrolysis of biomass in the absence of oxygen, and is used as a soil ameliorant for both carbon sequestration and soil health benefits
Calcrete	A cemented (hard) terrestrial accumulation of carbonate
Carbon Use Efficiency	A measure of the partitioning of carbon between microbial biomass growth and respiration representing net carbon gain to gross carbon assimilation. It is influenced by structure and activity of microbial communities and their access to substrates
Cation Exchange Capacity (CEC)	The total capacity of a soil to hold exchangeable cations.
Crop lower limit	The amount of water remaining after a particular crop has extracted all the water available to it from the soil.
Deep ripping	A soil modification practice which uses a tined implement and where the depth of working is below the surface soil layer (A1 horizon)
Denitrification	Microbial reduction of nitrate or nitrite coupled to electron transport phosphorylation resulting in gaseous N either as molecular N2 or as an oxide of N.
Disease Suppression	Disease suppression in soil occurs when disease development is suppressed even in the presence of the pathogen, susceptible host and environmental conditions. It is due to the microbiology in the soil.
Dissolution	The process of dissolving or breaking apart
eH	The rate at which electron exchanges take place in soil
Electrical Conductivity	A measure of the ability of soil water to carry electrical current, and is

(EC)	used as an indirect measure of soil salinity
Endosphere	The microbial community (and biological/chemical conditions) within the root tissues of a plant.
Exchangeable Sodium Percentage (ESP)	The relative amount of sodium ions present in soils expressed as a percentage of the total Cation Exchange Capacity
Gypsum	Gypsum is a soft sulphate mineral composed of calcium sulphate dihydrate
High Rainfall Zone (HRZ)	In south-eastern Australia, regions with annual rainfall above 500 mm
Hypervescent	Soil material containing more than 8% of soft, finely divided carbonate/strong effervescence with 1 M HCl
Immobilisation	Inorganic nutrients are taken up by soil microbes making them unavailable for plant uptake (the opposite of mineralisation)
Ksat	The saturated hydraulic conductivity of soil (Ksat) is the infiltration rate once soil has reached 100% saturation and the infiltration rate has become constant
Marl	A mix of clay and silt sized soil particles with a high proportion of fine earth (soft) carbonate fractions
Microbial Biomass (MB)	The mass of the living component of soil organic matter
Microbial quotient	The ratio of microbial biomass to soil organic carbon, it indicates how efficiently soil organic carbon is used by microorganisms, which is increasingly being used as an index of ecosystem development
Microbiome	The community of microorganisms in a particular environment
Mineralisation	The chemical release of inorganic nutrients from residues of soil organic matter
N Use Efficiency (NUE)	A measure of a crop or pasture's capacity to convert soil nitrogen into plant biomass or grain
Nitrification	The process by which ammonia is converted to nitrites (NO_2) and then nitrates (NO_3).
Phyllosilicates	A large group of minerals that includes micas, smectites, and kaolinites. They are important for soil formation.
Phytoremediation	The use of green plants and their associated microorganisms, along with proper soil amendments and agronomic techniques to either contain, remove or render toxic environmental contaminants harmless
Plant growth regulants	Chemicals used to modify plant growth such as increasing branching, suppressing shoot growth, increasing return bloom, removing excess fruit, or altering fruit maturity.

Pulses	Dried seeds of the legume plants, but can also mean legume crops grown for their dry seed (rather than as forage or for their immature seeds or pods).
Rhizodeposits	A wide variety of substances that originate from sloughed-off root cells and tissues; mucilages, volatiles, soluble lysates and exudates that are released from damaged and intact root cells
Rhizosphere	The region of soil in the vicinity of plant roots (~2 mm) in which the chemistry and microbiology is influenced by their growth, respiration, and nutrient exchange.
Salinity	The relative concentrations of dissolvable salts in the soil
Sodicity	A sodic soil is defined as a soil with an exchangeable sodium of greater than 6% of the cation exchange capacity. Above this threshold, soil structure is adversely affected.
Sorption	A physical and chemical process by which one substance becomes attached to another
Supravescent	Soil material containing more than 40% of soft, finely divided carbonate
Water holding capacity	The amount of water that a given soil can hold for crop use.
Water-limited yield potential	The maximum possible yield given the rainfall (amount and pattern) on a specific soil type if sowing date, current cultivars and nutrients, pests, disease and weeds were not factors limiting yield
Water repellency	A reduction in the rate of wetting and retention of water in soil caused by the presence of hydrophobic coatings on soil particles.
Water Use Efficiency (WUE)	A measure of a crop or pasture’s capacity to convert water into plant biomass or grain
Wetter	Agents which reduce the effects of repellence in soils by lowering the surface tension of the water which improves infiltration
Yield gap	The difference between current commercial yields and the yield that can be achieved when water and the environment are the only factors limiting yield
Zero point charge	The pH at which the net surface charge of adsorbent is equal to zero.