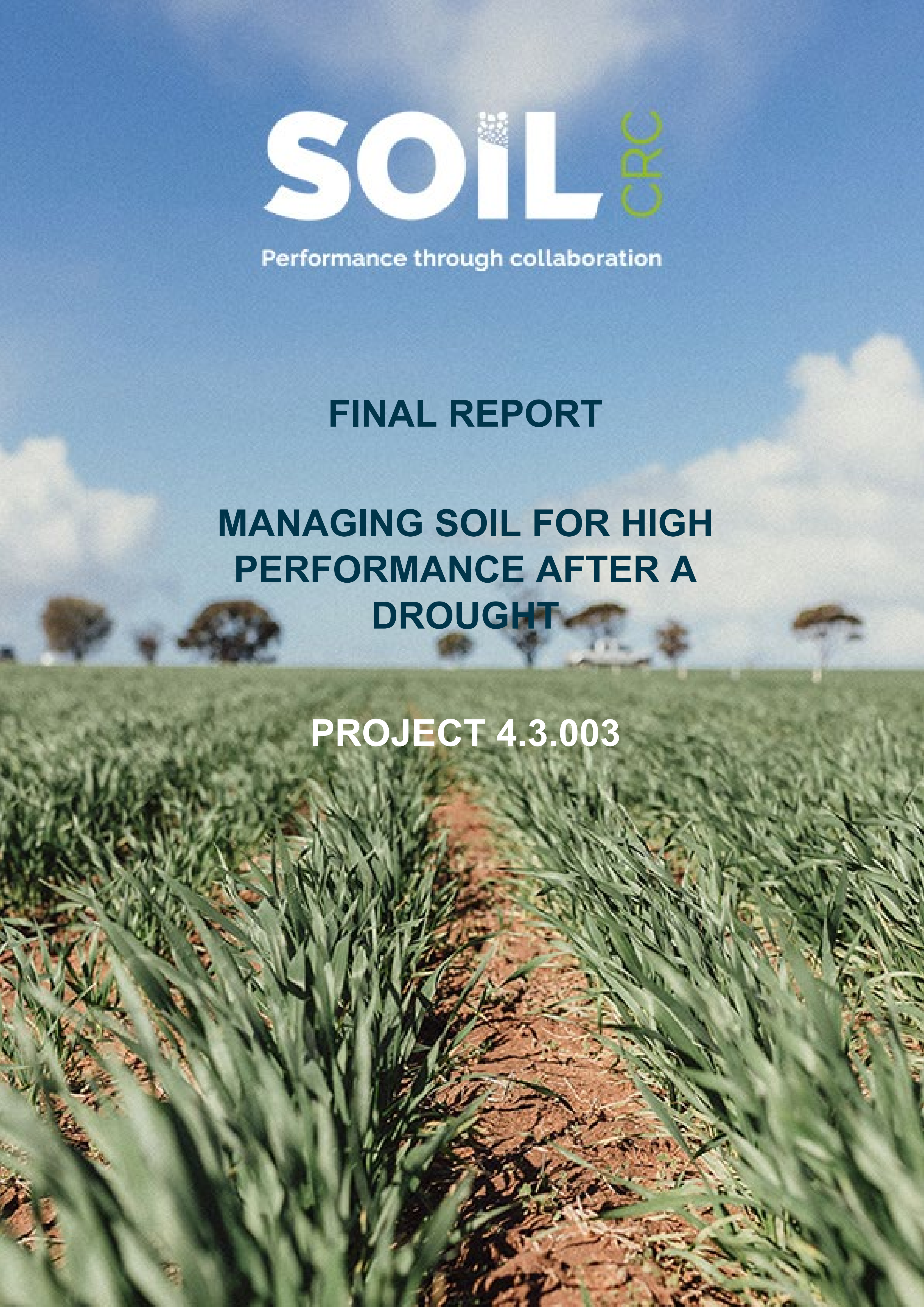

SOIL CRC

Performance through collaboration

FINAL REPORT

MANAGING SOIL FOR HIGH PERFORMANCE AFTER A DROUGHT

PROJECT 4.3.003

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PEER REVIEW STATEMENT

The Soil CRC recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The author(s) confirm(s) that this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated its:

- 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 2007), and provided constructive feedback which was considered and addressed by the author(s).

PROJECT PARTICIPANTS

Government of South Australia
Department of Primary Industries and Regions

AGRICULTURE VICTORIA

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EXECUTIVE SUMMARY

This project and review investigated the effects of drought on soils, strategies for managing drought-affected soils and how to recover soils and return them to full productivity. The project conducted detailed interviews with farmers, advisors and researchers to better understand how drought-affected soils were being managed 'on the farm' and this was supported by information sourced from the scientific and grey literature.

There were many common findings between the interviews and the literature review. These include:

1) The need to manage ground cover to reduce the potential for erosion and better understand the impact of erosion on farming systems.
2) The impact of drought on nutrient availability (especially nitrogen) and how this interacts with post-drought fertiliser regimes.
3) How different pools of soil biology interact with drought and their response when conditions improve.
4) Methods to reduce soil constraints for optimal capture and water use.

The interviews covered an applied and holistic view of the topic covering areas from the movement of weed seeds with fodder imports as part of a drought response to the mental health of farmers.

One of the interviewees commented that, "*A lot of our research has historically been very reductionist as it focuses on a specific context in isolation. Soil is a system you cannot isolate. [We] need an integrated system approach.*" This was confirmed in the literature where, despite the enormous body of research, the vast majority concentrated on assessing the effects of drought on soil, rather than evaluating integrated management practices or systems during and in the recovery phase.

OBJECTIVES

This project aimed to collect scientifically-based information about how soils react to extended periods of water deficit, how they respond when it does rain again, and most importantly, what management actions farmers can take to prepare their properties for drought, manage the drought while it is occurring and optimise the performance of their soils when the water stress of a drought is removed.

The project combined a literature review and interviews with a range of stakeholders from across Australia to garner their views on managing soils post-drought.

INTRODUCTION

The project comprised two distinct components—interviews and a literature review. The interviews, led by Agriculture Victoria, were with seventeen farmers, advisors, farming systems groups and researchers. They covered three key areas: the effects of drought on soils, strategies for managing these drought-affected soils and how the farming community can best support the recovery of soils. The literature review, led by the Department of Primary Industries and Regions – South Australia, comprised a detailed review of scientific and grey literature pertaining to how soils react to extended periods of water deficit, how they respond when it does rain again, and what management actions farmers can take to optimise the performance of their soils when the water stress of a drought is removed.

This report presents the details for the survey and literature review separately.

SURVEY - BACKGROUND

Australia is a semi-arid country in which all its soils have an inbuilt resilience to annual cycles of wetting and drying. However, modern agricultural practices can place increased demands on soil, with these soils working at an increased capacity, exposing vulnerabilities to prolonged cycles of moisture stress. Prudent management strategies for cropping and grazing enterprises can help farm businesses withstand these prolonged cycles of drying and, as a result, recover faster and be more resilient after a drought.

SURVEY - METHODOLOGY

Seventeen of Australia's leading farmers, advisors, farming systems groups and researchers participated in a phone conversation covering three key areas:

1) The effects of drought on soils.
2) Strategies for managing these drought-affected soils.
3) How the farming community can best support the recovery of soils.

Interviewees covered the geographical areas of South Australia, Western Australia, Queensland, Victoria and New South Wales. They also covered technical knowledge areas from grazing and grain production systems.

The project team considered a range of questions to ensure that knowledge gained from the participants captured appropriate and relevant information pertaining to the key topics. Through a consultative process with all project members and expertise in survey development within the Departments, the questions were fine-tuned to reflect project objectives.

Questions were tailored to the interviewees dependent on whether they were farmers, advisors and farming systems groups or researchers. Below is an example of a question set used for interviews with advisors and farming systems group representatives.

EFFECTS OF DROUGHT ON SOIL

1. What are some key characteristics/observations of drought-affected soils?
2. How does drought/prolonged water stress affect the soil structure? Biology? Nutrient availability?
3. What types of soils seem to be more susceptible/forgiving in drought? Does farming practice also influence this?

MANAGING DROUGHT-AFFECTED SOILS

1. What is the biggest issue with managing soils in drought?
2. What practices have you observed/tested that have helped farmers manage drought-affected soils?
3. What practices have you observed that have been detrimental to the soil/farming system, as farmers have tried to manage their drought-affected soils?

RECOVERY OF SOILS AFTER THE DROUGHT BREAKS

1. How have you observed soils responding to rain when it does come? Is this influenced by soil type/farming practice?
2. How can we best manage soils after drought?
3. What practices have you observed/tested that have helped transition soils out of these dry conditions, when this water stress is removed?
4. What practices have you observed that have been detrimental to soil recovery, that have been implemented when soils transition out of dry conditions?
5. What has helped farmers manage land after dry conditions? What is driving this (their attitude to risk, amount of land, nutrient application change)?

This summary report is based on the comments and experiences from the 17 interviews. In addition to the three aforementioned key topic areas, knowledge gaps to best support landholders coping with prolonged cycles of drying in the landscape were also identified and reported.

SURVEY - RESULTS

Information gathered from the 17 conversations was divided into the three overarching key topic areas

1. Major effects of drought on soil.
2. How these soils can be managed during drought conditions.
3. How these soils can then recover after a drought breaks.

Under each of these key topics, factors influencing the key topic, main points and direct quotes were pulled together and used in this summary report.

KEY TOPIC

Factor influencing key topic

Main points under one of the factors influencing the key topic

- Information from interviewees discussed relating to the factors influencing the key topic (when multiple information themes used to ascertain the **main points**)
- *"Direct quotes from interviewees relating to the factors influencing the key topic"*

EFFECTS OF DROUGHT ON SOIL

Ground cover

Loss of ground cover is one of the most obvious consequences of drought, having significant flow on effects in the landscape and on soil condition

- Reduced ground cover can be caused by overgrazing and burning in paddocks.
- Overgrazing can lead to grass butts being eaten to ground level, which particularly impacts the recovery of native perennial pasture in rangelands.
- Reduced ground cover can lead to soil crusting and surface sealing.
- Lack of ground cover reduces soil carbon, directly impacting water holding capacity and mycorrhizal fungi in the soil. *"The minute you see bare soil you are on the path to desertification."*
- It takes time to re-build ground cover after drought. *"A healthy soil is one that is protected by vegetation, whether it's dry or living. An unhealthy soil is one that is exposed, and the biology dies then you get leaching of nutrients and dust blowing."*

Crop type influences the amount of stubble retained going into a drought and consequently crop emergence the following year

- If the last crop sown in a paddock going into the drought is a pulse, ground cover does not last very long in the system before it is broken down.
- In stubble retained systems, if stubble is present in a drought, this results in increased surface roughness and shading of the soil, which reduces evaporation and conserves moisture. This is critical in drought conditions for the establishment of crops as research has shown that with a rainfall-limited autumn break, crops under a good stubble cover emerge better than those without stubble. This is not the case usually, with stubble often reducing crop emergence where there is a good autumn break and drought conditions are not observed.

There is increased pressure to utilise stubble for alternative purposes in drought

- Landholders with stubble in their paddocks may decide, due to financial drivers, to utilise stubble either for their stock or to be baled and sold.

Surface crusting increases with loss of groundcover

- Reduced ground cover can lead to soil surface crusting, which increases runoff and reduces infiltration. These crusts break down when rain is heavy and extended.

Ground cover loss can lead to exposed soil and consequently the loss of topsoil

Erosion

Bare soil is at increased risk of wind and water erosion

Bare soil reduces aggregate stability and increases erodibility and soil loss through water erosion

- To understand water erosion, the traditional framework has been the Universal Soil Loss Equation (USLE). It looks at cause and effect. Cause is the erosivity (force or the power) of the rainfall event. Resistance is the effect, the way the soil/land copes with the erosivity, called the erodibility. Slope length influences erodibility also, with a bigger slope having more erosivity events. Surface structure and organic matter are also very important in reducing erodibility.
- Organic matter has a low bulk density. If the soil is bare and rainfall events have high velocity, the organic matter is more susceptible to erosion. The slope of a paddock affects the velocity at which water will move across the landscape.
- Rainfall erosivity increases the further north you go in Australia, with ground cover becoming critical to erosion protection and mitigation.
- Bare soil leads to increased water runoff as there are fewer plants providing channels for water to infiltrate into the soil. Hydrophobicity caused by drought conditions makes the run-off worse.

- As droughts often break with large rainfall events, soil can wash off grazing paddocks and fallow paddocks and into dams.

Wind erosion can lead to nutrient loss in the topsoil

- Wind erosion is more likely to occur under drought conditions and results in the loss of nutrients.
- The topsoil is the most valuable resource on-farm with 10–20 per cent of the nutrient pool retained in the topsoil.
- The very top layers of the soil are the first to move under wind erosion conditions.
- When soil is lost to wind erosion there are often noticeable wind drifts against fences. Dust storms are visible in the local area as well as much further abroad, depending on wind direction and speed.

Cultivation can lead to soil loss

- If cultivation is used after a lucerne phase to alleviate compaction, soil crusting can develop.
- Cropping landholders who farm in cotton areas are using cultivation to manage weeds due to the sensitivity of cotton plants to traditional chemical weed and pest control methods.

Soil type can influence the amount of topsoil that is lost due to erosion

Influence of soil type

Younger soils are more resilient in drought

- Younger soils with a larger humic carbon pool are full of nutrients and are generally held in better physical and biological condition. They are therefore more resilient to erosive rainfall events and ill treatment, as an older soil will easily lose ground cover if not managed well.

Lighter soils are prone to reduced ground cover, increased surface crusting and increased erosion

- The reduction of cultivation as a general practice has increased a lighter soil's resilience to surface crusting.

- *"In the marginal areas in the Upper North of NSW, with less residue cover and less capacity for plants to grow and develop good root structure, these soils are exposed and can crust."*

- Crop and pasture residues have an impact on the vulnerability of the soil to erosion, as erosion is seen more in sandy soils, which often suffer from low productivity.

- Sandy soils drain quickly with the moisture being used, rather than stored. These systems are reliant on good, regular rainfalls.

- Lighter soils are naturally prone to surface crusting because of their particle size distribution.

Deep sands are less impacted by soil loss compared to heavier soils due to their inherently lower organic carbon levels

Duplex soils are the most susceptible to soil surface crusting

- Duplex red brown earth soils under cropping can be hardsetting.

Black, heavy soils have increased soil temperature but are able to recover quickly after drought

- Black soils have a higher soil surface temperature when exposed due to loss of protection in drought.

- Heavier soils don't tend to erode by wind as easily, due to good aggregation on the surface. However, they suffer when there is low/no ground cover and very strong winds, resulting in a powdery topsoil.

- If these topsoils are subsequently lost and the subsoil is exposed, new topsoil will form within a few years unlike a lighter soil which will take a very long time to recover following soil loss.

Soil structural problems can develop during drought in heavy Vertosols

- Not all of the eastern heavier dryland cropping soils of NSW are self-mulching, cracking black Vertosols. Many of the rest are cretaceous mudstones, with a lot of fine mudsand and silt in the surface, being prone to surface crusting.

- Because these cretaceous mudstone derived Vertosols tend to be in the drier zones, their organic carbon levels naturally are lower and can decline under cropping systems.

- If these Vertosols go 12 months to two years without stubbles, they can enter a cycle of steady decline. This in turn affects the surface aggregation of the soils, which is driven by clay content and clay mineralogy, particle size distribution, chemistry (sodic soils) and biology.

- If a crop is not growing in these Vertosols with silty topsoils every season, aggregation is reduced. *"Silt-sized aggregates of clay can be blown around under drought conditions, when these soils are usually friable and well aggregated."*

Soil type impacts the tendency for soil to display hydrophobicity

Hydrophobic soils

Water repellence is a chemical, biological and physical process

- Water repellence is developed through a fraction of organic matter that is innately hydrophobic with one end of the molecule repelling water. If there are enough of these molecules arranged on the soil minerals, then water isn't able to soak into the soil.
- These molecules are usually only a very small proportion of the total organic matter in the soil and can usually be decomposed by microorganisms or rearrange themselves in wet and dry cycles.
- When the soil is dry, there is less biological activity to break down these compounds.
- This is a usual process in wetting and drying, however in prolonged droughts, the issue is exacerbated.

Hydrophobic soils don't capitalise on rainfall events

- *"Rain tended to come in, in really violent storms with really intense rain and the water just tended to skid off the surface and not penetrate. So, there were situations where fence lines were wiped out and farm dams were full of a mix of mud and straw and a little bit of runoff water."*

Water repellence is more likely to occur in sandy soils and develops as the soil dries

- Non-wetting sands coming out of a drought are harder to manage. *"People really struggle with these as you need a decent break, more moisture is needed to re-establish a dry non-wetting sand than some of these other sandy soils that seem to recover a bit quicker."*
- This is a big issue in WA and SA as a large proportion of the ten million hectares of sands are prone to water repellence.
- Water repellency is usually a bigger issue in sands because the hydrophobic molecules are more able to dominate the surface areas of the sand's minerals, compared to the large surface area of clay particles.

Modelling has shown that water repellency can occur on heavier soils as well as sands

- Modelling undertaken in WA in their undulating heavier country predicts that after months and years of severe drought, water repellency could build up in the topsoil of heavier soils.
- However, with each new shower of rain, water repellency decreases.

MANAGEMENT OF DROUGHT-AFFECTED SOILS

Grazing management

Keeping livestock out of areas with low growth protects the valuable soil asset

- If stock are not removed from vulnerable soils, trampling can pulverise the soil surface.
- It's important to be able to react quickly/early rather than keep stock on the land.
- *"The soil is going to dirt…with grazing, people say I've got to keep my animals…but you keep the animals and you eat the grass into the dirt. You keep the animals because you think the animals are the most valuable assets, but it affects the healthy soil. Natural systems are our most valuable asset."*
- Feedlotting or exclusion areas can be used in grazing systems to keep stock off crops, allow plants to establish and the system to begin repairing.
- Virtual fencing can assist in better stock management.
- *"Most people think first about animals and second about soil. In theory for us idealists they should think about soil first as it has long-term implications for management if you lose it."*
- To hold soil in place is more important than keeping stock, because when the drought breaks, *"you've got somewhere to go."*
- Leaving paddocks clean over summer with stubble retained helps reduce erosion.
- If a crop isn't going to make it through the spring, and if grazing stock are put on too long then the paddock can lose valuable heat protection over summer.

Having cut-off points for when stock are removed from paddocks helps manage pastures if there are good supplies of fodder on hand

- Make early calls to take stock off the land. Individual businesses should have set criteria (e.g. groundcover targets) when this will occur.
- In a mixed cropping and grazing farm, *"it's really important to decide when you are going to sell the stock if there hasn't been enough rain for your crop. The soil is dramatically affected by grazing during the drought. So, making decisions about stock is probably the most important decision about how you're going to affect your soil in the longer-term."*
- There will always be green feed somewhere where the stock can be sent if required.
- Keeping two years' worth of fodder on hand at the end of each growing season can help drought-proof a farm.
- It doesn't matter what fodder type is available, as just having something that stock can eat in containment when dry conditions are observed is valuable, providing their nutritional needs can be met.

Selling stock, utilising stock containment areas or sacrifice paddocks and sending animals to agistment can be valuable alternatives to overgrazing paddocks

- Containment areas save paddocks and time on-farm, reducing the need to put bales out in the paddocks.
- Sacrifice paddocks that have a lot of trees and bushes can be useful, as they provide cover and reduce the risk of wind erosion in the containment areas.

- Modelling suggests that having stock in farming systems can safeguard the farm from drought.
- Containment areas may suffer heavy trampling but can be rejuvenated by strategic ripping/cultivation to bring up clods to the surface, which is preferable to keeping stock over the whole farm and pulverising all the soil surface structure.
- Surface crusts that have formed during drought can be broken up by stock, without affecting deep soil structure.

- *"Not as many destock as early as we'd like, it's a hard decision as we don't know when it will rain. Everyone wants to keep their genetics because they're the best, but if they haven't spent thousands on feed, they might have some dollars in the bank to restock."*

If stock are removed from paddocks early and subsequent rains come, this can be an opportunity to put more crop in and get some hay, or for pasture to re-establish

- *"If all of a sudden instead of having a thousand hectares of pasture you might say well, I don't have the stocking rate to cover that thousand hectares so I will lock in an extra thousand hectares of crop. And I might turn 100 hectares of that into hay."*

Pasture management

Drought can be a time to assess the species of pasture being used on farm and whether there are more beneficial alternatives that might be available

- Drought can be a time to evaluate traditional pasture and crop species versus using some of the newer species available. It is then important to understand that some crop and pasture species are, *"opportunistic and able to have a much wider window for establishment, and have the capacity to respond to sporadic and small rainfall events… such as deep roots (not just necessarily perennials)".*
- Pasture diversity, such as forbs and deeper-rooted perennials, puts carbon down deeper into the soil. *"There are lots of high-risk things that happen on farms in relation to crop/pasture selection. There needs to be the escape or coping mechanisms for pasture varieties in drought that can grow and set seed, with lots of pasture legumes that are available, this shouldn't be an issue."*
- With underperforming varieties of pasture legumes selected in the past, issues with seed bank depletion have occurred as some varieties are susceptible to seedling germination in false breaks or issues with shallow roots in dry conditions. This results in a reduced ability of the plant to set seed.

Manipulating a current pasture system is easier than completely changing it

- It is important to assess how well a system is working before an extensive pasture renovation is undertaken, as it is cheaper to manipulate something than it is to replace it.
- Some of the manipulation tactics for pasture might be things as simple as applying fertiliser more strategically or the application of herbicide to target broad leaf weeds at the right time to manipulate plant community composition.
- Consider appropriate pasture renovation options for a particular paddock and soil type if system manipulation cannot be undertaken. Give priority to better performing soils. *"It's important to make sure the paddock is clean. Minimum of two years weed control,*

preferably three years. If you will renovate, think about where to do it. If it isn't clean enough, go with a cash option, a cereal for grazing or through to crop."

Using correct and recommended seeding rates during drought aids pasture production

- Due to cost or lack of seed availability it might seem easier to sow less than the recommended seeding rates, however, it is better to sow less land and sow it at the higher/required rate.
- Early planning helps with the sourcing of required seed, such as getting in touch with seed suppliers before Christmas for seeds and inoculants.

Some varieties of legumes can be sown in summer, catching the break and providing feed for stock (or a brown manure) before crops get sown in Autumn

- In pastures it can be easier to sow what is wanted to be grown rather than what is the best fit for the production system, 'right plant right place'. *"Trialling which varieties might work well on the farm through growing a nursery paddock where four to five things are grown up as a monoculture, helps to see what grows and what works."*
- Legumes are much less forgiving of late sowing than grasses in terms of leaf production, with pastures usually going into the ground after the cropping phase. When pastures go into the ground late, they come up late, and then they don't have very good production.
- Some of the varieties can then be harvested through headers and sown in summer to break down the hard seed, so they are ready for the autumn break. Hard seed breakdown patterns will be different between the east and west of Australia.
- When these legumes grow, you can get good Autumn growth for feed.
- In a mixed farming system, the benefit of incorporating the legumes into the production system in summer is that there is no competition with the cropping program. *"Once you have the seed bank in place, put your cropping program over them and the cropping length you have will vary…you will eventually get into a system where you don't need to re-sow after the cropping phase".*
- Some new pasture legume species can be harvested with a header, making them more adaptable in a cropping system.
- Herbicide choice is more important when sowing legumes over summer to ensure residues will be broken down fast enough to not hinder the cropping program.
- Putting sub clovers and long season wheats in the same tube at sowing gives the benefit of a brown manure, without the risk of taking a paddock out of production for a year.

Perennial pasture systems can capture rain falling any time during the year

- Rainfall is captured by actively growing plants and turned into more biomass. Mineralisation of biomass residues results in nutrients being cycled back to the soil. Regenerative farming aims to incorporate perennial pasture principles into a farming system by having plants growing year-round, keeping the soil biology alive and active.

Using dual-purpose crops for grazing as well as harvest boosts both systems in a mixed farming operation

Dual-purpose crops, with sorghum and canola as examples, can bring grazing diversity into a farming system. These crops can be cut for hay if they cannot go through to grain harvest during drought conditions.

Crop Selection

Drought can be a time to assess the crop rotations being used on-farm and other more beneficial alternatives that might be more suitable

- Drought can be an opportunity to evaluate what crop varieties and species are being grown. Whether it be reverting to more traditional crop species that are tried and true or experimenting with any promising new and emerging crop varieties.
- It is important to include some crop species that are *"opportunistic and able to have a much wider window for establishment and have capacity to respond to sporadic and small rainfall events".*
- A lot of wheat is grown as a drought management tool, alongside barley and oats. *"Farmers revert to what they know."*
- Classic rotational sequences can be *"thrown out the window"*, but this helps get cash flow into the business.
- A reduction in legumes in the system can increase disease pressure as there are reduced breaks in the rotations. *"Farmers want something reliable after drought (wheat after barley or barley after wheat or vetch), and they are just more reliable than the canola or pulses. Lentils are not reliable enough."*
- If irrigated farms have reduced access to water, flexibility is required to be able to use the land for dryland wheat.

Sowing early varieties will utilise water earlier in the season

- In WA, landholders are utilising Victorian and NSW data to assess when to put a crop into the ground, usually earlier than traditionally done, to catch the first rains. *"We need to adapt our system to take advantage of utilising the plant available water that we've got there; cover that ground and keep it protected for as long as possible; and grow varieties that we would normally have ignored."*
- By choosing winter wheats instead of spring wheats, *"we're looking at opportunities to utilise plant available water earlier than we would have ever done before."*

Using higher performing legumes in the system increases soil nitrogen levels

- Choosing better performing legumes such as vetch and peas compared to chickpeas and lentils can increase soil nitrogen levels; there is also a need to move back to using early indicators/trigger points for when it's appropriate to sow legumes. *"When you look at the soil test results, there is a lot of nitrogen nutrition left in the soils, meaning legumes are definitely making a difference. I know that when you have had droughts you are not taking as much off, but I think a lot of that is having more legumes in the system."*
- If lots of legumes have been in the system, using more cereals to rebuild ground cover where stubbles have run down assists paddock recovery.

Multispecies cover cropping can help build soil health and crop production

- Cover cropping *"is teaching us about quorum sensing and is about good ground and encouraging deeper roots".*
- Sowing cover crops can help create feed, with lots of landholders using oats.
- Planting old seed, such as sorghum, into fallow paddocks as a cover crop, can increase ground cover and provide nutrients through mineralisation to encourage soil biological

activity. *"Mung beans were also planted as they are short season crops so they will get through before the frosts as well as some of the millets."*

Crop management

Choosing to fallow if there isn't the moisture to grow a crop conserves what soil moisture is available

Seeding systems that begin early and sow dry maximise water use

- Early sowing and the move towards dry sowing and long duration varieties captures any nutrients that were mineralised after a dry period.
- No-till farming systems provide flexibility to sow into dry soil and create furrows where the water can infiltrate when it rains.
- Edge row or near edge row sowing allows landholders to access nutrients and moisture that have accumulated under last year's crops. *"You have a channel with the furrow still there with an environment that is still working with the roots and the microbes are all still there, so it's getting better establishment."*

Light pulse stubbles and their lack of ground cover can create issues going into a drought

- The lack of stubble going back into the system is a major concern, especially in the Mallee with a recent shift towards including large amounts of legumes in the rotations (some up to 30–40 per cent).
- Legumes, however, have significantly reduced ground cover when harvested leaving more exposed ground and not enough ground cover to hold soil over summer.

Hydrophobic soils

Strategic tillage increases surface roughness, disturbing hydrophobic soils

- Strategic tillage is the major strategy to manage hydrophobic soils through increasing surface roughness, breaking up the hydrophobic layers and increasing water infiltration.
- Contour ripping can also be useful and acts similarly to disturb the hydrophobic soils.

Increasing the clay content of the soil reduces water repellency in sandy soils

- As sandy soils have a higher tendency of being impacted by water repellency, increasing the clay content of the soil can help reduce this.
- Clay spreading, the transport of clay from one part of the farm to the sandy hydrophobic areas, increases the clay content of the topsoil.
- Clay delving/spading mixes subsoil clay into topsoils, which increases the clay content in the topsoil.

Crop residues on the soil surface reduce the formation of hydrophobic coatings on soil particles

Wetting agents applied to the soil can increase the amount of water that can be captured in the soil

- Wetting agents/chemicals can be used to break down hydrophobic coatings of soil particles, however, these can be cost prohibitive. *“Fifty per cent of the time they seem to work and fifty per cent of the time they don’t. In gravel soils if you band a wetting agent in the seeding row, it’s more like ninety per cent success, however, these benefits have no residual impact.”*

Erosion controls

Heavy rains often break droughts, and this influences how soil moves in the landscape

- How well a paddock recovers depends on how the first rain comes. *“If you have intense events like what the Darling Downs got…then they experience very serious erosion (sheet, rill and gully), then their paddocks will have been affected a lot more than people who get the same amount over a few days.”*
- Most droughts seem to be broken by a flood, so soil suffers due to heavy rain falling on bare surfaces.
- Sedimentation of heavier soils has been observed on roads following rain. *“[You] don’t have control over this, rain can be very heavy and there’s lots of it, so it restricts what you can do and when you can do it.”*

Different soil types will behave uniquely under wind and water erosive events

- It’s important to understand soil types that have undergone erosion. For example, well-structured soil that erodes and exposes the subsoil will have recreated and replaced its topsoil again in a few years. *“Black soils don’t tend to erode by wind due to good aggregation on the surface, except when there is low/no ground cover and very strong winds and a powdery topsoil in poor condition.”*
- Sandy soils require cover because they are at a much higher risk of erosion.
- Properly assessing and understanding the different soils on a farm and then thinking about how these can be managed is an opportunity during drought times.
- Strategic cultivation, where ridges are created across the paddock to a height of 30 centimetres, can reduce wind erosion. This practice is not recommended on deep sands as there are no heavier soils/clods to be brought up to the soil surface. However, it might work on swales and flats where heavier subsoils (clods) can be brought up. Therefore, it is important to know the soil profile and land system to know if this will be successful.

Clay delving can protect topsoil from wind erosion

- Sandy soils with subsoil clay can be delved to bring up clay clods, forming an uneven surface and reducing wind erosion. *“A lot of these soils are structureless but in some cases, you can bring up clods.”*

Strategic cultivation can be used to manage compaction and weeds

- Cropping landholders who farm in cotton areas are using cultivation to manage weeds due to the sensitivity of cotton plants to traditional chemical weed and pest control methods.
- Strategic cultivation that is cloddy and has strips to reduce erosion is a successful method of erosion management. *“Nobody likes the dust…farmers are trying to do the best they*

can to keep their soil and their topsoil in place, especially when they see their fence lines disappearing. They don't like seeing it and are trying to act against it."

Pasture furrows can be used to reduce erosion

- Pasture paddocks on hillslopes with low ground cover suffer from erosion in droughts. Sowing pastures within furrows reduces runoff.

Strategic tillage reduces the impact of wind and water erosion

- Emergency measures include contour banks or pasture furrows or ripping up clods.
- Using cultivation to reduce the wind speed across the soil surface. *"Observations of whirly winds picking up soil and gaining momentum in similar spots in the landscape across time".*
- As drought breaks, ripping up clods and making furrows minimises erosion and stream pollution.
- Chisel ploughing can roughen up the soil surface and reduce the effects of wind erosion. This can be effective if the soil has the capacity to bring up clods (the size of a fist) and stabilise the paddock. If clods can't be brought to the soil surface, then the soil may suffer worse from wind erosion.
- In a bare fallow, consider ploughing the soil to increase surface roughness to reduce runoff and erosion. *"Run a set of offset strips through the paddocks, every second run, just before the heavy rains to get some surface roughness in the soil to capture the rain. This will help avoid sheet erosion. It is important to not loosen all the soil and cause rill and gully erosion in the process."*
- There may be a need in some places where erosion has occurred to put in contour bank systems.
- Mouldboard ploughing and spading can have a short-term erosion effect but have a longer-term benefit. Deep tillage work has been done in the past to bury water repellent topsoils as well as herbicide-resistant weeds. *"Some farmers notice that when they do mouldboard ploughing particularly and they invert the topsoil and expose the subsoil which is low in organic matter, they find that herbicides tend to be hotter, more biologically active, and can cause some crop damage at the same rates which are not damaging when you have an intact topsoil."*
- When summer weeds grow there are options for how these can be managed. Spraying them out to conserve moisture or ploughing the paddocks to get surface roughness to mitigate erosion may be the best options. In some cases, doing nothing may be the best option to keep cover on the paddock. All decisions need to consider what will work best in a particular farming system.

Strategic tillage will not ruin no-till farming systems

- Strategic tillage will not ruin no-till farming systems provided clods can be brought to the soil surface.
- There is concern in younger landholders, and those that have been in conservation tillage, that if they undertake cultivation on-farm they will destroy all their years of no-till farming. This is not the case. *"A whole range of recent reviews on strategic tillage says there is no particular issue with doing that [strategic tillage] to control wind erosion."*

Returning to conservation farming practices is required after undertaking strategic tillage

- Returning to conservation farming practices is required after undertaking strategic tillage. This will maintain the benefit of having protected soil structure and improved soil health over many years. *"You don't want to have to be locked into this if you are in a direct drill farming system, but if it's appropriate then it can be good."*

Ground cover

Maintaining adequate ground cover helps reduce erosion

- One of the biggest issues in drought is trying to keep ground cover on the surface to protect soil from erosion events.
- In cropping country, stubble retention between crops is important. Bare fallow increases the erosion risk.
- Sandy soils must have cover because they are at much higher risk of erosion, with a minimum of 700 kg/ha of attached stubble required on the ground to reduce erosion. If the stubble is loose *"it snaps, gets blown around, collects on the attached stubble and then that actually detaches the attached stubble, because of the weight against that".*
- On slopes, 70 per cent cover of pastures is required to reduce erosion. In rangelands, this minimum cover level is 40 per cent.
- In cropping country, about two tonnes of flattened wheat stubble or one tonne of standing stubble is required to reduce erosion. *"Growers are becoming more flexible in their systems, as seen by earlier sowing, better varieties and managing risk around sowing opportunities. As observed with early rains in the Mallee this year with farmers going around and sowing something (maybe barley) on their more susceptible ground, that may not even come to grain, but there is some ground cover."*
- Using a chemical fallow can help keep ground cover for longer, compared to cultivation. *"The consequences of not having a glyphosate or glyphosate type product available for cropping establishment or fallow preparation means that we will expose our soils to more erosion, whether it be water or wind."*

RECOVERY OF DROUGHT-AFFECTED SOILS

"In my experience, the most critical time to manage (soils) is after the break."

Basic soil literacy

Understanding basic soil health principles assists farm management and aids in progressing soil recovery

- When there is a lot of rain, *"systems are fine because the roots can be happy in that top area because there's enough rainfall and nutrients. But when the rainfall tap turns off a lot more constraints are revealed in those soils, more than people realise."*
- Due to soil specificity, there is no 'silver bullet' answer to how to help soils recover, as the same things won't work on all the different soil types.

- Soil literacy is not the priority for all landholders, and a lack of an innate understanding of a farm's soils can hinder recovery. *"When EM surveys became popular lots of agronomists assumed that is all you need, but there are other factors that are really important, like compaction, acidity and nutrient deficiencies etc. And given that Liebig's law of the minimum applies simultaneously, you have to deal with all those constraints before you can get good results."*
- Drought provides an opportunity to *"go back to the basics and think about topics like compaction, acidity, dispersibility and get a better understanding of soil constraints that might exist on-farm".*
- Instead of waiting for rain, good farm management is about assessing soil condition, identifying different soil types on the farm and any soil constraints that might exist and fixing them up while the drought is still on.
- To capitalise on drought-breaking rains, improve soil water use and reduce evaporation and runoff, it's important to have gathered data on the different soils. *"You actually need to collect some data and look at that".*
- Once water is in the soil, it can be held there, and when crops are planted, they can grow and inject cash flow into the farming system. *"Once that happens, then you know you can deal with other aspects of soil management on a farm."*

Upskilling lenders can help them understand what farming practices assist farms to survive drought

- *"We need to carefully assess soil on the farm and take appropriate action under the dry conditions so that you can really make the most of the good times when they come. Part of the process is educating the bankers and financial advisors so that they are asking the right questions of their farm managers."*
- *"What we need, is every farm considered separately and individually and the conditions on a particular farm measured accurately. And then once you have that data you can develop a systematic approach going into the future for the required soil management, linked in with the farm financial planners".*

Drought mindset

Landholders may bring caution experienced during drought into soil recovery after drought has broken

- Landholders are often still risk averse after drought.
- Some may have recency bias, which is thinking what's happened last year and the year before will happen again. This can drive decision making. *"Drought is going to happen. It's a matter of what you do when things are really, really good, you've got to prepare for the drought. Bottom line. Be prepared."*

It is important to manage expectations - things won't be the same, and that is ok

- Managing expectations about what is going to happen is required. In some situations, there is nothing that a farm manager can do, *"i.e. if there is not much stubble cover going into the drought then it's very hard to manage wind erosion, so you just have to manage your expectation that that will happen."*

There is an opportunity to assess what works and what doesn't, and what can be done differently

- There is more interest in regenerative agriculture.
- Post-drought is when landholders are looking to do something different. It can be a key time to be promoting healthy soils and what can be done differently to manage and maintain healthy soils
- Landholders who changed their risk profile after the millennium drought have been able to fare better during subsequent droughts as their pasture feed base is right and/or they are choosing lower risk crops. *"While it's a painful process, it's an excellent opportunity to look at how to set yourself up for the future."*

Larger agribusinesses have more opportunities to implement best practice and need to share knowledge

- Larger agribusinesses have the capacity to move resources and risk around their farms. *"Hopefully, leading family farmers can go to field days of big corporate farms to see if some of their management practices or ideas could be adopted on farm."*

Wetting up of soil

If a soil has been in prolonged dry conditions, it takes a longer time to wet up

- The soil takes a long time to wet up with initial drought-breaking rains, and then following subsequent rains it wets up quite quickly. Conversely, when it dries it takes a while to dry then it dries quickly.
- Drying has a different curve than wetting. Wetting is a convex curve and drying is a concave curve meaning it takes a long time for soil to wet up and a very quick time for soil to dry out.
- Soil needs time to wet up. *"What we don't know is how long it takes for the water to penetrate and be taken up by capillary action and that's an issue."*

The initial stages of any rainfall event after drought are the most erosive

- Rain after a drought is the most critical/damaging because it takes a while for the soil to wet up, therefore it can be more erosive before the soil starts absorbing water through capillary action. Hydrophobicity needs to be managed so that the soil absorbs moisture quickly.
- It's important to make sure water doesn't move too fast off paddocks, so it can infiltrate into the soil.
- Silty topsoils do not have much structure. When a duplex soil with a silty topsoil wets up, soil particles may realign and an A2 horizon can develop (over extremely long periods of drought). It is natural wetting and drying cycles that stop this happening.
- If soil is bare, then strategically cultivating to increase the soil roughness just before it rains can slow down the movement of water across the landscape, reducing erosion.

Different soil types will have different wetting and drying cycles

- It takes more water to wet up heavier soils and get plants growing following drought.
- Lighter soils can't hold as much moisture, but crops can more easily use the moisture that is available and ground cover grows faster.

- The moisture is more readily available in the lighter soils, they also run out of water sooner.

In drier climates, even a small change in slope can inhibit capturing rainfall where it falls

- Climates with naturally higher rainfall are inherently more resilient to water erosion as they have year-round vegetation cover and a natural tension in the soil maintaining soil structure. This is not always the case in drier climates.
- Gradient of slope becomes more important in these drier areas with less vegetation cover and soil structure. *"A five per cent slope in the Mallee might be equivalent to a fifteen per cent slope in Gippsland. So gradient is a lot more important."*
- It is important to slow down velocity. Ponds can help slow water down as it moves across the landscape.
- Sandy ridges often suffer from seeping as water soaks into the top of the ridge, moves down the slope, hits a harder layer underneath and then soaks out.
- In heavier soils, this can be managed by spreading the water with contours, or keyline areas that have a slight decrease in slope towards the spur. This encourages water to flow out across the spur, instead of concentrating in the gully. Grass strips can also help with this.

Ground cover management

Capitalising on rainfall events by sowing a crop or pasture will establish ground cover to protect against soil loss

- Once it has rained it's important to establish ground cover as quickly as possible. Sowing anything into the ground to get cover will reduce erosion and cover bare soils.
- Sorghum can be used (mixed farmers) as a dual-purpose crop if there is adequate rain after a drought. Young crops will catch future rainfall events instead of the water just running off.
- What is sown doesn't need to be something that grows big. It just needs to cover the ground to catch water
- Ground cover also provides organic matter in the 'boom and bust soils' in WA as when it rains, this activates the organic matter and *"springs everything to life".*
- Landholders may grow an early crop to get this cycling happening and then grow their normal crop later.
- Easy-to-grow crops such oats can be used as a cover crop in pasture, or growers can simply let seeds/butts of pasture germinate. *"This may be their only opportunity to plant something to get some good ground cover and to grow some fodder for their livestock."*

Getting stock back onto paddocks quickly can risk temporary overstocking as pastures recover

- It is important to hold off putting stock back into paddocks once pasture growth begins. *"Now is the most important time to get off the land and keep the stock away from it and let the functions get going."*
- If it is unavoidable, making rotations short can allow the vegetative matter to build up.

- Sowing cover crops can help create feed, but this will depend on the time of year, the window of opportunity for sowing, whether the crop is for grazing or grain and the market for these commodities.

Nutrient management

Over managed soils at the beginning of the drought can result in increased nutrients available during the recovery of a paddock

- In the initial years of drought, it can be hard for landholders to reduce inputs as these decisions are innately part of land management, in particular phosphorous fertiliser.
- Even when fertiliser use is cut back, plant production is cut back even more severely than the reductions in fertiliser and therefore un-leached nutrients can accumulate.
- This excess of nutrients applied during the drought, that have accumulated in the soil, may be available to the next crop or pasture.

As drought breaks, mineralisation increases and there may be excess nutrients available

- Coming out of an extended drought, improved soil fertility is generally observed. *"Fertility in the crop post-drought has a lot to do with the soil being warm and damp if you get a good break…soil is humming, and microbes are ticking, and mineralisation would be occurring and less requirements for P or N".*
- In most cases after a drought there will be phosphorous available that wasn't used the previous year, as well as nitrogen. *"Nutrient status is probably OK; nitrogen status is probably OK for a two-tonne crop…use some phosphorous at seeding and manage your nitrogen in the season going forward."*
- In the millennium drought, accumulation of phosphorous in regularly cropped soils was observed. However, unlike phosphorous, nitrogen did not accumulate as nitrogen application rates were matched to minimum plant requirements. Since legumes are the first thing to suffer in the drought, there is less opportunity to build up nitrogen reserves. Sulphur also tends to not build up as much during drought.
- As drought breaks the Birch effect is observed, where there is a burst of decomposition and mineralisation that releases nitrogen. There has also been very little leaching and denitrification due to previous moisture stress in the system.

Nutrients can be lost if topsoil has been displaced through wind and/or water erosion

- Plant nutrients will have been lost with finer particles in wind erosion and washed away with organic matter from water erosion, changing chemical fertility. *"Given that we knew how much soil had been shifting, (it was important to investigate) whether we had lost that nutrition over the fence."*
- Soil pH may change if the topsoil is lost, exposing lower layers of soil which might have a different pH, especially if calcium carbonate is under the surface.

Test for nutrient status to determine particular nutrients have accumulation or declined

- Managing soil requires data. If soils aren't monitored as to what is available or depleted within, this makes management of soils difficult. *"This means management of soils is typically limited to making chemical and physical measurements, because these are the issues we can change."*

- Landholders who regularly soil test are in the best position to respond in an informed way as the drought breaks, especially those who maintain some level of testing through the tough years.
- It is important to assess what nutrients may be available in the soil and not just assume that there aren't any nutrients available. *"Don't guess, test".*
- Soil testing can help identify nutrient status. *"Soil test the different parts of the landscape, the parts that have been wind eroded, and know what your fertility is."*
- Considering the different soil zones/production zones, soil testing can relate management and production to the different soils and how they behave in drought. This helps with getting more prescriptive about how nutrients are applied. *"For example, using three zones for the eroding soils - sand (dune), midslope and flat. This can assist in equating soil loss to nutrient loss."*
- Under drought there is less crop growth and less nutrient uptake. After drought, landholders commonly adjust their fertiliser program the next year, assuming that they have retained some of the nutrients from the previous year and therefore don't need to apply quite as much.
- Even if soil tests show elevated levels of phosphorus, some landholders may still apply phosphorus if prices are good. It is therefore important to know soil types and phosphorous buffering index.
- Under no-till systems phosphorous is often accumulated in the top few centimetres of the soil, resulting in subclinical deficiencies. It is therefore important to be cautious about reducing inputs without understanding the full profile of the soil.
- If there are no resources for soil tests, splitting applications of nitrogen can be useful. This allows the farmer to assess how much nitrogen might be needed later in the season.

To capitalise on nutrient availabilities that might be present following drought, root systems need to be ready

- Under drought there may have been reduced mineralisation of organic matter so there may have been some conservation of decomposable organic matter. When it does rain *"there is likely to be a flush of mineralisation that releases quite a lot of nutrients, such as nitrogen, sulphur, phosphorous."*
- Plant roots improve soil structure. Biology can then start turning over carbon, increasing it in the system.

Subsoil constraints

Drought is an opportunity to undertake amelioration on-farm

- Droughts can highlight unknown soil constraints. *"There is an ability to start to manage within a drought for after a drought. If you know what your constraints are, remove them."*
- Managing constraints can lead to faster recovery from droughts.
- Soils without a subsoil constraint will do better in drought. For example, soils without a sodic subsoil will do better because they have a bigger bucket of water they can access. Therefore, if the soil undergoes amelioration, it is ready for when rains come.

- If a subsoil has been successfully ameliorated before a drought, improved vegetation growth should be achievable during a drought, as plant roots have a larger soil bucket for accessing moisture. *"All soils can be resilient during a drought if they are managed correctly."*
- To capitalise on deep ripping, dry conditions such as those experienced in drought are preferred, so that when a ripper goes through the soil it shatters easily. In wet conditions, deep ripping can create a mess of the paddock. *"Another aspect of drought management is that the farmers who can afford it are in a position to apply treatments when they're most likely to work…even though the paddocks will look pretty awful…when the rain finally comes they'll get really good water entry and storage and the roughness will settle down."*
- If once every seven to eight years landholders undertake soil amelioration instead of fallow, this can help prepare the soil and assists recovery after a drought. *"The bottom line is we don't have a fallow year. We have an amelioration year…we spend from June to August ameliorating the soil like ploughing in a cover crop…then kill it and have a mulch on top."*

Not all ameliorations will work on all soil types, so it is important to understand soil type

- There can be issues when ameliorations are undertaken on the wrong soil types. For example, clay delving when the subsoil is very hostile or deep ripping heavier textured soils, as *"deep ripping of heavier soil types or bringing up hostile subsoils can result in issues with the establishment of crops."*

Deep ripping and deep-rooted perennials can alleviate subsoil compaction

- In lighter soils, mouldboard ploughing and deep ripping can be used to remove hard pans. This can be repeated every four to five years. This amelioration can be expensive, but *"all of a sudden you have more roots. You don't get as much leaching of nitrogen and nutrients. You have better plant available water and have more biomass on top."* Some farms are seeing double yields, years after ripping.
- Once hardpans are removed, roots can access moisture two to three meters down, moisture that is protected from evaporation because of its depth.
- In heavier soils, using deep-rooted crops such as tillage radish or other perennials can help break up soil.

Deep-placed organic matter can boost a plants response after drought

- Adding manure or other organic matter deep into the soil provides an area of nutrients for plant roots to access. This in turn increases nutrient cycling and biological activity, which leads to improved soil structure.

Attack sodic acid subsoils deep in the soil profile with a lime gypsum blend

- In some soils, placing a lime and gypsum blend into the subsoil can reduce sodicity, more so than gypsum on its own as the fine lime also has enough of an electrolyte concentration to reduce the amount of dispersion. *"If you put on a blended gypsum and lime, the gypsum gives the kickstart start and the lime is there for the long haul."*
- Following drought, large amounts of available moisture will dissolve gypsum applied to the topsoil. A reversion to dispersive conditions can occur. With lime in the system, it is persistent, and you still have that beneficial electrolyte effect *"except when the soil pH is too high, and the lime sits there".*

Mix lime deeper into the soil profile to reduce subsoil acidity

- Lime is insoluble and therefore doesn't move fast through the soil profile. Since soil acidity isn't always contained to the topsoil, mixing lime deeper can get it to where it needs to be. *"Mix lime in the top 10 centimetres with the next 20 to 25 centimetres to reduce the aluminium toxicity and get better plant growth."*
- Using a mouldboard, plozza or disc plough or a spader will help mix lime deeper. *"These will fix subsoil acidity and non-wetting soil."*

Implementing practices such as Controlled Traffic Farming can prolong the impact of soil ameliorations

Soil biology

Protecting microbial communities can assist with soil recovery after drought

- Increasing soil temperature, lack of moisture and limited resource availability will detrimentally affect microbial function.

Soil microbes recover extremely fast after a drought

- Microbes tend to go dormant when it is dry, but when it rains, soils hydrate and the soil biology is activated and the system 'gets going again'. *"Usually because of the unused nutrients in a drought, you can get explosive growth [post-drought]…in my experience, the most critical time to manage [soils] is after the break."*
- These hydrated soils lead to the rapid mineralisation of nutrients, providing a feast of soluble carbon for the microbes. *"In a space of a few days you can expect that most of the microbes have rejuvenated and become active…that is a natural cycle of wetting and drying."*
- Microbes need enough soluble carbon to metabolise.

Soil microbial activity contributes to soil surface aggregation

- Biology is key in the aggregation of the surface of the soil. *"So much of the aggregation is due to the biology: such as fine and superfine roots and exudates from roots. Any pasture soil surface will have much better aggregation in the surface because of the role of biology and constant turnover of organic matter in aggregating the surface soil."*
- Active plants growing in the soil assist biological turnover by providing organic matter as food. When organic matter starts to disappear from the system, the microbes that live on root exudates and fine roots begin to disappear due to their short lifespans. *"These microbes assist in 10 to 20 per cent of soil aggregation".*

Soil microbes contribute to the quick mineralisation of nutrients in the system after drought

- Mineralisation of nitrogen can be quick after drought as the *"bugs in our soils are very, very adept at reacting to quick rainfall events if you've still got root material in the ground. You may not have much on top, but you've still got enough organic matter under the ground."*

Disease and pests

Plant disease will generally reduce in drought years, however, some may increase

- In general, disease inoculum will reduce as dry conditions are experienced over sequential years. This is not a blanket rule, as some can increase.
- Crown rot, for example, builds up in a plant during spring when there is moisture stress. This is then carried over on the straw. During drought, stubble won't break down fast so this can still be an issue when the drought breaks and there is fast growth early.
- Root disease declines in correlation to production levels. With reduced plant growth in drought years, there are fewer roots and less material to be infected.
- There can be fewer foliar diseases in drought, due to reduced plant biomass and canopy cover.
- With reduced ground cover and a lack of moisture, reduced breakdown of stubble can be observed, and this can increase disease carryover.
- Disease can become a problem in areas where it wouldn't normally be as the host is around longer than it usually would be.

Predicta B can be used to understand disease pressure

Cropping cereals after drought removes the benefits provided by break crops

- As landholders often tend to crop back-to-back wheat, barley or oats after a drought, and there is a reduction of legumes included in the system, this can increase stubble borne and cereal diseases in the system.

Sowing interrow can help manage stubble diseases

- *"There is a perception that it could be good to sow back on the wheat rows with cereals again to access the phosphorous enrichment that is in the band where the previous crop was sown. However, this increases the chance of carryover of stubble diseases such as crown rot. If there is a high disease pressure, then moving to interrow or off row sowing can assist, as you are not right on the stubble."*

Drought can be an opportunity to manage some pest species

- It can be easier to control snails in drought years, due to increased bare ground providing spaces for snails to fall when flicked off the straw, and resulting in a better kill when sprayed with appropriate products.
- Fewer mice are often observed as they struggle to survive with less grain around.

Weeds and herbicides

If weeds haven't been managed during the drought they can increase when the drought breaks

- Weeds outcompete crops for moisture and nutrients. If soils are left bare in droughts, then when rain comes there is less competition and weeds can proliferate.
- Some areas have observed new weeds appearing after drought conditions. For example, in the Central West of NSW, there have been increased numbers of the weed cathead. Due to a lack of ground cover providing weed competition and higher than usual soil

temperatures, when it rains, new weeds are appearing in the paddocks, when they are usually not present in the farming system.

Weed control over summer is important to conserve moisture and nutrients

- After a drought *"work out how much feed you need and spray out the rest as all those weeds are doing is wasting water and nitrogen and helping with green bridge disease…get rid of as much as you can…if you have no stock, spray it all out."*

Some weed seed types may reduce during the drought

- Some weed seed banks can drop as there is less recruitment as they also suffer from the poor conditions during drought.
- Ants and termites will continue to consume weed seeds during droughts. In extended droughts we can even see the breakdown of hard seededness.
- Single year droughts can reduce the hardiness of weeds.

If pastures are neglected there can be issues with toxicities in stock

- When drought breaks, summer weed species will germinate in pasture paddocks and can cause issues in stock with excess nitrates and oxalates if they are consumed. Livestock losses are therefore a risk.
- Lucerne can be grown to reduce this and help with the re-establishment of pastures. However, if cash crops such as wheat, oats and barley are grown, they cannot compete early with summer weeds, therefore allowing weeds to establish.

Herbicide residue breakdown is likely to be reduced in drought years

- It is unlikely that all herbicides have been tested under all extreme events such as drought. Therefore, guidelines around residue breakdown for herbicides should be taken with caution during a drought.
- Preemergent herbicides can have a longer residual life in the soil.
- Herbicides are chemicals which are designed to act for a period of time against weeds and then dissipate so that activity levels drop away and they have no residual effects on the current or next crop that is planted in the paddock. However, in unusual circumstances such as drought, those residues might not break down as fast as normal and there may be more plant back toxicity effects the following year.
- Low microbial activity in drought reduces the ability of the microbes to dissipate the herbicide residues.

Rhizobia are especially sensitive to herbicides

- Herbicide residues are a big issue in pasture or grain legume systems. *"Farmers are aware of plant requirements but not always the soil and climate requirements on the labels such as pH, rainfall and moisture conditions required to break down the herbicides."*

Assessing if there is herbicide carryover in the soil will reduce the chance of herbicides affecting crops

- One way to assess if there are herbicides in the soil is to do a bioassay. This involves taking a soil sample that is suspected to have herbicide residues and plant a sensitive variety in the soil and observe how it grows. A safe option could be to grow more herbicide tolerant varieties following a drought to negate this possibility.

- Another way to assess herbicide residue is to take intact cores from paddocks where there may be herbicide carryover issues and plant the host species into the soils and see what damage levels there are, compared to a soil known to be treated with chemicals. Comparing resistant varieties with traditional varieties can be useful.
- A Soil CRC project is developing a decision support tool which can use soil types, climate types, seasonal rainfall and pH and give a probability that residues have persisted and could have toxic effects on the next crop.

SURVEY - TAKE HOME MESSAGES

"If a soil gets baked dry it hasn't fallen apart, it is still a productive soil, make sure you hold the soil where it is."

Important to:

Revisit basic soil literacy skills on the farm

- *"[It is] important to go back to the basics sometimes and talk about topics like compaction, acidity, dispersibility. Because when there is lots of rain, systems are fine because the roots can be happy in that top area because there's enough rainfall and nutrients. But when the rainfall tap turns off a lot more constraints are revealed in those soils, more than people realise."*
- *"Get the fundamentals right and the fancy stuff will follow."*
- *"The key thing is that there is a distinction between episodic rainfall scenarios in the northern region and the southern temperate region and different soil types, and the impact differences and the management options are different in northern Australia versus southern Australia. Some things are generic, but some things are quite specific because to a certain extent they are related to predictability of rainfall and the cropping cycle."*
- *"There isn't always intergenerational transfer of knowledge, so need to ensure that all farmers have access to basic drought management strategies."*

Manage expectations that things won't be the same and that drought is a natural part of our ecological systems

- *"Farmers' mental health is the biggest issue. It is important that they can manage their expectations that in dry times things won't be the same, and that is part of our ecological systems. Now we have tips and tricks that we can manage them more effectively. The land will recover. Mental health is really critical."*

Have flexibility in planning during droughts and be prepared for the next dry period

- *"Drought is going to happen. It's a matter of what you do when things are really really good, you've got to prepare for the drought. Bottom line. Be prepared."*
- *"If it looks like maybe good rains, growing some canola or beans can help."*

Opportunity to:

Assess what works and what doesn't, and think about doing some things differently

- *"The key rule of thumb is keeping your ground cover, encouraging your soil biology, flexibility in stocking and thinking about more innovative cropping approaches."*
- *"These droughts can provide moments when a farmer will have time to think that they can do something different and it's important to make sure the information is available*

for farmers so they can reassess the way that their systems are going because there is the opportunity for a paradigm shift. We have to take advantage of this."

- *"There are a lot of people just sitting around waiting for the rain to come. But what leading farmers need to be doing is assessing their soil condition, identifying the dispersive areas and fixing it up while the drought is still on so that when the rain eventually arrives, they can do something positive with that water … when the crop goes in, it can really take off and do its thing and get some cash flow going. And then once that happens, then you know that you can deal with other aspects of soil management on a farm."*

Undertake amelioration

- *'I think it's less complicated than we think it is. If a soil gets baked dry it hasn't fallen apart, it is still a productive soil…drought years are important to do erosion control...reducing stocking rate…roughing up if need be or growing a vigorous variety out of season if need be…the main thing is that if they want to crop with wheat, is that they are aware of the disease risk….last thing you want is 1/3 of the yield gone."*
- *"If you put a plough in and you overstock, and you take your cover off you have simplified and destroyed the soil's biology and its structure and then you bare it off and it starts to blow and it won't hold water."*

React quickly and capitalise on a window of opportunity after drought

- *"For an extended drought period we would expect from most paddocks this window of low weed seed burden, low disease burden and maybe an accumulation of some nutrients…the biggest weakness is being able to react to that from a financial and emotional point of view…to suddenly go from survival mode to 'I need to spend money to make money'."*
- *"The most sensitive time to manage a system is on the break of drought. Making the mistake of not capitalising on opportunities inhibits the soil and the system to recover quickly."*

Undertake research with a focus on an integrated system approach

- *"A lot of our research has historically been very reductionist as it focuses on a specific context in isolation. Soil is a system that you cannot isolate. Need an integrated system approach. We would be remiss to suggest that there will be a solution that will suit everybody."*

SURVEY - KNOWLEDGE GAPS

KNOWLEDGE GAPS IDENTIFIED BY PARTICIPANTS

Soil Biology

1. What is the short-term biological impact on soil aggregation in a drought? How long will that last?
2. How long do the different pools of soil biology survive in drought and what are their roles under drought conditions?
3. In the Darling Downs, long fallow disorder has been observed and explained by the decline of vesicular-arbuscular mycorrhiza. How does this play out in a drought?
4. Is there a microbe that could help in reducing hydrophobic soils?
5. What biological species are rebounding first after drought and how can this be related to profitability and productivity?
6. What is the role of macrofauna in drought affected soils? *"These seem to be as crucial for their involvement in nitrogen availability, water holding capacity and infiltration."*

Soil Chemistry

1. How do we deal with water repellency that develops in heavier textured soils during drought?
2. What is the role of polymers reducing hydrophobicity? *"They would be cheap, environmentally stable, and would reduce erosion and surface tension and help water infiltrate."*
3. Regionally, how much can you reduce nitrogen fertiliser following a drought, due to the quick mineralisation of nitrogen in the soil following a drought?

Soil Physics/Erosion

1. What statistical work has been undertaken to assess the loss of topsoil due to erosion?
2. What are the agronomic costs of losing the topsoil due to erosion in a drought? *"Research could capitalise on erosion events in paddocks and assess the yield losses in eroded paddocks and non-eroded paddocks. It's easy to understand the value of the nutrients lost, but not the biology, organic matter and soil structure loss."*
3. When should you stop and start deep ripping in a farming system? *"There is still a gap there (farmers not soil testing before ripping) in teaching people where they might get the most gains from ripping."*

Farming systems

1. Which regenerative agricultural techniques or approaches might increase soil resilience in droughts and what is the mechanism in which that happens? *"That's the gold mine…if we are going to stop desertification and climate change…more research in regenerative agriculture".*

2. How can we look at drought from a slightly different angle and see what approaches used by Traditional Owners could be adopted in modern agricultural systems?
3. What is the cost to the system of stock eating the last bit of stubble cover in a paddock compared to retaining that stubble? *"The detrimental effects are being observed on the system (rain not sinking in when it comes, pulverizing the soil, eating the roots out) with grazing sheep"*
4. What role do pasture legumes play in the system as a drought mitigation strategy?

General

1. What per cent ground cover is needed to protect the soil?
2. What happens to weeds with fodder moving around the country during droughts?
3. How long does it take to rebuild supplies of fodder after a drought?
4. Can better ground cover monitoring be undertaken so farmers can be advised when things might be getting bad on their farm?
5. Would it be better to give cash grants in drought to encourage best practice and avoid ecological detrimental consequences when landholders need to squeeze production off the land? *"There has been more emphasis on household assistance rather than fodder subsidies. Subsidising fodder sends the price up and transport up. They have provided money to put in more water supplies and long-term loans. Water supplies might mean you can keep stock longer when you perhaps shouldn't be keeping them."*
6. When we see a boom in productivity after a drought, is it soil management or soil type that has an impact on this response?
7. If you overcome your soil constraints the soil does seem to respond better after drought. Is this related to soil health or microbial activity or is it a structural or a chemical response?

REVIEW - INTRODUCTION

Australia is exposed to a variety of climates due to its large size and meridional extent (Herold et al. 2018). The majority of Australia's landscape lies in the southern subtropical region (15-20 degrees to 40 degrees south of the equator) except for parts of Northern Australia and Tasmania. Central and southern Australia are largely dominated by the subtropical high pressure belt, which is generally associated with clear skies, large sensible heat fluxes, and is collocated with Australia's deserts (Botterill and Wilhite 2005). The high degree of both seasonality and inter-annual variability arises due to the location of the subtropics between the tropical zone straddling the equator and the middle latitudes further north and south (Botterill and Wilhite 2005). A variety of climatic mechanisms influence weather systems in these zones and can interact in complex ways around the fringes of and across the subtropics. With such a wide range of climates, Australia experiences a great diversity of climatic extremes, including heatwaves, floods, droughts and frosts (Westra et al. 2016). The consequences of a variable climate generate an environment that is prone to prolonged periods of below-average rainfall (Botterill and Fisher 2003).

According to Wilhite (1993), drought is a "creeping phenomenon," the effects of which accumulate slowly over a considerable period of time. In general, a prolonged and abnormally dry period when the amount of available water is insufficient to meet the normal use characterises droughts (Anon 2020). However, 'drought' means different things different sectors of the society and no universally accepted definition has so far been developed (Sastri et al. 1982; Wong et al. 2010; Seneviratne. et al. 2012). Drought is a complex phenomenon and has various classifications including:

- meteorological (lack of precipitation)
- agricultural (deficit in soil moisture, and vegetation response)
- hydrological (deficit in runoff, streamflow, or groundwater storage)
- socioeconomic (social responses to water supply and demand) (Mishra and Singh 2011; van Dijk et al. 2013).

The onset of a meteorological drought is the first and is the driving force for the other drought categories. The onset of an agricultural drought may lag the meteorological drought, depending on the previous moisture present in the surface soil layers. The effects of hydrological drought persist long after a meteorological drought has ended (Heim 2002).

Normally, short-term droughts disrupt the water supply for agriculture, other industries, animal and human consumption, and interrupts the balance between the supply and demand relationships. Long-term droughts may require far more substantial changes in resource allocations and water storage management strategies in order to sustain the supply of resources (Dey et al. 2019). The isolation of the factors contributing to drought and its impacts is difficult because natural climate, water cycle, and vegetation processes interact with water resources management, agriculture, economy, and society in a myriad of ways. However, droughts are expected to increase in frequency and severity in many regions in the future as a result of decreased precipitation and increased evaporation due to a global climate change (Seneviratne. et al. 2012; Naumann et al. 2018; Dey et al. 2019). Therefore, the contributions of climate change, water management, and other natural or human factors to these impacts need to be understood to guide our expectations about, and response to, future droughts (Steffen et al. 2018).

Drought has significant impacts on soil and vegetation, with some of these impacts being effectively irreversible over the time horizons usually used in agricultural management decisions (McKeon et al. 2009). Most important and irreparable losses of droughts include pasture and soil degradation, which threatens the natural resource base of the farm. Amongst many other issues, drought reduces vegetation and litter cover of the soil exposing it to subsequent wind and water erosion. This affects the farm and the wider area, including through the dust storms (Webb et al. 2009; Tozer and Leys 2013). Dust storms tend to be more prevalent during droughts, which have a huge impact on the surface fertile soil loss and soil structure degradation. Drought can also lead to a greater spread of weeds from one farm to other farms or into public land. Increased incidence of forest/bush fires under the influence of drought can further increase the extent of losses including the losses of native animals and vegetation posting the irrecoverable damage.

REVIEW - DROUGHT MANAGEMENT

For centuries, Australia has been facing periodic water shortages and times of plenty, when the rains and floods come. Australian agriculture, therefore, it has a long and evolving history of drought management. Australia's drought mitigation policy moved towards a risk management approach in the early 1990s (Botterill and Wilhite 2005; Stone 2014), with a focus on enhancing farm productivity under water stress conditions. This strategy follows the same principle as adopted by the United Nations Convention to Combat Desertification (Anon 2019) and other countries (Hong *et al.* 2016) which divides drought risk management into four steps—prevention, preparedness, response and recovery (Figure 1). In the case of drought, prevention is almost impossible but the other three steps are crucial for effective management of adverse impacts. Therefore, this review is primarily focussed on the agricultural droughts that are characterised by low rainfall and directly affect the crop water availability, irrespective of soil type. Transient water deficit is a normal and universal experience for crop plants and most might evolve appropriate responses to cope with short-term water stress. When the deficit is over a prolonged time and occurs over large areas of agricultural land, significant yield losses occur. These losses are a function of the timing and duration of the drought stress, which has a proportional impact on the reduction in crop and pasture production, stress on the microbial and fungal communities in the soil, and affect physical, chemical, and biological processes in the soil. These changes are more pronounced in regions where extended water scarcity is unusual (Fierer *et al.* 2003). In addition to reduced agricultural production, drought also causes changes to the cycling of nutrients such as nitrogen and phosphorus. If drought breaks with heavy rain, that can increase nutrient mobility, leading to their losses and adverse effects on waterways (Gordon *et al.* 2008; Blackwell *et al.* 2013). Soil management during drought recovery is therefore important for sustaining crop production. This review analyses the impacts of droughts on soils and evaluates the existing practices and techniques to mitigate the harmful impacts of droughts on soil during the water stress and recovery periods.

Figure 1. Drought risks management. Source: Hong *et al.* (2016).

REVIEW - DROUGHT IMPACTS ON SOIL

The response of soils to drought varies greatly between them; the impacts depend on the soil's physical, chemical and biological characteristics and the severity of the drought. The main soil textures spread over the Australian drought-affected regions are sandy, texture contrast (duplex soils) and hardsetting clay soils. Sandy soils represent approximately 30 % of soils in the low rainfall south-eastern Australian cropping region (Unkovich 2014). Other major group of soils in the subtropical drought-affected region are duplex soils (Northcote 1960) which have texture contrast between A and B horizons. Normally, the subsurface horizon has medium to heavy textured clay overlain with a sandy to sandy loam surface layer. They cover almost 20 % of the Australian landscape (Chittleborough 1992). Calcium carbonate and calcrete are usually present at various depths in and variable proportions. Most of the dry region's soils are inherently low in fertility and organic matter, low water holding capacity and high water repellence (Roper *et al.* 2015), making it one of the most fragile cropping environments on the continent (Coventry *et al.* 1998). Sodicity, salinity and/or phytotoxic boron may be associated with the clays in some cases. These soil constraints, coupled with other subsoil hindrances, make these soils vulnerable to drought impact and recovery from the drought is more difficult.

The impacts of drought are experienced more severely in sandy soils, which have a low proportion of clay, low water holding capacity, low fertility, are deficient in organic carbon, low biological activity, and a small microbial population (Unkovich *et al.* 2020). Nutrient deficiencies of nitrogen, phosphorus, sulphur, zinc, manganese, copper, cobalt, boron, molybdenum and selenium have been recorded for sandy soils across low rainfall south-eastern Australia (Unkovich 2014). Presence of carbonates in these soils can also greatly reduce the availability of phosphorus, manganese, zinc and iron (Holloway *et al.* 2001). On the other hand, clay and loam textured soils are relatively better placed for adapting to water stress as they hold more water high suction and have a higher nutrient retention capacity. Structural degradation of clay-based soils can occur during droughts; this includes the development of wide and deep cracks in black, grey and brown clays (Vertosols) (Lucci 2019). Topsoils can become very dry and powdery; in this state, they are highly vulnerable to erosion.

WATER CONTENT DYNAMICS IN THE SOIL

The extent and severity of dry spells has a tremendous impact on the amount of water retained in the soil for crop production. Differences in the water holding capacity of soils are likely to influence the rate of soil drying and the onset of drought stress in crops. To manage soil water, however, we must understand the basic concept and evolution of the various theoretical models that have progressively defined the water availability to plants.

Factors affecting soil water availability

Under drought conditions, the crop lower limit of the water retention curve is important to evaluate the response of stored available water to crops. Numerous studies have related the estimated crop lower limit to various soil properties including soil particle size, organic carbon, bulk density, drained upper limit, and subsoil constraints (Gupta and Larson 1979; Hochman *et al.* 2001; Sadras *et al.* 2003). In fact, low and variable rainfall, heat stress, and high rates of evaporation make stored soil water important during dry periods (Freebairn *et al.* 1991).

Soil texture

Soil texture refers to the proportion of sand, silt, and clay particles and this largely controls how much water can be stored in the soil. It is generally accepted that the water holding capacity of coarse-textured (sandy) soils is much less than that of fine-textured (silty and clayey) soils. However, soils that have a higher amount of clay hold onto their water more tightly and there is a trade-off between soil-water storage capacity and the availability of that water for crops (Sadras *et al.* 2016). Many studies have shown a positive relationship between plant available water and clay content of Australian soils e.g. (Minasny *et al.* 1999; Rab *et al.* 2009; Rab *et al.* 2011) and hence have varied impacts from drought. However, under drought conditions, crop lower limit (or wilting point) has more impact on the water availability to plants. The drained upper limit is a soil property, whereas the lower limit depends on both the soil and the crop, because the depth, distribution and functionality of roots affect water uptake (Ritchie 1981).

Oliver and Robertson (2009) observed that soils with a clay content around 30 % can store about double the amount of water of sandy soils. Such differences are important for crops only when the soil-water content is close to the drained upper limit for the sandy soil, at which point the finer-textured soils become advantageous. Therefore, under low rainfall conditions when the profile is rarely filled the differences in plant available water between soils may not be critical. There is an interaction between climate and seasonal conditions with soil texture, which means that in wetter conditions soil texture may modulate yield whereas it exerts less influence under drier conditions. The exception would be under very low rainfall when soils with lower clay content can be more productive because they hold soil water less tightly.

Typically, at lower levels of stored soil moisture, clays hold water with such high levels of suction that plants will not be able to draw moisture from the soil. Below the crop lower limit seeds are unable to germinate, and at the end of the season, drying below wilting point causes crops to die. This means the amount of clay plays an important role in the moisture dynamics in the soil.

Table 1. Determining ease of germination for key soils (Kimba).

Soil (DWLBC Identifier)	Description	Surface texture	APSoil Representative soil	Air dry deficit (mm/mm)	Wilting Point (WP) (mm/mm)	Germination requirement = Moisture required to reach WP in top 10 cm + 10 mm	Chance (in 100) of Effective Apr-May rainfall meeting Germination requirement #	
							(i) Control	(ii) -20 % rainfall
A4	Calcareous sandy loam	SL	Upper EP No 314 (Cowell)	0.02*	0.08*	16	86	78
A5/A6	Gradational calcareous loam	L	Eastern EP EE064 (Cleve)	0.04*	0.08*	14	89	82
D1	Sandy loam over clay on rock	SL	–	0.02**	0.08**	16	86	78
D3	Loam over dispersive red clay	L	Eastern EP EE052 (Kimba)	0.05*	0.1*	15	88	81
G3	Thick sand over clay	S	Upper EP No 319 (Lock)	0.01*	0.02*	11	91	90
H3	Deep bleached sand (Lowan Soil)	S	–	0.01**	0.02**	11	91	90
L1	Shallow sandy loam on rock	SL	–	0.02**	0.08**	16	86	78

Notes: *value from APSoil; ** assumed or modified value; # From inspection of BoM (2009)
'Effective Apr-May rainfall' = Actual Apr-May rainfall, minus 30 % to account for soil moisture evaporation. Under the climate change scenario (ii) Apr-May rainfall is further reduced by 20 %.

Table 2. Approximate physical properties of some soil classes based on sand and clay content (adapted from Brady and Weil (1999)).

Soil type	Sand	Clay	Drained upper limit	Lower limit	Available water capacity
	(%)	(%)	(% water w/w)	(% water w/w)	(mm/m soil depth)
Sand	>75	5	14	4	100
Sandy loam	55-65	10	18	7	120
Loam	30-55	10-30	30	13	220
Clay loam	<30	30-40	34	18	210
Clay	<30	>40	42	25	160

Under drought conditions the extent of water retained at the lower end of the retention curve is important. For example, Liddicoat and Hughes (2009, personal communication) examined the germination threshold for different soils under a drying climate on the Eyre Peninsula (Table 1). They found that deep sandy soils are better placed to support germination, as they need less moisture to reach the wilting point as compared to other soils. There are higher chances of effective April-May rain meeting the germination requirement. The ranking for ease of germination for these key soil types at Kimba is (surface soil texture in brackets): G3, H3 (sand) > A5/A6 (loam) > D3 (loam) > A4, D1, L1 (sandy loam). Coarse-textured deep soils sometimes support better crop growth in strongly water-limited seasons than clays.

In the absence of soil retention data from field sites, rough estimations are provided for different soils (see Table 2, (Brady and Weil 1999)). According to this estimation, sandy soil normally holds 100mm water in a 1m profile between field capacity and wilting point, while in clay and loam soils this amount is 1.5 to 2 times higher than the sandy soil (Table 2).

Soil structure and bulk density

Soil structure refers to the arrangement of soil particles into stable units called aggregates (Marshall *et al.* 1996). The stability of soil structure is its ability to retain this arrangement when exposed to different stresses (Angers and Carter 1996) including drought stress. The composition, size, and arrangement of pore space between aggregates are important factors contributing to water storage and supply for plants—the ability of soil to transmit water depends on the presence of interlinked pores and their size and geometry. Connolly (1998) reported that pores between 0.2 and 30 μm in diameter are important for storing soil water to be extracted by plants roots and pores between 30 and 300 μm are important for infiltration and drainage. Similarly, soil strength increases as soil bulk density or soil suction (water or salinity stress) increases (Taylor *et al.* 1966) resulting in an exponential decline in water root penetration and a simultaneous reduction in the total porosity, volumetric air content as well as the average pore size (Watson and Kelsey 2006). Change in bulk density can result in a decrease or increase in the water holding capacity of the soil depending on the amount of compaction, initial bulk density and pore size distribution of the soil. These changes can have a severe impact on soil and crop performance under drought conditions.

Soil depth

Soil depth is a crucial component of drought management, especially in sandy soils. Numerous studies (Tennant and Hall 2001) have reported better adaptation of deep-rooted crops in drought-affected areas. Deep-rooted crops such as lupin (Hamblin and Hamblin 1985; Unkovich *et al.* 1994), wheat (Incerti and O'Leary 1990) and cereal rye (Hamblin and Tennant

1987) can develop roots and extract water up to 2m depth. The presence of a compacted layer at shallow depth can restrict water uptake beyond this layer (30-35 cm) in the South Australian Mallee (Sadras *et al.* 2005). However, factors other than resistance to root penetration may also contribute to poor root growth at depth (Walsh 1995), including accumulation of ions or organic chemicals hostile to plant roots, or a lack of nutrients in the soil. Other studies (Passioura 2002) suggested penetration resistance for restricting roots (1MPa for impedance and 5 MPa for complete cease), bulk density (Incerti and O'Leary 1990; Hamza and Anderson 2005); smaller plants (Passioura 2002), root thickness (Materechera *et al.* 1992), and high contents of iron and manganese oxides and $CaCO_3$ can form and cause cementing of the soil particles, resulting in a thin cemented layer of high strength. To ascertain whether bulk density or soil strength are limiting root growth requires measuring bulk density, soil strength (penetration resistance) and pore size distribution. With information on these three parameters, it may be possible to ascribe the relative contributions of bulk density and strength to compromised root growth (Unkovich 2014).

Subsoil constraints

Water stress coupled with other soil constraints such as salinity, sodicity, compaction, and high boron can have additional adverse impacts on the plant available water in a soil profile. For example, high soluble ion concentration (salinity) in the soil solution increases the osmotic effect on plant water extraction (Grieve *et al.* 1986; Rengasamy 2002) and toxic levels of sodium and chloride can directly affect root and shoot growth (Greenway and Munns 1980). Marschner (1995) and Orcutt and Nilsen (2000) reviewed the multiple effects of salinity and sodicity on plants and ascribed these effects to:

1. Reduced crop-available water, associated with high osmotic potential, resulting in reduced ability of roots to obtain soil water.
2. Impaired root growth and functions due to toxicity of sodium and/or chloride, and
3. Nutrient imbalance by depressing the uptake of other mineral nutrients.

Under drought conditions, the soil solution becomes more saline as the water evaporates from the soil surface. Rengasamy (2000) investigated the water profile of an Alfisol with sandy loam topsoil and clayey subsoil (Figure 2). They observed that plants struggled to take up water and showed drought-like symptoms when the total matric potential increased due to the negative osmotic potential from an average root zone salinity of 4 dS/m. Modified solution and exchange properties strongly influence the extent and severity of the exchangeable sodium per cent in the soil. With increased water stress, soil can reach the threshold electrolyte concentration (20 % reduction in soil hydraulic conductivity) (Ezlit *et al.* 2013) rapidly, which represents an arbitrary, but measurable, departure from the soil stable condition due to volume change in the clay domain (Quirk 2001). Hence, rapid moisture loss from the soil affects the dispersive potential (Rengasamy and Olsson 1991) leading to a more prominent effect of soil sodicity. High sodicity often causes deterioration of soil physical properties, resulting in poor soil–water and soil–air relations (McIntyre 1979; So and Aylmore 1993) and in plastic soils with elevated electrolyte concentrations (Rengasamy and Olsson 1993). As drought progresses, the sodic soils (especially Vertosols) develop deep cracks while waterlogging problems occur under sufficient rainfall conditions. Both situations require adequate management to regain soil structure and sustainable crop production. Rengasamy (2002) observed a linear reduction in the relative yield with a continued increase in the exchangeable sodium per cent beyond six (Figure 3).

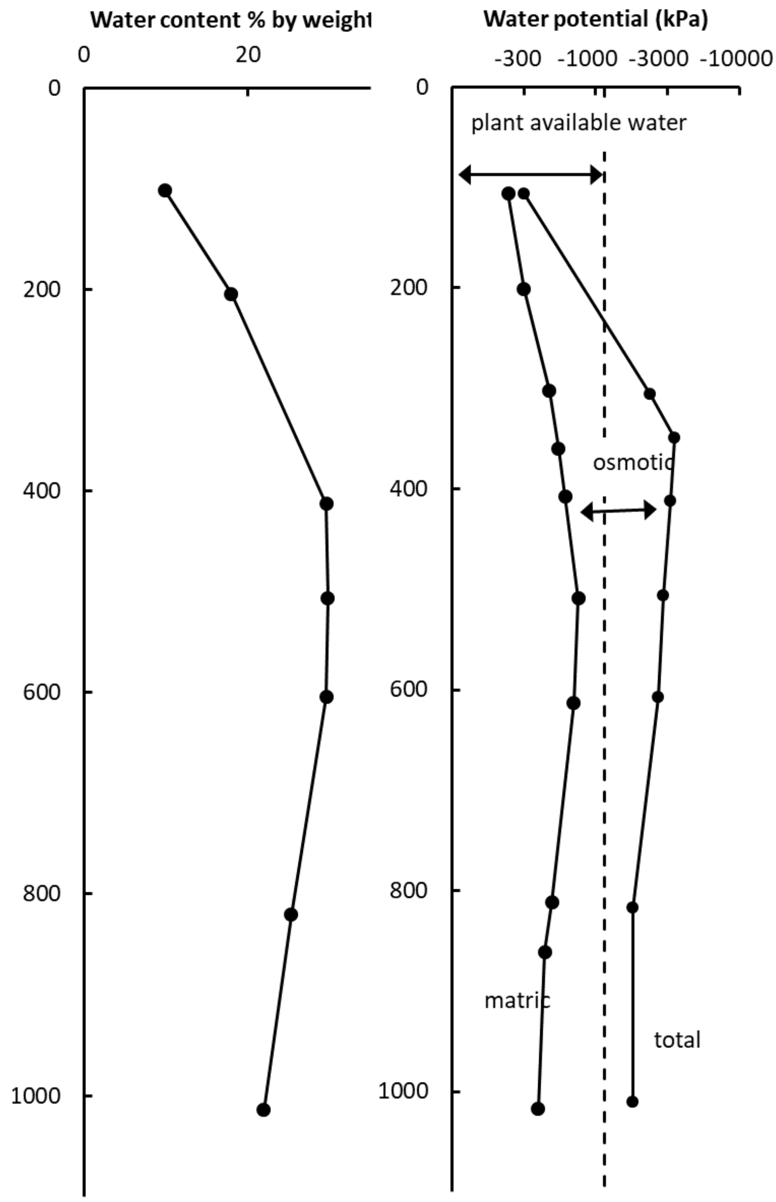

Figure 2. Gravimetric water content and soil water potential (matric and total) of an Alfisol profile. Source: Rengasamy (2000).

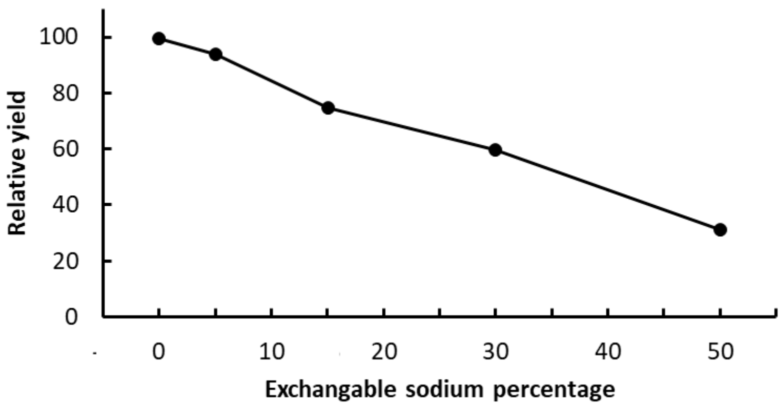

Figure 3. Relative yields of cereals (compared with potential yield) grown in Australian sodic soils (n = 25) in relation to average root zone exchangeable sodium per cent. Source: Rengasamy (2002).

In some soils, boron concentration has a drastic impact on crop production. The level of boron can increase under water stress along with soluble ion concentration (salinity) and sodicity. Earlier observations in South Australia reports that high soil boron considerably affected cereal production, particularly during dry seasons (Ralph 1986) due to increased boron concentration under water stress conditions.

Variable distribution of constraints spatially and with depth within a paddock further add to the adverse impact of drought on plant water availability (Dang *et al.* 2006a). The identification of crops and/or cultivars adapted to adverse subsoil conditions and/or able to exploit subsoil water may provide a tangible solution to sustainable use in soils with subsoil constraints (Richards 2002). The implications of subsoil constraints varies between soils (Dalgliesh and Foale 1998), such as salinity, sodicity, and chloride which can reduce the effective rooting depth and increases crop lower limit thereby reducing the amount of water and nutrients that plants can obtain from the soil (Sadras et al. 2003; Dang et al. 2006a). Dang et al. (2006b) quantified the impact of soil chloride concentration, saturated extract electrical conductivity, and exchangeable sodium per cent in various combinations in the subsoil accounted for 69–74 % of the variability in the crop lower limit of five crop species (bread wheat, canola, chickpea, barley, and durum wheat) in a study conducted at 19 sites on Vertosols (Figure 4). They reported that clay content had little impact (<10 % of variation in the crop lower limit) on the prediction of the crop lower limit. In a similar multifaceted study on drivers of the crop lower limit in course textured soils Sadras *et al.* (2003) reported stronger relationships between the crop lower limit and clay concentrations. They suggesting that between 5 % and 30 % of variation in the crop lower limit for wheat could be accounted for based on the soil clay content. Such impacts on the lower limit of water availability could have a more severe impact during the drought.

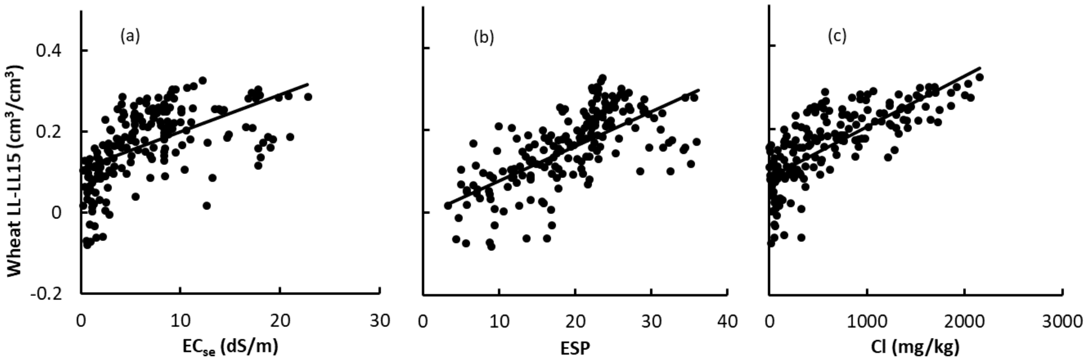

Figure 4. Relationships between apparently unused plant available water for bread wheat (bread wheat lower limit = crop lower limit – lower limit measured from texture, LL15) and (a) saturated extract electrical conductivity (ECse) (y = 0.0097x + 0.098, r2 = 0.31), (b) exchangeable sodium per cent (ESP) (y = 0.0082x + 0.0023, r2 = 0.47), and (c) chloride (Cl) in the soil profile (0.10–1.30m) (y = 0.001x + 0.083, r2 = 0.58) from 19 sites in south-western Queensland. Source: Dang *et al.* (2006b).

Waterlogging (due to sodicity) usually occurs when heavy rain during the recovery phase and the interaction between hypoxia and salt has a powerful negative effect on plant growth (Barrett-Lennard 2003). Another adverse impact of sodic soils during the recovery period is the formation of surface seals or crusts when the soil dries. It reduces water entry into the soils and impedes seedling emergence (Rengasamy and Olsson 1993). This seal is relatively thin and is characterised by greater density, higher strength, finer pores, and lower saturated hydraulic conductivity than the underlying soil (McIntyre 1958; Gal *et al.* 1984; Assouline 2004). Agassi and Ben-Hur (1991), and Morin *et al.* (1981) noted that the formation of a structural seal is a result of three complementary mechanisms:

1. Physical disintegration of surface soil aggregates, caused by the impact energy of the raindrops.
2. Aggregate slaking as a result of fast wetting of the soil.
3. The physicochemical dispersion of soil clays, which migrate into the soil with the infiltrating water and clog the pores immediately beneath the surface, to form the ‘washed-in’ zone.

The relative importance of the last mechanism depends on the electrical conductivity of the soil solution and the exchangeable sodium per cent of the surface soil. As the electrical conductivity decreases and the exchangeable sodium per cent increases, the clay dispersion is enhanced and the reduction in infiltration caused by seal formation becomes more pronounced (Agassi et al. 1981; Kazman et al. 1983; Ben-Hur et al. 1998). Moreover, an increase in the exchangeable sodium per cent decreases the stability of the soil structure, and this, in turn, could enhance soil detachment and soil loss (Agassi *et al.* 1994). Therefore, correct identification of subsoil constraints and their interactions in the soil with other variables is important to develop appropriate amelioration guidelines for achieving better outcomes.

SOIL EROSION

Soil erosion is a naturally occurring process that affects all landforms. In agriculture, soil erosion refers to the wearing away of a field's topsoil by the natural physical forces of water and wind and is accelerated by practices such as land clearing, overgrazing and soil cultivation. Erosion, whether it is by water or wind, involves three distinct actions—soil detachment, movement and deposition. Topsoil, which is high in organic matter, fertility and soil life, is relocated elsewhere ‘on-site’ where it builds up over time or is carried ‘off-site’ to accumulate against fence lines and buildings, across roads and in drainage channels. Soil erosion reduces cropland productivity and contributes to the pollution of adjacent watercourses, wetlands and lakes. Soil erosion is one of the most widespread threats to agriculture and the environment (Lal 2001; Nearing *et al.* 2004). It is the highest priority threat to the agricultural soils at the national level in Australia (Koch 2017).

Approximately 6.0 million hectares (58 % of cleared land) of agricultural land are inherently susceptible to wind erosion, and 3.2 million hectares (31 %) are inherently susceptible to water erosion (Unkovich 2014). Erosion of sandy soils has been an ongoing problem across much of low rainfall southern Australia and in a recent assessment by Smith and Leys (2009), it was rated as widespread on sandy soils across the Mallee systems in NSW, Victoria and SA, including the Eyre Peninsula. In some areas within this zone, it was rated as severe. On the other hand, a significant amount of water erosion can occur when drought breaks with heavy rainfall.

Wind erosion

Wind erosion is a major form of land degradation in the dryland farming areas of South and south-western Australia (Wallis and Higham 1998), with severe erosion events recurring every few years (Carter 1995). The processes of wind transport of soil materials have been reviewed extensively (Chepil and Woodruff 1963; Bagnold 1974). Recent studies are more focussed on modelling and mapping the erosion losses on a continental scale (Chappell *et al.* 2016; Chappell *et al.* 2019). Wind erosion has increased presence during drought and it can have adverse social, economic and environmental impacts. Repeated wind erosion of soil inevitably leads to changes in certain soil properties, many of which are irreversible and may lead to permanent degradation of the soil's productive potential. These include:

- Reduction in the fine particle fraction of the soil, which may reduce water holding capacity, and reduce cation exchange capacity.
- Loss of organic matter and nutrients, consequent loss of structural stability and increased erodibility of sandy-textured soils.
- Reduction in topsoil depth in localised areas from severe drift.

Wind erosion is triggered by the reduction of vegetative cover on the soil due to moisture loss by drought. Hot and dry conditions allow the particles in the top soil to detach from each other especially in sandy soils. The loose soil particles on the soil surface are easily blown away by the wind which usually occurs at an accelerated pace during the summer season over the Australian arid zone. Tozer and Leys (2013) reported the occurrence of dust storm events, as the result of wind erosion, at Buronga, NSW (near Mildura, VIC) from 1989 to 2012 (Figure 5). The intensity and volume of dust loss peaked during the Millennium drought (2001–2010). On-site damage from wind erosion occurs through the loss of topsoil, which can result in lowering of the soil surface and scalding, and loss of soil nutrients, organic matter and soil carbon (Leys and McTainsh 1999; Leys 2006). Windblown sand can also damage vegetation through abrasion or by burying it (Bennell *et al.* 2007).

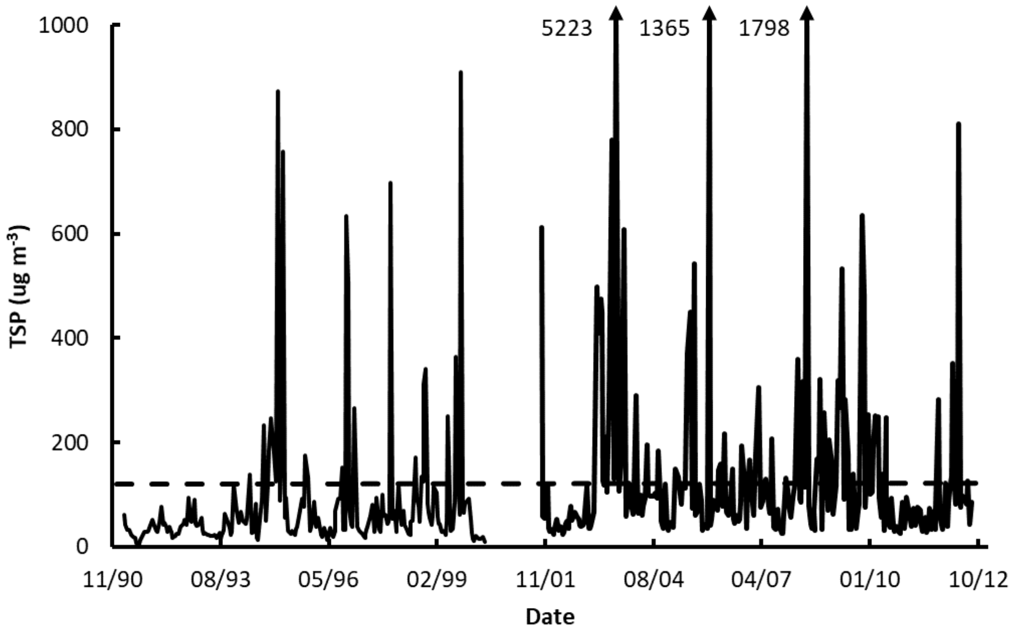

Figure 5. Total suspended particulate (TSP) matter concentrations at Buronga Dust Watch site. Dashed line denotes total suspended particulate matter of 100µg/m3. Numbers at the top of the graph indicates the measured TSP level of that date above the maximum y-axis value. Source: Tozer and Leys (2013).

Deep sandy soils are more prone to wind erosion than clay textured soils (Gorddard *et al.* 1982; Rowley 1982). Chappell *et al.* (2016) showed that nearly five times more soil was removed by wind and water erosion from cultivated land (-4.29 to +0.17 t/ha/year) than from uncultivated land (-0.91 to +0.05 t/ha/year) in Australia from the 1950s to 1990, thereby indicating a strong impact of land cover. Similarly, Dong and Chen (1997) estimated annual wind erosion from cropping land in semi-arid climates to be ~14–41 t/ha, which was two to four times higher than that measured for grassland. On a soil type basis, Harper *et al.* (2010) observed that Quartzose dune sands were particularly susceptible to erosion (47 % of total area eroded), whereas texture contrast soils formed on clayey, wind-formed lunettes (16 %) and deeply weathered regolith were less eroded (34 %). Soils formed on stripped regolith and on loamy surfaced lunettes and swales were not eroded. Wind erosion was strongly related to soil particle size distribution and surface horizon depth, only occurring on sandy surfaced soils, with <5 % clay and <3 % silt and >50 cm deep. The incidence of erosion markedly increased with small decreases in clay and silt contents below these thresholds. In some situations, erosion of the sandy A horizons of duplex soils will bring more clayey subsoil within cultivation depth, and the addition of clay due to cultivation may increase soil strength (Harper and Gilkes 2004) and this could reduce erodibility.

Where there is a substantial reduction in topsoil depth caused by wind erosion, the potential rooting depth and soil water holding capacity are reduced (Langdale and Schrader 1982). Wind erosion can also cause irrecoverable losses in soil fertility. For example, Leys and McTainsh (1994) found that the cation exchange capacity and available water holding capacity in the top one centimetre of a recently eroded soil that had been under fallow for 30 years was half of that of nearby soil with uncleared native vegetation. Below five centimetres depth, however, there were no differences between the two soils. Numerous studies determined extensive losses of organic matter and nutrients by wind erosion. These losses depend on the soil texture, aggregation, soil roughness, vegetation and wind speed. For example, studies with a wind simulator tunnel on a range of soils in the Murray Mallee (Leys and Heinjus 1991; Leys *et al.* 1993) have shown that eroded fine soil (<90mm) contains approximately two to four times higher concentrations of major nutrients and organic matter than intact topsoil. Thus, wind erosion selectively removes the nutrient and organic matter-rich fraction of topsoil. Unless erosion is controlled, the loss of topsoil results in a permanent decrease in yield potential which can only partially be restored by large additions of fertiliser or manure. Harper *et al.* (2010) estimated that the wind erosion induced soil carbon loss which was about 3 % of the total stock of carbon to one metre depth or 3.6 t carbon /ha for the eroded soils.

Dust can also have a positive impact on the agricultural land where it is deposited, as it carries organic carbon and nutrients, such as nitrogen or phosphorus, which contribute positively to soil health (Raupach *et al.* 1994; Cattle *et al.* 2009).

Water erosion

Erosion of soil by water is also a serious problem, especially when a heavy rain event occurs after a long drought. Soil erosion by water is a complex process that is driven by many factors, such as climate, soil, topography, plant cover and land use (Scott 2001). Initial detachment of soil occurs when the erosive forces of raindrop impact or flowing water exceed the soil's resistance to erosion. Drylands are particularly susceptible to gully formation because of sparse vegetation and a precipitation regime that favours infrequent but short, high-intensity rainfall events (Sidle *et al.* 2019). Numerous studies (e.g. Lang and McCaffrey 1984; Freebairn and Wockner 1986; Edwards 1991) on a plot scale (0.1 ha) have shown that the highest rates of erosion occur when the soil is bare and has been recently ploughed. Erosion rates decline if the paddock has not been ploughed, or when the stubble from the previous crop is incorporated into the soil (Lang and McCaffrey 1984). Rainfall intensity and duration play a key role in the extent of soil loss by erosion. Adamson (1974) and Edwards (1980) noted that the bulk of soil erosion losses over a long period could be attributed to a few storm events. They found that for improved pasture with erosion control banks, 89 % of soil loss was caused by storms in five out of the 22 years recorded. Similarly, on wheat plots, the largest soil loss from one storm event recorded by Edwards (1980) was 20 % of the total loss of 63.3 t recorded over the entire duration of the 30-year trial. It is also interesting to note that large soil losses were almost entirely confined to the fallow period, especially to the warmer months. It signifies that a large rain event after a long spell of drought could have devastating impacts on the degree of soil loss from agricultural fields. Similarly, Loughran and Elliott (1996) recorded the highest net soil losses in the order of 8–15 t/ha/yr under conditions of cropping (wheat rotation, potatoes, vegetables and vines). The lowest soil losses, generally in the order of 0 to 2.0 t/ha/yr, were recorded for grazing and forested areas. Similarly, Hairsine *et al.* (1993) measured 342 tonnes of surface soil loss per hectare for a paddock by two major storm events near Cowra, in the wheat belt of NSW, under traditional tillage. This was seven times greater than the estimated mean annual soil loss for the paddock. These studies suggest that land use is an important controlling factor for soil erosion. The annual soil loss due to water erosion can be estimated using a factor-based approach with rainfall, soil erodibility, slope length, slope steepness and cover management and conservation practices as inputs known as the Universal Soil Loss Equation (Wischmeier and Smith 1978; Renard *et al.* 1997; Teng *et al.* 2016). The soil erodibility and the ground cover and conservation options are likely to be negatively impacted by drought. When factors other than rainfall are held constant, soil losses due to water erosion (or erosion risk) are directly proportional to the level of rainfall erosivity (Wischmeier and Smith 1978). Yang and Yu (2015) estimated an 8.5 % decrease in the rainfall erosivity in NSW from 2000 to 2012 compared with the baseline period (1961–1990) (Figure 6). The decrease in rainfall erosivity corresponds to a 15 % decrease in rainfall from 577mm/year in the baseline period to 490mm/year in the recent period.

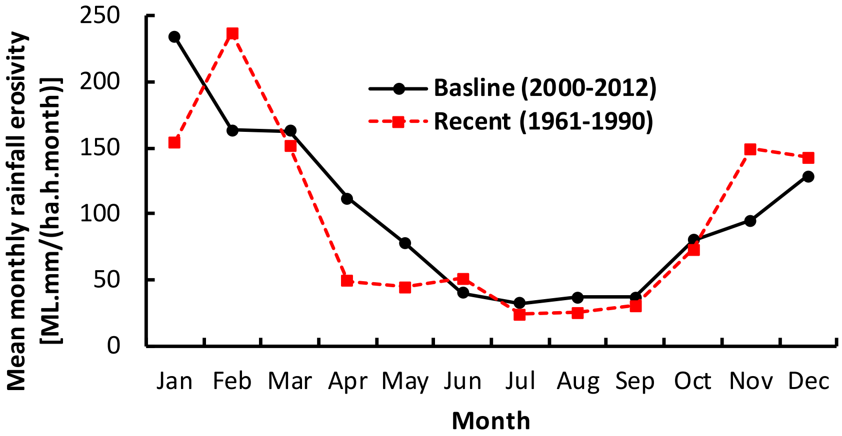

Figure 6. Monthly mean rainfall erosivity in New South Wales in baseline and recent periods. Source: Yang and Yu (2015).

Post-drought high intensity rain events can lead to dramatic surface soil loss which in turn can hugely impact the productive capacity of the soil. Such losses are irreversible and paddocks subject to the loss of fertile soil may take a long time to regain the same production level.

SOIL ORGANISMS

The soil biological environment contains microorganisms (Russell 1973) which have a varying response to drought, most often these include death or dormancy of the living components of the system (Lucci 2019). During periods of inadequate water availability, two main processes inhibit the functioning of soil microorganisms. As the soil dries, the water films coating soil particles become thinner and eventually discontinuous, and water is held more tightly to the aggregate surfaces and in smaller pores (Ilstedt *et al.* 2000), limiting the diffusion of substrates required by microbial populations. The type and extent of substrate, oxygen and moisture level influence the microbial activity in the soil (Figure 7) which has a varied impact on the nutrient cycling. Stark and Firestone (1995) found that in a silty loam soil, substrate limitation was the main limiting factor for the activity of nitrifying bacteria at the matric potential greater than -0.6 MPa, whereas when the matric potential decreased below -0.6 MPa, cell dehydration was the main factor. Griffin and Quail (1968) found that the movement of bacteria decreased rapidly when the diffusion pathway was disrupted at low matric potential. Wong and Griffin (1976) reported that bacterial movement ceased when the soil matric potential decreased from -0.02 MPa to -0.1 MPa.

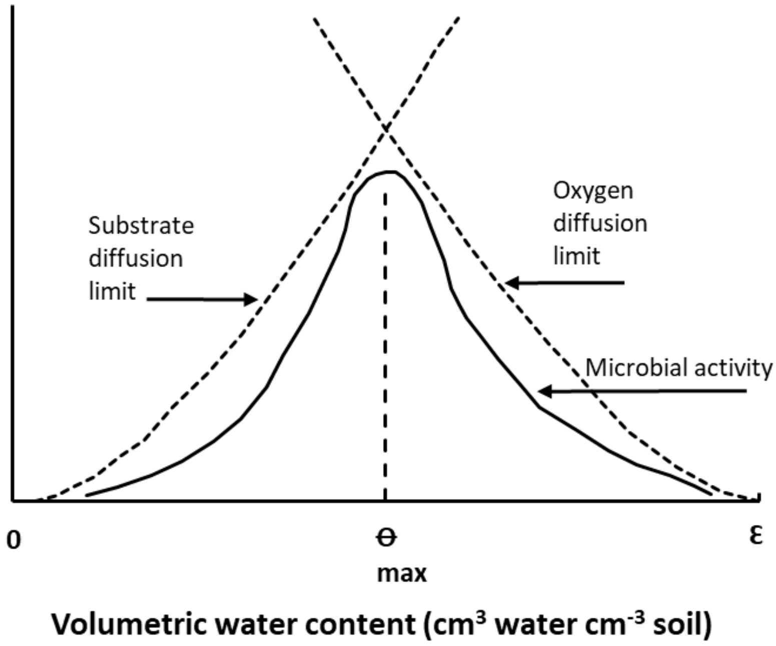

Figure 7. Generalized relationships among microbial activity, oxygen, substrate diffusion and soil water content. Source: Skopp *et al.* (1990).

If drying continues, the cell walls of bacteria can no longer maintain the osmotic water potential and may lyse (Griffiths *et al.* 2003). Although the exact relationships will vary for different microbial populations (and soil textures and intensity of drought), in general, a shift from temporary substrate limitation to irreversible physiological effects of dehydration will occur as drought severity increases. To counteract this, bacteria may synthesise ‘protective osmolytes’ to counter dehydration and maintain cell water potential. However, if drying is rapid they might not be able to synthesise osmolytes fast enough to keep up with the decreasing water potential outside their cells (Schimel *et al.* 2007). During unstressed conditions, Schimel *et al.* (2007) found that carbon and nitrogen in osmolytes make up 3–6 % of total cellular carbon and nitrogen. However, during extreme drought conditions, bacterial osmolytes may reach 30–40 % of total carbon and 60 % of total nitrogen. This is important because carbon and other nutrients released when cells lyse can be taken up by plants, used by other microorganisms, or lost via leaching upon rewetting. Moreover, the flux of nitrogen-solutes to maintain bacterial cell water potential can be 10–40 % of annual net nitrogen mineralisation in grassland systems (Schimel *et al.* 2007).

Severity of drought plays a key role in the responses of microorganisms in the soil. The effects of short-term drought on soil microbial communities remain largely unexplored, particularly at large scales and under field conditions because microbial communities adapt to moisture stress and show strong resilience when moisture stress is overturned. Microbial communities, particularly with high functional diversity, may be more tolerant to drought (and to other perturbations), but this tolerance is likely to be strongly associated with a range of biotic and abiotic features of the soil (Griffiths and Philippot 2013). Communities inhabiting grassland ecosystems showed particular resistance, suggesting they are well adapted to regular, seasonal fluctuations in temperature and rainfall often experienced in these areas (Griffiths *et al.* 2003; Waldrop and Firestone 2006; Cruz-Martínez *et al.* 2009).

Different types of microorganisms vary in their response to moisture stress. For example, fungi are generally detected in greater numbers than bacteria when soils are sampled during hot, dry periods in Australia (O'Sullivan *et al.* 2013) and in other comparable drought-adapted environments (Sher *et al.* 2013). Ochoa-Hueso *et al.* (2018) observed that drought significantly altered the community composition of soil bacteria and that the magnitude of the fungal community change was directly proportional to the precipitation gradient. Some species of fungi can grow optimally at higher temperatures (i.e. >35ºC) in arid soils (Hatzenpichler 2012). Vesicular-arbuscular mycorrhiza fungi often have positive effects on host plants due to fungal symbiosis during periods when the host plant is subject to stress due to drought (Augé 2000), salinity (Porcel *et al.* 2012), temperature (Braunberger *et al.* 1997), metals (Garg and Chandel 2011), and diseases (Baum *et al.* 2015). The vesicular-arbuscular mycorrhiza fungi can improve the water relations and increase the drought resistance of host plants (Davies *et al.* 1993; Sánchez-Díaz and Honrubia ; Davies *et al.* 1996; Subramanian *et al.* 1997). However, the extent of vesicular-arbuscular mycorrhiza benefits to plants largely depends on their community structure, crop species and/or genotype, soil characteristics, climatic and geographic context, and the interactions among these factors (Zhang *et al.* 2017; Tran *et al.* 2019). Most of the beneficial impacts have been realised in the studies under controlled conditions. In a field study, Ryan and Ash (1996) found that colonization of vesicular-arbuscular mycorrhiza on wheat roots was significantly reduced during drought suggesting that vesicular-arbuscular mycorrhiza fungi had no significant role in alleviating the drought stress experienced by the crop. Similarly, Thompson (1987) found that long fallow causes a decline in viable vesicular-arbuscular mycorrhiza fungi resulting in poor root colonization and symbiotic effects on a subsequent crop. Hence, many uncertainties about the response of microbial communities to water stress, though, remain contrary and unexplored.

NUTRIENT CYCLING

Nutrient cycling is defined as the transformation and movement of nutrients within and between the biotic (soil microbes and plant roots) and abiotic (soil solution and minerals) entities in the soil environment (Brady and Weil 1999). Carbon and nitrogen mineralisation are important nutrient cycling processes in soils, and they respond to water and heat stress differently. Many studies found that carbon cycling is altered in response to extreme weather events (Baldwin *et al.* 2015; Meisner *et al.* 2015; Liu *et al.* 2017) due to its impact on the microbial respiration (a proxy for soil organic carbon decomposition) and dependent on ecosystem type (Borken *et al.* 2006; Cleveland *et al.* 2010; van Straaten *et al.* 2010). Microbes exposed to drought periods may alter their rates of function due to physiological stresses, potentially changing the rate and pathways of carbon and nitrogen transformation (Schimel *et al.* 2007).

Hoyle and Murphy (2011) showed that as soil dries, nitrification occurs more quickly than other nitrogen-cycling processes, including mineralization. Generally, drought also enhances the inconsistency between microbial nitrogen mineralisation and plant nitrogen uptake, because microbes and plants differ in their sensitivity to water and heat stress (Collins *et al.* 2008; Schimel 2018). Consequently, water stress tends to reduce plant nitrogen uptake because of reduced demand, while nitrogen mineralisation processes including nitrification from the soil organic matter may continue at a high level during the dry season (Sullivan *et al.* 2012; Sher *et al.* 2013), leading to increased mineral nitrogen availability in soil.

The decomposition of incorporated residues (stubble or compost) and the subsequent mineralisation or release of ammonium appear less affected by seasonal changes in soil moisture (Schomberg *et al.* 1994; Coppens *et al.* 2007; Hoyle and Murphy 2011), allowing mineral nitrogen to accumulate in dry soils. If rainfall events occur when no crops are present, this mineral nitrogen pool may be quickly nitrified and lost from the system. Therefore, nutrients released from soil physical processes and the death of soil fauna can result in a net loss. However, nutrients released from the biological components that are dormant have the potential for reuse once revived post-drought.

NUTRIENT AVAILABILITY

Most Australian soils are inherently poor in fertility due to a low organic matter content and they need supplemental nutrient addition through chemical fertiliser for profitable crop and pasture production. Nutrient mineralisation and thus availability in the soil depends on moisture, temperature and microbial activity. Nutrient availability is also significantly affected by other soil factors including the concentration of the elements, soil type, clay per cent and clay type, organic matter concentration, and soil pH (Whitehead 2000; Bell and Dell 2008). Other studies report that climate, topography and soil properties are strong predictors of carbon mineralisation under different land uses and management regimes (e.g. Dalal and Mayer 1986; Badgery *et al.* 2013; Davy and Koen 2013; McLeod *et al.* 2013)). Soil texture, iron and aluminium concentration and clay mineralogy can also determine the extent to which soil organic carbon is decomposed (Baldock and Skjemstad 2000; Baldock *et al.* 2004).

Water stress and high temperature have an adverse impact on the extent, diversity and activity of the microbial community, which plays a key role in nutrient transformation in the soils. Van Gestel *et al.* (1993) indicated that up to 58 % of the total microbial biomass may be killed by soil drying and rapid rewetting. Turner *et al.* (2003) confirmed that lysed bacterial cells are the source of a large proportion of the increase in water-extractable organic phosphorus after soil drying. A portion of the microorganisms survive drying by accumulating cytoplasmic solutes that serve as osmoregulators in the cells. Upon rapid rewetting, the cells of some microorganisms will burst, caused by the influx of water into the cells, while others will survive by releasing intracellular solutes to maintain the proper cell turgor pressure and subsequently rapidly mineralise the compounds released by the dead microorganisms (Birch 1958; Halverson *et al.* 2000). Wiklander and Koutler-Andersson (1966) proposed three chemical processes that decrease phosphorus availability in dry soils. Drying would:

1. Increase the ion concentration in the soil solution, leading to phosphorus fixation.
2. Decrease the solubility of many compounds, including iron, aluminium and calcium phosphates, and
3. Induce oxidation, for example of Fe_2C to Fe_3C, which would lead to the formation of less soluble phosphorus compounds.

On the other hand, drying and rewetting in quick succession may result in the chemical breakdown of organic matter, thereby increasing phosphorus availability (Laura 1975). The physical changes induced by drying and rewetting can also have opposing effects. Disruption of bonds between organic compounds may increase mineralisation and thereby phosphorus availability, or aggregate breakdown may expose more phosphorus adsorption sites, which would decrease phosphorus availability (Raveh and Avnimelech 1978).

Under drought stress, nutrient uptake and translocation are also reduced due to a decreased rate of nutrient diffusion from the soil matrix to the absorbing root surface (Hu *et al.* 2007) and translocation to the leaves. A number of studies have shown a decrease in mineral accumulation and other physiological effects under water stress. Drought also causes stomatal closure, which reduces transpiration. The lower transpiration then limits nutrient transport from the roots to the shoot and can cause an imbalance in active transport and membrane permeability, resulting in a reduced ability of the roots to absorb nutrients (Hu and Schmidhalter 2005; Hu *et al.* 2007; Farooq *et al.* 2009). Therefore, drought causes low nutrient availability in the soil and lower nutrient transport in plants (Hu *et al.* 2007).

Nitrogen and phosphorus fertilisers are a key component of dryland grain production systems in Australia, where many soils have inherently low fertility (Perry 1992; Schwenke *et al.* 2019). Soil nitrogen supply is a major constraint for crop production and fertiliser nitrogen is usually necessary to attain profitable crop yields (Dimes *et al.* 1996; Schwenke *et al.* 2019). Low nitrogen recoveries have been explained by low nitrogen demand due to crop water stress (Myers 1978), and also by excessive rainfall resulting in significant leaching losses (Wetselaar 1967; Myers 1983). Drought can also affect the nitrogen cycle (as described above) through changes in soil nitrogen mineralisation, nitrification, ammonification, immobilisation, symbiotic nitrogen fixation (DeJong and Phillips 1982; Zahran 1999; Hungria and Vargas 2000), plant nitrogen uptake, and nitrogen loss (Homyak *et al.* 2017). Soil nitrogen content during the drought recovery period has a varied impact. Wetselaar and Norman (1960) studied the nitrogen supply following legume and grass ley systems at Katherine, NT, using conventional tillage methods. They found that the incorporated legume material was rapidly mineralised with the onset of seasonal rains but recovery of the mineralised nitrogen by fodder crops was limited (<50 %) because it was rapidly leached below the root zone. Similarly, applied phosphorus undergoes dissolution, diffusion and adsorption processes in the soil depending on the moisture level. About 70 % of the phosphorus applied became sorbed (fixed) onto soil particles (inorganic soil phosphorus) and 13 % became associated with the soil organic matter (organic soil phosphorus). Both of these pools ultimately contribute to increasing soil phosphorus reserves for future crops but the rate at which this happens can vary from weeks to years.

There is no universal understanding of the extent of phosphorus fixation in soils in relation to water stress because the phosphorus transformation depends on the number of factors described above. Even dry land conditions can either increase or decrease the residual value of fertiliser phosphorus for the next year's crop. Using phosphorus solutions (Bramley and Barrow 1992) and ground superphosphate (Bolland and Baker 1987) mixed throughout the soil, it was shown that air-dry soil conditions fixed inorganic soil phosphorus pools at a lower rate than where soils were maintained moist, because under moist soil conditions immobilising soil reactions proceed more rapidly. Indeed, the effectiveness of superphosphate for wheat growth applied and incubated in dry acidic soil was shown in glasshouse experiments to be similar to freshly applied superphosphate. Incubation in moist soil reduced phosphorus effectiveness (Bolland and Baker 1987). These experiments were undertaken with phosphorus mixed throughout the soil and hence were designed to measure the effects of soil moisture content on phosphorus adsorption. On the other hand, in calcareous soils, precipitation reactions of granular phosphorus can be enhanced in dry soil conditions. Fertiliser granules will dissolve because water vapour moves to the granule even when the soil is drier than field capacity, but as the phosphorus is present in a more concentrated solution in the soil this can promote precipitation reactions with calcium in or near the granule. This process does not appear to occur with fluid phosphorus fertilisers to the same extent and explains the better performance of fluid fertilisers compared to granular phosphorus forms in dry years (Holloway *et al.* 2001; Lombi *et al.* 2004). This means that in non-calcareous soils, less of the phosphorus applied in during drought would have been immobilised than in a more normal year (Reuter *et al.* 2007). The sorption/fixation processes may have been slower and perhaps confined to a smaller volume of soil. In calcareous soils, phosphorus losses through fixation are likely to have been unchanged or increased.

Review - Managing drought-affected soils

Managing drought-affected soils requires multiple technological interventions, which improve the long-term productive capacity and resilience of the soils against drought. The inherent goal for these technological operations is to mitigate the impact and enhance the soils' capacity against climate variability so that sustainable production can be maintained for a longer time.

It is pertinent to mention that the specific studies/reviews with a focus on 'soil management under drought' are scant and most of the literature on soil management focusses on long-term improvements of soil constraints for enhancing crop production. Therefore, we have targeted general soil improvement practices, which help manage soil efficiently, that are also highly applicable to drought conditions. We believe that most soil improvement practices such as structural improvement, erosion control, soil conservation, addressing subsoil constraints and fertility improvements developed over the years such as clay incorporation, tillage operations, fertiliser application, gypsum or liming, and compost/organic material addition could be the major contributors to mitigating the adverse impacts of drought and developing resilience in the soil. The ultimate goal for soil improvement should be to improve the soil's physical, chemical, biological and ecological condition, which has long-lasting impacts on the water holding capacity, fertility and biological health of soil including under drought, heat and climate change conditions. Rather than dividing the review based on improvements in soil attributes, we have discussed soil management based on the practices used to realise the overall goal of improved soil management.

CLAY INCORPORATION IN SOILS

Sandy and duplex (sandy or lighter-textured A horizon over a clayey B horizon) soils are widespread in the grain and pastoral regions of Australia where drought has comparatively more adverse impacts than in other regions. Plant growth on these soils is constrained by low water holding capacity, low fertility and water repellence (Schapel *et al.* 2017). Subsoil clay addition to sandy soil is a practice commonly used to overcome water repellence and improve water retention, fertility and plant productivity. Adding clay from the subsoil to sandy topsoil first occurred in the 1970s in south-east South Australia (Cann 2000) to overcome water repellence in sands (Ward and Oades 1993; McKissock *et al.* 2000).

Adding clay to sandy soils and clay incorporation is a complex and expansive exercise and the depth to clay-rich subsoil and the machinery available determines the appropriate amendment method (Davenport *et al.* 2011). The most common approach to ameliorate sandy soils is to add clay-rich material to the topsoil (Ward and Oades 1993; Cann 2000; Bailey *et al.* 2010; Hall *et al.* 2010; Betti *et al.* 2016), either by spreading or by delving (Cann 2000; Desbiolles *et al.* 2006; Hall *et al.* 2010; Davenport *et al.* 2011). Clay spreading is the only available option for deep sands where clay-rich subsoil is at more than 60 cm depth. Clay-rich subsoil is excavated from a nearby pit, spread on the surface and then incorporated. Delving is used where clay-rich subsoil is within 30-60 cm of the soil surface (Desbiolles *et al.* 2006) and purposely designed tines elevate the clay-rich subsoil into the sand above. After delving, elevated clay clods on the soil surface are spread using bars, dragging clay from the delve line into the area between delve lines (0.7–2m depending on machine design) and then incorporated using offset discs, spaders, etc. The area between delve lines is modified to the depth of incorporation but below this depth, the sand remains undisturbed. Spading can be used as a clay amendment method where clay-rich subsoil is within 30–40 cm of the soil surface. Subsoil clay is elevated and incorporated in one pass using specially designed 'spades' spaced 0.35m apart on a rotary axle (Davenport *et al.* 2011). While delving creates distinct areas of amendment, that is delve lines and areas between the delve line, clay spreading and spading result in a more uniform distribution of subsoil clay clods to the depth of incorporation. All clay amendment methods result in a mix of clay clods ranging in size from a few millimetres up to greater than 200mm (Schapel *et al.* 2019).

Davenport *et al.* (2011) suggested some important points to consider before clay application to soils:

- Assess the properties of the soil and clay to be added because the clay used for addition can vary significantly in the per cent of clay it contains. Characteristics of the clay to be assessed include clay per cent, pH, carbonate level and dispersion.
- It is best to avoid clay with a high pH, particularly when the target sand has a high or very high soil pH as this can increase the soil pH and cause nutritional problems in crops and pastures.
- Clay with a high level of carbonate should also be avoided as this can affect nutrient availability and plant root growth. High carbonate content can also reduce the availability of essential plant nutrients including phosphorus, manganese, zinc and iron.
- Where clays have a high pH or are calcareous, manganese and possibly zinc could be an issue on sensitive crops. Soil and/or tissue testing is recommended to determine plant nutrient levels.
- Clays that slake or disperse are ideal as they break down and spread quickly on the soil surface. However, when added at high rates, dispersive and slaking clays can form a crust on the soil surface, which if allowed to dry can set like concrete. Adequate incorporation is vital in these cases.
- Clay spreading/delving can alter both the nutrient status of the soil and the ability of the plants to take up nutrients. Nitrogen demand may increase with higher crop or pasture growth. Phosphorus levels may decrease slightly as the phosphorus levels in the clays are much higher than the topsoil.
- Red or black clays may provide additional nutritional benefits over other clay types. Rates of highly calcareous clays should be limited to prevent negative impacts on crop growth.

AMOUNT OF CLAY TO BE ADDED

The amount of clay to be applied will vary depending on the average annual rainfall, actual clay per cent, carbonate levels and depth of incorporation (Davenport *et al.* 2011). Rates may vary from 100 tonnes per hectare when using a high clay per cent or up to 200 tonnes per hectare when using subsoil with a low rate of clay or where the sand is deep and loose such as on top of sand hills. In the lower rainfall areas (<350mm rainfall) less clay should be used as it will tend to hold water in the topsoil rather than allowing water to move deeper into the soil profile. In these areas about 80-100 tonnes of clay should be applied per hectare. Davenport *et al.* (2011) suggested that the amount of dry clay-rich subsoil required to spread or bring to the surface can be approximately calculated using an equation:

$$t - ct \times (1400/pt) \times d/10 = clay\ t/ha$$

Where: *t* is target clay per cent, *ct* is starting clay per cent, 1400 is clay bulk density (based on an average bulk density of dry clay of 1.4 g/cm^3), *pt* is clay per cent of the subsoil material to be spread, and *d* is incorporation depth in centimetres.

Impact of clay addition to soil

Clay incorporation in sandy soil has shown a range of improvements including an improved resilience to drought conditions. The benefits include yield increases between 20–130 % (Cann 2000; Hall *et al.* 2010; Davenport *et al.* 2011), increased nutrient availability (Hall *et al.* 2010; Bailey and Hughes 2012), increased root growth (Hall *et al.* 1994; Bailey *et al.* 2010), increased water retention (Betti *et al.* 2015), decreased saturated hydraulic conductivity (Betti *et al.* 2016), and reduction in frost damage (Rebbeck *et al.* 2007). It results in significant changes in pH, cation exchange capacity, extractable macro and micro-elements (Rebbeck *et al.* 2007; Hall *et al.* 2010), increased root growth, increased organic carbon sequestration, and reduced nutrient leaching into the groundwater and reduced soil erosion. Subsoil clay addition to sandy soil may increase the soil organic carbon pool via improved plant growth resulting from increased nutrient and water retention. Hall *et al.* (2010) reported a 0.2 % soil organic carbon increase in the top 10 cm eight years after clay addition and Bailey and Hughes (2012) found a 0.4 % increase in soil organic carbon in the bleached A2 horizon up to seven years after adding subsoil clay. These studies indicate the potential for increasing soil organic carbon by adding subsoil clay to sandy soils. Schapel *et al.* (2017) showed that clay modification could increase soil organic carbon stocks (0–30 cm) by up to 14 t/ha in the south east of South Australia and 22 t/ha on the Eyre Peninsula (Table 3). However, delving was more effective in the south east of South Australia, while spading was a much superior treatment than others in the Eyre Peninsula (Schapel *et al.* 2017).

Table 3. Annual change in organic carbon stocks since clay modification in the South East and Eyre Peninsula of South Australia (Schapel *et al.* 2017).

Treatments	**Organic carbon stock**	**Increase in organic carbon stock**	**Number of years**	**Organic carbon stock change**
	(0–30 cm)*	**t/ha**		**t/ha/year**
South East				
Unmodified control	19.8	n.a.	n.a.	n.a.
Clay spread	33.5	13.7	9	1.5
Delved	34.0	14.3	9	1.6
Spaded	27.3	7.5	4	1.9
Eyre Peninsula				
Unmodified control	12.0	n.a.	n.a	n.a.
Clay spread	13.3	1.3	14	0.1
Delved	18.3	6.3	3	2.1
Spaded	34.5	22.5	3	7.5

*In soil mass of 5000 Mg/ha, n.a. = not applicable

The type of clay has a varied impact on the benefits of clay incorporation. For example, kaolinitic and illitic clays are more effective than smectitic or vermiculitic clays in alleviating water repellence (Ma'shum *et al.* 1989) as the kaolinite is spread more readily over sand grains and remains evenly distributed after drying (Ward and Oades 1993). Naturally dispersible illites and kaolinites underlie large areas of water repellent siliceous sand in South Australia (Ma'shum *et al.* 1989).

Although clay addition is a viable technique to improve the soil texture, structure, water and nutrient holding capacity and water transmission properties of soil, the level of improvement varies in different soils. For example, some clays that have high levels of salt and boron can produce poor results during the initial years until salt and boron levels are reduced by leaching. Therefore, clay addition may take a long time to realise the benefits. Moreover, the extent and severity of drought may delay the benefits of clay incorporation in the soils. There has been limited research on the implications of using clay with high levels of hostile elements (Davenport *et al.* 2011) and environments. Sometimes, over-claying could create a seal on the soil surface causing problems with crop emergence and water infiltration as well as problems with incorporation. As clay addition requires a large investment by farmers and can take many years to provide a return, the benefits and the timeframes may not match the investment, therefore, utmost care should be taken before going ahead with such intervention.

EROSION CONTROL MEASURES

Erosion control is one of the highest priority issues of land management in Australia. As the surface soil dries, it is loosened and more susceptible to being moved by wind. Different textures have different responses to erosion losses and require varied management options (Young *et al.* 2017). For example, clay addition can likely play a pivotal role in reducing the losses by erosion (Table 4), however, there is a lack of scientific data on the extent of erosion control following these practices.

Table 4. Erosion control measures based on soil type (Young *et al.* 2017).

Soil Type	**Treatment**
Sandy, loamy sand, clayey sand >1 m depth	Do nothing – avoid disturbing soil in any way. Import clay; spread, level and incorporate into topsoil (clay spreading).
Sand over clay – clay within 1 m of surface	Remove surface soil to expose clay; extract clay; spread, level and incorporate into sand (clay spreading).
Sand over clay – clay within 60 cm of surface	Rip into clay layer; bring clay to surface; level and incorporate (delving).
Sandy loam to heavy clay	Rip or cultivate to leave clods on surface.

In sandy-textured soils, when the clay content in the soil is <20 %, control measures include roughening the soil surface and adding and incorporating clay into the surface soils. The main goal of these practices is to slow down and break up wind flow (which in turn has less of an abrasive impact on the soil surface) and help in the formation of aggregates which increases the resistance to wind erosion. Clay addition can also have long-term benefits such as improved water holding capacity and fertility status. Water repellent soils (often sandy soils with clay content <3 %), are prone to surface dryness and makes them more susceptible to erosion. As described above, the use of clay spreading and delving practices for managing water repellent soils is becoming a significant factor in the protection of soils from wind erosion (Unkovich *et al.* 2020).

In duplex soils with clay at shallow depth, a single tine ripper can be used to create a deep furrow with high cloddy ridges, which can act as a preventative measure for erosion control. Rip lines can be spaced 10 – 20m apart and on sloping land are contoured to reduce the risk of water erosion. Strips of rough cultivation can break up wind sweep across bare, open areas and are often used after clover harvesting or stone picking. On very clayey soils, one cultivation should be sufficient to reduce wind erosion and provide protection until enough rain falls to stimulate plant growth (Table 4). However, the rough condition of the soil will make it difficult for spraying and seeding operations so some form of levelling (e.g. rolling) might be required. The ridges and clods on less clayey, cultivated soils will slump and furrows will fill with soil over time. Consideration will need to be given as to whether these soils should be cultivated again, based on the likelihood of windy weather and rain.

It is widely recognised that traditional, long-term cultivation practices, particularly soil tillage, promote wind erosion by destroying macro-aggregates (Elliott 1986; Singh and Singh 1996) and accelerating organic carbon mineralisation (Li and Chen 1998). Where land is eroding, a cultivator to work strips of land or the whole area might be required. Cultivation should aim to make the soil surface as cloddy as possible. Digging below the usual tillage depth and travelling very slowly will bring more lumps to the surface. Working at normal tillage speeds tends to break clods up more and create more dust. Therefore, minimum or no tillage is an important management option for erosion control. Discussion around these practices is included in the Conservation Tillage section of this review (page 56).

Stubble or trace mulching is a beneficial practice for reducing erosion losses. Essentially, the presence of any kind of vegetation or stubbles reduces the wind velocity, water erosivity and helps bind soil particles, which are more resistant to erosion. For example, Giles *et al.* (1998) compared different on-farm conservation and conventional tillage practices for erosion control on the Eyre Peninsula during 1994 (drought year) and 1995 (normal rainfall) (Figure 8). During drought conditions, conventional stubble management and burning resulted in the highest net soil loss consistent with low surface cover levels (20 %). It appears these management practices which retain adequate stubble cover (>20 %) in combination with reduced tillage (one cultivation prior to sowing) can provide protection when seasonal conditions are not particularly adverse. However, under severe conditions (such as 1994) even stubble management treatments can still suffer considerable soil losses. Direct drilling using zero-tillage seeding implements (narrow points or discs) with full stubble retention (light grazing only) would ultimately provide the best soil protection under more extreme seasonal conditions. The mechanical fallow paddocks were not worked again during autumn due to dry conditions, and the remnants of summer weeds which comprised much of the surface cover proved particularly resistant to being dislodged by the gale force winds. In 1995, a grazed pasture paddock that was scarified and harrowed just five days before the first major wind event had about 10 times higher soil loss (0.414 t/ha) than other pasture paddocks.

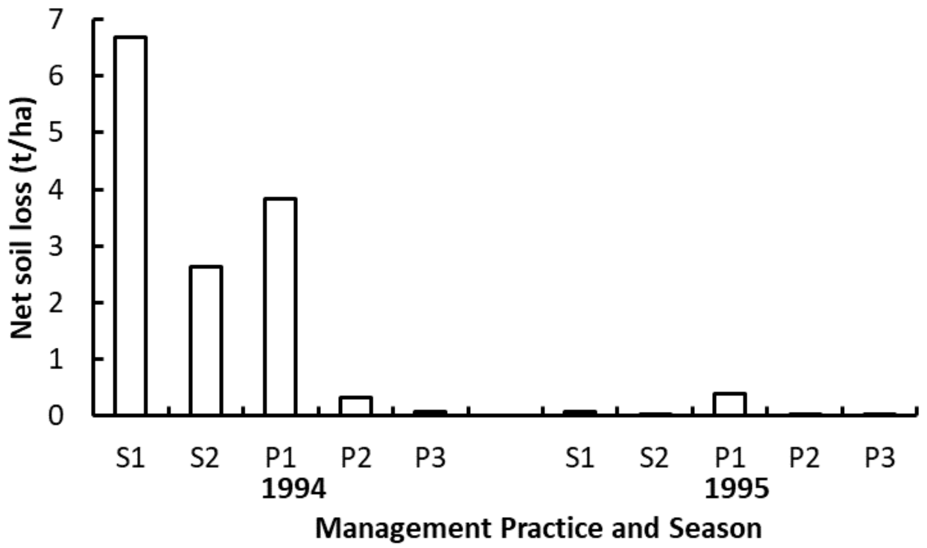

Figure 8. The impact of different stubble management practices in cropping and pastures on net soil loss during seasons with drought (1994) and normal rainfall (1995) (Giles *et al.* 1998). Treatments: S1-harrowed and burnt; S2-grazed; P1-short disced fallow; P2-chisel ploughed short fallow; P3-chemical fallow.

Many farmers are practising no-till or zero-till farming. The most difficult matter to decide is whether to minimise disturbance of the soil as much as possible by cultivating sparingly in strips, or to roughen the whole area by cultivating it all.

McTainsh *et al.* (2011) highlight the key features of better farming systems which help reduce soil erosion:

- Maintaining adequate plant residue cover for soil erosion protection by adopting stubble retention systems.
- Adopting minimum/zero tillage systems that have the dual aims of erosion protection and soil structure maintenance/improvement.
- Avoiding cultivation in high erosion risk periods.
- Reduction in burning stubbles.
- Using chemical fallowing rather than tillage.
- Integrated feral fauna and flora control programs, including biological controls.
- Fencing to land class through a developed farm plan.
- Retaining tall perennial vegetation on paddock boundaries.
- Avoiding grazing erosion-prone areas by fencing these areas.
- Intensive strip grazing/cropping.
- Land reclamation of degraded areas for both production and conservation uses.
- Involving agricultural commodity industries to promote better land management practices.

In pastures, stock management is very important to reduce erosion impact and soil degradation. Confinement feeding allows stock to be removed from paddocks before surface cover declines below critical protective levels. The highest risks associated with grazing occur in late summer and autumn when feed availability and the cover of annual crop and pasture residues is declining. Adopting more sustainable land management practices, such as no-till sowing and stubble retention, improves the protection of soil from erosion. No-till sowing involves sowing the seed in a narrow slot in the soil to minimise soil disturbance and maximise residue protection on the soil surface.

CROP AND PASTURE CULTIVATION

Keeping the soil covered with vegetation is the most important soil management strategy to reduce drought impacts, control erosion and increase productivity. It also helps build soil structure and carbon. Most of the crops in southern Australia are grown as part of a ley pasture–crop rotation where the pasture phase provides species diversity and has the well-documented role of maintaining soil fertility (Greenland 1971).

Different crops have a varied impact on soil structure. For example, numerous works (Clarke *et al.* 1967; Tisdall and Oades 1980; Baldock and Skjemstad 1999) showed that growing ryegrass could improve water stable aggregates (>2mm) on the surface soil of a red-brown earth but that the subterranean clover was not effective in improving aggregation. This was attributed to the low carbon to nitrogen ratio, which meant the clover roots were rapidly decomposed while the fibrous root system of the grasses persisted and promoted aggregation. The improved aggregation led to increased infiltration in the surface soil. Later on, Tisdall and Oades (1980) added that the results did not apply to soils where binding agents such as calcium carbonate and hydrous oxides of aluminium and iron were responsible for the stability of soil aggregates. In soils high in clay, aggregates are bound by the electrochemical effects of the clays and the interacting exchangeable cations. The plant roots, fungal hyphae and soil organic matter will have a lesser, but still important role in the stability of soil aggregates. Therefore, structural improvement can enhance the capacity of soil for better adaptation during water stress.

A feature of Australian cropping systems is the rotation of crops with legumes as an alternative to high inputs of nitrogenous fertilisers. There has been a significant trend towards continuous cropping with grain legumes such as lupins (*Lupinus* spp.), field peas (*Pisum sativum*), and faba beans (*Vicia faba*) included in the rotation in place of legume pastures, which brings numerous benefits for better soil management. Farmers in Victoria listed the following advantages of using grain legumes: addition of nitrogen (77 % of farmers surveyed); improvement of soil structure (56 %); benefit to next crop (27 %); good prices (20 %); weed and/or disease break (19 %); and good stock feed (14 %) (Cary *et al.* 1989). The benefit of legumes to the next crop is difficult to quantify and seems to depend on the soil nitrogen status, activity and rate of conversion of atmospheric nitrogen to plant available form by the symbiotic bacteria and the ability of the next crop to use it. Similarly, there was no difference between wheat yields after legume-fallow and fallow-fallow on higher nitrogen soil (0.194 % total soil nitrogen) (Jessop and Mahoney 1985). In a sandy soil in Western Australia, the average wheat yield advantage of a lupin-wheat rotation over wheat-wheat was 0.35 t/ha (Rowland *et al.* 1988). Schultz (1995) studied the long-term (1978–1993) impact of tillage, stubble mulch and nitrogen application in different crop rotations on soil properties and crop yields at Tarlee, South Australia. The best wheat yields were always in rotations that included a grain legume or legume pasture, with additional yield increases in all rotations when nitrogen fertiliser was used. By comparison, the effect of stubble retention or tillage treatments on grain yield was small and outweighed by the positive impacts of including legumes in the rotation or applying nitrogen fertiliser. There was a tendency for grain legume yields to decrease over the latter years of the trial—this was attributed to the build-up of plant diseases from growing the same species on the same plot every second year. Overall, the crop production data from the Tarlee rotation trial showed that grain yields can be maintained in continuous cropping rotations that include grain legumes. Researchers in various parts of Australia (e.g. Strong *et al.* 1986; Rowland *et al.* 1988; Silsbury 1990; Evans *et al.* 1991; Rowland *et al.* 1994) have examined wheat responses after grain legumes and the effect of applied nitrogen. These beneficial impacts of tillage and nitrogen application, apart from increasing productivity, also guard against water stress and high temperatures.

Cropping deep-rooted species that reach deeper into moist soil layers have been suggested as a drought mitigation option (e.g. Kemp and Culvenor 1994; Skinner *et al.* 2004). Although the main uptake of soil water and nutrients in drought-stressed, intensively managed grassland occurs within the most superficial soil layer down to 30 cm (Hoekstra *et al.* 2015; Prechsl *et al.* 2015), forage species could increase resource uptake by short-term root growth during a drought, as indicated by increased root biomass (Dreesen *et al.* 2012) or a higher proportion of root biomass at deeper soil layers under drought conditions (Wedderburn *et al.* 2010). Such evidence comes mainly from rhizotrons or container experiments and root growth data from forage species in the field is rare (Prechsl *et al.* 2015).

Rotations of crop species that host different soil-borne pathogens and insects reduce the need for pesticides, which reduces costs and the risk of crop contamination. In the absence of disease, the crop can take advantage of any extra nitrogen, improve its water use efficiency and increase yields. For example, in a red duplex soil in South Australia, Rhizoctonia infection of wheat and barley (*Hordeum vulgate*) nodal roots were less after legumes (lupins, field peas or beans) (mean 10 % of roots infected) than after continuous wheat plus 30 kg/ha nitrogen (14 % infected) and after grass-dominant pasture (15 % infected). Reduced infection and higher nitrogen after grain legumes gave an average wheat yield increase of 0.7 t/ha compared with wheat after pasture (King 1984). Additionally, the impact of moderate drought on crop productivity may be reduced by adding soil nutrients (Saneoka *et al.* 2004; Gimeno *et al.* 2014), although, it is unclear whether adding soil nutrients may play a significant role in reducing crop loss under severe water limitation.

CONSERVATION TILLAGE

Conservation agriculture practices are associated with reduced or no soil disturbance. Reduced tillage refers to any conservation system that minimises the total number of primary and secondary operations associated with seed planting relative to conventional tillage (Baker *et al.* 2007). Conservation tillage practices help improve soil structure, water holding capacity and soil fertility status which reduces the effects of drought.

FAO defines conservation tillage as a system that leaves at least 30 % residue cover on the soil surface to minimise surface run-off and soil erosion, reduces aggregate detachment and surface sealing and crusting, improves soil functions, and sustains crop production (Hoare 1992). While the 30 % residue cover may be appropriate for some soils, it is insufficient in others to reduce soil erosion to permissible levels. The optimum conservation system should have enough vegetative cover or crop residues to increase soil surface roughness and improve the infiltration capacity. A conservation tillage system must be matched to each soil based on site-specific criteria (e.g. farm profitability, severity of soil erosion, soil type, topography, and climate). The amount required varies according to soil type and erosion risk. For example, Mallee soils such as those at 'Greenacres' require approximately 0.5 to 1.0 t/ha of plant material for protection from erosion (Speedie 1980).

Numerous studies have reported that the adoption of minimum and no-till farming practices enhanced soil porosity and aggregation (Chan and Mead 1988; Carter and Steed 1992; Hobbs 2007) and increased microbial processes (Tisdall 1991), leaving a more friable soil surface profile making it easier to sow a crop. This improved soil texture reduces the shear force needed to move tyned implements through the soil. As soil structure is dependent on organic binding agents produced by soil microorganisms (Tisdall and Oades 1982), reduced soil disturbance and increased organic matter under direct drilling and stubble retention are likely to lead to an improvement in soil structure over time (Hamblin 1980). Organic matter provides food for soil fauna, such as earthworms, whose tunnels form stable pores for the passage of air and water.

Aggregate formation is an important process for building good soil structure. Somasundaram *et al.* (2017) found that water stable aggregates were not affected by tillage and stubble management. On the contrary, Carter and Mele (1992) showed a significant increase in aggregate stability under conservation tillage, especially for 2–10mm sized aggregates. These improvements in aggregates stability were reduced by standard wet sieving or the use of a dispersion test; which illustrated the fragile nature of these aggregates developed under cropping systems. Cultivation impedes the formation of aggregates by restricting the oxidation of organic carbon (Tisdall *et al.* 1978; Tisdall and Oades 1982); stimulating the microbial breakdown of organic binding agents and physically breaking bonds (Tisdall 1991), and reducing the populations of soil fauna which are unable to retreat down the profile (Greenslade and Greenslade 1983).

Although direct drilling gives long-term benefits to soil structure, several short-term disadvantages for crop growth have been identified. Soil strength at the top of the profile is often higher than in cultivated soil, restricting the root growth and water use of direct drilled crops. For example, direct drilled wheat in a loamy sand in Western Australia had lower water use (1.78mm water/day) compared with cultivated wheat (2.30mm water/day) (Hamblin and Tennant 1979; Hamblin *et al.* 1982). The differences in soil strength may become more marked as the soil dries out. At field capacity the soil strength of a direct drilled red earth was twice that of cultivated soil, rising to seven times as much when the soil was at permanent wilting point (Cornish and Lymbery 1987). Mineralisation of soil nitrogen may be slowed without cultivation, affecting grain yield and quality, particularly in low fertility soils. Direct drilled wheat on a yellow Podzol near Canberra had lower yields and nitrogen content (2.05 and 2.26 % nitrogen) than cultivated wheat (2.30 and 2.52 % nitrogen) (Gates *et al.* 1981). Although there is more water available to direct drilled crops at the end of the growing season (Cornish and Lymbery 1987), insufficient root growth and dry matter accumulation early in the season can prevent the crop from taking advantage of this. For example, nil fallow, direct drilled crops where rainfall was 425–450 mm/year yielded 10–20 % less than cultivated crops owing to poor early growth (Mason and Fischer 1986; Fischer *et al.* 1988).

The type of crop residue influences the rates of decomposition and mineralisation of organic nitrogen. Wheat straw was shown to decompose more slowly than legume (*Trifolium subterraneum* and *Medicago littoralis*) tops (Amato *et al.* 1987). Long-term stubble retention with reduced soil disturbance should gradually build up a population of organisms specialising in stubble decomposition. This will increase the rate and extent of stubble breakdown before sowing. Even with minimum cultivation, some stubble will be incorporated into the soil. Contrarily, the high carbon to nitrogen ratio after stubble incorporation produces bacterial immobilisation of nitrogen which may affect germination and early crop growth. Maximum nitrogen immobilisation occurs during the first three weeks to three months after incorporation (White *et al.* 1986). Therefore, less nitrogen will be available to plants after a short fallow or if stubble is incorporated close to sowing.

Increasing adoption of conservation agriculture has been driven by benefits to ecosystem services including climate change and drought mitigation, through increased carbon sequestration and/or reduced carbon dioxide emissions from soil (Wang and Dalal 2006; Palm *et al.* 2014; Somasundaram *et al.* 2017; Reeves *et al.* 2019). Ugalde *et al.* (2007) found that soil managed using conservation tillage has retained up to 25 % more carbon than conventional tillage practices over the past century under continuous cropping. Stubble retention also enhances biomass carbon inputs into the soil and reduces the decomposition and removal of biomass carbon from cropping land (Schlesinger 1999; Lal *et al.* 2007). Other benefits of conservation tillage include (Ellington and Reeves 1978; Cary *et al.* 1989).:

- Reduced land preparation time.
- Improved timeliness of sowing and a greater area of crop sown within a given time.
- Better soil trafficability in wet conditions.
- More land available for grazing prior to sowing.
- Reduced requirement for machinery, capital, labour and energy.
- Improved soil structure from less compaction and increased organic matter close to the surface.

Many Australian grain farmers are now well versed in the nature and benefits of conservation tillage, i.e., seeding with no prior cultivation. From the 1980s onwards, there was a rapid and widespread adoption of conservation tillage practices. The adoption rates for no-till practices across the grain growing areas of south-eastern and south-western Australia has surpassed 90 % (Llewellyn *et al.* 2012). There is evidence to suggest that the wide-scale adoption of no-till and other conservation agriculture practices has had a marked effect in reducing soil erosion in the cropping zones. For example, net soil erosion (1990–2010) in south-eastern Australia declined on average from −9.7 ton/ha/year to +3.9 ton/ha/year (Chappell *et al.* 2012). Conservation tillage has likely gone part of the way to reducing levels of soil erosion in cropping areas, but soil erosion has not been eradicated. Estimates that show a regional decline in soil erosion between 1990 and 2010 also show considerable spatial variability, indicating that many sampled locations have not greatly reduced soil erosion, most notably in the Mallee region (Koch *et al.* 2015).

DEEP RIPPING

Deep ripping aims to shatter compacted layers that prevent or reduce crop root penetration to deeper layers. Soil compaction mainly caused by heavy machinery is a widespread constraint to root growth (Dzoma *et al.* 2020). Other constraints that may occur simultaneously on sandy soils include water repellency, acidity and subsoil constraints such as sodicity. These limitations can potentially reduce the capacity of soil for sustainable crop production. Deep ripping is the most effective treatment to loosen compacted subsoils and allow roots to access soil moisture and nutrients at depth (Dzoma *et al.* 2020). The mechanical breakup of both surface and subsoil layers decreases bulk density and soil strength, increases total porosity, hydraulic conductivity, plant available water capacity, nutrient supply and microbial activity (Jayawardane and Chan 1994; Bell *et al.* 1997; Valzano *et al.* 2001; Hamza and Anderson 2005; Dzoma *et al.* 2020). Therefore, deep ripping is an excellent management approach to mitigate drought impact—especially for compacted sandy-textured soils—however, responses on other soils are often smaller and less frequent (Paterson and Sheppard 2008).

Deep ripping and crop yield

Ripping has a favourable impact on soil, with cereal yield increases of 22–37 % in the first year (Crabtree 1989; Anderson and Garlinge 2000). Soil type and depth have an impact on the effectiveness of ripping. Isbister *et al.* (2018) reported that responses to deep ripping in Western Australia were greater in sandy soils (20–37 % yield increase) than in loamy duplex soils more than 30 cm deep (22 %) or shallow duplex soils (4 %). Similarly, at Loxton and Caliph in South Australia, crop yield responses to ripping to 0.6m were greater on sands than on adjacent finer-textured soils, reflecting a shallower depth to high penetration resistance (15 cm for sands compared to 30 cm for finer-textured soils (Sadras *et al.* 2005)). Deep ripping is not recommended for all soil types; for sodic clays prone to dispersion, ripping is often detrimental to crop growth (Isbister *et al.* 2018).

In recent experiments conducted in Western Australia (Davies *et al.* 2017) from 2014 to 2016, ripping increased average wheat yields by 8 % for shallow ripping (30–40 cm), 35 % for ripping to depths of 50 cm or more, and 53 % for deep ripping with topsoil slotting. In other instances, deep ripping has boosted the production of crops on deep yellow sands (Hamblin *et al.* 1982; Delroy and Bowden 1986) and duplex soils (Hamza and Anderson 2005) by lowering soil strength and increasing root growth and water use in the subsoil. trial across the South Australian northern and southern Mallee, and the upper Eyre Peninsula conducted during the 2018 and 2019 cropping season on sandy soil revealed that deep ripping increased wheat yields by up to 135 % for shallow (20–40 cm) ripping, and up to 235% for deeper ripping to depths of 50 cm or more (Dzoma *et al.* 2020). Barley grain yield also showed an increase of up to 93 % for shallow (20–40 cm) ripping, and up to 193 % for deeper ripping (50 cm or more). There was a consistent trend of increasing grain yield with increasing ripping depth across all sites (Figure 9), but the deepest ripping treatment (70 cm) achieved the highest yield. Similar grain yield improvements with deep ripping (+60 cm) were previously reported at Waikerie (McBeath *et al.* 2018). Similar results of improved grain yields with deeper ripping have been reported by several authors (Davies *et al.* 2017; Isbister *et al.* 2018; McBeath *et al.* 2018; Moodie *et al.* 2018; McBeath *et al.* 2019). However, it is important to note that the highest yielding treatment does not necessarily translate to the most profitable and most sustainable tillage strategy. In addition, the optimum depth of ripping will depend on the depth of the compaction.

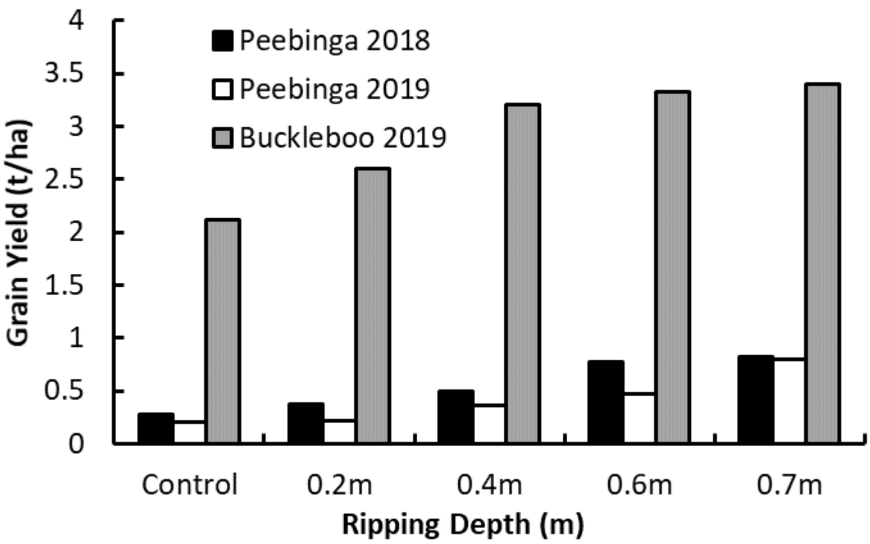

Figure 9. Cereal grain yield (t/ha) following ripping at Peebinga (2018, 2019) and Buckleboo (2019), Eyre Peninsula, South Australia. Source: Dzoma *et al.* (2020).

In ripped soils, crop transpiration accounted for a greater fraction of evapotranspiration than in unripped control plots and thus crop biomass and grain yield were higher following ripping (Sadras *et al.* 2005). There is some quantitative evidence that increased growth of crops following ripping results from the extraction of additional soil water which is otherwise unavailable (e.g. Holloway and Dexter 1991; Sadras *et al.* 2005). For example, Sadras *et al.* (2005) demonstrate 17mm more available water on a ripped sand hill at Loxton compared to an adjacent crop (wheat) on an unripped soil. Ripping increases root penetration in soils, giving access to a greater volume of soil and soil water if it is available. The legacy of the ripping will depend on the frequency of soil profile rewetting and the relative dependence of the crop on that fraction of the soil water, although the general experience has been that the effects are only apparent for one to three years (Paterson and Sheppard 2008). Improving the longevity of such treatments would be beneficial; but this may need a better understanding of the relative importance of machinery induced compaction, natural settling of sand and associated soil cementation, or soil fertility as possible contributors to poor root penetration. It is important to note that because the rainfall amount, intensity and distribution varies each year in Australian pastoral regions more than other in cropping regions in the world (Ray *et al.* 2015), there will be strong interactions between season (year) and the response to deep soil amelioration treatments.

Ripping with the use of ameliorants and nutrients

Under sodic soil conditions, deep ripping alone may not produce desirable outcomes. In a trial at Minnipa, Holloway and Dexter (1991) observed that deeper tillage with a chisel plough had no measurable effect on water use, root growth or grain yield. The ripping reduced soil strength to 30 cm but did not have an effect at the normal tillage depth (15 cm). Without ameliorating the chemical constraint (sodicity) the favourable impacts from physical manipulation (ripping) are unlikely to be realised (Rengasamy *et al.* 1992). Whenever mechanical disturbance is employed to treat subsoil sodicity, the subsequent stabilisation of soil structure via the addition of gypsum or other ameliorants is essential to maintain structural improvements and prevent soil from re-dispersing (Hamza and Anderson 2005; Adcock *et al.* 2007). Where amelioration is not applied, limited or no yield benefits are generally observed (Coventry *et al.* 1987; Dang *et al.* 2010; Hulugalle *et al.* 2010). In addition, when deep ripping is conducted, ameliorants need to be applied using slotting equipment in order to effectively mix them at depth

(Jayawardane and Blackwell 1985; Kirchhof *et al.* 1995; Oster and Jayawardane 1998). Slotting involves mixing ameliorants and soil in narrow (15 cm) parallel bands, and is much more effective at moving ameliorants into subsoils than application during ripping operations (Kirchhof *et al.* 1995). Recent advances in machinery have enabled the incorporation of slotting equipment into deep rippers to allow ripping and slotting to be carried out simultaneously (Anon 2009).

Deep tillage, with combinations of nutrients, organic matter, ameliorants or clay additions could play a role in ameliorating multiple constraints on sandy soils but as with any soil amelioration strategies they must be ground-truthed to ensure they are ready for adoption (Orgill *et al.* 2018). For example, deep ripping with lime application has a variable impact on soil properties and dry matter production of wheat (Figure 10). Although deep ripping increased water extraction by wheat by an average of 8mm during a drought season, it had no effect on water use in a wet season (Steed *et al.* 1987). Coventry *et al.* (1987) observed a significant impact of ripping and lime. The major effect of ripping was to increase the water use in winter from below the ripped zone (40 cm) compared with the un-ripped treatment. Lime, either with or without ripping, had no significant effect on crop water extraction. Sorptivity, a measure of infiltration, was increased by ripping alone and by ripping plus lime. Soil resistance was reduced by deep ripping; an effect which had persisted at least 30 months after the last ripping operation (Figure 10).

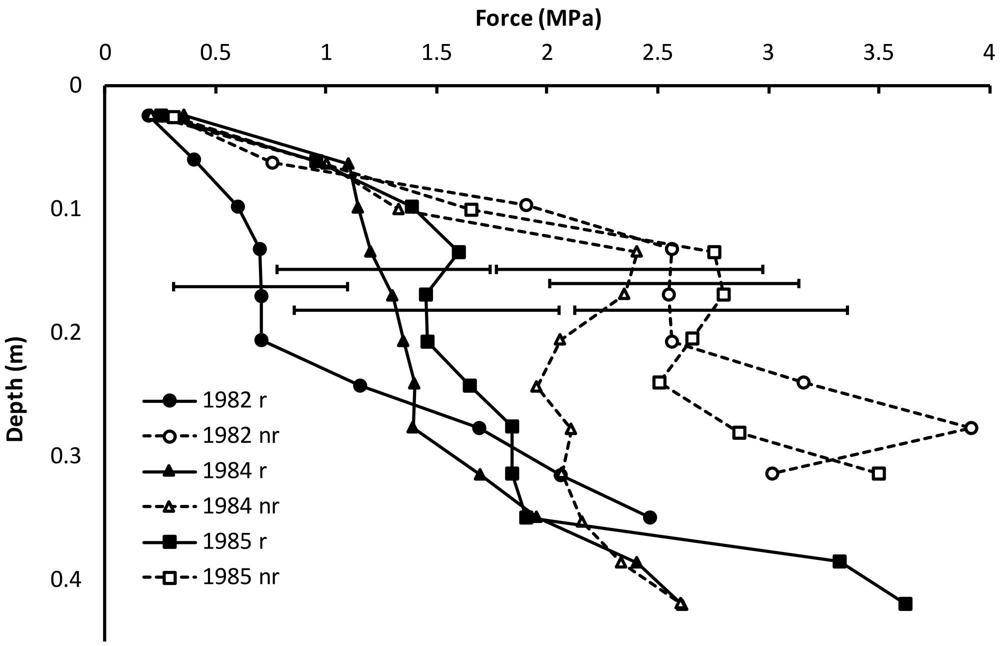

Figure 10. Penetrometer resistance (MPa) with depth for ripped and not ripped treatments (r = ripped, nr = not ripped). Source: Steed *et al.* (1987)

In an alkaline soil, Nuttall *et al.* (2005) observed that deep ripping with the equivalent of 7.5 t gypsum/ha did not reduce subsoil exchangeable sodium per cent or increase the yield of either wheat or barley over the time frame of their experiment. This lack of response is consistent with other studies on alkaline soils in the southern Mallee where deep ripping and gypsum failed to increase wheat yields. Nuttall *et al.* (2005) concluded that root growth was impeded by a hardpan, but the subsoils were chemically more benign than the Calcarosol considered in the experiment. Overall, this emphasises that the effectiveness of deep ripping with gypsum is soil specific.

Performance evaluation of deep ripping

The effectiveness and longevity of deep ripping depend on many site-specific soil parameters including soil texture, soil depth, degree of compaction, type and amount of clay in the soil, subsoil sodicity and other chemical properties of the soil. Davies and Lacey (2009) reported that deep ripping with tines spaced at 30 cm resulted in a significant increase in early and late shoot dry matter stage of wheat, but this benefit did not carry through to grain yield. It signifies that deep ripping has the potential to promote early biomass growth but in moisture-limited environments, one of the greatest potential downsides associated with deep ripping is that it increases the risk of 'haying off' when soil water reserves are low and the finish to the season is dry (Farre *et al.* 2008; Davies and Lacey 2009). Other studies found that deep sandy-textured soils are more responsive to deep ripping than finer-textured soils (Farre *et al.* 2008; Paterson and Sheppard 2008). On duplex soils, it is likely to only be effective when the clay B horizon is hospitable for root growth, although topsoil slotting has had success on duplex soil with sodic B horizons (Blackwell *et al.* 2016). Similarly, variable responses to deep ripping have been found on sandplain soils which can be related to several factors including crop type (Jarvis 1994), seasonality of rainfall (Henderson 1991), and thickness of the sand layer (Crabtree 1989). Crabtree (1989) found that depth of sand explained 63 % of the variation in grain yield response to deep cultivation, with duplex soils having >0.3 m sand over clay being the most responsive to ripping. Hall *et al.* (2010) found that the effect of ripping was diminished to a depth of 0.2 m one year after the treatment was applied and yield increases were apparent for three years after ripping. Therefore, deep ripping has a variable potential to improve soil conditions and enhance crop productivity, but there is a risk of low returns in low rainfall seasons (Dzoma *et al.* 2020). Essentially, deep ripping does not drastically change or mix the soil surface, though this can depend on the type of ripper used and surface soil texture, which means that deep ripping can have limited long-term benefits on the topsoil.

Soil amelioration by deep ripping is costly, so it is necessary to have significant and long-term benefits to achieve a good return on investment. Dzoma *et al.* (2020) reported that better returns are achieved when deep ripping is achieved below 60 cm. However, narrow tine spacing and going deeper than 60 cm may not give the best economical return in the first year because the yield gain and extra income may not outweigh the extra cost of ripping. The marginal benefits with ripping to 70 cm in the second year improved by more than 100 %, compared to shallow ripping. Therefore, the challenge that growers face is refining how best to ameliorate compacted soils at a reasonable cost, but at the same time maximising and prolonging the benefits.

The impact of deep ripping and application of ameliorants in the soil are site-specific and depend on soil texture and the nature and extent of subsoil constraints. The amount that growers are prepared to pay for radical amelioration options might be contingent on the present value of the land asset and the fraction of an individual field which is affected. More disruptive amelioration techniques (deep ripping or inversion tillage with or without the addition of ameliorants) are likely to affect water repellency, root penetration, water uptake and crop nutrition in complex ways and managing these multiple elements is a challenge.

SOIL ORGANIC MATTER AND ITS IMPROVEMENT

Soil organic matter is made up of decomposed plant and animal material as well as microbial organisms but does not include fresh and un-decomposed plant materials, such as straw and litter, lying on the soil surface. Soil organic carbon is the carbon associated with soil organic matter. Soil carbon can also be present in inorganic forms, e.g. lime or carbonates in some soils in drier regions. In Australian soils, total organic carbon is usually less than 8 % of total soil weight (Spain *et al.* 1983) and under rainfed farming it is typically 0.7–4 %. However, there is little quantitative evidence to support a specific threshold of soil organic carbon below which soil is considered to be of low productive capacity or degraded (Loveland and Webb 2003). Kay and Angers (1999) reported that when organic carbon in soil is below 1 % (e.g. sandy soils), soil health may be constrained and yield potential (based on rainfall) may not be achieved. However, Greenland *et al.* (1975) and Geeves (1995) reported that concentrations of soil organic carbon of <2 % are viewed with concern for many temperate zone soils used for agriculture, as these levels have been associated with severe soil structural deterioration and soil-based impediments to plant productivity.

In Australia, organic carbon stock in soils varies greatly across the continent (Minasny *et al.* 2017), ranging in the surface 30 cm from less than 10 t/ha in arid regions to 250 t/ha in cooler and wetter regions in natural ecosystems (Luo *et al.* 2010). Rapid changes in soil organic matter contents have been reported after major land use changes such as ploughing pasture (Johnston 1991; Jenkinson *et al.* 1994), and the rate of change in soil organic carbon under a new management regime usually decreases with time as a new equilibrium is approached (Janzen *et al.* 1997). Gifford *et al.* (1990) estimated that 39 % of the native-condition soil carbon stock in the upper one metre was lost from 1860 to1990, and Guo and Gifford (2002) found that the conversion of native forest and pasture to cropland reduced soil organic carbon stocks by an average of 42 % and 59 %, respectively, when normalised for depth. Luo *et al.* (2010) reported a total carbon loss of ~51 % in the surface 0.1 m of soil in Australian agroecosystems due to cultivation over 40 years. The long-term use of many soils for conventional agricultural cropping contributed to a decrease in soil organic carbon stocks by 30–60 % (Guo and Gifford 2002; Kopittke *et al.* 2017) with an associated decrease in their inherent fertility and productivity. Many authors attribute the decline in soil organic matter to reducing levels of carbon inputs, however, organic carbon still declines in no-till stubble retained cropping systems with substantial carbon inputs (Alvarez 2005; Kirkby *et al.* 2016). Kirkby *et al.* (2014) suggested that it is nitrogen availability that is limiting the formation of soil organic matter. Heenan *et al.* (2004) reported that after long-term (20-year) trials in Wagga Wagga, NSW (570 mm annual rainfall), traditional cropping (multiple tillage events and burning stubbles) was losing soil organic carbon at a rate of 400 kg/ha/yr, whereas conservation tillage (no-till and stubble retention) stopped soil organic carbon losses but did not lead to any detectable increases over the same period.

The quantity of organic carbon in a given soil is determined largely by clay content, climate, and organic inputs derived from different land uses (Hassink 1997; Verheijen *et al.* 2005; Maraseni *et al.* 2008). Published information on soil properties in Australia (Baldock and Skjemstad 1999), plus the rationale for soil classification (Isbell 2002), has led to the realisation that soil properties such as soil carbon content are inherently different between soil orders as well as being affected by land use and management (Sparrow *et al.* 1999; Cotching *et al.* 2002). Water availability has a major influence on soil organic carbon stocks in Australia, where both the total amount and distribution of annual rainfall are important (Hobley and Wilson 2016). Seasonal rainfall results in different rates of relative soil organic carbon inputs and losses in wetter and drier months (Hobley and Wilson 2016). Higher soil organic carbon stocks are often associated with higher spring and summer rainfall (Orgill *et al.* 2017). For example, Chan *et al.* (2010) observed a linear relationship between the level of soil organic carbon and the extent of rainfall, however, soil organic carbon accumulation under pasture was higher than in continuous cropping (Figure 11). Liddicoat *et al.* (2010) analysed the soil organic carbon data available in the ASRIS database for South Australian cropping and pasture soils. They reported that soil organic carbon for cropping soils was 0.5–2.0 % while for pasture soils the values were 1–3%. Cotching *et al.* (2013) found that soil organic carbon was strongly related to rainfall using principal components analysis. In contrast, where water is not limiting, radiation, temperature (Wynn *et al.* 2006) and land use (Bui *et al.* 2009) regulate biomass production. Biomass decomposition is controlled by temperature and water availability and the largest changes occur where total annual rainfall is between 400 and 600 mm (Luo *et al.* 2010). Soil organic carbon decreases with soil depth and different factors affect soil organic carbon in the topsoil and subsoil (Hobley and Wilson 2016). Environmental and management factors strongly influence soil organic carbon in the surface 10 cm with soil type and water availability more influential below 20 cm (Badgery *et al.* 2013; Hobley and Wilson 2016). Soils with no limitation to water availability have higher soil organic carbon below 10 cm than areas with seasonal rainfall or those from warmer, drier climates (Hobley and Wilson 2016). The dominating effects of climate and soil type may make modest changes in soil organic carbon stocks due to management factors difficult to detect (Orgill *et al.* 2017).

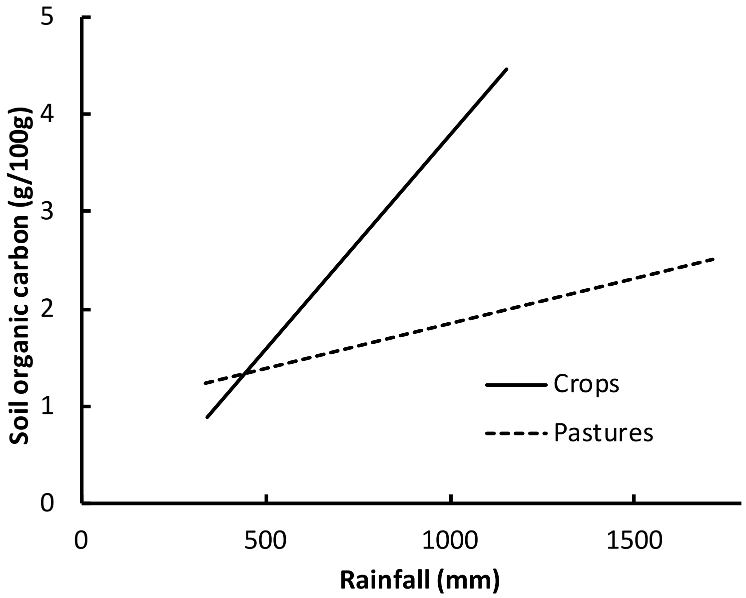

Figure 11. Soil organic carbon levels in pasture soils compared with cropping soils (0-10 cm) as a function of rainfall in NSW Source: Chan *et al.* (2010).

Soil organic carbon is widely considered an important measure of soil quality (Andrews *et al.* 2004) which helps mitigate the impacts of drought. Clay content plays an important role in determining the organic carbon content of a soil. Clay particles and aggregates can reduce losses of soil organic carbon by physically protecting organic matter from decomposition. Particles of organic matter can become adsorbed to clay surfaces, coated with clay particles or buried inside small pores or aggregates (Hoyle *et al.* 2011). All of these processes make it difficult for microorganisms to come in contact with organic matter. Therefore, the amount of organic carbon stored in soil tends to increase with increasing clay content (Figure 12). In contrast, in sandy soil, microorganisms can more easily access organic carbon due to low clay content. This causes greater loss of organic carbon by decomposition. The potential storage of organic carbon in soil is rarely achieved because climate reduces inputs of organic carbon into the soil. Moreover, lack of information on the link between pedology and organic carbon in the soils (Biggs and Grundy 2010) highlights the need to research this in Australia.

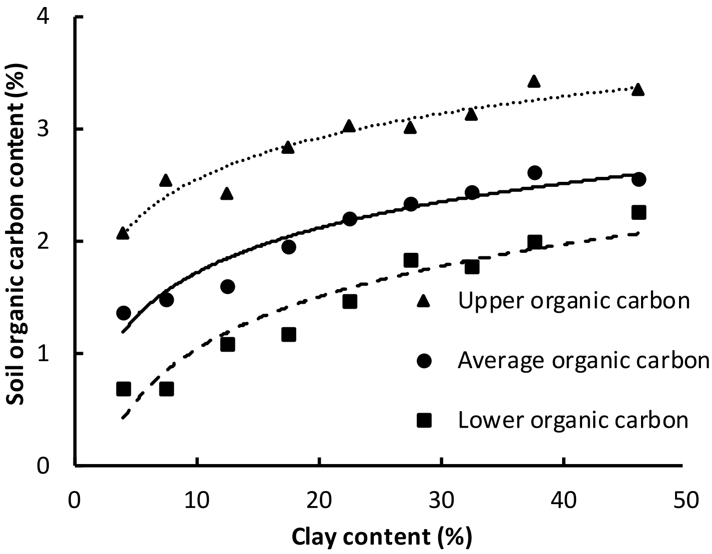

Figure 12. The relationship between clay content and the organic carbon content of 220 soils in a 10-hectare area of a paddock under cereal-legume rotation in the central agricultural region of Western Australia. The circles represent the average soil organic carbon value for each clay content while triangles show the highest value from the data (upper organic carbon) and the squares show the lowest values (lower organic carbon). Source: Hoyle *et al.* (2011).

The organic matter in the soil plays a key role in managing drought conditions. Under conditions of prolonged drought accompanied by crop failure and little return of crop residues to the soil, a soil with a high initial content of organic carbon will return to its former state of soil health more rapidly when the drought breaks than a soil with a lower soil organic carbon content (Hoyle *et al.* 2011). Soil organic matter, especially in sandy soils, improves fertility status and water retention capacity, decreases run-off, improves aeration, and produces a better soil structure or tilth by promoting granulation (aggregate formation) and reducing the damage from water and wind erosion. Soil organic matter can influence a range of functional soil properties, and each of these can contribute to productivity and sustainability, but this can vary depending on soil type (Murphy 2015).

Soil structure and soil physical properties

Soil organic matter plays a critical role in aggregate formation, stabilising soil structure, increasing porosity, water infiltration and overall water holding capacity, storing and releasing nutrients, and improving cation exchange and buffering capacity (Tiarks *et al.* 1974; Kladivko and Nelson 1979; Krull *et al.* 2004; Baldock 2007).). When bulk density decreases due to organic matter addition, pore size distribution is altered and the relative number of small pores (i.e. <30 µm diameter) increases, especially in coarse-textured soils (Khaleel *et al.* 1981; Pagliai *et al.* 1981; Schjønning *et al.* 1994). (Schjønning *et al.* 1994) The more porous soil structure increases infiltration capacity and hydraulic conductivity (Tiarks *et al.* 1974; Weil and Kroontje 1979; Ekwue 1992) and decreased run-off volumes (Hensler *et al.* 1970; Young and Mutchler 1976). Other benefits of organic matter additions include an increase in specific surface area resulting in increased water holding capacity at higher tensions (Gupta *et al.* 1977), decreased surface crusting (Mazurak *et al.* 1975; Epstein *et al.* 1976), a decrease in the amount of soil particles detached by raindrop impact (Mazurak *et al.* 1975). Similarly, Weil and Kroontje (1979), showed that infiltration rates in autumn were considerably larger in manured than control plots due to the large number of surface-connected burrows that had been formed.

Since soil organic matter is central to the formation of stable aggregates there is normally a close relationship between soil organic matter content and water stable aggregation in soils

(Chaney and Swift 1984; Haynes *et al.* 1991). Thus, adding organic wastes to soils normally causes an increase in the size and amount of water stable aggregates (Tiarks *et al.* 1974; Weil and Kroontje 1979; Ekwue 1992). Krull *et al.* (2004) published a major review of how soil organic carbon influences aggregate stability. They stated that processes of aggregate stability can vary depending on whether actively growing plants are present. However, the type of material and degree of organic matter decomposition has a significant influence on their effect on soil aggregation. Many researchers have demonstrated the value of adding easily decomposable carbon sources (e.g. green manure) to soils or artificial aggregates (Low 1954; Rennie *et al.* 1954; Monnier 1965). After a brief lag phase following fresh organic matter addition, there is a flush of microbial growth with a concomitant increase in physical entanglement by fungal hyphae and the production of extracellular polysaccharides capable of linking soil particles together. There is therefore a rapid rise in aggregate stability (Murphy 2015). By contrast, the addition of well-decomposed, composted material induces a slow and more steady increase in aggregate stability (Monnier 1965) since the organic matter consists mainly of humic substances which are relatively stable binding agents.

Many other studies (Tisdall and Oades 1980, 1982; Ekwue 1992; Angers and Carter 1996) also reported that aggregate stability increases more rapidly under actively growing plants, especially grasses with fine root systems, than under the simple addition of organic materials to the soil. Plant roots and hyphae form a 'sticky string bag' to enmesh soil particles (Oades 1993). Exudates and mucilage from the roots, hyphae, bacteria, and fauna such as earthworms provide mono- and polysaccharides and other organic materials, which enhance aggregate binding and stabilise the linings of biopores. Generally, the stability of macro-aggregates (>250 mm) is associated with the living soil organic matter (phytomass including finer plant roots, bacterial population and fungal hyphae) (Oades 1993). The stability of the microaggregates (<250–20 mm) is associated with the humic fraction and the stability of even smaller micro-aggregates <2–20 mm is most likely influenced more by clay structures, exchangeable cations and the potential effects of iron and aluminium sesquioxides (Murphy 2015). Thus, under drought conditions, as the moisture level drops rapidly, restricting the actively growing tissues could have an adverse impact on the stability of macroaggregates. However, such opinions need to be investigated under field conditions at different levels of drought/water stress. In general, it can be concluded that addition of organic matter via cropping or otherwise is beneficial for building more stable aggregates which can better withstand the effects of drought.

Biological soil health

As a food source for soil fauna and flora, soil organic matter plays an important role in the soil food web by controlling the number and types of soil inhabitants which serve important functions such as nutrient cycling and availability, assisting root growth and plant nutrient uptake, creating burrows and even suppressing crop diseases. For example, soil organisms (biota) obtain energy from decomposing organic matter, which in turn cycles nutrients, contributes to improved soil structure and water-holding properties. Thus, soil organic carbon and associated soil biota support pedological development, helping to stabilise soils from erosion and create pathways enabling greater water infiltration and utilisation (reducing run-off and shading from evaporation). Many researchers have shown that continual additions of farmyard manure usually increase the size of the microbial biomass (Martyniuk and Wagner 1978; Schnürer *et al.* 1985) and stimulate enzyme activities (Khan 1970; Verstraete and Voets 1977). Similarly, additions of organic manures to soils have also been shown to greatly increase earthworm populations (Edwards and Lofty 1982; Standen 1984). As already noted, such increased soil biological activity will tend to have positive effects on soil physical properties (Sanchez *et al.* 1989), typically on soil aggregation and macro-porosity. Many researchers (Khaleel *et al.* 1981; Metzger and Yaron 1987) have found direct relationships in bulk density and water holding capacity as a function of net increases in soil organic carbon caused by organic waste applications.

Conventional tillage breaks down aggregates and mixes crop residues with the soil, allowing direct contact between decomposing bacteria and the substrate (food source, in this case crop residues). In these soils, the physical protection of soil organic carbon provided by aggregates is lost and soil biota tends to be dominated by bacteria (Beare *et al.* 1992). In contrast no-till systems tend to be dominated by fungal hyphae which maintain links to plant residues left on the surface. In the presence of fungal-dominated pathways, soil carbon cycling often leads to a build-up of soil organic carbon in the form of relatively stable polymers (Stahl *et al.* 1999; Bailey *et al.* 2002), while fungal hyphae and roots are seen as key binding agents in stabilising soil aggregates for soils recovering from disturbance (Jastrow *et al.* 1998). Therefore, a reduction in tillage allows soil aggregation processes to re-establish with stable soil micro- and macroaggregates providing the best protection for accumulating soil carbon in the mineral-associated fraction (Jastrow 1996; Anderson 2009).

In a semi-natural grassland system of eastern Australia, Canarini *et al.* (2016) combined a management treatment (compost vs. inorganic fertiliser addition) and a drought treatment using rainout shelters (half vs. ambient precipitation). They found that the drought treatment did not affect the microbial community structure or organo-mineral carbon, while fertiliser only marginally increased organo-mineral carbon. In the surface soil (0–5 cm) organo-mineral carbon was strongly associated with fungi that may have been stimulated by root exudates, and by gram-negative bacteria in the deep soil (5–15 cm) that were more affected by particulate organic carbon and soil moisture. The researchers concluded that the grassland microbial community and its effect on organo-mineral carbon were non-responsive to the drought treatment, but sensitive to seasonal variation in soil moisture. Their findings also show that surface compost application can moderately increase soil carbon stabilisation under drought, representing a useful tool for improving soil carbon stability.

The beneficial effects of organic matter additions under drought are not straight forward as the results depend on the nature of the organic materials added, the effects of the organic materials on plant growth, the nutrient levels in the organic materials and the soil (Bronick and Lal 2005; Verchot *et al.* 2011) and the extent and period of drought.

Carbon sequestration

Generally, factors affect the organic carbon pools in the soil—temperature, moisture and microbial activity. The frequency and intensity of droughts can therefore greatly influence soil microbial community structure and carbon stabilisation. Increasing the amount of organic carbon stored in soil may be one option for decreasing the atmospheric concentration of carbon dioxide, a greenhouse gas (Schapel 2018). There are several strategies for carbon sequestration in the soil and the most effective ones are based on proper land use and soil management. Adoption of improved and science-based agricultural practices can be an important strategy to bring about a quantum jump in productivity, whilst enhancing environmental quality and mitigating greenhouse effects.

Increasing soil carbon stabilisation is an important strategy to mitigate climate change effects, but the underlying processes promoting carbon stabilisation with management practices are still unclear (Jha *et al.* 2020). Microbes are an important contributor to carbon stabilisation through the adsorption of microbial-derived compounds on organo-mineral complexes. Management practices, such as adding organic amendments might increase the soil carbon stock and mitigate drought impacts, especially in agroecosystems where large losses of carbon have been reported. Farming alters the carbon cycle, and the management of cropping systems will determine the amount of carbon dioxide emissions to the atmosphere as well as the potential for carbon sequestered in the soil. Marland *et al.* (2003) distinguished four sources of carbon dioxide emissions in agricultural systems:

1. Plant respiration.
2. Oxidation of organic carbon in the soil and crop residues.
3. The use of fossil fuels in agricultural machinery.
4. The use of fossil fuels in the production of agricultural inputs such as fertilisers and pesticides.

Carbon sequestration in soil, carbon storage in crop residues and carbon dioxide emissions from all farming activities should be considered as well as the indirect carbon dioxide emissions from energy use and primary fuel, electricity, fertilisers, lime, pesticides, irrigation, seed production, and farm machinery (Wang and Dalal 2006).

Applying balanced fertilisers for crop production plays a key role in regulating the organic carbon pool in the soil. For example, trial sites receiving long-term balanced nitrogen, phosphorus, and potassium fertiliser applications have been found to have 11 % higher organic carbon content than the control plots {Schjønning, 1994 #1157}. It appears that the soil organic matter formed due to fertiliser-induced crop yield increases (and thus increased organic matter returns) is of a more aromatic nature (and thus has a higher cation exchange capacity) than that formed due to farmyard manure additions (Christensen 1988; Schjønning *et al.* 1994).

Crop residues for organic carbon build up

Conservation tillage and crop residues can play an important role in building organic carbon stocks in the soil. They are an important and renewable source of nutrients, enhance soil fertility, improve soil structure, sequester carbon, and mitigate the greenhouse effect. The beneficial impact of these practices is discussed in a separate section (Conservation tillage on page 56). This sub-section describes the effects of conservation tillage on organic carbon in soils.

Early studies on soil organic carbon under Australian cropping conditions identified the importance of conservation tillage versus conventional tillage (Valanzo *et al.* 2005). However, no differences in organic carbon were found in areas with rainfall below 500 mm because of limitations to biomass production (Chan *et al.* 2003). With much of the broadacre production areas dominated by low rainfall, this has limited potential to build soil organic carbon through changes to agricultural practice (Liddicoat *et al.* 2010). Under grazing, pasture improvements including fertilisation, liming, irrigation and sowing more productive grass varieties generally resulted in sequestration rates of 0.1 – 0.3 Mg carbon/ha/yr with larger gains of 0.3 – 0.6 Mg carbon/ha/yr after conversion of cultivated land to permanent pasture (Sanderman *et al.* 2009).

Where water availability was limiting, there was little difference in organic carbon between management practices and it was concluded that conservation tillage may at best slow the rate of organic carbon loss (Cotching *et al.* 2013; Davy and Koen 2013; McLeod *et al.* 2013). The long-term use of multiple practices such as stubble retention, no-till, legume rotations and elimination of fallow may lead to increases in organic carbon (Robertson *et al.* 2015) and are likely to be adopted as long as they maintain or increase plant productivity and are economically sustainable (Cotching *et al.* 2013).

Increasing organic carbon input through management practices is essential for increased soil organic carbon but long-term storage is only possible with transformation to more stable organic carbon fractions. Transformation of particulate organic carbon into more stable forms of humus organic carbon and resistant organic carbon is essential as the less stable forms are more quickly lost from the soil following disturbance (McLeod *et al.* 2013). Humus organic carbon increases with depth and is influenced by soil texture, whereas particulate organic carbon decreases with soil depth and is influenced by management and climate factors (Davy and Koen 2013; Hoyle *et al.* 2016). In South Australian red brown earths, humus organic carbon was higher under cropping than mixed crop and livestock systems which may be explained by the higher fertiliser inputs required in a cropping system enabling the transformation from particulate organic carbon to humus organic carbon (Macdonald *et al.* 2013).

Questions regarding the ability of cropping areas below 500 mm annual rainfall to build soil organic carbon requires long-term research to be resolved. This is likely to include the latest developments in no-till, precision agriculture with full stubble retention to determine if best practice conservation tillage is capable of building soil organic carbon in these lower rainfall areas, or whether it just halts soil organic carbon decline (Liddicoat *et al.* 2010). Limitations to dry matter production also need to be addressed (for large areas of South Australia annual crop water use efficiency is estimated at between 50-70 %). When trying to maintain or improve soil organic carbon, care is needed with the application of fertilisers. Over-application of readily plant-available nitrogen can stimulate microbial attack and the consequent breakdown of soil organic carbon, while also being associated with emissions of the damaging greenhouse gas nitrous oxide, not to mention wastage of inputs and embodied energy (Liddicoat *et al.* 2010).

Increasing organic carbon potential by cropping

The potential to build soil organic carbon in cropping systems depends on the capacity to produce large quantities of crop biomass that can be returned and retained as carbon in the soil. Management that eliminates burning or removing crop residue, soil erosion, fertility decline, over-grazing, compaction and low biomass crops will help to maintain or build soil organic carbon levels. Options to increase soil organic carbon levels through changes to farming systems include: greater incorporation of pastures (including perennials) into cropping situations, and small management changes across large areas of degraded rangelands may offer significant potential (Liddicoat *et al.* 2010). Some biological (organic) farming methods have also been reported to offer soil organic carbon benefits and reduced emissions over conventional farming systems. The application of new technologies also offers significant potential to increase soil organic carbon levels. As discussed previously, soil modification through clay spreading, delving and spading appears to increase the capacity of soil organic carbon storage and is applicable across large areas. Soil organic amendments (e.g. manure, biochar, compost, biosolids, etc.) imported from off-site may also increase soil organic carbon but their application may be limited by availability and cost-effectiveness. Conservation farming techniques are readily accessible options to build topsoil soil organic carbon in cropping situations. This is due to reduced soil disturbance and differences in soil biological activity under conventional tillage versus no-tillage situations.

Soil organic matter can be a carbon sink or source of greenhouse gases depending on the soil and its environment and management (Sanderman and Baldock 2010), with consequent effects on atmospheric carbon dioxide concentrations. As such, more research is needed to determine whether new and evolving conservation farming techniques can achieve long-term soil organic carbon sequestration improvements (or perhaps just halt soil organic carbon losses). Existing Australian continuous cropping trial results have found that tillage practices have little or no effect on soil organic carbon levels where annual rainfall is less than 550 mm (Valanzo *et al.* 2005; Liddicoat *et al.* 2010). Note that these results were obtained from experiments that did not monitor organic carbon as the main purpose and in a number of cases very little data was provided on what the tillage practices were (Liddicoat *et al.* 2010).

Adverse impacts of added organic matter

Adding large quantities of organic manures to soils may have adverse impacts such as surface crusting, increased detachment by raindrops and decreased hydraulic conductivity (Olsen *et al.* 1970; Tiarks *et al.* 1974; Mazurak *et al.* 1975; Weil and Kroontje 1979) during the drought recovery, especially in sodic soils. The primary reason for this soil structural breakdown is the high content of monovalent cations (sodium and particularly potassium) in the added organic material. High concentrations of ammonium may also accumulate through the mineralisation of organic nitrogen. Indeed, at high rates of waste application, soil salinity levels can increase to the extent that germination of salinity-sensitive crops is inhibited (Epstein *et al.* 1976). Excess salts tend to be leached by rainfall and irrigation thus reducing potential salinity and soil physical problems but end up contributing to pollution of groundwater. Tiarks *et al.* (1974) found that when cattle feedlot manure was applied to soil in spring at 90–360 t/ha, it caused decreases in hydraulic conductivity. However, leaching over winter reduced salt content to levels where there was no detrimental effect on soil physical conditions. In fact, Tiarks *et al.* (1974) suggested that the increased organic matter content and enhanced aggregation in manure-treated plots may have promoted leaching of excess salts.

High rates of manure application in the soil can cause water repellence (Olsen *et al.* 1970). This is thought to be due to the production of water repellent organic substances by fungi involved in the decomposition of the manure (Weil and Kroontje 1979). Olsen *et al.* (1970) observed that the addition of dairy manure to an acid loamy sand caused a reduction in field capacity due to the presence of waxy, water repellent substances in the soil profile.

IMPROVED SOIL NUTRITION

Artificial fertilisers have been used in Australia for about seventy years and have produced some of the most spectacular crop and pasture responses in the world (Stephens and Donald 1959; Bell and Dell 2008; Brennan *et al.* 2019). These responses have been given by phosphatic fertilisers and by the trace elements copper, zinc, molybdenum, manganese, boron, and iron (Brennan *et al.* 2019). Nutrient input promotes root growth, makes roots absorb more water from deep soil layers, and therefore increases plant tolerance ability to drought, all being beneficial for crop production. Balanced fertiliser applications have numerous beneficial impacts on soils. For example, Nuttall *et al.* (1986) in a 25-year study noted that annual applications of nitrogen and phosphorus improved soil aggregation. Similarly, Darusman *et al.* (1991) found that 20 years of annual applications of nitrogen to arable land had resulted in significant increases in aggregation in the 6–14 cm soil layer, although bulk density and compatibility were unaffected.

Nitrogen management

The Australian grains and pasture industry has traditionally relied on the mineralisation of soil organic matter and plant residues as the primary source of nitrogen for crop production (Angus and Grace 2017), but this has proved increasingly inadequate as soil organic matter levels have declined by up to 60 % under continuous cropping (Dalal and Chan 2001). Nitrogen deficiency in the Australian soils under rainfed agriculture has long been thought to be a major contributor to the yield gap (Angus 2001; Gobbett *et al.* 2017; Smith *et al.* 2019). Hochman and Horan (2018) estimate that removing nitrogen deficiency would increase national farm wheat yields by 40 %. Mixed cropping/grazing systems are also changing due to continuous cropping, so the use of nitrogen fertiliser to maintain productivity and balance grain nutrient removal is increasing (Ryan 2010). The use of nitrogen fertiliser on Australian dryland grain crops more than tripled from<0.4 Mt in 1990 to 1.0 Mt in 2010, and currently stands at 1.4 Mt (Angus and Grace 2017). While there has also been a substantial increase in the area of grain legumes (which can provide significant amounts of nitrogen to subsequent crops (Peoples *et al.* 2017), at only 5 % of cropped area, their contribution to nitrogen supply is insufficient to compensate for the decline in legume pasture area (Angus and Grace 2017).

There is uncertainty about the seasonal nitrogen requirements for rainfed cropping systems. The timing of in-season rainfall (Hunt and Kirkegaard 2011) and accurate seasonal forecasts (Asseng *et al.* 2012) play a crucial role in the efficacy of nitrogen fertiliser applications. Availability of adequate moisture is essential to attain maximum nitrogen efficiency. Consequently, a large yield gap exists in seasons where the yield potential is largely limited by water (Hochman *et al.* 2012). Chronic under-fertilisation means that the soil nitrogen balance (defined here as fertiliser plus legume nitrogen inputs minus nitrogen export in grain and nitrogen losses due to leaching, volatilisation and denitrification) becomes negative over time. There is an increased reliance on mining soil organic nitrogen for crop nitrogen supply. This means that running positive nitrogen balances increases soil organic matter when residues are retained. The use of legumes (nitrogen fixing), manures and nitrogen fertiliser to return to a neutral soil nitrogen balance is essential for sustainable maintenance of soil organic matter in conservation cropping systems (Fettell and Gill 1995; Giller *et al.* 2015). Nitrogen fertilisation is likely to increase soil organic matter through increased inputs of crop residues (roots and straw) that results from improved crop growth (Halvorson *et al.* 1999), and also increased rates of humification via increased microbial activity (Kirkby *et al.* 2016). These beneficial effects of nitrogen application along with conservation tillage in turn help soil build a strong drought mitigation potential. Nitrogen fertilisation could also help to overcome drought-enhanced nitrogen limitations, although the growth response to nitrogen fertiliser might decline with decreasing soil moisture (Colman and Lazenby 1975; Lambers *et al.* 2008).

Drought effects on nitrogen cycling can strongly interact with nitrogen fertiliser applications (Hartmann and Niklaus 2012; Hartmann *et al.* 2013). Studies using stable isotopes of nitrogen provide valuable insights into the nitrogen cycling processes that affect soils and vegetation (Aranibar *et al.* 2008; Kleinebecker *et al.* 2014) under drought because they are relatively easy to measure and can provide time integrated information about nitrogen cycling (Robinson 2001). Aranibar *et al.* (2008) and Robinson (2001) observed that soil and plant nitrogen tend to be enriched with 15N with increasing aridity. In a multisite field experiment, Hofer *et al.* (2016) found that drought-stressed forage species were significantly impaired despite nitrogen fertilisation. However, species were highly resilient after the drought event, and formerly drought-stressed non-legumes even overcompensated by producing more above-ground biomass than the non-stressed controls (Hofer *et al.* 2017). The underlying cause of such overcompensation remains unknown. However, it suggests that nitrogen application can play an important role during the recovery period, irrespective of crop type. Measuring plant available mineral nitrogen in the soil during drought and post-drought periods could reveal to what degree soil and fertiliser nitrogen is accessible to plants and whether nitrogen resources not taken up during drought would become plant-available during the post-drought period given adequate water supply. Understanding the drought response of high-yielding and functionally different crop species can promote the development of farming options to adapt crop production to future climate conditions.

Nitrogen use efficiency is also an important factor in dryland agriculture and there are opportunities for improvement. For example, through better soil nitrogen testing, greater uptake of precision farming methods, slow-release coatings on urea, nitrification inhibitors and multiple smaller liquid nitrogen applications in response to favourable seasonal conditions (compared to a single large application). Synthetic nitrogen fertilisers have been implicated more generally in the degradation of soil organic carbon quality (causing decline in more permanent soil organic carbon fractions) in some situations. A recent survey of grain industry advisors (Schwenke *et al.* 2019) revealed that seasonal outlook, paddock history and soil testing were the top priority for determining nitrogen fertiliser requirements.

Phosphorus management

The supply of soil phosphorus has been a major factor limiting pasture and crop production in Australia. Traditionally, phosphorus deficiency has been corrected by applications of phosphorus with superphosphates. Applied phosphorus in the soil gets dissolved into the soil water and may undergo further transformations such as precipitation (by calcium, aluminium and iron), diffusion and subsequent adsorption on clay surfaces, while some is occluded in the clay and become unavailable to plants. Reactions that remove phosphorus from the plant available pool are generally termed fixation reactions and may be a combination of both precipitation and strong adsorption. Part of the dissolved phosphorus is also incorporated into the soil organic matter by the soil microbial biomass but can be later mineralised to soluble phosphorus by other microbial processes and exudates from plant roots. Soil microbes however compete with crop roots for soil solution phosphorus (McLaughlin and Alston 1986; McLaughlin *et al.* 1988).

Diffusion of phosphorus is a very slow process and phosphorus remains in the place where it was applied. Hence, under normal south-eastern Australian growing conditions, phosphorus is banded in the soil at points where plant roots can readily access it soon after planting i.e. close to or below the seed (Piper 1964; Alston 1980; Holloway *et al.* 2001). Top-dressed phosphorus, therefore, significantly reduces the ability of plant roots to access fertiliser phosphorus, even in sandy soils.

The effectiveness of directly applied phosphorus depends on several factors (Khasawneh and Doll 1979):

1. The chemical nature and physical form of the fertiliser.
2. Soil properties.
3. Type of crop or pasture species grown.
4. Climatic conditions.

Among these, the extent of soil moisture is the principal factor limiting dryland crop production in the main grain-producing areas of south-eastern Australia (Incerti and O'Leary 1990). Restricted soil moisture can influence plant phosphorus nutrition by altering phosphorus movement through the soil and plant uptake processes. Most phosphorus is taken up by plants through fine root hairs situated behind the growing root tip, meaning that phosphorus uptake is closely related to root length and therefore plant vigour (Tinker 2000; Solaiman *et al.* 2007). Restricted moisture will reduce plant vigour and the rate of root growth, which slows as the plant turgor pressure decreases and also because the penetration resistance of the soil increases as the soil dries. The rate of diffusion will also slow as soil moisture decreases and as the tortuosity (path length) increases. The ability of plants to access soil phosphorus during active root growth is therefore expected to be reduced under dry conditions (Mackay and Barber 1985; Simpson and Pinkerton 1989), even though Australian semi-arid wheat plants are physiologically adapted to compensate for a moisture deficit by increasing the root:shoot ratio (He *et al.* 2002). The availability of fertiliser phosphorus may also be reduced, although disproportionately high responses to phosphorus fertiliser under low soil moisture have been found in some studies (Strong and Barry 1980; He *et al.* 2002).

Borch *et al.* (2003) showed that optimising phosphorus nutrition improved drought resistance by reducing transpiration and increasing water acquisition from the medium. The improved water acquisition could be explained by increased root proliferation via longer main roots and less densely distributed lateral roots (Borch *et al.* 2003). Such phosphorus management techniques could be used effectively in cropping systems, where fast-growing, short-season annuals could be fertilised with a combination of slow and fast-release fertilisers, while slow-growing, long-season perennial vegetation could be fertilised with slow-release fertilisers (such as rock phosphate) to maximize the phosphorus use efficiency (Chien *et al.* 2009; McLaughlin *et al.* 2011). Moreover, the timing of phosphorus application, soil moisture status, and temperature interact to determine the availability of phosphorus to plants (Mackay and Barber 1985; Bramley and Barrow 1992). For example, in a field experiment at Mallala in South Australia using radioactive phosphorus sources, it was demonstrated that only 12 % of the phosphorus fertiliser applied that season was accumulated in a 95-day-old wheat crop which accounted for only 16 % of total plant phosphorus uptake (McLaughlin *et al.* 1988).

The effectiveness of phosphorus fertilisers added to soil also decreases with time, and the reduction is greater and faster in moist, warm soil than in dry, cool soil. In the experiments included in a meta-analysis (Suriyagoda *et al.* 2014), a variety of phosphorus sources were used and these were applied at various times before the analysis and included a range of soil moisture contents and temperatures. It was found that the availability of phosphorus was different across the experiments, even with the same source of phosphorus, which is a possible cause for some of the contradictory results reported.

Applications of phosphorus to soil can have considerable residual effects and the plant availability of the residual phosphorus can influence subsequent fertiliser phosphorus requirements (Probert 1985). Mullen (cited in Fettell and Scott (2003)) worked on two sites in central-western NSW during the 1972 drought and the 1973 recovery year. He concluded that of the 5–11 kg/ha phosphorus applied in 1972, 3–8 kg/ha were available the following year (Figure 13). Bolland (1999) observed that the residual effectiveness of fertilisers applied in previous drought years is enhanced in the following good rainfall season. Similar observations were made by Scott et al. (cited in Reuter *et al.* (2007)) in NSW and suggested that phosphorus rates can be reduced slightly from recommended rates, by approximately 20 % based on examination of soil test data. During severe drought/crop failure or low-yielding years, crops would have taken up only a small per cent of the fertiliser phosphorus applied during drought, partly because their root systems were severely reduced by water stress (Fawcett and Quirk 1962).

Soil type strongly influences phosphorus transformation and availability to plants under water stress conditions. In neutral and acidic soils, a significant amount of phosphorus fertiliser applied during drought may still be available for the next crop due to reduced and slower soil phosphorus fixation occurring in very dry soil conditions–rates of application could be reduced. In calcareous soils, phosphorus fixation should not be discounted in the drought year (Bolland 1999). Cost-effective fluid fertilisers should be considered as a replacement for granular phosphorus products. If the following season has improved rainfall, crops will have better access to fertiliser phosphorus applied in drought. Where crops failed due to drought and soil phosphorus status is at the maintenance phase, previous phosphorus application rates up to 5 kg phosphorus/ha should be considered (Reuter *et al.* 2007). Also consider the phosphorus buffering index, which defines how strongly phosphorus is held by the soil particles and how easily crops can access phosphorus from the soil solution (Burkitt *et al.* 2002; Moody 2007). Soils with a high phosphorus buffering index (such as the highly calcareous soils found on parts of the Eyre Peninsula in South Australia or the red soils of the Burnett region in

Queensland) have a higher critical soil phosphorus level for near maximum yield than soils with a low phosphorus buffering index (e.g. cracking clay/Vertosols of the Victorian Wimmera).

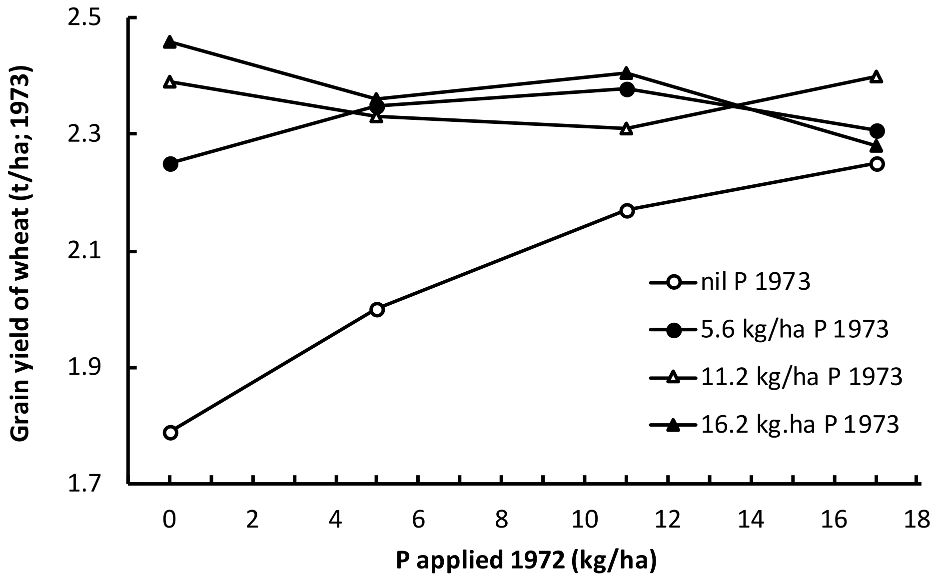

Figure 13. Grain yield of wheat (t/ha) in 1973 with varying rates of phosphorus fertiliser applied in both 1972 and 1973. The yields were averaged over two sites in central-western NSW. Source: Mullen cited in Fettell and Scott (2003).

DISPERSIVE SOIL MANAGEMENT

Many cropping and pasture regions in south-eastern Australia have naturally dispersive topsoils. Dispersive soils are prone to compaction, temporary waterlogging and reduced seedling emergence. These limitations pose challenges for cropping systems and make it hard to manage the recovery from drought. Dispersive soils are normally high in sodium or excessive exchangeable sodium per cent and are also often sodic with an exchangeable sodium per cent greater than six (Northcote and Srene 1972).

Table 5 summarises the sodicity rating and the relationship between the extent of exchangeable sodium per cent and the degree of dispersion and aggregate stability. Each of these categories need different gypsum application rates and other management operations to help manage these soils to improve crop production.

Table 5. Relationship between the degree of dispersion and the exchangeable sodium per cent.

Rating	Approximate exchangeable sodium per cent (%)	Comments
Non-sodic	<6	No dispersion evident after 24 hours. Aggregates slaked but not dispersed (milky) clay.
Slightly sodic	6-10	Dispersion (milky halo) evident after 24 hours. Soil aggregates slightly disperse.
Moderately sodic	11-15	Dispersion (milky halo) evident after several hours. Soil aggregates partially disperse.
Highly sodic	>15	Dispersion (milky halo) evident in less than 30 minutes. Soil aggregates completely disperse.

(Source: Davies and Lacey (2009))

Gypsum ($Ca_2SO_4 . 2H_2O$) is the most common chemical ameliorant used in the management of sodic soils. In the short-term, gypsum increases the electrolyte concentration of the soil solution (Quirk and Schofield 1955; Loveday 1974; Qadir *et al.* 2001) temporarily suppressing dispersion. In the long-term with repeated applications and/or high enough rates, the calcium in gypsum displaces the sodium on the soil particles, permanently ameliorating the issue. Gypsum is reasonably soluble; it is estimated that 120–130 mm of rainfall is capable of dissolving and leaching 1 t/ha of gypsum from the A horizon of a Sodosol (Greene and Ford 1985). As such, the positive influence of gypsum on sodicity is likely to be brief, requiring frequent reapplication (Valzano *et al.* 2001).

Traditionally in Australia, an exchangeable sodium per cent >6 has been used as a threshold value to indicate when gypsum is required to prevent dispersion in surface soils (Sumner *et al.* 1998; Rengasamy and Marchuk 2011). Gypsum has been used successfully to prevent excessive swelling and dispersion, increase structural stability and reduce soil strength (Doyle *et al.* 1979; McKenzie and So 1989; Dang *et al.* 2010) This has led to yield increases throughout the QLD and NSW grain growing regions (Table 6), and can often provide an economic solution for growers to treat sodicity (Dang *et al.* 2011; Orton *et al.* 2018). Although it has been well demonstrated that gypsum can provide a positive benefit (Table 6), not all soils show a positive response and the identification and characterisation of these soils requires further study.

Gypsum only improves soil structure in dispersive soils. The value of gypsum addition cannot always be predicted using the exchangeable sodium per cent as the soils respond to gypsum application due to the impact of other environmental factors (Churchman *et al.* 1993) such as salinity and mineralogy. If the soil is not dispersive, the only potential benefit of applying gypsum is to supply calcium and sulphur. Similarly, in the QLD and NSW regions, gypsum responses have been observed in soils with an exchangeable sodium per cent as low as three (Dang *et al.* 2010). In other cases, excess magnesium can cause soils to disperse more easily and at lower sodium contents (Dang *et al.* 2010).

Table 6. Examples of yield increases observed following the surface application of gypsum on dryland cropping soils throughout Queensland (QLD) and New South Wales (NSW) grain growing regions. Source: Page *et al.* (2018).

Location	**Rate of application (t/ha)**	**Change in yield**	**Reference**
Northern NSW	0, 12.5	0–610 % (wheat)	Doyle *et al.* 1979
Northern NSW	0, 2.5, 5, 7.5	0–230 % (wheat)	McKenzie and So 1989
Central NSW	0, 1, 2.5, 5	18–67 % (wheat	Valzano *et al.* 2001
Central & Southern Qld, Northern NSW	0, 2.5, 5	0–44 % (wheat, chickpea)	Dang *et al.* 2010
Southern Qld	0, 5	0–35 % (wheat, sorghum)	Thomas *et al.* 1995
Southern Qld	0, 9	No change (wheat, sorghum, cotton)	Hulugalle *et al.* 2010

Using exchangeable sodium per cent alone does not take into consideration the increase in soil electrolyte concentration (ionic strength) and subsequent increase in flocculation brought about by gypsum application (Dang *et al.* 2010). Inducing the electrolyte effect requires much lower rates of gypsum than are required to permanently displace sodium with calcium, which may make lower rate gypsum applications more economically feasible in some instances. As the effect is temporary, repeated applications or gypsum combined with organic amendments are required for longer-term effects. Our knowledge of the optimum rates of re-application, however, is currently poor and further work is needed to help growers identify gypsum-responsive soils. A dispersion test is currently the most effective method to gauge soil dispersion.

Applying lime to soil has been a management technique for several centuries (Gardner and Garner 1957). In Australia, as early as 1925, lime was reported to have significant benefits in the Riverina on an impervious red clay (Vertosol) subsoil two years after application (Shepherd 1925). From one lime and gypsum experiment (So *et al.* 1978), lime maintained an effect on soil structure similar to gypsum; increases in fine aggregates, water-stable aggregation and hydraulic conductivity were observed after approximately one year. Doyle *et al.* (1979) showed a significant yield increase of wheat on sodic grey clays (Vertosols) in north-western NSW after lime had been broadcast at a rate of 5 t/ha. However, in the above studies, very little (if any) mention is made of cation exchange. This suggests that lime can be effective in ameliorating sodic soils through the mechanism of cation exchange and electrolyte augmentation. Chan and Heenan (1998) found that exchangeable sodium and magnesium decreased and exchangeable calcium and electrical conductivity increased when lime was used. This highlights the potential to use lime to improve structure in dispersive soil, and these structural effects will have greater longevity and a consequence of slower dissolution of the lime. Unfortunately it also means that any short term effects are likely to be delayed as the lime is slow to dissolve (Shainberg and Gal 1982; Naidu and Rengasamy 1993). The ability for lime to dissolve is also greatly reliant on soil pH (as well as particle size and purity of the lime); therefore, lime may not have much impact on a soil with a high pH.

Studying the combined application of lime and gypsum, Valzano *et al.* (2001) reported an occasionally synergistic effect of lime and gypsum on soil structure and exchangeable sodium per cent reduction, which most likely occurred due to a combination of an initial pH-buffering effect, the naturally differing rates of dissolution for lime and gypsum, and a biological CO_2 effect (Figure 14). The basis of their research was that gypsum and lime operate on different solubility time-scales, augmenting the period of calcium availability.

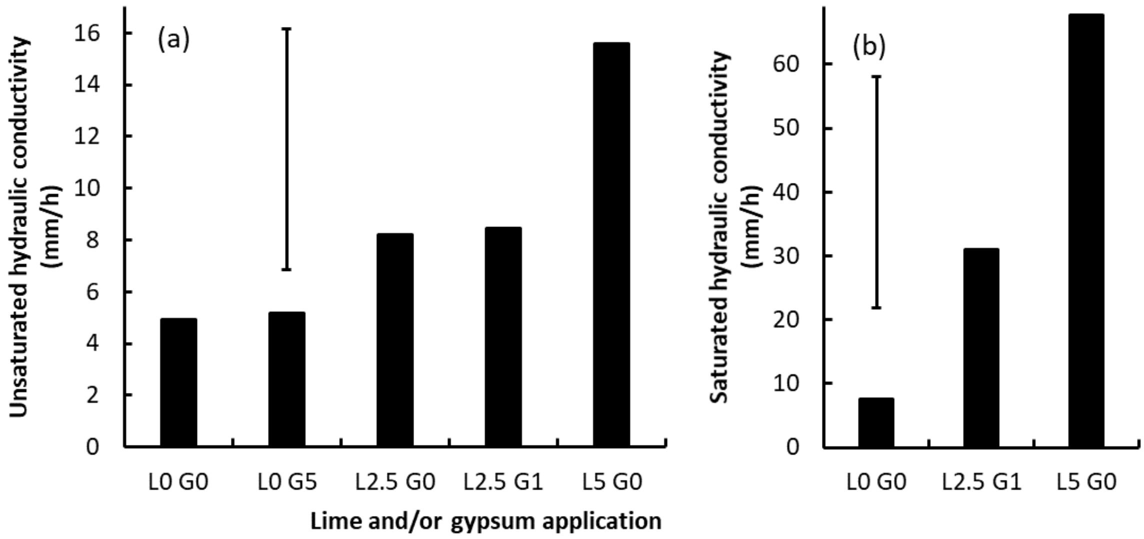

Figure 14. Surface hydraulic conductivity for selected lime (L) and gypsum (G) treatments. Capped lines show Tukey's HSD at P = 0.05. Source: Bennet *et al.* 2014.

The improved chemical status of the soil where calcium had been applied would result in enhanced soil structure, biophysical processes such as root enmeshing, and mucilage bonding. Increases in organic carbon are also likely to contribute to an improvement in soil structure (Tisdall and Oades 1979; Oades 1984; Tisdall 1991) and greater resilience against drought.

REVIEW - CONCULSIONS AND KNOWLEDGE GAPS

Despite the enormous body of research which examines the relationship between soil moisture content and crop production dynamics, productivity loss, crop nutrition, microbial activity, tillage practices, and quantifying the extent of soil erosion, the vast majority have concentrated on assessing the effects of drought, rather than on improving management practices during and in the recovery phase of drought. Though most erosion occurs with a few storm events, little research has been done in estimating event-based soil loss at the paddock scale, and the exact causes of variation in post-drought erosion by episodic events of strong wind or heavy rainfall which can result in enormous soil loss. Similarly, during periods of drought, numerous erosion measurement techniques have generated a great deal of data at different scales but scarce information is available on measuring the impact of different practices in reducing the soil erosion losses. More research is required to evaluate the impacts of different conservation practices on erosion; to measure and map soil thickness and erosion rates to reduce the uncertainty in erosion rate estimates and to better estimate soil production rates.

Accurate fertiliser application rates and timing play a crucial role in enhancing crop production during the drought recovery phase. However, in a recent survey of advisors (132) of New South Wales grain growers, Schwenke *et al.* (2019) reported that most advisors calculated nitrogen fertiliser required for yields within 10–15 % of crop potential indicating a large gap in their understanding the soil test based recommendations. Most of the growers relied heavily on the mineralisation of organic matter and plant residues as a primary source of nitrogen supply to their wheat crop and applied minimal nitrogen fertiliser. Low nitrogen fertiliser application may intensify a rapid depletion of other sources of nitrogen such as the organic matter pool. Consequently, soil organic matter levels may decline at a rapid rate; a 60 % reduction was observed under continuous cropping (Dalal and Chan 2001). Therefore, additional research is required to understand the interaction between conservation practices, soil type and crop choice on mineralisation in the view of increasing rainfall variability and frequent drought occurrence.

Further research is needed to better understand the long-term dynamics of water and solute fluxes in the soil-water-plant continuum and other soil-related issues such as nutrient cycling, microbiology, and biochemical interactions of organic matter added through crop residues. Research should examine these intricacies across a range of soil and landscape types. This work should include process-based modelling studies under future climate projections. To better understand the biogeochemical interactions in the soils, these studies should calibrate and validate broader-scale modelling used to extrapolate site-specific information on varied soil processes.

The above work should contribute to the development of decision support tools, including the development of erosion risk mapping for environmental assessments and soil management under future drought conditions. This would allow decision makers to assess the extent and magnitude of pre and post-drought soil management, preparedness, and to prioritise remedial activities after drought.

Subsoil constraints are another area which need an ongoing focus, especially to improve our understanding of how to manage salinity, sodicity, compaction, and fertiliser-induced acidity. In duplex soils, we often see more information on how to best use or combine ameliorants to treat multiple constraints concurrently. In instances where the treatment of constraints is likely to be uneconomical or take a long time, further identification of those crop species or cultivars that are most productive on constrained sites is required. This is particularly the case where multiple constraints are present, which requires crops to tolerate a variety of conditions. Increasing our knowledge in these areas represents a significant opportunity to improve the ability of growers throughout the region to profitably manage soil constraints during drought and recovery.

KEY MESSAGES

During drought

- Reduce wind erosion risk by removing stock early and maintaining minimum soil cover levels, avoid grazing failed crops.
- Target investment to the most reliable paddocks.
- Practice no-till seeding techniques and stubble retention.
- Establish permanent stock containment areas for lot feeding during droughts which, when used strategically, will take the pressure off land during dry periods or late starts.
- Avoid overgrazing native and exotic perennial grass stubs, as this will significantly affect regeneration.
- Consider sowing quick growing crops or annual pastures to provide cover and act as a break crop where pasture needs re-establishment .

- Practice no-till or sod seeding techniques for pasture establishment.

Immediately following drought

- Use soil tests to review fertiliser practice. Drought conditions can create a flush of nitrogen and phosphorus upon rewetting. Soil testing may enable cost savings by identifying levels of nutrients not used by crops in dry periods.
- Reduce erosion risk by establishing quick growing crops (provided they fit into suitable rotations).
- Maximise soil cover and water infiltration through on-row or side row sowing.
- In dry areas where subsoil salinity is an issue grow salt tolerant species such as barley.
- Ensure plant back periods for herbicides are considered as dry conditions increase breakdown periods.
- If soil diseases are suspected undertake disease testing, particularly if having wheat-on-wheat.
- Keep stock off paddocks until ground cover is at adequate levels for maximum growth.
- Use rotational grazing techniques for even grazing pressure and avoiding baring off weak areas.
- Ensure adequate number and location of watering points to reduce tracking, energy requirements and baring off susceptible soils.

Developing long term resilience in soils

- Increase soil carbon cycling by retaining surface residues and maximise plant carbon input via the roots by overcoming physical and chemical constraints in the topsoil and subsoil.
- Identify and treat any surface fertility or structural limitations where possible.
- Monitor soil pH in acidic soils including stratification and subsurface pH and develop a program to rectify issues.
- Understand the range of constraints in sandy soils and where relevant implement practises that reduce water repellency, overcome hard pans, and increase fertility.
- Identify subsoil constraints and consider innovative practices and research that could be suitable for the farm’s soil types and farming systems.

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APPENDIX A - SURVEY SUMMARY

Managing soil for high performance after a drought

AGRICULTURE VICTORIA

Australia is a semi-arid country in which all its soils have an inbuilt resilience to annual cycles of wetting and drying. However modern agricultural practices can place increased demands on soil, with these soils working at an increased capacity, exposing vulnerabilities to prolonged cycles of moisture stress. Prudent management strategies for cropping and grazing enterprises can assist farm businesses to withstand these prolonged cycles of drying and, as a result, recover faster and be more resilient after a drought.

Seventeen of Australia's leading farmers, advisors, farming systems groups and researchers were identified to participate in a phone conversation covering three key areas: the effects of drought on soils, strategies for managing these drought affected soils and how the farming community can best support the recovery of soils. Interviewees covered the geographical areas of South Australia, Western Australia, Queensland, Victoria and New South Wales. They also covered technical knowledge areas from grazing and grain production systems.

Questions were tailored to the interviewees dependent on whether they were farmers, advisors and farming systems groups or researchers.

This is a summary of the report and is based on the comments and experiences from the 17 conversations conducted. In addition to the three aforementioned key topic areas, knowledge gaps to best support landholders coping with prolonged cycles of drying in the landscape were also identified and reported.

Effects of drought on soil

Ground cover

- Loss of ground cover is one of the most obvious consequences of drought, having significant flow on effects in the landscape and on soil condition
- Crop type influences the amount of stubble retained going into a drought and consequently crop emergence the following year
- There is increased pressure to utilise stubble for alternative purposes in drought
- Surface crusting increases with loss of ground cover
- Ground cover loss can lead to exposed soil and consequently the loss of topsoil.

Erosion

- Bare soil is at increased risk of wind and water erosion
- Bare soil reduces aggregate stability and increases erodibility and soil loss through water erosion
- Wind erosion can lead to nutrient loss in the topsoil
- Cultivation can lead to soil loss
- Soil type can influence the amount of topsoil that is lost due to erosion.

Influence of soil type

- Younger soils are more resilient in drought
- Lighter soils are prone to reduced ground cover, increased surface crusting and increased erosion
- Deep sands are less impacted by soil loss compared to heavier soils due to their inherently lower organic carbon levels
- Duplex soils are the most susceptible to soil surface crusting
- Black, heavy soils have increased soil temperature but are able to recover quickly after drought
- Soil structural problems can develop during drought in heavy vertosols
- Soil type impacts the tendency for soil to display hydrophobicity.

Hydrophobic soils

- Water repellence is a chemical, biological and physical process
- Hydrophobic soils don't capitalise on rainfall events
- Water repellence is more likely to occur in sandy soils and develops as the soil dries
- Modelling has shown that water repellency can occur on heavier soils as well as sands

SOIL CRC Performance through collaboration AGRICULTURE VICTORIA

Management of drought affected soils

Grazing management

- Keeping livestock out of areas with low growth protects the valuable soil asset
- Having cut off points for when stock are removed from paddocks helps manage pastures, if there are good supplies of fodder on hand
- Selling stock, utilising stock containment areas or sacrifice paddocks and sending animals to agistment can be valuable alternatives to overgrazing paddocks
- If stock are removed from paddocks early and subsequent rains come, this can be an opportunity to put more crop in and get some hay or for pasture to re-establish.

Pasture management

- Drought can be a time to assess the species of pasture being used on farm and if there are more beneficial alternatives that might be available
- Manipulating a current pasture system is easier than completely changing it
- Using correct and recommended seeding rates during drought aids pasture production
- Some varieties of legumes can be sown in summer, catching the break and providing feed for stock (or a brown manure) before crops get sown in Autumn
- Perennial pastures systems can capture rain falling anytime during the year
- Utilising dual purpose crops for grazing as well as harvest boosts both systems in a mixed farming operation.

Crop Selection

- Drought can be a time to assess the crop rotations being used on-farm and other more beneficial alternatives that might be more suitable
- Wheat, barley and oats can be used during/after drought as safe and reliable cash crops
- Sowing early varieties will utilise water earlier in the season
- Using higher preforming legumes in the system increases soil nitrogen levels
- Multispecies cover cropping can be helpful in building up soil health and crop production.

Crop management

- Choosing a fallow if there isn't the moisture to grow a crop conserves what soil moisture is available
- Seeding systems that begin early and sow dry maximise water use
- Light pulse stubbles and their lack of ground cover can create issues going into a drought.

Hydrophobic soils

- Strategic tillage increases surface roughness, disturbing hydrophobic soils
- Increasing clay content of the soil reduces water repellency in sandy soils
- Crop residues on the soil surface reduce the formation of hydrophobic coatings on soil particles
- Wetting agents applied to the soil can increase water holding capacity.

Erosion controls

- Heavy rains often break droughts, and this influences how soil moves in the landscape
- Different soil types will behave uniquely under wind and water erosive events
- Clay delving can protect topsoil from wind erosion
- Strategic cultivation can be used to manage compaction and weeds
- Pasture furrows can be used to reduce erosion
- Strategic tillage reduces the impact of wind and water erosion
- Strategic tillage will not ruin no-till farming systems
- Returning to conservation farming practices is required after undertaking strategic tillage.

Ground cover

- Maintaining adequate ground cover helps reduce erosion.

Recovery of drought affected soils

Basic soil literacy

- Understanding basic soil health principles assists farm management and aids in progressing soil recovery
- Upskilling lenders can help them understand what farming practices assist farms to survive drought.

Drought mindset

- Landholders may bring caution experienced during drought into soil recovery after drought has broken
- Important that expectations are managed - things won't be the same, and that is ok
- There is an opportunity to assess what works and what doesn't, and what can be done differently
- Larger agribusinesses have more opportunity to implement best practice and need to share knowledge.

Wetting up of soil

- If a soil has been in prolonged dry conditions, it takes a longer time to wet up
- The initial stages of any rainfall events after drought are the most erosive
- Different soil types will have different wetting and drying cycles
- In drier climates slope becomes more important in trying to keep water where it falls.

Ground cover management

- Capitalising on rainfall events by sowing a crop or pasture will establish ground cover to protect soil loss
- Getting stock back onto paddocks quickly can risk temporary overstocking as pastures recover.

Nutrient management

- Over managed soils at the beginning of the drought can result in excess nutrients available
- As drought breaks mineralisation increases and there may be excess nutrients available
- Nutrients can be lost if topsoil has been displaced through wind and/or water erosion
- Test for nutrient status to understand if accumulation or reduction of particular nutrients have occurred
- To capitalise on nutrient availabilities that might be present following drought, root systems need to be ready.

Subsoil constraints

- Drought is an opportunity to undertake amelioration on-farm
- Not all ameliorations will work on all soil types, so it is important to understand soil type
- Deep ripping and deep-rooted perennials can alleviate subsoil compaction
- Deep placed organic matter can boost a plants response after drought
- Attack sodicity deep in the soil profile with a lime and gypsum blend
- Mix lime deeper into the soil profile to reduce subsoil acidity
- Implementing practices such as Controlled Traffic Farming can prolong the impact of soil ameliorations.

Soil biology

- Protecting microbial communities can assist with soil recovery after drought
- Soil microbes recover extremely fast after a drought
- Soil microbial activity contributes to soil surface aggregation
- Soil microbes contribute to the quick mineralisation of nutrients in the system after drought.

Disease and pests

- Plant disease will generally reduce in drought years, however some may increase
- Predicta B can be used to understand disease pressure
- Cropping cereals after drought removes the benefits break crops provide
- Sowing interrow can assist with management of stubble disease
- Drought can be an opportunity to manage some pest species.

Weeds and herbicides

- If weeds haven't been managed during the drought they can increase when the drought breaks
- Weed control over summer is important to conserve moisture and nutrients
- Some weed seed types may reduce during the drought
- If pastures are neglected there can be issues with toxicities in stock
- Herbicide residue breakdown is likely to be reduced in drought years
- Rhizobia are especially sensitive to herbicides
- Assessing if there is herbicide carryover in the soil will reduce the chance of herbicides affecting crops.

SOIL CRC Performance through collaboration   AGRICULTURE VICTORIA

Take home messages

"if a soil gets baked dry it hasn't fallen apart, it is still a productive soil, make sure you hold the soil where it is"

Important to

- Revisit basic soil literacy skills on farm
- Manage expectations that things won't be the same and that drought is a natural part of ecological systems
- Have flexibility in planning during droughts and to increase preparation for the next period of dry times.

Opportunity to

- Assess what works and what doesn't, and think about doing some things differently
- Undertake amelioration
- React quickly and capitalise on a window of opportunity after drought.

Knowledge gaps identified by participants

Soil Biology

1. What is the short-term biological impact on soil aggregation in a drought, how long will that last for?
2. How long do the different pools of soil biology survive in drought? What are their roles in drought conditions?
3. In the Darling Downs, long fallow disorder has been observed and explained by the decline of VAM. How does this play out in a drought?
4. Is there a microbe that could help in reducing hydrophobic soils?
5. What biological species are rebounding first after drought and how can this be related to profitability and productivity?
6. What is the role of macro fauna in drought effected soils?

Soil Chemistry

7. How do we deal with water repellency that develops in heavier textured soils during drought?
8. What is the role of polymers in the soil reducing hydrophobicity?
9. Regionally, how much can you reduce nitrogen fertiliser following a drought, due to the quick mineralisation of nitrogen in the soil following a drought?

Soil Physics/Erosion

10. What statistical work has been undertaken assessing the loss of topsoil due to erosion?
11. What are the agronomic costs of losing the topsoil due to erosion in a drought?
12. When should you stop and start deep ripping in a farming system?

Farming systems

13. Which regenerative agricultural techniques or approaches might increase soil resilience in droughts and what is the mechanism in which that happens?
14. How can we look at drought from a slightly different angle and see what approaches used by Traditional Owners could be adopted in modern agricultural systems?
15. What is the cost to the system of stock eating the last bit of stubble cover in a paddock compared to retaining that stubble?
16. What role do pasture legumes play in the system as a drought mitigation strategy?

General

17. What per cent ground cover do you need to protect the soil?
18. What happens to weeds with fodder moving around the country during droughts?
19. How long does it take to rebuild supplies of fodder after a drought?
20. Can we be doing better ground cover monitoring so farmers can be advised when things might be getting bad on their farm?
21. Would it be better to give cash grants in drought to encourage best practice, and avoid ecological detrimental consequences when landholders need to squeeze production off the land?
22. When we see a boom in productivity after a drought, is it soil management or soil type that has an impact on this response?
23. If you overcome your soil constraints the soil does seem to respond better after drought. Is this related to soil health or microbial activity or is it a structural or a chemical response?

APPENDIX B - FACT SHEET: CROPPING – MANAGING SOILS AFTER DROUGHT

Performance through collaboration

FACTSHEET

MANAGING SOILS DURING AND AFTER DROUGHT IN CROPPING SYSTEMS

Drought can damage soils, reducing yield after the drought breaks. The deterioration in soil condition can have wider economic, social and environmental effects on entire communities. Practices that protect the soil, reduce the impact of erosion or assist recovery to regain the productive capacity of soil, help to manage the effects of drought. Under most climate change scenarios, droughts will become more common in many cropping areas of Australia.

The impact of drought on soils and on productivity and profitability can be mitigated through careful management of soils during drought, immediately following drought and in between droughts by developing more resilient soils. This fact sheet summarises the key messages for farmers for managing soils during and after drought in cropping systems. They should be refined locally for best application.

During drought

- Reduce wind erosion risk by removing stock early and maintaining ground cover levels. Avoid grazing failed crops to maintain as much ground cover as possible.
- Retain stubbles, avoid ripping and tilling, direct drill seed.
- Target investment to protect most reliable paddocks.

Immediately following drought

- Use soil tests to gauge soil nutrient stocks and review fertiliser plans. Crops use less soil nutrients during drought. Rain after drought can create a flush of nitrogen and phosphorus, but erosion can reduce paddock fertility. Soil test to match the fertiliser plan to nutrient availability and crop needs.
- Reduce erosion risk by establishing quick growing crops (provided they fit into suitable rotations).
- Maximise soil cover and water infiltration through on-row or edge-row sowing.
- In dry areas where subsoil salinity is an issue, grow salt-tolerant species such as barley.
- Where soils are dispersive and water infiltration might be limited, consider application of gypsum to improve structure and water infiltration
- Consider extending plant back periods for herbicides as dry conditions increase the breakdown period.
- Monitor and control weeds as they can recover quickly and use soil water and nutrients.
- Test for soil diseases if they are suspected.
- Target investment to the most reliable paddocks.

Building soil resilience

- Adopt practices that increase and retain organic matter in the soil such as retaining crop residues and ameliorating subsoil constraints to encourage root growth, carbon inputs from crop roots, and carbon cycling.
- Identify and treat surface fertility and soil structural limitations.
- Monitor soil acidity and implement a liming program if required.
- Improve crop growth on sandy soils by reducing water repellence, overcoming hard pans and increasing soil fertility.
- Identify occurrence and distribution of subsoil constraints and consider practices that could be suitable for addressing those constraints such as subsoil manuring or modification.

HOW DROUGHT AFFECTS SOIL

Increased soil wetting up requirement

Generally coarse-textured sandy soils have a much lower water holding capacity than finer-textured silts and clays. However, soils with a higher clay content can hold water more tightly in their matrix. So while a greater volume of water can be stored in a clay soil, a higher proportion of this will be unavailable to plants. Following a drought, soils with a high clay content will require a significant amount of water to wet the soil profile beyond its crop lower limit (wilting point) and provide moisture for seed germination and plant growth.

Increased water repellence

Water repellence (where water ponds on the soil surface instead of infiltrating, or infiltrates very slowly) causes patchy crop establishment and exacerbates erosion risk. Drought makes water repellence worse. Sandy soils are more susceptible to water repellence.

Decreased soil microbiology

Microbial activity in the soil is influenced by the type and amount of substrate (food) available, and by temperature, oxygen and moisture content. During drought, the food source and the ability of microbes to move around the soil in solution is also affected. Lack of water can eventually lead to dehydration of the microbes and they break down. Different types of microbes respond differently to moisture stress. For example, fungi are generally more adapted to hot dry conditions than bacteria. However, soil microbes are quick to re-colonise following dry conditions and populations can bounce back provided soil organic carbon, the food source for soil biota, has not been lost through erosion.

Nitrogen may accumulate

During drought, crops take up less nitrogen, but organic matter continues to slowly mineralise, increasing the pool of plant-available N. After a drought breaks, there is often a strong increase in mineralisation causing a flush of nitrogen. Unused fertiliser can also contribute to increased soil nitrogen stocks.

Phosphorus may not decline

The type and rate of transformation from fertiliser phosphorus to soil phosphorus and fixation can vary widely because of the number of factors involved. When applied in a drought year, phosphorus can carryover depending on the soil type and whether phosphorus fixation occurs. Poor crop growth or a failed crop during drought will limit phosphorus uptake.

Chemical constraints

Less water in the soil increases the concentration of ions in soil solution so that chemical constraints such as salinity, alkalinity, sodicity and boron toxicity generally increase. Areas of saline topsoils can expand in dry years—evaporation of soil moisture concentrates salts in the surface layers and there is insufficient rain to flush them down the soil profile. These areas typically contract in size in wetter years or where surface cover reduces evaporation.

Increased physical constraints

Compaction and soil strength increase as soils dry out making it harder for roots to penetrate and restricting overall plant growth.

Increased erosion risk

One of the greatest effects that drought has on soils in dryland cropping areas is increased soil erosion. Drought leads to a decline in plant growth and vegetative cover over the soil surface. Diminished plant growth means fewer roots and less organic matter to bind soil particles. As soils dry out, they lose coherence and weight, and readily break down into smaller, lighter, more erodible particles. Sandy soils are more prone to wind erosion.

Wind erosion damages paddocks and surrounding areas. Soil blown off-site causes a range of environmental, economic and social problems. Soil erosion removes nutrients and carbon from the paddock and reduces the volume of soil available to plant roots, ultimately reducing the soil's productive capacity.

Water erosion commonly occurs after a drought breaks, particularly when heavy rain falls on bare ground. The main agents of water erosion are raindrop impact and flowing water and this can damage downstream land, watercourses, roads and other infrastructure.

Long fallow disorder

Drought can deplete arbuscular mycorrhizal fungi (AMF) in the soil. Without AMF, crops can fail to thrive, even when there is enough soil moisture. Plants will struggle to access nutrients, particularly phosphorus and zinc.

SHORT-TERM MANAGEMENT DURING AND AFTER DROUGHT

Rule 1. Maintain soil cover (ground cover)

- It is vital to protect soil from erosion. Soil cover has a major influence on the ability of crops and pastures to rebound following drought.
- Minimum soil cover levels will vary with soil type, slope and erosion susceptibility, but will be at least 50%. Check with local advisors.
- Remove livestock before critical soil cover levels are breached.
- Do not till or rip. Retain stubble and direct drill seed where possible.
- On eroding areas, emergency tillage can be used but only on soils able to maintain fist-sized clods following tillage. If sands are drifting, consider applying clay if suitable clay is available (i.e. does not have chemical issues such as elevated boron or sodium). Avoid disturbing sands unless clay delving.

Rule 2. Fine-tune fertiliser management

- Soil test to assess nutrient levels.
- Reduced rates of phosphorus application may be possible after a drought breaks. However, zero phosphorus inputs come with a risk of reduced seedling growth. Highly calcareous soils continue to fix phosphorus during dry weather and these soils may need normal rates.
- Provided there has not been major erosion, soil nitrogen may have increased through continued mineralisation. However, if erosion has depleted soil organic matter, mineralisation may be slow and different forms of nitrogen fertiliser, such as manures to add organic nitrogen back into the soil, may be necessary. Use nitrogen cautiously. Apply low levels up front, monitor plant nitrogen status and provide in-crop additions if needed.
- Consider fertiliser containing phosphorus and zinc if you suspect long fallow disorder. Fertiliser must be placed near the seed.
- Vary fertiliser rates across paddocks and zones as needed.

Rule 3. Crop management

- While it is tempting to quickly sow cereal as a cover crop, consider the rotation. Some soil borne diseases (e.g. crown rot) can become more severe after drought while for many others, inoculum levels are lower. If in doubt, test for soil diseases. Use proven crops and varieties rather than experimenting to get cover.
- On sandy soils, consider tackling water repellence with wetting agents. Sowing strategies include on-row and edge-row sowing, using winged points instead of knife points, and delaying seeding if the soil is still dry. Disturbing non-wetting soils when they are dry can make repellence worse.
- In many cases weed seed banks have been reduced. However, management options may be reduced due to plant back periods on previously applied herbicides. Read labels or guidelines where relevant.
- Monitor for long fallow disorder.

LONGER-TERM PRACTICES TO BUILD SOIL RESILIENCE

Soils that are more resilient to drought have a greater capacity to capture and store moisture, enabling crop roots to penetrate deeper and increasing biological activity and nutrient supply to plants. This leads to increased biomass production above and below ground which in turn will provide more surface cover and increased yields.

Sandy soils

Key limitations in sandy soils are compacted layers, water repellence and poor fertility. Deep tillage measures such as ripping and spading can break up compacted layers, improving aeration, drainage and root penetration. Ripping can break hardpans soil with less topsoil disturbance. If treating water repellence, spading (soil mixing), delving (bring heavier subsoil up through the profile) and mouldboard ploughing (inverts the soil, burying repellent topsoil) are longer-term fixes.

Clay spreading and incorporation on sandy soils can ameliorate water repellence. Adding clay to sandy soils increases the soil's capacity to store water and nutrients. However, adding clay to the soil can increase the amount of water required to wet up the soil beyond a crop's wilting point and provide plant available moisture so moisture stresses can occur earlier in drier years.

Undertake a soil test before adding clay to check the quality and to ensure that nutrient deficiencies and/or toxicities are not induced or are catered for. Care needs to be taken to ensure practices are suitable and timing correct to avoid exposure of the soil to erosion. Limitations need to be correctly diagnosed and then corrective practices examined with a cost benefit approach.

Controlling wind erosion

Key factors in protecting soils from wind erosion are deflecting wind flows away from the soil surface and maintaining soil aggregates so that individual particles cannot be easily dislodged. Barriers placed in the wind's path will deflect it upwards away from the soil surface. The greater the height of the barrier, the greater the deflection. On cropping soils, barriers can be clay clods but are most commonly plants or plant residues such as crop stubble. The barriers themselves must be well anchored to ensure they are not blown away by wind. Plant roots, organic matter and clay can help bind soil particles together, making them too heavy to be transported.

Preventing water erosion on sloping land when the drought breaks

A vegetative canopy or layer, living or dead, will absorb or dissipate the energy of a raindrop, reducing the breakdown of soil aggregates. The greater the area and the length of time the soil is covered by such a layer, the better the protection. Tillage practices that minimise soil disturbance are less damaging to soil aggregates. Applying gypsum can improve soil structure and water infiltration in dispersive soils. Structures and tillage practices that direct water movement across slopes rather than down them will slow flow velocity and give water more time to infiltrate into the soil.

Building organic matter

Greater plant biomass above and below ground provides more organic material to stimulate microbial activity, thereby accelerating nutrient cycling. Ameliorating soil constraints such as compaction, water repellence and acidity, and using appropriate fertiliser types and rates, help to maximise plant growth. Growing a diversity of plants, with different root structures, growing season lengths and associated microbial activity, can add organic matter to more of the soil. This diversity provides resilience and flexibility and helps to better adapt to seasonal variability. The growth of more biomass above ground provides more vegetative cover over the soil surface, protecting soils from erosion, increasing water infiltration into the soil and reducing evaporation. Below ground, roots help bind soil particles into aggregates that allow better circulation of water and air and make soil particles more resistant to erosion.

Managing acidity

Keeping soil pH in a range desirable for most plant growth (pH (water) 6-8; pH ($CaCl_2$) 5.5-7.5) is important to maintain crop growth. Many agricultural practices accelerate soil acidification. Harvesting removes alkaline material that would have otherwise returned to the soil. Ammonium-based fertilisers and legume-based pastures also speed up soil acidification.

A liming program based on regular pH testing will manage acidification. If subsoil acidity is the issue, lime must be incorporated, as it can take many years to leach into the soil of its own accord.

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The CRC for High Performance Soils (Soil CRC) is bringing together scientists, industry and farmers to find practical solutions for Australia's underperforming soils. The CRC aims to enable farmers to increase their productivity and profitability by providing them with knowledge and tools to improve the performance of their soils. The Soil CRC is the largest collaborative soil research effort in Australia's history. The Australian Government and the CRC's 39 participants collectively contribute $167 million to the Soil CRC through both cash and in-kind contributions. The Soil CRC has funding until 2027.

APPENDIX C - FACT SHEET: GRAZING – MANAGING SOILS AFTER DROUGHT

Performance through collaboration

FACTSHEET

MANAGING SOILS DURING AND AFTER DROUGHT IN GRAZING SYSTEMS

Drought can damage soils, reducing yield after the drought breaks. The deterioration in soil condition can have wider economic, social and environmental effects on entire communities. Practices that protect the soil, reduce the impact of erosion or assist recovery to regain the productive capacity of soil, help manage the effects of drought. Under most climate change scenarios, droughts will become more common in many cropping areas of Australia.

The impact of drought on soils and on productivity and profitability can be mitigated through careful management of soils during drought, immediately following drought and in between droughts by developing more resilient soils. This fact sheet summarises the key messages for farmers for managing soils during and after drought in grazing systems. They should be refined to suit local conditions.

During drought

- Reduce wind erosion risks by removing stock early and maintaining minimum soil cover levels.
- Avoid grazing failed crops to maintain as much ground cover as possible.
- Establish permanent stock containment areas for lot feeding during drought. When used strategically, containment areas take the pressure off land during dry periods or late starts.
- Avoid overgrazing native and exotic perennial grass stubs as this will significantly slow regeneration.
- Target investment to protect the most reliable paddocks.
- Consider sowing quick growing crops or annual pastures to provide soil cover and act as a break crop where pasture needs re-establishment.
- Practice no-till or sod seeding techniques for pasture establishment.

Immediately following drought

- Use soil tests to gauge soil nutrient stocks and review fertiliser plans. Pastures use fewer soil nutrients during drought. Rain after drought can create a flush of nitrogen and phosphorus, but erosion can reduce paddock fertility. Soil test to match the fertiliser plan to nutrient availability and crop needs.
- Reduce erosion risk by establishing quick growing cover crops or annual pastures where cover is required to stabilise eroding paddocks.
- Keep stock off paddocks until ground cover is at adequate levels for maximum growth. This level will vary with location and pasture type.
- Use rotational grazing techniques for even grazing pressure and avoiding baring out weak areas.
- Ensure there are enough, suitable placed watering points to reduce the distance that animals have to walk and the energy required to get there, and to reduce the risk of susceptible soils being bared out by excessive traffic.

Building soil resilience

- Adopt practices that increase and retain organic matter in the soil such as retaining crop residues and ameliorating subsoil constraints to encourage root growth, carbon inputs from crop roots, and carbon cycling.
- Identify and treat surface fertility and soil structural limitations.
- Monitor soil acidity and implement a liming program if required.
- Improve pasture growth on sandy soils by reducing water repellence, overcoming hard pans and increasing soil fertility.
- Identify the location and severity of subsoil constraints and consider practices that could address those constraints such as subsoil manuring or modification as appropriate for the location and soil type.

HOW DROUGHT AFFECTS SOIL

Increased soil wetting up requirement

Generally, coarse-textured sandy soils have a much lower water holding capacity than finer-textured silts and clays. However, soils with a higher clay content can hold water more tightly in their matrix. So while a greater volume of water can be stored in a clay soil, a higher proportion of this will be unavailable to plants. Following a drought, soils with a high clay content will require a significant amount of water to wet the soil profile beyond its crop lower limit (wilting point) and provide moisture for seed germination and plant growth.

Increased water repellence

Water repellence (where water ponds on the soil surface instead of infiltrating, or infiltrates very slowly) causes patchy crop establishment and exacerbates erosion risk. Drought makes water repellence worse. Sandy soils are more susceptible to water repellence.

Decreased soil microbiology

Microbial activity in the soil is influenced by the type and amount of substrate (food) available, and by temperature, oxygen and moisture content. During drought, the food source and the ability of microbes to move around the soil in solution is also affected. Lack of water can eventually lead to dehydration of the microbes and they break down. Different types of microbes respond differently to moisture stress. For example, fungi are generally more adapted to hot dry conditions than bacteria. However, soil microbes are quick to re-colonise following dry conditions and populations can bounce back provided soil organic carbon, the food source for soil biota, has not been lost through erosion.

Nitrogen may accumulate

During drought, crops take up less nitrogen, but organic matter continues to slowly mineralise, increasing the pool of plant-available N. After a drought breaks, there is often a strong increase in mineralisation causing a flush of nitrogen. Unused fertiliser can also contribute to increased soil nitrogen stocks.

Phosphorus may persist

The type and rate of transformation from fertiliser phosphorus to soil phosphorus and fixation can vary widely because of the number of factors involved. When applied in a drought year, phosphorus can carry over depending on the soil type and whether phosphorus fixation occurs. Poor crop growth or a failed crop during drought will limit phosphorus uptake.

Chemical constraints

Less water in the soil increases the concentration of ions in soil solution so that chemical constraints such as salinity, alkalinity, sodicity and boron toxicity generally increase. Areas of saline topsoils can expand in dry years. Evaporation of soil moisture concentrates salts in the surface layers and there is insufficient rain to flush them down the soil profile. These areas typically contract in size in wetter years or where surface cover reduces evaporation. These areas typically contract in size in wetter years or where surface cover reduces evaporation.

Increased physical constraints

Compaction and soil strength increase as soils dry out making it harder for roots to penetrate and restricting overall plant growth.

Increased erosion risk

One of the greatest effects that drought has on soils in dryland cropping areas is increased soil erosion. Drought leads to a decline in plant growth and vegetative cover over the soil surface. Diminished plant growth means fewer roots and less organic matter to bind soil particles. As soils dry out, they lose coherence and weight, and readily break down into smaller, lighter, more erodible particles. Sandy soils are more prone to wind erosion.

Wind erosion damages paddocks and surrounding areas. Soil blown off-site causes a range of environmental, economic and social problems. Soil erosion removes nutrients and carbon from the paddock and reduces the volume of soil available to plant roots, ultimately reducing the soil's productive capacity.

Water erosion commonly occurs after a drought breaks, particularly when heavy rain falls on bare ground. The main agents of water erosion are raindrop impact and flowing water and this can damage downstream land, watercourses, roads and other infrastructure.

Long fallow disorder

Drought can deplete arbuscular mycorrhizal fungi (AMF) in the soil. While more common in cropping situations, it can also occur in pastures that are drought affected. Without AMF, crops and pastures can fail to thrive, even when there is enough soil moisture. Plants will struggle to access nutrients, particularly phosphorus and zinc.

SHORT-TERM MANAGEMENT DURING AND AFTER DROUGHT

Rule 1. Maintain soil cover (ground cover)

- It is vital to protect soil from erosion. Soil cover has a major influence on the ability of crops and pastures to rebound following drought.
- Minimum soil cover levels will vary with soil type, slope and erosion susceptibility, but will be at least 50%. Check with local advisors.
- Remove livestock before critical soil cover levels are breached. Either sell, agist or establish a permanent stock containment area, but make decisions early to protect cover.
- Use sod seeding or no-till pasture establishment techniques, leaving trash on the surface.
- On eroding areas, emergency tillage can be used but only on soils able to maintain fist-sized clods following tillage. If sands are drifting, consider applying clay if suitable clay is available (e.g. does not have chemical issues such as elevated boron or salinity). Avoid disturbing sands unless clay delving.
- Rotation grazing when compared with longer set stocked techniques generally results in more even grazing across a paddock and less weak areas vulnerable to erosion.

Rule 2. Fine-tune fertiliser management

- Soil test to assess nutrient levels.
- Reduced rates of phosphorus application may be possible after a drought breaks. However, zero phosphorus inputs come with a risk of reduced seedling growth. Highly calcareous soils continue to fix phosphorus during dry weather and these soils may need normal rates.
- Provided there has not been major erosion, soil nitrogen may have increased through continued mineralisation. However, if erosion or overgrazing has depleted soil organic matter, mineralisation may be slow and different forms of nitrogen fertiliser (such as manure) may be necessary to add organic nitrogen back into the soil. Nitrogen fertiliser may be warranted especially if the upcoming pasture has low legume content.
- Consider fertiliser containing phosphorus and zinc if you suspect long fallow disorder. Fertiliser must be placed near the seed.
- Vary fertiliser rates across paddocks and zones as needed.

Rule 3. Pasture and grazing management

- While it is tempting to quickly sow cereal as a cover crop, consider the rotation. Some soil borne diseases (e.g. crown rot) can become more severe after drought while for many others, inoculum levels are lower. If in doubt, test for soil diseases. Use proven crops and varieties rather than experimenting to get cover.
- It is much cheaper and easier to manipulate an existing pasture than re-sow, particularly following a drought. Consider how to improve an existing pasture, for example, with extra fertiliser, weed control etc.)
- When in rotation with cropping, consider the long-term pasture and rotation aims rather than just the short-term needs of the establishing crop. Issues to consider are fertility, weeds, disease carryover and clover or medic seedbank.
- On sandy soils, consider tackling water repellence with wetting agents. Sowing strategies include on-row and edge-row sowing, using winged points instead of knife points, and delaying seeding if the soil is still dry. Disturbing non-wetting soils when they are dry can make repellence worse.

LONGER-TERM PRACTICES TO BUILD SOIL RESILIENCE

Soils that are more resilient to drought have a greater capacity to capture and store moisture, enabling crop roots to penetrate deeper and increasing biological activity and nutrient supply to plants. This leads to increased biomass production above and below ground which in turn will provide more surface cover and increased yields.

Controlling wind erosion

Key factors in protecting soils from wind erosion are deflecting wind flows away from the soil surface and maintaining soil aggregates so that individual particles cannot be easily dislodged. Barriers placed in the wind's path will deflect it upwards away from the soil surface. The greater the height of the barrier, the greater the deflection. On cropping soils, barriers can be clay clods but are most commonly plants or plant residues such as crop stubble. The barriers themselves must be well anchored to ensure they are not blown away by wind. Plant roots, organic matter and clay can help bind soil particles together, making them too heavy to be transported.

Preventing water erosion on sloping land when the drought breaks

A vegetative canopy or layer, living or dead, will absorb or dissipate the energy of a raindrop, reducing the breakdown of soil aggregates. The greater the area and the length of time the soil is covered by such a layer, the better the protection. Tillage practices that minimise soil disturbance are less damaging to soil aggregates. Applying gypsum can improve soil structure and water infiltration in dispersive soils. Structures and tillage practices that direct water movement across slopes rather than down them will slow flow velocity and give water more time to infiltrate into the soil.

Sandy soils

Key limitations in sandy soils are compacted layers, water repellence and poor fertility. Deep tillage measures such as ripping and spading can break up compacted layers, improving aeration, drainage and root penetration. Ripping can break hardpans in soil with less topsoil disturbance. If treating water repellence, spading (soil mixing), delving (brings heavier subsoil up through the profile) and mouldboard ploughing (inverts the soil, burying repellent topsoil) are longer-term fixes.

Clay spreading and incorporation on sandy soils can ameliorate water repellence. Adding clay to sandy soils increases the soil's capacity to store water and nutrients. However, adding clay to the soil can increase the amount of water required to wet up the soil beyond a crop's wilting point and provide plant available moisture so moisture stresses can occur earlier in drier years.

Undertake a soil test before adding clay to check the quality and to ensure that nutrient deficiencies and/or toxicities are not induced or are catered for. Care needs to be taken to ensure practices are suitable and timing correct to avoid exposure of the soil to erosion. Limitations need to be correctly diagnosed and then corrective practices examined with a cost-benefit approach.

Building organic matter

Greater plant biomass above and below ground provides more organic material to stimulate microbial activity, thereby accelerating nutrient cycling. Ameliorating soil constraints such as compaction, water repellence and acidity, and using appropriate fertiliser types and rates, help to maximise plant growth. Growing a diversity of plants—with different root structures, growing season lengths and associated microbial activity—can add organic matter to more of the soil. This diversity provides resilience and flexibility and helps to better adapt to seasonal variability. The growth of more biomass above ground provides more vegetative cover over the soil surface, protecting soils from erosion, increasing water infiltration into the soil and reducing evaporation. Below ground, roots help bind soil particles into aggregates that allow better circulation of water and air and make soil particles more resistant to erosion.

Managing acidity

Keeping soil pH in a range desirable for most plant growth (pH (water) 6-8; pH ($CaCl_2$) 5.5-7.5) is important to maintain in agricultural production. Soils tend to acidify more quickly in very productive pasture systems and where a significant amount of alkaline elements are removed in hay. A liming program based on regular pH testing will manage acidification. If subsoil acidity is the issue, lime must be incorporated, as it can take many years to leach into the soil of its own accord.

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