DISPERSIVE SOIL MANUAL

NORTHERN REGION

Managing dispersive soils: practicalities and economics

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Title: Dispersive Soil Manual:
Managing Dispersive Soils: practicalities and economics - Northern Region

ISBN: 978-1-922342-38-6 (online)

GRDC Contract Code: SMD2201-001SAX - The development of a grower technical manual for soil amelioration of sodic soils in the Northern Region

Published: March 2023

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Acknowledgements:

Excellent support was provided by:

- GRDC, Toowoomba, who initiated investment in the preparation of this manual;
- Soil science and agricultural economics colleagues (at University of Southern Queensland, University of New England, University of Queensland, Queensland Department of Agriculture and Fisheries, and New South Wales Department of Primary Industries) associated with preparation of the final reports for GRDC 'Economics of ameliorating soil constraints in the northern region: Projects A, B, C and D';
- Lawson Grains – particularly Nils Jacobson ('Uah', Forbes) and Mathew Wells – which provided invaluable data and paddock observations for the main case study in this manual;
- Ned Skehan (OptiSoil, Inverell), who prepared example farm maps, with assistance from Nick Barton, PCT-AG; and
- Stirling Roberton, Brian Murphy, John Rochecouste, Cristina Martinez, Bill Adams, Ned Skehan, Yash Dang, Neal Menzies, Tom Orton, Ehsan Tavakkoli, Warwick Dougherty, John Friend, Patrick Driver and Chris Guppy (review comments and assistance).

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COVER: Core sampling near Armatree, NSW.
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Executive summary

This soil management manual is designed for grain growers, agronomists and farm financial advisers. It proposes a method to diagnose and map dispersive soil and develop an amelioration plan (see **Soil assessment and amelioration overview** after the **Introduction**). Success with soil amelioration is demonstrated via case studies:

- Repetitive grain yield-gap losses on dispersive soil exceeding $1000/hectare/year can be overcome using gypsum, in conjunction with lime, where appropriate.
- Following soil and crop improvement, there have been net present value increases of up to $5500/ha over a five-year period and, based on 2022 grain prices, are achievable on strongly dispersive soil following gypsum–lime application.

Dispersive soils are widespread in the Grains Research and Development Corporation (GRDC) northern region. Dispersive soils become waterlogged when wet and very hard when dry, and often have a poor ability to accept and store water. Dispersion is associated with an excess of sodium ions on clay surfaces (sodicity), and is aggravated by a lack of electrolytes (salt) in the soil water. Sodic soil can be dispersive where exchangeable sodium percentage (ESP) values are as low as 4, and there are soils with an ESP of 26 that do not disperse due to factors such as salinity and the presence of lime that stabilise the soil. The associated poor structure in dispersive soil means that water is used inefficiently by plants, and soil organisms and plant roots often fail to function.

Treating dispersive soil – and the associated constraints such as compaction and excessive paddock flatness – can lead to significant yield and profitability improvements in the northern region. Diagnosing and treating soil issues is often cheaper than buying new cropping land; in some cases, the extra income from improved yield is greater than the initial value of the land.

Treatment options depend on which constraints are present, their severity and the budget for amelioration. As such, adequately understanding where the constraints are is the first step to designing an amelioration plan. Accurate soil constraint maps are first required to ensure that the most appropriate ameliorant, or blend, is applied to the correct spots within a paddock. Insufficient detail can lead to significant wasted dollars. A recent study found that gypsum misapplication following electromagnetic induction-based zoning on a 1000ha paddock wasted about $60,000 by applying gypsum where it was not needed - and not spreading it exactly where it was required - relative to a superior variable-rate amelioration design.

The next step is deciding which soils to invest in. Profitability mapping can help make investment decisions. If a soil is deemed too expensive to ameliorate, it may be better off put to another use such as provision of ecosystem services via deep-rooted perennials.

Gypsum is the most common ameliorant used to treat dispersive soil. Lime, which is cheaper per unit of calcium than gypsum, can also be used to treat dispersive soil if pH ($CaCl_2$) is <6.5. Lime is best used in combination with gypsum to provide both immediate and ongoing electrolyte and calcium benefits. Organic matter and elemental sulfur are being studied as ameliorant options and show promising results, but there is not yet enough data to draw clear economic conclusions.

Soil amelioration is usually considered an annual, variable expense. We propose that it should instead be considered as a sequence of capital expenses across a farm, paddock by paddock, where amelioration is improving the fixed asset (the soil) for future benefit. This longer-term view considers that returns are not usually immediate (as they are with fertilisers), and the large up-front expenditure gives long-term benefits well into the future. Adequate soil amelioration is often too expensive to be considered an acceptable annual expense.

List of abbreviations

ASC	Australian Soil Classification
ASWAT	Aggregate Stability in Water Test
BCR	Benefit/cost ratio
CTF	Controlled-traffic farming
EC	Electrical conductivity
ECe	Electrical conductivity (saturated soil extract)
EM	Electromagnetic
ES	Elemental sulfur
ESI	Electrochemical stability index
ESP	Exchangeable sodium per cent
EVI	Enhanced vegetation index
GR	Gamma radiometric
NDVI	Normalised difference vegetation index
NPV	Net present value
NV	Neutralising value (for lime)
OC	Organic carbon
OM	Organic matter
PAM	Polyacrylamide
PAWC	Plant-available water capacity
ROI	Return on investment

All dollar values mentioned in this manual are in Australian dollars.

Introduction

Soil constraints such as dispersion have an annual yield penalty costing billions in lost income across the GRDC northern region in eastern Australia. The boundaries of this area are shown in **Figures 3** (page 9) and **9** (page 15).

Historically, it has been cheaper and simpler to buy more farmland rather than to ameliorate moderate to severe constraints. As rural land prices in the northern region have reached an all-time high, and competition for land increases, there is incentive to look more closely at soil amelioration. In 2022, median farmland prices in northern New South Wales (NSW) and cropping areas of Queensland were $5000 to 6000/ha (Rural Bank 2022). Accurate soil testing and amelioration almost always cost less than this.

This manual presents a framework for grain growers (both family growers on small properties and large corporate farm managers) – and their agronomy/farm finance advisers – to make investment decisions to improve the profitability of dispersive soils on their properties. There are five parts in the manual:

- **Part 1: Dispersive soils in the northern region**

  This part describes – in simple terms – the science of dispersion and where it is likely to be a problem in the northern region.

- **Part 2: Diagnosing the problem**

  This part outlines a method to work out what dispersion is costing the farm and to map soil dispersion across high-priority paddocks. This method can be extrapolated to map entire farms.

- **Part 3: Creating an amelioration plan**

  This part outlines a procedure to fix soil dispersion problems and associated constraints (for example, compaction, acidity, salinity, paddock flatness) in a cost-effective manner.

- **Part 4: Economics of dispersive soil management**

  This part helps refine an amelioration plan based on net present value (NPV) and return on investment (ROI) ambitions, and financial and logistical constraints. The concept of 'soil constraints as economic opportunities' is explored.

- **Part 5: Checking that the plan is working**

  This part briefly describes how to audit the amelioration program. It also considers amelioration risks and mistakes.

The **Soil assessment and amelioration overview** after the **Introduction** outlines the key parts and steps in improving dispersive soils.

This manual draws strongly from the four ongoing GRDC projects falling under the title of 'Economics of ameliorating soil constraints in the northern region'. These projects were set up in 2018. Project A developed the ConstraintID software. Project B studied soil constraint management and amelioration options via core experiments and demonstration trials. Project C considered the economics of these activities. Project D organised a series of action learning group meetings that facilitated excellent communication between the project team, growers and their advisers across much of the northern region.

The six Project B core sites in southern Queensland and northern NSW are evaluating diverse and novel treatments to address dispersive soil and associated constraints in both topsoil and subsoil. The focus to date has been on the vast areas of naturally sodic soil that disperses when wet, causing problems such as waterlogging, excessive hardness when the soil dries, and poor soil water storage. Vertosols (cracking clays) and Sodosols (light textured topsoil overlying clay-rich sodic subsoil) are the main soil types (as described using the Australian Soil Classification; Isbell 2021) with dispersion/sodicity limitations in these regions.

As Project B fieldwork was initially delayed by severe drought, there are only two years of yield data (2020-21) from an unusually wet period for most of the study sites. Two years of yield data is inadequate for meaningful economic analysis – at least five years of measured yield response data are required covering a broad range of seasonal conditions.

As such, this manual brings together the early economic conclusions from these research projects and considers them in conjunction with important profitability results and technical details from previous soil improvement studies. Major successes are possible under both irrigation and dryland. An example (**Case Study B** (page 41)) is presented showing considerable grain yield improvement following dispersive soil amelioration – the increased profit exceeded the cost of buying the land after just a few years. Ignoring dispersion-induced grain yield gaps on dryland dispersive soils leads to large financial losses, year after year – typically costing growers more than $1000/ha annually. Ameliorants such as gypsum and lime are becoming more expensive as fuel prices for transport increase, so misapplication of ameliorants to non-responsive sections of paddocks must be minimised. High-quality soil survey information is therefore essential to guide capital investment programs for soil repair.

This manual also provides a geological framework to help extend the results from experimental sites at specific locations to other parts of the northern region.

To illustrate how soil dispersion assessment and management techniques described in this manual can be applied in a practical and systematic manner, map layers for an example paddock – part of the Lawson Grains 'Uah' property – are presented throughout. Use of the recently developed ConstraintID software (GRDC and University of Queensland) is emphasised.

A team effort

Applying the full set of methods outlined in this manual is technically challenging. Growers will – at least initially – require specialist input from experts in soil science, agronomy, farm economics, GIS and precision agriculture mapping, in addition to site knowledge collated by the landholders.

It is important to define who is responsible for what when overcoming soil-related yield gaps. Team members are likely to include:

- growers and their staff;
- general practitioner agronomists;
- accredited soil science specialists;
- precision agriculture subcontractors; and
- loan providers, farm valuers and leaders of comparative analysis groups.

Whether amelioration occurs is likely to be strongly influenced by the quality/dedication of soil management specialists hired by the growers/agronomists to assist with accurate and cost-effective soil assessment and management.

The different soil specialists available for hire in eastern Australia will invariably have their own potentially contrasting approaches to dispersive soil assessment and management. However, the methods described in this manual (or approaches that are similar) are being used with confidence by data-rich leading growers and their consultants. In the near future, it is anticipated that a much broader range of growers and their advisers (agronomists, bankers) will become aware of the large economic benefits associated with modern soil amelioration and will choose to be more involved. Recent increases in both grain prices and input costs are accelerating this process.

Agribusinesses are adapting and are aiming to provide the specialist soil assessment and management services described in this manual. However, much of the soil sampling work and dispersion testing can be carried out by growers and their staff with minimal supervision. It is a task well-suited to quiet times often associated with droughts.

A big challenge is that past and current amelioration experiments (such as Yates–Doyle, LIRAC) do not cover all possible constraint combinations that occur in numerous paddocks across the northern region. New on-farm trials are of critical importance. The soil amelioration options to consider for dispersive soil in the northern region (Table 5) are a valuable guide for this type of planning, but the shortage of soil science specialists means that it may be difficult for growers/advisers to get timely advice about which treatment combinations to include, which could be a serious barrier to adoption.

We envisage that with more focus on factors such as remnant vegetation and ecosystem services, an extra team member who is likely to be needed when overcoming soil-related yield gaps is an ecological soil scientist.

Limitations

It is widely recognised that a professional and comprehensive approach to assessing and ameliorating serious soil constraints on eastern Australian grain farms has often been lacking, but progress is now occurring. Although this manual collates the latest research findings, there are still many knowledge gaps and further research is required. Knowledge gaps are noted throughout the manual.

This manual will be updated by GRDC and its partners as scientific knowledge refinements and grower case study developments occur.

Soil assessment and amelioration overview

PART 2 DIAGNOSING THE PROBLEM	COLLATE EXISTING KNOWLEDGE	**Step 1** Draw a soil map based on local knowledge (page 14)	
		Step 2 Consider geology (page 14)	
		Step 3 Obtain crop performance maps (ConstraintID) and yield gap map; the cost of inaction (page 15)	
		Step 4 Field clues and existing soil data (page 17)	
	CONSTRAINT ASSESSMENT AND MAPPING	**Step 5** Low-density, yield-data-guided soil assessment (page 18)	One-metre-deep soil core every 50–500ha. Assess topsoil and subsoil dispersion, ESP; PLUS compaction, alkalinity/acidity, salinity, nutrients, surface flatness.
		Step 6 Compare soil test data with remote sensing layers (page 21)	Obtain extra remote sensing layers if relevant and cost-effective. Attempt to match soil data to remote sensing layers. If accurate predictions are possible for all of the key soil factors, use the remote sensing data as a low-cost alternative to further soil coring/analysis.
		Step 7 Flexible-grid, intensive soil sampling (page 22)	Prioritise topsoil assessment, with core sampling about every 5ha. Dig soil inspection pits to complement core sampling.
		Step 8 Map individual constraints (page 23)	Focus initially on soil dispersion maps.
PART 3 CREATING AN AMELIORATION PLAN		**Step 9** Soil amelioration requirements (page 26)	Choose priority paddocks. Work out ameliorant rates (where required) and cost of dispersion repair using inputs such as gypsum and lime. Plan the repair of associated constraints such as compaction, poor surface drainage and acidity. Estimate profitability following amelioration. Consider economic case studies.
PART 4 ECONOMICS OF DISPERSIVE SOIL MANAGEMENT		ROI mapping	
		Strip trials	Ideally, use strip trials before applying ameliorants to identify zones with maximum profitability.
PART 5 CHECKING THAT THE PLAN IS WORKING		Performance evaluation	Monitor yields and economic performance in ameliorated paddocks.

Part 1: Dispersive soils in the northern region

Dispersive soils are a challenge for growers across much of the northern region. Soil sodicity, a common cause of dispersion, affects nearly 70 per cent of the cropping land in NSW and Queensland (Orton et al. 2018). Across Australia, soil sodicity is estimated to cost $1.3 billion/year in lost income in wheat cropping alone.

What is dispersion and why is it a problem?

When a soil disperses in water, the aggregates collapse and the soil particles separate (**Figures 1** and **2**). As the soil dries, it becomes a structureless hardened mass, without inter-connected pores for infiltration and root growth. Poor aeration becomes a problem when a dispersed soil is moist.

There are two types of dispersion:

- spontaneous dispersion, where the soil disperses as soon as it gets wet; and
- mechanical dispersion, where a soil might be structurally stable but application of mechanical energy (for example, heavy raindrop impact, tillage or trampling of wet soil by livestock) may be enough to make the soil dispersive. A mechanically dispersive soil with a protective mulch may not disperse during rainfall but will disperse after tillage if the soil is moist.

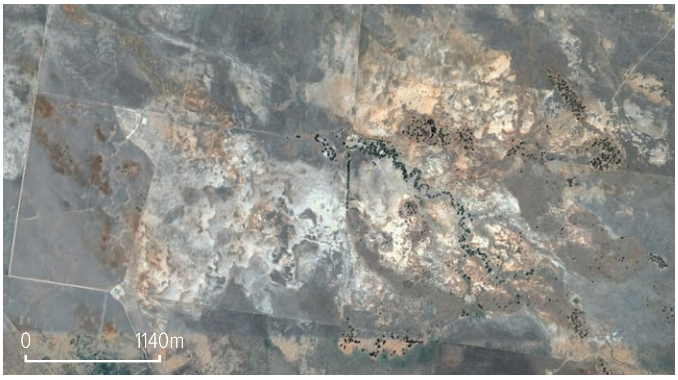
Dispersive soils present multiple physical challenges for crops. Surface crusts reduce seedling emergence, prevent infiltration (causing run-off and erosion), reduce subsoil moisture and limit gas exchange throughout the soil profile. Dispersive subsoil is often too dense for crop roots to penetrate, meaning less access to subsoil water and nutrients. As dispersive soils are often on flat landscapes, poor drainage means they are prone to waterlogging and bogginess. Nitrogen losses via denitrification can be large.

These physical challenges limit crop growth with run-on implications for soil biological activity. Soil organic matter (OM) is often lower in dispersive soil due to fewer plant inputs (Page et al. 2020). The high pH common in dispersive soils also lowers carbon (C) accumulation. Microbial activity is particularly lower in saline dispersive soils (Page et al. 2020).

The poor structure associated with dispersive soil provides a poor habitat for beneficial soil organisms.

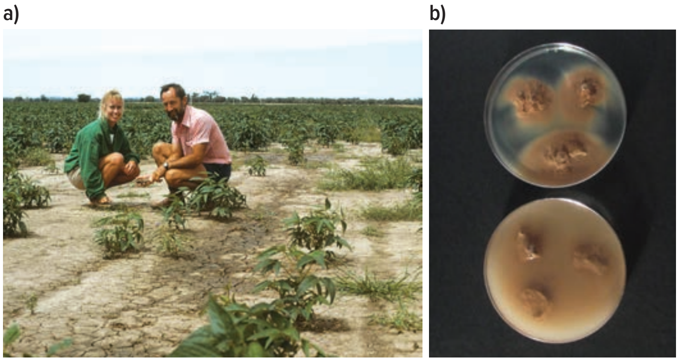
The connection between soil dispersion and sodicity/salinity is discussed below in the section **What causes dispersion and associated constraints?**

Figure 1: Evidence of dispersive topsoil in the northern region can be found on Google Earth® images. In this example, the pale fine sand and silt that has separated (during wet conditions) from unstable dark clay particles is clearly visible under subsequent drought conditions.



Source: Google Earth

Figure 2: Signs of surface dispersion: a) after drying in a paddock under irrigated soybeans near Condobolin; b) disintegration of natural (top) and disturbed (bottom) sodic aggregates in distilled water.



Source: David McKenzie

Where are dispersive soils in the northern region?

Existing soil and geology maps can provide a rough guide to dispersive soil locations; however, these are usually based on modelled properties and may not be true on every farm. The only way to know for certain where dispersive soil lies is to do a series of dispersion tests.

Dispersive soils typically have a high clay content, but some have a relatively light clay loam texture. Sands do not have enough clay to disperse. According to the Australian Soil Classification system, dispersion in the soil profile is more likely on Grey Vertosols and Sodosols, which are both widespread in the northern region (**Figures 3** and **4**).

Features of dispersion and associated constraints

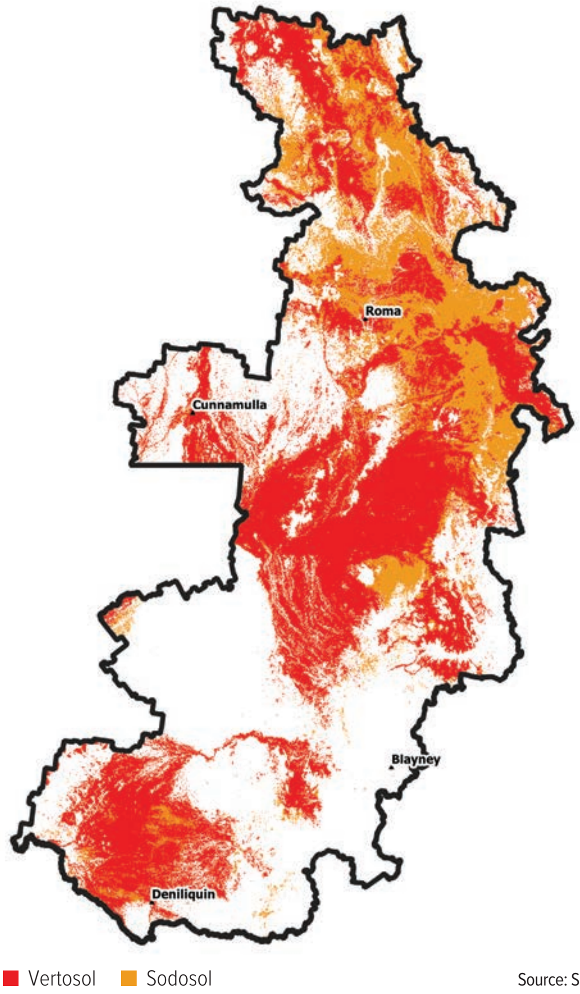
A variety of soil properties influence whether a soil is dispersive and how dispersive it is. Cation balance – particularly exchangeable sodium per cent (ESP) – salinity, OM, clay content and clay mineralogy affect dispersion. Generally, soils are more likely to disperse with:

- more than 30 per cent clay. Soils with less than 15 per cent clay are usually too sandy to disperse;
- ESP >5 (>3 when salinity is very low); see the next section **Sodic soil**;
- electrochemical stability index (ESI) (EC1:5 ÷ ESP) <0.02;
- salinity (ECe) <2 decisiemens per metre (dS/m);
- inadequate OM to bind aggregates;
- mineralogy – illite clays are more likely to disperse than other clay types (Sumner 1993);
- higher amounts of exchangeable magnesium, which can aggravate dispersion, particularly if illitic clay minerals are present, but it is a secondary issue compared with exchangeable sodium; and/or
- an increase in pH.

Dispersive soil is often accompanied by other constraints. Likely constraints include high pH; toxicities such as boron or chloride; nutrient deficiencies such as copper or zinc from high pH; elevated salinity; and low water use efficiency. Sometimes these constraints are as problematic as the dispersion itself.

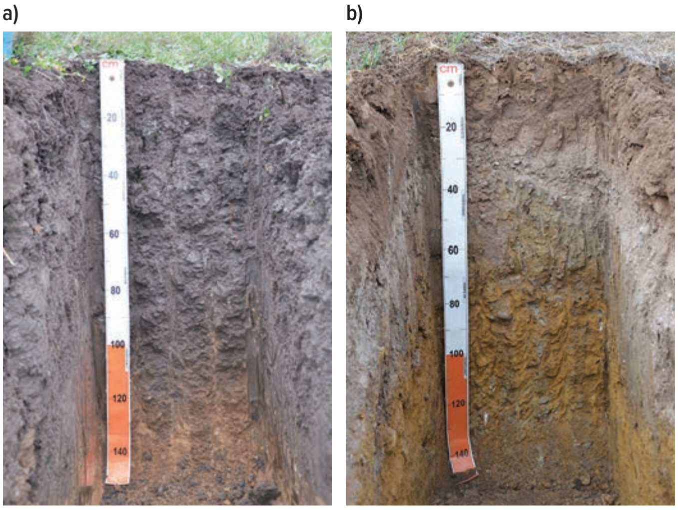
The characteristics of dispersive soil are further described below.

Figure 3: Distribution of Sodosols (orange shading) and Vertosols (red shading) within the GRDC northern region. There is no distinction here between the Vertosol suborders; Black Vertosols are less dispersive/sodic than Grey Vertosols.



Source: Searle 2021

Figure 4: Profile photographs: a) Grey Vertosol with sodic subsoil; b) Yellow Sodosol. Sodosols are alkaline and sodic soils with sharp increases in texture. Vertosols are cracking clays.



Source: David McKenzie

Sodic soil

Too much exchangeable sodium is a common cause of soil dispersion. When a sodic soil gets wet, the sodium ions weaken the links between negatively charged clay particles. This makes moist soil aggregates swell excessively and break, destroying soil stability. When the soil dries, the particles are still dispersed and the soil hardens into a tough mass without functional pores for water, air and crop roots to move through. Links to more details of these processes are presented in **Appendix A** (page 55).

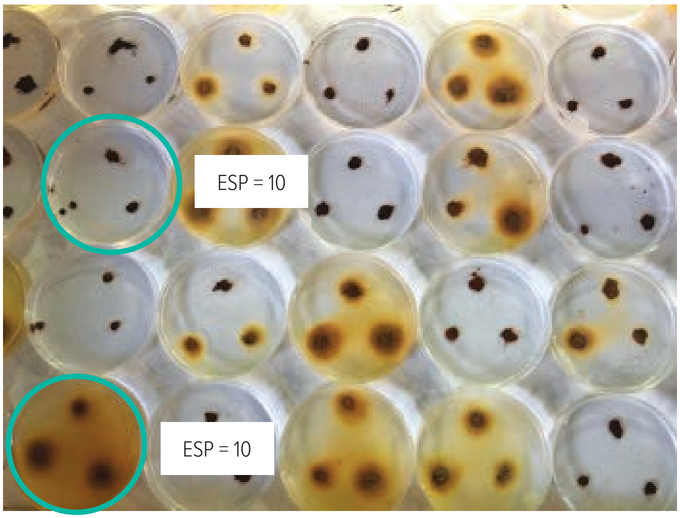
A soil with an ESP of more than 5 (McIntyre 1979) or 6 (Northcote & Skene 1972) has traditionally been considered sodic in Australia, and an ESP >15 is considered strongly sodic (Northcote & Skene 1972). The terms 'sodic soil' and 'dispersive soil' are often used interchangeably but they are not synonymous. Not all sodic soils disperse and there is no definitive ESP at which soil disperses. Using ESP as a measure of dispersion is not recommended. For example, when 980 soil samples from northern NSW and southern Queensland were tested, 38 per cent of the 737 samples with an ESP ≥5 did not disperse (Bennett et al. 2022). There have even been soils with an ESP of 26 that do not disperse (Thyer 2021). Analysis of 306 soil samples from southern NSW and northern Victoria found that 17 per cent with an ESP <6 dispersed, and 3 per cent with an ESP >6 did not disperse (Vance et al. 2002). Shainberg et al. (1980) noted that in distilled water, hydraulic conductivity can be impaired by dispersion at ESP values as low as 1 to 2 per cent.

In Bennett et al. (2022), a combination of ESP, pH and electrical conductivity was a better predictor of dispersion than ESP alone, but this was still inaccurate 17 per cent of the time.

Testing lime content in soil samples is a non-standard procedure in the grains industry, but Yates and McGarity (1984) noted in the Moree District that topsoil with a $CaCO_3$ content of >0.28 per cent did not disperse, regardless of ESP values. Clay soils that are subplastic are very stable in water, even when ESP is greater than 15 (McIntyre 1979).

Most crops do not suffer from sodium toxicity, but high sodium can interfere with the uptake of other cations such as potassium. Dodd et al. (2013) showed that up to an ESP of 19, the soil physical effects of sodicity on a Grey Vertosol were mainly responsible for poor cotton performance and its ability to accumulate potassium. At ESP >19, soil chemical constraints, high plant sodium concentrations (>0.2 per cent), and marginal plant manganese concentrations limited plant performance.

Figure 5: ESP values are sometimes a poor predictor of soil dispersion in the northern region.



Source: Roberton pers. comm. 2022

Salinity

Sodic soil is often saline. A saline soil has too much salt dissolved in the soil solution – the water/liquid in the soil pores. A soil is considered saline when ECe is >4 dS/m (Hazelton and Murphy 2016); however, every plant species has its own tolerance to salinity.

Salinity reduces crop growth by making it harder for the crop to take up water. The more salts in the soil solution, the more energy the plants need to take it up. If there is a higher concentration of salts in the soil solution than inside the plant roots, water moves out of the roots and into the soil water.

Too much salt can also cause chloride toxicity, which is seen on the leaf tips (dull yellow, dieback) and the plant is generally stunted. Chickpeas, for example, are more sensitive to chloride than wheat and barley.

If EC values seem unusually high, check sulfate levels. Elevated sulfate could be a clue that gypsum in the subsoil is leading to high EC results from the laboratory.

Table 1: An example of a dryland cropping soil with dispersion occurring despite ESP being <5. An ASWAT score >6 indicates dispersion.

Depth (cm)	pH ($CaCl_2$)	EC 1:5 (dS/m)	CEC (cmol(+)/kg)	ESP	ESI	ASWAT dispersion score	SOILpak compaction score
0–10	4.6	0.05	6.7	4.0	0.01	11	0.2
10–30	5.9	0.04	14.0	4.4	0.01	12	0.7
30–60	7.0	0.05	19.3	7.8	0.01	14	1.0
60–90	7.3	0.08	23.0	9.6	0.01	13	1.0

Salinity and sodicity

Where a soil is both saline and sodic, there is some benefit to soil salinity as salinity can suppress dispersion. As salinity increases, soil dispersion decreases. This means that saline–sodic soils often have higher infiltration rates and can produce good yields if the salts are high enough to suppress dispersion but not high enough to be toxic to plants.

However, just as there is no set ESP at which soil disperses, there is no universal index or threshold at which salinity begins to suppress dispersion. For example, a non-saline soil may disperse at ESP 4, whereas a more saline soil might not disperse when the ESP is 10. **Figure 5** shows two soils with an ESP of 10. The top dish is not dispersive, whereas the bottom dish is moderately dispersive.

The electrochemical stability index (ESI = EC1:5 / ESP) describes the relationship between salinity and sodicity. An ESI <0.05 suggests the soil is dispersive, with values <0.02 often associated with strong dispersion. Laboratory data and a paddock assessment of compaction severity are presented in **Table 1** for a grain cropping soil profile with topsoil that is non-sodic but strongly dispersive. At this site, the ESI score (0.01) was a more effective indicator of dispersion than ESP.

The Aggregate Stability in Water Test (ASWAT) (see the next section **Dispersion thresholds for crop growth**) is a valuable way to test dispersion. In **Table 1**, the ESP was <5 in the top 30 centimetres but the ASWAT score was 11 to 12, that is, the soil was not sodic but it was dispersive due to the low salinity.

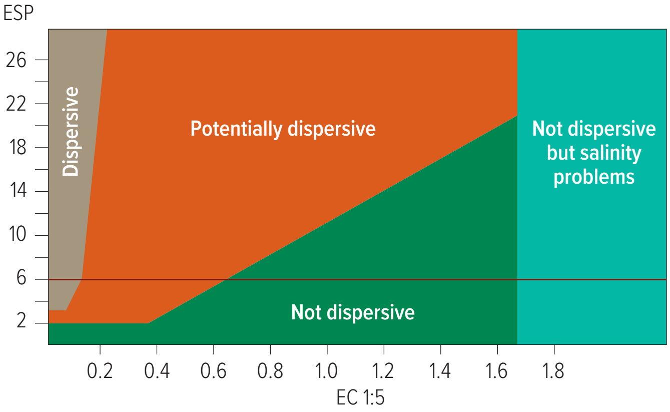
Transient salinity

Transient salinity is a form of salinity that interacts with sodicity/dispersion and is influenced by seasonal rainfall and crop evapotranspiration rather than by groundwater (Rengasamy et al. 2016). This type of salinity tends to be more prevalent in regions with less than 200 millimetres of annual rainfall. Two mechanisms that contribute to its transient nature are salt movement in the soil profile and changes in the ratio of salt and water. As crops transpire, they draw water and salts to the surface. As the soil dries, the salt concentration in the root zone increases. When it rains, the salts are diluted or leached and salinity drops. In drier years, there is less water in the soil and therefore a higher ratio of salt to water.

When transient salinity is present, it causes the same problems as permanent salinity: reduced root growth, decreased water availability for crop growth, and sometimes exacerbated boron toxicity. In theory, transient salinity can suppress dispersion. However, it is unclear if transient salinity levels can become high enough to do so and there is no universal index or threshold at which salinity from sodium chloride begins to suppress dispersion. Additionally, in wet years, rainfall can temporarily dilute the soil solution salinity, leading to aggregate swelling and dispersion.

What salinity, particularly transient salinity, highlights is that the soil system is dynamic and some soils may not always disperse. It is recommended to monitor soil conditions over time to keep ESP and salinity levels within the desired ranges (**Figure 6**).

Figure 6: Predicting dispersion using ESP and EC.



Source: Adapted from Central West CMA (2008), and Hazelton and Murphy (2016).
A more detailed version is shown in Appendix D.

Alkalinity – high pH

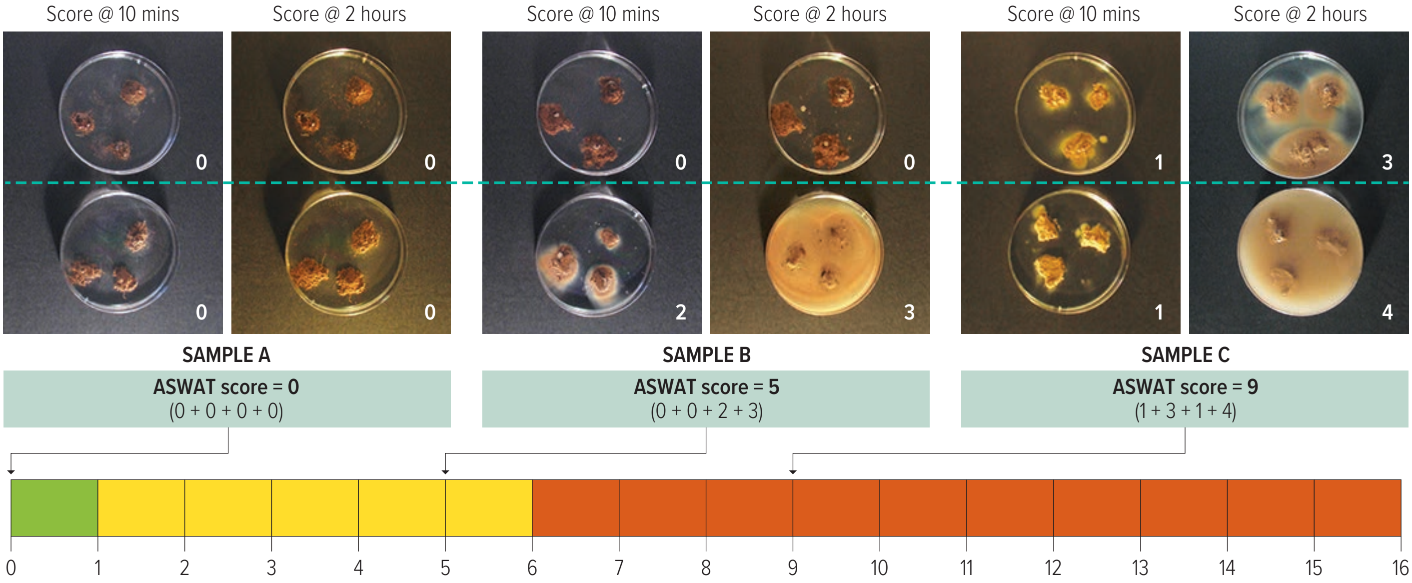
Alkalinity can exacerbate dispersion by affecting the negative charge on the clay particles. As the clay particle becomes more negative, it is more likely to repel other clay particles. In one study (Chorom et al. 1994), at a set ESP, soils with a pH of 9 were two to three times more likely to disperse than those with a pH of 6.

In cropping soils, when pH is >8.5, nutrient imbalances become more likely. At a high soil pH, trace elements (including iron, copper, manganese and zinc) become unavailable; whereas boron and molybdenum can be toxic. Sodium is also elevated; however, the sodium itself is not usually an issue for plants; it is what sodium does to soil structure (causing dispersion) that is the problem.

Compaction and dense soil

As dispersion destroys soil structure, high bulk density and elevated soil strength are common, making it difficult for roots to grow – particularly when the soil is dry.

Figure 7: The ASWAT framework for assessing dispersion severity.



Management needs:

🟩 Stable in water: keep up the good work 🟨 Avoid energy inputs on wet soil, e.g. raindrop impact, tillage, livestock trampling, machinery compaction

🟧 Add gypsum and/or lime to overcome dispersion

Source: Field et al. 1997 and McKenzie (2013)

Dispersion thresholds for crop growth

Different crops have varying tolerances to the problems caused by dispersion. Several research trials have attempted to quantify crop thresholds for aspects of dispersion, such as ESP, salinity and soil strength. However, there is not enough information to publish precise criteria (Page et al. 2021).

As farming is a business, what really matters is knowing how soil dispersion is affecting crop growth, yield and profitability.

Given that dispersion makes a soil waterlogged when wet and excessively hard when dry, we can safely assume that dispersion will adversely affect the performance of all grain crops.

The ASWAT (Field et al. 1997) (instructions provided in **Appendix B** (page 56) is an easy way to assess soil dispersion. It is derived from the widely used but more time-consuming Loveday and Pyle (1973) dispersion test. An ASWAT score of 6 or above (**Figure 7**) indicates that spontaneous soil dispersion is present in undisturbed aggregates and is likely to adversely affect crop growth and yield.

Part 2: Diagnosing the problem

How to diagnose soil dispersion

Diagnosing dispersion – its extent and severity – is the first step to knowing if dispersion is costing the farm money (and how much). Diagnosing dispersion accurately across the farm requires desktop analysis, paddock soil sampling, mapping, and reviewing yield maps and other spatial layers.

The end goal is to have a map of the farm highlighting areas of dispersion, in conjunction with topsoil and subsoil maps showing the location and severity of associated constraints affecting crop growth.

The exercise requires time, budget and trips into the paddock to develop useful dispersion and amelioration maps. The process needs to be adapted to the level of existing knowledge about the farm. Farms with more detailed historical soil testing, site knowledge and spatial layers will need less work to diagnose dispersion.

Overall, the process follows a series of steps to figure out where dispersion is and which amelioration treatments are likely to be effective and profitable, rather than trying to solve all soil problems immediately.

Steps in the process to diagnose and map soil dispersion

- **Steps 1–4:** Use existing site knowledge, geology maps, crop performance maps (for example, yield maps) and paddock clues to mark out focus areas for soil testing.
- **Step 5:** Low-density, yield-data-guided soil testing (one core every 50 to 500ha) in good and poor yield areas to identify soil constraints, their severity and impact on yield.
- **Step 6:** Compare soil test data to remote sensing layers such as electromagnetic induction to fill in the gaps between sample points. Continue to **Step 7** if layers and test results do not correlate well.
- **Step 7:** More detailed soil sampling (one core, or cluster of cores, every 5ha) to map individual soil properties of concern; for example, dispersion, ESP, pH, salinity.
- **Step 8:** Map individual constraints. These maps are the basis of amelioration; for example, gypsum rate maps.

The costs of an accurate diagnosis should be covered by the subsequent increased yield and reduced costs from accurate amelioration. For example, one recent study found that gypsum misapplication on a 1000ha paddock wasted about $60,000 by applying gypsum where it was not needed, and not spreading it exactly where it was required (Cockfield et al. 2021).

The best time to diagnose soil dispersion is when the landholder has adequate time to complete the above steps; for example, when farm activities slow down during droughts.

Tools and skills needed to diagnose soil dispersion are:

- time and motivation;
- technical expertise from a soil specialist, precision agriculture adviser and agronomist;
- aerial images of the property; e.g. colour images of bare topsoil during droughts are particularly useful. Print a few copies as several versions may be required to fine-tune and record data such as paddock clues. Adding notes or sketches of soil-related observations by landholders on the soil maps is invaluable information for associated agronomists and soil specialists;
- yield maps and other spatial layers; for example, normalised difference vegetation index (NDVI), ConstraintID, EM/elevation surveys; and
- existing soil test results. Consider both government-supplied soil data (if available with a favourable accuracy) and information collected locally by growers.

The aerial imagery from Google Earth®, for example, might be sufficient for this exercise. Go back through the historical images to try and find problem areas that require soil analysis and interpretation.

New farm versus existing site knowledge

If historical grower observations are not available, the process is similar but more reliant on spatial layers. To identify poorly performing areas and likely dispersive areas, the best layers to start with are geology maps, historical aerial images and ConstraintID.

Collate existing knowledge

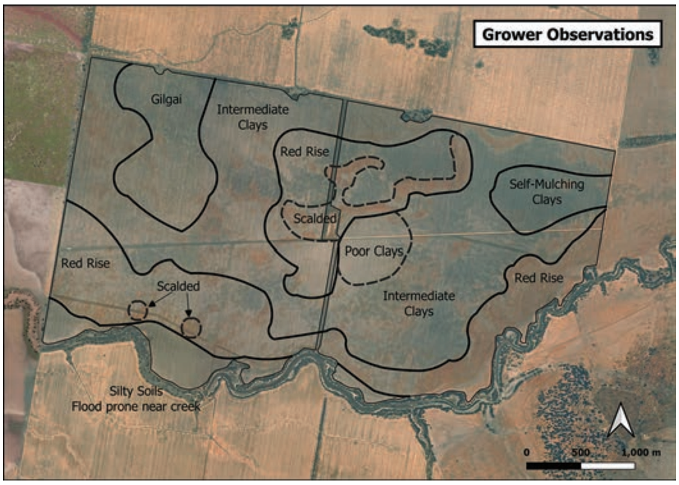
Step 1: Draw a soil map based on local knowledge

The aim of this step is to find areas of low productivity or poor yield that are likely to be associated with soil dispersion or related constraints. This is most easily done on an aerial image. Start by printing off large aerial maps of the farm and adding grower knowledge about soil types. Growers and their staff who have been on the farm for a while will have a strong impression of areas that perform well and those that do not. This knowledge is very valuable and can trump remote sensing data (although this will be refined and updated with data from spatial layers).

Go back through historical aerial images to see yield variations through good and poor seasons. Dry years are very good at showing where soil constraints might be a problem. If using Google Earth®, images with bare soil are valuable. Pale soil can be from low organic carbon associated with poor plant growth caused by dispersion. It can also be caused by the separation of pale-coloured silt and fine sand on slight ridges from the darker dispersed clay particles that settle in the low points (**Figures 1** (page 8) and **Figure 4b** (page 9)). Red tends to indicate favourable drainage, whereas yellow (**Figure 4b**) tends to be associated with the poor drainage that often occurs in dispersive soil.

An example paddock covering approximately 1200ha is shown in **Figure 8**.

Figure 8: 'Uah' example paddock in 2013, pre-purchase. This map was annotated by the farm manager in 2022.



Step 2: Consider geology

Overlay a geology map onto the map with hand-drawn boundaries. Even if the plan is to ameliorate only one test paddock to start, it is important to be aware that more than one distinctive geological unit can occur within a single paddock.

The geology information available for the northern region is much more detailed than a few years ago. The NSW geology map is found at: www.regional.nsw.gov.au/meg/geoscience/projects/seamless-geology-project. The spatial data can be downloaded and viewed on Minview (minview.geoscience.nsw.gov.au/) or the ArcGIS explorer app. The Queensland geology map can be viewed on Queensland Globe by selecting 'state surface geology'.

In NSW, the two geology units known to have large tracts of strongly dispersive soil are Inactive alluvial plains (CZ_a) and Colluvial sheetwash (Q_cs) (**Figure 9**). These units have been shown, via replicated paddock experiments, to respond profitably to gypsum and lime amelioration.

- Inactive alluvial plains (CZ_a)

  The ancient inactive alluvial plains associated with the 'Uah' Forbes GRDC core site and case study site described in this manual, and the LIRAC Condobolin experimental sites (see **Case Study B** (page 41); with economic data), are on CZ_a material deposited by large northerly-flowing rivers about 90 million years ago, prior to uplift of the Great Dividing Range. An overview of the geological history of these landscape units (pedoderms) is described by Ollier (1995) and White (1994).

  The Brown Sodosol gypsum–lime experiment near Peak Hill described by Valzano et al. (2001) is also on the CZ_a pedoderm. They recorded improvements of wheat grain yields of up to 43 per cent from a gypsum–lime blend, 2.5 years after application. Gypsum-responsive heavy clay soils of the Bland (Grogan and Morangarell districts) described by Dear et al. (2005) and Uddin et al. (2022) are part of the CZ_a landscapes.

- Colluvial sheetwash (Q_cs)

  The Yates–Doyle experiments on Grey Vertosols near Garah and Gurley (**Case Study A** (page 55)), and on a Brown Sodosol near Armatree (GRDC core site), are on colluvial sheetwash (Q_cs) material with a similar age to the CZ_a pedoderm.

In Queensland, the pedoderms associated with soil dispersion constraints are Bungil Formation, Wallumbilla Formation and TQr_QLD (**Figure 9**). The Talwood and Millmerran GRDC core sites are on the TQr_QLD unit; the Drillham core site is on the Wallumbilla Formation.

These ancient pedoderms in NSW and Queensland with large areas of dispersive soil are distinctly different from the younger active alluvial plains adjacent to and downstream of towns such as Dalby, Moree, Narrabri, Narromine and Forbes. These younger pedoderms are often derived from parent materials that are less sodic. Although the younger alluvium does have pockets of strongly sodic soil (for example, in the Warren District; described by Murphy and Duncan 2015), it tends to be less uniformly and severely dispersive across large areas.

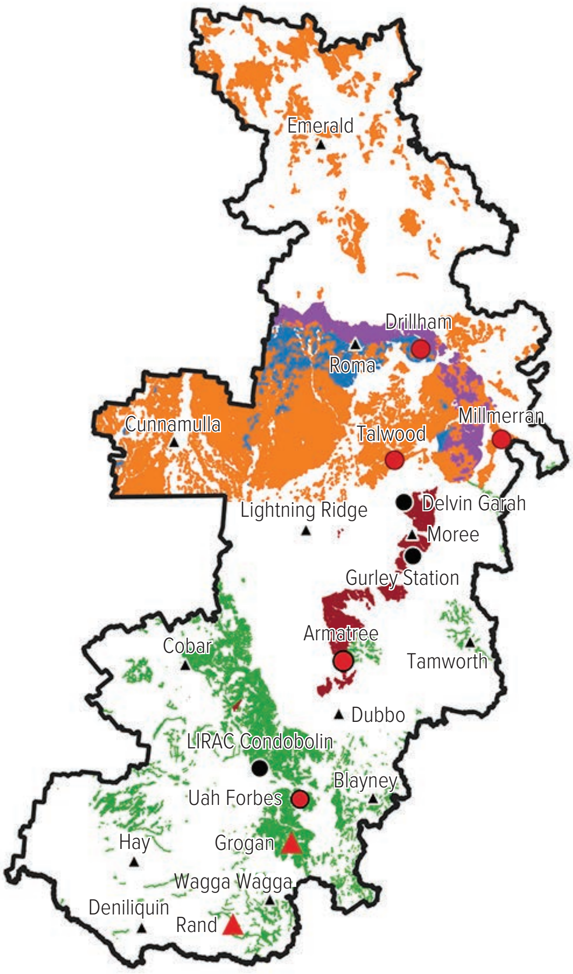
The location of the pedoderms in the area of interest at 'Uah' is shown on **Figure 10**.

In some southern areas, such as around Wagga Wagga, NSW, thick layers of dust (parna) form a large part of the root zone. In these cases, the underlying geology has little impact on soil quality in the root zone.

The input of dust during extreme drought prior to European settlement was accompanied by sodium-salt deposition that aggravated sodicity in soils of the northern region (Chartres 1995).

Much remains to be learnt about the relationship between geological history, clay mineralogy and dispersive soil distribution (and response to ameliorants) across the northern region.

Figure 9: Geology map of NSW and Queensland showing pedoderms associated with dispersive soil in the GRDC northern region that are known, via replicated experimental work under grain crops, to be strongly responsive to amelioration with gypsum/lime. There is a sixth GRDC core site at Spring Ridge NSW, but it is not shown due to a negligible response to amelioration after two years.



Dispersive soils study sites:
● Current UNE/QDAF/GRDC core sites
● Earlier UNE/NSW DPI sites with economic analyses
▲ Current NSW DPI sites
NSW geology:
🟩 Ancient pedoderms including inactive alluvial plains (CZ_a): Cretaceous
🟥 Colluvium (Q_cs): Cretaceous/Quaternary
QLD geology:
🟪 Bungil Formation (JKb) (sandstone): mid-Jurassic
🟦 Wallumbilla Formation (Ku) (mudstone, siltstone): Cretaceous
🟧 Colluvium (TQr–QLD): late-Tertiary/Quaternary

Step 3: Crop performance maps

Yield maps and vegetation index-based products, such as ConstraintID, are useful to find areas of good and poor performance within a paddock. Comparing soil tests from good and poor areas helps identify if dispersion or an associated constraint is causing the yield difference.

Normalised difference vegetation index (NDVI)

The NDVI shows how green the crop is. NDVI maps are calculated from satellite data. Most use a red–green colour range with red–orange colours representing low crop cover (for example, bare soil) ranging up to green representing dense crop cover.

Use NDVI maps to identify areas of good and poor crop growth. Early season NDVI maps can identify dispersive soil by showing patchy crop establishment. NDVI does not correlate directly with yield (as good biomass might not translate into yield) so use it in conjunction with yield maps. If NDVI maps show good growth but poor yield, this may be a clue that subsoil dispersion is limiting crop access to deeper subsoil moisture.

Use historical NDVI images to compare seasons. Dispersion may be more evident in wet seasons.

Enhanced Vegetation Index (EVI)

The EVI is similar to the NDVI but uses more wavelengths of light to correct some of the NDVI inaccuracies. For example, NDVI readings will change based on the time of day (the angle the sun hits the leaves). EVI corrects for this as well as for atmospheric conditions, distortions in the reflected light caused by particles in the air, and signals from ground cover.

ConstraintID

ConstraintID is an online tool developed by the University of Queensland. It offers historical (from 1999 onwards) and current NDVI information via satellite imagery. At the time of writing, ConstraintID (constraintid.com.au/About) was free to use. The tool uses satellite imagery to generate an EVI. The index shows which parts of the paddock were above or below average.

To refine the maps, ConstraintID recommends collecting soil data to 1.2 metres deep from three to four locations in the consistently high-yielding areas and three to four locations in the consistently low-yielding areas. Soil parameters to focus on include dispersion (ASWAT score), ESP, CEC, pH, salinity, chloride levels and compaction severity.

Figure 10: 'Uah' paddock location in relation to geology. Map from NSW MinView where orange shading = ancient inactive alluvial plains (CZ_a), known to be sodic/dispersive; cream shading = recent alluvium derived from the ancient material (Q_af).

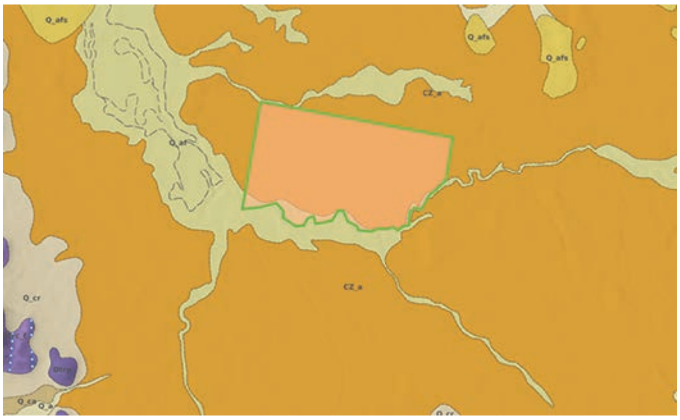
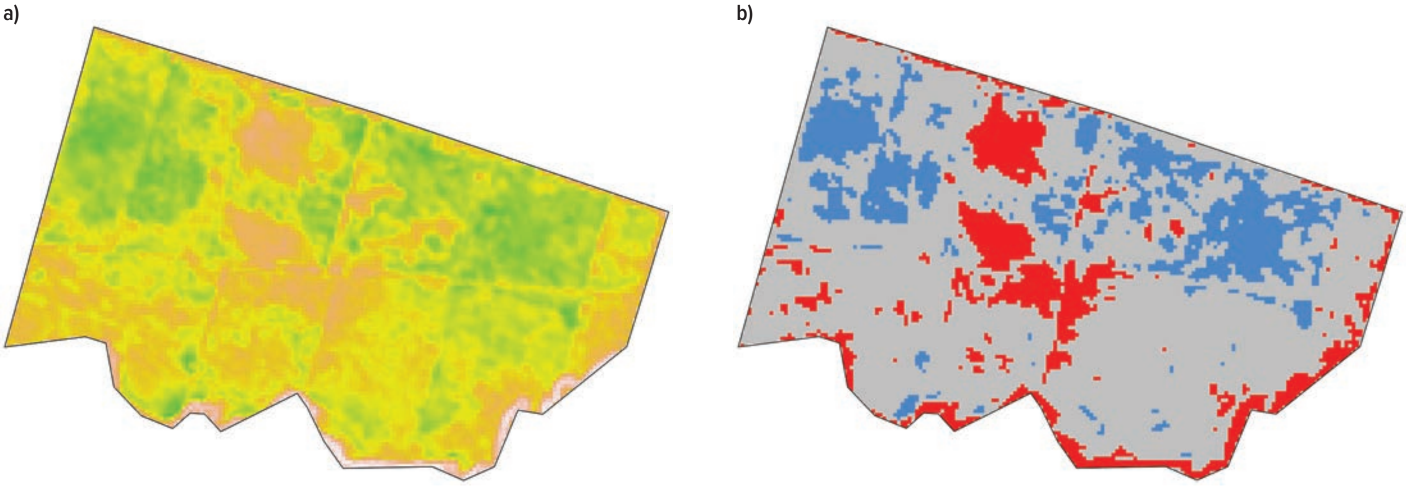


Figure 11: 'Uah' ConstraintID maps: a) long-term average EVI map; b) consistently low-yield (red), high-yield (blue) and inconsistent yield (grey) areas.



a)

b)

Figure 11 shows the EVI map from ConstraintID for 'Uah'. The data has not been calibrated with soil data or winter cropping years (a calibration option in ConstraintID). ConstraintID also maps consistently high and low-yielding areas (**Figure 11b**). Some of the consistently low-yielding areas in the middle of the paddocks roughly align with areas the manager marked as scalded and poor clays.

Yield maps

Yield map data (**Figure 12**) is highly valuable but it can take significant effort to turn the raw data from the harvester into clear maps. Data may need cleaning to remove errors, very high or low readings, and to calibrate from multiple headers. Showing yield in the same colour palette/legend across the whole farm makes it significantly easier to compare paddocks.

If yield map data is not already being collected, now is the time to start. Most harvesters can record yield data.

Go back through historical aerial images and yield maps to see yield variations through good and poor seasons. Wet years often lead to waterlogging associated with poor drainage caused by dispersion and aggravated by paddock flatness. Dry years can also show where soil constraints are adversely affecting soil water intake and storage.

The value of yield maps

To help understand the ongoing adverse impact of dispersion on farm profitability, actual yield data can be compared with modelled yield data using actual rainfall data for 'Uah' and the French–Schultz equation (French & Schultz 1984, Bowman & Scott 2009) to provide yield gap and yield gap cost maps (**Figures 13** and **14**).

This knowledge helps calculate the budget that can be justified for soil constraint assessment and management, and prioritising those subsections of a farm that will generate the quickest and highest returns on investment following soil amelioration.

In **Figure 14**, there is a broad north–south strip where the yield gap gave a loss of >$1000/ha in 2015. However, alongside it was a zone in the north-eastern section of the paddock (with the same inputs such as fertiliser) where grain yields were close to potential for the rainfall that occurred in that year. Comparing soil sample data from these two areas is likely to reveal the cause of the yield gap.

Yield gap calculation methods are discussed in **Part 4** (page 29).

Notes on data quality

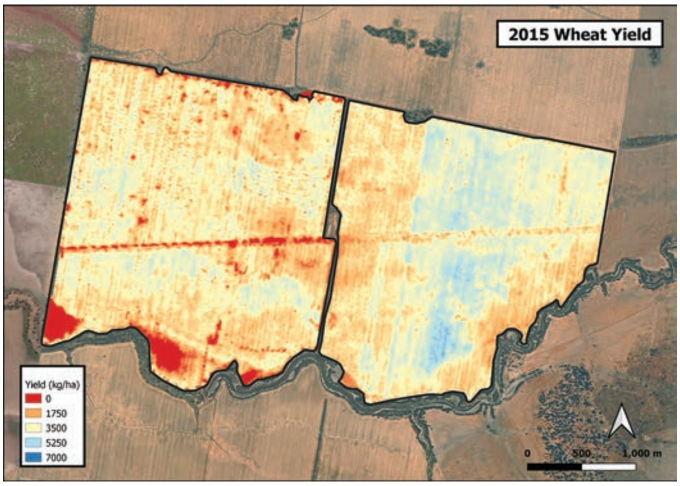
Spatial layer quality varies with scale, resolution and the quality of the underlying data.

Resolution becomes more important as paddocks become more variable. Highly variable dispersion needs higher-resolution maps to accurately map changes.

Yield map resolution is the width of the harvester; often 12m but ranging from 9 to 18m. The accuracy is only as good as the data recorded. Although technology is improving, there can be errors in the yield data, caused by blockages, temporary loss of GPS signal, signal and grain flow delays, poor calibration, and start and end pass delays. Self-calibrating yield monitors take the hassle out of calibrating for different crops at the beginning of each season, but can be problematic in low-yielding crops. Yield maps need to be cleaned to remove bad data points if they are to accurately reflect yields (Bryce & Pluske 2021).

NDVI resolution varies from 3cm to 30m per pixel depending on the data source. NDVI has some limitations. Cloud cover can prevent NDVI from being calculated. Every crop gives different readings at various growth stages. For example, flowering canola can give low NDVI values. During early crop growth, the soil has more of an impact on readings as leaf area is small (Bryce & Pluske 2021).

Figure 12: 'Uah' 2015 yield map.



Step 4: Paddock clues and existing laboratory data

Use paddock clues (gathered from direct experience on the farm) and existing laboratory data to determine where to sample soil within a target paddock.

Paddock clues

Paddock clues are free indicators. Use them to guide more in-depth investigations. Some common signs of dispersive soil include:

In plants:

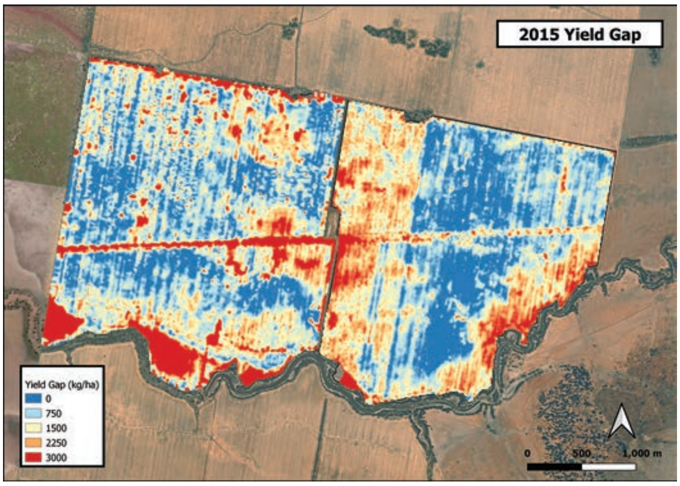
- poor crop growth, including sparsely vegetated areas or bare patches (**Figure 2** – page 8);
- lower yield than expected;
- poor seed establishment from the surface crust or hard-set soil;
- cloudy water in puddles; and
- shallow root growth.

In the soil:

- dense or hard subsoil;
- ground stays boggy and sticky for extended periods after rain;
- soil very cloddy after tilling (**Figure 15**);
- slow water infiltration;
- surface crusting;
- poor tyne penetration;
- narrow tillage window: 'Sunday soils' are too wet to till on Saturday and too hard and dry to till on Monday; that is, a very narrow non-limiting water range accompanied by slow upward movement of water in response to evaporation; and
- light-coloured sand and silt particles concentrating on ridges, with darker-coloured clay in the depressions (**Figure 2** (page 8)).

It was paddock clues (particularly clod coarseness variations) that made the 'Uah' manager realise that unsuccessful gypsum application in one paddock, based on an inaccurate EM-derived zone management map, was resulting in a gypsum misapplication cost of $60,000.

Figure 13: 'Uah' 2015 wheat grain yield gap map based on data processing via the French–Schultz (1984) equation.



Laboratory data

Existing soil data can help refine the sampling plan (next step, **Step 5**). Dispersion tests are the highest priority, followed by ESP and EC data. **Table 2** outlines helpful laboratory tests and thresholds.

There are several formulas that attempt to predict dispersion, such as ESI in **Table 2**. These are further outlined in **Appendix C**. Use these if you have the existing laboratory data and time to run the calculations.

Table 2: Soil tests and the chemical data thresholds at which dispersion is more likely.

Parameter	Threshold
Exchangeable sodium per cent (ESP)	>5 (>3 when EC is very low)
Electrochemical stability index (ESI) ($EC_{1:5}$ ÷ ESP)	<0.02
Salinity (ECe) (dS/m)	<2

Figure 14: 'Uah' 2015 yield gap cost map showing areas of lost income across the site, based on Figure 13. Assuming that the main reason for the yield gap losses is treatable soil constraints, this map represents the ongoing cost of inaction associated with inadequate soil management. Yield gap calculation methods are discussed in Part 4 (page 29).

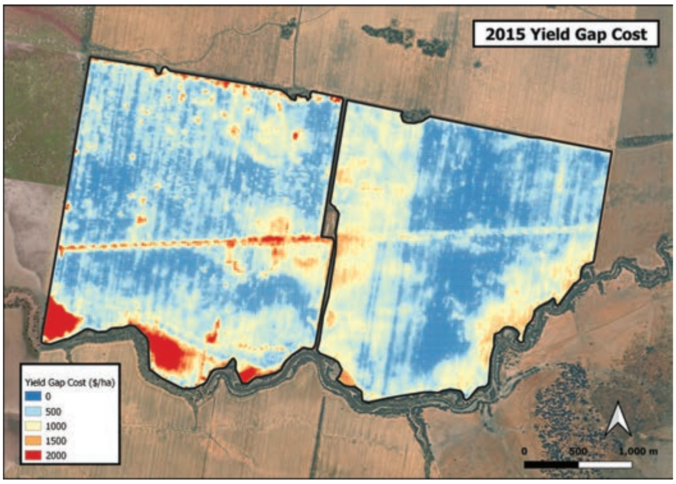
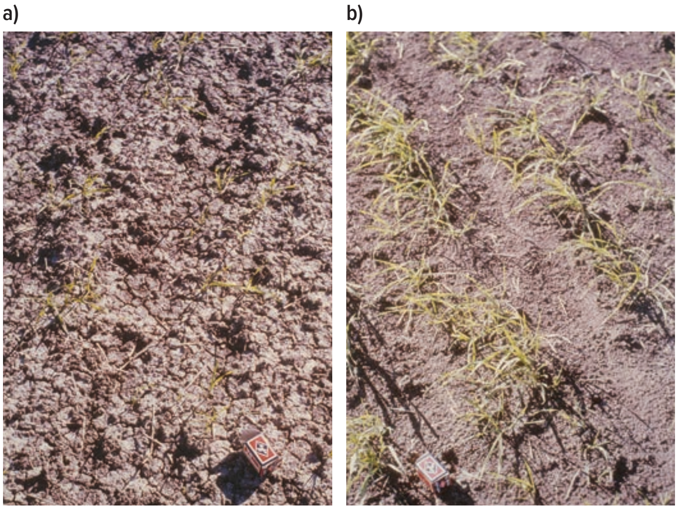


Figure 15: Surface tilth near Moree: a) untreated dispersive/sodic soil; b) the same soil following gypsum treatment, with greatly improved wheat seedling emergence.


a)
b)

Source: David McKenzie

Constraint assessment and mapping

Step 5: Low-density, yield-data-guided soil assessment

To begin the soil management planning process, select paddock(s) where the greatest urgency exists with soil constraints. This will likely be the paddock where grain yields are consistently lower than expected and the cause is not frost, disease or other agronomic issues.

The next step is to identify the zones with contrasting crop growth in a target paddock. Then undertake comprehensive low-density soil sampling in each zone to understand the nature of the topsoil and subsoil constraints to at least 1m deep.

Sample the soil with a sampling intensity of approximately one core (1m deep) for every 50 to 500ha. Ensure that both high-yielding and low-yielding sections of each contrasting geology unit within the paddock are sampled. Do not sample too close to the edge of a zone.

Although it is common practice to use EM surveys to guide sample locations, it is not recommended. Severe sampling bias can occur if the contrasting colour patterns on an EM map are used as the initial guide for soil sampling locations. This is discussed more in the section on EM surveys. For improved accuracy, use yield map information (for example, ConstraintID) as the main initial guide for sampling site selection in **Step 5**.

Dispersion testing is the first priority, but also consider testing for associated constraints such as compaction, acidity/alkalinity, salinity, nutrients and surface flatness. Overcoming just one of several constraints (for example, dispersion) will not boost yields unless the associated constraints are dealt with simultaneously.

The main aim of low-density soil testing is to find which soil properties (such as dispersion) correlate best with grain yield declines. With this knowledge, remote sensing layers can be selected (if sufficiently accurate) that estimate dispersion (and possibly associated constraints) in-between sampling sites (**Step 6**). If there is no correlation, the results from the low-density soil testing also indicate which topsoil and subsoil properties need to be assessed in more detail in **Step 7**.

Figure 16: Nominated low-density sampling sites at 'Uah'. Soil sampling sites chosen in areas of good and poor yield on the different soil types. Gilgai samples are on a depression (site A) and a mound (site B). Twelve sample sites across 1200ha = 1 site every 100ha.

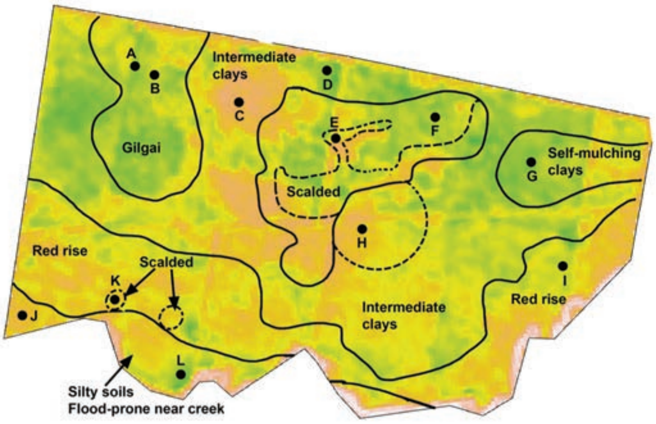


Figure 16 shows the low-density soil sampling sites nominated by the 'Uah' manager. Site locations were chosen to cover good and poor yield areas in the different soil types drawn by the manager. Note that the manager ended up skipping **Step 5** (and **Step 6**) and moving straight to more detailed sampling (**Step 7**). This decision was based on EM survey data correlating poorly with dispersion at this site and the subsequent $60,000 gypsum misapplication loss in one paddock. It had been established that topsoil dispersion occurred in this paddock when ESP >4. However, the nominated soil sampling locations in **Figure 16** will be useful for the upcoming assessment of subsoil constraints.

The ideal laboratory analysis suite for this step includes at least dispersion, pH, salinity (EC), CEC and ESP, for both topsoil and subsoil. ESP and CEC are required to calculate gypsum application rates that deliver both beneficial electrolyte effects and long-term improvement through replacement of exchangeable sodium by calcium. pH data indicates the extent to which lime can be used as a substitute for gypsum. **Figure D4** in **Appendix D** (page 62) shows some typical ESP and EC values for soil one year after adding lime and gypsum.

As dispersion testing is the only definitive method to measure the severity of structural instability in water, collect soil samples from each location. Growers collecting samples themselves need to collect a handful of aggregates (at least six) from each sampling depth (typically 0 to 10cm, 10 to 30cm, 30 to 60cm, 60 to 100cm) down to 1m depth. They can either send the samples to the laboratory for analysis or test it themselves. If sending to a laboratory, one with NATA accreditation is preferable. If soil samples are moist (consistency of plasticine), they should be air dried before sending. A clean, dry plastic jar is ideal for packaging aggregates before posting (plastic is cheaper and less risky to post than glass). The sample bag/jar does not need to be sterile. If doing an ASWAT at the farm, instructions are provided in **Appendix B** (page 56).

During sample collection, record surface soil colour, paddock flatness and compaction severity if possible. Update the soil performance map as needed with paddock clues of dispersion.

Once the sample results are ready, compare the results with threshold values, such as those in **Table 3**. The **Step 5** low-density dataset for 'Uah' is incomplete, but approximate results for a single site are shown in **Table 3** from the nearby constrained paddock hosting the GRDC Project B core site experiment (Bennett et al. 2022). The results suggest that subsoil dispersion, salinity and alkalinity are constraints.

Table 3: An example of data collected via a Step 5 low-density soil assessment at a GRDC core site near the 'Uah' example paddock (Bennett et al. 2022). A traffic-light colour coding system has been used to highlight – in red – where the soil data indicates soil conditions unsuitable for crop growth and in need of amelioration (where possible). Each of the 10cm depth intervals is within the recommended sampling depths, that is, 0 to 10cm, 10 to 30cm, 30 to 60cm and 60 to 100cm.

Grower/Contact	Nils Jacobson	Paddock name	Waterway
Core ID	1.3.1	Sampling date	27 July 2018
Profile sampled	0–10cm, 10–20cm, 40–50cm, 60–70cm	UTM zone	55
Easting (mE)	585329		
Northing (mN)	6285161		

	Depth (cm)	Result	Low	Marginal	Sufficient/ Desirable	High	Excessive
pH (1:5 H_2O)	0–10	6.46			🟩		
	10–20	7.62			🟩		
	40–50	9.07				🟥	
	60–70	8.12				🟧	
pH (1:5 $CaCl_2$)	0–10	5.60			🟩		
	10–20	6.71			🟩		
	40–50	8.05				🟧	
	60–70	7.92				🟧	
EC (1:5 H_2O; dS/m)	0–10	0.187		🟧			
	10–20	0.217		🟧			
	40–50	0.464			🟧		
	60–70	2.458					🟥
CEC ($cmol_c$/kg)	0–10	22.25			🟩		
	10–20	23.02			🟩		
	40–50	32.98				🟧	
	60–70	46.63					🟥
Ex. Calcium (%)	0–10	52.15		🟧			
	10–20	50.27		🟧			
	40–50	48.90		🟧			
	60–70	59.47		🟧			
Ex. Magnesium (%)	0–10	36.41				🟧	
	10–20	37.79				🟧	
	40–50	33.44				🟧	
	60–70	27.60				🟧	
Ex. Potassium (%)	0–10	4.61			🟩		
	10–20	2.38		🟧			
	40–50	1.19		🟧			
	60–70	1.15		🟧			
ESI	0–10	0.03		🟧			
	10–20	0.02	🟥				
	40–50	0.03		🟧			
	60–70	0.02	🟥				
	Depth (cm)	Result	Desirable	Acceptable	Moderate concern	High concern	Extreme concern
Ex. Sodium (%)	0–10	6.83			🟧		
	10–20	9.56			🟧		
	40–50	16.46				🟥	
	60–70	11.77				🟥	
	Depth (cm)	Result	Stable (0–1)	Potentially gypsum responsive (2–5)	Gypsum responsive (6 or greater)		
ASWAT score	0–10	5		🟧			
	10–20	8			🟥		
	40–50	7			🟥		
	60–70	10			🟥		

Figure 17: a) EM spatial layer (DualEM 21S, 36m-wide swath); and b) ESP comparison at ‘Uah’. The bordered areas show poor correlation between these two factors.

a)

b)

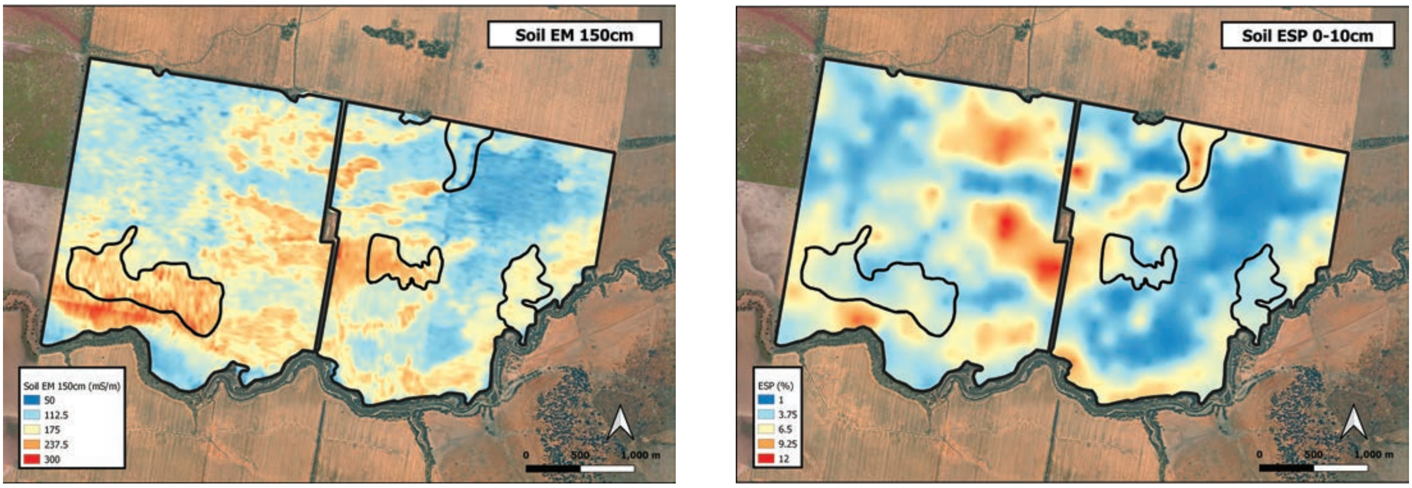
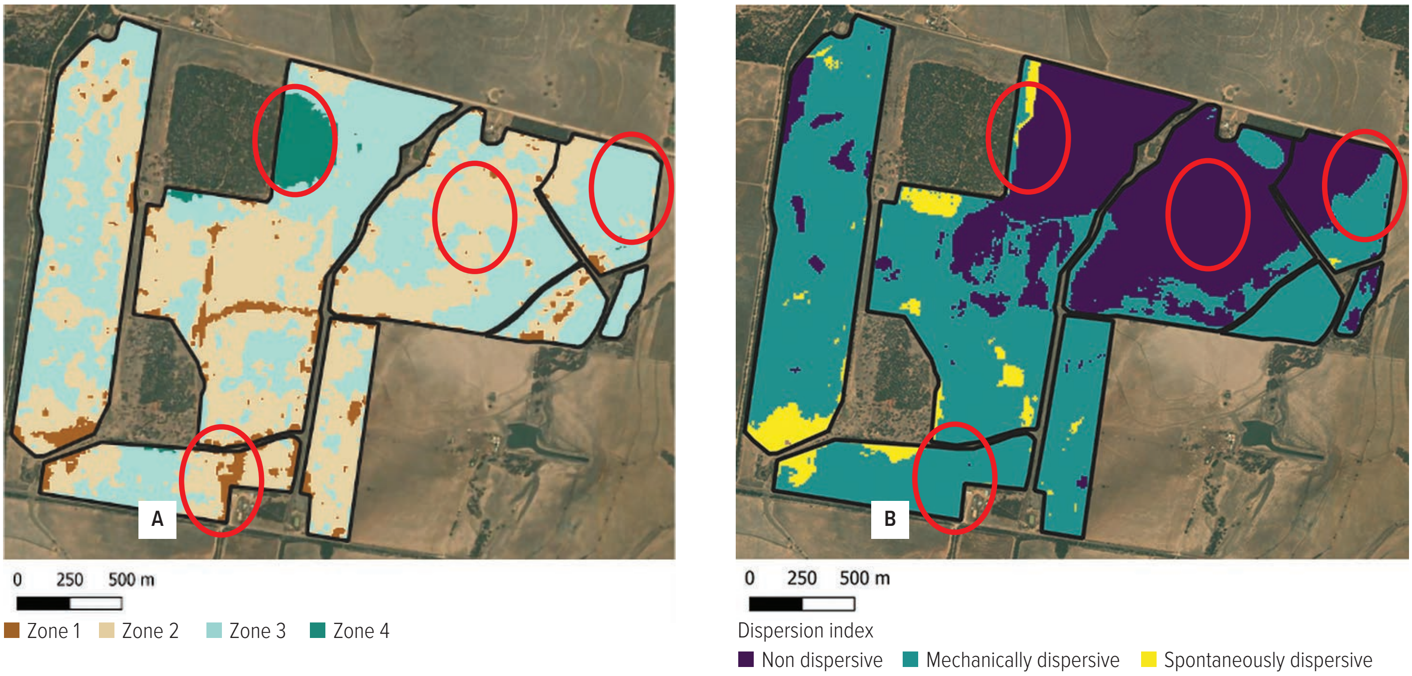


Figure 18: Comparing surface dispersion and EM maps in the northern region. Red ovals show selected areas where the two layers do not correlate.

a) Zone by EM

b) Surface dispersion (0–10cm)

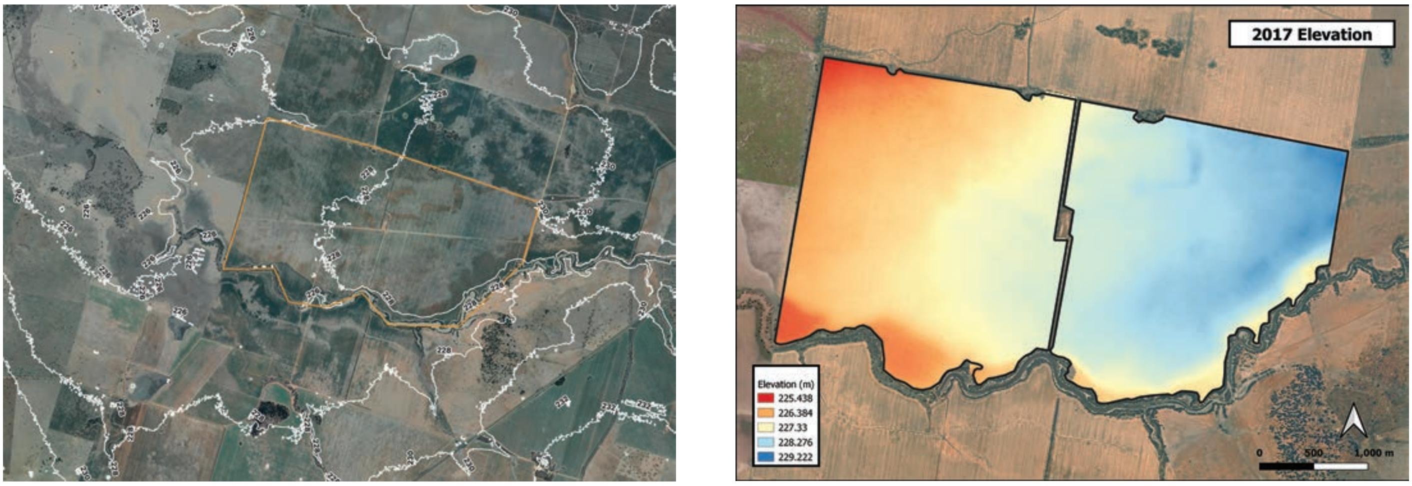


Source: Stirling Roberton

Figure 19: a) ‘Uah’ elevation data from NSW Elevation Data Service; and b) elevation map collated from a RTK planting pass in 2017.

a)

b)



Step 6: Compare soil test data with remote sensing layers

There is a small chance that remote sensing layers such as surface soil colour, elevation, EM or radiometrics (environmental covariates) simultaneously can accurately map dispersion, bulk density, pH, salinity, paddock flatness or nutrient deficiencies/toxicities in the areas of the paddock not sampled in **Step 5**.

The environmental covariates that will be discussed further below include:

- surface soil colour;
- EM surveys;
- elevation maps;
- gamma radiometrics; and
- mineralogy.

If these layers are already on file, compare them with the soil data collected in **Step 5**. If the soil data and layers match, for example, if all soil tests with topsoil dispersion fall in the same EM category, further soil sampling is not needed. However, it is more likely that spatial layers will have enough error to lead to significant misplaced amelioration and wasted money, as was the case in one paddock at 'Uah'. **Figure 17** outlines some discrepancies between the EM survey results and topsoil ESP results, indicating that, in this case, an EM survey (despite the attraction of its low cost per hectare) is not a consistently accurate method for measuring topsoil ESP. This conclusion is consistent with the following statement from McKenzie and Ryan (2008): "Total reliance on EM survey as a surrogate for soil survey is unwise, as even a rudimentary understanding of the technique and insight into natural soil variation will show."

Additionally, soil constraints usually have their own separate variation patterns across a paddock and rarely change in tandem (**Figures 17, 18** and **21** (page 23)). It is therefore nearly impossible for a single remote sensing system to accurately map multiple soil factors such as dispersion, compaction and acidity. If there is no covariate map that lines up accurately and consistently with existing soil dispersion data, more soil sampling and analysis is required.

If the farm does not have remote sensing layers it is not necessary to get them to map dispersion.

Surface soil colour

A pale-coloured surface can align well with topsoil dispersion. Some areas, such as in **Figure 1**, are easy to see on satellite images. However, surface colour is unlikely to help diagnose subsoil dispersion.

EM surveys

An EM survey is a valuable tool for subsoil salinity assessment but it should not be the starting point to diagnose topsoil and subsoil dispersion. If salinity is highlighted as a key constraint in **Step 5**, an EM survey is recommended as there is likely a strong correlation between EM data and the soil salinity. The EM data will provide an excellent low-cost measure of salinity across paddocks.

But where dispersion is highlighted as a key constraint, an EM survey will generally not be recommended to map that constraint as there is no direct correlation between EM data and dispersion measurements. Although a high EM reading could mean high salt levels in the topsoil (which may have made the soil more sodic), it could also mean high clay content and/or the presence of moisture.

If EM survey data already exists, compare it to the soil data collected in **Step 5** to see if it accurately maps dispersion. It is highly likely that the two datasets will not match. **Figure 18** compares dispersion and EM data. The red ovals show selected areas of discrepancy. Oval A on the EM map contains three different EM zones, but the whole area is dispersive (Oval B).

Many situations exist where EM surveys have led to big losses for growers. Uneven rainfall (for example, heavy rain from a thunderstorm occurring in a narrow strip across a wheat paddock) and run-off inflows can complicate EM map interpretation, and there are often crop growth factors that are unrelated to soil constraints but affect residual soil moisture, for example, frost damage and uneven weed/pest pressures.

Although EM maps are cheap, using them alone is likely to cause major measurement errors on soil amelioration requirement maps and create costly ameliorant misapplications. It is not necessary to get EM maps to diagnose soil dispersion.

Elevation maps

Although EM data is often not useful when assessing soil dispersion, the elevation data that is usually measured simultaneously with EM is a valuable layer to have. It can be used to produce paddock slope maps and show where surface drainage might be needed. More detailed elevation data can also be collected during planting (**Figure 19b**).

Free regional slope/elevation data is available for NSW and Queensland; however, it may have inadequate resolution for application at the paddock scale. Compare the detail in **Figure 19a** (regional data) to **19b** (site data).

NSW data is available from the NSW Elevation Data Service. Queensland data can be found at QTopo and at Queensland Globe.

Gamma radiometrics

Gamma radiometrics (GR) data is commonly collected to assess the levels of isotopes such as potassium (K), uranium (U) and thorium (Th). The number of gamma ray counts across the whole spectrum is the total count (TC). GR can be used to gauge changes in soil texture, mineralogy and salinity. Wilford (2008) noted that sandy wind-blown (aeolian) material usually has low concentrations of the isotopes. In contrast, finer-textured, high-quality aeolian dust (parna) depositions exhibit moderately high values for thorium.
If you already have professionally produced GR maps, check to see if they align with dispersion and other soil constraints on the farm. Radiometrics information is used by geologists to assist with production of maps such as **Figure 9** (page 15), and can be valuable for soil factor mapping at the paddock scale. But it is not essential to get GR maps to diagnose and map soil dispersion.

Mineralogy

Proximal sensing systems are being developed with potential to assess clay mineralogy in a cost-effective manner. Some clay types, such as illite, are more sensitive to dispersion. However, there is no easily accessible proximal sensing technology currently available.

Step 7: Flexible-grid intensive soil sampling

Flexible-grid soil sampling is more intensive, with one detailed soil assessment every 2 to 50ha.

Start with a grid of sampling locations, then move the locations to suit the property and landscape, for example, move points off roads and away from fence lines. The grid will change for each paddock based on the landscape and existing site knowledge.

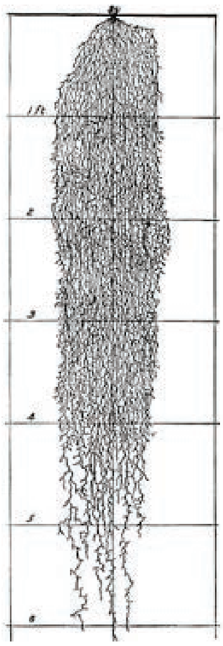
At a site near Warren, NSW, Roberton et al. (2020) showed that sampling more intensely than every 2ha is unlikely to be beneficial under dryland cropping. At ‘Uah’, a grid intensity of one sample (each comprised of six bulked samples) per 5ha was used.

Although flexible grid sampling is an improvement from bulked sampling and EM-guided zone sampling, further refinement can be achieved through the use of advanced geostatistical procedures (see Gruijter et al. 2006) (Roberton pers. comm.). Specialist consultants such as OptiSoil are needed for this.

Topsoil assessment is the priority in **Step 7**, except in rare circumstances where low-density sampling (**Step 5**) suggests no topsoil constraints. Detailed subsoil sampling can be performed later if funds are limited, although it is more efficient to collect both topsoil and subsoil samples at the same time and store some of them until required for analysis. Ideally, there should be some subsoil analysis, as cereal roots can grow more than 2m if not constrained by soil conditions or water (Breslauer et al. 2020, Lilley & Kirkegaard 2016). An unconstrained subsoil can significantly improve yields and crop resilience by providing access to greater supplies of water and nutrients (**Figure 20**).

The process for intensive data collection is the same as in **Step 5**. Coring with the objective of assessing the key soil factors identified in **Step 5** (dispersion, ESP, CEC, EC and pH) will be the main priority, but also aim to record surface soil colour, paddock flatness and compaction severity if possible. Accurate soil compaction assessment is best done via soil pits, but coring is usually an acceptable method if the soil is dry. Instructions on how to accurately measure soil bulk density (a direct and well-known measure of soil compaction severity) are provided by McKenzie et al. (2002b), and Dalgliesh and Foale (1998). Guidelines for the rapid assessment of compaction severity via visual soil assessment (including the SOILpak score; McKenzie 2001) are described by Emmet-Booth et al. (2016).

Figure 20: Mature root system of winter wheat, showing dense root growth more than four feet (1.2m).



Source: Weaver 1926

Growers collecting the samples for dispersion testing need to collect a small jar or plastic bag of aggregates (at least six aggregates) from each sampling depth. Common sampling depths are 0 to 10cm, 10 to 30cm, 30 to 60cm and 60 to 100cm. Growers can either send the samples to the laboratory for testing or test it themselves. Instructions for the ASWAT are provided in **Appendix B** (page 56). Procedures for comparing ASWAT data with other soil dispersion methods (e.g., the Emerson aggregate test) are described by Hazelton and Murphy (2016).

Send a sample from each core location to the laboratory to test pH, salinity, ESP and CEC. ESP and CEC are necessary to calculate gypsum application rates. If the laboratory is going to do the dispersion testing and chemical testing, follow their instructions about the required amount of soil per sample.

Soil pits versus soil cores

Soil pits are a great way for growers and their advisers to see what is happening in and below the root zone – particularly variations in soil structure, soil colour, pH (via rapid test kits), root growth and soil biological activity. Soil pits complement core sampling. There will be far fewer soil pits than cores. Dig one to two soil pits in each of the key areas, such as very high or low-yielding areas.

Soil cores are fast and convenient to collect for soil sampling and minimise paddock disturbance, but cannot provide the comprehensive and accurate soil assessment provided via the use of a freshly exposed profile in a soil pit. Growers are more likely to understand their soil structure, plant root condition and soil biological activity via a freshly trimmed soil pit profile than through the use of soil core inspections. Soil cores usually have a strongly disturbed exterior and generally are too narrow to provide clear observations, even after they have been split open.

Soil pits provide better data on dispersion severity and compaction severity (bulk density, SOILpak score). Testing these soil factors using cores can lead to highly inaccurate results as the soil may be strongly disturbed, particularly when the soil is moist. Soil pit reference data provides a way of checking on possible errors associated with soil coring.

Soil pits can be dug before or after detailed soil sampling (**Step 7**). A benefit of using pits before detailed soil core sampling is that it encourages important dialogue between growers and soil advisers early in the soil assessment process. It facilitates a mutual understanding of all aspects of the soil assessment and amelioration process at each new site – particularly soil survey options and farm profitability/risk management issues.

If digging pits before doing core sampling, the pit locations should be chosen using both grower and soil specialist knowledge. The pits should cover the range of soil conditions and crop yield performance across the farm. This process works particularly well when a grower and farm staff have been on a property long enough to gain strong local knowledge, but is difficult to do without any prior knowledge of the site. If working with a new site, someone with specialist digital soil mapping knowledge should help choose the sites. Pre-existing regional soil survey information from government agencies may also be valuable for this task.

Alternatively, soil pit profile assessment after detailed soil core sampling (**Step 7**) is a straight-forward process. A detailed soil core survey will highlight which points on the farm are representative of the range of soil conditions that exist across a farm, that is, the points at which soil pits should be dug to gain extra information, particularly soil profile photographs and Australian Soil Classification (ASC) assessment. Soil profile photographs are valuable to capture soil and plant root condition at the time of assessment, to compare to in later years. The ASC assessment will help choose soil amelioration options (**Table 5** (page 25)).

Where a controlled-traffic farming (CTF) system is in place, the repeating patterns of soil compaction across the farm mean that only a small number of inspection pits (at right-angles to the direction of travel) is required to thoroughly assess compaction severity, in-between and under wheel tracks. However, extra pit inspections will be required where significant legacy compaction exists from before CTF was introduced, particularly where natural rates of soil structural form improvement through shrink–swell processes are slow due to low CEC values.

Step 8: Map individual constraints

Use the soil results from **Step 7** to map each of the relevant constraints (for example, dispersion, ESP, ESI, CEC, pH, salinity, compaction) for topsoil (0 to 10cm), and perhaps subsurface (10 to 30cm), upper subsoil (30 to 60cm) and deep subsoil (60 to 100cm). These maps (see example ESP map in **Figure 18**) will be made with point data and will be used to make the soil amelioration requirement maps in **Step 9**.

Constraints need to be considered independently as:

- they will vary across the paddock in their own distinctive patterns; for example, all dispersive areas will not necessarily also be saline; and
- all constraints need to be addressed to achieve the maximum yield boost following amelioration.

Figure 21 shows the variation in topsoil ESP, pH and CEC at 'Uah'.

Associated constraints cannot be ignored due to Liebig's 'Law of the Minimum' (Wallace & Terry 1998). For example, if a paddock has dispersion problems that are successfully overcome using gypsum, but associated serious compaction issues are not corrected via deep loosening, then crop yields will continue to be poor despite dispersion being treated.

Cost of diagnosing soil dispersion and associated constraints

The cost of diagnosing soil dispersion will vary based on the size of the area, the number of soil samples, existing site knowledge and subcontractor costs. Detailed surveys cost more but can also lead to significant savings by applying the correct amelioration in the right place.

A frank conversation between growers and their agronomy/finance consulting team is needed to find the optimal balance between survey costs and expected benefits. For many grain growers, a low tolerance to risk (particularly concerns about future droughts) has a big bearing on this decision. However, an evaluation of the repeated financial losses associated with yield gaps (and the profitability data described in the case studies) puts the capital investment cost of accurate soil assessment in perspective.

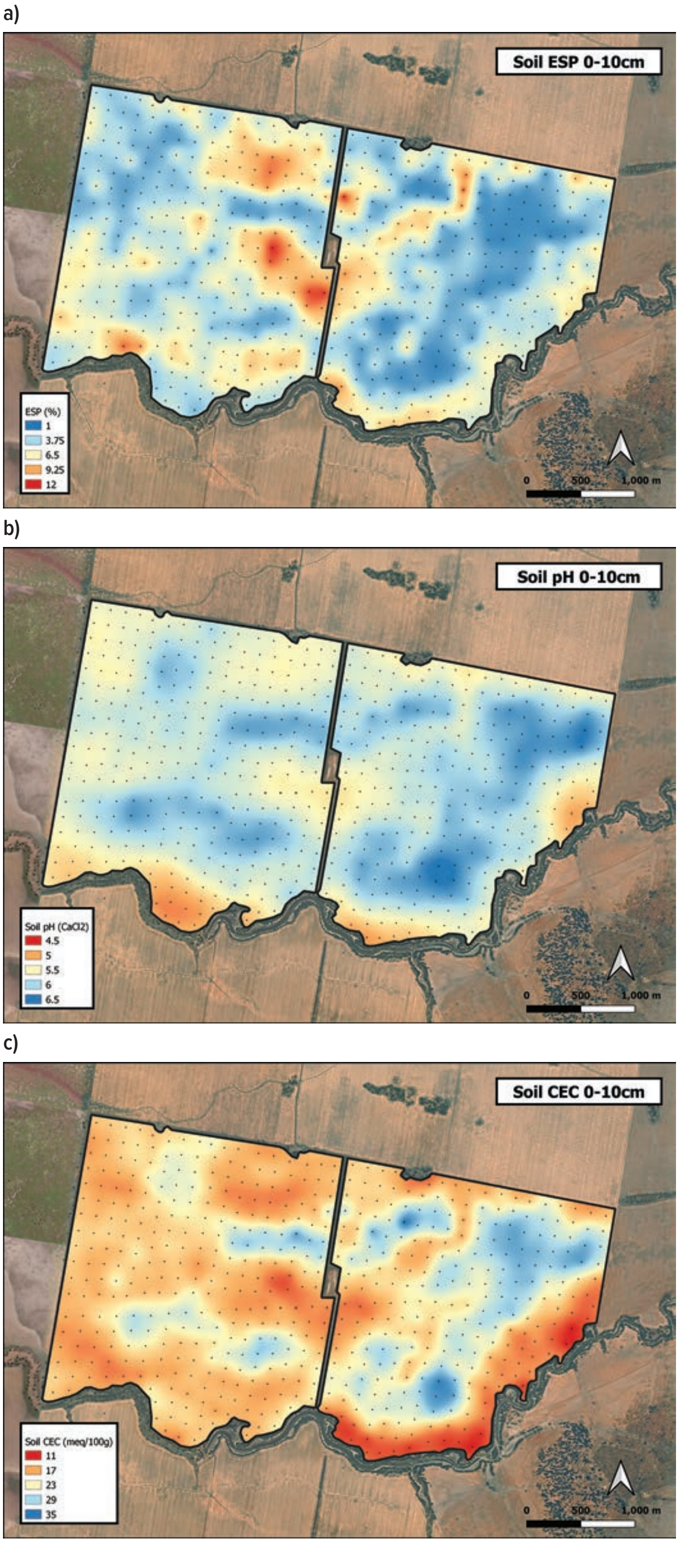
Consider:

- consulting fees for the adviser and soil science specialist;
- laboratory analysis for soil core samples;
- mapping contractor services;
- costs of spatial layers (for example, high-resolution imaging); and
- fees for contractors (such as corers, backhoe, soil surveyors) to undertake soil core and pit assessments.

As a rough guide, the 'Uah' managers set aside $11/ha every year for soil sampling and mapping. The whole-of-farm approach was to start with a key problem paddock, then assess/ameliorate the rest of the farm in quarter sections (approximately 2500ha) during each sampling round.

The approximate commercial cost of testing four cores at four depths (that is, 16 samples) would be approximately $1200 to $1900, depending on the laboratory (Bennett et al. 2022). Discounts might be available for larger sample volumes.

Figure 21: 'Uah' topsoil (0 to 10cm) maps based on soil samples collected every 5ha: a) ESP; b) pH; and c) CEC. Note how each soil property has its own pattern of variation. Black dots show soil sample locations.



Part 3: Creating an amelioration plan

Amelioration and management options

Based on the diagnostic work in **Part 2**, you should have a reasonable idea of the extent and severity of dispersion and associated constraints. Choosing an effective amelioration option and working out the cost is the next step. In the initial stages of a soil improvement program, it is usually better to invest in hectares with the best economic potential for improvement.

Soil amelioration is usually considered an annual, variable expense. In contrast, we recommend that soil amelioration should instead be considered as a sequence of capital expenses across a farm, paddock by paddock, where amelioration is improving the fixed asset (the soil) for future benefit.

There are three broad approaches to dealing with dispersive soil:

1. amelioration using products such as gypsum to permanently fix, or at least suppress, the problem;
2. management changes such as improved CTF systems and better surface cover; and
3. land use change.

In situations where it does not make economic sense to ameliorate, land use change may be the last resort. This is discussed more in **Part 4**.

Table 4 outlines the main amelioration options for dispersive soil and the various constraints. These are discussed in more detail in **Appendix D** (page 59). An integrated management approach combining ameliorants and management options might be the best solution. For example, CTF and retaining stubble while ameliorating poorly performing areas.

Table 4: Main amelioration and management options for dispersive soils and associated constraints.

Constraint	Amelioration and management option
High exchangeable sodium causing dispersion	Gypsum if pH $CaCl_2$ >6.5 Gypsum + lime if pH $CaCl_2$ <6.5 Organic matter
Compaction	Ripping Biocultivators (crop roots to create biopores and/or cracks) Controlled-traffic farming
High pH	Elemental sulfur Gypsum (minor impact, mostly on highly alkaline subsoil with low carbonates)
Salinity	Salt-tolerant crops Phytoremediation Leaching Surface flushing
Gilgai, too flat	Earthworks, drainage

Of the amelioration and management options listed in **Table 4**, only lime, gypsum and ripping have enough economic data to draw clear conclusions. Organic matter and elemental sulfur are promising, but not yet proven as cost-effective. These options are discussed more in **Case Study D** (page 46).

Table 5 lists the main constraint combinations in dispersive soil in the northern region, with amelioration options. Where budget is tight, amelioration focuses on topsoil improvement. This will work well in years with favourable rainfall patterns but not as well in dry years when crop roots have to grow deeply into untreated subsoil. Where budget is available, both topsoil and subsoil are improved. This allows crop roots to grow deeply and function well in both wet and dry years. An important consideration is a soil's capability. A Grey Vertosol or Brown Sodosol, ameliorated to a depth of 60cm, will still be moderately constrained when compared with a soil such as Black Vertosol with low salinity and sodicity in the subsoil that can allow root penetration to at least 2m deep.

Calculate ameliorant rates

Once the ameliorants are chosen, calculate the necessary application rates.

Gypsum calculations

Gypsum requirement (GR) will depend on whether you want to completely replace the sodium with calcium or are aiming for a specific ESP. The amount of gypsum required to replace sodium with calcium is calculated using the following equation (from Oster & Jayawardane 1998, modified by Bennett et al. 2022):

Gypsum requirement =

$$0.0086 \times \mathbf{F} \times \mathbf{D} \times \mathbf{BD} \times (\,\mathbf{ESP}_a - \mathbf{ESP}_b\,) \times \mathbf{CEC}\,\frac{1}{\mathbf{P}}$$

Where:

F = gypsum exchange inefficiency factor. Use 1.33

D = soil depth in metres

ESP_a = starting ESP

ESP_b = final ESP. Use 3

CEC = cation exchange capacity (millimole per kilogram; $mmol_c/kg$)

P = purity factor, to account for varying gypsum purity

BD = soil bulk density expressed as grams per cubed centimetre (g/cc)

The gypsum exchange inefficiency factor accounts for not all of the calcium in applied gypsum being exchanged with sodium on the clay exchange sites. Some will flow downwards through macropores and miss sodic zones; some will displace exchangeable magnesium and potassium rather than exchangeable sodium. The purity factor (P) accounts for gypsum rarely being 100 per cent pure. Recycled gypsum often includes cardboard and mined gypsum can include clay. Pure gypsum is 18.6 per cent sulfur. If a source has 14.9 per cent sulfur, it is 80 per cent pure.

Table 5: Soil amelioration options to consider for dispersive soil in the GRDC northern region.

Soil types (Australian Soil Classification)	Dispersive Vertosols and Sodosols		Self-mulching Vertosols (sodic subsoil)	
	Soil amelioration strategies to focus on: Not to be ranked – they are all important for each paddock/soil/yield gap zone under consideration (Liebig's 'Law of the Minimum' is assumed to apply whereby crop growth is restricted by the most limiting factor influencing plant performance)			
Main constraint combinations	**Tight budget**	**Finance available**	**Tight budget**	**Finance available**
1. Surface dispersion/sodicity (if pH is neutral or acidic, use gypsum–lime blend)	Gypsum – split dose Organic matter*	Gypsum – all at once Organic matter*	n/a	n/a
2. Subsoil dispersion/sodicity	DELAY	Gypsum – all at once	DELAY	Gypsum – all at once
3. Surface compaction	Ripping if possible + controlled traffic (CTF)		Ripping (if compaction is severe; SOILpak score <0.5) + CTF	
4. Subsoil compaction	Deep-ripping if possible + CTF		Deep-ripping (if compaction is severe) + CTF	
5. Surface dispersion and surface compaction combined	Gypsum (split) + rip Organic matter*	Gypsum (all) + rip Organic matter*	n/a	
6. Surface dispersion and subsoil compaction combined	Gypsum (split) +rip	Gypsum (all) + rip	n/a	
7. Subsoil dispersion and surface compaction combined	DELAY	Gypsum (all) + rip	DELAY	Gypsum (all) + rip
8. Subsoil dispersion and subsoil compaction combined	DELAY	Gypsum (all) + rip	DELAY	Gypsum (all) + rip
9. Acidic surface pH	Lime		n/a**	
10. Acidic subsoil pH	DELAY	Lime	n/a**	
11. Acidic surface pH + (5)	Lime + gypsum (split) + rip Organic matter*	Lime + gypsum (all) + rip Organic matter*	n/a**	
12. Acidic surface pH + (6)	Lime + gypsum (split) + rip Organic matter*	Lime + gypsum (all) + rip Organic matter*	n/a**	
13. Acidic surface pH + (7)	DELAY	Lime + gypsum (all) + rip	n/a**	Lime + gypsum (all) + rip
14. Acidic surface pH + (8)	DELAY	Lime + gypsum (all) + rip	n/a**	Lime + gypsum (all) + rip
15. Alkaline surface pH	Elemental sulfur (ES)*		Elemental sulfur (ES)*	
16. Alkaline subsoil pH	DELAY	ES*	DELAY	ES*
17. Alkaline surface pH + (5)	ES* + gypsum (split) + rip Organic matter*	ES* + gypsum (all) + rip Organic matter*	n/a	
18. Alkaline surface pH + (6)	ES* + gypsum (split) + rip Organic matter*	ES* + gypsum (all) + rip Organic matter*	n/a	
19. Alkaline surface pH + (7)	DELAY	ES* + gypsum (all) + rip	DELAY	ES* + gypsum (all) + rip
20. Alkaline surface pH + (8)	DELAY	ES* + gypsum (all) + rip	DELAY	ES* + gypsum (all) + rip
21. Nutrient deficiency – in addition to any of the above scenarios	Fertiliser		Fertiliser	
22. Paddock too flat and/or gilgai country – in addition to any of the above scenarios	Earthworks to improve surface drainage		n/a	
23. Paddock erodible – in addition to any of the above scenarios	Erosion control earthworks and/or stubble		Erosion control earthworks and/or stubble	
24. Saline subsoil – in addition to any of the above scenarios	Select salt-tolerant crop varieties			

* There is economic uncertainty around organic matter and elemental sulfur. This is discussed more in Case Studies A and D.

** n/a = for this soil type (Self-mulching Vertosols), acidity is unlikely to occur. However, it can be an issue in Sodosols.

For example, if a soil has a bulk density of 1.3 g/cc, the CEC is 200 (mmol+/kg) (that is, 20 cmol+/kg), the soil depth to be ameliorated is 0.15m, the starting ESP is 10, and the gypsum has a purity factor of 80 per cent:

$$\text{GR} = 0.0086 \times 1.33 \times 0.15 \times 1.3 \times (10-3) \times 200 \left(\frac{1}{0.8}\right)$$

$$= 3.9\text{t/ha}$$

Lime calculations

To convert the gypsum amount into a lime rate that supplies the equivalent amount of calcium, multiply the gypsum rate by 0.58.

Using the example above, 3.9 x 0.58 = 2.3 tonnes of lime.

Gypsum–lime blends

As lime is a source of calcium, it can help treat dispersion where the soil is both acidic/neutral and dispersive (less common than alkaline dispersive soil). Lime is unlikely to help if the soil is alkaline.

Lime can be a lower-cost source of calcium compared with gypsum, making gypsum–lime blends an option where the soil is sufficiently acidic. A suggested strategy (updated from Abbott & McKenzie 1996) is to calculate the gypsum rate as above, then blend as follows:

for pH $CaCl_2$ 5.4 – 6.5, use a mixture of about 75:25 gypsum to lime.

for pH $CaCl_2$ 4.8 – 5.3, use a mixture of about 50:50 gypsum to lime.

If the pH is >6.5, use all gypsum. If the pH is <4.8, use all lime, with the rate calculated as above.

There is very limited research on gypsum–lime blend optimisation. One trial north of Parkes, NSW, studied the combined effects of lime and gypsum (Valzano et al. 2001). The starting surface pH ($CaCl_2$) was 5.4. The results suggested lime and gypsum can sometimes have a synergistic effect (if the application rates are high enough) caused by the different solubility rates of the products. Initial dissolution of gypsum slightly lowers the pH, thereby improving lime solubility. The calcium from gypsum also displaces some sodium and induces the electrolyte effect to suppress soil dispersion. Continued availability of calcium over time from both gypsum and lime lowered ESP and improved soil structure. Follow-up work by Bennett et al. (2014) on the same site, 12 years later, found improvements in aggregate stability where lime had been applied (either alone or with gypsum), but not where gypsum had been applied alone. The authors suggest the total amount of calcium applied was the driving factor (lime containing more calcium than gypsum), leading to improved soil and vegetation health.

The above suggestions on gypsum–lime blends are for land managers willing to experiment. **Case Studies A** (page 37) and **B** (page 41) show that when topsoil pH is <6.5, lime can deliver calcium to successfully treat dispersive topsoil.

Step 9: Soil amelioration requirements

Maps

Soil amelioration maps outline what amelioration is required where. There should be separate maps for the amelioration option(s) requirements for each separate soil constraint, such as gypsum, lime, and/or surface drainage earthworks (for example, to deal with gilgai challenges). For deep-ripping requirement mapping, refer to **Step 7** and GRDC (2022).

A mapping contractor will be required to generate these variable-rate maps and to interpolate the areas between the point data.

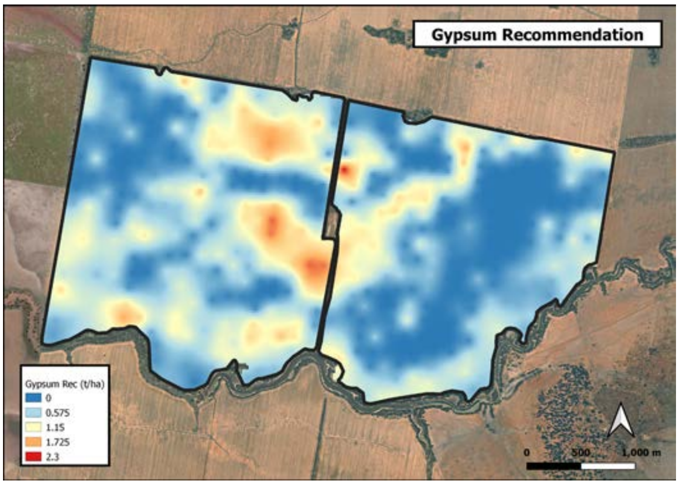
A variable-rate gypsum map (total requirement for permanent displacement of exchangeable sodium by calcium) based on the 'Uah' ESP data (**Figure 20** – page 22) is shown in **Figure 22**. At 'Uah', the manager's observations were that topsoil became poorly structured (coarse, hard/flinty aggregates when dry, paddock signs of dispersion when wet) where ESP >4.

This true variable-rate approach represents a big step forward from both the traditional method of applying single-rate blanket applications of gypsum and the more recently developed but often inaccurate zone management method for applying gypsum based on EM maps. In the 'Uah' example, true variable rate means having a specific amelioration application rate for each 5ha sampling unit across the paddock, based on soil coring and accurate laboratory analysis within each of those units. Zone management generally refers to larger subsections of a paddock being given specific rates of amelioration, but which often have large estimation errors due to poor correlation between key soil factors such as dispersion severity and environmental covariate(s) – usually EM.

All maps will have errors. More intensive soil sampling from **Step 7** will create more detailed maps with less chance of error, but it will not be perfect. Research is ongoing to develop modelling techniques that generate more accurate maps.

An experienced soil specialist with access to point data shown on the individual constraint maps should be able to study the landscape, ask the right questions and produce a variable-rate amelioration map with acceptable accuracy.

Figure 22: 'Uah' variable-rate gypsum map based on 5ha soil sampling.



Summing amelioration costs

An important part of **Step 9** is calculating the hectares of each amelioration, as this is needed to work out overall amelioration costs and tonnage requirements. This data can be extracted from the individual soil constraint maps (**Figure 23**).

At 'Uah', the mapped gypsum requirement was 660t. At $110/t, this equates to $72,600.

An advantage of expressing a soil constraint in terms of cost of repair per hectare is that the repair maps for all relevant constraints (dispersion, excessive flatness, acidity) all use the same units ($/ha) and therefore can be stacked to provide a comprehensive total cost of repair map for each paddock, or group of paddocks, on a farm (**Figure 24**) (McKenzie 2003).

Costs

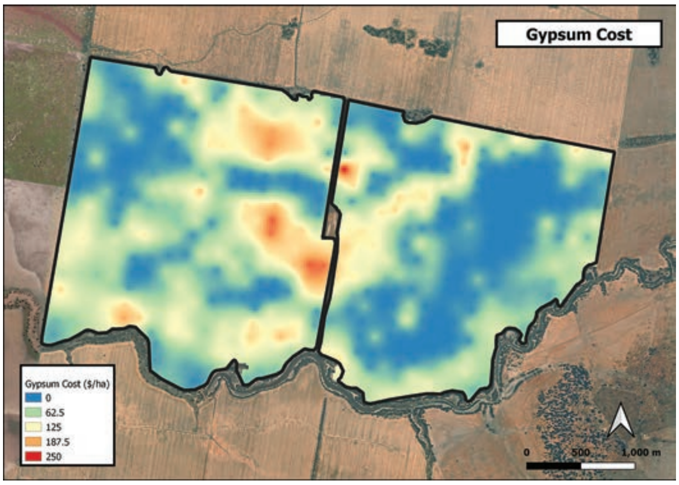
Use the list of amelioration options from **Table 5** above and the hectares of each constraint from **Step 9** to calculate the cost of amelioration. **Table 6** provides a guide to amelioration costs in the northern region. These costs only include purchase, transport and spreading where specified. Other costs such as machinery parts, wear and tear and depreciation are not included.

Table 6 presents an average of costs in the northern region. Costs will vary depending on the source, quality and location. For example, lower purity gypsum or lime requires more product to be effective. Gypsum purity is discussed in **Appendix D** (page 59).

Transport can be a large part of an overall amelioration cost. **Figure 25** shows the location of gypsum and lime sources and associated transport distances to specific farms across the northern region in NSW and Queensland. In **Figure 25a**, the orange lines show a 400km (dashed) and 800km (solid) radius distance from mined gypsum sources (for example, Winton, Bourke). The green lines show a 400km (dashed) and 800km (solid) radius distance from by-product gypsum sources (Sydney and Brisbane). In **Figure 25b**, the green lines show a 200km radius from the lime sources.

Multiply the transport distance lines by the cost of transport ($/t/km) to obtain approximate transport costs. The cost of transport has gone up considerably in recent times due to rapidly increasing diesel fuel costs.

Figure 23: 'Uah' gypsum cost map.



The gypsum sourced from Sydney and Brisbane is recycled gypsum derived mainly from waste plasterboard. The gypsum from western NSW and western Queensland is a mined lakebed mineral. Agricultural lime is derived from limestone mines along the Great Dividing Range; the deposits were originally ancient coral reefs that have been uplifted.

Managing high amelioration costs

If the cost of amelioration is greater than the amelioration budget, there are some opportunities to customise the amelioration plan to fit the budget. The main opportunities are with gypsum use.

1. If gypsum is becoming cost-prohibitive, there may be an opportunity to use lime as a cheaper calcium source instead (discussed below). This will only be useful if soil pHca is <6.5.

Table 6: Example costs for ameliorants in the northern region. Further work is required to determine the full cost of subsoil treatments where several ameliorants are required simultaneously, at a range of sites with contrasting subsoil constraints.

Amelioration option	Cost ($/t)
Surface gypsum	100–135
Deep gypsum	90–125
Surface organic matter	45–80
Deep organic matter	35–70
Elemental sulfur	800
Lime*	25–60
Management option	**Cost**
Shallow rip	$50/ha
Deep-ripping	$200–280/ha

Notes:
- Organic matter includes crop residues and cattle/sheep/poultry manure.
- Deep amendment prices are cheaper than surface amendments as they do not include the cost of application/incorporation. This is due to application costs being highly variable.
- Lime does not include spreading. Spreading costs will range from about $10 to 25/ha.

Source: Cockfield et al. 2022

Figure 24: Individual soil constraint cost of repair maps for three stages of soil management at 'Uah'. Stage 1 has been completed to date. Stages 2 and 3 are planned for the future. Deep-ripping is not considered necessary at this site due to strictly managed CTF, plus decompaction in-between wheel tracks via shrink–swell processes.

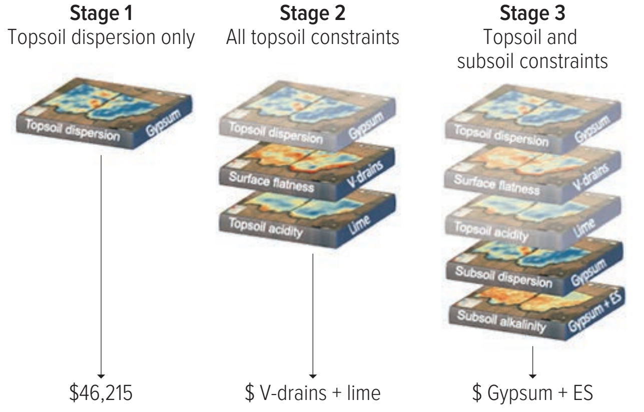
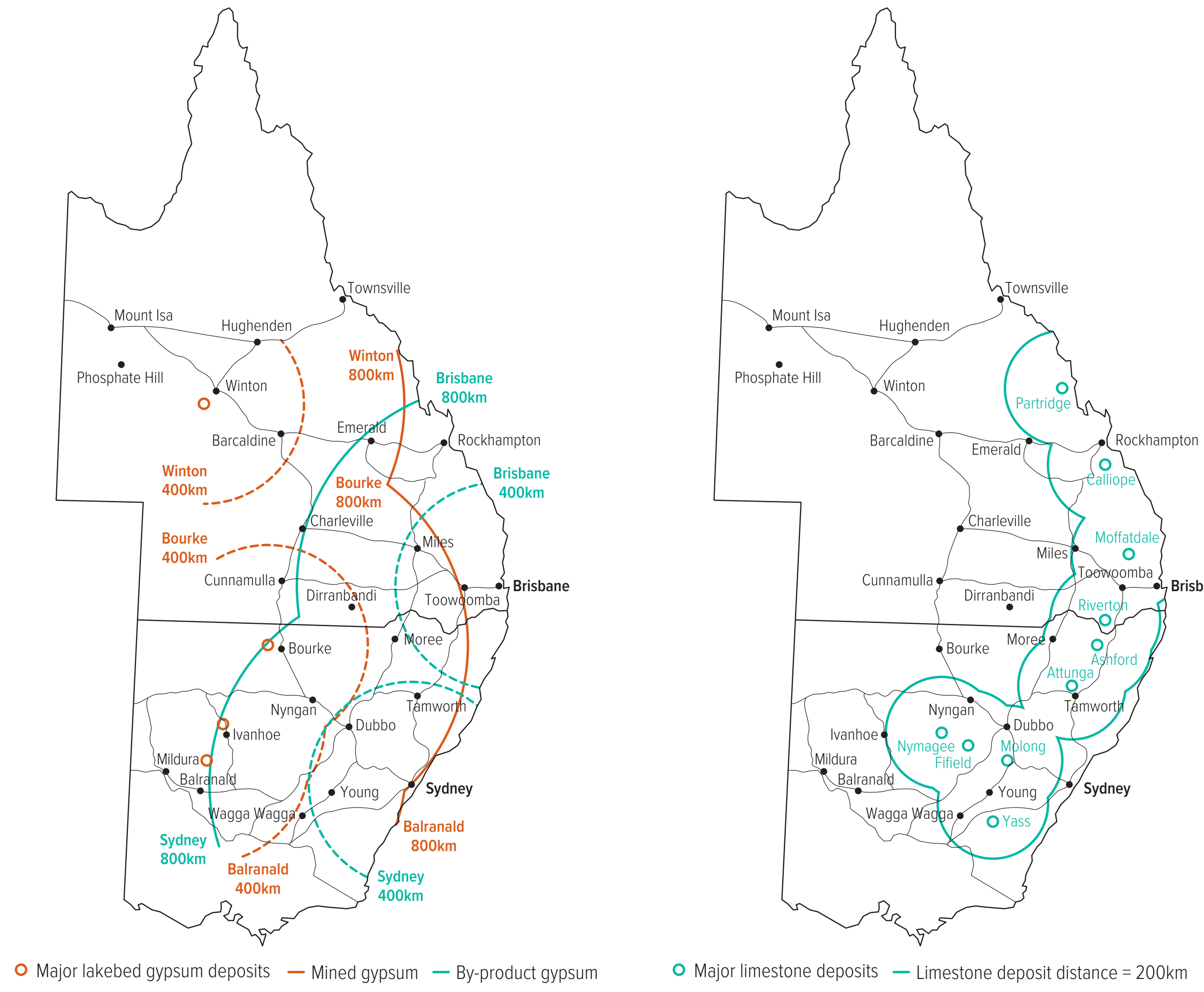


Figure 25: Northern region transport distance maps: a) gypsum; and b) lime.



a) Gypsum transport Isocost lines

b) Lime transport Isocost lines

2. Split the gypsum applications and spread the costs over several years. The smaller applications will manage dispersion via the electrolyte effect and eventually permanently displace exchangeable sodium.

One risk of the split dose approach is failing to apply the follow-up doses and having the paddock return to dispersive conditions. The simplest option therefore (if the budget allows it) is to apply the full requirement in one application. Split gypsum applications for overcoming subsoil dispersion are not feasible due to the high cost, and potential disruption of favourable soil structure, of the associated repeated ripping.

Gypsum–lime blends, often cheaper than gypsum alone, are an option when the topsoil is acidic enough for the lime to become soluble. Gypsum–lime blends are cheaper as lime provides a lower-cost source of calcium than gypsum. For example, where gypsum costs $110/t and lime is $70/t, the cost of calcium from gypsum (23 per cent calcium, if free of impurities) is $472/t, but only $175/t when derived from lime (40 per cent calcium). As many grain farms are closer to lime quarries than to gypsum sources, the use of lime as a sodic soil ameliorant can also reduce transport costs.

As treating dispersive soil often requires large ameliorant inputs, variable-rate application technologies are essential to keep costs down. High blanket rates quickly become cost-prohibitive, particularly in highly variable paddocks. Ameliorants therefore have to be applied only where they are needed.

Longevity

How long it takes to remove the constraint depends on the amelioration option used, how well amelioration is performed and post-amelioration management. When gypsum is applied in split doses, the short-term electrolyte effect of dissolved gypsum – that is, 'the salt effect' – is likely to be transient and will be lost due to leaching in a couple of seasons when rainfall is above average; persistence of the effect is greater during droughts. Exchanging sodium with calcium is permanent but requires higher doses of gypsum. Repeated applications will eventually have a cumulative effect on sodicity that gives permanent improvement of soil structural stability. Ongoing dispersion testing monitors when the electrolyte effect is wearing off and when the next split dose of gypsum (possibly in conjunction with lime) needs to be applied.

Without CTF, the benefits from an associated ripping operation may only last a few months when conditions are moist. A soil that is strongly compacted will prevent full expression of the benefits of ameliorants to overcome dispersion.

Part 4: Economics of dispersive soil management

Improving dispersive soil is largely an economic decision. The overarching question is: Is it better to buy new land, fix this land, or put it to a different use? Historically, it was cheaper to buy new land. With rural land in northern NSW and Queensland having a median price of $5000 to 6000/ha in 2021 (Rural Bank 2022), and with high grain prices due to global shortages, many amelioration strategies are now a more financially attractive option. Ameliorating soil constraints is an economic opportunity to boost profits into the future.

If the cost of amelioration outweighs the benefits from yield improvements, the land may be better put to a different use.

Assessing the economics requires calculating:

1. the yield gap from dispersion (what is dispersion costing the farm?)
2. the costs of diagnosing dispersion and associated constraints across the farm (outlined in **Part 2** (page 13) but will vary for each situation)
3. amelioration costs (outlined in **Part 3** (page 24)).

Then a decision needs to be made about which areas of the farm will benefit most from amelioration.

The point at which soil amelioration strategies are deemed profitable will vary based on the grower's risk appetite, financial position and their expectations of investment returns (that is, an investment of $1000/ha with a 10-year payback period may be deemed profitable by one person but non-profitable by another).

What is dispersion costing the farm?

Without intervention, dispersion is a cost that recurs year after year and when it is widespread across a farm, adds up to a significant total over several decades. For example, assuming a wheat price of $500/t, the annual cost of the yield gap on sodic soil without amelioration in Case Study A averaged $1450/ha on a farm near Gurley and $1238/ha near Garah.

One method to estimate what dispersion is costing the farm is to look at yield and returns in areas that are not dispersive and compare these values to dispersive areas. For example, if paddocks on non-dispersive soil are yielding 3t/ha, but yields on 800ha of dispersive soil are only yielding 1.8t/ha, there is 1.2t/ha x 800 ha = 960t of yield to be realised. Assuming wheat is $500/t, this means dispersion is costing the farm $480,000 each wheat crop.

The value of yield gap quantification is shown above in the example from 'Uah' (**Figures 13** and **14** (page 17)). Yield gaps are usually calculated by comparing potential grain yield based on farm rainfall records (French–Schultz equation) relative to actual grain yields measured via headers.

Wheat grain yield (t/ha) =
WUE * (stored soil water + growing season rainfall – evaporation)

Where: WUE = water use efficiency

Growing season rainfall is from April to October (inclusive)
https://www.agric.wa.gov.au/iaagseasons/PC_94498.html

Or use an online calculator, for example, the yield potential calculator on the Soil Quality website. This calculator assumes that every extra millimetre of available soil water beyond a threshold of 110mm soil water will produce 20kg of wheat/ha.

Then, as above, calculate the lost income from the yield gap.

Yield gap maps (expressed as $ loss/ha) can be produced periodically to visualise where the greatest yield gaps occur.

Yield gap numbers are theoretical. To be realised, successful agronomic management must be implemented (in addition to soil amelioration inputs), and yield gains realised to bridge this gap.

Working with yield gap ranges

Yield gaps will range across the farm. Choosing yield ranges, for example 1 to 1.5t/ha or 1.5 to 2t/ha, can make this step simpler. Then calculate the lost income based on the upper number of the range as this will give a conservative estimate.

For example, where the yield on non-dispersive soil is 3.5t/ha, **Table 7** combines the yield ranges into categories.

Even with the best amelioration equipment and intent, yields may not meet expectations every year due to other factors such as frost and pests/diseases.

Table 7: Yield gap categories and associated farm income losses.

Yield (t/ha)	Hectares	Yield gap* (t/ha)	Total lost (t)	Lost income** ($)
1.1–1.5	200	2	400	200,000
1.6–2.0	100	1.5	150	75,000
2.1–2.5	150	1	150	75,000
2.6–3.0	250	0.5	125	62,500
3.1–3.4	200	0.1	2	1000
Total				**413,500**

* Yield gap is calculated by subtracting the upper number on each yield range from the yield on non-dispersive soil on this farm (3.5t/ha).
** Assuming a wheat price of $500/t.

Return on investment (ROI) strip trial approach

Estimating yield improvements from amelioration is necessary for basic economic analysis. The best way to know how the paddock will respond to amelioration is to test it out in the paddock.

The return on investment (ROI) strip trial approach, developed by Dr Stirling Roberton in conjunction with Dr John Bennett, installs a series of farm-specific harvester-width strip trials spanning across variable soil constraint types and uses the yield response information obtained from these strips to guide investment decisions outside of the trial area. These strip trials can be used to identify maximum-ROI zones. This is a cautious approach that builds valuable soil data systematically. Ensure that control (untreated) strips are included.

The aim of strip trials is to work out the economically optimum amelioration plan for the paddock. Once the trials are in place, they will provide fast and cheap yield response data for best-bet ameliorants, in relation to adjacent untreated (control) areas, year after year. The process has been amended slightly for this manual. The original approach began with strip trials crossing the main problem areas; however, to know where to place the strips and being able to extrapolate the trial findings to the rest of the paddock requires first knowing where the constraints are. This is why this manual suggests soil sampling first to map dispersion and associated constraints.

The ROI strip trial approach is as follows.

1 Choose an area to run amendment strips

The area chosen should ideally have both the constraint and be representative of paddock variability, for example, areas of varying dispersion. A control ‘nil’ strip should run alongside each trial strip (**Figure 26**). Using the soil constraint maps from **Part 2** (page 13) will help position the trial strips in a way that covers as much of the contrasting soil factor of interest (usually dispersion/sodicity) variation as possible.

If detailed soil constraint maps are not yet available, position the trial strips in a way that covers major yield/NDVI contrasts within a paddock. However, choosing the right ameliorants to test relies on soil test results from, as a minimum, high and low-yielding areas of the paddock (that is, **Step 5: Low-density soil assessment**).

These trials are a long-term investment, requiring several seasons of data. The trial strips are oriented in a way that fits in with existing CTF wheel tracks, which allows grain yield along the strips to be measured at low cost via GPS-guided headers. Soil sampling along the trial strips occurs before applying ameliorants (**Figure 26**).

2 Conduct intensive soil sampling along each treatment strip (Figure 26)

These samples are used to identify which soil constraints or soil types are providing the largest yield response once ameliorated. Send samples to the laboratory to test for the relevant constraint. For example, if the treatment strip is gypsum to lower ESP, at least test ESP, EC and dispersion in each sample in the relevant layer.

3 Apply ameliorants at one blanket rate per strip

For example, apply 2t/ha gypsum in one strip, 0.9t/ha lime in another strip. The idea behind blanket rates along a strip is it requires less intensive soil sampling during trial establishment and can be used to back-calculate where the rate was too high or too low.

4 Collect yield data (from the header) for a few seasons

Yield analysis requires a yield response calculation, where every harvested point along each strip is compared directly to its closest control point in the nil strip. This will identify which parts of the trial strips are getting the biggest yield responses.

Figure 27 compares the total yield map to the strip trial yield map. Looking at the total yield map, there does not appear to be any yield difference in this area. But when comparing yield in the trial strips to the closest control point, the yields in the strips are about 0.8t/ha higher than the control. The image on the right is showing yield increase, rather than total yield, hence the difference between **Figures 27a** and **27b**.

5 Extrapolate the yield response from the trial strips to the rest of the paddock

The aim is to estimate which other areas of the paddock will produce a similar yield response if ameliorated. This helps choose areas that will provide the largest yield response and ROI from amelioration. Being able to gauge ROI in this detail is useful to justify investing in soil amelioration, whether for internal budgeting or external financing requests (Roberton 2022).

This extrapolation process works best when detailed soil factor maps (separate maps of dispersion, ESP, EC, pH etc. for the target depth intervals) are available.

Which amelioration options are economically viable?

Every grower and business will have their own acceptable level of economically viability, which at its core is the expected ROI and how soon payback happens. With investments such as a superannuation fund, ROI values of about 10 per cent are considered acceptable. However, a risk-averse grower may require an ROI value of 100 per cent (recovery of costs in one year) when investing in soil improvement. At the very least, amelioration should provide some increase in yield/profit above the costs spent on amelioration.

Projected return on investment mapping

Bennett et al. (2022) have noted that mapping the assumed ROI of soil amelioration options is a way to tailor the strategy to available cashflow and access to finance, which will ultimately determine how priority areas are targeted across the farm.

Figure 28 maps four ROI scenarios in a 100ha paddock. The transition between the images from left to right demonstrates how investments may be targeted, based on the individual's risk profile. The approaches range from: a) a high-cost approach where the whole paddock/farm is ameliorated using variable-rate (average 16 per cent ROI); to d) the most conservative investment, where only the high-returning areas are targeted (average 25 per cent ROI).

Scaling this up to represent a 2500 ha farm, the investment decision to make is the difference between a $383,000 investment with a seven-year payback (16 per cent ROI), and a $90,000 investment with a four-year payback (25 per cent ROI) noting that approaches towards the left will have a larger net benefit due to increased area treated; however, at an increased investment. There is no right or wrong preference to which end of these images an individual may choose, as it depends solely on the financial position and risk appetite of the individual.

This approach allows the individual to adjust their preference based on annual production performance, where they may prefer the strategy to the left in high cashflow years, and towards the right in low cashflow years. Logistics is an important consideration when choosing to ameliorate smaller areas of the farm/paddock, as paddock application efficiency would be decreased due to the areas of non-application.

ROI maps may also be used to develop farm-specific soil investment plans that can be presented to suppliers of agricultural finance. This is discussed more in the section **Soil as a capital asset**.

The ROI maps can be accompanied by net present value (NPV) maps to give a more thorough economic overview for each new job.

Figure 26: Example strip trials with detailed soil sampling locations to test out different amelioration approaches. Samples are 60m apart. Sampling depth intervals are 0 to 10cm, 10 to 20cm, 40 to 50cm, 60 to 70cm.

Figure 27: Paddock yield map a) compared with yield response map b) where points in each treatment strip are compared against their closest control nil strip.


a) Yield (t/ha)

b) 2020 yield increase

‘Uah’ diagnosis and amelioration plan

Sodicity-induced dispersion was a constraint on 60 per cent of the total area (10,500ha) at ‘Uah’; flatness affected 80 per cent of the farm (Cockfield et al. 2021). Subsoil salinity and high subsoil pH were also issue. The low-density topsoil and subsoil sampling (**Figure 16**) has not been completed, but confidence with high-quality pre-existing topsoil data allowed the manager to move directly to detailed sampling.

Diagnosis

The soil was sampled using 5ha grid sampling units. Within each unit, six 0 to 10cm soil samples were bulked together. At every 10th soil core, a 0 to 60cm nutritional soil core (nitrogen focus) was also collected. The cost of topsoil sampling, laboratory analysis and mapping was approximately $11/ha, equating to $13,200 across the sampled paddocks.

The ‘Uah’ manager is considering having each sample analysed separately rather than bulking samples.

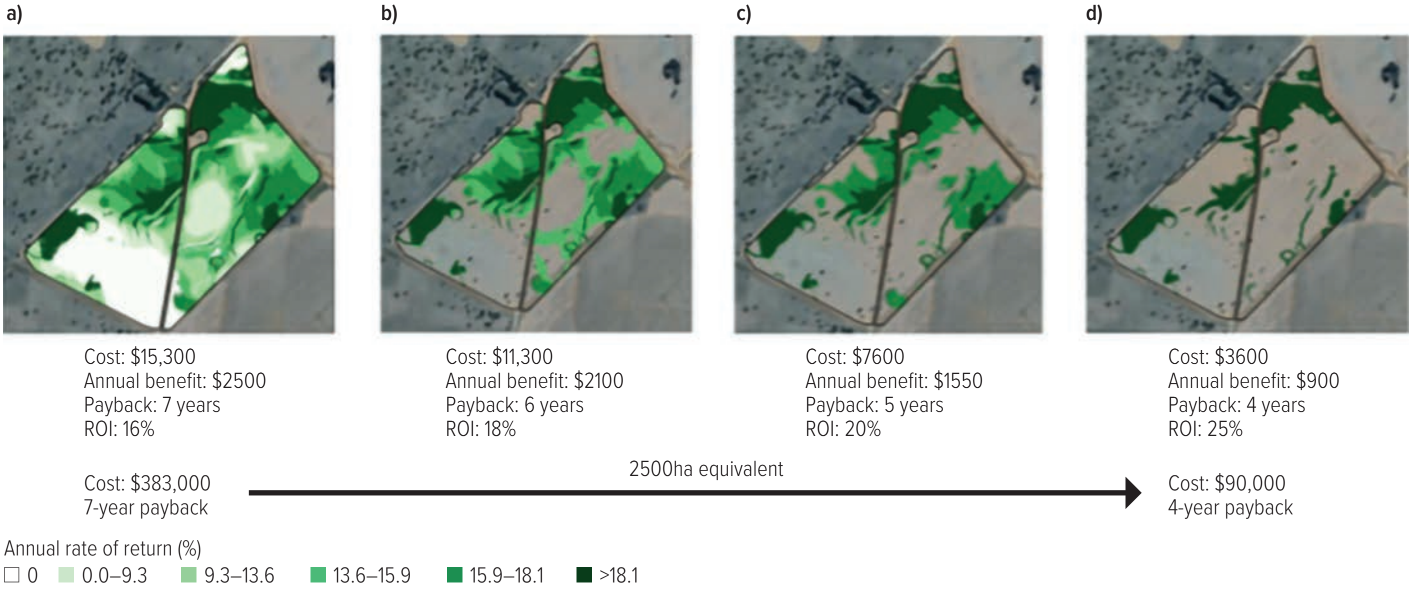
Amelioration plan

As sodium-induced topsoil dispersion was the key issue, gypsum applications were prioritised. Gypsum was applied as per **Figure 22** (page 26). A larger percentage (relative to 2015) of the eastern end of the example paddock had excellent wheat growth, with impressively low yield gaps in 2021 (**Figure 29**).

Across the 1200ha, the yield gap cost in 2015 was $733,877. In 2021, it was $845,738. Although gypsum seems to have improved yields largely in the eastern paddock, particularly along the south-eastern boundaries, poor yields in the western paddock stemming from waterlogging in gilgai country has outweighed the benefit in 2021, which had an unusually wet winter. Surface drainage challenges will be dealt with during **Stage 2** of soil management planning (**Figure 24** (page 27)).

‘Uah’ has an effective CTF system that is strictly maintained. Any contractors coming onto the farm must have wheel configurations that exactly match the ‘Uah’ system. Therefore, much of the soil in-between the wheel tracks with legacy compaction challenges appears to have loosened naturally over five years via shrink–swell processes. As such, ripping may not be needed.

Figure 28: The relationship between spatial amendment cost, annual benefit, payback time for the amendment investment and the overall return on investment. This demonstration depicts how an individual’s appetite for risk could be applied to the possibility of nominal returns.



a) Cost: $15,300
Annual benefit: $2500
Payback: 7 years
ROI: 16%

b) Cost: $11,300
Annual benefit: $2100
Payback: 6 years
ROI: 18%

c) Cost: $7600
Annual benefit: $1550
Payback: 5 years
ROI: 20%

d) Cost: $3600
Annual benefit: $900
Payback: 4 years
ROI: 25%

Cost: $383,000
7-year payback

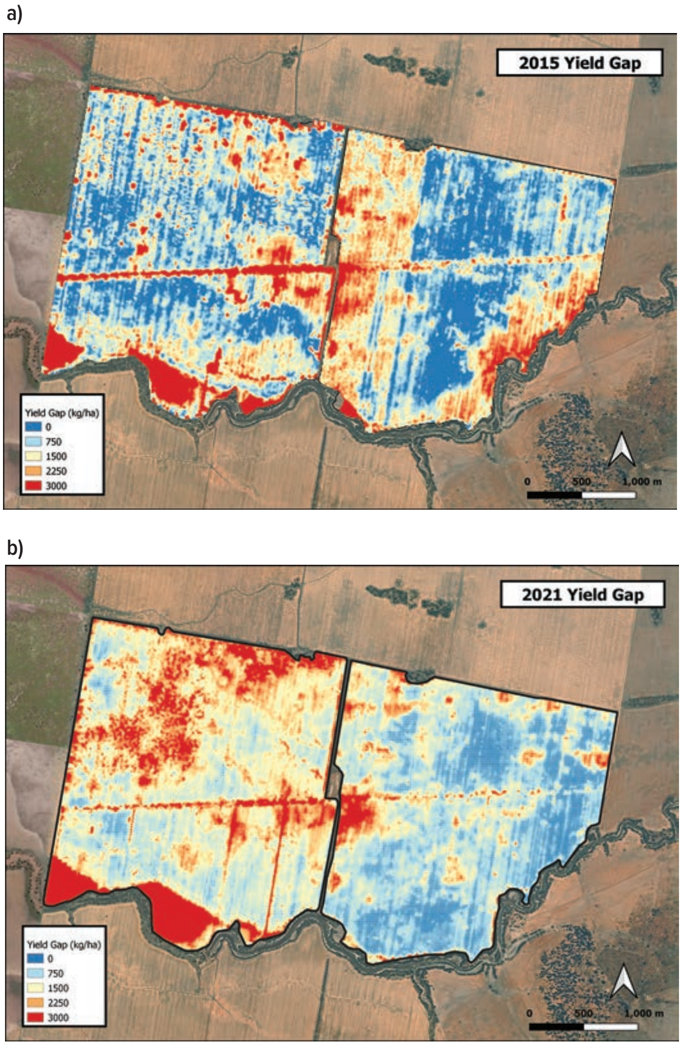
Cost: $90,000
4-year payback

Next steps

Based on the 2021 yield gap map (**Figure 29b**), the main remaining problem areas are where gilgais are present (north-eastern section of the paddock) and run-off water accumulates. This is not surprising, given that 2021 had above-average rainfall with the paddock very wet at times. Unavoidable flooding of the crop in the south-western corner alongside the creek greatly reduced grain yields. In the non-blue-shaded sections of the paddock, subsoil assessment (that is, completion of **Step 5**) is required to determine the extent to which further cost-effective improvements in yield can be achieved.

'Uah' staff are likely to prepare ROI and NPV maps, at some stage, for this example paddock and use them to assist with the planning of further amelioration.

Figure 29: 'Uah' yield gap maps: a) 2015; and b) 2021.



a)

b)

Soil as a capital asset

Soil amelioration is often viewed as an annual or variable expense, making many operations seem too expensive. However, the nature of soil amelioration – a big up-front cost with long-term payback and benefit – makes it better viewed as a series of capital expenses over several years, paddock by paddock. Ameliorating dispersive soil is improving the fixed asset, the soil.

The main up-front costs are detailed soil testing, mapping and the cost of ameliorants. If done correctly, the data from soil testing and mapping only needs to be collected once and can form the basis of a long-term soil amelioration plan. Properly implemented dispersive soil amelioration leads to long-term improvements and capital expenses are soon recovered. Treatments at Condobolin (Case Study B), for example, showed strong gains five years on, up to $5500/ha (NPV, 5 per cent interest rate). In this case, the profitability improvement was greater than the value of the land.

New research is required to explore the linkages between productivity improvements on constrained soil following amelioration and land valuation processes. Farmland valuation procedures are required that give financial rewards (in the form of improved land prices at auction) to growers who ameliorate constrained soil in a professional manner.

Dry years

During dry years, spending naturally decreases. There is a strong and logical reluctance to take on more debt. However, soil improvement is a long-term gain. Periods of lower activity on the farm are a good time to begin detailed soil mapping and developing a soil amelioration plan. While this means initially going backwards financially, the land is ready to perform better when the rain comes. Some soil amelioration activities, such as deep-ripping, work better with drier soil.

Land value

In the late 1990s, Ringrose-Voase et al. (1997) attempted to quantify how changing land quality could impact land value. The authors argued that if the market price of agricultural land was more sensitive to soil properties and degradation, there would be more economic incentive to adopt soil conservation practices. They tested the relationship between soil properties, productivity, and gross margin (GM) in the Wagga Wagga district where acidity was the main soil constraint.

The paper discussed the concept of encouraging purchasers of farmland to test soil before purchasing, and to then negotiate land price discounts (relative to median market prices for representative land in the same soil landscape types) on the basis of the cost of restoring soil properties (for example, liming to overcome acidity constraints) to a point where soil condition is non-limiting for crop growth. Conversely, sellers of farmland could perhaps obtain a premium by testing soil to prove that soil condition has been optimised and amelioration is not required.

This study needs to be followed up with an investigation of the relationships between land valuation procedures and soil amelioration planning in dispersive–sodic landscapes in the northern region. There is great potential to use accurate and comprehensive soil data for both annual crop productivity improvement well into the future, and land valuation planning.

Alternative land uses and ecosystem services

Living with the problem/cutting losses

In some cases, a highly constrained patch of land would be better taken out of cropping or put to a different use. The cost to ameliorate such land for cropping far outweighs potential yield benefits. Likely areas include extreme salinity, very steep land (>10 per cent slope), rocky outcrops and extreme gilgai.

Simply stopping cropping can cut losses. Depending on the condition the land is in and if there is native vegetation close by, there may be options to gain biodiversity or carbon credits. Note that this space changes often so always check the latest guidelines.

Pasture

Compared with grain cropping, salt-tolerant pasture, forage and fodder crops may be more successful in increasing ground cover, soil water use and overall productivity in highly constrained subsoil areas of south-west Queensland. Results from a trial conducted on a highly constrained Vertosol subsoil (1100mg Cl/kg in top 1m soil depth) in the Roma district showed that burgundy bean and lucerne were more effective in extracting soil moisture from deeper subsoil when compared with perennial lablab, butterfly pea and *Vigna* sp. Two years of lucerne extracted almost twice the amount of moisture in the subsoil when compared with two years of wheat cropping (Dang et al. 2007).

Returning land to pasture might yield carbon credits in the long term. Once the paddock becomes a more active ecosystem than under cropping, it may be possible to get biodiversity offsets on the same patch of land. These credits may then be available to the market for purchase by developers, other land managers or the Biodiversity Conservation Trust to offset the impacts of development or land clearing.

Fertilised tropical grass pastures were reported by Banks et al. (2020) to have increased pasture production, deeper and more abundant root mass and greater soil profile moisture storage on sodic texture contrast soils (Sodosols) in the northern NSW slopes and plains, which are known for their limited agricultural productivity under native grasses and cropping. Their observational study compared root abundance, soil structure and soil physical parameters (dispersion, bulk density, porosity and pore distribution) in sodic texture contrast soils under native and adjacent, well established and fertilised tropical pastures. Fourteen years after establishment, mean root abundance was significantly lower in soils under native pasture and greater in the tropical grass pasture system. Dispersion values were high in native pastures but soils under tropical pastures had to be physically worked to cause dispersion. Bulk density under native pasture was significantly higher than in tropical grass pastures. Total soil porosity of topsoils and upper B horizons was consequently lower in native than in tropical grass pasture. Tropical grass pasture upper B horizons had a threefold greater macroporosity (pores >30µm), than under native pastures.

Agroforestry

Commercial agroforestry could provide income on land with highly constrained subsoil. Paddock trials in 2006 at Roma, Theodore and Charters Towers (Singh et al. 2007) tested an Australian native Kalpa (*Millettia* spp.) in highly saline soil. Kalpa is a deep-rooted, perennial, salt-tolerant and nitrogen-fixing tree legume. Kalpa also has some potential to sequester carbon and produce biodiesel. The trees performed well in harsh conditions, being saline tolerant to about 30dS/m (50 per cent sea water) and having good frost tolerance (survived minus 5ºC frost at Roma). The project tentatively suggested a plantation of Kalpa trees could produce 2000kg (2200 litres) oil/ha within five to seven years after planting. Kalpa is just one potential agroforestry crop illustrating that highly constrained land could be put to a different, economically viable use. Other agroforestry species are likely to be available with adaptation to the various climatic conditions in the northern region.

Ecosystem services

An emerging trend in Australian farming is using subsections of a property to provide ecosystem services via biodiversity conservation. One of the options in NSW is for landholders to put land under a stewardship agreement to improve the interconnectivity of remnant patches of native vegetation. **Table 8** describes the potential role of ecological soil science specialists in this process.

Another potential opportunity is improvement of downstream water quality in creeks and rivers through better management of dispersive soil in the farmed areas of a property. The stormwater from paddocks with ameliorated topsoil is less likely to carry dispersed clay in suspension than runoff from zones with untreated dispersive topsoil. Such release of sediments is associated with loss of habitat for native fish and deterioration of water quality, leading to more algal blooms (Prosser et al 2001). These impacts also create better conditions for exotic species such as carp to outcompete native fish (Driver et al. 1997).

The parts of **Table 8** shaded **green** refer to the zones on a farm producing annual grain crops; row 4 refers specifically to constrained land, which is the focus of this manual. Variable-rate amelioration aims to have as much of the land as possible in a condition close to the required 'ideal soil factor' specifications for the crops being grown. In contrast, the native vegetation zones with deep-rooted perennials that have inherent adaptation to the existing natural soil conditions will not receive ameliorants such as gypsum, even if strongly dispersive, meaning that spatial variability of soil factors such as sodicity, salinity and pH will be maintained – rather than being homogenised via amelioration. The role of the soil security concept in holistic agricultural soil management has been described by McBratney et al. (2014) and Bennett et al. (2021).

Table 8: Soil-related professional inputs required by growers involved with both dryland grain cropping and the provision of soil-related ecosystem services.

Land use	Main soil functions	Economic opportunities for the farmer	Possible farmer responses	Soil-related professional inputs required by farmers	Soil security categories
1) Native vegetation in pristine condition, i.e., soil not impacted by European settlers, but under the influence of climate change.	Carbon pool. Biodiversity conservation Storing and filtering of water and nutrients.	Conservation of rare flora and fauna – and the associated endangered soil conditions.	Unlikely to be found on most farms in the northern region.	Ecological soil science specialist.	Genosoil (reference soil).
2) Degraded remnants of the native vegetation; damage associated mainly with grazing by sheep, cattle, goats, feral pigs, etc.	As for (1).	Conservation of rare flora and fauna. Carbon credits. Biodiversity credits.	Carry out a detailed ROI/ NPV soil assessment and commence a biodiversity improvement program.	Agricultural soil science specialist. Ecological soil science specialist.	Genosoil – damaged.
3) **Farmland** close to having the "ideal soil" specifications for the crop species/variety under consideration.	Biomass production (*Food Security*). Carbon pool. Storing & filtering of water and nutrients.	Having land values that are a true reflection of the excellent soil conditions and productivity that exists. Maybe carbon credits.	Keep up the good work. Optimise agronomic inputs.	Agronomist. Agricultural soil science specialist.	Phenosoil – small yield gaps.
4) **Farmland** constrained by a mix of both natural (eg. sodicity/dispersion) and farmer-induced (e.g., compaction) soil impacts where repair is economically feasible.	As for (3).	Improved annual profitability and a boost to land values. Maybe carbon credits.	Carry out a detailed ROI/ NPV soil assessment and commence a 'true variable rate' soil amelioration program on the non-Genosoil zones.	Agricultural soil science specialist. Agronomist.	Phenosoil – large fixable yield gaps.
5) Cleared areas constrained by major soil problems (e.g. rock near surface, severe salinity) where repair is not economically feasible.	As for (3).	Carbon credits. Biodiversity credits.	Convert poor-quality farming land to native pasture and trees.	Agricultural soil science specialist. Agronomist. Ecological soil science specialist.	Phenosoil – large intractable yield gaps.

Source: David McKenzie, unpublished data

Case studies – more profit from soil amelioration

The following four case studies from the northern region show various yield improvements and increased profit from ameliorating dispersive soil.

Financial modelling devised by Professor Geoff Cockfield (University of Southern Queensland, Toowoomba) has been applied to case studies A, B and D. The core method of the financial modelling (from Cockfield et al. 2022) is calculating net marginal gains of treatments (revenue gains less additional costs of treatments). There is a case for distributing some of the enterprise fixed costs (such as rates, base electricity, office costs) to the treatment program but for the sake of simplicity, we excluded those. Then, we applied two economic indicators to the data:

- NPV is the current value of yield increases from soil amelioration. The calculation subtracts the cost of amelioration from yield benefits, and takes into account interest rates (discount rate); and
- ROI describes the value of amelioration (yield increase) compared with its cost. The ratio of yield increase value divided by cost of amelioration is expressed as a percentage. The ROI calculation in these case studies also accounts for interest rates.

Net present value is an important indicator of long-term profitability. However, it may not be a very persuasive indicator for growers. It does not address growers' concerns about cashflows and managing expenditures across highly variable seasons. For NPV, higher values are better, with no tapering off of NPV improvement over time also desirable. Consistent improvements in NPV following soil assessment and amelioration, year after year, should lead to improvements in land value. This is discussed more in the section on **soil as a capital asset**. NPV uses a 5 per cent interest rate, based on low interest rates and low inflation over the past 20 years; however, there may be a case for revising this to 7 per cent, a rate conventionally used in government estimation of NPV.

For return on investment, payback period is the time or number of crops it takes to recoup the treatment cost; this is another way of expressing ROI. A five-year payback period implies 20 per cent per year ROI, a four-year payback is 25 per cent and so on. USQ staff estimated this without any discounting to reflect the way we discussed ROIs with growers. This is a useful financial heuristic with its relevance to cashflow management and intuitive contribution to near-term planning.

Benefit/cost ratio (BCR) provides another form of ROI in comparing the net benefit with the costs, also with the 5 per cent discount rate. This provides some relativity at a quick glance. This was not calculated in these case studies.

The Yates–Doyle study (**Case Study A** (page 36)) shows that it is possible for grain yields to be close to potential (that is, yield gap removal) in some years following soil amelioration.

The LIRAC results (**Case Study B** (page 41)) show that large and persistent boosts in financial performance are possible with soil amelioration, with returns after five years exceeding the original purchase price of the land. However, the LIRAC soil was highly variable, meaning accurate soil constraint maps (typically based on topsoil and perhaps subsoil samples from one soil core, or group of cores, per 5ha) are required up-front on farms with this type of soil distribution to ensure that the most appropriate ameliorant, or blend, is applied to the correct spots within a paddock.

Both of these studies have shown that when topsoil pH is <6.5, lime can deliver calcium to treat dispersive topsoil.

Case Study D (page 46) does not yet have enough yield data (<5 years) to draw economic conclusions, but some preliminary results are presented. For **Case Study C** (page 44), it was not possible to conduct more detailed economic analysis at the time of writing.

CASE STUDY A: Dryland wheat on dispersive Grey Vertosols near Moree, NSW

OVERVIEW

SITE: ‘Gurley Station’, Gurley, NSW; ‘Delvin’, Garah, NSW (**Figure 9** (page 15))

DURATION OF THE EXPERIMENTS: five years; 1973–77

RESEARCH TEAM: University of New England, Armidale; NSW Department of Primary Industries, Tamworth

RESEARCHERS: Bill Yates, John McGarity, Bing So, David Doyle, David Tayler, Peter Horn

TREATMENTS UNDER CONSIDERATION; all gypsum and lime treatments were surface-applied: Gypsum (by-product phosphogypsum); 12.5t/ha, 2.5t/ha, 1.25t/ha lime; 5t/ha and sulfur 120kg/ha; deep-ploughing (25cm) to lift natural lime nearer the surface and to remove any near-surface compaction; organic matter; chopped hay, 12t/ha

PUBLICATIONS: Yates (1972); Doyle et al. (1979); Yates and McGarity (1984)

At ‘Gurley Station’ (Gurley) and ‘Delvin’ (Garah), Grey Vertosols were present with inherently dispersive/sodic surface soil, minimal deep vehicle compaction and no serious nutritional limitations. About 38 per cent of cropping soil in the area was estimated to have a suppression of dryland wheat yield due to topsoil instability (dispersion index in the range 9 to 12) (So & Onus 1984). Experiments were established in 1973 and 1974 to test the feasibility of using applied gypsum, lime, deep ploughing and organic matter (chopped straw) to overcome topsoil dispersion problems.

Key conclusions:

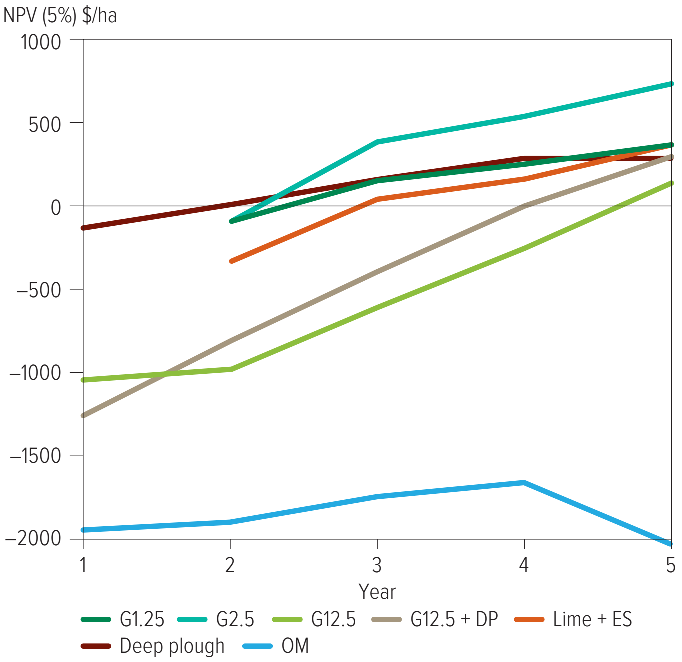
- Gypsum at 2.5t/ha was the most profitable treatment.
- It is possible for grain yields to be close to potential (that is, yield gap removal) in some years following soil amelioration.
- The 12.5t/ha gypsum treatment gave permanent displacement of sodium in topsoil and part of the subsoil.

Yield response

Yields close to potential were achieved in two of nine ‘site years’ (two sites: ‘Gurley Station’ and ‘Delvin’, with data collected for five and four years, respectively); gypsum 12.5t/ha treatment at ‘Gurley Station’ in 1977 and at ‘Delvin’ in 1974 (**Table 8** (page 35)). But the overall outcome was that yield fell far short of potential, even after amelioration.

Some treatments were persistent and gave impressive yield gains that were still present after five wheat growing seasons (1973–77), particularly gypsum 12.5t/ha (**Table 8**).

Figure 30: Net present value (NPV) performance of Case Study A; dryland wheat; high grain prices per tonne (wheat $500). The cumulative NPV values (5 per cent interest rates) are calculated via the grain yield increases, relative to the controls. Gypsum cost (purchase, transport, spread) = $110/t; lime (purchase, transport, spread) = $70/t; deep-plough = $60/ha, organic matter = 12t/ha chopped straw ($1800/ha).



Profitability

ROI and payback period are shown in **Table 9**. **Figure 30** shows NPV.

The gypsum treatments were profitable (**Table 9**, **Figure 30**), particularly with high grain prices ($500/t wheat price). Of the treatments under consideration, gypsum (2.5t/ha) was the most profitable. Despite poor persistence at ‘Delvin’, deep ploughing also was profitable but large financial losses were associated with applications of 12.5t/ha chopped straw.

Figure 30 shows the economic benefits of applying gypsum (2.5t/ha), with reliance on the electrolyte effect, rather than as a single large dose (12.5t/ha).

Table 9: Grain yields of ameliorative treatments at 'Gurley Station' and 'Delvin'. The modelled potential (rain-limited) wheat grain yields were calculated using the French–Schultz equation (1984) and rainfall data from the study sites.

Treatment	'Gurley Station'					'Delvin'			
A Series Experiments: Wheat grain yield, t/ha (gypsum surface application was in January 1973)									
	1973	1974	1975	1976	1977	1973	1974	1975	1977
Control	1.1	0.8	1.7	0.7	1.0	0.2	1.1	1.4	1.8
Chopped straw (12t/ha)	0.8	0.9	2.1	0.9	–	1.5	2.5	1.3	2.0
Deep plough (DP) 25cm	1.0	1.1	2.1	1.0	1.2	–	2.3	1.2	1.7
Gypsum (12.5t/ha)	1.8	1.0	2.6	1.5	2.0	1.4	3.3	1.7	2.6
Gypsum (12.5t/ha) + DP	1.5	1.8	2.6	1.7	1.8	0.6	3.5	2.0	2.8
LSD (p=0.05)	0.5	0.6	0.6	0.3	–	0.3	0.5	0.4	0.3
B Series Experiments: Wheat grain yield, t/ha (gypsum and lime surface application was in April 1974)									
Control		0.5	1.0	0.7	1.0	–	0.7	1.5	1.5
Gypsum (1.25t/ha)		0.5	1.6	1.0	1.3	–	1.5	1.5	1.9
Gypsum (2.5t/ha)		0.9	2.1	1.1	1.5	–	1.7	2.1	1.8
Lime (5t/ha) + S		0.7	1.9	1.0	1.5	–	0.7	1.9	1.9
LSD (p=0.05)		ns	0.5	0.3	ns	–	0.7	0.4	0.4
Potential yield, t/ha (French & Schultz 1984)	**4.3**	**3.3**	**5.3**	**4.3**	**2.2**	**3.0**	**3.5**	**3.3**	**6.4**

LSD = Least significant difference. NS = Not significant.

Source: Doyle et al. 1979

Effects on soil properties

The 12.5t/ha gypsum treatment permanently displaced sodium in topsoil and part of the subsoil (to a depth of 45cm at 'Gurley Station'; McKenzie 1982 (**Figure D1** (page 59)). The 1.25t/ha and 2.5t/ha gypsum treatments only provided a temporary electrolyte improvement in the topsoil.

Lime is much less soluble than gypsum and was slow to suppress soil dispersion, but significant yield benefits were eventually observed at both 'Gurley Station' and 'Delvin' with lime treatments. These were:

- 0.9t/ha in 1975 at 'Gurley';
- 0.5t/ha in 1977 at 'Gurley'; and
- 0.4t/ha in 1975 and 1977 at 'Delvin'.

As lime is not soluble in alkaline soil and most sodic soil is alkaline, lime is often ineffective as a treatment for dispersion. However, the topsoil pH ($CaCl_2$) values at 'Gurley Station' (6.1) and 'Delvin' (6.3) were below the threshold of ~6.6 nominated by Richards (1954) for adequate dissolution of lime to improve sodic soil. In many parts of the northern region, lime provides a lower-cost source of calcium compared with gypsum. Where the topsoil is acidic–neutral, gypsum–lime blends could improve the potential ROI by lowering input costs.

In a nearby follow-up experiment described by So and McKenzie (1984), rain infiltrated much deeper following the application of 7.5t/ha gypsum (by-product phosphogypsum; **Figure 31** (page 40)). Moisture increased noticeably from 20 to 100cm at Garah compared with the plots that received no gypsum. Rain following the application in March 1978 was well above average.

The deeply infiltrating water on the gypsum-treated soil had an elevated electrolyte concentration caused by dissolved gypsum, but profile chloride concentrations were reduced (McKenzie 1982) indicating that the gypsum improved soil structure enough to leach existing salts from the profile. Under these circumstances, nitrogen losses via deep leaching on lighter textured Grey Vertosols (for example, the 'Gurley' soil) can be significant and may result in crop growth restrictions due to nitrogen deficiency.

At Gurley:

- Down to a depth of 40cm, the gypsum plots had better drainage (that is, less waterlogging; lower soil water content) than the control plots.
- Below a depth of 45cm, the gypsum plots had higher plant-available water contents than the untreated control plots.
- A problem at Gurley was that the untreated soil surrounding the experimental site was too boggy to sow the wheat crop (sowing finally occurred around mid-August, that is, a very late and undesirable sowing date). The lack of water extraction by a growing wheat crop meant that soil water was lost as deep drainage where gypsum had been applied. The deep drainage water contained leached nitrogen, so the wheat crop that eventually grew at the site was nitrogen deficient following gypsum application. This prevented improved subsoil water contents being converted into grain yield improvements.

At Garah:

- Down to a depth of 15cm, the gypsum plots had better drainage (that is, less waterlogging) than the control plots.
- Below a depth of 15cm at Garah, the gypsum plots had much higher plant-available water contents than the untreated control plots.
- There was no evidence of deep drainage losses of water and dissolved nitrogen.
- During spring, the wheat crop grew much better (for both early sowing and late-sowing) where gypsum had been applied. The control plots were adversely affected by crown rot disease.

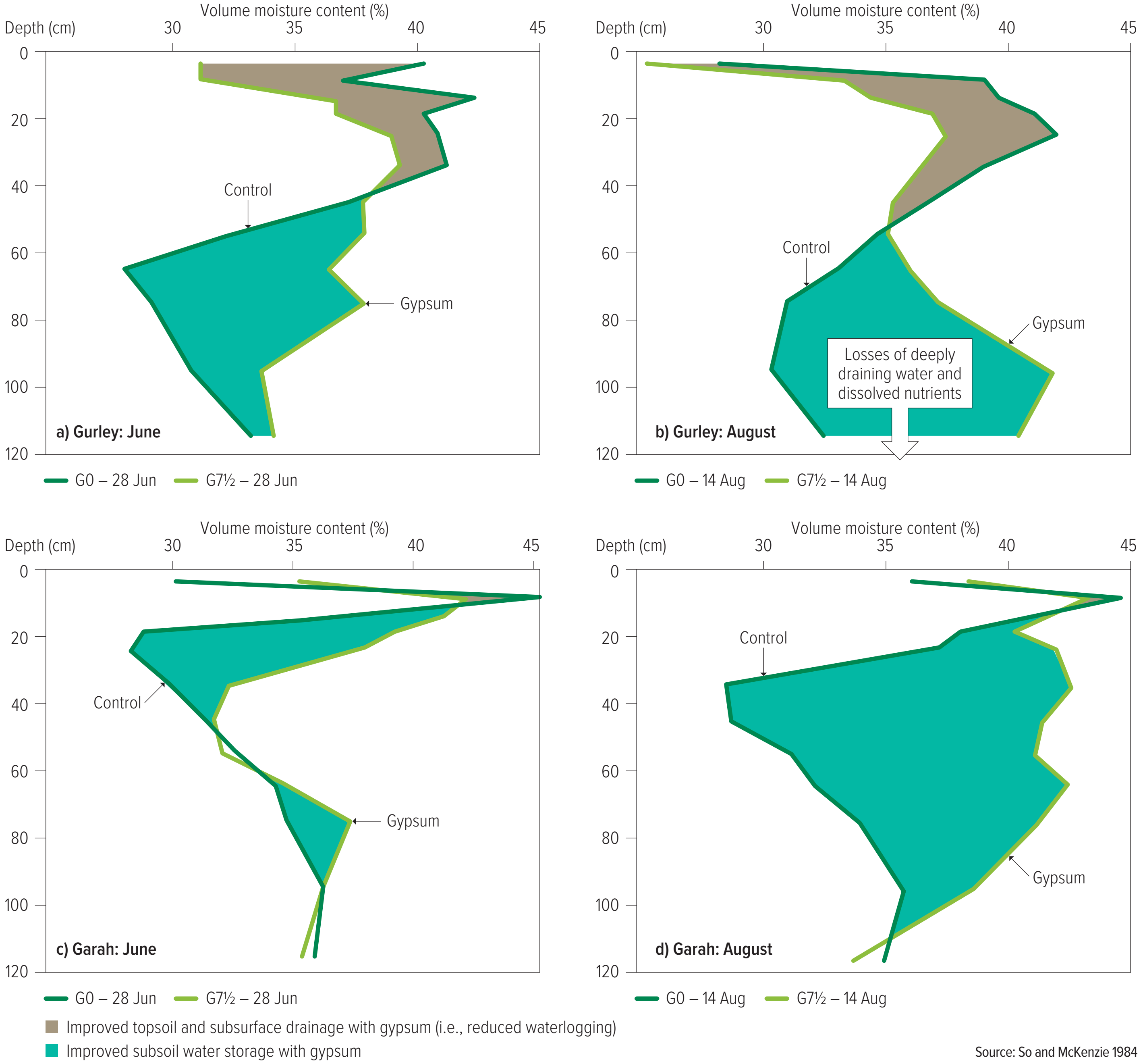
Although both soil types were Grey Vertosols, the Garah soil had a higher clay content than the Gurley soil. Sometimes it is claimed that gypsum improves water storage by increasing the soil's water holding capacity. It is true that gypsum improves water storage, but it does this mainly by improving the soil's ability to take in water (Abbott and McKenzie 1996).

Table 10: Return on investment (ROI) and payback time of the Yates–Doyle gypsum–lime experiment (Case Study A); dryland wheat; ROI and payback times at ‘Gurley Station’ and ‘Delvin’ with medium ($250) and high ($500) wheat grain prices per tonne. The ROI values (5 per cent interest rates) are calculated via the grain yield increases, relative to the controls.

		Initial cost ($/ha)	ROI (%)			Estimated payback time (years)
			YEAR 1		YEAR 4/5	
			1973	1974	1977	
$250/t wheat						
Gurley	OM	1800	–3		–6	loss
	DP	60	–52		313	2
	G12.5	1375	12		55	>5
	G12.5 + DP	1435	6		60	>5
	G1.25	138		15	186	3
	G2.5	275		37	185	3
	Lime + ES	450		13	90	>4
Delvin	OM	1800	17		36	>5
	DP	60	–		340	2
	G12.5	1375	18		71	>5
	G12.5 + DP	1435	7		67	>5
	G1.25	138		30	186	2
	G2.5	275		74	151	2
	Lime + ES	450		26	36	>4
$500/t wheat						
Gurley	OM	1800	–7		–13	loss
	DP	60	–103		627	2
	G12.5	1375	25		110	5
	G12.5 + DP	1435	12		121	5
	G1.25	138		125	371	1
	G2.5	275		81	370	2
	Lime + ES	450		–2	180	4
Delvin	OM	1800	34		71	>5
	DP	60	–		679	2
	G12.5	1375	37		141	4
	G12.5 + DP	1435	13		135	4
	G1.25	138		250	373	1
	G2.5	275		162	302	1
	Lime + ES	450		–3	72	>4

Where OM = organic matter (chopped straw), DP = deep plough, ES = elemental sulfur, G = gypsum.
🟩 = the most successful gypsum treatments.
🟧 = five or more years until amelioration cost is recovered.

Figure 31: Volumetric water content as a function of depth on poor-yielding sodic soil at 'Delvin' (Garah) and 'Wyndella' (Gurley) in the wet winter of 1978, with and without gypsum (7.5t/ha). Gypsum was applied as a single dose in March 1978. The water content measurements were taken in late-June 1978 and repeated six weeks later, in mid-August.



Source: So and McKenzie 1984

Shortcomings

Case Study A (page 37) had several shortcomings:

- The study needed to be greater than five years' duration, especially for the evaluation of lime, which appears likely to have a greater persistence in sodic soil than gypsum following a series of wet years.
- No sequential split applications of gypsum were included in the experimental design. Loveday (1976) has noted the importance of adding follow-up split applications of gypsum to maintain the beneficial electrolyte effect until permanent displacement of exchangeable sodium by calcium has been achieved.
- Alternative forms of gypsum, for example, coarse-mined gypsum with relatively low solubility (Abbott & McKenzie 1996), gypsum–lime blends and subsoil applications were not assessed.

CASE STUDY B: Irrigated soybean, canola and wheat on a dispersive Grey Vertosol near Condobolin, NSW

OVERVIEW

SITE: Lachlan Irrigation Research Advisory Council (LIRAC) farm, Condobolin (**Figure 9** (page 15))

DURATION OF THE EXPERIMENTS: 5 years; 1988–1993

RESEARCH TEAM: NSW Department of Primary Industries

RESEARCHERS: Len Banks, Tony Bernardi, David McKenzie, Karen Rose, Yin Chan

TREATMENTS UNDER CONSIDERATION: Gypsum 10t/ha; gypsum 2.5 + 2.5t/ha (split application); lime 4.8t/ha; a blend of gypsum 5t/ha + lime 2.4t/ha; raised beds and flat irrigation

PUBLICATIONS: Chan et al. (1999); McKenzie et al. (2002a)

Lime is a more concentrated form of calcium than gypsum, and many areas with sodic soils in NSW are closer to lime deposits than to sources of gypsum (McKenzie et al. 1995). Therefore lime often is much cheaper to buy and transport, per tonne of calcium, than gypsum. But as dispersive soils are often alkaline, and lime has a very low solubility in alkaline soil, it is often assumed that lime will not improve dispersive soil.

An experiment was established in 1988 at the Lachlan Irrigation Research Advisory Council (LIRAC) farm near Condobolin, NSW, to explore the economic feasibility of using lime to at least partially replace gypsum for sodic soil amelioration. The experiment was established on a Grey Vertosol.

The different treatments used in the study were as follows:

- phosphogypsum (gypsum; $CaSO_4.2H_2O$) added as a large single dose of 10t/ha;
- phosphogypsum (gypsum; $CaSO_4.2H_2O$) split across two smaller annual applications of 2.5t/ha each;
- finely ground limestone (lime; $CaCO_3$); and
- a 50:50 blend of calcium from gypsum and lime.

The study compared the effects of the different treatments on chemical factors influencing the structural stability of a sodic Grey Vertosol. The soil had a dispersive topsoil with an ESP ranging laterally from approximately 6 to 12 (**Figure 32**). Surface pH (0.01 M $CaCl_2$) before treatment was 6.3. The subsoil was saline.

Crops were either planted on flat land (border-check irrigation layout) or raised beds (0.15m high, with furrows spaced 1.5m apart). Both systems were flood-irrigated with water from the nearby Lachlan River. Due to the importance of demonstrating results directly to local growers who partially funded the work via LIRAC, each of the 30 plots was large enough (0.18ha) to allow commercial farming equipment and techniques to be used under a CTF layout. The impact on crop grain yields and profitability of each treatment was assessed via the growth of two summer crops (soybeans, 1988-89, 1989-90) and three subsequent winter crops (canola/wheat/canola, 1991–93). The discussion here focuses on the flat-land plots.

Economic data is presented in Table 10 (ROI and payback period) and **Figure 33** (NPV).

Key conclusions from **Case Study B** (page 41) include:

- NPV increases over a five-year period on the strongly sodic soil (ESP 10 to 12) were up to $5500/ha using a 5 per cent interest rate scenario. On less sodic soil (ESP ~7), the most profitable option gave an NPV increase of $2300/ha.
- After three years, the gypsum–lime blend (on soil with topsoil ESP of 10 and 12) gave NPV values greater than median price per hectare for farmland in 2020 of $1873 for the Lachlan Municipality, which includes Condobolin (Blewitt 2021).
- After 5 years, there were very strong long-term gains (high ROI, high NPV) from the gypsum–lime blend (especially ESP = 10 and 12) and lime alone (especially ESP = 7). There was no sign of a major tapering off of responses in year five.
- After five years, the most profitable treatments were gypsum + lime on replicates one and two (the higher ESP plots), and lime only on replicate three.
- ROI data indicates strong short-term gains from gypsum (2.5t/ha).
- There were financial losses in year one from lime, which was very slow to activate, and gypsum 10t/ha.
- Small repeated 2.5t/ha gypsum doses gave bigger profits than one dose of 10t/ha of gypsum.
- With current (2022) high grain prices, the estimated payback period for amelioration was less than one year for all treatments under consideration. The only exceptions were gypsum (10t/ha) and the gypsum–lime blend on the least sodic soil (ESP ~7).

Figure 32: Spatial variability of surface ESP at the LIRAC site, prior to treatment application, 1988. The replicate plots responded to ameliorants in contrasting ways, so they were treated as separate demonstration strips.

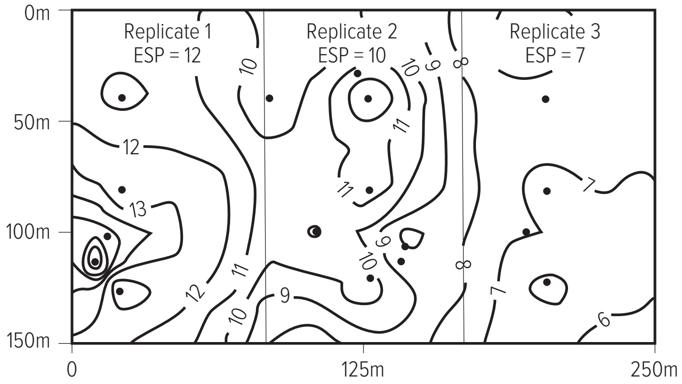


Table 11: Return on investment (ROI) and payback time of the LIRAC gypsum–lime experiment (Case Study B); irrigated soybeans; ROI and payback times with medium ($500 soybean and canola; $250 wheat) and high ($1000; $500) grain prices per tonne. The ROI values (5 per cent interest rates) were calculated via the yield increases, relative to the controls.

		Initial cost ($/ha)	ROI (%)		Estimated payback time (years)
			Year 1	Year 5	
$500/t soybean and canola, $250/t wheat					
ESP = 12	G2.5+2.5	275+275	163	333	1
	G10	1100	61	248	2
	L4.8	336	94	590	2
	G5 + L2.4	718	100	444	1
ESP = 10	G2.5+2.5	275+275	220	252	1
	G10	1100	67	123	2
	L4.8	336	62	341	2
	G5 + L2.4	718	137	325	1
ESP = 7	G2.5+2.5	275+275	54	206	2
	G10	1100	21	58	>5
	L4.8	336	55	398	2
	G5 + L2.4	718	12	146	5
$1000/t soybean and canola, $500/t wheat					
ESP = 12	G2.5+2.5	275+275	326	665	1
	G10	1100	122	495	1
	L4.8	336	187	1180	1
	G5 + L2.4	718	200	888	1
ESP = 10	G2.5+2.5	275+275	440	505	1
	G10	1100	133	247	1
	L4.8	336	125	683	1
	G5 + L2.4	718	273	650	1
ESP = 7	G2.5+2.5	275+275	107	412	1
	G10	1100	42	116	3
	L4.8	336	111	796	1
	G5 + L2.4	718	24	293	5

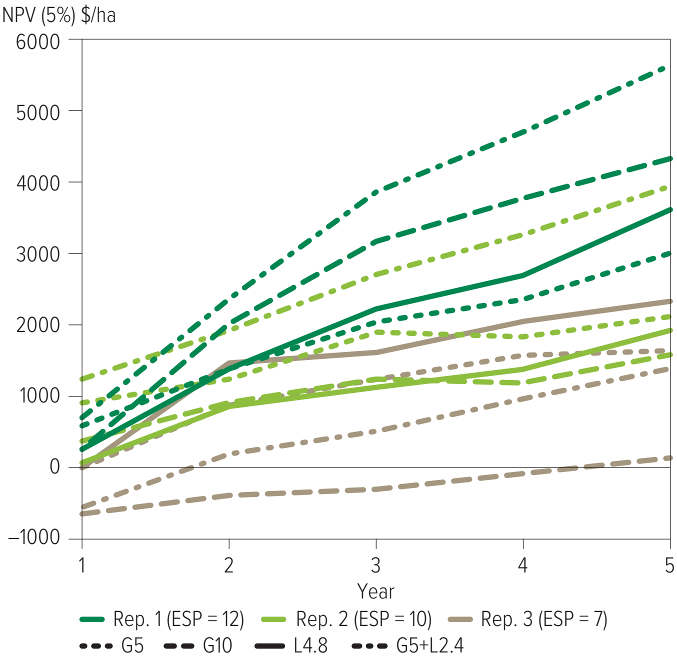
Where OM = organic matter, DP = deep plough, L = lime, G = gypsum.
🟩 = the most successful ameliorants.
🟧 = five or more years until amelioration cost is recovered.

When interpreting the ROI values in Table 11 (in some cases >1000 per cent), keep in mind that a superannuation fund is considered to be doing well when yearly ROI >10 per cent.

It was noted that where lime was used as an ameliorant, pH_{ca} increased to values greater than seven (the point at which lime has negligible solubility), but pH eventually came down after about six months. This apparently was due to the presence of organic acids as crop residues decomposed following rain. New research is required to learn more about the dynamics of lime (inorganic carbon) and organic carbon in dispersive soil during and after amelioration.

The next stage in this financial analysis of **Case Study B** (page 41) is estimating the approximate cost of soil testing that is required for a paddock with patterns of ESP variation similar to the LIRAC site. This is because the full cost of improvement for this soil type needs to include both the cost of ameliorants and the cost of a soil survey that is sufficiently accurate to ensure placement of the most appropriate ameliorants where they are required spatially.

Figure 33: Net present value (NPV) performance of the LIRAC Condobolin gypsum–lime experiment (Case Study B). Calculated with high grain prices per tonne for the 1988–93 soybean/soybean/canola/wheat/canola rotation (soybean @ $1000/t; canola @ $1000/t; and wheat @ $500/t). The cumulative NPV values (5 per cent interest rates) are calculated via the grain yield increases, relative to the controls, for each replicate. Gypsum cost (purchase, transport, spread) = $110/t; lime (purchase, transport, spread) = $70/t.



CASE STUDY C: Bland Catchment, NSW – studies on Sodosols

OVERVIEW

SITE: Rand and Grogan, southern NSW (**Figure 9** (page 15))

DURATION OF THE EXPERIMENTS: 2017–21

RESEARCH TEAM: NSW Department of Primary Industries, Wagga Wagga

RESEARCHERS: Team led by Dr Ehsan Tavakkoli

TREATMENTS UNDER CONSIDERATION: Gypsum; ripping; organic matter (pelletised pea straw, pelletised wheat stubble, chicken manure); nutrients

PUBLICATIONS: Dear et al. 2005, Uddin et al. 2022.

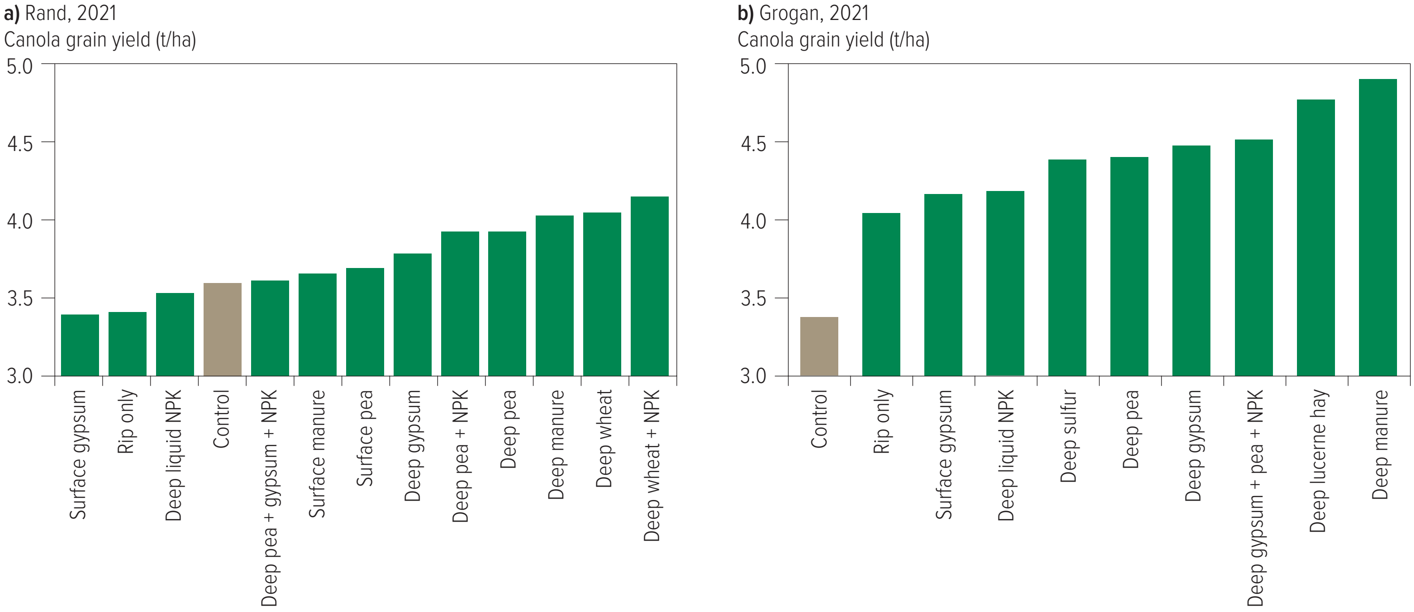
The information for this case study has been largely sourced from Uddin et al. 2022. It is proposed that more economic data about Case Study C will be available in future versions of this manual.

Key conclusions:

- Combining amendments gave the best yield results. Deep-placed pea straw pellets + gypsum + nutrients and deep-placed gypsum + pea straw pellets consistently led to significantly improved yield.
- Deep-placed amendments increased root growth, which led to increased grain yield through better water use from deeper clay layers.
- Amendments reduced soil pH and ESP and increased microbial activity.

The trial sites had been under continuous cropping (cereal/canola) for more than 50 years. The soil at both sites was a Sodosol with a texture-contrast profile. Limitations included high bulk density, low hydraulic conductivity and ESP >12 below 20cm depth.

Figure 34: The mean effect of surface or deep-placed amendments on grain yield of canola (cv. Dimond) grown in an alkaline dispersive subsoil at 'Rand' (a) and 'Grogan' (b), 2021.



Yield improvements

The various amendments significantly affected crop grain yield over five years. Deep-placed amendments had more of an impact than surface amendments. The combination of organic and inorganic amendments resulted in significant and consistent improvements to crop yield.

At Rand in 2021, canola grain yield increased by 12 to 15 per cent following the deep placement of wheat stubble, wheat stubble + nutrients and manure (**Figure 34**). At Grogan, canola grain yield increased by 39 per cent (gypsum + pea hay + nutrients), 42 per cent (lucerne hay + gypsum) and 45 per cent (manure). Yield responses to surface ameliorants and ripping were not significantly different to the controls at both sites. This is presumably due to the constraints being more severe in the subsoil and for this reason, treating the subsoil was more effective.

Returns

Over five years, the treatment with the highest gross return was deep gypsum (**Table 12**). This project presents cumulative gross return, compared with NPV in the other case studies.

Although the deep-placed organics led to higher yields, the cost of these amendments lowers the overall returns. The authors note the tentative but promising finding that *in situ* farm-grown products such as wheat and pea stubble can improve soil condition and yield similar to animal manures and gypsum. If these findings are confirmed, along with the most efficient way to apply these amendments to the soil, growers potentially have a large supply of inexpensive organic ameliorants on hand.

Table 12: Grain yield and cumulative gross return (2017–20) for barley (2017; $220/t), wheat (2018; $250/t), canola (2019; $600/t), wheat (2020; $250/t) and canola (2021; $800/t) at Rand. Data is sorted from highest to lowest $.

Treatment	Yield (t/ha)	$/ha
Deep gypsum	22.7	8700
Deep wheat + NPK	22.6	8698
Deep pea + NPK	22.3	8682
Deep manure	22.3	8645
Deep pea	22.7	8635
Deep wheat	22.3	8614
Deep pea + gypsum + NPK	23.0	8577
Surface manure	20.6	7981
Surface pea	19.7	7769
Deep liquid NPK	20.6	7671
Surface gypsum	19.1	7550
Control	19.3	7497
Rip only	19.3	7465

Impacts on soil and crop roots

Adding gypsum reduced pH in the amended subsoil by 0.86 units (from 8.99 to 8.13). Tavakkoli et al. (2022) found that where sodic subsoil low in calcium carbonate had extremely high pH due to the presence of bicarbonate salts, the application of gypsum could significantly reduce the alkalinity. This occurs due to the reaction of dissolved calcium from applied gypsum with the bicarbonates to form calcium carbonate (lime) precipitates.

Lowered pH following gypsum application also resulted in a significant reduction in soil dispersion. This is due to alkalinity increasing negative charges on the surfaces of clay particles, which increases clay dispersion; therefore lowering pH reduces this charge and impact on dispersion. pH was not affected by other treatments.

Combining organic and inorganic amendments can improve soil chemistry, soil physical properties and biological activity. For example, adding organic matter and nutrients provides substrate for enhanced biological activity resulting in increased macro aggregation and improved subsoil structure. These additive effects can have highly beneficial impacts on yield.

The number of visible roots in the amended subsoil layer (20 to 40cm) increased the most with deep manure and deep pea-straw pellets. All subsoil amendments improved root growth to some degree.

CASE STUDY D: Dryland grains core sites at six locations in Queensland and NSW

OVERVIEW

SITES: NSW–Forbes, Armatree, Spring Ridge.
Queensland–Talwood, Millmerran, Drillham.
Site locations are shown on **Figure 9** (page 15)

DURATION OF THE EXPERIMENTS: two years but ongoing until 2026, with GRDC support

RESEARCH TEAM: USQ (Stage 1 of project), UNE, DAFF

RESEARCHERS: John Bennett, Chris Guppy, David Lester, Stirling Roberton, Craig Birchall, Richard Flavel, Cameron Silburn, David McKenzie

TREATMENTS UNDER CONSIDERATION: Surface gypsum to reduce ESP to 3%; subsurface gypsum to reduce ESP to 3% in half the soil volume (Queensland) and a quarter of the soil volume (NSW); ripping to 20cm, and deeper where possible – nitrogen, phosphorus and potassium applications into the soil profile at 20cm depth; subsurface organic amendment applications, feedlot compost in Queensland (10t/ha) and lucerne pellets in NSW (20t/ha); elemental S applied at 1.5t/ha at depth as part of a comprehensive treatment application strategy in alkaline subsoils.

PUBLICATIONS: Lester et al. (2022)

Key conclusions:

- Gypsum is not having a noticeable impact. Deep placement of gypsum or organic matter is too expensive, relative to the returns from these early trials, to recommend. The cost of deep placement of gypsum was not offset by resulting revenue increases. This may be caused by the extended wet weather. In dry years, the value of gypsum may become more apparent.
- Deep-ripping + gypsum gave better returns than gypsum + other treatments.
- Where soils only needed medium-high (for example, 3 to 4t/ha), rather than high (≥6 t/ha) rates of gypsum (Forbes and Armatree) and yield responses were good, financial outcomes were positive from five to 10 crops.
- Deep-ripping with nutrients (NP(K)Zn) had the most positive financial outcomes across all sites, and at four out of five sites, the addition of the high rate of NP(K)Zn to deep-ripping was also positive, if it is assumed that the effects persist for four or five years.
- Longevity is a key consideration. The combination of surface gypsum and deep-ripping was positive in all cases by an estimated 10 years and in two cases, by five years.

Overall, wet conditions have meant that the full impact of amendments on improving soil structure, and particularly increasing PAWC through improving soil structure and porosity, are not likely to be observed. However, these conditions are also ideal to allow the gypsum, and possibly elemental sulfur, to dissolve and spread through a larger volume of soil than would have occurred in drier years.

Treatments

Treatments included combinations of:

- shallow ripping (20 to 25cm);
- fertiliser at normal (50kg N/ha, 30kg P/ha (50kg K/ha) Zn in bands) and high (280kg N/ha, 100kg P/ha; additional K and Zn equivalent to extra from OM) rates;
- deep-ripping (rip to 25cm then re-rip to ≈35cm);
- surface-spread gypsum;
- deep (subsurface) gypsum in bands;
- elemental sulfur (ES) in bands; and
- banded organic matter (OM).

Table 13: Soil descriptions at each site.

	NSW			Queensland		
Location	Armatree	Forbes	Spring Ridge	Dulacca	Millmerran	Talwood
ASC	Red Sodosol	Brown Vertosol	Black Vertosol	Grey/Brown Vertosol	Grey/Brown Vertosol	Red/Brown Vertosol
Key soil parameters	Not dispersive (0–10cm) to dispersive (10–20) subsurface, to strongly alkaline and dispersive at depth, compact surface layers	Not dispersive (0–10cm) to dispersive (10–20) subsurface, to strongly alkaline and dispersive at depth	Moderate ESP and salinity in surface, increasing to high ESP and salinity at depth, but both are non-dispersive due to the salinity	Surface soils not spontaneously dispersive but subsurface highly dispersive	Surface and subsurface soils not spontaneously dispersive, very compact soil through the profile	Surface soils not spontaneously dispersive, subsoil highly dispersive at 60–70cm.

Table 14: Net present value ($/ha) by cropping years. Values from years four to ten are estimates only.

		NPV after crop year ($/ha)				
Site	Treatment	One year	Two years	Four years	Five years	Ten years
Armatree	Shallow-rip	26	18			
	Shallow-rip + fertiliser	28	29			
	Deep-rip + fertiliser	46	192	559		
	Deep-rip + high NP(K)Zn	–50	110	478	679	
	Surf gyp, shallow rip, fert.				92	368
	Surf gyp, deep-rip, fert.				222	682
	Deep gypsum + fertiliser				–73	376
	Surf + deep gyp, fertiliser				–502	–1
	ES + surf gypsum, fert.				–642	–99
Drillham	Shallow-rip	–24	64			
	Shallow-rip + fertiliser	–74	–86			
	Deep-rip + fertiliser	–22	35	313		
	Deep-rip + high NP(K)Zn	–410	–351	12	292	
	Surf gyp, shallow-rip, fert.				–812	–696
	Surf gyp, deep-rip, fert.				–247	325
	Deep gypsum + fertiliser				–1094	–639
	Surf + deep gyp, fertiliser				–2142	–1818
	ES + surf gypsum, fert.				–1583	–1211
Forbes	Shallow-rip	–11	–120			
	Shallow-rip + fertiliser	213	203			
	Deep-rip + fertiliser	3	610	1351		
	Deep-rip + high NP(K)Zn	–117	327	881	1017	
	Surf gyp, shallow-rip, fert.				138	750
	Surf gyp, deep-rip, fert.				–80	708
	Deep gypsum + fertiliser				572	1639
	Surf + deep gyp, fertiliser				604	2282
	ES + surf gypsum, fert.				–261	1156
Millmerran	Shallow-rip	–81	–15			
	Shallow-rip + fertiliser	–126	–3			
	Deep-rip + fertiliser	–179	–103	48		
	Deep-rip + high NP(K)Zn	–624	–465	–215		
	Surf gyp, shallow-rip, fert.				–153	358
	Surf gyp, deep-rip, fert.				–1185	–919
	Deep gypsum + fertiliser				–166	367
	Surf + deep gyp, fertiliser				–1388	–910
	ES + surf gypsum, fert.				–1621	–1231
Talwood	Shallow-rip	–31	–13			
	Shallow-rip + fertiliser	–94	0			
	Deep-rip + fertiliser	–155	–42	167		
	Surf gyp, deep-rip, fert.				–402	128
	Deep gypsum + fertiliser				–1731	–1666
	Surf + deep gyp, fertiliser				–2239	–1944
	ES + surf gypsum, fert.				–1996	–1891

🟩 = positive results

The various combinations are outlined in **Table 14**.

Gypsum rates were calculated to remediate the ESP down to 3 per cent in either or both of the top 20cm of soil and either half of the soil volume (Queensland) or a quarter in NSW in bands from 20cm down to 50cm depth (Lester et al. 2022).

The Queensland sites have had a total of six crops grown over two years but only grain yield from five. The 2020-21 sorghum crop at Millmerran was damaged by mice and rain. Most crops have had favourable in-crop rainfall.

The NSW sites had one winter crop each in 2020, followed in 2021 by a winter crop at Forbes and Armatree and a sorghum crop at Spring Ridge sown in October. All sites and crops have had wet to very wet fallows and growing seasons.

The Spring Ridge data is not shown due to a negligible response to amelioration after two years.

Economics

Table 13 presents the NPV data for the five main core sites. Results for years one and two are based on actual data; values for years four, five and 10 are estimates based on the assumption that the benefits observed so far will persist as per **Case Studies A** (page 37) and **B** (page 41). Use the crop performance estimates for Years 4, 5 and 10 cautiously. GRDC has invested in providing real data and future versions of the manual will include the updated data.

Preliminary results include:

- Boosted fertiliser treatments (high rates of NP(K)Zn) had an immediate and positive effect on yields at most sites, but the NPVs were not universally positive.
- Organic treatments (compost, lucerne pellets) also appeared to increase yields at most of the sites, but due to the very high application costs ($480/ha) from what were 'proof of concept' trials, these were not profitable. The average revenue response for the deep organic matter treatment was $220/ha. Provided the yield effects lasted more than three crop years, there would be a positive financial outcome.
- Deep-ripping (at 30 to 40cm) was profitable within one crop year at two sites, within two years at another and within four years at another two sites. Shallow-ripping (10 to 20cm), which was presumed to have only a short-term effect, had 'first-year-after-amelioration' crop benefits at only two sites, with others either showing no yield gains (two of five sites), or net losses (two sites).
- There were some positive responses in terms of yield and revenue from the application of gypsum or gypsum–lime at most sites, but in the best cases there would need to be at least a five-crop sustained benefit for these to be economically feasible due to the high up-front costs. The two best cases had superior outcomes due to a relatively low amount of gypsum to offset levels of sodicity and/or good yield responses.
- The combination of deep-ripping and gypsum resulted in much better returns than gypsum in other treatment combinations. This is mostly a function of the distribution of benefits from each of the treatments. That is, ripping has an immediate benefit and gypsum has some immediate benefit but is assumed to sustain benefit over time.
- The impacts of gypsum, either surface-spread or deep-placed, on yield are not yet evident. Subsurface gypsum applications potentially have been ameliorating the soil profile during the period since application, but seasonal conditions with high rainfall in-crop probably have not required any substantial use of subsoil water.

Organic matter

Large additions of organic matter to the subsoil (both natural and synthetic, for example, polyacrylamide) is not yet a proven cost-effective soil amelioration option. Doyle et al. (1979) did not find any long-term economic benefits after five years (see **Figure 30** in **Case Study A** (page 37)). The trials discussed in **Case Study D** (page 46), using new machinery and different organic matter sources, should provide some up-to-date conclusions by 2025. The results from Project C suggest that although some organic matter treatments were associated with increased yields, the costs of application outweighed any revenue gains.

The type of organic matter, its chemical and physical properties, incorporation method and the properties of soil being amended all affect the outcome.

For the Project B core sites in NSW, lucerne pellets were successfully used as a source of organic matter to improve crop yields in dispersive soil. Lucerne pellets have a low sodium content, but the cost is likely to be prohibitive (>$10,000/ha). The associated Queensland trials used feedlot manure, which is cheaper, but it comes with chemical limitations such as an excess of sodium ions that may need a calcium source to counteract it. After lots of rain, a manure-treated soil that seems stable can

Table 15: Indicative ranges of the number of years to recoup initial treatment cost. These estimates are based mainly on persistent observations from previous studies.

	Effect time (years)	Millmerran	Talwood	Dulacca	Armatree	Forbes
Shallow-rip	1–2	2+	2+	<1	1+	
Shallow-rip + fertiliser	2–3	2	2	3+	1+	<1
Deep-rip+ fertiliser	3–4	3	2	1+	1	<1
Deep-rip + high NP(K)Zn	3–5	5		3+	1+	1
Surface gypsum + fert.	10+	5+		26	4	3+
Surface gyp, deep-rip, fert.	10+	5+	6+	6	4+	2+
Deep gypsum + fertiliser	15+	20		12	5+	4+
Surf. gyp, deep gyp, fert.	15+	14		25	9	3
Surf. gyp, deep ES, fert.	15+	19		19	13	5

suddenly have structural issues associated with elevated ESP following the leaching of electrolytes. An example of this problem has been presented by Chan et al. (2007). They described a situation where high application rates of sodium-rich poultry manure inadvertently led to a serious loss of soil structural stability.

Organic matter may become more feasible as a profitable ameliorant if machinery can be developed to insert within-paddock crop residues as 'vertical mulches' in dispersive soil.

Elemental sulfur

Unexpectedly, the elemental sulfur had oxidised after the first season, leading to the natural lime dissolving and the *in situ* creation of gypsum. This was surprising as the window of time when the elemental sulfur was present and oxygen and water were both available was quite small at most of these sites, particularly given the depth at which it was placed and the amount of water in the profiles. Elemental sulfur usually has a lag period where the microorganisms that use it as an energy source multiply enough to oxidise the elemental sulfur. This suggests that the populations of sulfur-oxidising bacteria in the subsoil may be greater than expected given the absence of elemental sulfur in the profile.

Longevity

The key points from **Table 15** are that:

- most of the treatments where there was a positive yield response showed potential to recoup costs within an acceptable investment timeframe;
- deep-ripping showed potential net benefits at all sites; and
- if there was a transformative (long-term) effect from the gypsum treatments, then even the worst outcome (23 years) would be the equivalent of more than a 4 per cent ROI, which equates to recent, modest investment returns more broadly. The best results (from Forbes) were the equivalent of 20 to 30 per cent annual ROI.

Long-term economic analysis of GRDC demonstration strips / satellite sites (Roberton 2022) on a broad range of dispersive soil types will be undertaken in about 2025, in addition to ongoing analysis of the six core sites.

Part 5: Checking that the plan is working

Performance evaluation

The best way to check performance is with yield maps and/or yield gap maps. **Figure 35** shows the 2015 and 2021 yield and yield gap maps for 'Uah'. Note the significant reduction in the yield gap from 2015 to 2021 in much of the eastern part of the paddock; during this time, sodic topsoil was successfully treated with variable-rate gypsum.

Risks and mistakes

All soil amelioration comes with risks and the potential for mistakes. The worst-case scenario is that the mistake leads to a yield penalty for years to come. The more likely scenario is wasted money from unnecessary or poorly placed amendments. And the ongoing cost of yield gaps can add up – especially as grain prices are going up in response to global grain shortages.

The first step to avoiding mistakes is knowing the types of constraints and where they are. This is why it is critical to properly and accurately identify dispersive soil and the associated constraints.

Mistakes are more likely when you are not aware of variability within paddocks. Knowing soil variability and where the issues are helps you choose the right tools for the job.

Risks of the various amelioration options

Applying ameliorants in the wrong place can stem from improper use of EM surveys to map areas requiring gypsum or lime + gypsum, and/or over-reliance on ESP data and a lack of dispersion (and other) testing.

A soil can return to being dispersive if the second dose of a split-dose program is forgotten.

Ameliorating dispersive soil can cause deep leaching of nutrients – particularly nitrogen – to beyond the depth of crop roots in wet years.

Different sources of organic matter have their own unique challenges. Composted feedlot material, for example, can contain lots of sodium, leaving residues of sodium salts as it breaks down, which can make the soil more dispersive. Test organic matter sources before applying.

Using elemental sulfur to treat dispersion is still experimental. There is economic uncertainty about the use of ES to lower pH and produce gypsum *in situ* in soil containing $CaCO_3$ nodules. There have been strong positive responses to ES in recent projects, but it is expensive and accidentally applying too much could cause serious acidity constraints.

Deep-ripping failure

Decompaction failure may be a consequence of ripping when the soil is too wet or not working deep enough. When the soil is too wet, ripping tynes slice through the soil rather than fracturing it. This can also add to compaction by making plough pans to the sides of the tynes. If the soil is too wet, wait until the soil is dry enough to shatter and not smear. To test, take a handful of soil and roll it into a rod shape. If you can roll it to 3mm diameter or smaller, the soil is too wet. If the rod continually breaks when trying this, the soil should be dry enough to rip (Anderson et al. 2007).

Ripping tynes spaced too far apart might not fracture enough subsoil. To get good subsoil fracture, tyne spacing should be roughly equal to the depth you are trying to rip. For example, if trying to rip to 500mm, tynes should be a maximum of 500mm apart. If tynes are 600mm apart but you are only ripping to a depth of 300mm, the tynes are too wide to fully fracture across the subsoil. More detail about this important topic is presented by Godwin and Spoor (2015).

Bringing dispersive subsoils to the surface is another potential hazard when deep-ripping.

Re-compaction due to CTF failure

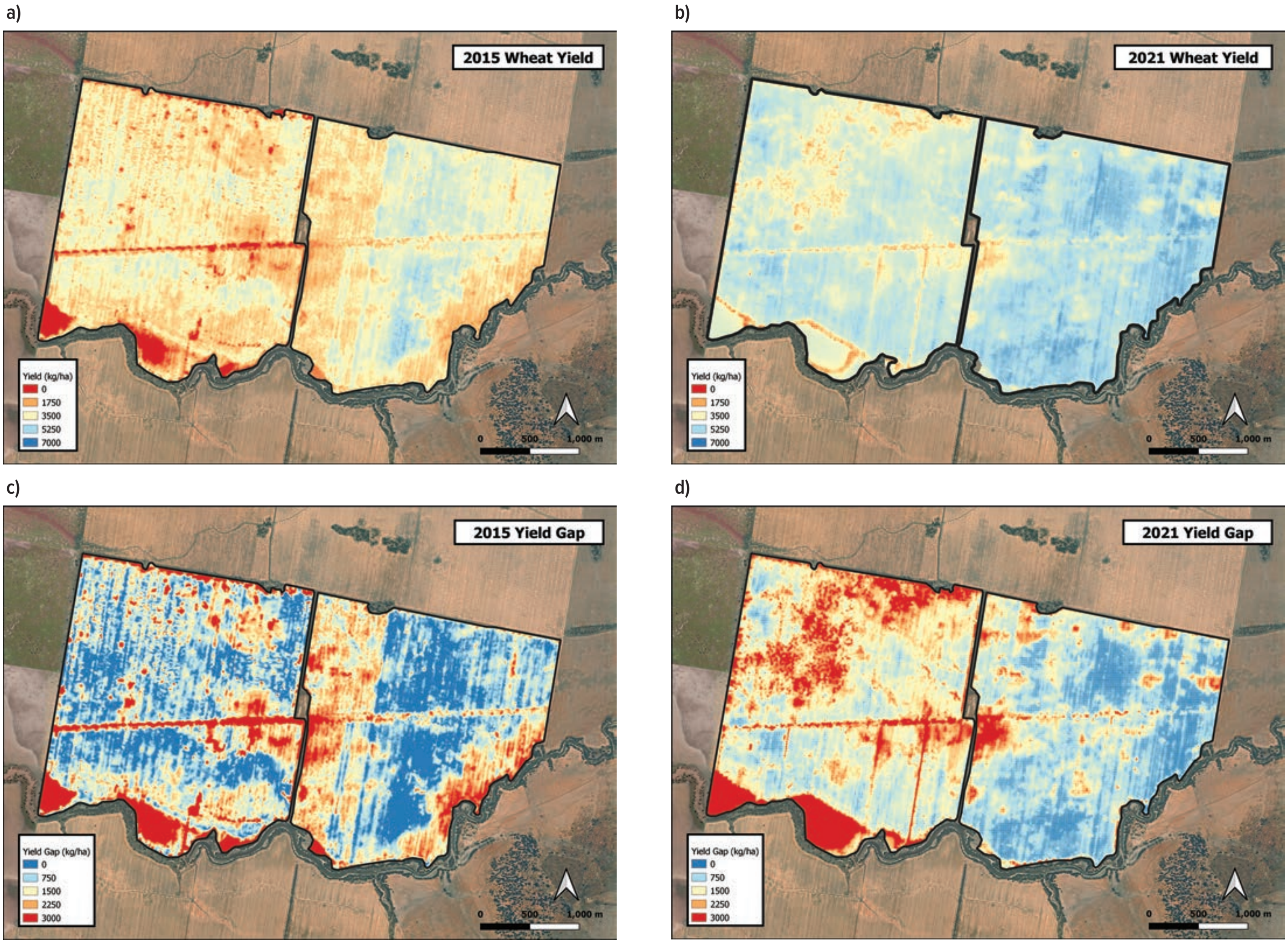
If heavy farm machinery deviates from CTF laneways, the spreading deep compaction quickly negates previous deep-ripping benefits and makes it much more difficult to get yield gains when the soil is also dispersive and treated with an ameliorant such as gypsum or lime.

Ongoing monitoring

Yield maps are the best way to monitor how effective the soil amelioration program has been. If yield improvements start to reverse, re-sample the soil to determine which follow-up amelioration techniques are required to prevent further declines in performance.

Use yield maps to provide an annual or biannual assessment of costs versus ameliorant-induced yield increases, and monitor economic indicators such as ROI, time to payback and NPV.

Figure 35: Wheat grain yield maps (a and b) and grain yield gap maps (c and d) for 2015 and 2021 at 'Uah'.



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Appendix A: More detailed science

For more detail behind the assessment and management of dispersive–sodic soil, see *Dispersive (sodic and magnesic) soils in Australia: The mechanisms, distribution and management; a review* (Rengasamy et al. 2016).

The Rengasamy et al. (2015) report provides detailed information about the following topics:

- processes and energy changes during hydration of dry aggregates;
- the influence of organic matter on dispersion;
- the role of clay mineralogy in swelling and dispersion;
- the influence of soil pH on clay dispersion;
- the cations ratio of soil structural stability (CROSS), which takes into account the influence of exchangeable magnesium and potassium in clay dispersion;
- threshold electrolyte concentration; and
- the concept of 'dispersive potential'.

The Rengasamy et al. (2016) report also classifies the different types of sodic soil in Australia. To improve communication about the various combinations of dispersion (rather than ESP) and pH for topsoil and subsoil, Rengasamy et al. (2016) suggested using the following system. Under both categories of 'topsoil' and 'subsoil', there are four subcategories. By choosing first a category, and then a subcategory, there are 16 (four times four) possible combinations of sodic soil categories.

Topsoil	Acidic dispersive OR Neutral dispersive OR Alkaline dispersive OR Non-dispersive (but may be saline)
Subsoil	Acidic dispersive OR Neutral dispersive OR Alkaline dispersive OR Non-dispersive (but may be saline)

This classification scheme was used by the GRDC Project B team when seeking suitable sites for the Project B core sites and demonstration locations. The team searched for dispersive grain-producing sites that were different to soil used for the Yates–Doyle work (neutral dispersive topsoil overlying alkaline dispersive subsoil).

The NSW Department of Primary Industries and cotton industry soil manuals also contain important descriptions of scientific processes relevant to this GRDC *Dispersive Soil Manual*. A link to a SOILpak manual relevant to northern region grain growers is as follows:

- McKenzie DC, 1998, *SOILpak for cotton growers*, third edition, NSW Agriculture, https://www.cottoninfo.com.au/sites/default/files/documents/SOILpak.pdf
  See Chapter E3 ('Effects of sodicity and salinity on soil structure') and E4 ('Clay minerals')

Appendix B: Aggregate stability in water test (ASWAT)

The best way to know if a soil is dispersive is to test it directly. The Aggregate Stability in Water test (ASWAT) (Field et al. 1997), derived from the Loveday and Pyle (1973) CSIRO procedure, is low-cost, accurate and practical. It is one of several available dispersion tests; an alternative approach is the Dispersion Meter procedure described by Anderson et al. (2007).

An overview of ASWAT is shown in **Figure B2**. The test has two steps: first, testing dry aggregates from the paddock, and second, testing of moistened and remoulded aggregates from the same sample. The remoulding simulates how the soil will respond to mechanical disturbance such as cultivation when wet.

Equipment

- Deionised water or rainwater. Chlorinated tap water can interfere with the results.
- Three soil aggregates per site. Aggregates should be about half a centimetre in diameter.
- Clear containers. Plastic Petri dishes are used by laboratories, but old jars with flat bottoms also work well.

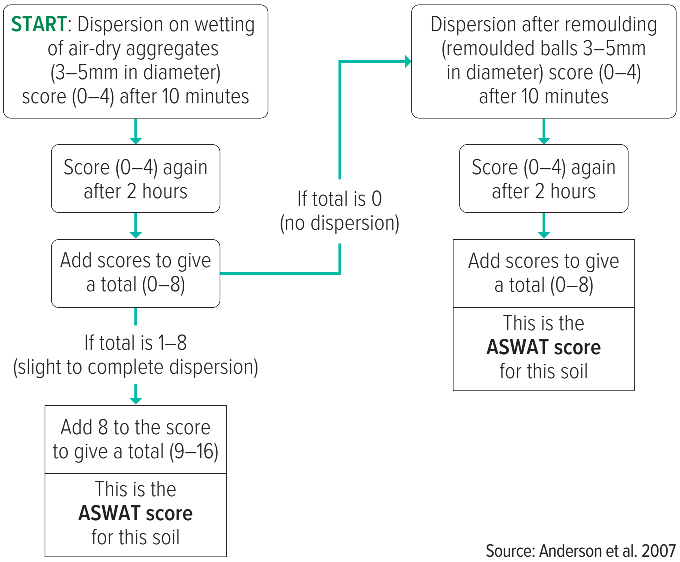
Instructions

1. Put a few centimetres of water into each dish/jar.
2. Place three aggregates gently into the water.
3. Check on the aggregates after 10 minutes and again after two hours and give each jar a score for each time period. For no milkiness around the aggregate, score 0; for slight milkiness, score 1; for obvious milkiness, score 2; for considerable milkiness, score 3 and for complete dispersion (sand grains in a cloud of clay), score 4. Where two aggregates have one dispersion score (for example, 2), but the third aggregate has a different score (for example, 0), record the majority score, that is, 2. Use the images below (**Figure B1**) as a scoring guide, from 0 (not dispersive) to 4 (completely dispersive).
4. If the soil does not disperse after two hours, take aggregates from the same sample bags and mould them when moist (use deionised water to moisten the soil) into a small cube. Place the cubes into a fresh dish of water and start from Step 3 again (that is, score after 10 minutes and two hours).

To obtain the full score (ranging from 0 to 16):

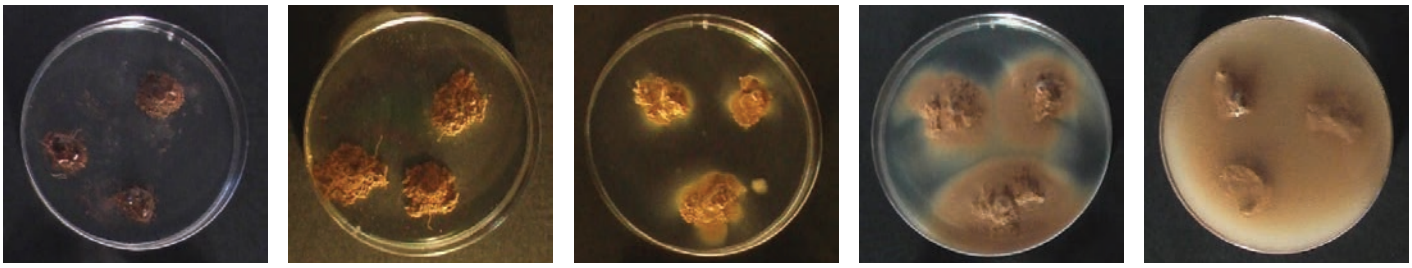
- for soils that showed some dispersion in steps 1 to 3 (that is, you did not need to remould), add the 10-minute score + the two-hour score + 8, giving a score ranging from 9 to 16.
- for soils that scored 0 in steps 1 to 3, add the remoulded scores for 10 minutes and two hours together, giving a score between 0 and 8 (see **Figure B2**).

Figure B2: The ASWAT score procedure.



Source: Anderson et al. 2007

Figure B1: Reference photographs of degree of dispersion associated with scores, respectively (left to right), of 0, 1, 2, 3 and 4.



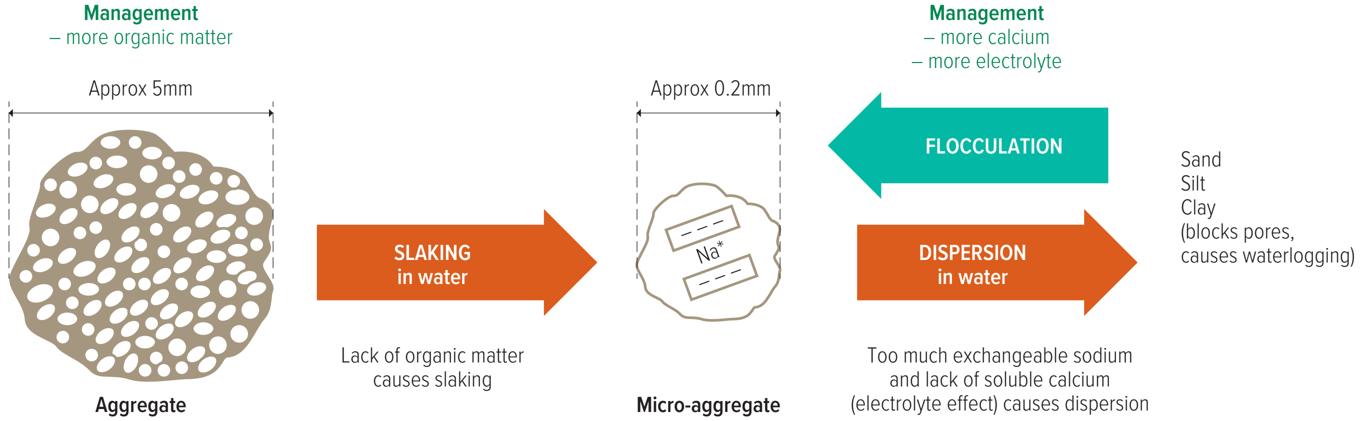
If the soil has a full score of 6 or more, it is spontaneously dispersive and highly likely to respond to gypsum. If the soil only disperses after remoulding, dispersion is likely to be limited to times after wet soil has been worked.

The process of slaking also needs to be considered. Only some northern region soil disperses, but almost all of it slakes. Slaking is the collapse in water of aggregates to create micro-aggregates (**Figure B3**). It is a physical issue usually caused by low organic matter.

Aggregates slake when they are not strong enough to withstand the pressure of the sudden influx of water into their pores. Soils that slake but do not disperse need different management approaches than dispersive soils; the main focus is organic matter accumulation (if possible) to improve soil structural stability (**Figure B3**).

For cracking clay soil types (Vertosols), slaking to form microaggregates is beneficial because it leads to the regeneration of good structural form. This is termed self-mulching. In contrast, slaking is a problem in loamy soil with poor shrink-swell potential as it can set very hard when dry (Anderson et al. 2007).

Figure B3: Processes associated with slaking and dispersion of soil aggregates (not drawn to scale).



Source: Modified from Anderson et al. 2007

Appendix C: Laboratory data and calculations

Following assessment of dispersion using the aggregate stability in water test (ASWAT) (Appendix B), the ESP and ESI soil analysis methods and calculations are used to determine why a soil is or is not dispersive and to assist with selection of ameliorants.

Exchangeable sodium per cent

Laboratory tests for cation exchange capacity measure the amounts of exchangeable sodium, calcium, magnesium and potassium. This is used to calculate exchangeable sodium percentage (ESP) (Hazelton and Murphy 2016). The sum of exchangeable cations is referred to as cation exchange capacity (CEC).

$$\text{ESP} = \text{exchangeable Na} \times 100 / \text{CEC}$$

ESP and CEC data are needed to calculate gypsum–lime application rates.

It may eventually be possible for these accurate but laborious ‘wet chemistry’ soil analysis procedures to be replaced by lower-cost ‘proximal sensing’ techniques. An approach under consideration is to estimate ESP and ESI (and perhaps clay mineralogy) via rapid scanning of soil cores using new sensing technologies. This topic is the subject of ongoing research.

Electrochemical stability index

The electrochemical stability index (ESI) (Blackwell et al. 1991; McKenzie 1998) was developed to describe the relationship between salinity, ESP and dispersion. ESI is calculated as:

$$\text{ESI} = \text{EC}_{1:5}\ (\text{dS/m}) / \text{ESP}$$

Soils with an ESI <0.05 are potentially dispersive. When using the ESI for an ESP of 6, a salinity level ($\text{EC}_{1:5}$) of 0.3 dS/m is the threshold below which dispersion may occur. These concepts are illustrated below in **Figure D4** (page 62).

Refinements to the ESI calculation are discussed by Hulugalle and Finlay (2003).

The following methods are examples of secondary procedures which can provide additional insights. Research is ongoing to improve these and associated techniques and their interpretation guidelines.

Sodium adsorption ratio (SAR)

Another commonly measured sodicity parameter of soil and irrigation water is sodium adsorption ratio (SAR). SAR is the concentration of sodium divided by the square root of calcium plus magnesium in the soil solution:

$$\text{SAR} = \text{Na} / \sqrt{(\text{Ca}+\text{Mg})}$$

where the concentrations of cations are in mmol/L (Hazelton and Murphy 2016).

Like salinity, SAR (for soil) can be measured using either saturation extracts or 1:5 soil:water extracts. Relationships exist between SAR and ESP (Anderson et al. (2007):

For saturation extracts	ESP approximately equals SAR
For 1:5 extracts	ESP approximately equals 2$\text{SAR}_{1:5}$

Cation ratio of structural stability (CROSS)

It has been known for a long time that the main cations Ca, Mg, Na and K vary in their flocculating power to stabilise clays (Hazelton and Murphy 2016). The relative flocculating power of the cations is Na = 1, K = 1.8, Mg = 27 and Ca = 45 (Rengasamy and Marchuk 2011). Yet in the calculation of ESP and SAR, K is not considered and Mg is assumed to have equal flocculating power as Ca. Therefore, Rengasamy and Marchuk (2016) have proposed the following ‘cation ratio of structural stability’ (CROSS) calculation.

$$\text{CROSS} = (\text{Na}+0.56\text{K}) / \sqrt{(\text{Ca}+0.6\text{Mg})}$$

where the concentrations of cations are in mmol/L.

Hazelton and Murphy (2016) have suggested that as an initial approximation, the values used to interpret SAR could be applied to CROSS.

Appendix D: Amelioration information

In this appendix, more detailed information is provided about the following ameliorants:

- gypsum;
- lime;
- gypsum–lime blends;
- organic matter;
- elemental sulfur; and
- biological ameliorants.

Further information is also provided regarding improving soil properties with lime and gypsum, as well as the legal considerations of gypsum application in NSW and Queensland. Extra management options are described to deal with associated constraints.

Ameliorants

Gypsum

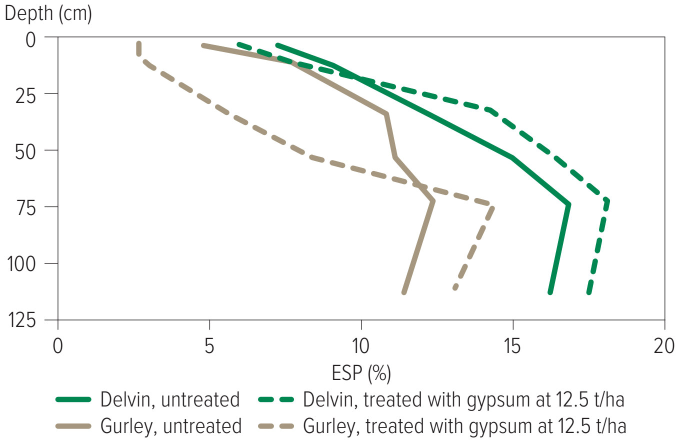
Gypsum (calcium sulfate) is the most common treatment for dispersive soil caused by too much exchangeable sodium and, to a lesser extent, exchangeable magnesium and potassium. Gypsum is a sparingly soluble salt that is usually purchased in the dihydrate form ($CaSO_4.2H_2O$), but sometimes is available as hemihydrate 'plaster of Paris' that is, $CaSO_4.0.5H_2O$. Gypsum helps improve soil structure in the short term by suppressing instability through its electrolyte (salinity) effect, and in the long term by replacing sodium ions with calcium ions (Loveday 1976). This electrolyte effect is temporary and does not require much gypsum (typically ~2t/ha). It only lasts while there is undissolved gypsum available in the soil so the effect tends to peter out by the second or third season, but this reduction is hastened by higher than average rainfall. Coarser gypsum maintains the electrolyte effect longer than finely ground gypsum. For a longer-term fix, the calcium replaces sodium, which helps the soil form stable aggregates. The sodium ions are displaced off the soil particle and into the soil solution, where they are ideally washed deeper and out of the root zone. Usually much more gypsum is needed for this to happen, relative to the amount required to maintain the short-term electrolyte effect. One consequence is that those displaced sodium ions move into the subsoil and worsen sodicity there (**Figure D1**).

Adding gypsum to non-dispersive soil will at least give the crop calcium and sulfur, the latter being important for canola nutrition.

Sources and cautions

Gypsum is usually mined in arid zone lakebeds or produced as a by-product from the manufacture of phosphatic fertilisers (phosphogypsum) or recycled from waste plasterboard. Phosphogypsum is less available now in eastern Australia, relative to the 1970s when it accumulated as waste at fertiliser factories in Newcastle and Brisbane.

Figure D1: Exchangeable sodium percentage as a function of depth and gypsum treatment at 'Delvin' (green) and 'Gurley Station' (brown) (Case Study A). The solid lines are for the untreated controls. Both soils are Grey Vertosols, but the 'Delvin' soil has a higher clay content and CEC than the 'Gurley Station' soil (McKenzie 1982).



Before buying a gypsum product, always request an analysis test sheet. Gypsum quality is assessed by purity and fineness. In NSW, purity means the per cent of sulfur in the gypsum. Most of the gypsum sold in NSW is calcium sulfate dihydrate, which has 18.6 per cent S when completely pure.

Fineness describes the size of the gypsum particles. This is important as it largely determines how quickly the gypsum dissolves in water. Lumpy gypsum may be difficult to spread and is slow to dissolve. More detail on gypsum purity is provided in **Table D1**.

Mined gypsum (**Figure D2**) tends to contain more impurities – mostly soil and lime. It gets sticky and becomes heavier when wet, which can be costly to transport and difficult to spread. Mined gypsum is often lumpy or crystalline, with reduced solubility (**Table D1**). But it is the preferred source if there are concerns about the toxic impurities cadmium and/or fluoride that may be found in by-product phosphogypsum. Test sheets require careful scrutiny.

By-product gypsum can occasionally contain toxic impurities such as cadmium and fluoride. It is easy to apply too much cadmium, so if the test sheet shows elevated cadmium, avoid recycled gypsum on acidic soils where cadmium is more available. Fluoride is a concern for plants or grazing animals that are sensitive to fluoride. Most of the fluoride is calcium fluoride, which is highly insoluble in water, and the remaining fluoride can be rendered unavailable by the clay soil. However, there is still a chance of some plant uptake of fluoride.

Phosphogypsum can contain a small beneficial amount of phosphorus (0.1 to 0.3 per cent) as phosphoric acid. Phosphogypsum is usually purer and more soluble in water than mined gypsum.

Gypsum from recycled plasterboard can contain thick paper scraps that blow around the paddock and look untidy.

Figure D2: Examples of mined (A and B) and by-product (C and D) gypsum products available in NSW.

Source: Abbott and McKenzie (1996)

Table D1: Purity and solubility of the gypsum products shown in Figure D2.^

Gypsum product	Purity*	Solubility (dS/m)**
A (mined, Bourke)	17.1% S; 92% $CaSO_4$	0.4
B (mined, Riverina)	15.0% S; 81% $CaSO_4$	1.0
C (waste plasterboard, Kurnell)	18.3% S; 98% $CaSO_4$	2.1 (particle size <2mm) 1.0 (particle size 2-4mm)
D (phosphogypsum, Newcastle)	15.8% S; 85% $CaSO_4$	1.9

^ Pacific Fertiliser Pty Ltd reported on the quality of 31 gypsum products available for purchase in Australia in 2015: pacificfertiliser.com/files/PacFert_Gypsum_Research_2017.pdf

* Per cent S and per cent $CaSO_4$ expressed on wet weight basis (product as supplied)

** Solubility expressed as electrical conductivity of solution obtained by adding the equivalent of 10 grams pure $CaSO_4$ to 1 litre demineralised water, gently shaking (20 times end-over-end) and centrifuging for 10 minutes.

Source: Abbott and McKenzie (1996)

Relatively expensive new gypsum products (for example, nano-gypsum) are being developed as a possible alternative to mined gypsum and by-product gypsum for subsoil amelioration, but practical recommendations regarding their potential use within the grains industry will not be available until paddock evaluation has been completed.

Application methods

Gypsum and lime for dispersion control are usually broadcast (**Figure D3** (page 62)). As rain dissolves applied gypsum, it starts to move into the root zone. Some gypsum will move back up again as water evaporates. Gypsum is best applied well before sowing to maximise subsoil water storage, particularly under dryland conditions; that is, give the gypsum time to work so you can capture more pre-season rain.

Waiting for gypsum to treat subsoil dispersion can take many years depending on how deep the dispersion is and the rainfall patterns. In wet years, there can be a noticeable improvement in a few months. The So and McKenzie (1984) trial discussed in **Case Study A** (page 37) found that gypsum washed in by above-average rainfall quickly led to better drainage and less bogginess in the topsoil.

The key to treating subsoil dispersion is getting the ameliorant to where it is needed. As gypsum dissolves then moves with water, it has the potential to permeate into the soil from a surface application and move down into the subsoil.

Deep-ripping can help place gypsum into the subsoil but this comes with the risk of bringing hostile subsoil to the surface or inducing mechanical dispersion and making the problem worse. Only deep-rip when the soil is dry. As ripping may bring some subsoil to the surface, factor in a possible extra gypsum application.

Deep placement options include subsoil injection and via shrinkage cracks. It is difficult for machines to apply ameliorants evenly at depth. Consider using pellets and prills, which flow more easily but are more expensive. Options are currently limited.

Aerial spreading is an option but more common on pastures. Aerial spreading might be suitable for small top-up applications but is unlikely to be economical for large up-front applications. Superphosphate contains ~50 per cent gypsum, so phosphate application for pasture improvement also improves soil structural stability where dispersion is a problem.

Tavakkoli et al. (2022) found that where sodic subsoil low in calcium carbonate has an extremely high pH due to the presence of bicarbonate salts, the application of gypsum can significantly reduce the alkalinity. This occurs due to the reaction of dissolved calcium from applied gypsum with the bicarbonates to form calcium carbonate precipitates.

Deeply leached applied gypsum can also overcome subsoil acidity problems through neutralisation of exchangeable aluminium by the sulfate ions from dissolved gypsum (Levy and Sumner 1998). Vertosols with strongly acidic subsoil, induced apparently by growth of the pre-existing brigalow forest, exist in the northern region (McKenzie et al. 2004).

Lime

Lime (calcium carbonate) is mostly used to treat soil acidity. As it is a source of calcium, it can help treat dispersion where the soil is both acidic/neutral and dispersive (less common than alkaline dispersive soil). Lime will not help if the soil is alkaline. Soil pH needs to be below 6.5 in $CaCl_2$ for lime to be soluble enough to displace sodium, although at the site described in **Case Study B** (page 41) lime application to improve soil structural stability temporarily increased topsoil pH ($CaCl_2$) to above 7 before a reduction occurred about six months after application.

In many parts of the northern region, lime provides a lower-cost source of calcium than gypsum. For example, where gypsum costs $110/t and lime is $70/t, the cost of calcium from gypsum is $472/t, but only $175/t from lime. As many grain farms are closer to lime quarries than to gypsum sources, the use of lime as a sodic soil ameliorant can also lead to transport savings (**Figure 25** (page 28)).

In the past, sodic soil has been assumed by many as being too alkaline for added lime to be effective. This may be because testing a 0 to 10cm soil sample can show a higher pH than testing the 0 to 2cm upper layer, which may be acidic enough to allow lime dissolution in the upper part of the topsoil. Also, the topsoil is often permeated with decomposed plant roots that generate organic acids and create low-pH zones adjacent to continuous vertical macropores where applied lime readily dissolves.

Using lime to control dispersion only targets the top few centimetres of the profile.

Emerson (1977) noted that lime could be used instead of gypsum, provided time is given for the carbonate to be reprecipitated as clay-sized particles to increase its solubility.

Table D2: Gypsum quality rating.^

Purity as percentage sulfur (S) (wet weight basis and equivalent percentage $CaSO_4$)

S (%)	Equivalent % $CaSO_4$	Purity rating	Remarks
<12.0	<65	Low	Expensive freight per unit of calcium
12.0–14.0	65–75	Medium	Mostly mined gypsums
14.1–16.0	76–85	High	Mostly by-product gypsums; some mined gypsums
16.1–18.6	87–100	Very high	Some mined and by-product gypsums

Fineness as a percentage passing a 2mm sieve

Fineness (%)	Fineness rating	Remarks
0–50	Low	Some mined gypsum products
51–80	Medium	Most mined gypsum products
81–100	High	Some by-product gypsums

Water content (%)

Water content (%)	Water content rating	Remarks
0–5	Low	Most mined gypsums; some by-product gypsums
6–10	Medium	Some by-product gypsums
11–15	High	Some by-product gypsums
> 15	Very high	Difficult to apply; expensive freight per unit of calcium

Content of chloride as percentage Cl (wet weight basis)

Cl%	Cl rating	Remarks
0–1.2	Low	Suitable for all agricultural purposes
>1.2	High	Suitable for reclamation of saline-sodic soils but not for other agricultural purposes

^ Incitec Pivot Fertilisers (2021) has noted that under state legislation in Australia, gypsum is categorised into a number of grades depending on its purity. The minimum concentrations are: Grade 1: >15 per cent S, >19 per cent Ca; Grade 2: >12.5 per cent S, >15 per cent Ca; Grade 3: >10 per cent S, >12.5 per cent Ca. The percentage of gypsum that is capable of passing through a 2mm sieve must be stated on the label. In comparison, the particle size criteria to determine fineness for lime has been set at 0.25mm (250micron).

Source: Abbott and McKenzie (1996)

Cautions

The main factors determining lime quality include acidity neutralising value (NV), particle size distribution and solubility. Pure calcium carbonate (or pure limestone) has an NV of 100 per cent. The higher the NV, the purer the product. Particle size affects how fast the lime will work; smaller particles have more contact with the soil so they react and dissolve faster and more uniformly through the soil. The rate of lime dissolution is also affected by its solubility.

Always request an analysis/test sheet for the lime product before you buy. There are various online calculators to compare lime sources, for example: soilquality.org.au/calculators/lime_comparison

Application methods

Lime is usually broadcast. Placing lime deeper in the profile requires ripping or subsoil injection.

Gypsum–lime blends

Gypsum–lime blends may be useful where:

- there are budget restrictions (lime is a cheaper source of calcium); and
- topsoil pH is <6.5.

The gypsum will provide a quicker response to suppress dispersion, whereas the lime, with its higher calcium content, provides a longer-term benefit. The lime in gypsum–lime blends also provides a moderate supply of electrolytes over an extended period. Gypsum–lime blends are discussed more in **Part 3** (page 24).

Cautions

There is limited experimental work on gypsum–lime blends for dealing with dispersive soil.

Improving soil properties with lime and gypsum

Figure D4 shows the impact that adding lime and gypsum can have on soil ESP and EC. Ideally, a soil sample will have results in the green-coloured section. The test data overlayed on the ESP/EC chart shows a soil sample with a starting ESP of 10, and EC of 0.10dS/m. After 2.5t/ha of gypsum was added, ESP dropped to about 7, and after 5t/ha of gypsum was added, ESP dropped to about 6. Lime (5t/ha) had a smaller but still noticeable impact, with ESP dropping to about 8. In both cases, the lowering of ESP was accompanied by increases in EC (salinity) of the soil solution, which made the soil less prone to dispersion.

If **Figure D4** reflected a wet season and gypsum leached, both point B and point C would move horizontally to the left and the soil would enter the orange zone and revert to being dispersive, even though ESP has been reduced by amelioration from 10 to either ESP=7 (2.5t/ha gypsum) or ESP=6 (5.0t/ha).

Organic matter

Organic matter improves aggregate stability and is a source of nutrients. As it decomposes, soil electrolyte concentration is increased, which reduces dispersion.

Trials at 'Rand' in southern NSW suggest that when farm-grown products such as wheat and pea stubbles are mixed with nutrients, their addition in the soil improves soil aggregation, root growth, water extraction and grain yield and these treatments are comparable to animal manures and gypsum (Uddin et al. 2022). These results are yet to be confirmed. But if verified, this means that grain growers have a potentially large supply of relatively inexpensive organic ameliorants already available in their paddocks, which will increase the application options and viability of correcting subsoil sodicity/dispersion.

Sources

Common sources of organic matter include chicken manure, pea straw and wheat stubble. Pea hay and lucerne can be pressed into pellets. Biosolids (that is, processed human waste) are another option and are often cheaper than buying animal manures or greenwaste.

Polyacrylamide (PAM), a synthetic organic material, has given mixed results. It can improve both slaking and dispersion, but there is uncertainty about persistence and profitability. There may also be problems with PAM breakdown products being toxic (carcinogenic).

Figure D3: GPS-guided spreading equipment at 'Uah'.

Source: Nils Jacobson

Cautions

Composted feedlot material can contain high amounts of sodium, leaving residues of sodium salts as it breaks down, which can make the soil more dispersive (Chan et al. 2007).

Unless it is a mixed farming enterprise and there are on-farm sources, animal manure must be purchased. The cost of freight can quickly become prohibitive.

Biosolids have strict testing requirements. A landscape assessment by a suitably qualified person (SQP), for example, a soil scientist, is necessary before biosolids can be applied. This is to limit both offsite impacts and unwanted impacts on the paddock soil.

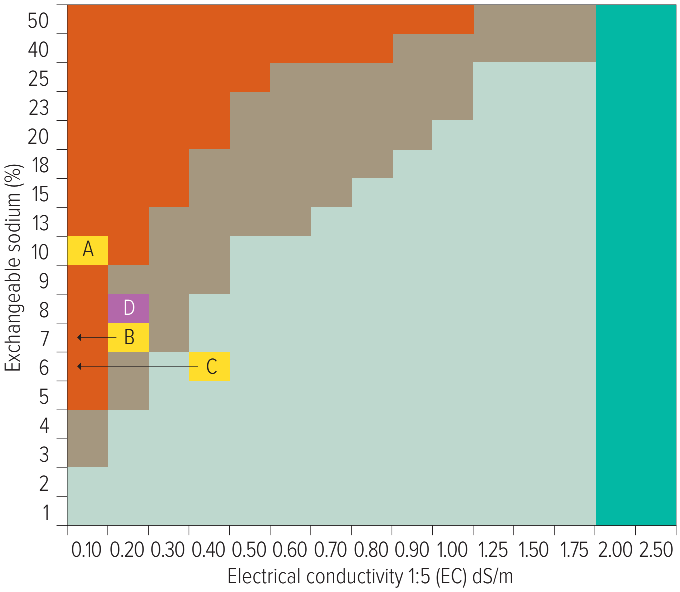
If on-farm stubbles are used, this may come at the cost of soil surface protection against wind and water erosion. There are situations where stubbles must be burnt to break crop disease cycles.

Application methods

Organic matter usually needs incorporation, which disturbs the soil and can induce dispersion and/or hard-setting. Various institutions are working on methods to inject organic matter into the subsoil, but none have yet proven commercially viable.

Vertical mulching (or slot mulching), where slots or channels are cut into the soil and filled with mulch/crop residues, has been used for several decades. One benefit is that the mulch helps keep the soil slots open, allowing better drainage and gas exchange (Frazier and Bertrand 1959). However, progress has been impaired by the lack of robust machinery to simultaneously harvest crop residues, add nutrients and then insert it into the soil via vertical slots.

Figure D4: Some typical values of exchangeable sodium and salinity one year after adding lime and gypsum for a soil with a spontaneous dispersion threshold ESP of 4.



🟧 Instantaneous dispersion on wetting
🟫 Strong dispersion after working or raindrop impact
⬜ Generally stable or slight dispersion after working or raindrop impact
🟩 Usually stable to dispersion but plant growth affected by salinity (Ca salts are better for plant growth than Na salts)
🟨 A – Initial ESP and EC (ESI = 0.01)
🟨 B – 12 months after addition of 2.5t/ha of gypsum (ESI = 0.03)
🟨 C – 12 months after addition of 5.0t/ha of gypsum (ESI = 0.07)
🟪 D – 12 months after addition of 5.0t/ha of lime (ESI = 0.025)

The graph is based on a red brown earth (Red Sodosol) surface soil near Peak Hill, NSW, dominated by illite (Valzano et al. 2001).

Arrows to the left of Points B and C represent pathways associated with an ameliorated soil reverting to being dispersive when leaching with low-EC water occurs in wet years.

Source: Brian Murphy pers. comm.; adapted from Rengasamy et al. (1984), Blackwell et al. (1991), McKenzie (1998) and Valzano et al. (2022)

Waste to land – legislation considerations

New South Wales

In NSW, applying wastes such as compost to land is governed by the Environment Protection Authority (EPA). 'Waste' has a very broad definition. All organic materials that could be used to ameliorate dispersive soil are considered 'waste' by the EPA. There are specific guidelines for some types of organic matter. It is always best to check with the EPA as guidelines can change.

Applying organic matter to agricultural land as a soil amendment does not need a licence for products and amounts you would reasonably use to deal with soil dispersion, such as manures and greenwaste.

To use biosolids, the product needs to be processed according to the EPA's Environmental Guidelines: Use and Disposal of Biosolids Products, undergo thorough testing and the user must meet strict record-keeping and reporting requirements.

When processed to the EPA's requirements, compost can be used freely on land to improve soil health and structure. Composted materials must reach a sufficient and sustained temperature to destroy harmful microorganisms, seeds and other weeds. The composting process and testing requirements are specified by the EPA in The compost order 2016 (NSW EPA, 2016). Testing includes glass, metal and rigid plastics (>2mm), plastics (>5mm), salmonella, *Escherichia coli* and fecal coliforms.

If composting on-farm, ensure the material has suitable chemistry and does not have pathogens.

When buying compost, make sure it has been tested to *Australian Standard AS4454-2012 Composts, soil conditioners and mulches*. Even if the EPA does not require analysis, it is a good idea to have any organic matter tested to make sure it is not contaminated or have undesirable chemical properties.

Queensland

Recent amendments (2018) to Queensland legislation have given on-farm composting more flexibility. With the amendments, you no longer need an environmental authority (EA) under the *Queensland Environmental Protection Act 1994* to compost and use the compost if the organic material is generated and composted on-farm. An EA is also not required if the composting is carried out at a site where intensive animal feedlot farming, pig farming or poultry farming is carried out. You can import organic material from another agricultural or livestock production activity. However, you will need an EA if organic material is received from a source other than an agricultural or livestock production activity (Capelin 2019).

Elemental sulfur

Elemental sulfur (ES) reduces dispersion in alkaline sodic soils by dissolving naturally occurring lime in the soil, which lowers pH and produces gypsum *in situ*. It neutralises the carbonates in the soil, via microbes that produce sulfuric acid, and makes the pH more suitable for crop growth.

Incorporating ES can speed up oxidation. As the conversion is biological rather than chemical, it can take many months and will be faster in warmer, wetter conditions. Much remains to be learnt about this topic (Mulvany et al. 2019). It is very important not to apply too much ES; otherwise soil acidity becomes an issue. Small incremental doses are likely to be less risky than single large applications. Accurate soil survey information is particularly important for farmers considering ES application to improve dispersive soil.

Biological ameliorants

Biological ameliorants, such as packaged soil microbes, may be tempting but there is little research on their efficacy or value for treating dispersive soil. Overcoming physical and chemical constraints with practices recommended in this manual creates a better environment for soil biology.

Management practices

Minimise tillage

If a soil is prone to mechanical dispersion (it disperses after it has been worked), avoid ripping the soil when it is moist. Ripping might break up compaction in the short term but this will be undone by inducing dispersion. Ripping into dispersive subsoil can also bring clods of it to the surface. Highly dispersive subsoil is best left untouched. Moderately dispersive soil might tolerate ripping, so it is best to do a test strip first. Rip a small section and see what happens after it rains. If the rip lines infill and become denser than before, it is best not to rip any more of the paddock. If you do decide to rip, use the opportunity to place ameliorants to depth. Soil pit inspections are valuable for determining the degree of shattering from deep-ripping and the amount of strongly constrained subsoil accidentally lifted by ripping tynes. Implementing CTF will be beneficial as the soil will be highly prone to compaction after ripping.

Moving to no-till, CTF and residue retention after treating compaction and surface crusts is an opportunity to maintain soil structure and build OM. Residues reduce the rate of soil wetting, which can further minimise slaking and dispersion. Better water infiltration can wash sodium further into the profile and help gypsum move deeper into the soil.

Crop rotations

Crops such as lucerne and safflower can act as biocultivators. Their strong root systems can create root channels and wide vertical deep shrinkage cracks in the dense subsoil that future crop roots can use. This approach is particularly useful if there are rocks in the soil that interfere with ripping.

Cultivars that germinate rapidly and have higher seedling emergence force are better equipped to deal with surface crusting from dispersive soil.

Lucerne

Where ongoing waterlogging is an issue, lucerne can help dewater the soil profile. Several trials in south-western NSW found that lucerne dries the profile more than continuous cropping (Dear et al. 2005). The soil profile can be 15 to 50mm drier in the top one metre due to lucerne's high water use; deep root channels improve infiltration and delay waterlogging.

One risk is if a dry year follows the lucerne crop, there could be reduced yield from lower plant-available water. Removing lucerne in spring can lower this risk by allowing time for the root zone to be recharged with rainwater.

Phytoremediation

If high sodium is the main concern, certain crops can remove sodium ions to gradually decrease sodium concentration in the root zone.

Studies in Sudan (Greene and Snow 1939) have shown that

Oldman Saltbush can accumulate significant amounts of sodium in its foliage. However, this sodium-rich foliage has to be harvested and then transported to a sodium salt disposal area.

There are crops that can sustain a decent yield under saline–sodic conditions and accumulate high leaf tissue concentrations of sodium; for example, Rhodes grass (*Chloris gayana* Kunth). A harvest of 10t of dry biomass would remove the equivalent of 2.5cmol Na/kg from the surface (0 to 0.15m) soil (Page et al. 2020). This is not a short-term solution. Work in Western Australia (Barrett-Lennard et al. 2022) suggested it would take 20 years to remove half the salt. Further research is required.

Dealing with associated constraints

Compaction

Bennett et al. (2022) have given the following warning about deep-ripping: "Anecdotally, it has been observed that ripping, and discussion of intent to rip, has increased throughout the Northern Grains Region. Whether driven by this project, or some other influencing factor, it must remain at the forefront of research, extension and industry funders' minds that a mass movement of unbridled deep ripping could have a much more detrimental outcome than the positive one intended. Where dispersive soils are ripped without treatment, the destruction of continuous pore networks that support current soil function will be destroyed limiting current production beyond previous lows. Additionally, deep ripping should not be thought of as a seasonal reset for compaction from uncontrolled traffic. Deep ripping should only be viewed as a renovating strategic action, with conservation and minimum tillage agricultural practices reinstated post-renovation. The soil moisture within the ripping profile must be well below the plastic limit in order for shattering, rather than smearing and pore sealing, to occur in the soil. The conclusion here is that while deep ripping is a very easy undertaking, it still requires sufficient spatial understanding at the sub-field scale in order to be beneficial, which means Certified Professional Soil Scientists should still be consulted prior to the undertaking."

Successful deep tillage requires a sound understanding of the interaction of ripping tyne design and spacing with soil physical characteristics. An excellent overview of this topic has been published by Godwin and Spoor (2015).

Decompaction via shrinkage cracks developed by deep-rooting crops such as safflower is another approach to consider, where soil CEC is sufficiently high. However, safflower tends to establish very poorly in sodic soil in mid-winter due to impeded drainage and associated low seedbed temperatures. This means that topsoil dispersion needs to be corrected prior to a successful soil structure reset using a rotation crop such as safflower with deep taproots that extract deep subsoil moisture strongly in early summer and creates wide vertical shrinkage cracks to a depth of up to two metres. A compacted Vertosol 'biologically ripped' in this way can be successfully shattered and loosened even further via subsequent deep-ripping.

If you are not already using CTF, the tendency of dispersive soils to recompact is good motivation to consider it. Without CTF, wheel tracks on a paddock cover up to 80 per cent of a paddock in one year when cultivation, sowing, spraying and harvesting are taken into account. After several years of cropping, most of a paddock is subject to compaction by wheel traffic.

Expect compaction to return quickly if not using CTF.

More on compaction in the northern region is covered in the GRDC factsheet *Correcting layers of high soil strength with deep tillage* (grdc.com.au/correcting-layers-of-high-soil-strength-with-deep-tillage-northern-region).

Excessive paddock flatness and gilgai

Earthworks can level-out gilgai but if done poorly can also expose dispersive soil. The best method is to scrape off the topsoil, level the subsoil, then spread the topsoil back across the surface. Taking shortcuts by only levelling can bury non-dispersive topsoil and leave more hostile subsoil at the surface.

Another option is to install laser-guided V-drains through the gilgai country so that water can escape after rain.

pH extremes

If the soil is highly alkaline, gypsum and elemental sulfur can lower pH.

Lime raises soil pH in acidic soil.

Adjusting soil pH to something more amendable for crop growth will improve nutrient availability.

Salinity and chloride

Crop selection for salt-tolerant varieties is usually the best way to deal with salinity. If salinity is >4dS/m, consider switching to salt-tolerant pastures.

However, amelioration is possible. Das et al. (2022) have discussed the challenge of leaching unwanted salts from a strongly saline–sodic alkaline Vertosol. Leaching with low-EC water causes dispersion to occur, which interrupts the sodium chloride displacement process. Gypsum, possibly in conjunction with elemental sulfur and organic matter, overcomes this problem of inadequate leaching by displacing exchangeable sodium to maintain soil structural stability and infiltration.

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