TACKLING AMELIORATION ON VARIABLE SOIL TYPES

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A HANDBOOK FOR GROWERS

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COVER: Burned stubble (right) in preparation for ploughing with a modified one-way plough, Meckering, WA.
PHOTO: Alisa Bryce

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INTRODUCTION

Soil constraints are estimated to cost Australian growers more than $1 billion each year in wheat alone (Orton et al. 2018). Done properly, ameliorating soils boosts yield and profit.

While research into and uptake of soil amelioration has increased in the past few years, there are still some barriers that prevent growers from tackling soil problems. Soil variability, cost and deciding where to start are the commonly cited reasons.

Paddocks with multiple soil constraints and variable soil types are tricky to manage. Choosing the ideal amelioration option for every soil constraint within the paddock can create a patchwork of different operations, machinery, inputs and management. This can make tackling soil constraints seem like a hassle not worth going through, even before considering if profit gains make that hassle worthwhile.

Yet many growers are successfully ameliorating soil constraints in variable paddocks. While the ideal solution is just that – ideal – and may not be practical, good profit gains are still possible from smart soil amelioration in variable paddocks. Where there is limited time, budget or available machinery, or there is just too much variability, paddocks can still be ameliorated using the best compromises of operations, machinery, inputs and management.

The first step in dealing with soil constraints is understanding where they are, how much area they cover and how they are affecting productivity. This requires planning and budget. When advisers are asked where they would invest the soil amelioration budget on their farm, a common answer is “start by setting aside $10,000 to $20,000 to properly work it out”.

In general, amelioration costs are only a very small fraction of the land value and, if done properly, improve the productivity and return on investment in that land for many years. Good amelioration potentially increases the value of the land longer term. The key is ensuring amelioration costs do not disrupt the cashflow of the business and are profitable in the short to medium term.

This handbook presents a method to identify soil constraints and develop a plan for soil amelioration. Figure 1 outlines the process. While the examples used in this handbook have a Western Australian focus, the methodology to assess soil constraints and prioritise soil amelioration options is nationally relevant.

Part 1 – Identification describes how to assess soil constraints across the farm. To know what soil problems to fix, you first need to know what problems you have. Using existing knowledge, spatial layers such as yield maps, NDVI and radiometrics, you can map soil types, constraints and changes across the farm, then check and refine with ground-truthing.

When there are thousands of hectares to consider, identifying constraints across the whole farm can feel like a mammoth task. It might seem easier to start by trialling one amelioration process, or by addressing only a few paddocks. This is true when implementing amelioration, but when planning, a considered approach of the whole farm facilitates better business decisions. Ripping because the neighbour does might, through sheer luck, work on your farm. Or it might be a waste of time and money. A clear plan makes decisions regarding costs, logistics, capital investment and use of contractors easier. More planning time and work upfront also means a better job and fewer problems later. As with many decisions, the five Ps are true in the case of soil amelioration – PRIOR PREPARATION PREVENTS POOR PERFORMANCE.

By the end of Part 1 you will have a soil amelioration map that shows the main soil type areas, their soil constraints and amelioration options. There may be a large range of potential amelioration options.

Part 2 – Prioritisation describes how to whittle down the potential soil amelioration options to ones suitable for your farm. Using this smaller suite of options, decide on a whole-farm approach, such as tackling the biggest areas, lowest risk areas or best return on investment. Next, prioritise which paddocks to start with and plan your approach to fix constraints within these paddocks.

There are multiple ways to prioritise where to start ameliorating soil constraints; no one way is right or wrong. Choose the method that works best for your farm and situation.

Part 3 – Implementation compiles advice on implementing amelioration and lists some common risks and mistakes.

Rocky Ridge Farm is an example farm used in Parts 1 and 2. It demonstrates just one way to use this handbook to assess and prioritise constraints, and describes why the grower made certain choices.

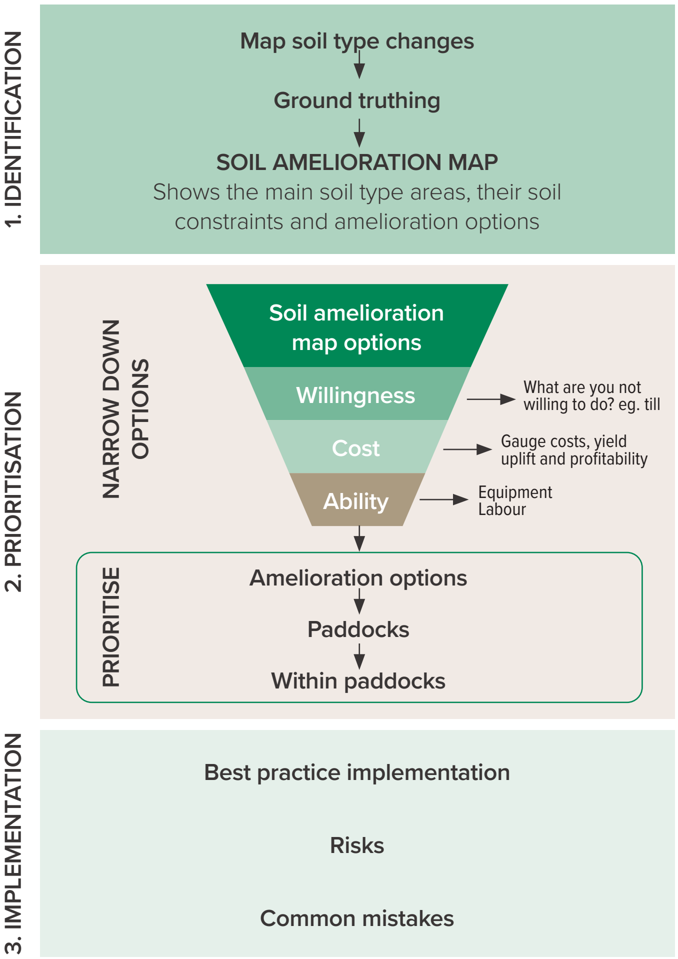


Figure 1: Process overview for identifying, prioritising and ameliorating soil constraints.

PART 1 – IDENTIFICATION

Why assess soil constraints across the whole farm?

The main reason to look at soil constraints across the farm, as opposed to paddock by paddock, is dollars– whether dollars are spent, saved, wasted or better spent elsewhere. Profitable amelioration requires good business decisions and you cannot make good decisions (cost to fix, benefits and longevity of benefits) if you do not know what you are dealing with.

Compared to what you are likely to spend on soil amelioration and the costs of getting it wrong – both wasted inputs where amelioration did not work and lost revenue where amelioration was not optimal – the resources deployed at this early stage are comparatively very cheap.

Looking at the whole farm makes it easier to identify where soil amelioration will be most profitable, where the easier paddocks to fix are, and puts soil constraints into perspective. Starting at the individual paddock scale tends to put too much focus on minor soil variations. These variations may be important when deciding what amelioration method to use, but can make assessing the extent, severity and impact of constraints across the farm more difficult.

Sometimes a soil constraint only affects a small area within a paddock but, because it looks bad, it gets more attention than that area justifies. Until the extent and severity is quantified across the farm, we do not truly know what impact it is having on business profitability.

Zooming out to the farm scale can make in-paddock variability appear negligible in the whole scheme of the farm and the business. Calculating the severity and area of constraints is the first step to prioritising where to start fixing them.

Soil types and constraints inevitably go across paddock boundaries. You cannot fully capture how big soil problems are unless you zoom out from the paddock level and up to the farm level.

Perhaps most importantly, you can make a multitude of better financial and logistical decisions when thinking at the farm level, including the following:

1. **The rate of 'ramp up' of soil amelioration** – There can be huge opportunity costs in delaying or not ameliorating. Increased profit and risk mitigation can be forgone if the business fails to realise profitable amelioration investment options or invests in amelioration at the wrong rate.
2. **Where to begin the amelioration program** – This will likely be your least variable paddocks or the ones with the most yield uplift. It is hard to know which ones these are without looking at all paddocks. Plus, you will mobilise faster with a plan to implement when the conditions are right, instead of making decisions on the fly.
3. **Which constraints to tackle first** – The high-return, low-risk targets that may cover a small area, or the lower-return targets that cover big areas? For example, to rip and spade 200ha (infrequent and costly but good likely return) or to apply wetters to 2000ha (every year or two, but cheaper, and more variable responses and returns).
4. **Whether to try and fix multiple constraints at once** – Amelioration packages that fix multiple constraints simultaneously to minimise costs and paddock disruptions and give better returns. For example, liming for acidity, deep ripping to shatter compaction, and mixing for water repellent sand and lime incorporation and to stimulate weed seeds will increase yield uplift more than liming, deep ripping or mixing on their own.
5. **Short-term mitigation versus long-term amelioration** – Where to start ameliorating and where to keep treating symptoms for now. For example, if tackling non-wetting, where to mix or clay the soil and where to use wetter or on/edge/cross-row sowing.
6. **Which order to address paddocks in** – Low-priority paddocks might include those with other risks, such as frost or waterlogging, that can diminish or destroy returns from amelioration. Or paddocks where post-amelioration establishment and trafficability are likely to be poor, dampening potential yield uplift.
7. **Timing** – Paddock rotations and weed density affect the best timing for some soil ameliorations.
8. **Assessing whether paddocks are worth it** – Paddocks that are too hard to ameliorate or not worth ameliorating because they are too variable, or constraints are uneconomical to fix.
9. **Payback calculations** – Calculating the likely capital costs and annual operational costs, the likely returns on these costs and their payback periods.
10. **Buying versus hiring equipment** – If there are enough hectares of soil amelioration needed to justify purchasing equipment, or if it is better to borrow or dry hire equipment or use a contractor.
11. **Machinery suitability** – If existing machinery will be adequate for the job.
12. **If purchasing**:

- The best machinery for the soil constraints across your farm.
- If multiple machines are needed.
- If a multi-purpose machine to tackle multiple constraints in the one pass – such as a Horsch Tiger or Väderstad TopDown – can do an adequate job. They could be a good option initially because they can be used on more hectares, but once those hectares are done their usefulness declines and some areas might need more specialised machinery such as a deep ripper or delver.

Starting at the farm scale does not mean ignoring in-paddock variability. In-paddock variability is important for making management decisions, especially where the soil type or depth to subsoil can change multiple times across the paddock. Start with the farm scale for the multiple reasons described above, then look more closely at paddocks where you know variability is high. The mapping exercises in this section might reveal more variability than you had realised was present, allowing better business and management decisions. For example, soil variability may be too great to do a proper delving job to treat water repellence, making wettings agents and/or changing seeding systems a better option.

How to assess soil constraints across the whole farm

Aim

To produce a farm map that indicates soil change boundaries, potential yield uplifts and a soil amelioration plan.

The process

Mapping and assessing soil constraints across the farm has three main steps.

Step 1 is mapping. It fuses existing farm knowledge and readily available spatial information on where soil types change, what the soil types are, productivity gaps and soil constraints.

This assists, speeds up and reduces potential costs of ground-truthing, which is Step 2.

The end goal, Step 3, is to develop a map of soil improvement zones across the farm, the precursor to profitable soil amelioration.

Step 1: Mapping

Soil changes

Soil type is the main determinant of potential productivity. Soil type also dictates what inherent and agriculturally induced constraints can limit realisation of that potential. In variable paddocks, knowing where the main soil types change (transition zones) is as important as accurately describing the soil types, because soil type transitions affect where amelioration starts and stops.

Productivity gaps

The productivity gap map captures where realistic opportunities exist to improve yields and therefore the profitability of soil amelioration. It looks at areas that used to perform well but have declined, or soil types that should yield well but do not. The aim is to find areas limited by fixable constraints, such as compaction, rather than other environmental factors, such as frost, that are difficult to manage.

Soil constraints draft

This is a first pass at estimating where different soil constraints exist. It will assist and speed up the next step, ground-truthing, but not replace it. Many growers and advisers start their amelioration planning at this step, using their knowledge and experiences to identify known and potential amelioration areas. Knowledge of paddock performance helps validate spatial data before driving into the paddock.

Step 2: Ground-truthing

Ground-truthing is essential for identifying soil constraints and, in conjunction with the maps from Step 1, for gauging where they are located. Ground-truthing turns various forms of spatial data into practical information used to inform the soil amelioration plan. Direct sampling, such as using a penetrometer and deep subsoil sampling, can also help identify soil constraint locations and boundaries.

Step 3: Soil amelioration map

Step 3 combines all the information from the maps and ground-truthing to show:

- what constraints are on the farm;
- where they are located; and
- the area they cover.

This map will help you make an informed decision on what soil amelioration packages will be most practical and profitable for the farm.

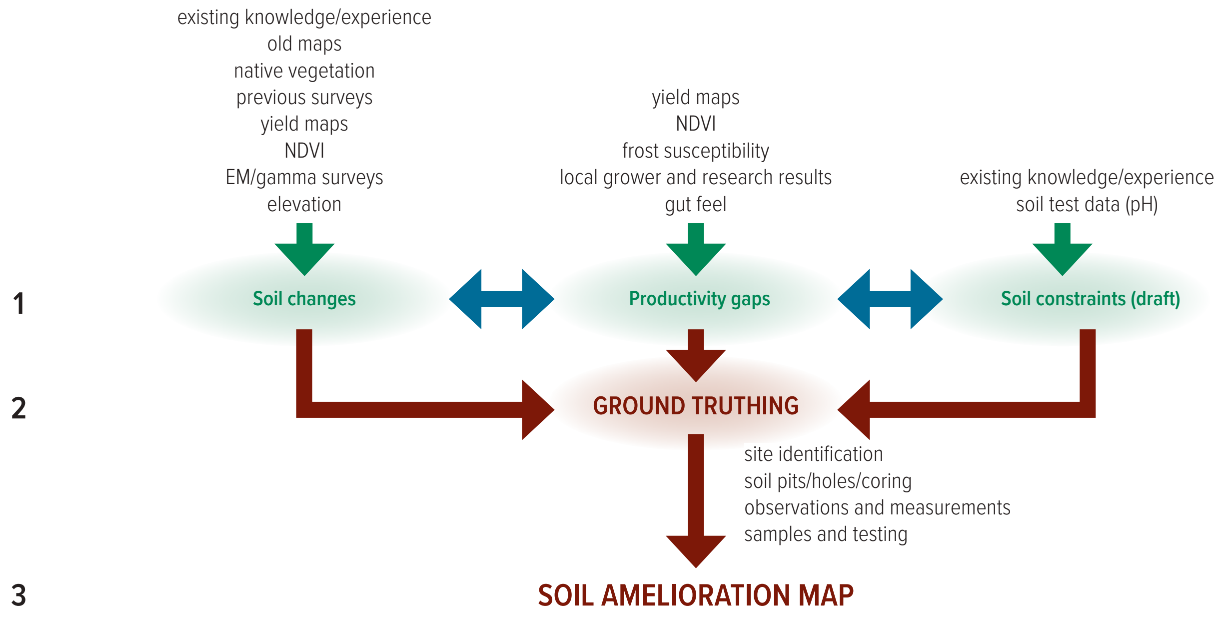


Figure 2: Overview of soil constraints identification process.

A soil change map, which shows where the main soil types and properties change across the farm, is a good place to begin if you are just starting out with soil amelioration or are on a new block. Some growers will prefer to start with information they already have, such as management zones, or with the soil constraints map.

Getting started

Consider whether to do this exercise by hand on paper, on a computer or both. Much of the work can be done by simply drawing on printed aerial maps. If you are comfortable using a mapping software platform, such as the one supplied with your harvester if it is a yield mapping or a generic mapping program, you might prefer to make the maps on the computer. If not, you might just end up very frustrated; if you know this is likely, stick to pen and paper.

If working by hand, you can draw the soil changes, productivity areas and soil constraints on one map or on three separate maps. The benefit of working with three different maps is that there is less bias from the previous step. For example, if drawing on one map you might try to shrink or expand soil constraints to match productivity gaps, even though low productivity might not be due to soil issues. What matters is that you can easily see each layer and where they overlap. Working in mapping software makes it easy to turn layers on and off.

If you have been on your farm for several years and have seen crops through variable seasons, you will already know most of the information needed for the first three steps. If you are less confident about where soil types change and soil constraints are located, looking at old soil maps and using spatial layers can help. Spatial layers such as gamma radiometrics (GR), electromagnetic (EM) surveys, normalised difference vegetation index (NDVI), elevation and/or yield maps are mostly used in software but are also useful to refine hand-drawn maps, be they on a computer or in hard copy.

In theory, more layers of spatial data should make better maps, but when you get to the point where adding the next layer of data makes things more confusing rather than clearer, it might be time to stop adding layers. It is very likely your first layer of data, which is typically drawing what you already know, will be your most valuable layer. Figure 2 shows the various spatial layers useful in each step.

The resources required for these steps include:

- your time for mapping and ground-truthing;
- aerial images;
- computer and software expertise if using data from computer platforms and/or if using mapping software;
- printed maps if working on paper;
- your adviser's time to clean and interrogate yield maps and other spatial information, assistance with drawing maps and/or ground-truthing; and
- existing soil tests.

Software such as Google Earth and ArcGIS Earth provide reasonable aerial imagery. If you cannot distinguish between different areas using the default aerial image, try using the historical images in the mapping software because they often highlight different characteristics to the default (different time of year, different ground cover). Aerial images taken when ground cover levels are the lowest, such as late autumn or a week or so after seeding, are the best times to see soil colour. In most cases this type of aerial imagery is all you need – it is the 10 per cent that gets 90 per cent of the work done.

Most mapping and precision agriculture platforms use aerial imagery as a background layer. Other platforms sell higher resolution aerial images. Data Farming, for example, sells high-resolution aerial images (three metre resolution) at $1.50/ha + GST.

What you will need:

- large printed aerial images of the farm, the bigger the better – print a few in case you decide to make separate maps or make mistakes;
- pens/markers/highlighters;
- preferred software (optional); and
- spatial data layers you want to use.

When to do this exercise

The best time to start is when you are in a planning mindset and have time to do a proper job. Late spring is good. This also provides a subsequent opportunity for reflection and ground-truthing while sitting on the harvester.

Step 1. Mapping

The soil change map

The objective is to draw where the main soil types across the farm change. This stage should not be taxing. If you find yourself thinking too hard about where soils change, the changes probably are not big enough to worry about.

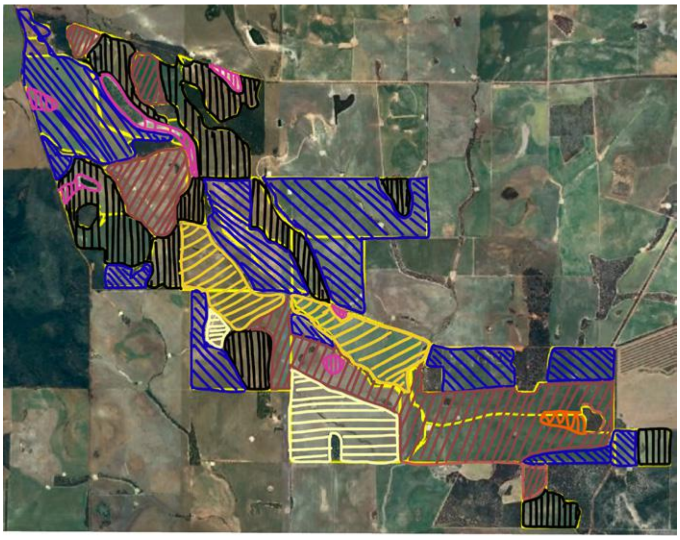
You are after the main changes in soil type, such as sandy soil versus loam versus clay, where gravel comes in/stops, or where topsoil gets shallow. Do not worry about mapping subtle changes in gravel content or depth to the next soil layer. Sand over clay versus sand over gravel is good enough.

Things to think about when drawing soil type changes include:

- where soils look (colour, nature of surface – flat, cloddy/rugged) and feel (underfoot, when driving across, when working) different;
- where yields distinctly change;
- where tractors work harder or easier when tilling; and
- how paddocks behave in wet and dry conditions: for example, where water runs off, tyres get sticky and where you get bogged when it is wet, or where the crop hays off quickly in a dry spring.

There are usually five to 10 main soil types across a farm. If you are drawing 20-plus soil types, think about if and how these differences will affect management decisions. You might be able to merge some areas. Small areas (less than 2ha) are unlikely to alter final decisions unless you are already considering liming or rock crushing.

Add in soil names if you know them, but they are not critical. Colloquial or your own descriptions of soil types, for example, gutless sand and Sunday country, are equally fine. Then add some basic descriptions of what you know about the soil, such as texture (sand, loam and clay are a good starting point), depth to an



Ironstone
Sandy duplex
Brown loam
Shallow white clay
Pale sand
Rock (magnetite)
Coloured sand

Figure 3: Rocky Ridge Farm with hand-drawn soil types on a Google Earth image.

impermeable layer and colour. Include any other characteristics you consider important such as rocky outcrops, types of gravel, hardsetting surfaces and known dense subsurfaces.

Broad soil types in the WA grain belt include:

- deep sand – white, grey, yellow;
- coloured sand over gravel, loam or clay (commonly called duplex soil; it is handy to note the depth of the sand layer if you know it);
- deep loam;
- shallow loam over gravel or clay;
- ironstone/cemented gravel;
- rocky outcrops;
- gravel – in a matrix of sand or loam;
- clay (red, brown, grey).

For many growers, the process above will be good enough to make a soil change map; experience suggests the maps will be about 80 per cent correct. Figure 3 shows soil types hand-drawn onto an aerial image. The soil types were drawn using only grower knowledge, before looking for further information such as from soil landscape maps or old soil test data. Rocky Ridge Farm is an example farm used throughout this handbook.

Using soil landscape maps and soil data

Existing soil landscape maps and soil data can give clues to soil types and transitions. Some useful sources include:

- Old farm surveys – Previous owners or generations may have had the farm surveyed before clearing vegetation or buying the land. Maps were often based on native vegetation, a good and regionalised indicator of soil type. Many farm surveys of soil type have been conducted previously as part of Landcare and research activities.
- Natural resource information for Western Australia (NRInfo) is a free online tool to view soil landscape, hydrology zones, vegetation, digital elevation models and other maps. You can also see individual soil points DPIRD (formerly DAFWA) has collected over the years. Most soils are at least labelled with soil types; some have laboratory data too. Go to https://maps.agric.wa.gov.au/nrm-info/
- Soil landscape mapping – This landscape and soil data is available as a free download. Go to https://data.wa.gov.au/ and search for 'soil landscape.'
  - Download the files then view in mapping software such as QGIS or Google Earth.
  - To view the soil landscape data online, select 'web services and API', and click 'web mapping service'. This will open NationalMap. You need to zoom in to see the different soil landscape maps.
- SoilMapp is a free iPhone Operating System (iOS) app developed by CSIRO. It collects data from ASRIS and ApSoil, the database also behind APSIM. It works best on an iPad. The maps use the Australian Soil Classification. Some cores have laboratory and field data.

Adding detail with spatial layers

Adding spatial layers while drawing soil changes may help better define soil change transitions, particularly if mapping a new block. The best layers to use at this stage are yield maps, NDVI and aerial photography. They are easy to access, free or cheap, and measure or reflect yield or plant growth, which in turn helps diagnose soils and where they change. Even in their rawest form yield maps provide a good indication of soil type differences, water-holding capacity and rooting depth. When using yield maps to look for soil differences, canola and wheat need to be considered separately as certain soil types can have markedly different impacts. For example, canola tends to do well in ironstone gravels, where wheat performs poorly (Isbister et al. 2016).

If soil variability cannot be explained by combining these readily available layers with existing knowledge, you may want to consider investing in additional layers that correlate with soil type and/or offer greater resolution. These layers are typically GR, EM surveys and higher resolution aerial photography.

Gamma radiometrics

GR measures the radiation from naturally decaying radioactive isotopes to help predict mineral composition and texture of the soil which, in turn, helps identify where soils change and what they are changing from and to. Data is commonly collected for the isotopes of potassium (K), uranium (U) and thorium (Th). The number of gamma ray counts across the whole spectrum is the total count (TC). Ternary maps that show the relativity of the three isotopes are sometimes created. GR mostly works in the top 0.3m but can work to 1m depth. It is strongly influenced by geology and works best on landscapes with variable mineralogy and on heavier soils. GR can be used to gauge changes in soil texture, if there is clay or gravel in the top 30 centimetres, and depth to clay or gravel.

Aerial GR surveys are low resolution and best used to gauge broad changes in soil texture and mineralogy, for instance across a catchment or as a cheap and easy first look at a whole farm. Aerial surveys at 100m resolution are free from Geoscience Australia (from the Geophysical Archive Data Delivery System). You will need to know how to download the vector/raster layers and, once downloaded, you will need software such as QGIS or precision agriculture software to view it.

Higher resolution GR surveys are made by towing a GR unit across the paddock. The unit collects readings every 5m. The resolution of the final maps depends on the distance between transects; 36m transects are common but, depending on cost and time, transects can be closer together or further apart (12 to 72m). The data is then processed (cleaned, points shifted if necessary), extrapolated to make maps, and the areas between the transects interpolated (which is why ground-truthing is so important). If working with raw data, which can come as a spreadsheet, statistical software and skill is needed to generate the maps for each isotope and the total count. Map colour schemes can vary depending on the data range and number of categories used. If the ranges are too big, for example one colour is used to represent readings from 10 to 20, this may mask important changes in the soil.

Electromagnetic surveys

EM surveys measure apparent soil electrical conductivity (ECa), which is an indirect measure of salinity but is also indicative of soil texture and moisture. Higher EM readings could come from more moisture, clay or salts, therefore ground-truthing is important. In non-saline sandplain and lighter soils, EM is mainly influenced by soil moisture and how deep it is to the clayey subsoil. To reduce the influence of soil moisture it is best to survey during summer. Most agricultural surveys use dual-EM, which integrates ECa to depths of 0.5m (shallow) and 1.5m (deep).

Airborne EM is possible, but expensive, usually reserved for mineral mapping and of limited use for agriculture because transects are every one to six kilometres.

EM works well to define soil changes and types in regions that have texture-contrasting soils, such as sand versus clay. In landscapes with deep sands, the readings can often be low and with little variation; they are not as useful to distinguish soil type differences. In WA, where soils are predominantly sandy and ironstone ridges and gravels are common, experience has shown EM works best when combined with GR to help map soil types.

Ground-based EM and GR surveys can be done at the same time. A survey that measures both EM and GR costs roughly $10 to $15/ha, without any ground-truthing or interpretation, and $25/ha with ground-truthing and interpretation – although the final cost will vary depending on paddock complexity. A survey will realistically cover about 50ha per hour, running on approximately 36m transects and collecting a data point every 5m. Some companies hire out equipment to do surveys. Indicative cost for hire of EM units is $3.50/ha (+GST) with a daily hire fee, which includes data processing.

Using EM and GR maps to find soil changes

Before ground-truthing, EM and GR surveys can be used to identify where soil types might change. Comparing high and low readings can show transitions, but be careful because 'high' and 'low' are relative and ambiguous terms when looking at EM and GR maps. High, low and all categories in between are typically created in mapping software and the categories change with each map. Unless the same high/low categories are used across the whole farm, a low EM reading in one paddock could be a high reading in another. To complicate matters further, readings vary from region to region, farm to farm and even paddock to paddock. Relative values can be as important as absolute values.

As the values are so variable, EM and GR maps must be ground-truthed to relate the readings to soil properties and constraints. Ground-truthing is not a straightforward process and requires careful thinking about how the spatial patterns in EM and GR maps relate to existing knowledge, plus direct soil inspections and sampling.

Figure 4 is an example of using a GR ternary map to approximate soil type transitions.

Depending on how complex a paddock is, viewing EM and each radiometric element individually might make finding soil

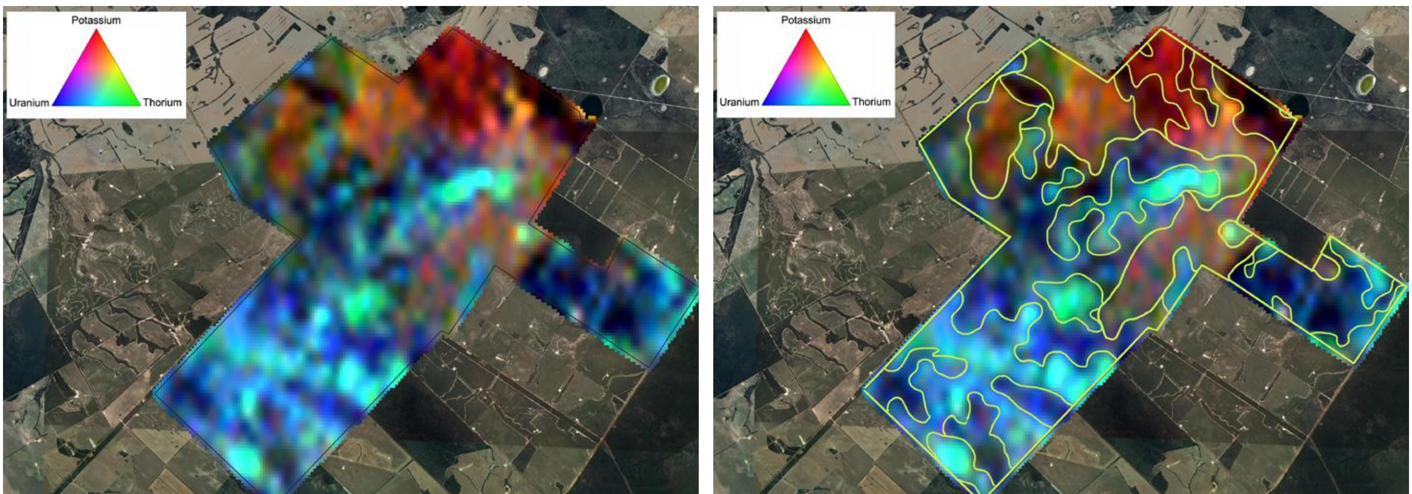


Figure 4: Left – Radiometrics potassium (red), thorium (green) and uranium (blue), where uranium is the dominant signal. Right – Potential soil transitions drawn on the map.

Table 1: Possible interpretation of gamma radiometrics (GR) ternary maps (see Figure 4).

Colour (ternary map)	Dominant element	Possible interpretation
Red	Potassium	Clay within 30cm Granitic soil
Green	Thorium	Ironstone gravels Surface gravel Gravel sands (values slightly lower)
Blue	Uranium	Clay Saline soil/salt creeks Weathered gravel Maybe calcareous
Cyan	Thorium + Uranium	
Magenta	Potassium + Uranium	
Yellow	Potassium + Thorium	
White	Potassium + Thorium + Uranium	Can show active erosion Clay, rock, or gravel near surface
Black	All low	Deep sands Highly weathered landscapes

boundaries easier. Some growers look at the various layers to find the one(s) that most closely match what they know about the soils in their paddocks. This can change from paddock to paddock. You can look at EM and GR elements individually, combine two elements or all three elements (total count (TC) and ternary maps), or use a combination of individual radiometric element maps, while others combine EM and some or all radiometric elements.

Indicative soil properties

GR and EM can also be broadly used to indicate soil properties. Again, the surveys must be ground-truthed before making any management decisions.

With GR, the dominant element tends to relate to the clay or gravel content in the soil. Uranium is the least stable and therefore least reliable of the elements and is not commonly used in WA for mapping soil types/changes.

Using Figure 4 as an example, where a red, green and blue palette has been applied to a ternary map, possible soil properties are heavier clayey soil (blue areas), lighter soils (red areas) and rocky concretions at or near the surface (green areas). Table 1 lists possible colour interpretations.

For EM surveys:

- high EM could mean clay, moisture, salt or sodic topsoil; and
- low EM could indicate sand or gravel.

Using EM and GR layers together has proven useful for estimating soil changes and soil types. Table 2 lists possible interpretations of combined EM and GR data.

Table 2: Possible interpretation of EM and GR layers.

EM and radiometrics	Possible interpretation
Low EM + high thorium	Sand and gravel (ironstone gravel)
Low EM + high potassium	Loamy sand
High EM + low TC*	Saline sand
High EM + high TC	Clay soil, clay close to surface
Low EM + moderate TC	Gravel, bedrock
High EM + moderate TC	Duplex soils
Low EM + low TC	Deep sand
Low EM + high TC	Gravel, bedrock

*TC = total count

Productivity gap map

The objective of this step is to map where you think there is potential to improve yield by removing soil constraints, where productivity is not as good as it used to be, or where it could and should be better.

Most growers have a 'gut feeling' for this which comes from:

- comparing low yields on a soil type with what that soil type yields elsewhere on their farm;
- their own deliberate or 'accidental' trials;
- results at other farms;
- research results; and
- a belief that "this soil should be producing more than it is".

Keep your thinking simple. You are not trying to determine why productivity is low, you are just marking where you think productivity could and/or should be better.

Also draw other obvious factors that impact production but are not directly soils related, such as frost and waterlogging. This will shape the riskiness of tackling soil constraints on such areas (Part 3 of this handbook).

Adding detail with yield maps and NDVI

Yield maps

Yield maps are an excellent source of objective information. They show both actual yields and yield relativities across different areas and seasons. Yields can relate directly to soil types, but care is required when deciding if there is yield improvement available on any given soil type. For instance, poor-yielding areas may be pale deep sands (where water-holding capacity will limit yield uplift regardless of soil amelioration) or they may be acidic wodjil soils (where there is scope for yield uplift from liming and mixing). Yield maps are also stark reminders of where frost or drought-prone areas are.

When working with yield maps it is better to show all yields in the same colour palette across the whole farm, commonly using just cereal yields. This creates a more consistent map that is easier to read than a map with different crops and yield categories. However, this type of map can be more time consuming to make if you are unfamiliar with precision agriculture software. Different yield categories across the farm are often faster to make but will have a different legend for each paddock, making it difficult to identify where the big potential yield uplift areas are across the farm.

Most harvesters can record yield. If you are not yet collecting yield map data, or if you are and you are not looking at it, it is time to start. Raw yield data is on hand and cheap, but if you want to interrogate it further it may need cleaning to remove very high or low readings, to recalibrate data from multiple headers and other adjustments.

Compare high-yield/low-yield years

Use a good year (with high yields and no adverse effects on yield such as frost or a dry spring) as an indicator of what areas can yield when everything goes well. Compare it to another year when moisture, especially in spring, was the main limitation. The good year shows what the country can do; the dry year shows how different areas stack up when the pressure is on.

If the yield difference between the good and tough seasons is not from variation in soil type (plant-available water capacity) it is likely to be due to a soil constraint; for example, non-wetting early delaying emergence, or a subsoil constraint such as acidity, compaction or sodicity limiting moisture availability late in the season.

Yield changes over time

Multiple years of yield maps can be used in various ways. One of the simplest is to view, or to analyse using software, how yield has changed in paddocks over time. It is likely that areas where yields have declined or failed to increase at the same rate as other areas have yield uplift potential.

Maps of macro trends, that is, multi-year averages of yield, can take out some of the seasonal variability so yield uplift areas from correcting soil constraints can be better identified. Soils that do not have constraints tend to be both higher and more consistent yielding because they have more resilience in tougher seasons. Other factors such as frost, waterlogging and/or dry years need to be considered when comparing yield maps.

Figure 5 shows three ways to use yield maps. These methods are not new, but uptake remains low, suggesting it is possible to get similar information by viewing and interpreting yield maps with paddock knowledge. NDVI maps can be compared in the same way.

The maps in Figure 5 were collated from five years of yield data. In Figure 5c, 'variably average' and 'variably > average' might represent where yields could be better.

Normalised difference vegetation index (NDVI)

NDVI shows how 'green' the crop is. It is calculated from data captured by a satellite. NDVI results are presented as a colour map, where each colour corresponds to a certain range of values. Like radiometrics and EM, there is no standard colour palette for NDVI maps, but most software uses the 'red-green' palette, meaning red-orange-yellow tints indicate bare soil or dead/sparse vegetation (or low plant biomass), and all shades of green are a sign of medium to dense vegetation cover (high plant biomass).

NDVI can be used to look for areas of good/poor plant growth. It does not diagnose the issue but shows where to look. Early season NDVI is good for identifying constraints that affect crop establishment, such as non-wetting or sodic soil.

Figure 5a: Mapping yield averages over several seasons highlights the *yield relativity* of different areas and consistently higher and poorer yielding areas.

Figure 5b: Mapping *yield consistency* (or variability) can show where yields fluctuate most from season to season.

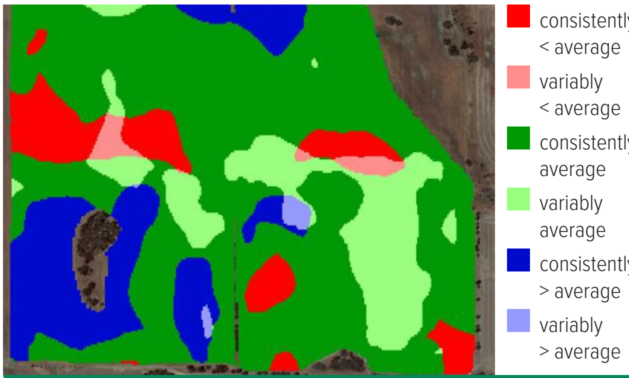


Figure 5c: Maps that combine yield averages and yield variability (*yield relativity x yield consistency*) show where the yields and their consistency can be improved, which is likely related to underlying soil constraints.

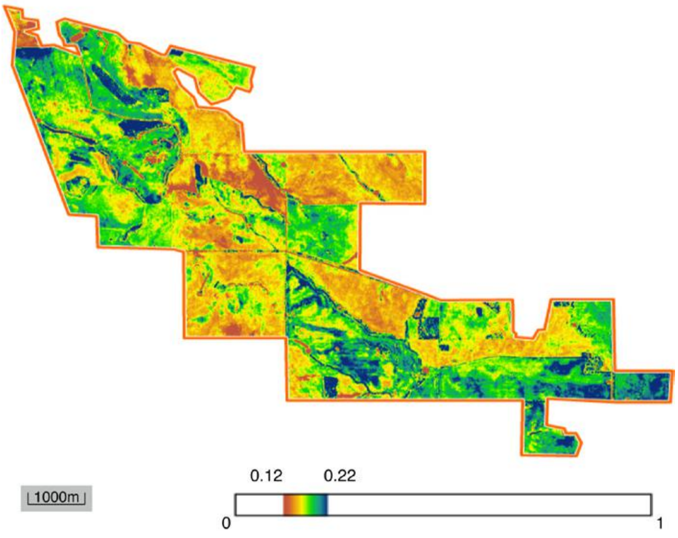


Figure 6: Rocky Ridge Farm NDVI map. Uniform orange areas are paddocks in canola.

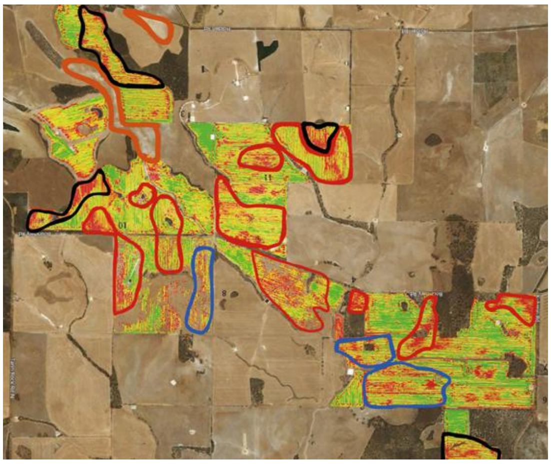


Figure 7: Rocky Ridge Farm productivity gap map.

NDVI is a good indicator of plant biomass and yield potential, but it does not always correlate well with actual yield. Seasonal conditions such as frost or no spring rain can cause high biomass crops to yield lower than expected based on NDVI earlier in the season. It can be used as a surrogate for yield maps where they do not exist and as a complementary tool where they do.

Large areas can be viewed and comparisons made very quickly using NDVI. It is a cheap data layer to source and historical images can be accessed to look at paddock variation over time, both within and between seasons. Changes in NDVI through the season are very useful, especially for looking at areas where establishment is slow (less NDVI early in the season compared with surrounding areas).

In cereals, especially in landscapes with less adverse seasonal events such as frost and waterlogging, there is usually a good relationship between peak NDVI relativity and grain yield relativity. Where this is not the case, comparing NDVI to yield is powerful to gauge where high NDVI (presumably good plant biomass) is not reflected in high yield, that is, good plant growth is not transferring into yield. This is usually an indicator that plant roots are unable to access moisture from deeper in the soil later in the season because of a subsurface constraint.

Most precision agriculture web-based platforms and some farm planning software offer NDVI layers. There may be an extra cost to access the data in a format to be used for zoning.

Figure 6 is a NDVI map of Rocky Ridge Farm.

Figure 7 shows the productivity gap map for Rocky Ridge Farm, based mainly on grower experience and knowledge, then adjusted using the yield map (the base layer in Figure 7) and comparing the yield and NDVI (Figure 6) maps.

Soil constraints map

Use your existing knowledge to map:

- where you know there are soil constraints; and
- where you believe there must be some type of soil constraint, but do not know exactly what it is and want to investigate further.

This can be drawn on your soil types map or on a fresh map.

The soil constraints map makes ground-truthing easier and quicker by:

- mapping constraints that are already identified and therefore do not need ground-truthing or just need a quick confirmation; and
- better targeting where to go to look for soil constraints, rather than driving across paddocks and guessing.

Draw zones on the map and label them as best you can. The list below should help – label with one or more of these:

- rocky outcrops;
- ironstone/cemented gravel;
- topsoil acidity;
- subsurface acidity;
- non-wetting;
- agriculture-induced compaction (more common in sandier soil);
- dispersion/sodicity (see GRDC fact sheet 'Dealing with dispersive soils' – refer Useful resources);
- surface crusting;
- dense heavy textured surface soil; and
- dense heavy textured subsoil (further description as sodic subsoil, or just densely packed, is useful).

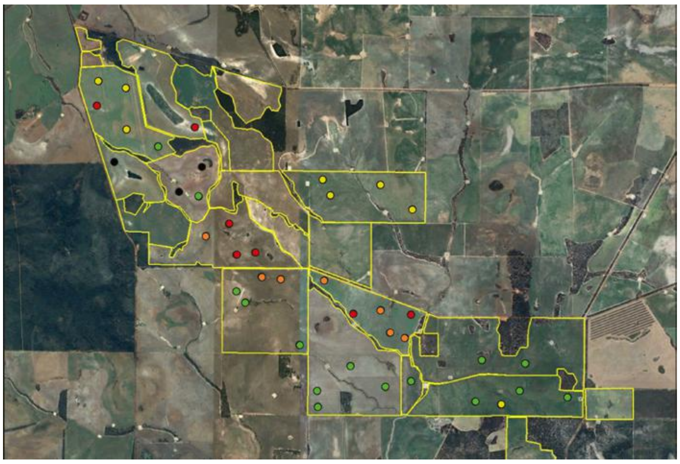


Figure 8: Rocky Ridge Farm acidity map.

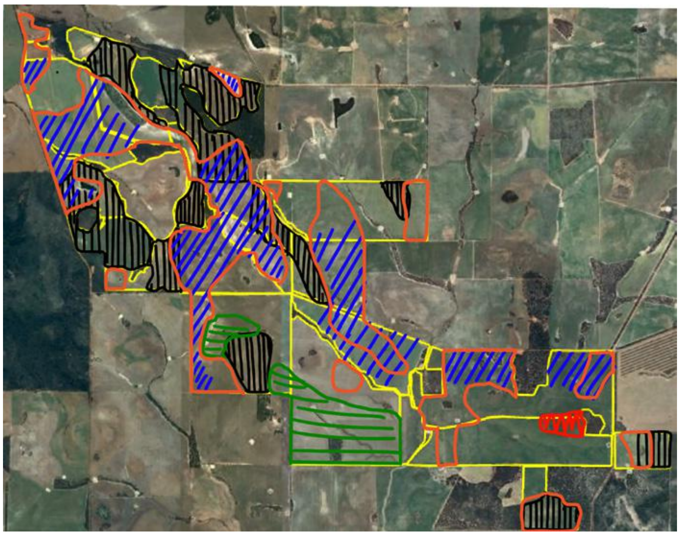


Figure 9: Rocky Ridge Farm draft soil constraints map (where the grower thinks the constraints are).

If you have an inkling of the depth of a subsurface problem, write that down too. Previous owners or, if it is a family farm, older generations, might have valuable knowledge.

Figure 8 is an existing acidity map from Rocky Ridge Farm showing where topsoil and subsoil acidity is an issue.

Handy data to have on hand when making the soil constraints map includes the following:

- Soil test data – Especially soil pH data (to depth in 10cm increments, or 0 to 10cm plus different layers as commonly done as part of EM/GR surveys).
- Your soil change map – To consider where constraints may exist. For instance, with compaction you may want to flag your sandy soils and then within them rocky areas that may cause a problem for deep ripping.
- NDVI – Especially early in the season when it can show the extent of non-wetting soil's impact on plant establishment (makes it easier to draw where non-wetting soil is on a map).
- Airborne GR – For depth to gravel and/or clay. See Table 1 for possible interpretation of radiometrics survey data.
- Ground-based EM and radiometric surveys – Because radiometrics and/or EM can approximate soil type and depth to gravel or clay, and they can be useful for having a stab at what soil constraints exist and where (see Figure 9). See Tables 1 and 2 for possible interpretations of radiometrics and EM maps.
- Yield maps – If the constraint is causing yield decline, yield maps can show where the constraint is located. This might be less obvious if the whole paddock/farm is compacted.
- Elevation data – Commonly recorded as part of normal operations in MyJohnDeere/Ag Leader®. This can correlate to soil types and their constraints. Elevation maps are also useful to delineate low-lying areas prone to frost and waterlogging. Five metre contour data is available from Geoscience Australia's ELVIS (Elevation Information System). Two metre contour data is available for most of the WA grain belt from https://catalogue.data.wa.gov.au/dataset/dpird-2-metre-contours. The map is missing sections in the south-west corner of WA. You will need software to read shapefiles or GeoPackage (.gpkg) files to view the data.
- Tractor data, such as fuel consumption or drag data – Commonly recorded as part of normal operations in MyJohnDeere/Ag Leader®. You might be able to see more compacted areas/dense soil where fuel use increases, but interpret this with care because readings may vary more with working conditions (for example, wet versus dry) than with soil constraints. Fuel use might also indicate heavier soil types that will not respond to ripping. Also be aware that the whole paddock might be compacted.

Software

Depending on your skills and inclination, software can be useful or stressful for viewing and manipulating spatial data. If you are deciding whether to use software for this exercise, a good rule of thumb is if you are already competent with the software, it is likely to help. If you need to purchase and/or learn a new program while also mapping soil constraints, you are more likely to give up on the whole exercise. In this situation, stick to pen and paper or get help from someone who can use software, such as an adviser or precision agriculture consultant.

There are a multitude of programs to view and manipulate spatial data. For this exercise, the main things you need to be able to do are:

- view whole farms and paddocks spatially;
- mark out different areas within paddocks; and
- quantify different areas within paddocks.

Google Earth and ArcGIS Earth are free, easy to use and might be all you need. These platforms let you draw polygons, view historical aerial imagery, import and view map layers from other programs, and adjust transparency of layers to see if and where they overlap.

QGIS and other sophisticated mapping software such as ArcGIS Pro have very powerful mapping and data analysis capabilities.

QGIS is open source and free, the downsides being it can have software bugs (as it is open source) and has a steep learning curve. It has more functionality to merge and manipulate layers than Google Earth/ArcGIS Earth, but is considerably harder to use. If you are only using it to view spatial layers, however, it is relatively easy to navigate. ArcGIS Pro is expensive but more powerful.

There is a range of precision agriculture software that specialises in provision and use of spatial information. Programs that can make variable fertiliser maps will also be able to view and interrogate different spatial layers. If you already have farm management or planning software, you can likely use it to get spatial layers, such as aerial images and NDVI.

Sophisticated functionality, such as merging multiple spatial layers to define and quantify management zones, is useful, especially if using EM and GR data. Otherwise, creating management zones tends to be more useful when managing inputs such as fertilisers and is better used once soil constraints have been corrected.

If you have a mix of spatial data in various formats (for example, hard copy and electronic) and in different software programs, it is up to you if you use them as they are or aggregate them into one place – usually one program. As aggregating can take considerable skill and time, and this exercise is unlikely to be repeated soon, it might be easier to look at the individual layers in their current format and work mainly with pen and paper, and use software only if and when necessary. Your eyes and brain are the most important tools for this exercise.

Products that link your machinery to your farm management software, for example, MyJohnDeere or Farmer Core, can capture lots of on-farm data, such as fuel use and run time. It can be viewed, manipulated and exported into other software. The data can be useful for finding compacted areas (for example, higher fuel use) but careful interpretation and ground-truthing is needed. It can add a degree of complexity to this exercise.

Precision agriculture consultants can help with any step of the process.

Assessing data quality

Spatial layer quality can vary wildly. When assessing quality, consider scale, resolution and underlying data attributes. The resolution is important to consider if the soil changes are very variable, as coarser spatial data may not accurately map changes.

With soil landscape maps, the bigger the scale, that is, 1:250,000 versus 1:50,000, the lower the resolution. Digital elevation models (DEM) at 2m are more accurate than DEMs at 5m.

Aerial radiometric surveys will be lower resolution, and therefore lower quality, than ground-based surveys. Airborne radiometrics, for example, tend to run on 100m transects, compared with ground-based surveys on approximately 36m transects.

Yield map resolution is the width of the harvester, 9 to 18m. The accuracy is only as good as the data recorded. While technology is improving, errors end up 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 having to calibrate for different crops at the beginning of each season, but are not perfect, particularly in low-yielding crops. Yield maps need to be cleaned to remove bad data points if they are to be an accurate reflection of yields. This is not necessary if you are just interested in yield relativities.

NDVI resolution varies from 3cm to 30m per pixel depending on the data source. Drones give much greater resolution than satellites. The most readily available satellite imagery has a resolution of 10m. NDVI has some quirks to keep in mind. 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 because leaf area is small. Using NDVI to measure vegetation density is problematic as once the canopy closes NDVI might not distinguish between low and high vegetation density.

Step 2. Ground-truthing

Ground-truthing soils in the paddock is the most time-consuming part of making the soil amelioration map, but also the most critical and rewarding. Ground-truthing helps turn data and thoughts into a material soil amelioration plan. Looking at spatial layers and soil maps can help ground-truthing but cannot replace it. As good as some spatial data is, it can be seasonally specific or out of date; soil constraints can get worse gradually over time and/or only present in difficult seasons.

Going through the mapping exercise in Step 1 makes ground-truthing faster and more accurate. You can gauge how many sites you need to visit and where they are. Mark the sites you will ground-truth before heading into the paddock.

When to ground-truth

Ideally, ground-truthing is done both during the growing season and in summer/autumn, but most ground-truthing tends to happen in the drier months because this is when soil amelioration is on people's minds. It is also when access within paddocks is easiest.

When ground-truthing early in the growing season you can check if crop establishment has been hindered by non-wetting soil, and if there are subsoil constraints limiting critical early root growth (Bryce and Pluske, 2020b). Later in the season (near or after senescence) is a good time to see if roots did not reach subsurface moisture. Crops with poor root development, especially poor downwards growth, are more dependent on ever-variable in-season rainfall. In summer/autumn you can check if there is subsurface moisture that the crop was not able to utilise during the season.

Where to ground-truth

By zone

Sites should be in the centre of the areas identified in the mapping exercise (Figure 10). You can drive to sites using a hard copy map or by loading a map layer into a mobile GPS program such as Google Earth, Save Location GPS or GPS Waypoints.

Areas to avoid include near fencelines, gates, stock tracks and camps, dams, where fertiliser or lime were previously stockpiled and headlands.

The number of sites in each area should be proportional to the size of each area. The rule of thumb is one detailed soil assessment per 50ha. Instructions to do a detailed assessment are outlined in 'How to ground-truth'. Where areas are considerably less than 50ha it can still be a good idea to do a detailed soil assessment, but in the interests of time often a quick 'shovel in the ground assessment' will suffice.

Ground-truthing EM and GR surveys

Ground-truthing and sampling plans are different if they are based on ground-based EM and/or radiometrics surveys. The aim is to core in areas that cover the range of EM and radiometrics values. Focus on the ranges that cover the most hectares – if most of the paddock has an EM value between 0 and 40, do more cores in those areas. Figure 11b is an example EM map showing a transect of ground-truthing cores in the 0 to 60 reading range. Cores were also collected from the 60 to 200 range, but are not marked on the map. In this case, the purpose of mapping and coring was to find depth to clay to decide whether to delve, spade or spread clay.

This type of ground-truthing is essential to make proper use of EM/GR data. It is a more clinical and mathematical approach than ground-truthing by soil or productivity areas. Existing soil knowledge can be used when selecting coring sites, or alternatively can be discarded if considered biased or you are wanting to stick wholeheartedly to the clinical approach.

Correlating soil properties with EM and GR data usually involves coring to about 1m depth, noting and photographing the cores and their depths to clay/gravel, and sending samples to the laboratory. Because it is systematic, the location of cores may not align with areas where there are visual clues of constraints and may not consider other soil properties in the field that might be hindering yield. Additionally, the coring sites are chosen based on map readings, not because they are in areas that need targeted sampling. Ideally, EM and GR should be used in conjunction with other soil information rather than being the sole source of it.

How to ground-truth

For this exercise, ground-truthing is not about classifying or naming soil types. The aim is to work out what soil issues are limiting yield, which is largely about looking for layers in the soil that hinder root growth, whether physically or chemically, or water-repellent surface soil. See *A simple guide for describing soils* (Stuart-Street et al. 2020) for detailed information on assessing soil in the field (see Useful resources).

Knowing where soil types change is more important than knowing official soil names. You can call your soils whatever you want, and the best names are what you've always called them – things such as buckshot/pea/forest gravel, Sunday country, Morrell, gutless sand, pear tree country, sandplain or mallee.

There are two ways to assess each site: either dig a hole as deep as you can or work through the soil layers one-by-one. For either method, you want to start by marking the site on your map and/or with a GPS, then noting the soil surface and taking notes and photos. You will not remember all this information later, so take the time to write it down in the field. Appendix 1 (at the back of this handbook) contains a simple field sheet to use for this exercise.

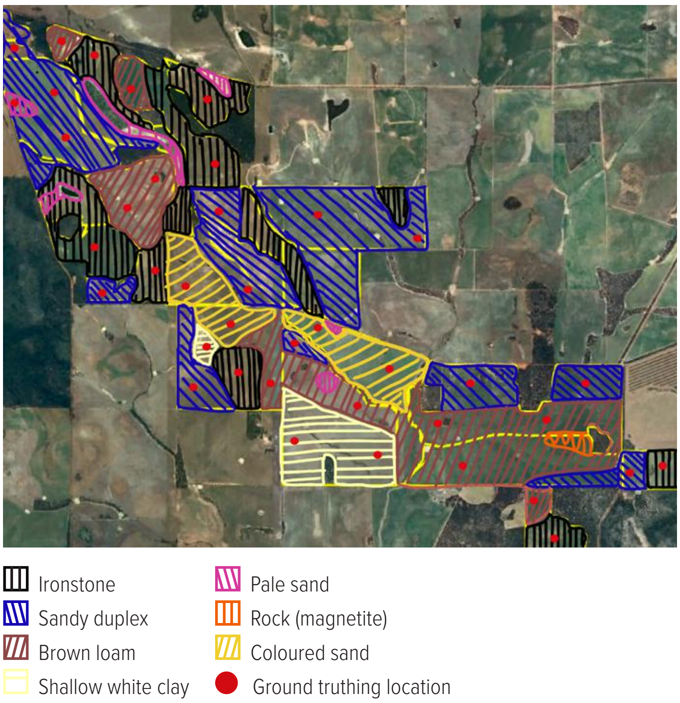


Figure 10: Ground-truthing locations on Rocky Ridge Farm.

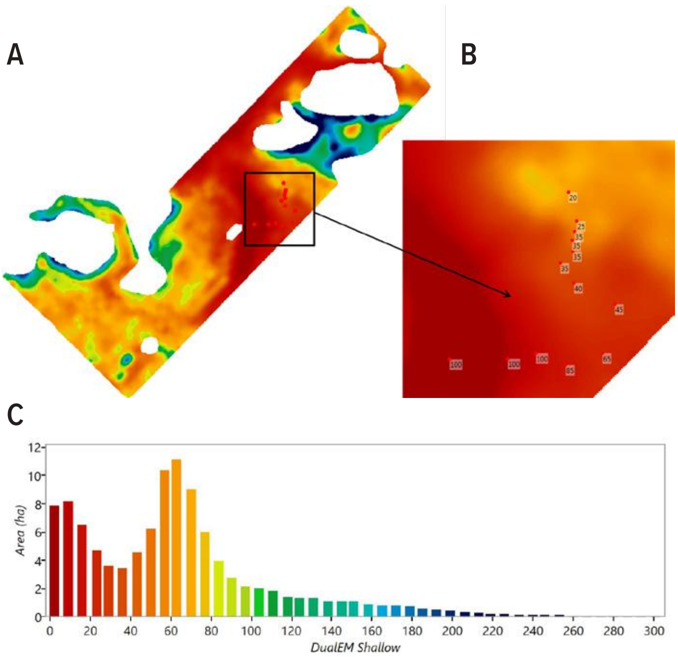


Figure 11: a) EM map; b) Soil core locations and depth to clay; c) EM scale showing the number of hectares in each EM reading.

If your local soil knowledge is still developing, ideally head into the paddock with a local adviser who is familiar with soil constraints.

Tools:

- Hard copy and/or electronic version of your map with your ground-truthing plan.
- GPS (there are a multitude of GPS apps available).
- Shovel – in most cases a good post-hole shovel will suffice. You can see more from pits dug with a backhoe or front-end loader, but it will take too long to assess all the soil areas this way. Save them for tricky soils. Coring or augering is useful to determine the depth of soil layers, especially hard layers.
- Pocket knife, screwdriver, rod, trowel or similar sharp tool to pick at the soil and test soil density down the surface of the hole.
- Tape or other measure to estimate soil layer depths. Soil tends to destroy tape measures. If you cannot get a plastic tape measure that rolls up (no mechanism to clog up with soil) you can mark out 10cm increments on your shovel's handle.
- Camera/phone to take photos.
- Sample bags.
- Permanent marker and pens.
- Penetrometer or DIY push-probe version, for example, a length of reinforcing bar (12 to 20 millimetres diameter) with a handle, or a wool bale spike. A penetrometer tests how compacted the soil is down the profile and is best used when the soil is at or close to field capacity; most soils harden when drying. Using a penetrometer when the soil is too dry or too wet will throw off the results. You can source a penetrometer that records pressure (handy if doing research), but a good DIY version suffices for ground-truthing in most cases.
- Optional: pH test kit to crudely assess acidity/alkalinity; can be handy to decide if samples should be collected for laboratory analysis to accurately measure soil pH.
- Optional: a variety of alcohol strengths (beer, wine, liquor) to test water repellence.

1. Start at the surface

Are there rocks? If so:

- what type? (limestone, granite, ironstone/cemented gravel)
- how many? (not much, moderate, a lot)

Is there gravel at the surface? If so:

- how much? (not much, moderate, a lot)
- how dense? Has it formed a cemented or hard layer?
- what type of soil is around the gravel? (light/medium/heavy, sand/loam/clay)

If there are no rocks or gravel at the surface, start with soil texture. Use terms that make sense to you to describe the soil, such as light/medium/heavy or sand/loam/clay.

If the surface is sandy, check for non-wetting. If ground-truthing during the season, this will be obvious – the soil should be wet but it is not, there are likely to be gaps in crop rows, erratic emergence and dry patches, particularly in inter-rows.

If ground-truthing in summer/autumn, scrape away the top 5mm to make a flat surface and gently put a few drops of water on the soil. You must scrape the top as the top few millimetres can absorb water but hide water repellence just below the surface. Time how long it takes for the water to filter into the soil:

- less than 10 seconds = low repellence;
- 10 to 60 seconds = mild repellence; and
- more than 60 seconds = moderate to severe repellence.

You can also use increasing strengths of alcohol to crudely gauge the extent of water repellence and to compare the relative water repellence of different soils. Start with water as described above. If infiltration is greater than 10 seconds, try mid-strength *beer* (3.5 per cent). If the *beer* infiltrates in less than 10 seconds it is moderate repellence, but if it does not infiltrate within 10 seconds try *wine* (9 per cent). If *wine* takes longer than 10 seconds to infiltrate the soil then it is severely repellent and you may want to break out a *fortified wine or spirit* to see how long and just how severe the repellence is.

On soils heavier than light or sand, check for a hardset or crusted surface which could indicate dispersive soil. Consider if rainfall has run off (an indicator of dispersive soil) or infiltrated downwards (an indicator soil is not dispersive). If the surface crusts, collect a sample to do a DIY dispersion test (instructions at the end of this ground-truthing section).

2. Find depth of first soil layer

The first soil layer is not the organic matter seam in the top few millimetres to centimetres. Most soils have darker-coloured organic material at the surface – this is normal and is not necessary to describe for this exercise.

A simple way to start is to push your shovel into the soil. If it abruptly hits a hard layer or there is a point at which it is noticeably harder to dig, there is a good chance that is where the soil changes and is the depth of the first layer. Look at the face of the hole to see if a change in soil corresponds to where digging gets tough. If the soil gets gradually harder to dig, it might be a gradational soil where clay content is increasing gradually with depth.

You can then crosscheck your findings using your penetrometer near (15 to 30cm) where you are digging your hole. Compare the depth at which it gets tough to push the penetrometer to where digging gets tough and what you can see in terms of soil change. There is a strong chance they are correlated.

At the depth where the first layer ends there might be a distinct change in colour, an obvious change in soil texture such as more clay or gravel, a very strong/dense layer of soil or a cemented gravel/rock layer. In lighter soils you may not see any distinct change where the shovel and penetrometer get tougher to use. This should be an immediate flag for compaction because the increase in soil strength is not due to a change in soil layer, but from compaction within the layer. In deep, pale sands there may not be any change in soil layer or soil strength; dig down until you cannot reach any further or are beyond the tillage depth of machinery.

a) Water-repellent gravelly sand over gravel that is loose enough for roots to grow down about 20cm before it gets too dense for further root growth. Hard to dig beyond 20cm too. pH testing required.

b) About 20cm of sand (water repellent) over dense next layer that is too hard to dig. pH testing required.

c) Five to 10cm of water-repellent sand over about the same depth of gravel plus sand, over dense next layer that is too hard to dig. pH testing required.

d) Gravelly sand (10 to 15cm) over dense next layer that is too hard to dig. pH testing required.

Figure 12: Ground-truthing images. Photos: Wayne Pluske

Once you have identified where the first layer finishes, note its depth, describe what it is and move onto the next layer (the subsoil).

3. Check the subsoil

This is important because it will affect your amelioration options, especially tillage ameliorations and claying. The most likely subsoil options are:

- rock;
- coffee rock (hardened/cemented layers of sand, usually very dark brown to black);
- ironstone/cemented gravel;
- clay;
- gravelly sand; and
- loam.

As with the topsoil, note the colour, texture and if there is gravel. If the subsoil is clayey, check:

- for mottled colours, which can indicate periodic waterlogging; and
- if the clay is cracking or non-cracking.

If the soil texture changes and the soil is very hard to dig, you likely have clay or very high-strength soil below the first layer. If the soil is obviously clay and you feel like you need machinery to dig deeper, you have done enough. If you can, keep digging.

If the soil texture does not change, dig down to 60 to 80cm if you can. If you are using machinery, or feeling enthusiastic, you can keep digging to see what is deeper and measure the maximum depth you can ameliorate to.

Now you will have a soil face where you can see the crop root zone and any soil changes down the profile. Take a photo of the face and note the site and photo link (because you will not remember which photo belongs to which site later). You will use the soil face to check for constraints in the next steps. Figure 12 shows various soil profiles and constraints.

4. Check crop roots

If there is a crop in the ground, check root depth and quality. Use the sharp tool to pick and probe at the soil face to track where roots are. Early in the season is a good time to see how quickly roots are growing. Late in the season, near or after senescence, is a good time to see if roots could not reach subsurface moisture. Stunted, distorted or thickening roots mean there is a problem.

Look beyond the depth of rooting to see what issues are preventing further growth; canola and cereal roots can grow more than 2m if not constrained by soil conditions or water (Kirkegaard 2020; Breslauer et al. 2020; Lilley and Kirkegaard 2016). The barrier to root growth can be obvious in soils where there is a stark contrast between layers, for example, sand over dense clay. In lighter soils, check where root growth finishes relative to where using your shovel and penetrometer gets tough. If the two are the same and there is no obvious constraint (such as a change from sand to clay), compaction is the likely limitation to deeper root growth. If pushing is easy and there is no obvious visual constraint, acidity or nutrient toxicity might be the problem.

5. Physical barriers to root growth

Physical barriers to root growth include ironstone/cemented gravel, agriculturally compacted layers, dense subsoil and tight gravel layers.

If there is cemented gravel or another distinct layer, note how deep and thick they are and check the soil face to see if roots have grown into them. If there is no crop currently growing, you might be able to see old roots or root channels.

If it is a deep, lighter soil, gently poke your finger down the side of the exposed soil face to check if and where the soil gets hard. See if this corresponds to where root growth stops and where the shovel and penetrometer (used near the hole) get tough to push. If these three things align (tough finger poke, tough penetrometer push and less roots, and especially if roots look thick and stubby), you are looking at agriculturally induced compaction.

Agriculturally induced compaction is more obvious on lighter, sandier soils. Often there will be a zone of compaction (20 to 40cm thick) before the soil is easy to dig again. If you have a penetrometer that can measure hardness and the soil is moist (near field capacity), you can use this to further confirm the compaction. Soil penetration resistance values above 1.5 megapascals affect root growth and severe restriction occurs above 2.5MPa (Davies et al. 2018; Parker and Reynolds 2017). Plant root growth is limited to old root channels when soil penetration resistance is greater than 3MPa.

To check for compaction in gravelly soil, run your hand down the gravel. The ease at which gravel comes out is a reasonable indicator of how much the gravel is impacting root growth – something that you can crosscheck by looking at where roots are growing to, in relation to where the gravel is. If the gravel comes off the soil face very easily, it is probably not compacted and the roots will be able to grow through. If the gravel stones are so tightly held in the soil that you have to pick out each piece of gravel with a sharp pointy tool, it is likely they are hindering root growth. Penetrometers do not work in gravelly soil because they tend to hit gravel stones and give false soil strength readings.

Dense subsoil is different to agriculturally induced compaction. It tends to be a hardened layer containing considerable clay and/or loam and might be dispersive. Check for soil dispersion using the instructions on page 20 ('How to test soil dispersion').

6. Chemical barriers to root growth

Chemical issues are often impossible to see. You might have an inclination they exist because there is no obvious physical barrier to root growth on the soil face of your hole, yet the roots are not growing as deep as you think they should.

Chemical barriers include acidity, salinity and nutrient toxicities, including boron. Sodicity is a chemically induced barrier (caused by too much sodium) that presents mainly as a physical barrier (hardsetting soil).

Chemical barriers are best identified by collecting samples, ideally in increments of 10cm down the profile, and sending them off for laboratory testing. As a minimum, compare the soil from just before root growth stops and just below where it stops.

If you have been cropping for a while, unless you have applied bullish rates of lime for many years, it is likely there will be an acid zone somewhere that limits root growth, particularly on lighter soils. Most growers already have some indication of pH levels from previous soil testing. However, because soil testing has historically focused on fertiliser rates, determined from shallow 0 to 10cm sampling, it has not been rigorous enough or deep enough to properly gauge the acidity problem.

If you only have old (more than four years) pH results, only surface sample results, or are dealing with known acidic soils, it is time for a decent pH testing program, irrespective of assessing other soil constraints. Acidity gradually gets worse, slowly reducing root growth year after year. It can then be a slow and/or expensive exercise to fix acidity. In the long term, preventing acidity before it becomes a major production constraint is easier and cheaper than trying to ameliorate strongly acidic soil.

Knowing pH is critical before doing any form of soil amelioration because:

- most tillage amelioration methods present an opportunity to apply and mix lime to maximise its effectiveness, particularly in tackling subsurface acidity; and
- amelioration could bring acidic subsoil to the surface. You need to know if you are going to bring acidity up, and if so, whether the amelioration will be worth it, or if you need to apply lime before and/or after the amelioration.

7. Collecting samples

If the soil is uniform down the profile (deep sand, deep loam) collect samples in 10cm increments. Where there are different soil layers, collect samples from within each layer – these can be a 10cm vertical increment of the layer or a sideways/horizontal sample into the layer. Do not contaminate samples by mixing soil layers into one sample.

Test pH to at least 30cm, preferably 50 to 70cm on sands. This is to identify acid zones in the soil and, if you are considering inverting soil by ploughing, to gauge upfront how much more lime might be required after ploughing.

If there is a distinct change in soil type down the profile and the next layer down is impenetrable (for example, ironstone/cemented gravel, dense clay), sample in 10cm increments down to that layer, because it is unlikely roots will grow into it. If considering ripping or delving that layer, test it too.

If you have not tested phosphorus (P) in the past three years, sample the 0 to 10cm and 10 to 20cm layers for P testing as well. It may make sense to apply P before tillage amelioration if P needs distributing below the top centimetre of soil.

Some growers are doing the same with trace element fertilisers, especially copper (Cu) and zinc (Zn), because the plant availability of these nutrients is very dependent upon even distribution through the root zone. Potassium (K) is often applied before tillage, using the opportunity to boost levels and availability or because it is easier logistically.

If salinity is a concern or your EM survey suggests salinity, make sure it gets tested too. Many laboratories will measure and report salinity in conjunction with pH.

If you are planning on delving, spading or claying to treat water repellence, knowing the quality of the clayey subsoil is critical. Test dispersion, clay percentage (as this will determine final spreading rate) pH, salinity, K, phosphorus buffering index (PBI) and hostile elements such as boron. Some clays with a high PBI can tie up P. In soil, boron levels greater than 15 milligrams per kilogram and salinity (ECe) greater than 12dS/m have been found to negatively impact crop yield (GRDC 2011). See ‘Risks and mistakes’ in Part 3 for more information.

Record the details of each sample you collect (site, depth, date) and why you collected it.

8. Check soil type boundaries

On the way to your pre-determined sites in the different areas, stop near your soil transition lines, and/or if you see a difference in soil types as you are driving, to do a quick shovel-in-the-ground assessment to check if the transition lines on your map need to be adjusted. A shovel-in-the-ground assessment means

Example soil profile

The soil profile below is from Rocky Ridge Farm. A blank copy of the record sheet is at Appendix 1.

<table>
<tr><td colspan="2">Paddock: Shearing Shed</td><td>Site no: SS-8</td><td colspan="2">Date: 11/01/2020</td><td colspan="2">Photo time: 11:05am</td></tr>
<tr><td colspan="3">Soil name: deep sandy duplex</td><td colspan="2" rowspan="2">Surface gravel: none</td><td colspan="2" rowspan="2">Non-wetting: mild at surface</td></tr>
<tr><td colspan="3">GPS no./coordinates: SS8</td></tr>
<tr><th>Layer</th><th>Depth</th><th>Gravel/rocks</th><th>Texture</th><th>Colour</th><th>pH</th><th>Notes</th></tr>
<tr><td>1</td><td>10cm</td><td>None</td><td>Sand</td><td>Grey brown</td><td>5</td><td></td></tr>
<tr><td>2</td><td>10 to 55cm</td><td>Minimal</td><td>Sand</td><td>Lighter brown</td><td></td><td>Gets a bit tougher at 30cm</td></tr>
<tr><td>3</td><td>> 55cm</td><td>Minimal</td><td>Clay</td><td>Reddy-orange-brown</td><td></td><td>Mottled colours</td></tr>
</table>

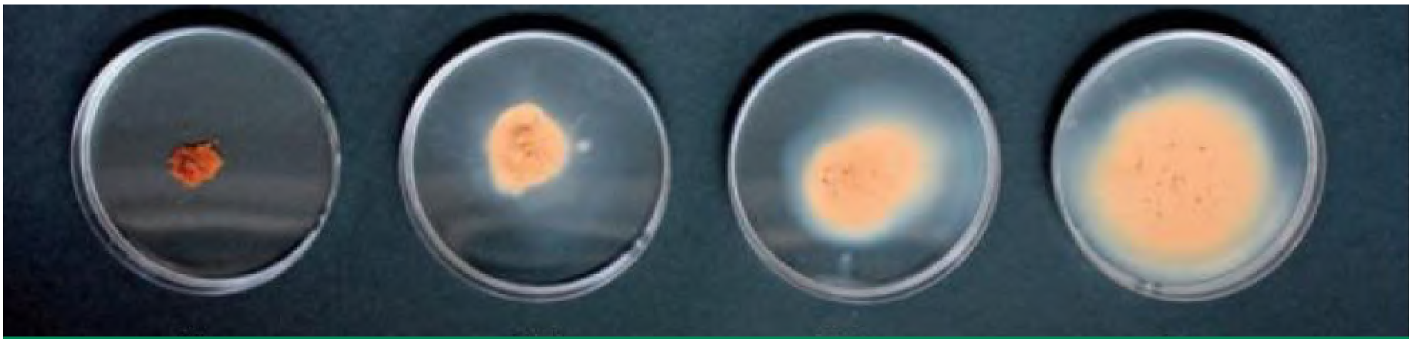


Figure 13: Degrees of soil dispersion (nil to severe) for soils that are non-sodic to highly sodic (from left to right). Photos: Alison Lacey, DPIRD

checking soil texture, depth and colour. Push the shovel into the ground until it hits the next soil layer. Level the shovel to pull up the soil and check colour and texture. This could confirm, for example, that you are still on a yellow sand.

How to test soil dispersion

The DIY jar test

The easiest (and cheapest) way to gauge if your soil is dispersive is the 'jam jar' test, more formally known as the Emerson Aggregate Test. Collect small dry soil clumps (aggregates) about 5mm diameter from representative areas, making sure you know where each one has come from. Collect at least two from each sample area.

If you are on duplex soils and think there is subsoil dispersion, collect aggregates from different layers in the soil, noting the depth. Because sand does not disperse, you only need to collect samples from soils that have some clay in them.

Back in the house, office or shed, set up a series of clear containers – jars, glass cups, plastic cups or petri dishes. The containers need to be wide enough so you can gently place (not drop) the aggregates in the bottom of the container. If the aggregates are damp/wet, leave them out to dry for a day or two before continuing.

- Put a few centimetres of distilled water or rainwater into each container. Do not use chlorinated tap water as this can interfere with the test.
- Place each aggregate gently into a container with the water.
- Watch the aggregates for the first 10 minutes, then check again after 30 minutes, two hours and 24 hours.

If the water around the aggregate turns cloudy, the soil is dispersive. The cloudier the water, the more dispersive the soil. Similarly, the faster dispersion becomes obvious, the more dispersive it is. In highly dispersive soil, the water will turn cloudy within minutes. Wait the full 24 hours before making your assessment as dispersion can take a while to show up in low to moderately dispersive soil. If more than half of the aggregate disperses (for example, 'moderate' dispersion or more, as shown in Figure 13), the soil is highly likely to respond to gypsum.

If the aggregate crumbles – which will occur within the first few minutes if it is going to happen – but the water does not go cloudy, the soil has slaked, not dispersed. Slaking is a physical problem and means the aggregates were not strong enough to withstand the pressure of the sudden influx of water into the pores. It is usually caused by low organic matter. Slaking is very common and does not cause the same management problems as dispersion.

Soils can both slake and disperse. A soil that slakes will not necessarily disperse, while a soil that disperses will also slake.

Common soil types and constraints

Certain soil types come with inherent constraints and predispositions to agriculturally induced constraints. Figures 14a and 14b are very simple representations of 15 broad soil types in WA. These soil types are largely based on the groupings in MySoil (https://www.agric.wa.gov.au/managing-soils/mysoil). There are a multitude of variations within each soil type, for example, multiple variations on a deep sand. However, these variations will not have a big impact on management requirements.

Figures 14a and 14b show the texture of the first and second soil layers and list possible constraints within each layer. In reality, soils are more complicated and may have more layers, but from a management perspective for soil constraints it is generally best to start by understanding the topsoil and what soil texture it overlies. For a more detailed description of soil types see MySoil (DPIRD 2019a) and *A simple guide for describing soils* (Stuart-Street 2020).

The list of constraints is a starting point to give an indication of the type of issues you might encounter. It is a guide only. Constraints will vary across and between farms, particularly for agriculturally induced issues and where management has been different. For example, long-term liming on a deep sand may have already eliminated acidity.

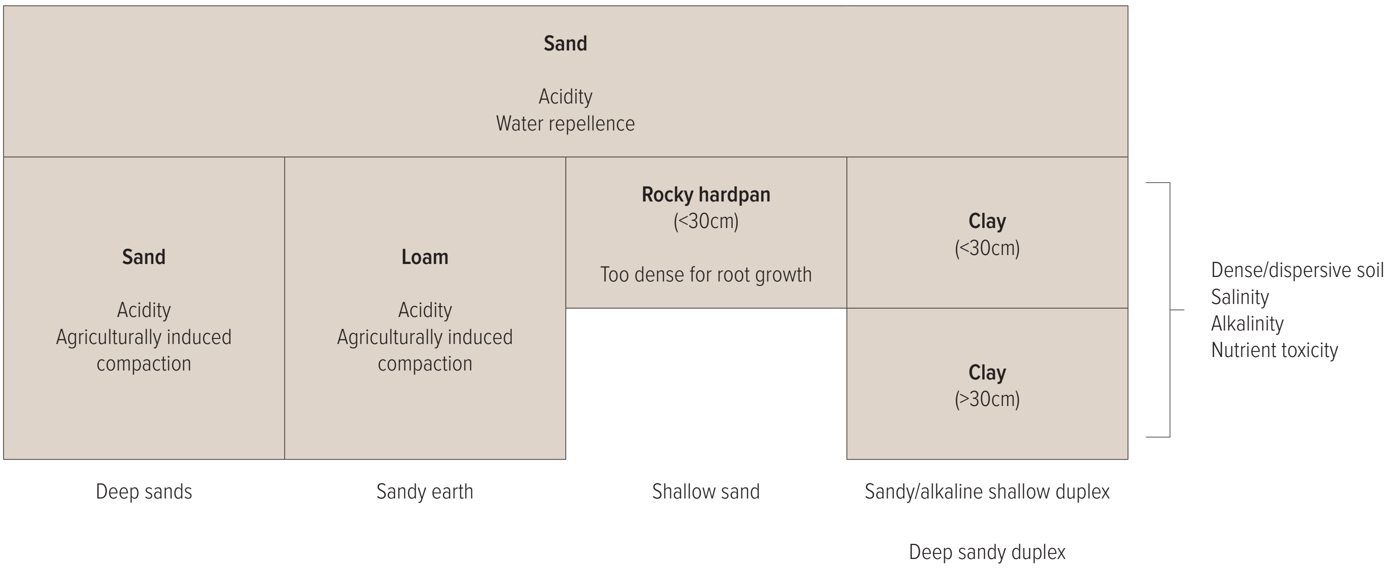


Figure 14a: Simplified and stylised representation of broad soil types (deep sands, sandy earth, shallow sands, sandy shallow duplex, alkaline shallow duplex, deep sandy duplex) in WA.

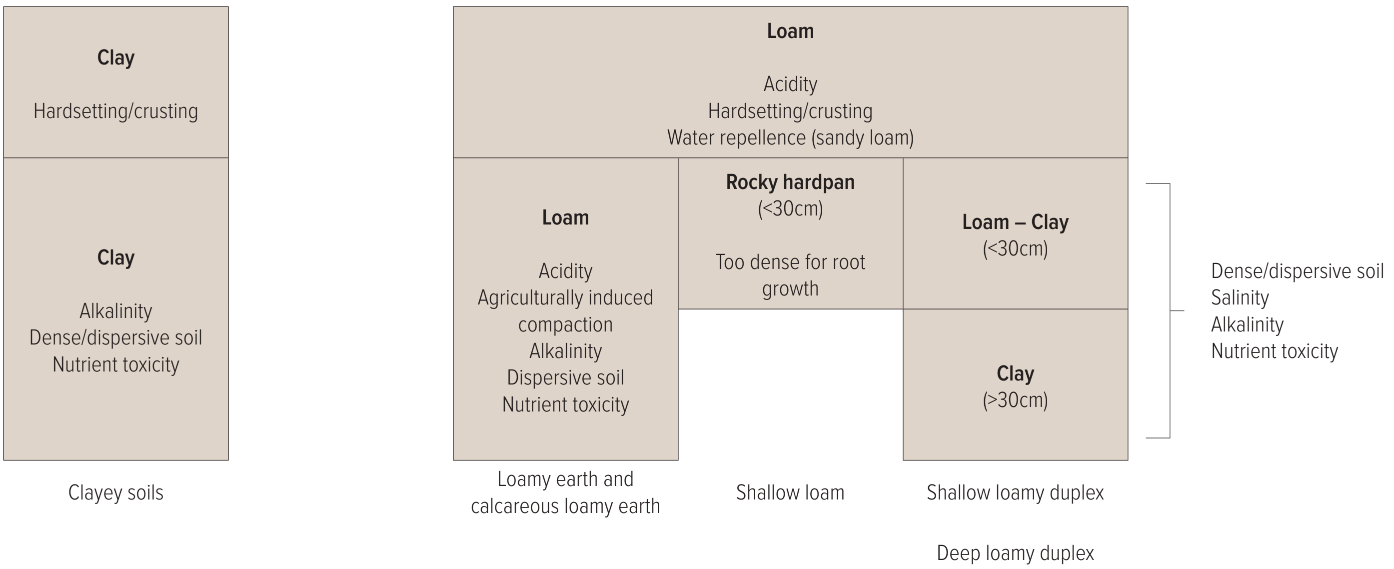


Figure 14b: Simplified and stylised representation of broad soil types (clayey soils, loamy earth, calcareous loamy earth, shallow loam, shallow loamy duplex, deep loamy duplex) in WA.

The following images are photos of some of the broad soil types with layers and potential constraints listed. Unless otherwise specified, images are sourced from MySoil (DPIRD 2019a) with permission from DPIRD.

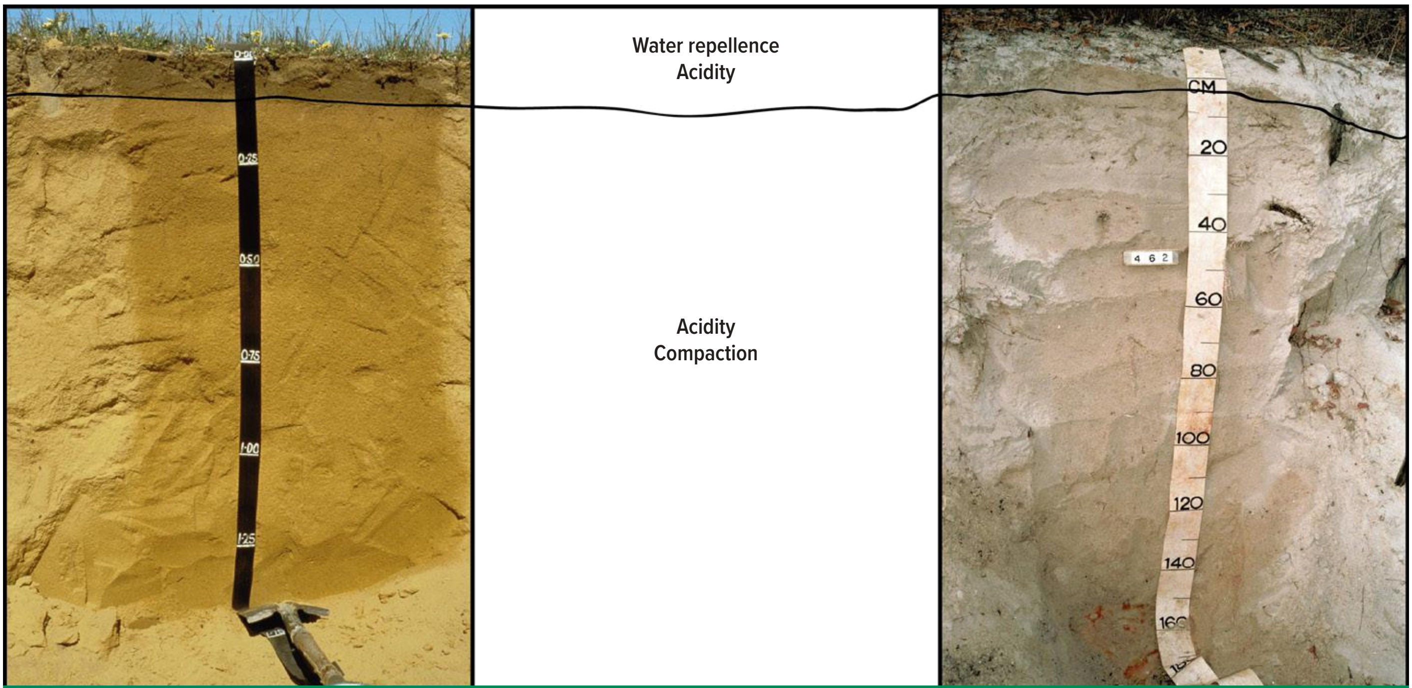


Figure 15a: Deep sands.

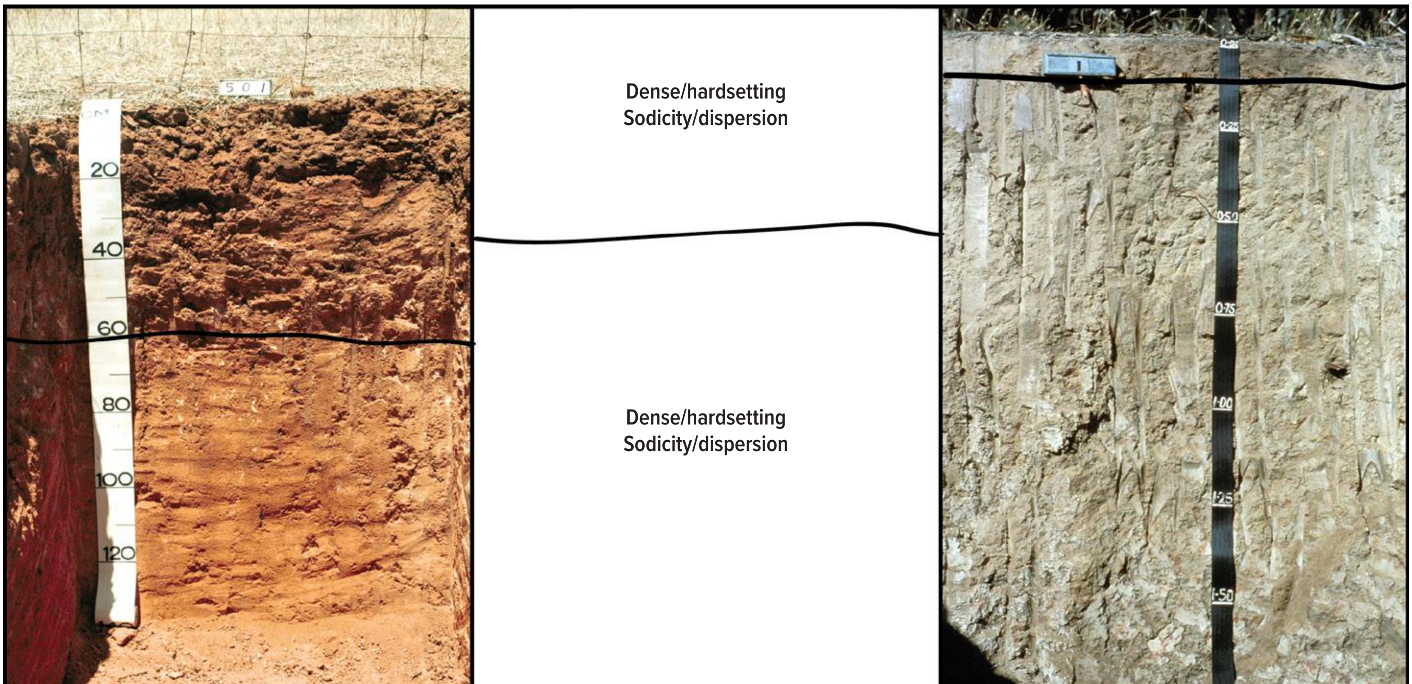


Figure 15b: Clayey soils.

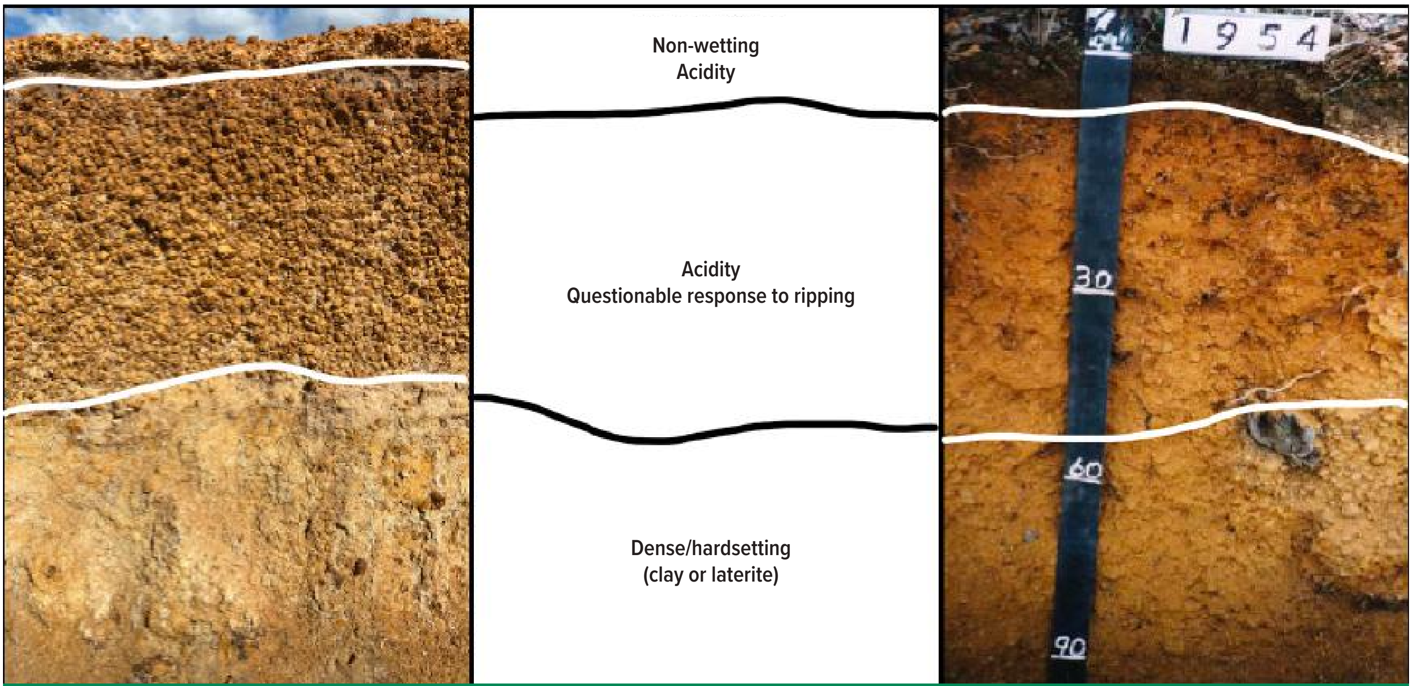


Figure 15c: Gravelly soils.

Photos: Wayne Pluske (left) and Doug Sawkins (right)

Note: If you can run your hand down the soil profile and gravel falls out easily, it is unlikely to be responsive to ripping. If gravel stays put, it may respond to ripping.

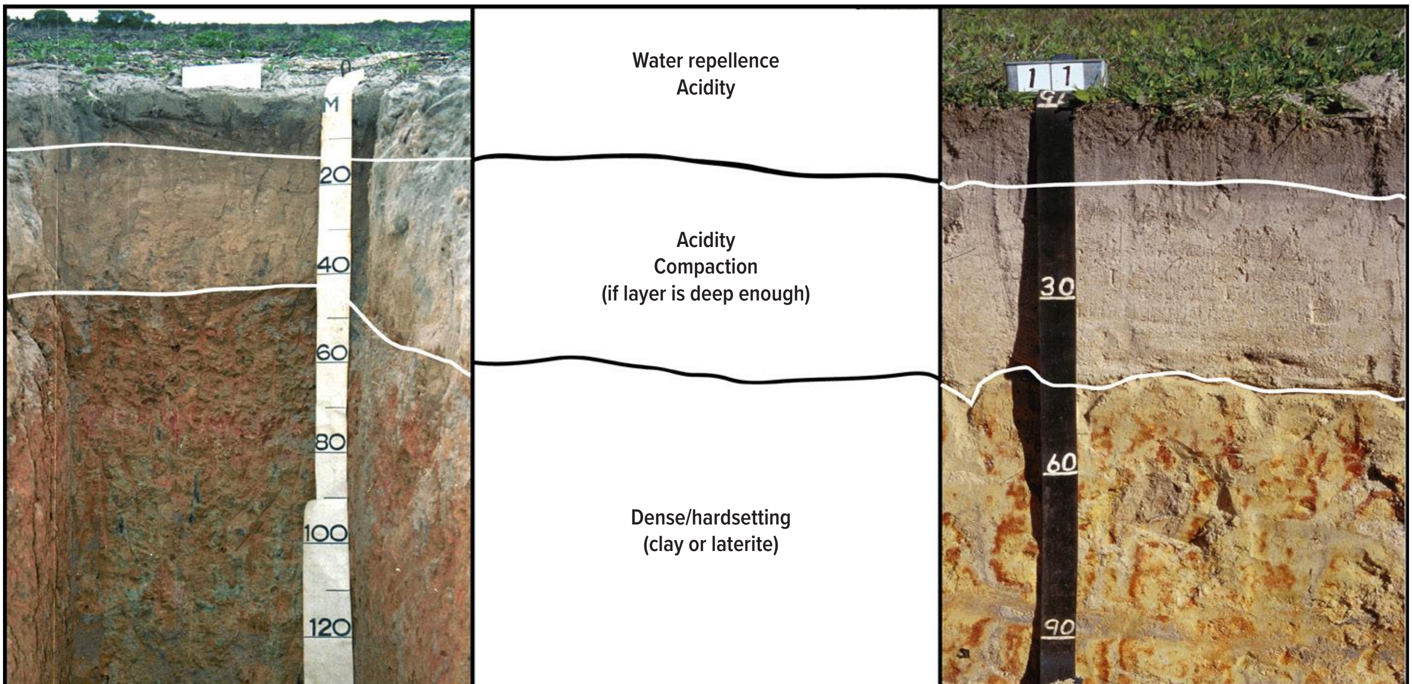


Figure 15d: Deep sandy duplex.

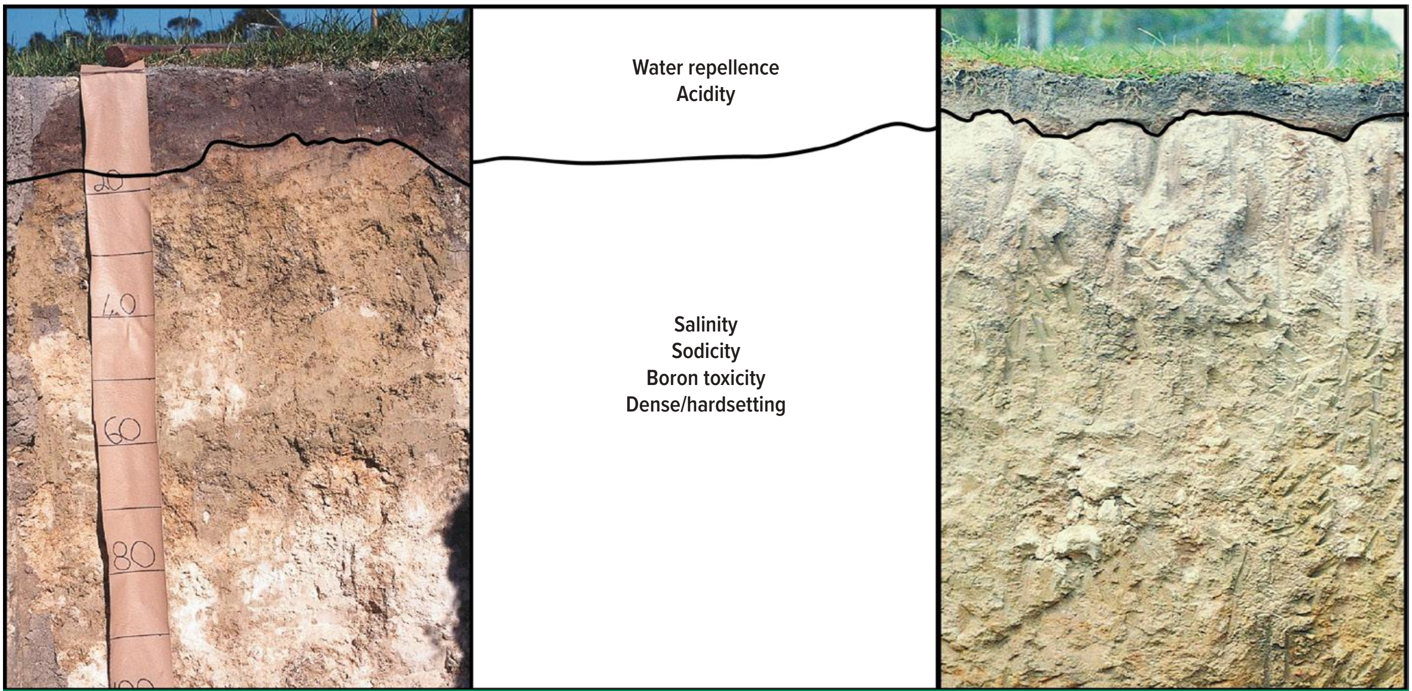


Figure 15e: Shallow duplex.

Note: There are other soil layers within the second soil layer. In the soil on the right, there is another clay layer where the soil starts to become darker. As these layers are both clay, they could have similar constraints and have not been differentiated.

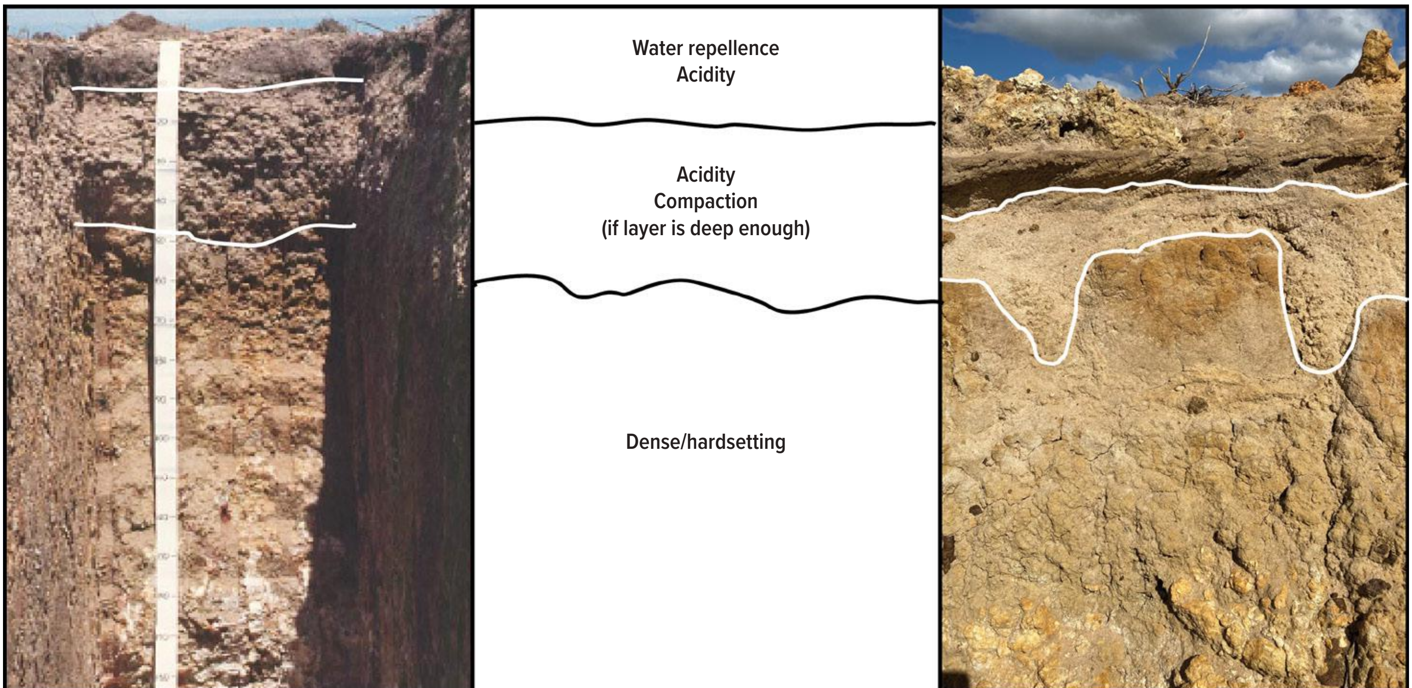


Figure 15f: Sandy gravels over clay (duplex). Photos: Doug Sawkins (left) and Wayne Pluske (right)

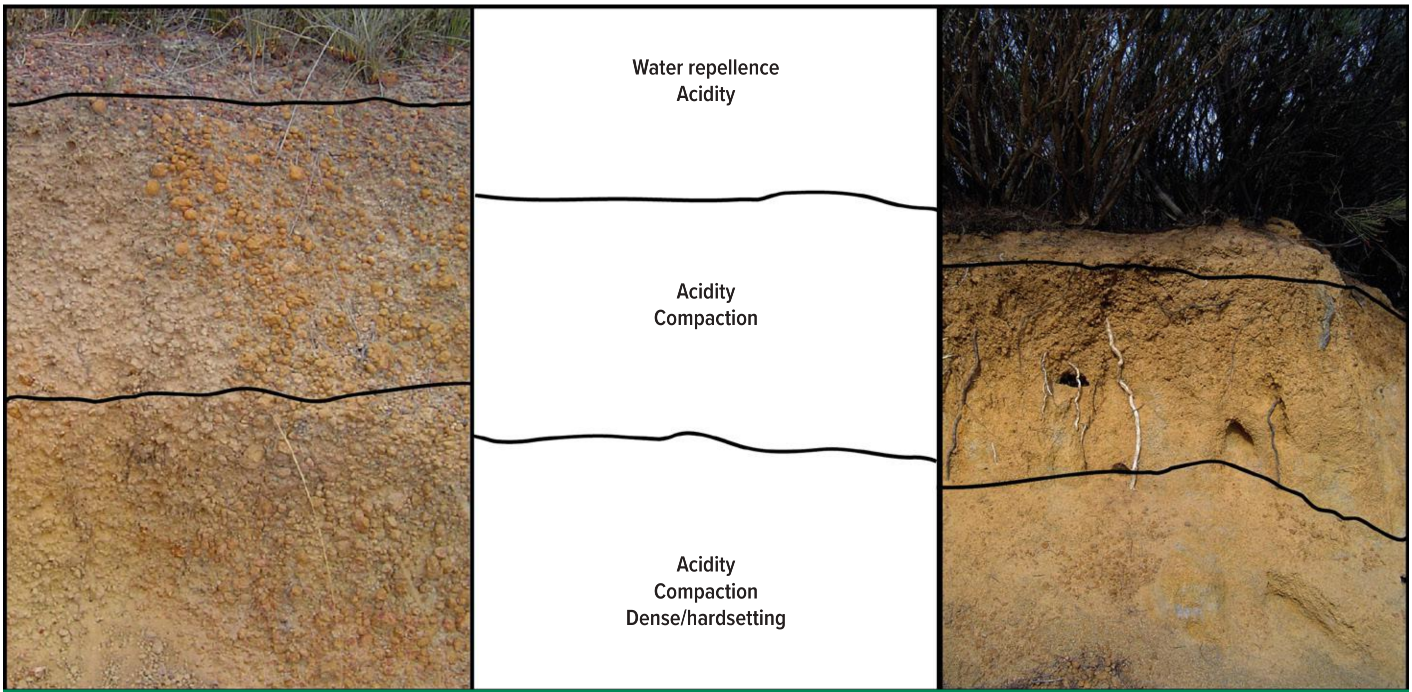


Figure 15g: Sandy gravels and sands over gravel.

Step 3. The soil amelioration map

Goal: a map that shows the main soil type areas, their soil constraints and amelioration options.

After ground-truthing it is time to bring all the information together to create a soil amelioration map. This is both your base map and roadmap for tackling soil constraints in variable paddocks. It helps determine how and where the soil amelioration budget is allocated to improve yields and profits.

The worst-case scenario in generating this map is that it gives you evidence that some paddocks are too variable to consider ameliorating in certain ways, enabling you to remove them from your 'paddock by amelioration method' to-do list. What you thought would be good amelioration for a paddock (for example, ripping and mixing) may need to be adjusted (for example, to using wetters or cross/on/edge-row sowing). After successfully ameliorating some paddocks, the soil amelioration map can help you target and maybe even reinvestigate subsequent paddocks, for example, paddocks you are now more confident of mixing.

As your earlier map(s) might be a mess, it may be easier to start a fresh map. You will likely need to:

- adjust soil change boundaries from ground-truthing;
- relabel some soil types; and
- label soil constraints.

You should have checked soil type boundaries while out in the paddock and adjusted accordingly. For example, compare soil types in Figure 3 (before ground-truthing) to Figures 16 and 17 (after ground-truthing). It is unlikely the zones in your draft soil constraints map matched with what you found when ground-truthing, but if it did, you simply need to write the constraints identified through ground-truthing in each zone. It is more likely that ground-truthing exposed some inaccuracies in your soil type transition lines. Move the transitions to better reflect where soil types change. If you are still not confident about soil type boundaries, revisit the layers of information you used to create the soil map and consider sourcing additional layers. At this stage, you may find there is an economic argument for paying for spatial layers and/or assistance.

If you have done everything on hard copy up until now, this can be a good time to transfer the layers to software such as Google Earth/ArcGIS Earth because it will be easier to move transition lines and sum up the various areas. Figure 17, the final soil type map for Rocky Ridge Farm, was made by drawing different coloured polygons in Google Earth. The area of each soil type was then summed (Table 4).

To make the soil amelioration map you can either:

- label each area with its constraint or its combination of constraints; or
- draw and label individual constraints, then overlay these maps/layers to show where multiple constraints are.

If working on paper this can get messy – using multiple maps may be required – as is the case for Rocky Ridge Farm (Figures 18 and 19). If using software, all layers can be added to the one mapping project and transparency functionality used to view and overlay them.

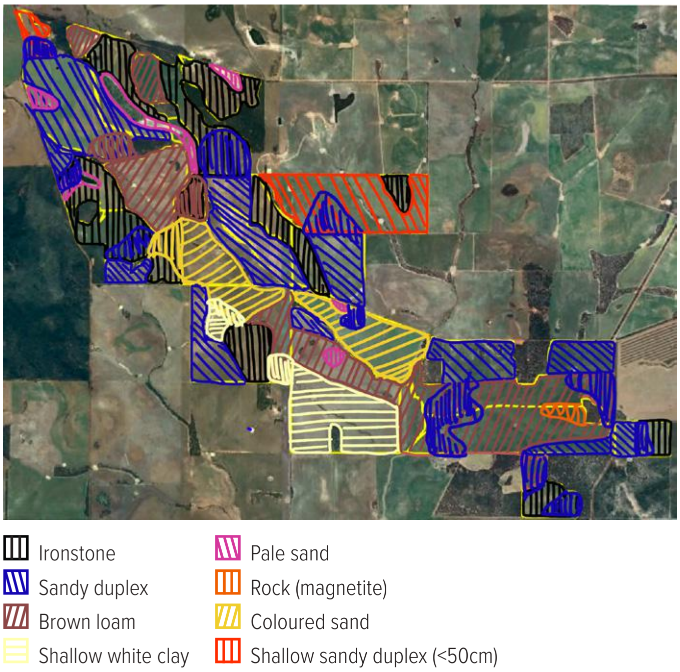


Figure 16: Rocky Ridge Farm updated hand-drawn soil map after ground-truthing.

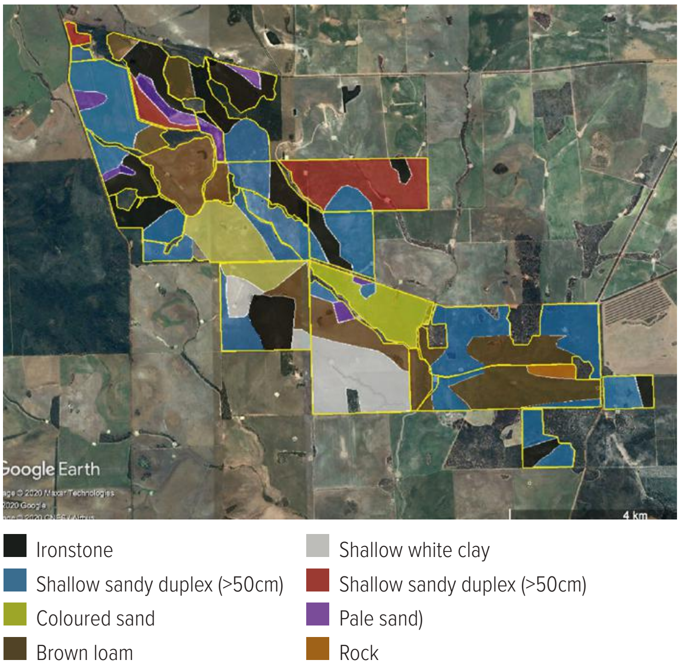


Figure 17: Rocky Ridge Farm final soil types map.

Table 3: Typical solutions to fix single and multiple soil constraints.

Problem	Typical solution	Notes
Topsoil acidity	Top-dress lime	Shallow mix (10 to 15cm) will help
Subsoil acidity	Top-dress lime + mix	Lime takes many years to move a few centimetres into the soil. Top-dressing and waiting could mean 10 or more years before the lime even reaches the acidic layer(s) so mixing is beneficial
Topsoil + subsoil acidity	Top-dress lime + mix	Deep mix will help
Compaction	Deep rip	Straight tyne rip working into the compacted zone, not above or below the zone
Non-wetting	Long term: delve, clay or mix	If clay is: • 30 to 50/60cm, delve • <30cm, rotary spader or maybe mouldboard. A heavy delving machine is likely to bring up too much clay. A deep ripper fitted with five to nine tynes is a more appropriate machine • >60cm, clay and incorporate
Non-wetting	Short term: wetting agents, seeding systems	
Topsoil sodicity	Top-dress gypsum	
Subsoil sodicity	Top-dress gypsum, inject materials	
Acidity + non-wetting	Top-dress lime + mix	
Non-wetting + compaction	Deep rip + mix	Potential to delve as well
Acidity + compaction	Top-dress lime + deep rip	Inclusion plates may help
Acidity + non-wetting + compaction	Top-dress lime + deep rip + mix	Potential to delve as well
Cemented gravels	Rock crushing	

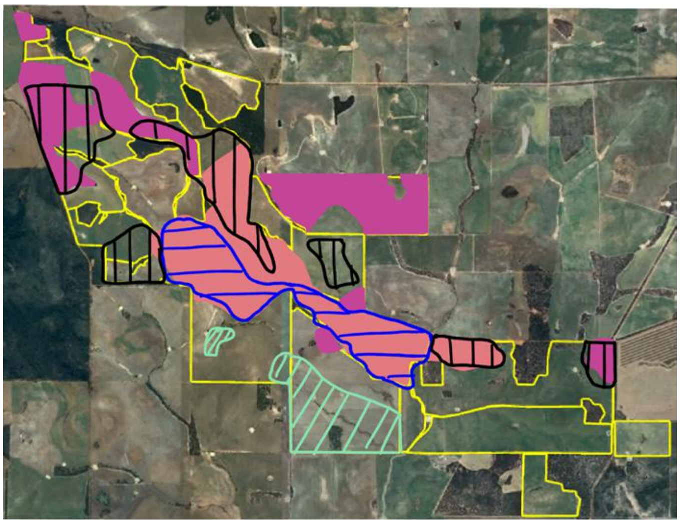


Figure 18: Rocky Ridge Farm soil constraints – compaction, non-wetting, hardsetting surface.

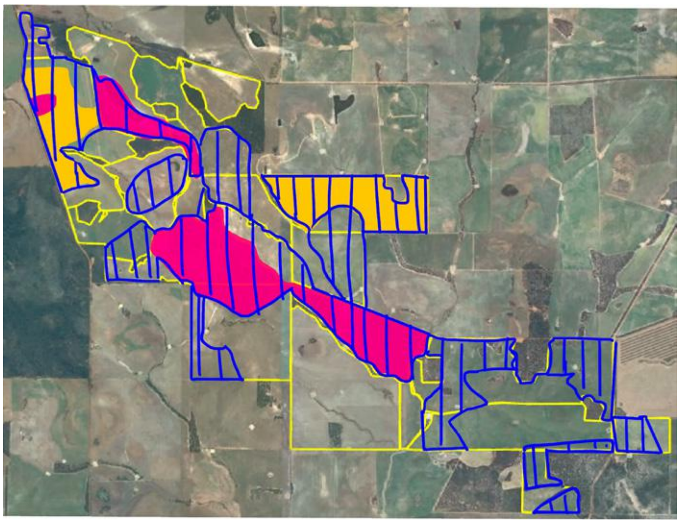


Figure 19: Rocky Ridge Farm soil amelioration map. Ripping areas are marked out in Figure 18.

Add up the hectares of each soil constraint to quantify areas of single and multiple constraints. This is much easier to do in a mapping software program. Then look at amelioration options. Table 3 lists some common constraints and amelioration options.

Figures 18 and 19 present soil constraints and ameliorations for Rocky Ridge Farm. Figure 18 shows areas to rip, divided into areas where a good response is anticipated (because there is a deeper sand layer) and where there is less confidence of a response (shallower sand layer). The hardsetting soil is earmarked for gypsum in the future. Figure 19 shows areas where more detailed pH testing is needed to refine lime rates and where to mix in the lime to deal with known subsurface acidity. The acidity information is drawn from the sparse data in Figure 8 and the productivity gap map (Figure 7). The grower needs to embark on a more detailed pH testing program.

Options to fix constraints

Where possible, aim to address multiple constraints at once for the following reasons:

1. If you are going to disturb the soil surface with tillage amelioration, use the opportunity to disturb whole paddocks and fix as much of the paddock as you can within one season. It is better to have the same or similar seedbed across the whole paddock than a patchwork across the paddock.
2. The full yield benefits of ameliorating one constraint will not be realised if other constraints remain. Yields may improve but only up to the point where another soil constraint becomes the yield-limiting factor. For example, only ripping compacted acidic sand will increase yields up to the point where acidity compromises yield.
3. Tackling multiple constraints can improve the longevity of amelioration and profit gains.
4. In the long term it is easier to do a proper job upfront. It is better to fix a whole paddock, know that paddock is done and move onto the next one. Ameliorating parts of a paddock with intentions to come back and fix the rest later often leads to half-ameliorated paddocks persisting for many years.

Liming

Top-dressing lime will address acidity in the top few centimetres of soil. The most effective way to tackle subsurface acidity is to physically mix lime into the acid layers. Top-dressing lime and waiting for it to move deeper of its own accord can take years, costing lost production in the meantime.

Incorporating by mixing is only effective if the lime is mixed through the acidic layer. Incorporation can also move more alkaline topsoil and residual-free lime near the surface (from previous lime applications) down to where it is of more use. Before applying lime and doing any incorporation, you need to know the pH levels through the main root zone to determine how much lime is needed and where it needs to go.

Gypsum

Gypsum is the most common treatment for dispersive sodic soil. Gypsum helps improve soil flocculation (aggregate formation) in two ways. In the short term, the calcium (Ca) in gypsum increases the ionic strength (the salinity) of the soil solution, which suppresses dispersion. In the long term, Ca in gypsum replaces sodium (Na) on soil particles, the underlying cause of sodicity, which helps the soil form aggregates. The Na ions are leached deeper into the soil profile as water drains.

Table 4: Rocky Ridge Farm soil types, constraints and amelioration options.			
Soil type	Area (ha)	Constraints	Amelioration options
Gutless pale sand	75	Top and subsoil acidity + severe non-wetting Maybe compaction but >50cm and below ripping depth	Lime and mix Lime and wetter Lime and cross/on/edge-row sow
Rock	15	Rock at surface	Rock crushing
Sandy duplex (shallow <30cm)	178	Severe non-wetting + subsoil acidity Subsurface is like concrete	Lime and mix
Sandy duplex (deep >50cm)	732	Mild non-wetting + subsoil acidity + possible compaction at 30 to 40cm Very dense subsurface – but some roots growing into it	Lime and mix Lime and mix and rip Delving in the longer-term?
Brown loam	486	Mild acidity at 10 to 30cm	Maintenance liming, follow-up monitoring
Coloured sand	236	Mild non-wetting + subsoil acidity + compaction at 30 to 50cm	Lime and Plozza plough in Year 1. Look at deep ripping in Year 3.
Ironstone	355	Laterite layer at surface and deeper in some places Water repellence Acidity unknown	Rock crushing Rock crushing then try to rip Wetting agents. Soil mixing in the longer-term. Soil mixing in the longer term
Shallow white clay	183	Hardsetting surface (dispersive) + dense subsoil	Gypsum

This change is permanent, unless more Na is added to the soil. See the Dealing with dispersive soils fact sheet (Pluske 2020) for more information.

Where subsoil sodicity is a problem, surface-applied gypsum can be slow to work because it needs to be at depth to be effective. Gypsum will gradually move through the profile with rainfall – it could take two years for the gypsum to dissolve from the surface soil (Menzies and Kopittke 2015). Treating subsoil sodicity is likely to take years because the soil already has low permeability and considerable quantities of gypsum are needed. Applying too much gypsum at once (more than about five tonnes per hectare) can temporarily increase soil salinity. In low-rainfall areas, gypsum could take a decade or more to move, and in very dense subsoil any displaced Na may be unable to leach.

Deep ripping

Ripping is most effective at fracturing deeper (more than 30cm) agriculturally induced compaction layers on sandy soil types. Soil type, depth of compaction layer, gravel (how much, type and depth) and soil conditions at the time of ripping affect how well ripping will work.

On shallower sands and soils with inherently hard subsoil, such as sodic and/or very dense subsoil, ripping responses are less predictable. If the subsoil is chemically hostile, for example, sodic, saline and/or high boron, exercise caution if contemplating ripping into it because the chemical constraint(s) are likely to be more limiting than compaction. Even though ripping can give roots greater ability to grow deeper, they might not because of subsoil toxicity. Ripping can lift subsoil upwards, bringing the toxic soil towards the surface and reducing rooting depth.

There has been some success – and many poor results, too – where soils with a sodic subsurface layer have been ripped with inclusion plates (Blackwell et al. 2016).

Summary of constraint areas.	
Constraint	Area (ha)
Compaction (confident ripping response)	244
Compaction (potential ripping response)	380
Severe water repellence	328
Mild to moderate water repellence	428
Ironstone and magnetite (for rock crushing)	370
Hardsetting/sodic soil	183

Ripping responses can be less predictable and profitable:

- in low-rainfall areas, as there may not be enough subsoil moisture post-ripping for the crops to use; and
- where yield potential is lower – any given percentage increase in yield from ripping is still a lower absolute yield increase.

Mixing

Soil mixing blends topsoil and subsoil with multiple aims, including:

- diluting surface non-wetting soil with wettable soil from deeper in the profile;
- distributing surface-applied lime and more alkaline topsoil (from previous lime applications) into the subsoil; and
- distributing surface-applied clay when claying to overcome water repellence.

Mixing also stimulates weed seeds and mineralisation of organic nitrogen. Consider the weed seedbank and weed control options before mixing soil.

It is common and good practice when mixing soil to take the opportunity to pre-apply nutrients that are immobile in soils to improve their positional availability to roots (especially copper, zinc and phosphorus). Soil tests and fertiliser history can help decide if it is a good time to top up these nutrients. Some growers are also pre-applying potassium.

Different machines are used to mix soil with variable success: spaders, one-way disc ploughs, specially modified Plozza ploughs (every second disc removed, good on gravels), multi-purpose machines (for example, Horsch Tiger, Väderstad TopDown), mouldboard and square ploughs, cultivators, scarifiers, offset discs, stubble crunchers and even aggressive harrows and chains.

The better soil-mixing machines can work to a depth of about 30cm. If there is deeper subsoil compaction, ripping will be required in addition to mixing – hence the attractiveness of one-pass multi-purpose machines and machines with very large discs that can do both jobs reasonably well. If you are doing two operations to rip and mix within the one year, deep ripping before mixing to loosen the soil protects mixing equipment, improves mixing and can remove buried obstacles such as rocks and stumps. Mixing before ripping can be problematic because ploughs cannot dig as easily, traction can be poor (slippage) and there can be difficulties staying on lines. If wanting to mix first, many growers mix in year one to realise some yield uplift and then rip a few years later after the soil has settled, making the ripping operation easier but delaying the total yield uplift.

Delving lifts subsoil clay upwards, even into the topsoil. Delving tynes are usually used to bring clay subsoil into water-repellent topsoil, from a maximum depth of about 70cm. Delving tynes differ from ‘straight’ ripping tynes in that ripping tynes aim for maximum disturbance or shatter at depth without bringing subsoil up.

Inversion

Soil inversion flips the soil, bringing subsoil to the surface and placing the topsoil at depth. Soil inversion is usually used to ameliorate water-repellent sandplain soils and is often employed because it has the additional benefit of burying weed seeds. On sandy soils with limited clay at depth, such as deep pale sands, repellence tends to redevelop soon (in about five years), compared with the 10-plus year benefit on soils with more clay at depth.

Mouldboard and square ploughs are specifically designed to invert soil and, if set up properly, will do the best job. They can be used as more of a mixer (less inversion, more mixing) by altering the plough set-up and operating faster. Modified one-way disc ploughs (Plozza ploughs) can be set up to do more inverting than mixing of soil by fitting different discs and altering the cut angle.

Avoid inverting shallow duplex soils with clay subsoil, especially if the subsoil is hostile.

The decision to mix or invert depends on many factors including weed burden, gravel content (Plozza ploughs are more resilient on gravel soils than mouldboard and square ploughs) and the amount and type of clay brought to the surface. Too much clay at the surface can cause crusting and hamper crop establishment and operations for many years.

Claying

Spreading clay-rich subsoil excavated from elsewhere is a long-term fix for non-wetting sand. It is used where clay-rich subsoil is deeper than about 60 to 70cm and too deep for machinery to delve up. Generally, clay is excavated and spread in strips across the paddock. If the clay is very uneven and/or cloddy it will need evening out with smudging bars or similar. Typically, the claying process is:

- ‘board’ (or smudge) to level the surface;
- spread clay;
- smudge up to five to six times at different angles; and
- incorporate (usually by ploughing).

The following methods are used for clay spreading:

- Scraper – spreads the clay in rows, sometimes overlapping and sometimes with space between each row. You will need smudging/spreading bars and/or cross working to spread the clay more evenly.
- Spinner – multiple spinners crush and spread the clay. This method can achieve more even clay distribution but can be slower than scrapers.
- Multispreader – heavy duty required. Works better on subsoil that has few large clods. It will take a few passes to get the clay rate even across the paddock.

Rock crushing

Rock crushing machines smash cemented gravels, small rocky outcrops and nuisance rocks at and near the surface. They rip and then smash rocks into smaller chunks, without bringing deeper ones to the surface. Multiple passes are usually required to get to a working depth of 20 to 45cm.

Seeding systems

Various seeding options can improve establishment in non-wetting soil by:

- grading repellent soil out of the furrow;
- reducing the flow of repellent soil into the furrow;
- using preferred pathways along last year’s crop row; and
- placing seed near furrow sidewalls and having more crop rows and plants per unit area (paired rows).

Seeding system options include on-row sowing (sowing along last year’s crop row), edge-row sowing (sowing within a couple of centimetres of last year’s crop row), cross-sowing (sowing at an angle to last year’s crop) and paired-row sowing (placing a row of seeds into both sides of the furrow).

Seeding systems, similar to wetters (below), treat the symptom rather than correct the problem. They tend to have lower yield uplift than ameliorations that fix the problem, such as claying and mixing, but are advantageous in that they allow large areas to be treated each season with reasonable probability of gaining some benefit. They are good options if there is high variability within a paddock, for example, variability in the depth to clay within tens of metres, that makes tillage a risky option.

Wetters/moisture retainers

Wetting agents and moisture retainers lower surface tension on non-wetting soil so water can infiltrate and/or improve moisture availability to roots. To date they have been more reliable on gravels than on sandy soils. Applying wetters through the seeder bar is more common than blanket applications with the boomspray. Different products have varying requirements on where they should be placed in relation to the seed, so read the label. Some can be applied with the seed (Bryce and Pluske 2020a) and some are compatible with liquid fertiliser.

Boomspray applications can provide some benefit on highly repellent patches or areas with a high weed burden. If they wet the whole soil, rather than just the seeding furrow, synchronous establishment of the crop and weeds makes subsequent weed control easier.

PART 2 – PRIORITISATION

To prioritise soil amelioration:

1. Start with the soil amelioration map and options you have identified for each zone.
2. Work out the costs and yield uplift for each amelioration zone. You will use these throughout the prioritisation section.
3. Whittle down the options by removing things you are not willing or able to do. This considers practices (for example, tilling), cost, labour, equipment, confidence and risk. You should end up with a smaller suite of options suitable for your farm and constraints.
4. Decide on a whole-farm approach to tackling constraints. Common approaches are largest areas of constraints, most profit, easy and simple fixes, and low risk.
5. Prioritise paddocks on which to do the amelioration.
6. Plan your approach to fix the various constraints within prioritised paddocks.

Willingness to ameliorate

The first part of prioritising soil ameliorations is to decide what you are willing and able to do, which can be done by ruling out what you are not capable of doing or prepared to do. What paddock preparations, inputs, machines, operations, post-amelioration tidy ups and machines will you not do or use, regardless of how strong a case there is for them? Common things growers rule out include:

- changing seeding systems to use wetters/moisture retainers;
- changing fertilisers, adding more boxes, adding liquid systems and/or varying granular and liquid fertiliser placements;
- changing seeder bar or seeder points;
- tilling the soil;
- using a plough;

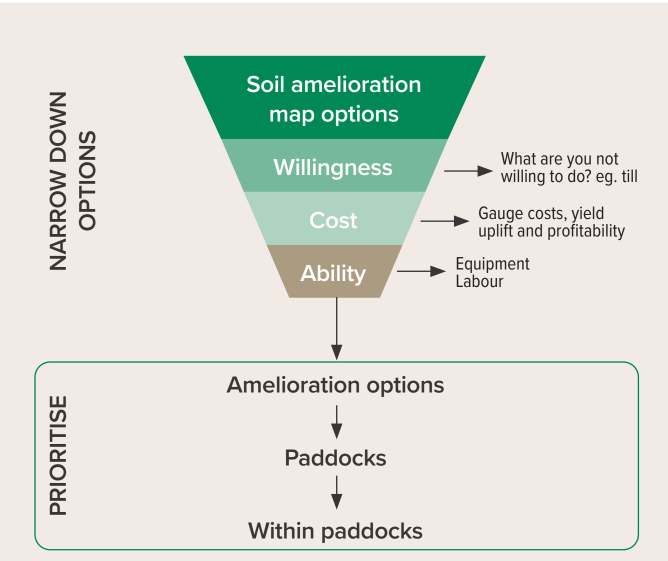


Figure 20: Process to identify and prioritise amelioration options.

- leaving the soil surface vulnerable to wind erosion at any time;
- picking rocks/stumps;
- levelling paddocks; and
- going off controlled-traffic farming (CTF) run lines.

Costs and yield uplift

After removing unrealistic amelioration options, the next step is to work out where soil amelioration is likely to be profitable. Like any investment, amelioration is best considered and undertaken with an idea of profitability, rather than investing in it and then seeing what the returns are. This sounds obvious, but there is a surprising amount of soil amelioration and machine purchases without good business cases to back them up.

Some amelioration options and paddocks will have low returns or very high risk and are best avoided. Others might appear profitable on someone else's farm or in someone else's business, but the numbers might not translate to your farm and business.

While there are guides and examples (see Table 5) to amelioration costs and yield uplifts, they should be treated just as that and not used in place of what you know, have seen and read about locally, or even your gut feel. They are a guide to check your thinking or to use if you are gauging these numbers for the first time.

ROSA (Ranking Options for Soil Amelioration) (DPIRD 2019b), developed by the Department of Primary Industries and Regional Development (DPIRD) in WA, is a decision-support tool that can help determine which soil amelioration options will be most profitable. ROSA covers the main amelioration options including claying, deep ripping (more than 40cm), gypsum to address dispersive soil, liming to address topsoil acidity, liming to address subsoil acidity, soil mixing (less than 40cm), wetting agents and combinations of them. Once users enter data on rotations, soil, budget, current and expected yields, ROSA estimates yield potential after fixing both single and multiple constraints for the next 10 years. ROSA then ranks which options are most profitable.

Depending on where you are in your soil amelioration journey, ROSA could be all you need to make strategic decisions. Many advisers use ROSA to gauge what constraints, or combinations of them, clients should tackle first, in turn leading to more tactical advice on operational and practical decisions. Contact DPIRD for a copy of ROSA.

Costs

Costs should consider all equipment, ameliorants, labour and parts for the amelioration operation itself, and any pre and post-amelioration work required such as levelling, rock/stump picking, smudging and rolling.

Operational costs include contractors, machine hire, machine purchase and depreciation, fuel, labour (including your own and skilled labour for tasks such as mouldboard/square/modified one-way ploughing, ripping variable paddocks and delving), parts such as hoses, tynes, points and discs, ameliorants such as lime and gypsum (on-paddock cost), and machine repair and maintenance. Additional costs that are sometimes forgotten include:

- working dry uses more fuel and wears out equipment faster;
- topsoil slotting plates added to rippers increase drag and fuel consumption;
- points wear out more quickly when working faster;
- increased wear and tear on machinery, especially when working dry and/or deep; and
- tidying up paddocks takes longer than expected.

If in doubt about the cost for an operation, a reasonable assumption is that the maximum cost will be a contractor's rate, because they will have included all the costs you should, plus their own margin.

Table 5 compiles the approximate costs and longevity of various soil constraint amelioration options.

Table 5: Guide to soil constraints amelioration costs.

Management option	Working depth (cm)	Typical cost ($/ha)	Approx. depth of amendment incorporation (cm)	Longevity
Equipment				
Deep ripping	30 to 70	$45 to $100 $150 to $200 (dry ripping)	10 to 15	Two to 10 years depending on soil type and traffic management
Ripping with topsoil inclusion plates	30 to 70 (slots to 40cm, tynes to 70cm)	$40 to $120	30 to 40	
Shallow leading tyne ripping	40 to 50	$40 to $50	10 to 15	
Ripper with wings or opener	30 to 40	$45 to $60	20 to 25	
Subsoil clay delving + incorporation	60 to 120	$300 to $450	10 to 15 (clay incorporation)	
Offset discs	10 to 15	$40	10 to 15	
Large offsets	10 to 45	$30 to $70	20 to 25	
One-way plough	15 to 25	$30 to $40	15 to 25	
Modified one-way disc Modified one-way plough	20 to 40	$40 to $80	15 to 30	Three to five years
One-pass combination tillage	30 to 35	$70 to $100		
Rotary spader	25 to 40	$120 to $150	28 to 35	Three to 10+ years
Mouldboard plough	25 to 40	$100 to $150	28 to 35	More than 10 years
Square plough	30 to 40	$80 to $100		Five-plus years
Delving		$120 to $150		More than 10 years
Clay delving + incorporation		$300 to $450		More than 10 years
Clay spreading + incorporation		$370 to $2000 Costs vary with clay amount and incorporation method. Spreading costs $120 to $650/ha for 50 to 250t/ha of clay.		More than 10 years
Rock crushing		$500 to $600		More than 10 years
Subsoil manuring		$1300 (Victorian data)		
Ameliorants				
Banded wetting agents		$8 to $25		One year
Blanket wetting agents		$20 to more than $50		One to two years
Gypsum		Variable		
Lime		Variable		

Source: Data compiled from Gazey & Davies 2019, Davies et al. 2019a, GRDC 2019 and grower experience

Yield uplift

Your predicted yield uplift from soil amelioration needs to be realistic, based on your ability to ameliorate your soil types. Media and pub talk tend to promote best-case responses and therefore the upper range of gains. These should be ignored or tempered with your own knowledge and situation. For instance, liming and ripping an acid, compacted, coloured deep sand can increase production markedly. It is unrealistic to expect the same yield uplift on an acid, pale sand that holds less water, or on a more neutral pH deep loam where roots are already able to get to depth. Use your productivity gap map – it provides your realistic expectations of yield uplift post-amelioration.

It is always tough to decide if improving poorer areas to make them 'okay' is better than making good areas even better. The chances are that existing good areas do not have serious soil constraints and that management (weed control, fertilisers, pesticides, rotation, varieties) are the main keys to unlocking what is already high yield potential. However, it is tempting to think there could be even more untapped yield. Without any objective yield information of higher yields, the best way to assess if there is yield uplift potential from soil amelioration in these areas is to test soil amelioration.

The sections below show some examples of yield uplifts, but there can be huge variability. More severe constraints and amelioration undertaken properly give bigger benefits. Poor amelioration will result in suboptimal uplift and there will be no yield uplift at all if ameliorating misdiagnosed constraints.

Liming

Yield gains from liming come from both yield uplift and prevention of yield declines, as acidity worsens in the absence of lime. There is generally a 12 per cent yield uplift from applying 2t/ha or more of good-quality lime to acidic soil (Gazey 2018).

If subsoil acidity is an issue, top-dressing lime is unlikely to give as much yield uplift as top-dressing and incorporating lime. This is because it can take more than 10 years for the lime to reach the acid subsurface layers. Research is still underway quantifying the yield benefits of top-dressing versus incorporating lime, but it is already apparent that yield uplifts are quicker and larger.

Because lime takes time to work, there may not be a response in the year of application. Responses can be small and difficult to pick up, but tend to increase from year two onwards.

Deep ripping

In most cases, there are positive responses to deep ripping agriculturally compacted sands. Soils with clay less than 15 per cent can have yield increases from ripping of about 45 to 135 per cent in the season of ripping. Returns can decrease every year thereafter until ripped again.

The longevity of the ripping response, which can have a big impact on profitability, and the decision to rip or not varies for some well-known reasons such as re-compaction by machinery, soil type, nutrition and rainfall. For example, some loamy sands can resettle in a few seasons to form a hard layer even in CTF systems, as can deep-ripped sands that are waterlogged. The variability of ripping response is also affected by temperature and rainfall, particularly in low-rainfall areas where ripping can increase biomass so the crop uses more water keeping cool in a hot dry spring and has less available for grain fill.

The average yield response across different soil types to deep ripping is 20 to 30 per cent, with responses becoming more variable and riskier as soils get more clayey.

Some growers have reported an additional one to 1.4t/ha, that is, double the yield in some cases. One research trial reported 300kg/ha four years after the rip (Fulwood 2019). Another grower in Geraldton reported an extra 35 per cent yield from ripping at 300mm, and 53 per cent at 600mm on pale sand (Benjamin 2020).

With topsoil slotting, the response in trials has varied from 11 to 78 per cent (Parker 2017; Davies et al. 2017). Topsoil slotting generally adds additional yield response over standard deep ripping in sandy soils (Parker et al. 2017).

Controlled traffic farming (CTF)

Up to 80 per cent of compaction occurs in the first pass of machinery (Parker and Isbister 2020). CTF can increase the longevity of soil amelioration by reducing the area of the paddock wheeled each season. CTF matches the operating width and wheel track spacing of all cropping machinery to reduce wheeling from 45 per cent, which is common in standard no-till farming systems, to about nine to 13 per cent, depending on chosen operating width, that is, 18m or 12.2m.

Soil mixing

The efficacy of soil mixing to lift yield depends on what mixing is being used for, that is, to tackle non-wetting, mix in lime or other amendments, or both. Yield uplift can also come from increased mineralisation of nitrogen.

Deep soil mixing on deep sands/deep sandy duplex can give an average yield boost of 200 to 700kg/ha (Davies et al. 2019b). Some growers have reported 100 to 150 per cent yield increases on lighter soil types after applying lime and mixing the soil.

Soil inversion

Like soil mixing, soil inversion has a wide range of yield impacts. The average yield benefit across multiple years with good autumn rainfall is 500 to 900kg/ha (Davies et al. 2019b).

Water repellence amelioration

For mitigation measures such as wetters, moisture retainers and on-row sowing, the average response is 220 to 520kg/ha (Davies et al. 2019b). The upper end of responses comes from banded wetting agents. Data cautiously suggests a five to 10 per cent increase from paired, on and edge-row sowing.

Responses to adding clay, whether through delving or spreading and mixing, have ranged from 20 to 130 per cent across cereal, lupin, and canola crops (GRDC, 2011). Yield benefits from claying can last for more than a decade and are more likely when:

- sands are deep (more than 60cm), but have reasonable plant-available water-holding capacity;
- soils are highly repellent;
- cation exchange capacity is low (less than 3 meq/100g); and
- potassium (Colwell) is marginal or deficient (less than 50 mg/kg) (Davies et al. 2020).

Dispersive soil

Yield responses to treating dispersive soil with gypsum are variable. Sodic dispersive soil is often associated with alkalinity, salinity and/or high boron. If these issues are present, there may not be a yield response to applying gypsum as it is only treating the excess sodium.

The average benefit from top-dressed gypsum is five to 15 per cent and is mostly applicable to loamy or heavier soils with high exchangeable sodium, low salinity and low organic matter (Pluske et al. 2018).

Deep placement of organic and inorganic amendments into sodic subsoil is being trialled in NSW. Results so far indicate increased grain yield in the order of 20 to 40 per cent for three successive years (Uddin et al. 2020). Topsoil slotting has also shown some promise in calcareous loamy earths and grey clays (Blackwell et al. 2016; Parker 2017).

Assessing the likely benefit from amelioration

To assess the likely economic benefit from ameliorating soil constraints, the simplest calculation is:

Margin = (yield uplift x grain value) – cost

This method can be good enough where the yield uplift is clearly large compared with the cost of amelioration. However, the calculated margin can change significantly depending on how well costs are calculated. Where multiple inputs and operations are involved, or where there is uncertainty around yield uplifts, including uncontrollable seasonal conditions, the calculation above is best used to determine if a more detailed analysis of profitability is warranted. Such analysis needs to consider all direct and hidden costs, and ideally examine the consequences of less-than-expected yield uplift.

Two examples of more detailed financial modelling are given below. **Example 1** is an evaluation of the benefit of a single-tillage amelioration activity – spading.

Example 2, liming and modified one-way ploughing the coloured sand at Rocky Ridge Farm, shows how evaluating the benefit gets more complicated when multiples inputs and/or operations are involved.

In both examples, soil amelioration is predicted to improve returns substantially in the short to medium term. In general, amelioration costs are only a very small fraction of the land value and, if done properly, improve the productivity and return on investment in that land for several years. Good amelioration potentially increases the value of the land longer term. The key is ensuring amelioration costs do not disrupt cashflow of the business and are profitable in the short to medium term.

Soil amelioration comes with risks that can reduce yield uplift, and poor amelioration can cause yield penalties for many years. Part 3 outlines common amelioration risks and mistakes. A poor amelioration job can end up costing more, increasing the payback period. Using Example 1, if due to poor planning or a bad season the yield uplift is only half of that predicted for the first two years, it will take four years to recover the cost of spading. Or, if grain prices drop by 20 per cent, there is only a 43 per cent return over five years compared with a 104 per cent return. Changing the yield uplift and other parameters can show a few different scenarios and scope out a wide range of potential returns.

The sheer cost of ameliorating can be daunting and risky for some growers when weighed up against smaller capital and per hectare investments with known efficiency and productivity gains. The risk of amelioration not delivering expected returns tends to be lower in more reliable rainfall regions. Long-term simulation modelling by Farre et al. (2010) found more consistent positive yield responses in higher rainfall areas, wetter seasons and a loamy duplex soil (compared with loamy sand soil, even though the loamy sand had bigger yield responses).

Another common reported benefit of amelioration is greater confidence to apply inputs such as fertilisers and pesticides to chase higher yields after ameliorating soils where root growth and access to water was limited. Crops are more resilient to the vagaries of seasons, allowing a more bullish approach to production. The variability within and between seasons is uncontrollable, but the cost of that variability can be better managed by ameliorating the soil.

Assumptions for both examples (see pages 35–37).

	Grain price ($/t)	Yield uplift (t/ha):
Wheat	$260	0.60
Canola	$520	0.30
Barley	$210	0.65
Discount factor = 3%		

Example 1: Spading 800 hectares

In this example, total cost of spading is $220/ha. Based on the expected yield uplift, the cost of amelioration outweighs returns in year one but is recovered after year two, with returns of approximately $150/ha in year two. To break even in year one there needs to be a 0.85t/ha yield increase. The benefit over five years is approximately $450/ha, or 104 per cent.

COSTS

Spader		
Hire ($/hr)	$180.00	
Hire ($/ha)	$102.27	Hire / coverage (1.76ha/hr)
Spader width (m)	4	
Speed (km/hr)	4.4	
Coverage (ha/hr)	1.76	Width x speed x 0.1
Hours	455	Spader area / spader coverage
Tractor		
Cost ($)	$480,000	
Residual ($)	$200,000	
Life (hr)	4000	800hr/yr
Ownership ($)	$280,000	Cost – residual
Ownership ($/hr)	$70	Ownership / life
Ownership ($/ha)	**$39.77**	Ownership per hr / spader coverage
Fuel use (L/hr)	60	
Fuel price ($/L)	$1.10	
Fuel cost ($/ha)	**$37.50**	
Tractor repairs and maintenance + running costs ($/ha)	**$8**	Registration, insurance etc.
Labour		
Price ($/hr)	$40	
Cost ($/ha)	**$22.73**	1.76ha/hr for 800ha
COST ($/ha)	$210.27	Tractor + fuel + repairs and maintenance + spader hire + labour
TOTAL COST incl. 5% borrowing cost ($/ha)	$220.79	

Returns

Returns are calculated every year, considering the costs and yield uplift.

Expected return =

$$\frac{\text{Year 1 crop farmgate price x crop type uplift (kg/ha) x Year 1 uplift (\%)}}{100} - \text{total cost}$$

e.g.

$$\frac{260 \times 0.6t \times 100 - \$220}{100} = - \$64.79$$

Net Present Value (NPV) adjusts the yearly expected return value using a discount rate of 3%.

Expected return NPV = Expected return / 1.03

	Crop	Yield uplift (t/ha)	Yield uplift (%)	Expected return ($/ha)	Expected return NPV ($/ha)
Year 1	Wheat	0.60	100	– $64.79	– $64.79
Year 2	Canola	0.30	100	$156.00	$151.46
Year 3	Wheat	0.60	95	$148.20	$139.69
Year 4	Barley	0.65	90	$122.85	$112.43
Year 5	Canola	0.30	80	$124.80	$110.88
Five-year NPV benefit ($/ha)					**$449.67**

Per cent return over five years	**104%**	(NPV benefit – total cost) / (total cost x 100)
Break-even yield uplift Year 1 (t/ha)	**0.85**	Total cost / Year 1 crop farmgate price

Example 2:
Incorporating lime and ploughing at Rocky Ridge Farm

At Rocky Ridge Farm, the total cost of spreading lime and incorporating with a modified one-way plough, then rolling, is $165/ha. Based on the expected yield uplift in year one, the cost of amelioration outweighs returns in year one, but is recovered after the second harvest with returns of approximately $150/ha. To break even in year one there needs to be a 0.63t/ha yield increase. The total benefit over five years is approximately $475/ha, or 189 per cent.

COSTS

Lime		
Rate (t/ha)	2.5	
Price ($/t)	$13	
Transport ($/t)	$19	
Spreading ($/ha)	$8	
Spread lime cost ($/ha)	**$88**	= (rate x price) + (rate x transport) + spreading
Ploughing and rolling hours		
Modified one-way plough coverage (ha/hr)	3	
Modified one-way plough hours	79	amelioration area / plough coverage
Roller coverage (ha/hr)	15	
Roller hours	16	amelioration area / roller coverage
Tractor		
Cost ($)	$300,000	
Residual ($)	$50,000	
Life (hr)	6000	
Ownership ($)	$250,000	
Ownership ($/hr)	$41.67	
Ownership plough ($/ha)	$13.89	
Ownership roller ($/ha)	$2.78	
Ownership ($/ha)	**$16.67**	
Fuel use – modified one-way plough (L/hr)	36	
Fuel use – roller (L/hr)	55	
Fuel price ($/L)	$1.10	
Fuel cost ($/ha)	**$17.23**	(fuel modified one-way / modified one-way coverage) + (fuel roller / roller coverage) x fuel price
Tractor repairs and maintenance ($/ha)	**$5**	

Modified one-way plough		
Cost ($)	$25,000	
Residual ($)	$20,000	
Life (hr)	800	
Ownership ($)	$5000	
Ownership ($/hr)	$6.25	Modified one-way plough ownership / life
Ownership ($/ha)	**$2.08**	
Modified one-way plough repairs and maintenance ($/yr)	$2500	Discs, hoses, seals, tyres, etc.
Repairs and maintenance ($/ha)	**$10.59**	
Roller		
Cost ($)	$95,000	
Residual ($)	$60,000	
Life (hr)	4000	
Ownership ($)	$35,000	
Ownership ($/hr)	$8.75	
Ownership ($/ha)	**$0.58**	
Roller R&M ($/ha)	**$0.50**	
Labour		
Price ($/hr)	$40	
Modified one-way plough ($/ha)	$13.33	Price / modified one-way plough coverage
Roller ($/ha)	$2.67	Price / roller coverage
Labour cost ($/ha)	**$16**	
COST ($/ha)	**$156.66**	Spread lime cost + tractor ownership + fuel cost + tractor R&M + modified one-way plough ownership + modified one-way plough R&M + roller ownership + roller R&M + labour cost
TOTAL COST incl. 5% borrowing cost ($/ha)	**$164.49**	

Returns

Returns are calculated every year, considering the costs and yield uplift.

Expected return =

$$\frac{\text{Year 1 crop farmgate price x crop type uplift (kg/ha) x Year 1 uplift (\%)}}{100} - \text{total cost}$$

e.g.

$$\frac{260 \times 0.6t \times 80}{100} - \$165 = -\$39.69$$

NPV adjusts the yearly expected return value using a discount rate of 3%.

Expected return NPV = Expected return / 1.03

	Crop	Yield uplift (t/ha)	Yield uplift (%)	Expected return ($/ha)	Expected return NPV ($/ha)
Year 1	Wheat	0.6	80*	– $39.69	– $39.69
Year 2	Canola	0.3	100	$156	$151.46
Year 3	Wheat	0.6	95	$148.20	$139.69
Year 4	Barley	0.65	90	$122.85	$112.43
Year 5	Canola	0.3	80	$124.80	$110.88
Five-year NPV benefit ($/ha)					**$474.76**

* Due to late seeding/poor establishment

Per cent return over five years	**189%**	(NPV benefit – total cost) / (total cost x 100)
Break-even yield uplift Year 1 (t/ha)	**0.63**	Total cost / Year 1 crop farmgate price

Ability to ameliorate

Having removed what you are not willing to do and what is not good value for money, the next step is to consider what is practical to do. Be realistic about your ability to implement amelioration and manage post-amelioration crops.

Equipment and labour

Assess machines that are available for leasing/borrowing as if you were buying one. Using a suboptimal machine because “it is in the area” may not be a good decision. Try to determine how good a job the machine and/or contractor do. It’s not uncommon to hear “it’ll deep rip to 500mm” only to discover the rip is closer to 350mm. If your paddocks are going to need levelling and/or rolling after amelioration, find out if the contractor/machine can do that too. If not, you will need to find a way. Removing rocks and stumps brought to the surface can take a considerable amount of time during periods of the year when labour might be needed elsewhere and severely reduce the area of tillage amelioration you can cover.

Consider what labour you have, when it is available and what it is capable of. Skills are required to set up and use mouldboard, square and one-way ploughs, to know where to lift the ripper/delver and if/when to alter speed. A poor job because of unskilled labour can result in suboptimal amelioration and even make paddocks worse than they were prior to amelioration.

Buying and sharing amelioration equipment with other grower(s) is becoming more popular. This can mean competing interests if multiple parties want to use the equipment at the same time, but growers are using sharing arrangements to mitigate this problem.

One starting point with equipment is to check which of your amelioration options you have appropriate machinery for. This can provide clarity in the prioritisation process, ruling some paddocks out of amelioration (because of no access to machinery and/or labour) and prioritising paddocks that you have the gear and skills to do. Prioritising ameliorations, then checking you have the equipment/labour to do them, is better than finding ameliorations to do with the equipment/labour you have. The former is considered and targeted, the latter is reactive to what already exists.

Post-amelioration equipment must also be considered. Post-amelioration soil is softer and can be less buffered, needing extra attention with machinery trafficability, seeder bar set-up and pre-emergent herbicide rates. Poor post-amelioration management can negate any yield benefit. Make sure:

- you can prepare a firm, even surface for seeding (crushing rocks and soil clods, filling in holes, making sure there are no rutted or overly deep wheel/tramline tracks on the headlands, because they can ‘shake’ boomsprays) – this may involve levelling using a plough, cultivator, scarifier, chain, harrows or the like;
- you have a roller suited to the job, if one is required (Bryce 2020); and
- your seeder bar can seed into the surface you are going to create.

Prioritising across the farm

After you have narrowed down soil amelioration options to those you are willing and able to implement (and possibly removed some paddocks from this process, for now) there are a few ways to prioritise which amelioration options to start with.

The best return on investment (ROI)

This strategy targets ameliorations that will make the most money; it might not necessarily be the largest area. Calculating costs using ROSA and/or as in the examples one and two (see previous pages) are good ways to help work out likely returns.

Paddocks with a better ROI are typically those with inherently better soil types but where current productivity is limited by the identified constraints. Paddocks with other non-fixable issues, such as frost or waterlogging, are riskier propositions from a ROI perspective.

Prioritisation based on returns needs to be weighed up against absolute costs (capital and variable) of the ameliorations and their riskiness. Some ameliorations are largely variable costs (wetters, moisture retainers) but others, especially tillage ameliorations, can require considerable capital investment.

Largest area first

This approach starts by tackling constraints limiting yield on the largest areas of the farm, as estimated in the identification section.

Prioritising amelioration this way is especially important if contemplating machinery purchases. As obvious as it sounds, it is important to know how many hectares a machine will be used on before acquiring it. It is not uncommon for a grower, enthused by reports of large yield responses to, say, deep ripping, to purchase a ripper only to find a few months later that it is only suitable on a small portion of their farm and that a multi-purpose machine or mixer would cover more hectares and have been a better purchase.

Simple-fix ameliorations

This is how many growers start soil amelioration: doing the easiest things first. Easy options tend to be those that use existing machinery and avoid unfamiliar machinery and multiple or complex operations.

On deep, lighter soils the starting point is typically deep ripping to smash a compaction throttle, ideally where there are no acidity problems. This is because there is no extra expense in applying and mixing lime at the same time, ripping is relatively straightforward and the response is immediate and large.

On non-wetting gravels it is typically tackling non-wetting using wetters, moisture retainers or mixing, or experimenting with equipment such as cultivator bars fitted with wide sweeps.

Simple-fix options are usually also low-risk options.

Low risk

A low-risk approach starts with ameliorations with limited scope for financial or operational mistakes; for example, ameliorations that do not leave the soil surface vulnerable to wind erosion or likely to lift poor-quality clay or too much clay to the surface.

Starting with low-risk ameliorations is a good strategy if you are new to soil amelioration and/or concerned about how variability within paddocks will affect the overall amelioration result.

Low-risk activities are:

- cheaper to implement – for example, addressing non-wetting surface soil with wetters or cross-row sowing, as opposed to delving or borrowing a machine or engaging a contractor (so cost is pretty much fixed) to rip and/or mix a paddock; and
- more likely to work, so there is less risk of wasted dollars.

Proof of concept

Some growers want proof in the paddock before deciding what to tackle or whether to buy machinery. This will delay getting amelioration underway but can give very valuable data to work with in future years and while planning your budget. It is a cheap way to try out amelioration options before investing in machinery you might not need.

Commonly, a proof of concept means borrowing a machine or using a contractor to tillage ameliorate the one paddock considered most likely to respond. It can also involve using a machine that you know is suboptimal (for example, a plough, cultivator, chisel plough) to see if it makes any difference because, if it does, it builds confidence that investing in better amelioration will deliver better results.

Prioritising paddocks

Once you have worked out the overall strategy for the farm, the next step is to prioritise paddocks. Again, there are multiple ways to approach prioritisation at this scale.

Whole paddocks you can ameliorate in one year

It is better to ameliorate 100ha in one paddock than 20ha in five different paddocks. This is why zoning ameliorations is so important – to know what to do within the paddock and to pick the best paddocks to do.

Tillage ameliorations disturb the soil surface and can make paddocks soft, bumpy and tricky to seed and work afterwards. Even with the greatest levelling and rolling, the soil surface can be soft and uneven. Seeder bar wheels can fall into ridges. Unless your seeder bar has independent depth control on all tynes, seed depth control can be compromised, undoing all the good amelioration work.

After amelioration, a consistent surface to seed into is just as important as a good surface.

A consistent surface means you do not need to change the seeder bar set-up or seeding depth while seeding the paddock. Establishment will be more even across the paddock and you can manage the paddock as a whole rather than managing ameliorated zones differently to non-ameliorated areas. This makes other management decisions and their timing, such as fertiliser, herbicide and fungicide applications, much easier.

Experience also says that when parts of the paddock are not ameliorated but left to 'fix up later' it does not happen (claying and rock crushing are possible exceptions). Amelioration moves onto much easier targets than the non-ameliorated areas or it becomes too much of a hassle to come back into partially ameliorated and now more productive paddocks to disturb parts of it.

Addressing the whole paddock in the one season should include fixing acidity and using the opportunity to address crop nutrition. Trace elements and phosphorus are relatively immobile and have more chance of ending up somewhere useful in the root zone when the soil is mixed. Mixing can also redistribute bands of phosphorus that have formed near the soil surface over the years. If the crop needs it and it makes sense logistically, consider top-dressing potassium before mixing.

Paddocks where better crop establishment will markedly lift yields

Better crop establishment is always a high priority, because if the crop does not establish well it does not matter if everything else is done right. Improving establishment is reasonably easy to tackle (for example, with wetters, on/edge/cross-row seeding).

On top of yield loss from a slow start, staggered and patchy establishment can disrupt management for the rest of the season; spraying and fertilising paddocks with plants at different growth stages is suboptimal.

Paddocks where non-wetting is the only constraint are an obvious target for stopgap solutions such as wetters, on/edge/cross-row seeding and for longer term amelioration. If acidity is also a constraint it is wise to address it at the same time (see below).

Tackle multiple constraints at once

Look for paddocks where one amelioration option can tackle multiple constraints. For instance, if there is non-wetting at the surface and stratified acidity down the profile, mixing (after liming, if necessary) is a good option across the whole paddock. Liming and a multi-purpose machine could be used to tackle agriculturally induced compaction, stratified acidity and non-wetting all at once.

Ameliorations that move or mix applied lime through the soil will not only address the primary constraint(s) they are tackling, but also improve lime efficacy; that is, make the most of the tillage amelioration to fix the acidity issue. Similarly, you can apply P and trace elements such as Cu and Zn pre-amelioration to increase the amount and positional availability of them in the soil.

Easy paddocks

Paddocks that are easier to deal with include:

- paddocks that have the largest portion that can be ameliorated; for example, if there are two paddocks, one with 50 per cent that needs ripping and one that needs 80 per cent ripping, the latter is the easiest paddock;
- those with fewer zones; for example, a paddock where one distinct zone in the paddock needs ripping and the rest of the paddock needs modified one-way ploughing is easier to tackle than a paddock where four zones need ripping and another four zones need modified one-way ploughing;
- those with constraints that you already have the skills and equipment to tackle;
- those where there will be nil or minimal post-amelioration operations such as rock/stump picking or levelling; and
- those where pH testing indicates no capital (to fix acidity) nor maintenance (to avoid acidity) applications of lime are needed because there is no need for lime to make the most of the amelioration.

Easier paddocks also tend to be lower-risk paddocks and are therefore good to start with if you are new to soil amelioration.

Low-risk paddocks

This approach targets paddocks with a low risk of failure. This includes:

- avoiding paddocks you are unsure about; for example, if you are unsure if the dense subsurface layer is sodic or not, whether dense subsoil or gravel will come up to the surface, or whether materials brought to the surface will be shattered by the roller; and
- avoiding areas prone to events out of your control such as frost, waterlogging or a dry spring because, even if amelioration goes perfectly, the season can obliterate your returns.

Other risks and mistakes that may help prioritise paddocks are discussed in Part 3.

Paddocks going into cereals

The simplest and least-risk phase in the rotation after tillage amelioration is cereal. While it is tempting to cash in on the amelioration in year one by sowing canola (more responsive, more valuable crop, better grass weed control), crop establishment from its small seed can be unreliable. Some growers have mastered canola establishment after soil amelioration, but many others have not.

Amelioration can stimulate some grass weed problems in year one that are difficult to control in most cereals (hay crops and imidazolinone-tolerant barley are possible exceptions) but it is better to tolerate and deal with them as best you can and then still realise the amelioration benefits with canola in year two, when establishment is more reliable.

Timing

The timing of some ameliorations (deep ripping, mixing) is critical to success; this is where having your own machinery is good. The time when the soil is right for amelioration (commonly after summer/autumn rain) is also the time when everyone wants to do it. Not everyone can use a contractor or a dry-hired machine at the same time. If your area for amelioration is small, it is likely you will slide down the contractor's list unless they are "passing by". If you cannot do the amelioration at the right time, doing nothing is a better option. Poor amelioration costs the same as a good amelioration job but comes with additional costs, such as missed yield uplift or extra operations to fix areas.


Figure 21: Left – Soil too wet to rip. Right – Cloddy surface after mouldboard ploughing. Photos: Courtesy of DPIRD and Simon Wallwork.

In-crop, in-fallow and in-pasture ripping are becoming increasingly popular because they can be done when conditions are ideal and when there is spare machinery and/or labour. It is important to think through the practicalities first because, for instance, if your ripping tractor is the same as your sowing tractor, the area of in-crop ripping that you can do will be limited to what you can rip after finishing sowing.

Planning your approach in the paddock

Every paddock will have a different approach depending on the soil constraints and chosen amelioration options. Common to all options are timing, order of operations and adjusting as you go.

Timing

One of the best things you can do when planning soil amelioration is get the timing right. Work to the conditions, not the calendar.

Right timing largely means ameliorating when soil conditions are best. Applying soil amendments (lime and gypsum) can be flexible and is typically done before the season and before any working by machinery. Most ameliorations involving machinery are more effective when there is soil moisture. The benefits of working in the right soil moisture conditions include:

- reduced wind erosion risk;
- tillage equipment works better – sands are more cohesive, able to better hold onto the spades of a spader, or to 'hold and fold' on discs and plough boards for mixing;
- able to work deeper;
- able to operate more efficiently – reduced resistance compared with drier soil uses less horsepower, less fuel, puts less strain and wear on equipment and lowers maintenance costs;
- weed control – opportunity for non-chemical weed control (tillage) after significant rain; and
- a better job of soil mixing, so the benefits last longer. Proper mixing should ameliorate water repellence for three to five years and evenly mix lime and more alkaline topsoil through the subsurface. Insufficient mixing, especially in pale deep sands, can exacerbate water repellence or reduce it for only one to two years. Poorly mixed lime will not be as effective against acidity as it could be.

The exception is mouldboarding gravels, where inverting is better done dry. Work as late as possible to minimise erosion.

Signs it is too wet to work include:

- poor trafficability, the obvious one being bogging;
- soil is sticking to the equipment;
- machinery is slicing through the soil, not shattering and shifting soil, and potentially creating a hardpan below and/or to the side of its working area; and
- if you can roll the soil into a sausage (Figure 21), it is too wet to rip. Very sandy soil cannot be rolled into a sausage even when saturated. For sands, visible moisture is a clue it is too wet to work. These soils often drain within a few days.

Signs it is too dry to work include:

- ripping tynes are not getting down to the depth you need – this means knowing what depth is compacted before you start and checking the ripper has broken it up;

- you are pulling large soil clods to the surface, which ordinarily would not happen;
- there is too much wheel slip;
- you are operating considerably slower and/or using more fuel than expected; for example, if you normally work at 6km/h and can only work at 2km/h, or if you typically use 100L/hour of fuel and are using 150L/hour;
- you are breaking tynes or wearing down points faster than expected; for example, you expect a set of points to last 300ha but they wear out after 80ha; and
- subsoil is not holding onto spades/discs so it is not moving to the surface.

Order of operations in the paddock

Where paddocks need multiple operations to properly deal with all constraints, the order of operations is important to do a good job. Because every situation is different there are no hard rules; however, there are some general rules:

- rip before spading (and delving) to find rocks/stumps that could damage the spader and to loosen the soil;
- apply amendments such as lime before mixing; and
- if claying, rip as the last operation, as clay application, smudging and mixing will cause compaction.

Example 1. Three parts of the paddock need different amelioration

This acidic paddock has ironstone gravel, non-wetting gravel and compacted deep sand. The following is one way to tackle this paddock:

1. Apply lime to the whole paddock before any tillage.
2. Rock crush the ironstone gravel and plough the whole paddock in late summer/early autumn, conditions permitting. Wind erosion is less of a risk where there is gravel and the surface is left rough. Rock crush and plough first because it is easier to turn the ripper on ploughed areas than to turn the plough on ripped areas.
3. Deep rip the sand later, if/when conditions are right.
4. After the three operations are complete, level the rugged surface of the paddock and roll it as late as possible before seeding.

Example 2. Parts of the paddock need ripping and all or some of the paddock needs spading

Start by ripping the whole paddock, reducing ripping depth to 'skate' through the areas that cannot be deep-ripped. Then spade the parts of the paddock that need it. Similar to Example 1, level and roll the uneven soft surface across the paddock.

Adjust as you go

Be prepared to adjust the amelioration plan as you work. This could mean lifting the ripper to skate over areas that should not be ripped or adjusting working depth if depth to clay is variable. Some machines can take 20 to 30m to adjust; it pays to be prepared. Some adverse outcomes of not adapting to the paddock are outlined in Part 3. Mapping and ground-truthing should have given you a reasonable idea of soil changes in the paddock, but there can still be variation, such as changes in subsoil depth or rocks at depth that were missed. When ripping, ploughing and spading, the tractor working harder might indicate heavier soil or rocks. Some growers who know they need to vary ripping depth or avoid certain areas put a paddock map on an iPad, or similar, to track the various zones while working. It is also wise to check the job as you go, such as working depth or quality of the rip. If you are not getting the outcome you want, stop and/or adjust set-up.

Prioritising at Rocky Ridge Farm

At Rocky Ridge Farm, the grower identifies three paddocks to ameliorate (Figure 22) by liming, rock crushing and modified one-way ploughing plus rolling. These paddocks are chosen for the following reasons:

1. They are going into cereals, are low-risk with regards to frost, and are more uniform than many other paddocks.
2. The ameliorations are easy and low risk:
   - The grower can access a rock crusher and already owns and has experience with a modified one-way plough and roller.
   - Rock crushing will improve operational efficiencies (run lines, crop establishment, weed control) elsewhere on the farm. The rock areas harbour weeds that spread to the rest of the paddock. The grower wants to encourage a flush of germination for better control.
   - Modified one-way ploughing has multiple benefits of diluting water-repellent surface soil and mixing more alkaline topsoil and freshly applied lime.
3. There is good expected yield uplift on the coloured sandy soils (0.6 to 1t/ha) that make up most of the paddocks.
4. Anticipated returns from liming, mixing and rolling are good, with the cost of amelioration recovered in year two (calculated in Example 2 on page 36). Using the lower end of the yield uplift range for wheat (0.6t/ha, from Example 2 on pages 36 and 37) the estimated return (NPV) over five years is $475, or 189 per cent.
5. Some deep sandy duplex soil will be treated in the process and the grower will gauge its responsiveness. Year one is a low-risk, low-cost opportunity to trial mixing on this soil type. If it responds well, the grower will have confidence to target paddocks with deep sandy duplex soils next.
6. The grower currently does not have access to a ripper and believes:
   - the three targeted paddocks represent enough amelioration work for one year; and
   - the additional yield uplift with ripping is expensive compared with liming and modified one-way ploughing.

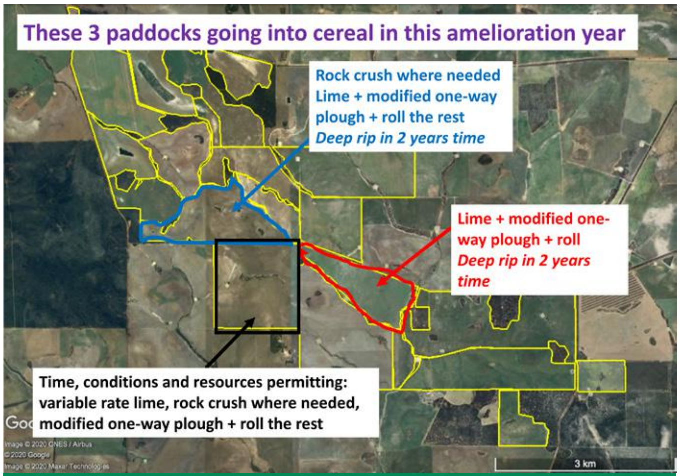


Figure 22: Priority paddocks at Rocky Ridge Farm.

The grower has not ruled out deep ripping the coloured sandy soil with subsoil compaction in two years' time when the paddock has settled and the grower has worked out how/who/what will do the deep ripping. The grower feels it is important to experience success with familiar ameliorations before ramping it up to deep ripping, which is uncommon and unproven in the region.

The plan is to:

- intensively sample the red paddock to determine lime rate, apply the lime, modified one-way plough and roll;
- intensively sample the blue paddock to determine lime rate, apply the lime, rock crush where needed, modified one-way plough and roll; and
- if the grower can do it this year, ameliorate the black paddock by variable rate liming, rock crushing where needed, modified one-way ploughing and rolling.

This plan is enough for the grower to implement in year one. The grower will assess how the crops respond to gauge how applicable this amelioration method will be on the deep sandy duplex soils. The grower will also:

- use research trials and what other growers are doing locally to gauge the cost-effectiveness of deep ripping on coloured sands and deeper duplex soils;
- consider changing seeder bar set-up (maybe year one, more likely year two) to use moisture retainer on water-repellent areas until they can be ameliorated by mixing;
- explore on and edge-row sowing (costs, yield uplifts, ease of implementation) as a longer-term strategy for better and earlier crop establishment;
- implement a more targeted soil testing strategy to decide where to apply lime and monitor its effectiveness over time; and
- budget permitting, apply lime to paddocks likely to be modified one-way ploughed within the next two to three years, in preparation for its mixing.

Table 6: Soil types prioritised at Rocky Ridge Farm.

Soil type	Area (ha)	Constraints	Amelioration options	Potential yield uplift	Priority*
Gutless pale sand	75	Top and subsoil acidity + severe non-wetting Maybe compaction but >50cm and below ripping depth	Lime and mix Lime and wetter Lime and cross/on/edge-row sow	0.2t/ha – in a good year	Low
Rock	15	Rock at surface	Rock crushing	Maybe 0.1 to 0.2t/ha	Ongoing, whenever get around to it
Sandy duplex (shallow <30cm)	178	Severe non-wetting + subsoil acidity Subsurface is like concrete	Lime and mix	0.3 to 0.4t/ha	Medium
Sandy duplex (deep >50cm)	732	Mild non-wetting + subsoil acidity + possible compaction at 30 to 40cm Very dense subsurface – but some roots growing into it	Lime and mix Lime and mix and rip Delving in the longer-term?	0.6t/ha Maybe 0.75t/ha if overcome compaction	High
Brown loam	486	Mild acidity at 10 to 30cm	Preventative/maintenance liming	Prevent yield decline	Low
Coloured sand	236	Mild non-wetting + subsoil acidity + compaction at 30 to 50cm	Lime and rip and mix Lime and rip	0.6 to 1t/ha	High
Ironstone	355	Laterite layer at surface and deeper in some places Non-wetting Acidity unknown	Rock crushing Rock crushing then try to rip Soil mixing in the longer-term	Ease of working Maybe 0.2t/ha from rock crushing alone	Try and see what happens
Shallow white clay	183	Hardsetting surface (dispersive) + dense subsoil	Gypsum	0.3 to 0.4t/ha, mainly from better establishment	Low

* Priority is based on yield uplift

Case study – Farm 1: Using EM and radiometrics to decide where to mouldboard, Plozza and rip

1. Background

The grower bought a mouldboard plough (MBP) because he was confident it was a good option to:

1. bury weed seeds;
2. fix non-wetting; and
3. mix lime.

After some initial success and mistakes (where the MBP brought sodic clay to the surface, Figure 1) he decided to target MBP to deep sands and gravelly sands. To do this the grower needed to know where these soil types were and – equally importantly – to know where they were not, to prevent further mistakes that would take a long time to rectify, if they could be rectified at all.

Figure 1: Early mistake mouldboarding unsuitable soil, which brought sodic clay to the surface. Photo: Simon Wallwork

2. The process

The grower used Google Earth (GE) to roughly draw soil type changes across the farm. He liked GE because it showed familiar landmarks – you could always locate yourself and therefore think about what you knew about that area.

The grower contemplated NDVI but did not use it to find soil types because NDVI changes within and between seasons. EM/gamma are more consistent across time, as they measure soil type characteristics.

EM/radiometrics survey

To refine soil type boundaries, the grower organised a ground-based EM and radiometrics survey (Figure 2).

Aerial radiometrics did not have good enough resolution to see soil type changes. Similarly, as the farm has largely low-clay content soils, EM alone was not good enough to differentiate between sand and gravel.

Although the survey also collected shallow EM readings, radiometrics potassium (K), uranium (U), total count and ternary maps, only deep EM and radiometrics thorium (Th) were used to refine soil type boundaries. This was because these layers best reflected what the grower knew about the paddocks, particularly where ironstone came in. Radiometrics Th has a good correlation with gravel.

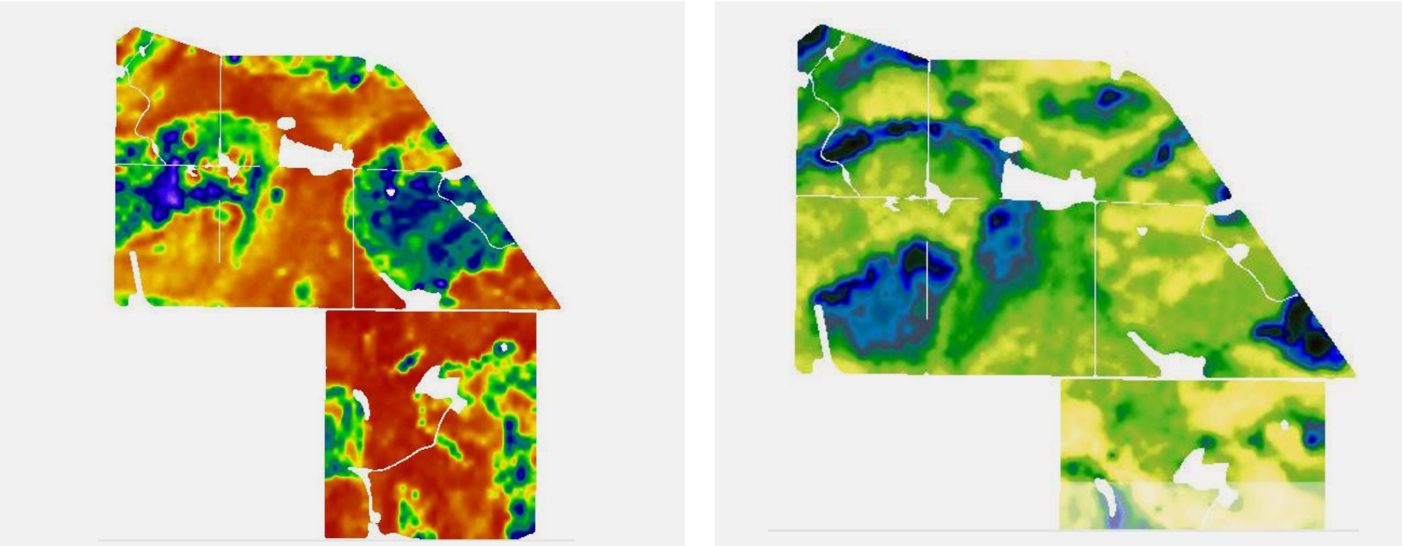


Figure 2: Ground-based deep EM (left) and radiometrics thorium (right).

Relative versus absolute values

The grower used relative (rather than absolute) survey values to refine soil type changes as the soil landscape changed across the farm. This meant values differed from paddock to paddock. For example, in paddock J19 the boundary for gravels was Th value of 50+; in paddock J18 this was 20+ (Table 1; Figure 3).

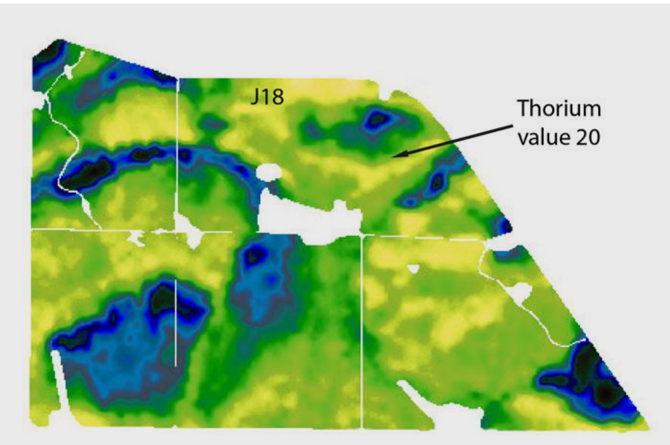


Figure 3: A Th value of 20 was chosen in paddock J18 because it explained what the grower knew of the soil types in the paddock and where they changed.

The EM/GR survey helped refine where the soil type boundaries were and identified that the majority of the farm land area was suitable for mouldboard ploughing.

Table 1: Dual EM and radiometrics thorium values groupings.

Paddock	Survey	Raw values grouping
J19	Dual EM deep	0 to 25
	Dual EM deep	25 to 50
	Dual EM deep	50+
	Thorium	0 to 50
	Thorium	50+
J18	Dual EM deep	0 to 20
	Dual EM deep	20+
	Thorium	0 to 20
J10	Dual EM deep	0 to 12
	Dual EM deep	12+
	Thorium	0 to 18
	Thorium	18+
J7	Dual EM deep	0 to 26
	Dual EM deep	26+
	Thorium	0 to 16
	Thorium	16+

Combining EM and Gamma

The grower then combined the two EM categories with the two Th categories to get four categories that related to his in-paddock knowledge of soil types.

		EM	
		Low	High
Th	Low	Sand	Clay loam
	High	Gravel	Loam

This generated the map shown in Figure 4. The EM x Th class colours vary from block to block. In this case it was very important to know what the legend was for each section – red in one block could equal brown in another.

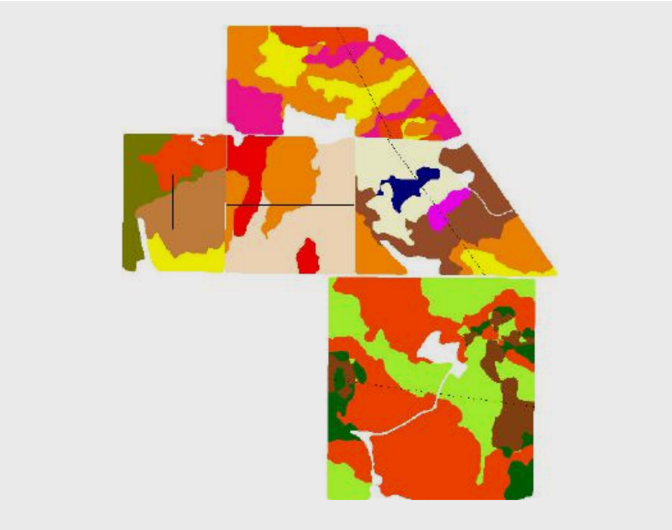


Figure 4: Combined EM and Th map. Note that because different criteria were used in each block, the colours vary from block to block.

Selecting areas suitable for MBP

The bottom block was mouldboarded before the soil survey work was undertaken. The surveys identified – after the fact – that areas on the bottom right-hand side of the map should not have been ploughed (dark green and brown areas, Figure 5a). These were sodic loamy subsoils that, when inverted by MBP, brought up large clods that were detrimental to crop establishment (Figure 1). The lime-green areas were sandy soils and confirmed suitable for MBP.

Reddy areas were gravelly soil and set aside for Plozza ploughing.

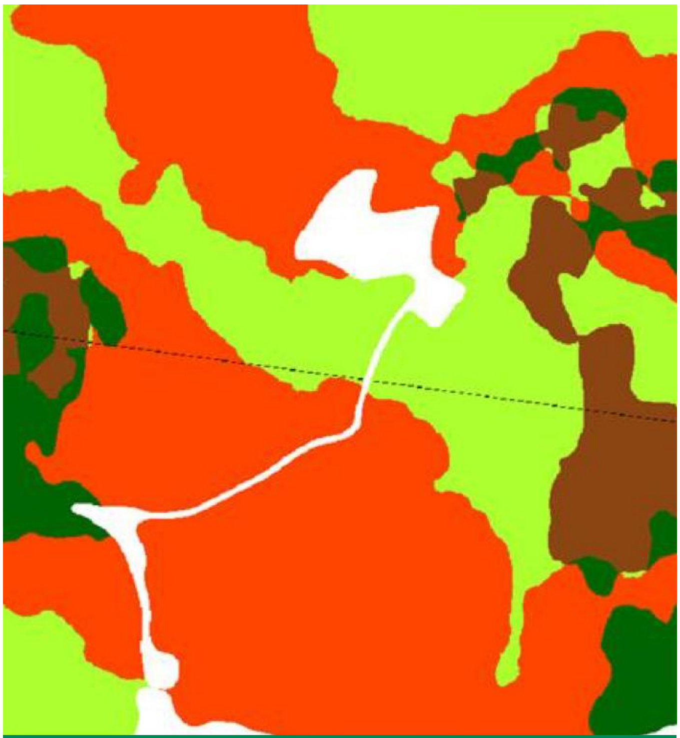


Figure 5a: Bottom farm block.

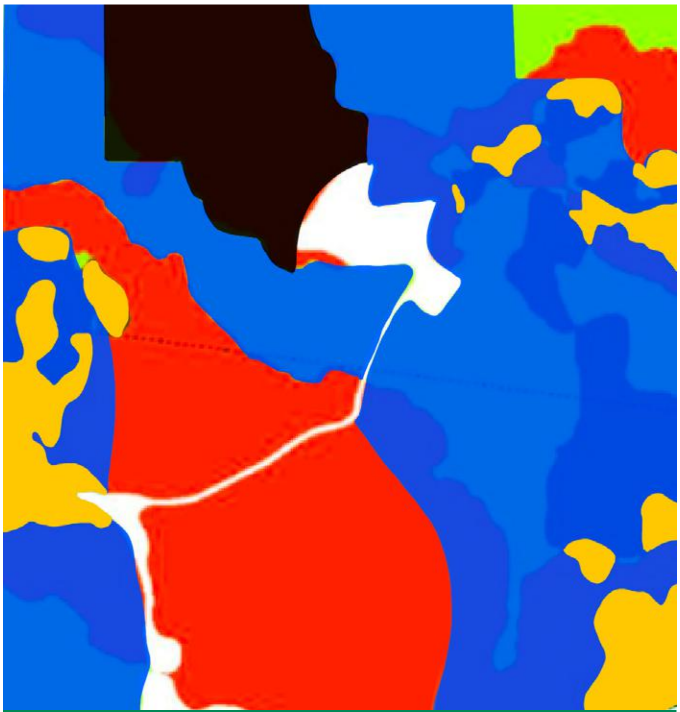


Figure 5b: Mouldboarded areas (blue), area trialled Plozza (black), and area that should not have been mouldboard ploughed (solid yellow = sodic subsoil).

3. Lessons learned

The grower has now mouldboarded most of the suitable soil across the farm (blue areas, Figure 6). The black areas are gravels and were Plozza ploughed in 2020. Gravels were Plozza ploughed because:

- it was not possible to get complete topsoil inversion with the MBP;
- gravels are particularly wearing on the MBP; and
- the large Plozza discs can achieve good soil inversion while being more resilient to wear in gravel soils.

The next improvements are to:

- Plozza plough the rest of the gravels (red on Figure 5); and
- deep rip (50 to 60cm) on the deeper sands that have been mouldboard ploughed.

In hindsight, it would have been better to ameliorate whole paddocks at once (that is, MBP appropriate part of paddock, plus Plozza plough appropriate part of paddock, plus deep rip appropriate part of paddock) so the grower could finish the surface of the whole paddock at the same time. Instead, parts of the paddocks were soft from MBP for five to six years. By the time the grower was ready to Plozza plough or deep rip, the MBP soil had settled, meaning the grower was going to create soft patches in the paddock again.

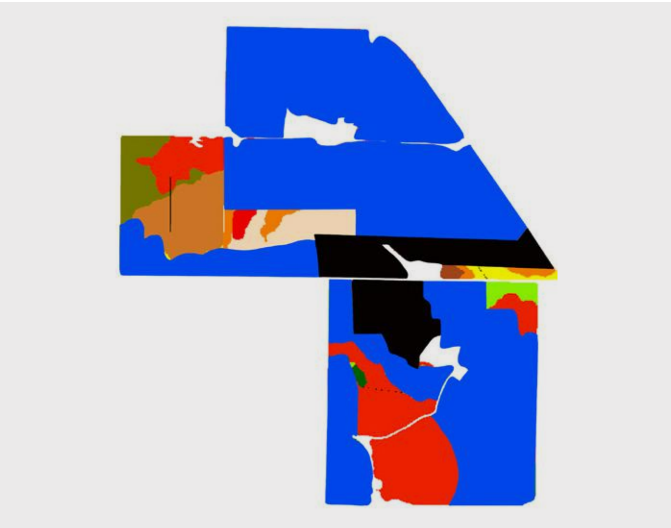


Figure 6: Areas that have been mouldboarded (blue) and Plozza ploughed (black).

4. Costs and returns

Ground-based EM and radiometrics survey = $18/ha

Mouldboard plough =
$140/ha (contractor @ $120/ha + fuel @ $20/ha)

Total cost = $138/ha

The first-year yield uplift from MBP averaged an estimated 900kg/ha of cereal. At $250/t this equates to gross profit of $87/ha in Year 1 ($225/ha uplift – $138/ha costs).

Six years on, yield is still higher than pre-amelioration yields.

Figure 7: RGT Planet barley, October 2020. Left-hand side – MBP 2015, right-hand side – untreated. Estimated 500kg/ha difference.

PART 3 – IMPLEMENTATION

Tips before starting soil amelioration

1. If conditions are not right – such as too wet or too dry – be prepared not to ameliorate. Working in the wrong conditions can:

■. make constraints worse;

■. increase erosion risk; and

■ mean a poor amelioration job with ongoing opportunity cost (from less than maximum yield uplift) for years to come.

It is unlikely you will go back and fix a poorly ameliorated paddock for several years.

2. It is better to do a good amelioration job on a smaller area than a poor job on more hectares. If you cannot do as much as you wanted in any one year, because of machinery or fiscal constraints or because conditions are not right, ameliorate a smaller area properly and use mitigation measures on other areas. For example, use wetting agents instead of mixing.

Doing a smaller amount each year also reduces wind erosion risk in any given year.

3. Try to ameliorate whole paddocks at once, rather than sections, for the following reasons:

■. Amelioration can make a mess of the paddock surface. Get it all over and done with in the same year.

■ It is easier to deal with post-amelioration issues when the whole paddock has been disturbed. A consistent surface to seed into means your seeder bar and seed depth, herbicide efficacy and plant establishment are more consistent. Renovating part of a paddock creates smaller zones that have to be managed differently.

■ Every other management decision and timing are largely the same for the whole paddock.

4. Plan how to deal with your ameliorated surface before you start. Make sure you have good levelling and rolling gear if you need them.

5. Check if your seeding bar can handle ameliorated soil. Even with the best levelling and rolling, the soil surface after ripping and mixing can be soft and uneven. Seeder bar wheels can fall into ridges. Unless your seeder bar has independent depth control on all tynes, seed depth control can be compromised, undoing all the good amelioration work, at least in year one.

Best practice implementation

Deep ripping

■ Aim to rip when there is good stubble coverage. Cereal is usually better than canola or lupins.

■ Rip headlands last so you can turn when ripping up and back ripping.

■ If possible, do not rip tramlines on headlands to reduce the potential of deep ruts that will be hit at 90 degrees before turning. These are brutal on machinery and operators.

■ Be realistic about the hectares you can rip properly. Trying to do too much leads to poor results and lowers the return on investment. You will end up going too fast, too shallow, ripping in the wrong conditions – or all of the above.

■ Rip to the required depth. Ripping too deep means more fuel use. Doubling ripping depth can quadruple the power needed. Ripping too shallow and not breaking the compaction throttle is a waste of time and money. Aim to get the tynes just below the bottom of the compacted layer.

■ If you are aiming for topsoil incorporation, slow down. There is more topsoil incorporation at slower ripping speeds.

■ C-shaped tynes can bring some subsoil closer to the surface. If bringing up weed seeds is a concern, use straight tynes. C-shaped tynes also leave the paddock more exposed to wind erosion.

■ Use a roller afterwards to reduce wind erosion risk. See the ‘Rolling’ section on page 53 for more information.

Rough guidelines for ripping post-seeding:

■ Grower experience is that ripping three to four days after seeding can result in patchy germination, but the crop recovers. Some growers have found ripping up to 10 days after seeding has had minimal impact on plant numbers. This timing can also mean a better ripping job because the soil is not too dry. Even later ripping (Z32 and later) tends to damage more plants, but some growers have achieved positive results, especially when ripping has been followed by rain.

■ The yield increase from ripping and the value of the crop make canola an attractive in-season ripping option. Canola is more sensitive to plant losses and canola yield is sensitive to plant density. Do not rip before two-leaf stage. Wider row spacings give more space to rip with lower risk of crop damage. GPS guidance such as real-time kinematic (RTK) will help keep the ripper between crop rows and minimise crop damage.

Inclusion plates

■ Topsoil slotting works best when the surface soil is dry and the subsoil is moist. Topsoil needs to be dry so it flows into the slot. This is especially important if topsoil slotting to treat water repellence.

■ Crop residue, especially residue that has not been chopped and spread adequately, can make topsoil slotting less effective.

- If the aim is to treat subsoil dispersion by slotting top-dressed gypsum, take care not to bring sodic subsoil to the surface. This process requires considerable operator skill.
- To improve topsoil burial with inclusion plates:
  - increase plate length – increasing plate length improves burial without increasing draught much, especially when working faster (increasing plate length by 60 per cent has a negligible impact on draught);
  - increase plate height – taller plates bury soil deeper than shorter plates;
  - go slower – the faster you go, the less burial you get;
  - do not work plates too deep; and
  - if you need to go faster, get longer plates.
- Things that increase draught force include:
  - working with the plates deeper (also reduces topsoil inclusion);
  - increasing ripping depth while keeping the plate depth constant; and
  - taller plates – a 290mm tall plate increased draught by about 40 per cent, while a 440mm tall plate increased draught by about 70 per cent (operating at 150mm under the surface (Ucgul et al. 2019a)).
- If tractor horsepower is limiting, aim to find a compromise between plate height, working depth below the surface, and the depth of desired amelioration.
- Working too deep below the lime depth in the topsoil will bury the lime shallower so it may not come into contact with deeper subsoil acidity.
- If you work too shallow, especially if the top of the plate is not in the soil, topsoil will not drop down into the slot. This can leave big slots in the soil that are a problem for plant establishment.
- Working too wet can cause similar problems as working too shallow.
- Topsoil inclusion tends to increase as the distance between inclusion plates increases. More topsoil is buried in the upper layers of the soil.
- Topsoil will fall in from where the top of the plate is. For example, if the top of the plate is running at 50mm deep, the top 50mm should collapse into the slot. If you are incorporating lime, for example, the top of the plate should run at the bottom of the lime layer. If it is running too deep, too much un-limed soil can fall into the slots and lime may not get as deep as you need it to.
- Inclusion plates can leave big ridges, especially in heavier soils. These will need to be rolled afterwards.
- There can be some sideways soil compaction to the sides of the plates. Shorter plate walls cause less compaction than longer plate walls.
- Anecdotally (from Isbister et al. 2017):
  - Plates that have not been reinforced tend to wear after about 200ha. Finer sands tend to wear out plates faster. Welding 'sacrificial steel' to the outside leading edge of the plate increases longevity.
  - Working wet leaves worse ridges between furrows.
  - Tapering the plates slightly towards the back improves soil flow and reduces soil sticking on the plate face.
  - The bolt that holds the plates open can cause stubble blockages. PVC pipe over the bolt can reduce blockages.

Spading

- Spading can bring up rocks and stumps that will have to be picked up and carted off the paddock. Leave some runs where you do not spade (leave every say fifth or 10th bay) so you can drive down these unspaded bays to access rocks and stumps, instead of driving across spaded country to access them. Once you have used these unspaded bays to pick the spaded bays, rip the remaining bays.
- It is often a good idea to rip the paddock before spading to:
  - remove buried obstacles that can damage the spader;
  - ensure the spader can work to the desired depth;
  - make spading easier;
  - avoid slip clutches going off excessively; and
  - improve mixing.
- The faster you go, the less uniform the mixing job.
- Roll the paddock after spading for a firm seedbed. See the section on rollers (see page 53) for more information. Wheels behind the spader can also provide some soil firming while leaving soil ridges to minimise wind erosion risk.

Delving

- Map subsoil depth and ground-truth before delving to minimise mistakes.
- Delving works best from 30 to 60cm, with an upper effective limit of about 70cm. Some delvers can technically go more than 1m deep, but they may not be able to pull clay up close enough to the surface.
- Soil test before delving to make sure the clay you are bringing up is worth the time and cost. The section on soil testing in Part 1 – Identification has more information (see page 18). Test for clay content, dispersion, pH, salinity, Colwell potassium, boron and carbonates if you suspect alkalinity. Clay content and quality often varies with depth so, if necessary, test various depths within the clay. Testing is cheap compared to the cost of poor delving.
- You will need a minimum 400hp tractor.
- Prepare the paddock before delving by:
  - removing stubble to stop it getting bunched around the delving tynes; and
  - spraying out weeds.
- Grade sand blowouts with clay-rich subsoil to try and match the clay rate in other parts of the paddock and make a level surface.

- Rocks and stumps are a big problem for delving tynes. Ripping before delving can help identify some buried obstacles. Thorium radiometrics can also give clues about subsoil rocks.
- The ideal operating angle for delving tynes is 45 degrees.
- Delving leaves the soil surface very soft, with big ridges and patches or chunks of clay. This needs to be tidied up to incorporate the clay and reduce the ridges. Use a smudge bar, stubble cruncher, chaining or similar to smooth the surface before incorporating. Options to incorporate include spading, ploughing, cultivating and aggressive harrows.
- Work in the same direction as paddock operations. It is extremely difficult to work at an angle to delve lines.

Clay spreading and incorporation

- Do small amounts each year to manage erosion risk.
- Soil test before clay spreading to work out the spreading rate, clay quality and if other amendments such as lime are needed. The section on soil testing in Part 1 – Identification has more information (see page 18) . Test for clay content (percentage), dispersion, pH, salinity, Colwell potassium, Phosphorus Buffering Index (PBI), boron and carbonates if you suspect alkalinity. Some exchangeable sodium in the clay is good as it helps the clay disperse better in the topsoil. Up to 12 per cent exchangeable sodium is acceptable. Too much sodium and you increase the risk of surface sealing.
- For clay rates greater than 150t/ha, incorporate with offset discs or tyned implements; for clay at 150 to 350t/ha use a rotary hoe, spader or disc plough.
- Vertical tillage machines such as Horsch Tiger and Joker, Väderstad TopDown and Bednar Swifter are also good for incorporation.
- For greater than 350t/ha clay you will probably need a spader for good incorporation. Subsoil clay needs to be more than 30cm deep, as there is a risk the spader will bring up more subsoil clay.
- Break up clods of clay before spreading so it incorporates well.
- It is possible to incorporate clay with a mouldboard plough by operating it at a shallower depth and with higher speed, which will result in mixing rather than inversion. It will not mix as well as a spader.
- Keep some clods and ridges in the soil to reduce erosion.
- Soil will be very soft. Tramlining is important.
- Always deep rip as the last operation when claying. Otherwise, the soil compaction caused by clay spreading and incorporation will reduce or negate the benefits of claying.

Ploughing

- The faster you go, the less topsoil burial there is. Increasing ploughing speed from five to 15km/h significantly decreases the depth of topsoil burial.
- Increasing ploughing depth beyond 200mm removes more topsoil from the surface but does not have a significant effect on the depth of topsoil burial.

Mouldboard ploughing

- Mouldboard ploughs are better at inverting soil than one-way ploughs.
- Mouldboards only invert when the subsoil is wet. If it is too dry the soil will just flow around the board.
- Setting up the mouldboard plough for complete soil inversion does not mix surface applied amendments very well.
- To mix with a mouldboard plough, work a bit shallower and faster to do an 'incomplete' inversion. If you have limed beforehand, this can also create an angled path of limed soil to depth for the roots to follow.
- Using skimmers on mouldboard ploughs correctly can increase the amount of topsoil burial below 100mm depth (Ucgul et al. 2019b).
- Inversion works better when there is limited crop residue on the surface.
- Know the soil pH profile before starting. If you bring acidic subsoil to the surface you will need to apply additional lime after ploughing. Measure topsoil pH again after inversion to check if lime is required.
- If you have acidity as well as water repellence and a high weed burden, mouldboarding can be a good way to deal with all three.
- When mouldboarding soils with heavier clay subsoil, you may need to incorporate this clay after it has been brought to the surface. You can incorporate with the mouldboard by operating faster and shallower.
- Deep loamy sands often do not need subsequent mixing as not enough clay is brought to the surface to cause sealing/crusting.

Square ploughs are similar to mouldboard ploughs, but do not come with skimmers. Inversion generally is not as complete as using a mouldboard, but in the right conditions can still do a good job. The tips above – except for comments about skimmers – apply to square ploughs too.

Modified one-way plough

- Before starting, choose whether you want to mix or invert and set up the plough correctly for that job. Test, check for bent jump arms, and adjust set-up before the day you plan on starting amelioration.
- Typical speeds are four to six kilometres per hour. Slower speeds are necessary if you are trying to invert or need to work as deep as possible.
- Working too fast when trying to invert ends up mixing instead. Faster speeds increase mixing but reduce the depth of mixing. Too fast puts the machine at risk of rock or stump damage.
- Choose the speed that is doing a good job. If paddock soil type varies you may need to change working speed across the paddock.
- Mixing works better when the soil is drier. Soil inversion is likely to be better with moderate or greater soil moisture levels.
- Too much crop residue makes it harder for the plough to bury the topsoil properly. Dry stubble is easier to handle than wet

stubble. The ploughs have a much better stubble handling ability on gravel soils with dry stubble than soft sands with damp stubble. If in doubt, the less residue the better.

- Leave about 50m clearance around the paddock to start to give plenty of turning room.
- If working in blocks in the paddock (because one-way ploughs traditionally turn left), choose an odd number of runs in the first block so that when you do the last run in a block you are turning left to head to the next block in the paddock.
- Do the last two runs of each block with the rear axle raised (feathering) to avoid leaving a land end (trench) in the paddock.
- If working anti-clockwise around the paddock, raise the plough on the corners to make a roadway into the centre of the paddock via the headlands.
- Do the headlands last so:
  - you are not making a mess of them when turning and carrying the plough; and
  - you have a chance to level if necessary.
- To avoid axle damage, reduce speed when the plough is in soft soil, that is, previously or partially ploughed paddock sections. This is critical when the plough is being carried.
- Too much wheel slip could be from incorrect tyre pressure, uneven weight distribution, or a too-small tractor.
- After ploughing, smooth the surface with a vigorous anchor chain, a cultivator or speedtiller. Work on an offset. Some growers find working at six per cent helpful.
- After smoothing, the paddock needs rolling to make a firm seedbed. Rolling is critical for good establishment in the first year. Roll as late as possible prior to seeding (to keep the surface rough and less vulnerable to wind erosion for as long as possible) and as soon as possible after rain before the topsoil dries out. If you are ploughing while the soil is drier, leave the paddock surface rough until just before seeding.
- Duplex sands can leave a clumpy surface that can help manage wind erosion risk. Deep sandy soils are less likely to have the clumpy surface effect, so this needs consideration for wind event management.
- Roll heavy enough that a standard 4WD ute can be driven on the worked paddock in 2WD without significant difficulty. At this point most seeding bars will get by with careful operation.

Rock crushing

- Patience is critical. Rock crushing is breaking up rocks once and for all – they are not coming back.
- You will need a four-wheel drive tractor with greater than 450hp, or at least 400hp if using a track machine.
- Wheels are better than tracks on the rocky country typically being worked.
- Allow three passes to do a good job. The third pass should level the surface.
- In some cases, the surface will also benefit from a light level afterwards. The surface will be rough if the machine has been operating too deep, too fast, or both.
- Machines typically work at about 10km/h (1ha/hr with three passes).
- How well rock breaks will depend on rock type, speed, depth and conditions. Some rock softens when wet and is best worked when wet, for example, sheet ironstone. Adjust in the paddock to find the right combination of depth and speed.
- Clues you are working too deep include:
  - very bumpy ride;
  - spinning or wearing out tyres;
  - bringing up big boulders;
  - stopping frequently; and
  - making a mess of the paddock.
- Start shallow with the first pass then begin increasing depth.
- Working too deep runs a risk of sudden stopping. Machines with hydraulic tynes that ride over obstacles can reduce this risk.
- Working too wet on clayey soils makes a sticky mess. It is possible to get bogged in the pockets of clay between the rocks. Some machines have rib cleaners on the back that make working in wet conditions easier.
- Some machines struggle with wet stubble flexing and snaring instead of cutting.
- Avoid granite. The machine will ride over basalt. One way to test how a rock will respond to crushing is to hit it with a sledgehammer. It the sledgehammer bounces back at you, the rock is too hard. If it cracks or shatters (like quartz), rock crushing will work.
- If there are boulders in soft sand, work fast (about 12km/h) and shallow to hit the rock with force while it is still anchored in the ground. Repeated passes will soften the soil around the rock and increase the risk of rocks being pushed into the soil rather than crushed. Working shallow also reduces the risk of picking up the boulders instead of crushing them.
- If the seeder ends up flicking up boulders, more passes of rock crushing were needed. A paddock is 'done' when the machine starts pulling very smoothly.

Risks and mistakes

Preventing mistakes

Prevention is better than cure. These are the key ways to minimise mistakes:

1. Know your soil types and constraints

Mistakes are more likely when you are not aware of variability within paddocks. Knowing soil variability and where the issues are helps you to choose the right tools for the job. Mistakes are more common when using the wrong amelioration technique for the problem. This is why the Part 1– Identification section is critical.

2. Work to the conditions, not the calendar

Some of the most easily preventable mistakes happen when working at the wrong time. See the Timing section on page 39.

3. Check amelioration as you are going

With all operations, constantly check how effective they are as you work and correct where necessary. For example, check that:

- you are ripping at the desired depth;
- soil is inverting, if that is the goal;
- big clods or excessive amounts of clay are not coming to the surface; and
- you are getting the desired amount of soil mixing.

If amelioration is not working properly, stop. Persisting just because you have started can end up a very expensive exercise, with the cost of amelioration and potential yield penalty for years to come.

Risks

Soil amelioration comes with risks. As the benefits of soil amelioration outweigh these risks, the best thing to do is to reduce the chance of mistakes and unwanted events.

1. Wind erosion

Some wind erosion is inevitable. Strategies to minimise wind erosion aim to:

- keep as much cover on the soil as possible – erosion risk increases when there is less than 50 per cent ground cover, such as stubble (at least 30 per cent anchored) or soil conglomerates and/or gravel; and
- shrink the window where the soil is left exposed to erosion – this might mean changing the timing of some operations or even eliminating them.

Tips to minimise wind erosion risk:

- Work to the conditions, not the calendar. Generally, this means not working dry.
- Sow a cover crop as soon as possible.
- Ameliorate a small area of the farm each year. This makes it easier to ameliorate at the opportune time and limits wind erosion risk.
- Retain as much standing stubble as possible when ripping. Thin straight ripping shanks damage stubble less than inclusion plates or delving tynes.
- Ripping after a cereal and before sowing another cereal maximises ground cover and lowers wind erosion.
- Roll as late as possible before seeding.
- Use a roller that leaves ridges in the soil.
- Where there is low stubble cover, avoid heavier and more ridged rollers as they do more damage to the standing stubble. Because stubble is more effective at reducing wind erosion than soil ridges, consider a lighter/smoother roller, as long as you are still firming the seedbed.
- Consider the prevailing wind directions when setting tramline orientation. Tramlines at 90 degrees to the prevailing wind direction lower erosion risk, but this is not always practical. In sandy soils where erosion risk is high, avoid orientating the tramlines in the same direction as prevailing wind.
- Research which months of the year are the windiest and have the strongest wind. If possible, aim to avoid ameliorating in these months if paddocks have a high wind erosion risk.
- Use strategic wind breaks to slow wind velocity. Erosion is more likely once wind speeds hit 28km/h.

2. Haying off

Haying off is a risk after ripping in seasons with a dry finish. Crop roots grow more vigorously on ripped soils, producing more biomass and using the subsoil water faster, leaving insufficient water for grain filling. Consider applying less nitrogen if haying off is likely.

3. Stirring up weeds

Amelioration changes where weed seeds are in the soil. Fully inverting the topsoil can bury weeds to 20 to 40cm, which is too deep for most species to emerge from.

Other methods that mix or disturb the topsoil more evenly distribute the weed seeds between about three to 35cm. This buries some weeds too deep to emerge, can make many pre-emergent herbicides less effective as seeds are too deep for effective contact, and can stimulate a germination event (an autumn tickle effect). From field observations, wild oats tend to get effectively buried, while capeweed is less likely to be buried. More uniform weed emergence, combined with the increased bioavailability of herbicides after renovation, will make weeds easier to control.

Aim to not disturb inverted soil for at least five years to keep the weed seeds buried at depth. This will remove the risk of some weeds germinating again (those that will not be viable after about five years). Non-wetting sands can be tricky to leave undisturbed as they are prone to compaction and future deep ripping can bring seeds back to the surface. In this case, be prepared with a plan for weed control.

Common amelioration mistakes

1. Bringing hostile subsoil to the surface

Not checking subsoil quality before ripping, mixing, inverting or clay spreading can cause problems for years. Some growers who have brought sodic clay, saline soil and/or high boron soil to the surface have suffered yield penalties for 10 years and counting (Isbister et al. 2020).

A lesser concern is induced micronutrient deficiencies. High rates of alkaline subsoil can induce, for example, manganese deficiency in lupins.

Check subsoil chemistry before working. Test for clay content, dispersion, pH, salinity, boron and carbonates if you suspect alkalinity. See the section on soil testing in Part 1 – Identification (see page 17). If the subsoil is better left at depth, check while working that you are not accidently bringing it up. If you are, stop ASAP.

2. Cloddy surface

Working too dry and too deep into heavier subsoil are the main causes of a cloddy surface. The best way to prevent it is to wait for better conditions and adjust working depth (if possible).

The size, hardness and chemistry of the clods affects how you deal with them. Ridged rollers can bust up some clods, but on sandy soils the clods can just get pushed back into the ground to cause problems at seeding. Break up clods with a shallow tillage disc machine. Some roughness is good to reduce wind erosion risk.

Clods can also happen when the clay used to treat non-wetting does not slake or disperse, instead staying in clumps on the surface.

3. Not working deep enough

This usually happens when you are working too dry. For example, with the right soil moisture mouldboarding can work down to 40cm, but when dry it might only work to 25cm.

Check while working and if you are not getting into the right soil layer, whether ripping, mixing or inverting, stop.

4. Not fracturing soil when ripping

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 conditions are better.

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 300, the tynes are too wide to fully fracture across the subsoil.

Some growers rip on a wider spacing to cover more ground. There can still be some, but lesser, yield benefit from wider tyne spacing (Parker et al. 2017).

Working beyond the breakout capacity of the tynes can mean a poor ripping job, as well as more wear-and-tear on machinery. Once the tynes start to bend backwards and lose the correct angle of engagement, they lose the lift and shatter effect you are after. They are also probably not working as deep as you need.

5. Not bringing enough clay or too much clay to the surface when delving

This happens when you do not know subsoil depth and/or are working in the wrong conditions, or you should be using a different operation, for example, claying instead of delving.

Map and ground-truth subsoil depth before delving and adjust while working. If necessary, wait for better conditions. If you have brought too much clay to the surface, incorporate well to prevent surface crusting.

6. Surface crusting

Surface crusting happens:

- after soil inversion, where too much clay was brought to the surface then dried out before it was incorporated;
- from poor incorporation after clay spreading; or
- if dispersive clods are brought to the surface. When it rains, the clods can break down and form a crust.

The risk of crusting depends on how much clay was brought to the surface, the exchangeable sodium content of the clay, and organic matter. Generally, more clay + higher sodium + lower organic matter = more risk of crusting.

Crusting can stop crops emerging as the surface is too hard for the seedling to break through. It can also encourage shallow evaporation. Combined, this makes it harder for small-seeded and shallow-sown crops to establish.

If there is too much clay at the surface, incorporate before it dries out. If it has dried out, shallow working (with a high-speed disc-tillage machine) might be able to break it up. If the clay is dispersive you might need to apply gypsum to reduce crusting.

Increasing the seeding rate and trying to get the crop up before the soil dries too much can help. Minimise traffic and re-compaction.

7. Making non-wetting worse

Working too dry can make non-wetting worse by fluffing up the topsoil without diluting it with more wettable subsoil. Research has repeatedly shown that disturbing non-wetting soils when they are dry makes repellence worse and water infiltrates more slowly.

If this happens there are a raft of mitigation measures to improve establishment while planning for longer-term amelioration. Options include:

- wetting agents and moisture retainers (more reliable on gravels – results are variable on sandy soils);
- on or edge-row sowing (requires some investment in guidance systems);
- cross-seeding;
- deeper seeding with longer-coleoptile varieties;
- ribbon or paired-row seeding;
- increasing the seeding rate (makes more sense with cheaper seeds); and
- furrow sowing to grade water-repellent soil out of the furrow and into the ridges. The repellent ridges help harvest water into the furrow, improving the chances of infiltration.

8. Subsoil rocks damaging equipment

Working a paddock for the first time can mean finding subsoil rocks that damage equipment. They can bend the ripper's hydraulic arm and break tynes.

Airborne radiometrics can help identify where rocks are closer to the surface (see Part 1 – Identification). High thorium is often indicative of rocks, which needs to be confirmed with ground-truthing. Because airborne radiometrics are low resolution, they can act to create 'rock warning zones' where rocks are more likely to be. When operating and approaching rock zones, be ready to lift the ripper if you see/hear/feel a rock or the tractor starts working harder. If rocks are dense enough and cover enough area to warrant rock crushing, start with rock crushing.

9. Pre-emergent herbicide damage

Herbicides, specifically pre-emergents, can become more toxic to crops after soil amelioration. Herbicides tend to bind to soil organic matter (OM). As amelioration reduces or buries OM, there is less of a buffer, making the herbicide more prone to leaching. Soft soil is also more prone to movement from wind and water, which can take the herbicide with it and cause off-target damage. Couple this with trickier seeding depth control and more soil throw, and you may cause more crop damage than planned.

See the section 'Rethink your herbicide plan' below for more information.

10. Poor water infiltration

Caused by poor clay incorporation after spreading. To fix, incorporate clay to 10 to 15cm to make sure it is in the non-wetting soil layer(s).

Post-amelioration management

Ameliorated soils need different management, particularly when seeding and managing herbicides.

Rolling

Soil amelioration leaves the surface soft, making seeding tricky. Rolling firms the surface for seeding. A weighted roller, either towed behind the ripper or used in a separate pass, can:

- break up clods brought to the surface during ripping;
- push rocks back into the soil (so it is better to pick up large rocks before rolling);
- conserve soil moisture;
- improve trafficability and flotation of the seeding bar (less sinkage and fewer wheel ruts);
- be an opportunity to embed or firm-up tramlines, especially if you have ripped on an angle (which busts up tramlines); and
- firm the surface and reduce inter-row ridges from the tynes before seeding, for better sowing depth control and seed-soil contact to improve seed imbibition (water uptake) and germination.

Different rollers are designed to achieve a specific result and soil finish depending on soil type, moisture content and stubble levels.

On sandier soils, flatter and lighter rollers are effective – such as a coil packer or drum roller with limited ridging/teeth. The exception is on sandy duplex soils where, if you try and pull up hard clods, it can be tricky to crush them. As the clods are harder than the surface soil, the roller might push them back into the ground instead of breaking them up.

If you have variable paddocks the key trait to look for in a roller is the ability to change pressure. Being able to alter the packing pressure means you can use it on multiple soil types, adjusting as needed. A hydraulic roller, or a drum roller you can fill to control the weight, are both good options. However, adding weight from the ripper frame can cause the tynes to lift up and you do not rip as deeply. It becomes a balancing act between ripping depth and keeping enough weight on the roller. High stubble cover is more forgiving of heavier/ridged rollers. Rollers are likely to flatten the stubble but leave some anchored in the soil.

Where wind erosion is a big concern; roll as late as possible before seeding and use a roller that does not destroy the stubble. Where there is low stubble cover, heavier and more ridged rollers will do more damage to the standing stubble. Because stubble is more effective at reducing wind erosion than soil ridges, consider a lighter/smoother roller, as long as you are still firming the seedbed.

Rollers that leave ridges in the soil, for example, Cambridge roller and ring rollers, reduce erosion risk. Coil packers might seem like a good compromise; they are light, leaving more stubble intact while also creating a ridged herringbone pattern in the soil. Coil packers are good if you only need a light pack but are not much use after ripping more than 300mm deep or in damp conditions. If it is not making a good seedbed you may as well not roll at all. Smooth rollers such as drum rollers leave the surface flat and more prone to erosion, particularly where stubble cover levels are low.

Using rollers that leave the soil vulnerable to wind erosion should be done later and as close to seeding as possible. The downside being this is a separate operation and, if the tramlines of the tractor that is pulling the roller are different to the 'proper' tramlines, that is the first bit of re-compaction.

On undulating surfaces, very wide, rigid rollers can result in uneven packing, as the roller will not always be in contact with the soil along its full length. Cambridge-style rollers, where the rings move individually, are better in those conditions.

If the ground is wet, tyre rollers, spring rollers, or a ring roller with a U-shaped profile can work well. If the ripper is leaving wide furrows, you will need a heavy weighted roller. When the ground is loose and dry (with few clods), consider a tyre or drum roller.

Some rollers are simply unsuitable for certain conditions. Bulldozing the soil instead of rolling over it is a clear sign the roller is either too heavy or too small in diameter. Rollers that are too small will tend to sink in, pushing the soil in front of them and making ridges out to the side. Anecdotally, rollers that are part of the machine are more likely to bulldoze than towed rollers.

Some hydraulic rollers have accumulators on their lift cylinders to 'float' the roller, so ripping can be deeper and the roller will not bulldoze the soil.

Machinery adjustments for soft soil

Make machinery adjustments to cope with soft soil (from Parker et al. 2019):

- Increase tyre width and reduce tyre pressure for better flotation (also better for reducing compaction).
- Use wider press wheels so they do not sink too much and bury the seeds too deep. Wider press wheels are also good for stopping the bulldozing effect if the weight of the bar carried on the press wheels is too heavy.

- Use a lightweight seeding system with regulated seed boots.
- Lock castor wheels.
- Half-fill the air-cart tanks.
- Use light seeding bars. Some growers who are undertaking large areas of deep ripping or soil amelioration have set up light seeding bars specifically for seeding soft soils.
- Avoid deep working points as there is a bigger risk of sowing too deep. Shallow working seeding points can help minimise soil throw and give more even sowing depth compared with deep working points. This approach should best be combined with contour-following technology.
- You do not need underseed cultivation, such as DBS, as the soil is already soft.
- Use ground-following seeding equipment to control the operating depth of each row with a press wheel-based mechanism.

Rethink your herbicide plan

Reorganising the soil surface can change how pre-emergent herbicides behave in the soil.

Herbicides, specifically pre-emergents, can become more toxic to crops after soil amelioration.

Soil amelioration, particularly inversion, reduces the organic matter (OM) content of the topsoil. OM intercepts and binds a proportion of herbicide applied to the soil. By having less OM for the herbicides to bind to, the herbicides are 'hotter' (more biologically available). Less binding also means the herbicide is more mobile, which can increase the risk of herbicide moving from the inter-row into the furrow and coming into contact with your crop.

As ameliorated soils are soft, it is harder to control seeding depth. With greater variability in seeding depth it is likely more seeds will be closer to the herbicide. Softer soils can also be less stable, particularly in the first season after renovation when there is little stubble cover. This increases the chance of soil-containing herbicide getting blown or washed into furrows. In some cases, the furrow walls can collapse because the soil is loose, moving the herbicides closer to the crop seed. A softer soil surface also means more soil throw and increased likelihood of soil from one row being thrown into adjacent rows, increasing the risk of crop injury.

To reduce the risk of crop damage with herbicides:

1. Closely read and follow the herbicide labels. Some herbicides have clear advice to not use in light soils with low OM levels and some recommend lower rates in those scenarios. Do not reduce rates of newer herbicides unless there is research to support it. Lower rates may be sublethal for weeds and therefore ineffective, or even induce metabolic resistance in recurrent generations.

2. Consider not using pre-emergent herbicides in the first year. The risk in the first year is particularly acute with severely reduced soil structure and no stubble cover. This option is more suitable after complete soil inversion (rather than ripping or mixing), as burying the weed seeds can give excellent weed control.

3. Use an early post-emergent herbicide. This gives you a chance to assess the size of the weed burden and what the most frequent weed species are. These herbicides are mostly taken up through contact on the leaf (not through the soil) so there is no additional risk of crop damage from changes to the topsoil.

4. Choose your next crop with care. IMI-tolerant crops, particularly barley, are commonly sown. Hay is an option if the surface is flat and devoid of rocks, clumps and sticks, but soil re-compaction is a risk. Canola has many herbicide options and is more crop-safe for both pre and post-emergent herbicides, but it is trickier to sow after soil amelioration than a cereal.

5. Apply herbicide when the soil has higher moisture as this gives the herbicide a better chance of binding to the topsoil. Applying to dry soil has an increased risk of herbicide movement, especially if you get rain soon after application.

Other agronomic considerations in the renovation year

General comments for working in the renovation year:

- Lupins and canola are a risky choice if planting in the first year after ripping below 40cm.
- Inoculate lupins before sowing into inverted soil as the existing *Rhizobia* may have been buried.
- Go back to controlled-traffic farming (CTF) or consider starting CTF to minimise re-compaction.
- Consider wheat varieties with longer coleoptiles as they have a better chance of emerging if sown deeper.
- Consider salt and/or boron-tolerant species if you have clayed or delved.
- Consider broadcasting seed in soils that have been deep ploughed. Press the seed down with packers or press wheels. Broadcasting when the soil is wet can mean faster crop emergence and the crops can grow into loose, moist soil.

Case study – Farm 2: Using spatial layers to assess soil constraints and develop a soil amelioration plan

1. Background

The grower recently purchased a new block. The grower and consultant knew there were some soil constraints – acidity (confirmed by low pH results in 0 to 10cm samples), dispersive soil and water repellence–and thought there could be areas with subsurface compaction. Being a new block, they had little existing knowledge to draw upon. Their approach was to use multiple spatial layers and ground-truthing to map soil type zones, generate variable-rate lime and gypsum maps and determine where they could pursue the tillage ameliorations they had at their disposal.

2. The process

The grower and consultant started by using aerial images of the block. However, it soon became apparent that:

- variations in soil types were not obvious in aerial images;
- they were not able to relate subtle changes in aerial images to soil types;
- they would need to do a lot of ground-truthing to check where soils changed and what the properties of different soils were; and
- given the points above, they needed additional information.

They sourced readily available information, including aerial gamma radiometrics (GR) data and NDVI, and then conducted a ground-based EM and GR survey.

Figure 1: Aerial image of farm.

Gamma radiometrics

Aerial GR gave a rough idea of soil type changes but was not detailed enough. The ground-based GR survey gave more detail.

In Figures 2 to 5, compare the resolution of the aerial GR maps (a) with the ground-based GR maps (b).

Case study courtesy of Agronomy Focus and Viridis Ag

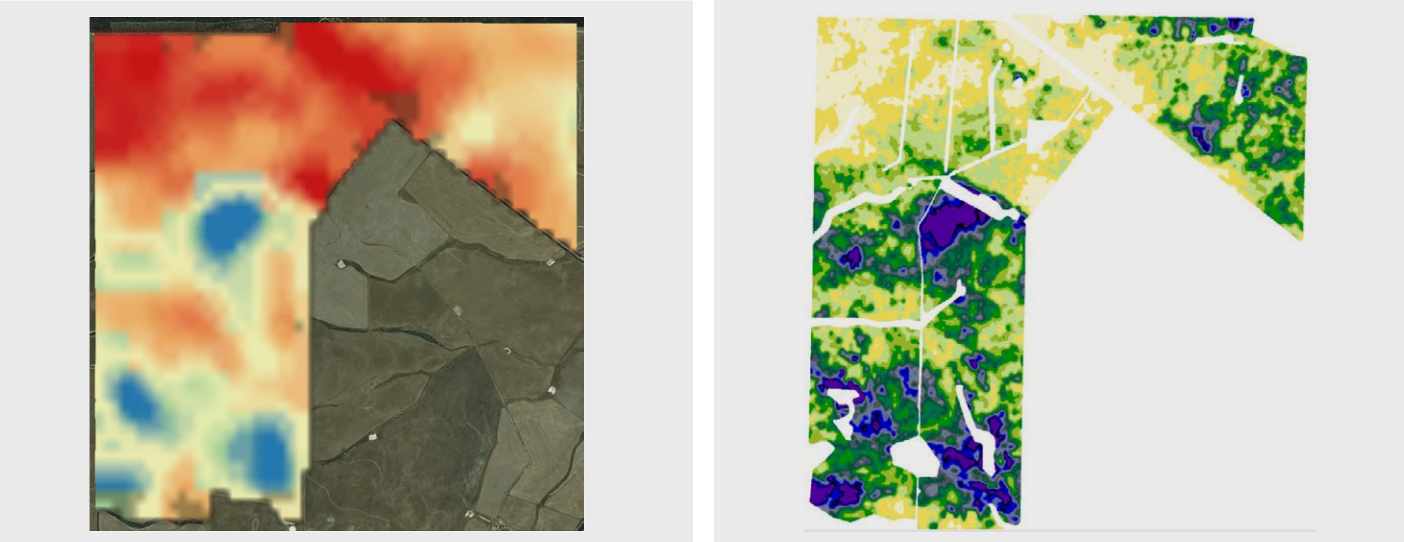


Figure 2: (a) Thorium aerial; (b) thorium ground-based.

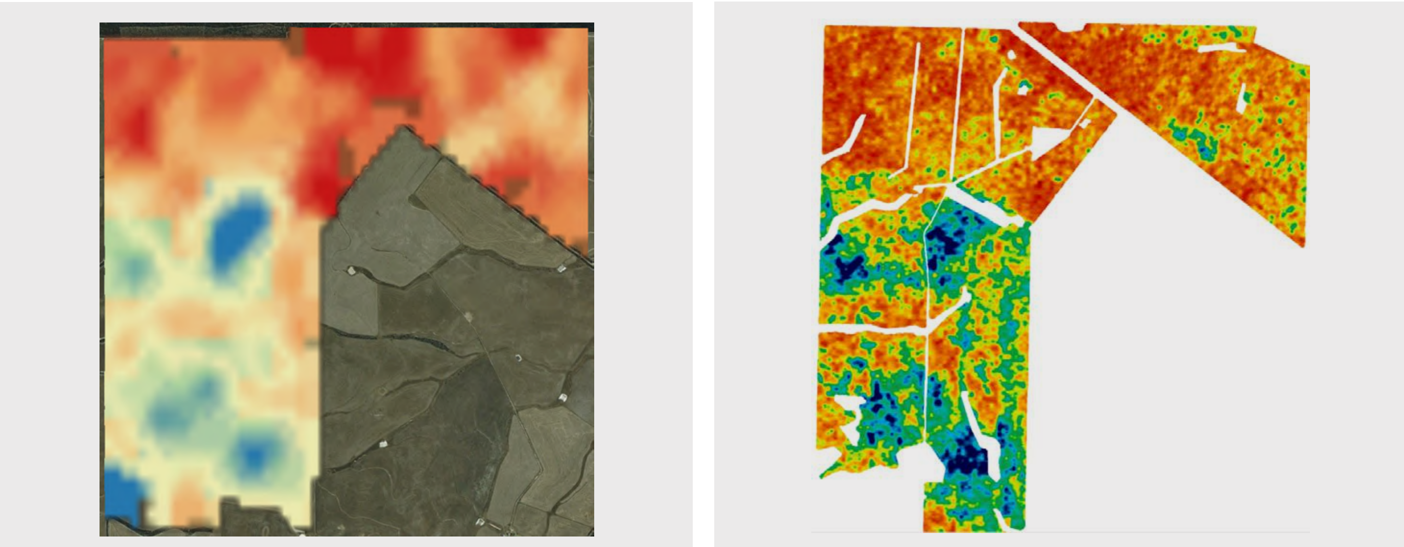


Figure 3: (a) Uranian aerial; (b) uranian ground-based.

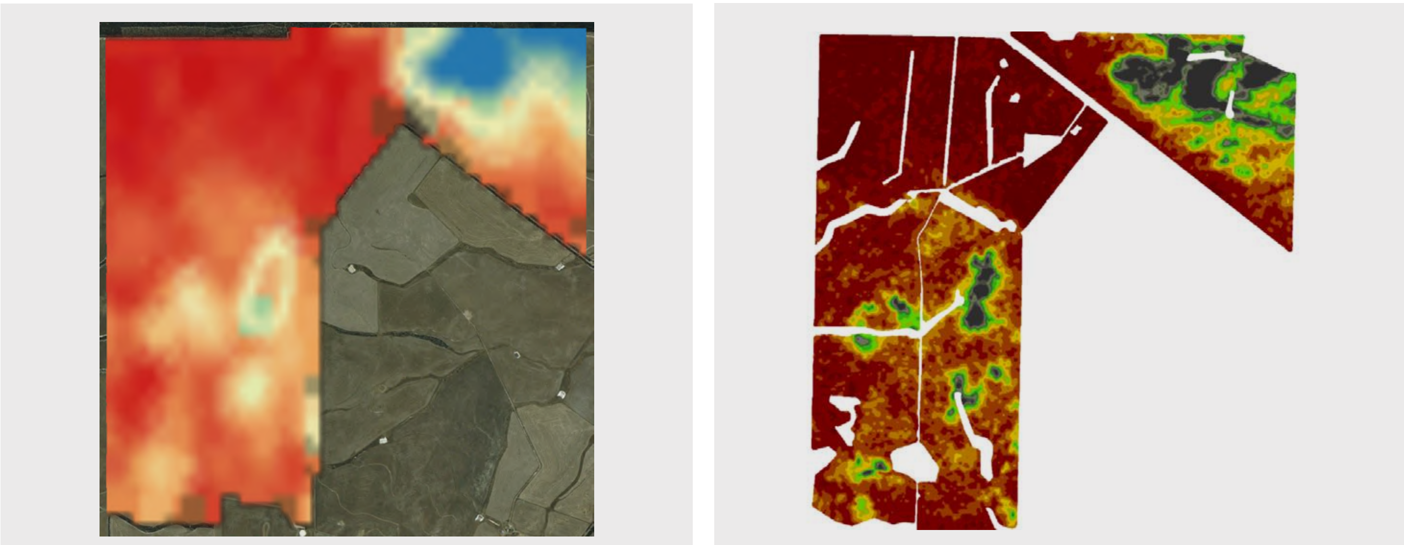


Figure 4: (a) Potassium aerial; (b) potassium ground-based.

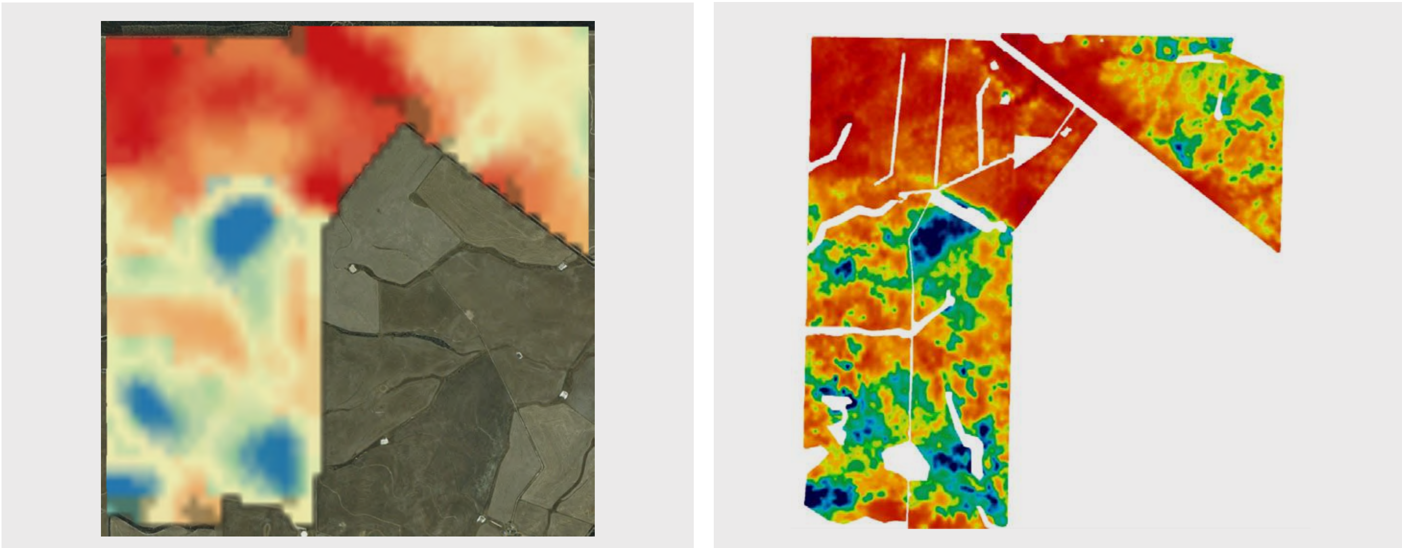


Figure 5: (a) Total count aerial; (b) total count ground-based.

EM survey

The shallow and deep EM surveys were similar.

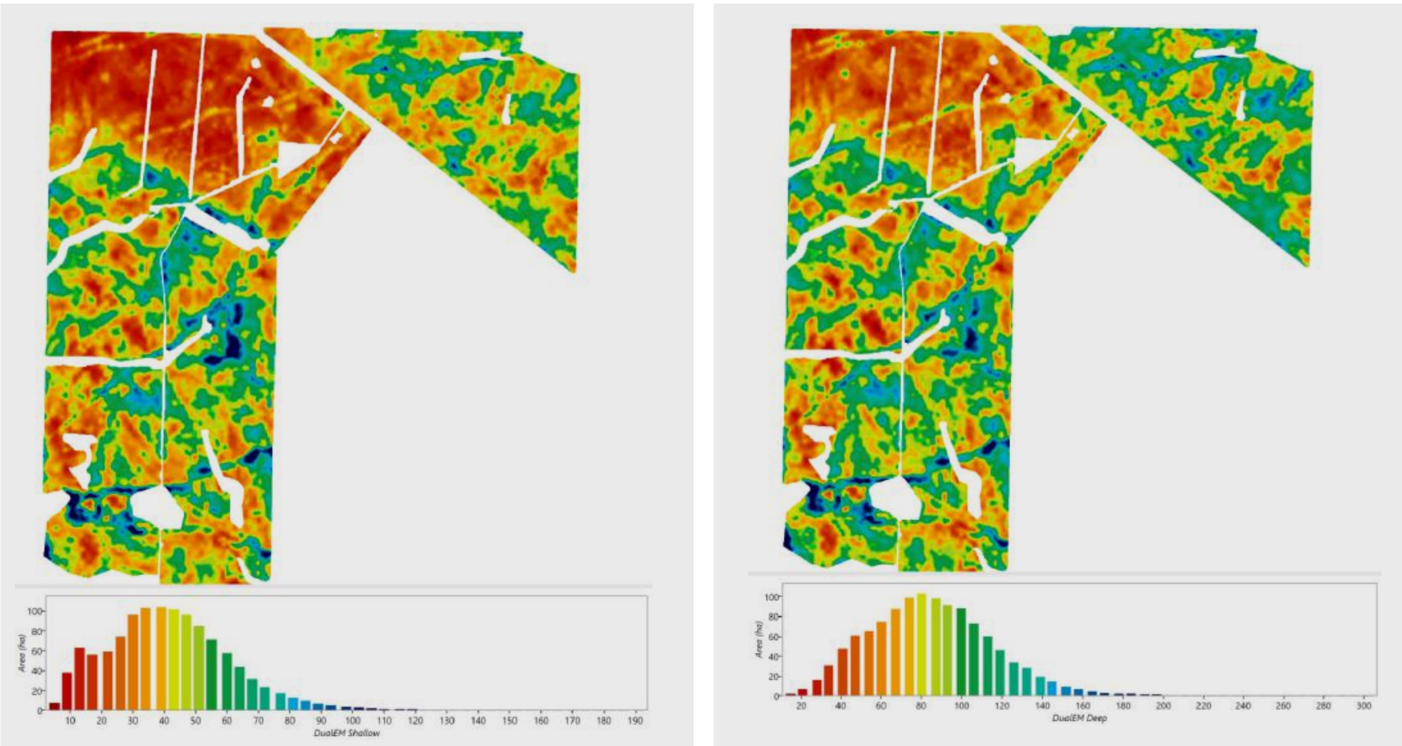


Figure 6: (a) Shallow EM survey; (b) deep EM survey.

Ground-truthing

Soil core ground-truth locations were chosen to cover the range of results in EM and GR in the survey. Sites for GR were selected using the Th, K, U and/or TC maps, usually using the map or combination of maps that backed up what the grower/consultant thought.

All sites are marked as 'EM' and 'GR' on the shallow EM map (Figure 7).

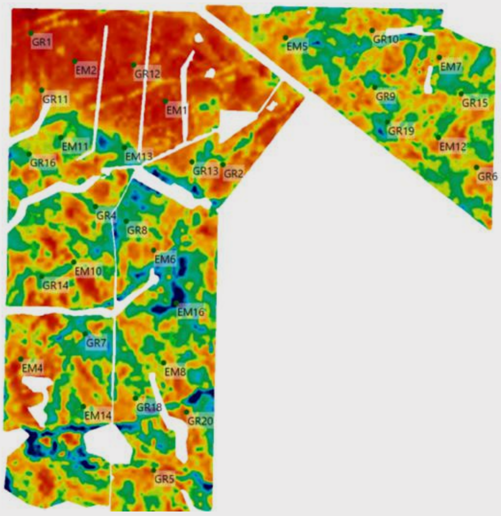


Figure 7: Shallow EM map.

Soil cores were taken from all sites and photographed. To correlate the EM/GR survey results to soil type and depth, soil type for the top and second soil layers were recorded and the depth to the clay/gravel/reticulite second layer was measured.

Soil samples were collected for laboratory analysis from 0 to 10cm, the first soil layer (soil above the clay subsoil which included the 0 to 10cm sample) and the second soil layer (subsoil).

Figure 8: Soil cores.

The soil survey EM/GR results were correlated with soil depth and the laboratory test results, specifically pH and exchangeable sodium percentage (ESP), which in turn were correlated to lime and gypsum rates.

Those correlations were then extrapolated across the surveys to develop variable rate gypsum and lime maps (see page 61).

Correlation graph

The correlation between Deep DualEM readings and ESP was $r^2 = 0.69$. R^2 describes the strength of the relationship between the EM map and ESP readings. The closer the number is to 1, the stronger the correlation.

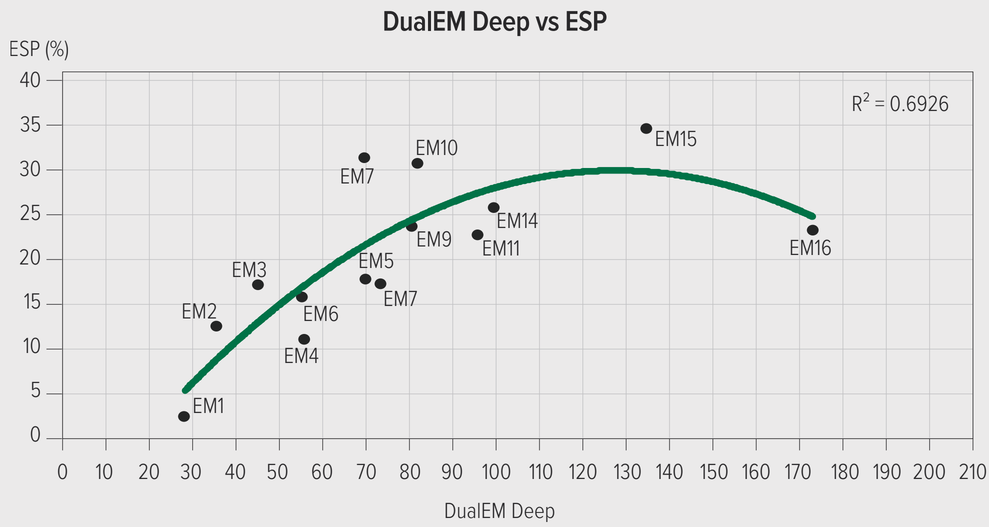


Figure 9: Correlation graph.

Satellite imagery to check gypsum rates

Satellite imagery was used to detect poor canola establishment (red areas in Figure 10) which could be related to the most sodic, gypsum-responsive areas. Ground-truthing was critical to confirm the reason for poor establishment. The low biomass in the south-east was due to dispersive soil, but the section along the northern edge was due to wildlife damage.

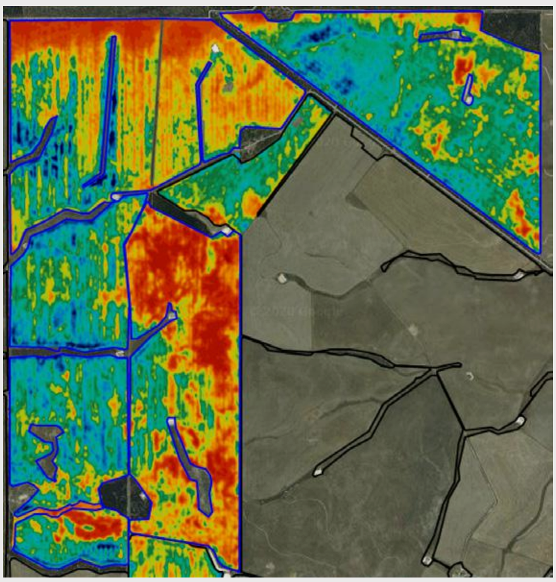


Figure 10: Satellite imagery was used to check gypsum rates.

Variable rate (VR) gypsum map

The correlation between EM shallow + U GR and exchangeable sodium percentage (ESP) was used to generate an ESP map (Figure 11).

Rates of gypsum, based on ESP and exchangeable cation results, were mapped to show where and how much gypsum needed to be applied, where:

- red = 0.5t/ha
- orange = 1.5t/ha
- green = 2.5t/ha
- blue = 3t/ha

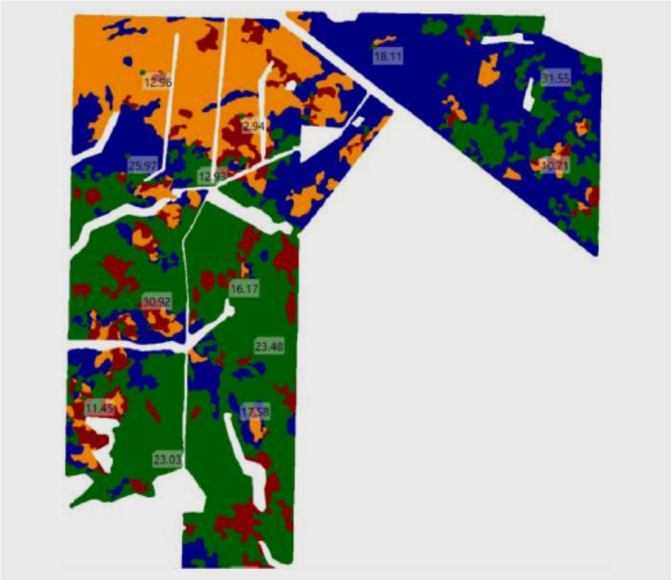


Figure 11: VR gypsum map.

Simplified VR gypsum map

The rate zones were then smoothed and simplified for practical application of gypsum.

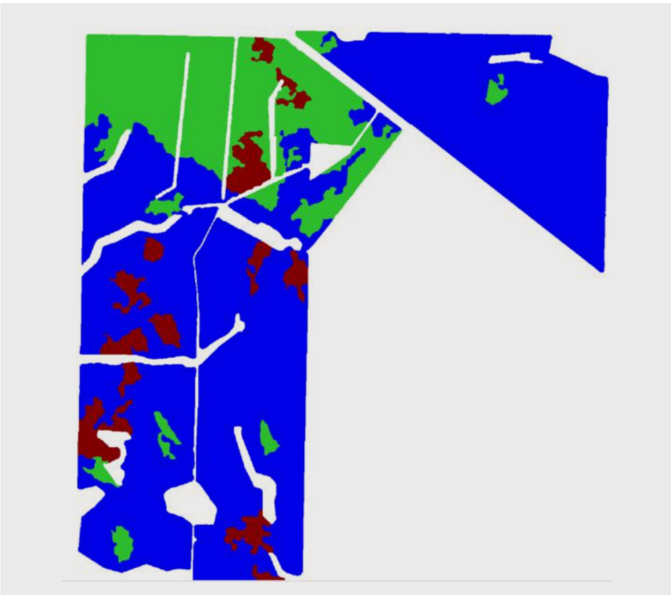


Figure 12: Simplified VR gypsum map.

VR lime map

The correlation between EM shallow and soil pH of the first soil layer, plus historical soil test results for pH, were used to generate a pH map. The pH map only crudely related to the soil type map, suggesting previous management had more impact on acidity.

Rates of lime, based on soil pH, were then mapped to show where and how much lime needed to be applied, where:

- red = 3t/ha
- yellow = 2t/ha
- light blue = 1t/ha
- dark blue = 0t/ha

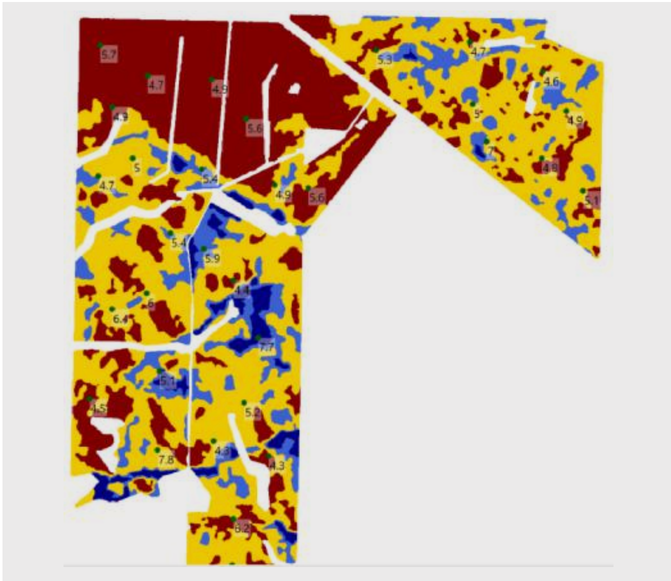


Figure 13: VR lime map.

Simplified VR lime map

The rate zones were then smoothed and simplified for practical application of lime.

Figure 14: Simplified VR lime map.

Soil types map

Combining the soil core depth data, laboratory data and surveys generated a soil types map. This was then ground-truthed and altered based on the in-paddock findings and by revisiting the soil cores.

Figure 15: Soil types map.

Table 1: Soil types.

Zone	Area (ha)	Soil Type
Purple	838.2	Shallow duplex, clay within 20cm of surface
Green	189.7	Sand and gravel over clay >25cm
Cream	145.9	Sand over clay >25cm

3. The amelioration plan

More ground-truthing was conducted to determine other soil constraints. Spatial information used in the process was:

- EM – to help distinguish between sand/rock (low conductivity) and clay (high conductivity);
- GR K – low for sand and gravel, higher for clay, very high for limestone and granite;
- GR Th – low for sand, medium for clay, high for gravel and granite;
- NDVI – to detect good and poor-performing crop areas to guide where to ground-truth to identify the cause of poor performance.

Ground-truthing the soil type map showed:

- Shallow duplex, clay within 20cm of surface (purple zones) had moderate to severe water repellence that was hindering crop establishment. The best amelioration strategy was speed tilling to mix and dilute water-repellent topsoil, and maybe bring up some clay from the second layer in the process. In places where heavier clays were at or near the surface, the high-speed disc-tillage machine; might loosen and soften the clay. Spading or delving would not be appropriate as the depth to clay is too shallow.
- Sand and gravel over clay >25cm (green zones) had water repellence and moderate compaction in the first layer. It was decided a one-pass rip (to a depth that scratched the clay layer) and mix, using an existing machine, was the best amelioration. But it was important drivers were vigilant and responsive to where this soil type starts and stops, because ripping too deep would bring conglomerate rocks to the surface.
- Sand over clay >25cm (cream zones) had water repellence and moderate compaction in the first layer. The solution was the Horsch Tiger to scratch the clay layer and mix the topsoil.

Using the resources and machinery they had access to, the order of implementation within a paddock was:

- apply variable rate gypsum and/or lime;
- shallow rip with Horsch Tiger;
- high-speed disc-tillage machine; and
- roll the areas that had been shallow-ripped.

Amelioration strategies were trialled in year one (including on a whole paddock) to assess their effectiveness, check the accuracy of the soil type zones, and perfect the mapping and amelioration processes. This then meant the trials could be extrapolated to similar soil types across the block, so that in year two and beyond amelioration could be scaled up with confidence.

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GLOSSARY

Electromagnetic (EM) survey

- EM surveys measure apparent soil electrical conductivity (ECa) which is an indirect measure of salinity. It is also indicative of soil texture and moisture. EM surveys are usually ground-based. Most agricultural surveys use dual-EM, which integrates ECa to depths of 0.5m (shallow) and 1.5m (deep).

Gamma radiometrics

- Measures the radiation from naturally decaying radioactive isotopes to help predict mineral composition and texture of the soil. Data is commonly collected for the isotopes of potassium (K), uranium (U) and thorium (Th). Gamma radiometrics mostly works in the top 0.3m but can work to 1m depth.

Normalised Difference Vegetation Index (NDVI)

- NDVI shows how 'green' the crop is. It is calculated from satellite data. NDVI results are presented as a colour map where each colour corresponds to a certain range of values. Normally, red-orange-yellow tints indicate bare soil or dead/sparse vegetation (or low plant biomass), and shades of green are a sign of medium to dense vegetation cover (higher plant biomass).

Productivity gap map

- Farm or paddock map showing where there is potential to improve yield by removing soil constraints.

Soil change map

- Shows where the main soil types and properties change across the farm.

Soil amelioration map

- Shows what soil constraints are on the farm, where they are located, and what area they cover. The soil amelioration map is generated using the soil change map, productivity gap map and ground-truthing data.

Yield consistency

- How consistent (or variable) yield is in a paddock over time.

Yield relativity

- How the yield at each point within the paddock compares to the yield at all the other points within the paddock. Yield relativity is calculated by comparing yield averages over several seasons. It can show consistently higher and poorly performing areas.

Ternary map

- Generated from a radiometrics survey. Shows potassium, thorium and uranium on a single map.

Yield uplift

- The expected increase in yield from undertaking soil amelioration.

Net Present Value (NPV)

- Accounts for the time value of money. For example, $5 today may be worth less than $5 in 10 years' time.

USEFUL RESOURCES

Geoscience Australia - Digital Elevation Data
http://www.ga.gov.au/scientific-topics/national-location-information/digital-elevation-data

Geoscience Australia – Radiometrics
https://www.ga.gov.au/scientific-topics/disciplines/geophysics/radiometrics

GRDC Deep Ripping separate Fact Sheets (for southern, western and northern regions):
https://grdc.com.au/correcting-layers-of-high-soil-strength-with-deep-tillage-western-region

GRDC Fact Sheet - Dealing with dispersive soils – Western Region
https://grdc.com.au/resources-and-publications/all-publications/factsheets/2020/dealing-with-dispersive-soils-fact-sheet

Natural Resource Information for Western Australia
https://maps.agric.wa.gov.au/nrm-info/

A simple guide for describing soils
https://www.agric.wa.gov.au/identifying-wa-soils/simple-guide-describing-soils-0

Soil information across Australia
https://www.soilscienceaustralia.org.au/about/about-soil/soils-data-maps-and-information-sources/

SoilMapp
https://www.csiro.au/en/research/technology-space/it/soilmapp

Soil quality and technical information
http://soilquality.org.au/

WA data – for landscape maps
https://data.wa.gov.au/

Soil Quality ebooks

- Available on Apple Books, the *Soil Quality* ebooks are a free interactive learning resource for farmers, agricultural professionals and students. Expert knowledge, interactive maps, virtual field and laboratory experiences, case studies, scientific evidence and industry perspectives make this series of publications a credible, integrated information source on soil quality in agricultural systems, presented in layers of information allowing readers to choose the level of detail they require.

Soil Quality: 1 Constraints to Plant Production

- An overview of soil constraints presented as an interactive learning experience using video, case studies, diagrams, text and maps. This ebook discusses critical soil functions, factors influencing production, soil quality indices and constraints to plant growth, industry priorities, economic impact and monitoring of soil quality at the farm scale. Link: https://books.apple.com/nz/book/soil-quality-1-constraints-to-plant-production/id1317079117

Soil Quality: 2 Integrated Soil Management

- Harnessing a vast amount of research information and data in an easy to navigate format, as well as industry perspectives, video tutorials and case study discussions; this ebook examines major soil constraints such as soil acidity, compaction, water repellence, alkalinity and sodicity, and other difficult to manage soils. It explores each constraint's impact on production, including industry priorities and economic impact, before examining several management scenarios such as precision agriculture and monitoring soil quality at the farm scale. Link: https://books.apple.com/nz/book/soil-quality-2-integrated-soil-management/id1350650941

Soil Quality: 3 Soil Organic Matter

- This ebook discusses the current soil organic matter status in WA's south-western agricultural region; the composition and contribution of organic matter to soil function and resilience; how to measure changes in carbon stocks and on-farm management. Using graphics, case studies and video; the ebook provides answers to commonly posed questions about soil organic matter and how this relates to soil function and soil quality. Link: https://books.apple.com/nz/book/soil-quality-3-soil-organic-matter/id1444338744

Soil Quality: 4 Soil Acidity

- This ebook provides current evidence for soil acidity status in WA's south-western agricultural region for surface and sub-surface soils; considers degradation and management of the soil resource in a broader context; describes the chemistry of changes in soil pH and associated impact on plant and soil. Using calculators, graphics, case studies and video; the ebook provides answers to commonly posed questions about nutrient availability and soil biology in acid soils; providing clear guidelines on assessing and managing soil acidity. Link: https://books.apple.com/nz/book/soil-quality-4-soil-acidity/id1484613085

Soil Quality: 5 Soil Biology

- This ebook focuses on soil biology for WA and includes current knowledge on best practice soil techniques in an easy-to-navigate format. It includes information on beneficial and disease-causing organisms and the influence of the environment and management on soil habitats which impacts on soil production and resilience.Link: https://books.apple.com/au/book/soil-quality/id1554057153

APPENDIX 1 – SOIL RECORD SHEET

Soil record sheet						
Paddock:		**Site no:**	**Date:**		**Photo time:**	
Soil name: GPS no./coordinates:			Surface gravel:		Non-wetting	
Layer	Depth	Gravel/rocks	Texture	Colour	pH	Notes
1						
2						
3						

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