IMPACT STORY
Transforming sandy soil productivity in the Southern cropping regions of Australia

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Challenge

Across the Southern regions of Australia, growers have been observing 'water left behind' after growing crops in sandy soils. This poor crop water use is due to several constraints in sandy soils that present challenges for crop production. Soil amelioration to overcome high soil strength, water repellence, and low fertility has been shown to profitably improve crop production, and efforts to better understand the situations in which to apply amelioration practices have gained strong momentum in recent years. There is the potential for the conversion of large areas of sandy soils to more productive and resilient farming systems in the Southern cropping regions of Australia.

CSIRO Agriculture & Food's response

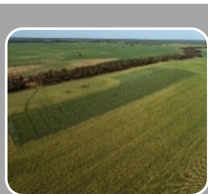
CSIRO's Agriculture & Food (A&F) Business Unit has a long history of collaborating with growers, advisers, farming systems groups, government agencies and universities across Australia to address soil and crop productivity issues. Improving the resilience and productivity of vulnerable and infertile soils across all season types has been a strategic focus area of CSIRO's Drought Resilience Mission. In alignment with CSIRO A&F's strategic focus, a team of A&F scientists with expertise in soils and farming systems and collaborators initiated a scoping review in 2015 to understand the constraints to productivity and innovations to improve them in the sands of the Southern region. This was followed in 2016 by a $9.3 million project funded by the Grains Research and Development Corporation (GRDC) that brought together CSIRO A&F, the University of South Australia, the South Australian Research and Development Institute of the Department of Primary Industries and Region (PIRSA-SARDI), Frontier Farming Systems, Mallee Sustainable Farming, Trengove Consulting and Ag Grow Agronomy. The Sandy Soils project aimed to increase crop water use efficiency in underperforming sandy soils in low to medium rainfall areas of south-eastern Australia by improving the diagnosis and management of constraints. The key outcome of the project was to provide, by June 2023, grain growers and their advisers in the Southern cropping region access to cost effective techniques to diagnose and overcome the primary constraints to poor crop water-use on sandy soils.

What was achieved

Over the course of 6 years, the Sandy Soils project made significant gains, summarised in Figure 1.

IMPROVED UNDERSTANDING OF SANDY SOIL CONSTRAINTS AND AMELIORATION TECHNIQUES

- High soil strength, water repellence, poor nutrient supply and low pH identified as key constraints to crop root growth, water use and crop productivity
- Ripping, ripping with inclusion, and spading shown to be cost effective soil amelioration techniques to address the key constraints



RANGE OF SOIL AMELIORATION TREATMENTS AND DATA MADE AVAILABLE TO GROWERS AND ADVISERS

- More than 100 sandy soil treatments trialled on-farm in a project involving growers, advisers, and researchers
- All trial findings made publicly available via a database, to allow evaluation of amelioration options in the context of a range of soils and climate

INNOVATIONS IN TILLAGE-BASED MACHINERY FOR SOIL AMELIORATION

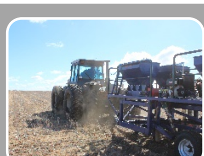
- Innovations made to tillage-based machinery (redesign of inclusion plates; custom-designed bar for one pass spade and sow; and strip spading to ameliorate paddocks in stages)
- Machinery innovations are easily adapted onto existing commercial machinery for more effective soil amelioration treatments, with lower application risks (i.e. soil erosion)
- Growers and advisers understand which tillage based machinery equipment is best suited and most cost-effective to treat the key constraint

IMPROVED CAPACITY TO MAKE EVIDENCE-BASED DECISIONS

- Growers able to make informed decisions about most suitable management options for improving sandy soils
- Growers have a better understanding of the various components in the decision-making process reinforced with a decision tree available on the SANDBOX app

IMPROVEMENTS IN CROSS-REGIONAL CONNECTIONS

- A diversity of industry representatives attended project events (growers, advisers, agribusinesses, contractors, banks and other agencies)
- Network of collaborators openly sharing knowledge and data to progress innovations in sandy soils
- Peer-to-peer exchange of knowledge and learning among growers



EARLY SIGNS OF ADOPTION

- Early indications that 50% of growers with constrained sands are using deep ripping on parts of their land in 2022 and planning to double the area ripped in the next five years.
- Growers are also using spading, deep ploughing and inclusion ripping to ameliorate constrained sands

Figure 1. Key achievements from the Sandy Soil project (photos: Sandy Soils project team)

Improved understanding of sandy soil constraints, amelioration techniques and crop yield responses, and cost-benefit of investment in amelioration. The Sandy Soil project has filled key gaps in knowledge regarding sandy soil constraints on crop root growth and water use, which affect crop productivity. Key findings suggest that hard-setting, compaction processes, and water repellence in sandy soils constrain crop root exploration and water use. Through scientific experimentation and a rigorous validation process, the project identified sandy soil amelioration techniques that can address these constraints and improve yields. In addition, return on investment and cost-benefit analyses generated estimates of the profitability and financial risks of different amelioration techniques. These multiple sources of analyses and information identified that mechanical amelioration techniques focused on changing the soil profile (i.e. tillage) as the best combination of managed cost and positive yield response. Further experimentation provided additional information on how to best set-up and use ripping, spading and inclusion ripping machinery to optimise yields and reduce the costs.

Filling the above knowledge gaps was key to providing growers and their advisers a range of soil amelioration options to consider for further trials on their farms. It also helped growers and advisers to think through the relevant components of costs, expected yield responses and financial risks associated with each option.

Range of soil amelioration treatments and data made available to growers and advisers. Over the course of the project, a total of 128 treatment combinations were developed and assessed for their effectiveness in improving crop productivity; in providing economic returns; and in minimising risk. A total of 35 on-farm trial sites were used to test these treatments which were managed by the Sandy Soils project team. A Sandy Soil Sandbox Tool (https://shiny.csiro.au/soil-sandbox/) was developed to provide growers and advisers access to tools to diagnose the key soil constraints on their farms, the results of on-farm trials, and soil management options for the four most prevalent sandy soil constraints. Having access to this data and options has been instrumental in helping growers better understand the pros and cons of different soil amelioration practices and to support their greater adoption.

Innovations in tillage-based machinery for soil amelioration. The Sandy Soils project's engineering team (University of South Australia) developed some innovative engineering solutions to facilitate the implementation of more effective soil amelioration treatments. These innovations also aimed to reduce application risks (such a soil erosion) and be easily adapted onto existing commercial machinery. The engineering team looked into the concept of topsoil slotting practice which was introduced via Western Australia research in early mid-2010s to promote topsoil layer inclusion into a deep ripped profile. The team then optimised this practice (renamed 'inclusion ripping') for performance and reliability, using advanced computer simulations of soil-tool systems, via DEM modelling. The development of knowledge around how the inclusion ripping process naturally occurs, and what avenues exist for optimisation, led to the redesign of inclusion plates and the optimisation of settings behind the deep ripping tine for improved inclusion performance and energy efficiency. Modular designs were then tested to demonstrate the impact of key design features on inclusion capacity and drawbar power requirement. These improved designs were developed and used by the Sandy Soil project team to enhance soil and crop responses. They also demonstrated a more cost-effective application of inclusion ripping for the amelioration of deep sandy profiles, relative to the deep ripping practice adopted across most cropping regions of Australia. This uniquely Australian innovation is being explored for use into broader soil contexts.

Other technological innovations in the Sandy Soils project included the development and evaluation of an innovative solution for integrating crop seeding into spading machines which mix sandy soil and amendments down to 400mm depth. The engineering team adapted seed banding coulters for a soft seedbed onto a custom-designed floating bar fitted within the spader itself for connection to an air-seeding source. This system allows for one pass 'spade and sow' soil amelioration, alleviating the need for a separate crop seeding operation (typically challenged by poorly trafficable soft seedbed conditions) and minimising the risks of soil erosion with groundcover able to establish rapidly and uniformly. The Sandy Soils project application of this innovation showed higher emergence efficiency and better seed placement than the baseline practice of seed broadcasting pre-spading or during spading informally adopted by growers in the region.

The engineering team also modified an existing spader technology for ameliorating paddock in stages, such as under a strip amelioration format allowing for zones in between 400mm wide spaded strips to retain full residue cover and protect bare strips against erosion. An existing spader was modified to successfully evaluate a proof-of-concept 'strip-spade and sow' treatment, with the experiences shared with the manufacturer who pursued a commercial option. The concept of strip amelioration and strip farming has seen recent innovations and larger scale demonstrations, which may prove a safer way to ameliorate paddocks that are highly exposed to soil erosion risks.

Improved capacity among growers to make informed, evidence-based decisions about management of sandy soils on farm. The Sandy Soils project has supported growers in making decisions about their management of sandy soils. In comments provided by growers at the Sandy Soils events, they highlighted the importance of carrying out pilot tests on their sands to better understand soil constraints, assessing how to address them, understanding the amelioration treatments and how to manage the treated soil, and being aware of the complexity of the soil and treatments. These comments demonstrate growers' increased understanding of the various steps in sand amelioration decision-making processes – i.e., the need to clearly define the problem and identify the key soil constraint, to develop and implement a plan, and to evaluate the results so that improvements can be made.

Improved cross-regional connections. The Sandy Soils project has fostered stronger connections across the diverse environments with sandy landscapes in the southern region. Over the course of the project, there has been a shift in both the way that various groups have collaborated to find innovative solutions to constraints of sands and in the diversity of industry groups participating in project events. This was most notable in the end-of-project masterclass workshops which involved presentations from soil scientists, agronomists, agricultural engineers, economists, and farm advisers, often with cross-regional representation. Participants were diverse and included growers, advisers, machinery dealers, contractors, banks, and land valuers. Machinery company dealers' engagements in these forums focused more on learning to better engage with growers, and less on pushing their products. The Sandy Soils project also played a key role in facilitating the exchange of knowledge both with and between growers. The project's six Sandy Soils Masterclass events were delivered as a Roadshow in 2022, and a second Roadshow was held in 2023. These events saw the attendance of both growers who had not adopted sandy soil management techniques and growers who were implementing some techniques and wanted further information to refine their ongoing activities.

Early signs of adoption of soil amelioration practices among growers. There is evidence of potential uptake of sandy soil treatments[1]. Growers indicated that they expect to substantially increase the

[1] Source: 57 growers surveyed at Sandy Soil Roadshows (2022).

proportion of their sandy soil that they will treat using mechanical treatments in the near future[2]. If growers' expectations come to pass, only 23% of cropped sandy soil in the southern region will escape being treated in the next five years. Both growers and advisers also indicated that they expect that mechanical treatments will be more profitable over larger areas of sand than non-mechanical treatments. It is important to note, however, that these early signs of adoption vary across growers and the types of soil management practices they are using (solely mechanical, solely non-mechanical, and different mixtures of mechanical and non-mechanical practices) and whether their farms are in low or medium rainfall zones. The Sandy Soils team found in the survey feedback from growers attending the roadshow, those who were not treating their sandy soils in any way reported that they would be doing something in the future. They expect to carry out deep ripping on 41% of their sand area and non-mechanical treatments on 12% of their sand area in the next five years. And those who are currently not carrying out mechanical treatments are not only expecting to enthusiastically adopt deep ripping but also other mechanical practices such as clay spreading and delving. The cost of treatments compared to the potential returns are higher for the low rainfall zone compared to the high rainfall zone for both mechanical and non-mechanical treatments. This is seen in the lower proportion of sandy soil area that is expected to be profitable for non-mechanical treatments in the low rainfall zone. The more similar expectations in both rainfall zones for the mechanical treatments may be pointing to the more convincing returns and rapid payback periods of mechanical treatments.

The Sandy Soils project has also contributed to positive changes within CSIRO and A&F. Some of the notable contributions are:

Broadening of horizons across expertise in the soils and systems space across CSIRO. The Sandy Soils project involved multiple staff across A&F Programs, which resulted in better harnessing of soils expertise for the delivery of farming systems solutions.

Improved alignment between A&F strategic priorities and new GRDC funding. This improved alignment set a leading example of the impact that can be delivered through fewer, bigger investments led by CSIRO. The Sandy Soils project demonstrated A&F's capacity to lead complex projects across multiple institutions with an agile approach that allowed the project team to vary the workplan according to the most impactful portfolio of research. An example of this was the project team's decision to redirect significant investment in the partnership with the University of South Australia when it became clear that optimisation of the set-up of machinery, combined with new options to improve tine design would deliver increased impact on-farm.

Strengthening of CSIRO's role as a trusted advisor. CSIRO is strongly positioned as the trusted advisor for Australia due to the organisation's legacy and rich experience in delivery of high-quality soils and agricultural systems research. A&F's leadership of the Sandy Soils project leveraged CSIRO's experience and track record in coordinating and delivering innovative agricultural research across region/state boundaries. Additionally, the objectives of the project were strongly aligned to A&F's *Resilient Farming Systems Impact Area* objectives including contribution to increased profitability over cycles of drought, diagnostics for yield gaps and data-driven decision making.

[2] This varied for the different soil amelioration options, ranging from growers reported that they estimated that they would increase their area of sandy soil treatments between 1.3 and 1.5 fold for delving, deep ploughing; 2.2 fold for deep ripping; and 3 fold for clay spreading.

How it was achieved

Capability

The successes of the Sandy Soil project can be partially attributed to the diversity of scientific and other capability that team members and project partners brought to the project, and its adaptive and bespoke approach to bringing in different skills as needed:

Multidisciplinary capability. The team brought together a diverse and complimentary set of science and technical capability. The CSIRO members of the team had expertise in soil science, agronomy, economics and farming systems. Soil scientists and agronomists from the State Government of South Australia's Department of Primary Industries and Regions (PIRSA) were also involved in the project and played a key role in the delivery and co-ordination of some regional research sites. The University of South Australia had agricultural engineering capacity which was key to helping identify the best tillage techniques to overcome a constraint, and to innovating and optimising the design and implementation of tillage with growers. Additional science capacity included two postdocs who were brought in to drill down into specific problems linked to soil constraints and to the engineering of soil mixing.

Expertise in regional delivery. The Sandy Soils project team also included key partners with additional expertise that was critical to the success of the project. This included independent research providers (Frontier Farming Systems, Trengove Consulting and AgGrow Agronomy) who managed experimentation in the Yorke Peninsula, Mallee and southern NSW environments in collaboration with the project team. The team also worked with key groups with expertise in regional delivery, which included capability in extension and communications (co-ordinated by PIRSA-SARDI). They engaged with 3-4 farming systems groups operating in the regions to help set up and manage key events, including the Sandy Show Masterclass events, and worked with GRDC communications and grower groups personnel to develop videos, podcasts and groundcover content.

Adaptive, bespoke approach to capability requirements. Capability brought into the Sandy Soil project shifted over time. The team brought in key expertise as needed. For example, once the team realised that the technology was heading towards heavy machinery, the team reached out to Pinion Advisory Pty Ltd, an agribusiness partner specialising in the analysis of machinery investments. This allowed the team to link the economic cost-benefit analyses conducted by CSIRO team members to farm-scale analyses of machinery investment.

This approach to integrating different capability, and adapting it as needed, enabled the Sandy Soil project team to flexibly and effectively respond to emerging needs, opportunities, and challenges.

Connections and responsiveness

The way the team connected and was responsive to the broader agribusiness sector in the region also was important. This included who they connected with and how those relationships changed over time. These are discussed further below:

Previous relationships, track records and projects. The Sandy Soils project built on previous relationships and R&D with growers and key industry groups in the southern region of Australia and with GRDC. It also leveraged CSIRO A&F's track record in addressing soils and crop productivity issues and built on key findings from previous scoping studies on sandy soils. These were instrumental in enabling the CSIRO team to bring together growers, universities, state government agencies, independent research providers, farming systems groups, and independent farm advisers to secure a 7.3 million (AUD) investment from GRDC. Securing such significant funding, for 6 years, provided the Sandy Soils team the necessary financial resources and security to build a team and partnerships with the right mix of individuals, organisations, and groups, and capability, required for the success of the project.

Collaboration with growers and local networks of agricultural advisers and farming systems groups. The project worked directly with growers across 35 different farm locations. Conducting experiments on their farms with different intensities and different scales was critical to adapting and refining the sandy soil amelioration techniques/technology. The growers also played a key role in advocating the work and providing feedback. This included helping diagnose soil constraints and providing feedback during the application of soil treatments, as well as providing advice on how to best reach out to other growers. The latter was instrumental to the success of the project as there is a lot of competition for growers' time and attention; their calendars tend to be packed and it is critical to be able to clearly articulate what is different in what one is offering.

Growers in the region have a history of working with agricultural advisers, and most growers have established relationships with specific individuals in the project team. The Sandy Soil project team reached out to several advisers who provided independent critical review of project progress and direction along with the whole-farm profit-risk case studies that were developed collaboratively between CSIRO and Pinion Advisory Pty. The team also engaged with 3-4 farming systems groups operating in the regions. These provided a direct link to growers and were instrumental in helping set up and manage key events such as the Sandy Show Roadshows.

Engagement with agribusiness sector. The project also worked with agribusiness partners. In addition to the economic expertise that Pinion Advisory Pty Ltd contributed to the team (discussed above), involving agribusiness partners in discussions that scientists had with growers on-farm bolstered scientists', and the project's, credibility. It also helped change the nature of discussions with growers. Additionally, the team provided opportunities for machinery company dealers and contractors to learn about the range of soil treatments and emerging findings. As a result, machinery companies have become more interested because of existing relationships and the opportunity to secure contracts for sales of machinery that are modified based on project recommendations.

Extension and communications to broaden connections and remain responsive to emerging feedback and opportunities. The Sandy Soils team pursued a range of extension and communication activities which have included presentations at GRDC updates, field crop walks, technical meetings and other industry events when the opportunity arose. They hosted two 'roadshows' through a series of Masterclass events where they visited approximately nine locations (across Central EP, Upper EP, YP, SA Mallee, Vic Mallee and NSW Mallee) to present the key messages for diagnosing and managing soil constraints in low-medium rainfall sandy soil environments. In addition, a range of visual and written outputs including fact sheets, succinct reports, workshop presentations, journal publications, and the Sandy Soil Sandbox Tool have been made widely available to growers and advisers, and a broader audience (key project partners, GRDC, scientists and others interested in soil amelioration).

These extension and communications activities played a key role in connecting different groups together – including within the agricultural industry sector in the region (e.g. growers, advisers, machinery companies, other agribusiness companies) and beyond (e.g. growers and scientists). They also were critical to connecting these groups and others to the findings and new knowledge being generated by the project, and in doing so, raising broader awareness and understanding of both the complexity of, and tangible options for, improving sandy soils. The field crop walks, technical meeting and other industry events, and other consultation activities enabled two-way exchange and learning among growers and scientists which was instrumental to the Sandy Soils capacity to be responsive and adaptive. This ensured the soil amelioration treatments trialled were guided not just by the science but also growers' needs and constraints.

Engagement with other R&D groups working on sandy soil amelioration. The project also reached out to the Sandy Soils research teams led by DPIRD in Western Australia, who have a long history of working with growers on soil amelioration. Connecting with WA provided an opportunity for two-way learning, as the work in WA and Sandy Soils project were quite different, due to inherent differences in the sandy landscapes in the two regions which, when combined, exceed 8M ha of cropped land. Connections with soil amelioration R&D internationally also have been fostered through the Global Sands Conference (Wisconsin, USA, June 2023). This has led to CSIRO hosting the next conference in Adelaide in 2025.

Science and technological offering

The Sandy Soils project's scientific and technological contributions built on an extensive body of previous soils and crop production research, and soil amelioration trials, but also pushed the horizons of those areas of work. These were key to the project's scientific and technological achievements.

Small preliminary studies as building-blocks. Gaining a better understanding of the effect of constraints in sandy soils have for crop yields and building on that to inform potential soil amelioration techniques, was recognised as being an important first step towards pushing the scientific and technological horizons in sandy soil amelioration. In 2015, a smaller project was funded which mapped the extent of sands in cropping land of the Southern region, reviewed the existing research, and surveyed growers for their existing sands management strategies. The findings from that project, along with a long history of CSIRO research seeking to improve the agronomic management of crops in sandy landscapes, allowed CSIRO to play a leadership role in the Sandy Soils Project investment. The first phase of the Sandy Soils project involved a series of in-paddock meetings with growers across the project geography where key issues and management strategies were discussed. This initiated a series of paddock transects in which the key constraints of the sandy part of the paddock were measured and described.

Ongoing field trials, combined with deeper science investigation, to demonstrate robustness. The above preliminary steps led to the development of experimental designs which included amelioration based on mechanical (tillage) and non-mechanical (amendments) options and combinations of both. In addition, following some promising early observations in the first growing season of experiments, the project was varied to invest in a deeper understanding of critical science gaps. Two postdocs were added to the project to better understand the soil physical constraint (hosted by CSIRO) and to optimise soil mixing tillage techniques (hosted by UniSA).

Technology not pre-defined. The Sandy Soil project's starting point was not focused on a specific sandy soil amelioration treatment or technology but rather on a whole suite of possibilities with the aim of narrowing down options. Through a range of observations, it became apparent that the physical constraint to crop root development and resource use was presenting as a key constraint across almost all sites characterised, but the nature of this physical constraint was not well understood. Initial experimental results also indicated that tillage-based techniques to overcome the physical constraint were likely to present he most cost-effective options for growers.

Tailoring the terminology. Initially, there was a lot of reluctance by local growers around tillage as the technology to improve sandy soils. The reluctance was linked to growers' identity as custodians of the land and the historical association of tillage with soil erosion. The team was keenly aware that referring to the soil treatments as tillage could create anxiety and hamper uptake. The team deliberately replaced the term 'tillage' with the word 'amelioration' which had a more positive connotation of repairing a problem. The team also explicitly communicated from the start that mechanical treatment of soils via tillage was only going to be a cost-effective option if it was a treatment that had longevity allowing for infrequent and strategic use. The team also shared with growers and advisers the early results from the mechanical soil treatments. This helped them see the benefits that crops with high early vigour and ground cover, along with increased yield and therefore residue over summer, could present for managing erosion risk.

The team did not dismissed concerns regarding the potential damage that these mechanical soil amelioration treatments can cause. Part of the work with the engineers from the University of South Australia has been to continue to evolve the technology so that soil damage is minimised while still providing crop productivity benefits. The team also engaged in the robust groundcover project (listed in the appendix) which looked to innovate the amelioration strategies to reduce erosion risk (e.g. through strip amelioration and amelioration plus sowing strategies practices).

Technological innovation that is modular and can be used with existing machinery. Working with the machinery companies, and with growers and advisers, helped the team evolve the technology. This included innovations to existing equipment used by growers. Rather than starting from scratch and building a new machine to till the soil, the engineering team in the Sandy Soils project developed innovative modular inclusion plates that could be attached on existing machinery. The simplicity of this improved plate design and setting up solutions was met by strong grower interest, particularly via social media exchanges which facilitated self-made adaptations onto existing deep ripping equipment and started to influence the range of inclusion plate options provided by manufacturers. It also has led to growers and the project coming up with further ideas, such as the possibility of extending the adaptation of inclusion plates onto delving machinery as well as spader-mounted rippers to expand these machinery impacts on soil profile amelioration outcomes.

Delivery and scaling approach

Scaling and integration embedded from the beginning. From the very start of the project, the potential to scale the soil amelioration technology was embedded in the delivery approach. The project deliberately collaborated with independent research providers, such as Frontier Farming Systems, Trengove Consulting and AgGrow Agronomy, because they were regionally based, had a history of working with growers directly, and were directly involved in research including with CSIRO scientists. In addition, the farming systems groups MSF, AIREP, MFMG and NSS were key partners in the project for the delivery of communication and extension. Their deep connections in local communities and districts, and their approach to working with growers and researchers, made them very effective for supporting research delivery. Their expansive networks also made them good potential avenues for scaling out the research and technology.

Strong and regular engagement with growers was also key to the project's delivery. With any technology, there is the potential of an adoption/dis-adoption cycle. Cognisant of this, the project team 'book-ended' the project with roadshows, where they talked with growers and others in the beginning and at the end of the project. Part-way through the project there was a realisation that the rate of adoption was much faster than had been anticipated and the team was concerned that growers did not have sufficient understanding of how to optimise their machinery set up and operation for the tillage techniques they were utilising. Mindful of the potential of this leading to dis-adoption down the track, the team purposefully shifted to increase project investment in agricultural engineering for the development of key advisory factsheets. The aim of these factsheets was to ensure that the project made available to growers the evidence around the best tools for the constraint and optimised set up to manage the balance between increasing productivity while minimising erosion risk.

Focus on decision-making process around the technology. The team also moved away from a sole focus on the technology. The team worked with growers on the decision of an investment in amelioration by considering the questions of 'what's my problem?' – 'what are the tools available?' - 'what does are the likely responses when I implement these tools?' – 'what is the money I am going to make?'. The Sandy Soil Sandbox Tool supported growers to explore these various questions. This approach was not initially embedded but emerged as the team engaged with growers and recognised the importance of growers improving their understanding of, and decision-making process around, the application of the technology.

Looking back: key reflections and lessons learned

Supporting the right mix of partners and adjusting as you go is critical. Collaborations were key to the success of the Sandy Soil project. This is a common approach in farming systems research – you start with a core project team, and their partners have avenues to attract other investment for more localised issues and local partners. It is not uncommon that a project grows with supplementary projects and partners. Additionally, bringing in new expertise or partners as needed is critical. Project teams do not necessarily know at the start of the project who is needed. Partnerships and collaborations in farming systems projects need the flexibility to grow over time, as well as to shift. This requires flexibility, including financially, to adjust who joins and exits over the course of a project. In the Sandy Soil project, a total of six contract variations were implemented. These variations were made to add post-docs; a new program of work which delivered ~24 additional sites to the initially planned research experiments; a revised workplan to deliver increased focus on agricultural engineering; and the delivery of the roadshow event. A final variation was made to allow for increased publication outputs in the final stages of the project.

Balancing innovation and science can be challenging. Because of the innovation in the soil amelioration treatments, which were adapted based on feedback from growers and other partners, the team found that they had different treatments with different data. This posed a challenge for the analysis of the data. Additionally, the nature of the project at the start was to try everything in a very broad way; to trial >100 different treatment combinations. This risked nothing being refined and posed a challenge for demonstrating consistency and replicability of results for these treatments.

Additionally, because of the focus on developing treatments and technology that growers could apply on their farms, and doing this via extensive consultations with growers, there was less emphasis on understanding the processes that control the constraints on sandy soils. The team ended up being able to link the amelioration treatments to specific soil constraints and to ensure treatments were addressing those constraints, but it happened through a different route (development and on-farm testing of treatments, feedback from growers, then adjusting measurements and analyses to allow it to be linked it back to the constraint) than what the typical science route is (identification of constraint, then iterative processes developing, testing, and refining treatment).

Being aware of the technology adoption/dis-adoption cycle and identifying means to curtail dis-adoption is important but hard. Half-way through the project the team raised concerns about the rapid rate of adoption of deep ripping on farm and applying the technology to soils on which crops would not respond positively, but advisers suggested that growers would identify solutions to any problems that might arise. It was seen as being the biggest opportunity for the next step in scaling and delivery, and that the project team needed to allow growers to "figure it out" if they encountered any operational setbacks along the way. Mindful of the risk of dis-adoption down the line, the project team successfully convinced growers, and partners, to take a more considered, slower approach to adoption of the soil treatments.

Externalities. Land values have increased dramatically over the past decade at the same time as increased farm-scale has been seen as a means to improve farm profitability. Financial restrictions on the ability to purchase additional land and to scale has meant that the value proposition for investing back in poor-performing land has changed and that growers might be more likely to ameliorate sand than in the past. Machinery values also escalated in the project lifetime which may have effected adoption of sandy soil amelioration, especially among growers who needed to purchase both the tillage equipment and upgrade their tractor to pull the tillage equipment. Moreover, seasonal climate has also had an impact on growers' likelihood to adopt soil amelioration practices. A grower's income is very dependent on seasonal climate and anecdotal observations suggest that the proportion of growers who have invested in soil amelioration was higher in the Eyre Peninsula which over the course of the project had more seasons of above average rainfall than in the Mallee region which had several seasons of well below average rainfall.

Looking forwards – where to next?

The current Sandy Soil project investment will end on November 30, 2023. At the time of writing this impact story, a new investment was being negotiated around three key programs of work: (1) where, when and how to ameliorate sands in sandy landscapes (2) how to identify and realise the new yield potential in ameliorated sands, and (3) the enabling technologies to manage crop production in ameliorated sands (trafficability, nutrient inputs, time of sowing etc.). The table below provides a summary of insights gained from the current Sandy Soil project that could be taken into account in the design and delivery of future sandy soil amelioration R&D investments.

	LOOKING FORWARDS – CONSIDERATIONS FOR FUTURE SANDY SOIL AMELIORATION INVESTEMENTS		
	Do more of?	**Do less of?**	**Do differently?**
Connectedness and responsiveness	▪ Maintain the network of state agencies and independent research providers to address questions specific to a region (e.g. time of sowing, optimal N rate, crop choice, etc.). ▪ Engage with discipline specific expertise (e.g. engineering) outside of CSIRO recognising the role it has for our impact	Maintain collaborations that are not delivering for either party	Allow growers to be more engaged in the experimental design phase to ensure Participatory Action Research processes are active throughout the project
Science and technology offerings	Investigate the following questions: ▪ Where to start and stop with amelioration techniques in the landscape? What are the technologies that we can use to conveniently predict this? Once this is optimised, is it possible to better predict how long treatments will last? ▪ How will we feed the new yield potential in ameliorated sands? ▪ Can we further innovate the tillage techniques for cost-effective inclusion of amendments? ▪ How do we manage some of the paddock and farm level post-amelioration issues e.g. trafficability, erosion risk, investment risk?	▪ At start of project, the initial approach was to try everything in a very broad way. The risk was that by stacking all those treatments together you have nothing refined. There are some clues we got out of that work that allows us to refine those and have another look at them and explore what/if, under certain scenarios, other treatments could be added on top of what we are doing. ▪ Very large experiments that attempt to simultaneously address multiple research questions which can result in very context specific findings ▪ Small plots are highly controlled for traffic and are not the right experimental technique to address the question of traffic	▪ Multiple research questions might be best addressed in small standalone experiments delivered by our collaborators in the regions rather than trying to have all-encompassing complex experiments. ▪ There are some treatments that we compared on nutrient equivalence (e.g. fertilisers vs. manures). This created high salt loads and uneconomical treatments for fertilisers. We can refine these comparisons and even use blends of the sources. ▪ Better integration of small (plot) and large (strip and paddock) scale experimentation
Delivery and scaling	Maintain our regional presence and reputation as a trusted and engaged adviser in this research space	Events that are to meet a quota rather than events that are designed around a key new message/ finding that requires sharing and/or discussing	More strategic co-ordination of extension and communication would allow for more effective delivery and scaling

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APPENDIX 1. Sources of information and additional resources

Journal papers

McBeath T, Gupta V, Desbiolles J, Davoren B, Llewellyn R (2023) Seed row placement relative to the previous crop stubble row can harness systems benefits on water repellent sands. Crop and Pasture Science doi:10.1071/CP23157

Unkovich M, McBeath T, Moodie M, Macdonald L (2023) High soil strength and cereal crop responses to deeper tillage on sandy soils in a semi-arid environment. Field Crops Research, 291:108792.

Ucgul, Saunders, Li, Lee, Desbiolles 2018. Analysing the mixing performance of a rotary spader using digital image processing and discrete element modelling (DEM). Computers and Electronics in Agriculture 151 (2018) 1-10.

Factsheets

Measuring constraints on sands to inform management. Diagnosing sandy soil constraints: water repellence and pH extremes Factsheet https://grdc.com.au/diagnosing-sandy-soil-constraints-water-repellence-and-ph-south-west

Measuring soil strength with a penetrometer. Diagnosing sandy soil constraints: high soil strength Factsheet https://grdc.com.au/diagnosing-sandy-soil-constraints-high-soil-strength-south-west

Crop nutrition for sandy soils. Diagnosing sandy soil constraints: Nutrition Factsheet https://grdc.com.au/diagnosing-sandy-soil-constraints-nutrition-south-west

Understanding passive inclusion ripping https://grdc.com.au/inclusion-ripping-technology-national

Understanding the process of soil profile mixing with rotary spaders. Soil mixing by spading Factsheet. https://grdc.com.au/soil-mixing-by-spading-national

Technology considerations for cost-effective subsoil loosening. Ripping technology Factsheet. https://grdc.com.au/resources-and-publications/all-publications/factsheets/2022/ripping-technology-national-fact-sheet

Database via App

https://shiny.csiro.au/soil-sandbox/

APPENDIX 2. Summary of the projects involved in the Sandy Soil work

Project name and WBS	R-08786-01, Increasing Production on Sandy Soils in Low and Medium Rainfall Areas of The Southern Region
CSIRO team (lead + team members)	Therese McBeath, Rick Llewellyn, Lynne Macdonald, Jackie Ouzman, Bill Davoren, Willie Shoobridge, Rachel Hennessey, Masood Azeem.
Key partners	UniSA, PIRSA-SARDI, MSF, AIREP, MFMG, NSS, Frontier Farming Systems, Trengove Consulting, Unkovich Consulting, Pinion Advisory, AgGrow Agronomy.
Duration/time	2017-2023
Project name and WBS	CSP00195, Soil Constraints Initiative- Management of Non-Wetting Sands
CSIRO team (lead + team members)	Therese McBeath, Rick Llewelyn, Lynne Macdonald, Vadakattu Gupta
Key partners	Murray Unkovich, James Hall
Duration/time	2016
Project name and WBS	R-91117-01, Smart Farms
CSIRO team (lead + team members)	Jackie Ouzman
Key partners	Frontier Farming Systems, Trengove Consulting, AIREP
Duration/time	2022-2023
Project name and WBS	R-18274-01, DAWE Robust Groundcover
CSIRO team (lead + team members)	Therese McBeath, Bonnie Flohr, Belinda Stummer, Bill Davoren, Willie Shoobridge, Rachel Hennessey, Stasia Kroker.
Key partners	MSF, Frontier Farming Systems, AIREP, PIRSA-SARDI, UniSA
Duration/time	2022-2024