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Performance through collaboration

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Sandy soils: Organic and clay amendments to improve the productivity of sandy soils

Literature review

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Amanda Schapel, Richard Bell, David Davenport

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PROJECT OVERVIEW

An evaluation of the role of subsoil organic matter (OM) and clay amendments on subsoil root function, water and nutrient availability and biological processes.

The project will provide a clearer definition of the domain of sands and climates where clay and organic amendments are likely to deliver the most benefits, and which amendments appear promising for further testing.

We hypothesise that step changes towards high performance sands will come from permanently increasing reactive surface areas through the addition of clay, recalcitrant organic matter, or both.

SUMMARY

The fundamental limitation of sandy soils is the low reactive surface area. The limited capacity to supply resources, water or nutrients, to the roots of crops is the core reason for low productivity of crops and pastures on sandy soils. The breakthrough in high performance sands will be to permanently increase the reactive surface area with added clay, recalcitrant organic matter, or both to address the inadequate supply of resources.

There are an estimated 11.85 M ha of sandy soils in Southern Australia. Current practices to address constraints to production can be expensive (e.g., clay addition) or can create a high erosion risk (e.g. spading or mouldboard plough). Despite considerable field work, there is still not a clear understanding of why and when amendment options will be effective. The opportunity exists to develop novel amendments for long-term amelioration of sandy soils that require less material to be applied and be more cost efficient

The objective of the project is to increase the understanding of the benefits of current treatments by conducting a meta-analysis of relevant experiments and demonstration sites across Australia with clay and or organic matter addition to sands. The meta-analysis will be informed by a review of international and Australian literature and will highlight gaps in current knowledge.

The project aims to:

- characterise amendments in relation to improving the productivity of sandy soil
- examine the effect of amendments on the physical, chemical and biological properties of sandy soils
- identify the diversity of effective soil amendments available to land managers, or to better match current amendments to particular soil and regional scenarios, to drive improvements in farm productivity and profitability
- identify novel organic and clay amendments that can improve amelioration practice, longevity and increase in profit.

BACKGROUND

Sandy soils are used for agriculture in many regions of the world but are generally not considered high performance soils (Usowicz and Lipiec 2017). Deep sands (Arenosols) cover approximately 900 million hectares (M ha) of the world's surface (FAO/UNESCO 1995) with the highest proportion in Africa (51%) followed by Australasia (21%) (Yost and Hartemink 2019). Profiles of other soil groups with deep sand over clay (e.g. Regosols, Leptosols, Fluvisols) often share similar characteristics to deep sandy soils.

It is estimated that there are 11.85 M ha of sandy soils in Southern Australia (2015 Dataset from State agencies) comprising 7.05 M ha of sand over clay and 4.8 M ha of deep sandy soils (Table 1). Western Australia has the largest distribution of sandy soils located across the wheat belt and southwest coastal regions. In South Australia, sandy soils occur across large areas of the Eyre Peninsula, South East, and Mallee regions, whilst Victoria has smaller areas concentrated in the Mallee. In New South Wales, sandy soils are scattered throughout the south-west cropping belt and are also common (up to 30% of the landscape) between Ardlethan in the east and Cobar in the north west (Haskins and Whitworth 2016).

Table 1. Area of sandy soil in Southern Australia. Data compiled from State Agencies (2015).

	Area (M ha)			Area (Proportion as %)		
	Sand over clay	Deep sand	Total	Sand over clay	Deep sand	Total
ACT	<0.01	0.00	<0.01	0	0	0
TAS	0.13	0.04	0.18	2	1	1
NSW	0.22	0.12	0.34	3	3	3
VIC	0.82	0.49	1.30	12	10	11
SA	1.45	1.57	3.02	21	33	26
WA	4.42	2.58	7.00	63	54	59
TOTAL	**7.05**	**4.80**	**11.85**	**100**	**100**	**100**

Agricultural productivity on sandy soils is low, often only achieving 30–40% of water-limited yield potential (Hall et al. 2010; Macdonald et al. 2019). As sandy soils represent at least 20% of the Australian cropping area (Scanlan et al. in press), it makes economic and environmental sense to achieve high performance from these soils. Constraints to production on sandy soils are most evident in the broad acre grains industry, mixed farming, and livestock grazing systems.

CHARACTERISING SANDY SOILS

Sandy soils have inherently low water-, nutrient- and organic carbon-holding capacity, are prone to compaction, water repellence, wind erosion, acidification, and leaching of nutrients beyond the rootzone. Therefore, sandy soils have restricted capacity to supply water and nutrient resources to the roots of crops.

Depth of sands varies with some having clayey subsoils (duplex soils) within the potential plant root zone. Depending on depth, these soils can have higher nutrient and water storage than deep sands but clays are often poorly structured, restricting root growth and causing temporary waterlogging. Low amounts of organic carbon levels can affect nitrogen mineralisation leading to inefficient use of nitrogen fertiliser.

Sands often have multiple limitations hence diagnosis and treatment of the main constraints to production needs to be a key focus for raising their productivity (Hall et al. 2020). With multiple limitations, there will generally be a weak response to inputs unless the key constraints are overcome at the same time.

For the purposes of this study, sandy soils are defined as soils with less than 10% clay content in the surface 30 cm of soil and include sands (<5% clay), loamy sands (5–8% clay), and clayey sands (8–10% clay). Such profiles fall within the Australian Soil Classification orders Kandosol, Tenosol, Calcarosol, Ferrosol, Rudosol, Kurosol, Chromosol, and Sodosol (Isbell 2002). The proposed Arenosol order for ASC will incorporate deep sands currently classed as Tenosols.

Key sandy soil groups

The groups of sandy soil considered in this review include:

- Deep sandy soil > 90 cm to B horizon (4.8 M ha)

Deep sandy soils have sandy textures greater than 90 cm in depth. Subsoils are differentiated from topsoils by stronger colouration caused by changes in clay, iron oxide, or fine carbonate contents. They have often formed in sediments deposited and reworked by wind (Hall et al. 2009).

- Sand over clay (7.05 M ha)

Sand over clay (duplex soils if the sandy A horizon is less than 70 cm depth) soils have sandy topsoil and a distinct colour and texture boundary to the clayey or clay-loamy subsoil. Some sandy duplex soils feature a bleached subsurface layer (A2 horizon) which is generally 10 to 60 cm thick and especially infertile. Shallow variants are defined when subsoil clay is within 30 cm of the soil surface (Schoknecht 2002). Topsoils are often aelioan in nature but clay translocation has been a dominant soil-forming process in many of the profiles (Hall et al. 2009).

Gravelly sands can occur in both sandy soil groups of interest. They are considered to have greater than 15% gravel (> 2 mm in size). Gravel can affect hydraulic conductivity and water retention in sandy soils. Ironstone gravel has been reported to increase plant available water-holding capacity with the greatest effect expected in water-limited cropping regions where yield is constrained by restricted root growth (Scanlan et al. in press). The presence of gravel affects applied amendments and machinery used to incorporate them.

While sandy soils vary across a continuum, they have a number of distinctive properties that can be used for classification.[1]

[1] *For a thorough review of constraints to crop production on sandy soils in south-eastern Australia, see Unkovich 2014.*

ORIGIN

Parent material is the most significant single determinant of soil properties as they have particular properties that influence the soils formed from them (Hall et al. 2009).

Newsome (2000) examined the origins of the deep sand profiles on the Victoria Plateau in WA and concluded that they were derived from in situ deep weathering. There was little evidence of aeolian re-working of these sand materials. Elsewhere however, aeolian processes best explain the origin of the deep sands in southwest Australia (Commander et al. 2002).

Geological origins and geomorphic processes affect the shape and size of sand particles. Grain shape (rounded or angular) can influence root growth with lower wheat root length and higher soil strength observed in sands with angular particles (Lipiec et al.2016; Scanlan et al. in press). Sandy soils can be derived from siliceous or carbonaceous parent material. Siliceous sands are generally neutral to acidic in pH and carbonaceous sands are often strongly alkaline.

Particle composition

Sandy soils have a high percentage of sand and a low percentage of clay particles. The proportion and type of clay, silt and sand (coarse, medium and fine) particles determine many soil properties, including nutrient- and water-holding capacity, soil structure, storage and protection of organic carbon. The combined effect of clay and silt (fine fraction) is important for properties such as water and organic carbon (OC) storage. The fine fraction has a larger surface area than the coarse fraction (sand) enabling higher amounts of water and nutrient to be held. The fine fraction is a key driver of soil organic carbon storage through stabilisation of organic matter via interaction with the mineral surface (Wiesmeier et al. 2019). In sandy soils, silt particles may be particularly important as they have been reported to double water storage with a doubling of the clay plus silt fraction (Bell et al. 2015). The relative concentration of these fractions is also important with silt and clay, potentially increasing cementation leading to high resistance to plant root penetration.

Therefore, in sandy soils, small differences in composition of the fine fraction can deliver important differences to soil properties and hence have a strong effect on management. A sandy soil with 5% clay will have substantially greater reactive surface area for nutrient and water reactions than those with 1% clay.

PRODUCTION INFLUENCES

Nutrient-holding capacity

Surfaces of clay minerals and organic matter (colloids) are generally negatively charged and attract positively charged cations such as calcium, magnesium, potassium and sodium. The number of exchange sites in the soil is expressed as the cation exchange capacity (CEC) and is an indicator of the inherent fertility of a soil.

Low clay and organic matter concentrations in sands results in low CEC, poor pH buffering, and low nutrient retention. As a result, management practices can induce rapid and substantial changes in soil properties and can have compounding effects such as an inherently low CEC being further reduced by soil acidification. Nutrient deficiencies common on sandy soils include nitrogen (N), phosphorus (P), potassium (K), sulphur (S), zinc (Zn), manganese (Mg), copper (Cu), cobalt (Co), boron (B), molybdenum (Mo), and selenium (Se) (Moore 2004). Soil pH can affect nutrient availability. On calcareous sandy soils, phosphorus, manganese, zinc, and iron deficiencies occur with the degree largely determined by the fine carbonate content. On acidic sandy soils, toxic levels of soluble aluminium can severely inhibit root growth.

Soil pH also influences the soil's CEC through variable surface charge on the colloids. As pH increases, the density of negative charges on the colloids increase, effectively increasing CEC. The permanent component of CEC has been regarded as derived predominantly from the aluminosilicate clay fraction while the variable charge component is mainly in the organic matter fraction, the broken edges of kaolinite clays and oxyhydroxides of iron and aluminium (Loveland and Webb 2003). Net positive charge can develop on acid sands dominated by variable charge (Wong and Wittwer 2009). Sorption of nitrate and sulphate increases when acid sands develop positive net charge, and conversely leaching of these anions is inhibited and delayed.

Ions, solutes (including pesticides), and water can readily leach past the root zone and be lost from the root area or cause groundwater contamination, due to the high permeability of sandy soils. Phosphorus can leach on very pale sands even at low concentrations in the soil (Sharma et al. 2015; Sharma et al. 2017; Sharma et al. 2021). This is unique to some sandy soils as phosphorus leaching doesn't occur on any other soil texture class unless available levels are well above critical levels for crops (Sharma et al. 2017).

Water-holding capacity and plant available water

Water availability is a major limitation in most Australia rain-fed agricultural systems, and hence soil water-holding capacity strongly affects plant productivity. Water-holding capacity is primarily controlled by soil texture (particle size) and organic matter. Sands have lower total water-holding capacity than clays because of the lower proportion of capillary and micropores.

Heavier textured soils generally outperform sandy soils due to higher water storage and their ability to maintain crop water supply despite unreliable rainfall during critical growth periods. However, sandy soils often outperform heavier-textured soils during low rainfall seasons with regular small rainfall events. This is because sandy soils are able to acquire plant available water quickly after light showers due to their low wilting point (Maschmedt 2000) so the majority (~60%) of soil water is plant available, and significant volumes of water can penetrate deep enough to slow evaporative losses.

Low plant available water storage in sandy soils can also be induced by restrictions to root growth resulting from factors such as pH, fertility, and compaction. The importance of overcoming these restrictions to root growth was demonstrated by a 0.62 t/ha increase in grain yield (56 kg/ha/mm efficiency) from an additional 10.5mm of water extracted post-anthesis from the 1.35–1.85 m layer in a Kandosol subsoil (Kirkegaard et al. 2007).

As sandy soils have low clay, and often low clay plus silt concentrations, organic matter can strongly influence their water-holding capacity. The effects of organic matter can be direct or indirect through increased infiltration resulting from improved structure.

Water repellence

Sandy soils can be susceptible to water repellence restricting the uniform infiltration of rainfall into the soil. Water repellence causes uneven and variable wetting of the soil, leading to increased run-off, patchy plant germination and emergence, and poor utilisation of nutrients as plants cannot access nutrients in the resultant dry patches of soil.

In agricultural soils, water repellence is primarily caused by waxes produced during the breakdown of crop and pasture residues. Due to the low surface area of sands, these waxes coat a larger fraction of the soil surface than a more clayey soil. Water repellence does not necessarily occur every year, but is more common in years of low, early winter rainfall (Maschmedt 2000).

Water repellence affects more than 10 M ha of arable sandy soils in Southern and Western Australia (Roper et al. 2015) with greatest problems on soils with less than 3% clay content (Unkovich 2014).

Soil structure

Soil structure is important for air and water movement into the soil and is vital for healthy plant growth. Structure describes the arrangement and organisation of the solid soil particles and the pore spaces surrounding them. In all but loose sands, individual clay, silt, and sand particles arrange themselves to form peds or aggregates. This creates intra- and inter-aggregate pore spaces that change the flow of air and water and storage of organic matter. The amount and type of clay and the amount, shape and size of sand grains affects the way the soil particles pack together.

Soils with little clay can be hard and massive due to high proportions of silt or very fine sand. These particles, when mixed with small amounts of clay, iron, manganese, and aluminium oxides, can cement soil particles forming a compacted layer. The presence of materials such as calcium can also bind inorganic and organic compounds. Generally, stable aggregation is strongly influenced by iron and aluminium oxides in humid soils, and by organic matter in semi-arid soils.

Organic matter plays a key structural role in soils, providing the ‘glue’ between particles to maintain pore spaces between silt and sand particles. It supports soil biological activity whose exudates and fungal hyphae are important for soil aggregation. In a pot experiment using a sandy soil, increases in aggregate stability were largely attributed to the growth of hyphae that cross-linked sand grains in the aggregates with little involvement of microbial polysaccharides (Degens et al.

1996). Fungal hyphae may be integral to accessing moisture stored in micropores preventing a rapid haying off seen in plants and could enhance drought tolerance (Allen 2007). The mechanisms of how reverse flows (hydraulic redistribution from plant to fungus) works is not well understood but the ultimate importance of mycorrhizae in plant–water relations depends on drying patterns, soil pore structure, and number of hyphal connections extending from the root into the soil (Allen 2007).

The low organic matter, clay, and water-holding capacity of sands generally limits aggregation, making them susceptible to wind erosion if there is insufficient surface cover. Wind erosion can strip fertile topsoil, further limiting the available resources for plant growth in sandy soils.

High soil strength

Soil structure deterioration causes high soil strength. High subsurface soil strength induced by cropping is a major limitation in sandy soil. Tillage and the surface tension created when soils dry, as well as heavy machinery and the compressive force from the weight of the machinery, all contribute to high soil strength.

A sandy soil with a wide distribution of sand to clay particles (broad range of particle sizes) will compress more readily than a sand with a narrow particle distribution; e.g., a coarse sand with little clay (Scanlan et al. in press). Smoother sand grains (rounded) are more likely to compact than rough grains (Scanlan et al. in press).

High soil strength and bulk density reduce root growth, affecting crop yield. Values exceeding 2.5 MPa for soil strength and 1.6 gcm^{-3} for bulk density (McKenzie et al. 2002) are commonly used as upper values indicating restrictions to root growth.

Reactive surface area

Reactive surface area is a combination of surface area per unit mass and chemical reactivity per unit soil mass. CEC is the most common measure of chemical reactivity and captures the ‘activity’ of chemical reactions at the surface of clay-sized minerals and organic matter. Other measures include anion exchange capacity, P buffering index, and soil organic matter content. A kaolinite clay particle has about 1,000 times the external surface area as the same weight of sand particles (Table 2). This greater reactive surface enables higher adsorption and release of nutrients.

Table 2. Estimates of surface area (square metres per gram) and chemical reactivity (CEC in cmol per kg) of various soil minerals (adapted from Hall et al. 2009, Hoyle 2013, Lonappan et al. 2016, Yang et al. 2019)

Mineral/Amendment	Specific surface area (m^2/g)	Chemical reactivity (CEC cmol/kg)
Sand	0.01 – 0.1	< 2
Silt	1.0	0-2
Kaolinite	5-100	1-20
Biochar	50-500	10-120
Illite	80-200	10-40
Iron and aluminium oxides	100-400	0-4
Smectite	280-750	60-150
Vermiculite	300-500	80-150
Zeolite	500-800	150-450
Organic matter	550-800	40-200
Humus	800-900	250-400
Allophane	1000	25-150

The addition of materials to sandy soil with higher reactive surface area such as clay, organic matter, or materials high in sesquioxides, should permanently increase the reactive surface area in the soil. This will improve soil nutrient as well as water-holding capacities through the associated benefits of aggregation and soil structure. Ultimately, plant growth on amended sandy soils should be improved as key constraints to production are overcome. Increased biomass growth in turn increases the amount of organic matter added to soils.

Organic matter and carbon

Soil organic matter has received significant attention for its critical role in maintaining or improving agricultural soils. Organic matter (OM) is essential for a number of physical, chemical, and biological processes (Baldock and Skjemstad 1999) including; creating aggregates of soil particles, stabilising structure, increasing water infiltration and overall water holding capacity, storing and releasing nutrients, and improving cation exchange and buffering capacity (Baldock 2007; Hoyle 2013; Murphy 2014). It has a critical role as a food source for soil organisms, increasing their diversity and activity so they can cycle nutrients and compete with pests and pathogens (disease suppression). Organic carbon (OC) is the carbon associated with OM, typically between 40–60%, and is used as a laboratory measure of OM.

Increasing soil OC content has been linked to improved land management, fertility, water-use efficiency, productivity (Chan et al. 2003; Lal 2004; Liddicoat et al. 2010; Sanderman et al. 2010), reduced erosion, increased resilience against the impacts of climate change (Paustian et al. 2016), and OC storage (Lal 2007).

Organic carbon comprises four actively decomposing fractions: dissolved, particulate, humus and resistant. As OM is transformed, it becomes more nutrient rich, and recalcitrant (resistant to decomposition by soil microbes). Long-term OC storage is only possible with biological transformation of particulate OC to more stable OC fractions, humus, and resistant OC, as less stable forms are more quickly lost from the soil following disturbance (McLeod et al. 2013).

Organic matter fractions are affected by different factors. Under Australian conditions, particulate OC decreases with soil depth and is influenced by management and climate factors, whereas humus OC increases with depth and is influenced by soil texture (Davy and Koen 2013; Hoyle et al. 2016). The proportion of the fractions in the total soil OC pool is more important than the total size of the pool (Loveland and Webb 2003) or the starting OC of the soil (Hijbeek et al. 2017). Transformation from the particulate to humus fraction could be limited in soils with insufficient nutrients (Kirkby et al. 2013). A near constant C:N:P:S ratio for the humus fraction can provide a reliable basis on which to determine the extent that availability of N, P and S might limit the building of SOC through the humus fraction (Kirkby et al. 2011). For micro-organisms to efficiently transform organic matter to humus, additional nutrients may need to be added (Kirkby et al. 2014).

Microbes produce and consume OC and there is a need to balance the dual role of mineralisation and stabilisation. Stabilisation of OC is important for ensuring efficient adsorption whereas decomposition (mineralisation) releases nutrients for plant growth.

PRODUCTIVITY IN AGRICULTURAL SYSTEMS

Agricultural systems need to be economically viable and environmentally sustainable. Each agricultural system has a potential productivity that is determined by the available water, temperature, sunlight, and nutrients. If there are factors limiting crop growth and production, then the potential productivity will not be achieved. Productivity is measured by the amount of biomass grown in grazing systems or the yield of cropping systems.

Comparing the biomass or grain yield of an amended soil to unamended control provides a relative measure of productivity. Alternatively, the measured yield can be compared against a modelled yield that considers the amount of rainfall and this is known as the water-limited yield potential or water-use efficiency (Holzworth et al. 2014).

Water availability is a major limitation in Australia’s dryland agricultural systems. In sandy soils, water-limited yield potentials are often between 30–40% (Hall et al. 2010; Macdonald et al. 2019). Management strategies can help crops achieve higher water-limited yield potential. Some limiting factors to productivity are relatively easy to overcome through management strategies whilst others are more difficult and expensive.

BUILDING SOIL FUNCTION AND RESILIENCE

Resilience to challenging times can be inferred from lower (coefficient of) variation of yield measured over time for amended relative to unamended soil (Chen et al. 2017).

Reductions in crop yields are common in drought stressed agricultural systems and are likely to become more frequent with climate change. To balance this, soil amendments are often used but typically only lead to marginal improvements (Kallenbach et al. 2019). However, biological amendments and biostimulants may improve the crop's capacity to better tolerate climate change (Farrell et al. 2017a).

Microbial biomass and activity can be more sensitive indicators of change in soil function than total soil OC (Wiesmeier et al. 2019). Changes in the ratio of soil microbial biomass C to soil OC can indicate if a soil is losing or gaining OC. A higher microbial biomass carbon to OC ratio can indicate more efficient microbial turnover, and correlation to soil chemical parameters may identify limiting factors in OM turnover (Wiesmeier et al. 2019).

RELATIONSHIP BETWEEN PRODUCTIVITY AND ORGANIC CARBON

Although soil OC is considered critical to soil function, its relationship with productivity is often questioned due to differences in soil texture, climate, and land use (Oldfield et al. 2019).

Studies on eroded soil have shown that a reduction in OC is linked to reduced crop yields, however increasing OC does not necessarily lead to increased yield (Celestina et al. 2019). Increased crop yields over the last 50 years have occurred despite reported decreases in soil OC (Loveland and Webb 2003). Yield is often assumed to drive OC levels but Oldfield et al. (2019) demonstrated whilst there was an initial linear relation between yield and OC, this stabilised by 2% soil OC. Loveland and Webb (2003) proposed critical soil OC values of 3.5% for clay textured soil and 1% for sandy soil. This corresponds to Kay and Angers (1999) critical value of 1% for soil OC below which the soil's capacity to perform key functions is constrained, such as supply of nitrogen from plant residue, effectively preventing crops from reaching the water limited yield potential.

This indicates that whilst OC is an important factor in increasing crop yield, other explanatory variables, such as mineral nutrition, are also important.

CHALLENGES FOR SANDY SOILS AND HOW THEY CAN BE OVERCOME

The fundamental limitation of sandy soils is their low reactive surface areas. This leads to limited capacity for supplying resources (water or nutrients) to the roots of crops, resulting in low yields of crops and pastures. The breakthrough in improving the performance sands will be by permanently increasing their reactive surface areas with added clay or recalcitrant organic amendments to address the lack of supply of resources to plants.

The addition of amendments should increase soil OC. In sandy soil, a value of 1% OC appears to be an effective critical value for sandy soils below which the soils capacity to perform key functions is affected (Loveland and Webb 2003; Kay and Angers 1999). One of the most important effects of low OC levels is the reduction in the soil's capacity to mineralise nutrients. This means an increased reliance on other forms of nutrient supply either from synthetic or organic sources.

Oldfield et al. (2019) found that increasing soil OC is not directly substitutable for using inorganic nitrogen fertilisers in high input systems, however at lower rates of nitrogen input (< 50 kg ha^{-1}), increasing soil OC from 0.5% to 1% could potentially maintain yield and reduce nitrogen fertiliser inputs by about 50% for wheat crops. Therefore, increasing the OC content could help reduce nitrogen inputs and potentially help close the yield gap on sands in rain-fed cereal cropping in Australia.

For micro-organisms to efficiently break down organic matter to humus, mineralise nutrients for plant growth and ideally increase soil OC concentration, the addition of supplementary nutrients may be required (Kirkby et al. 2013). For every 1000kg of humus, the soil will also require 80 kg of N, 20 kg of P, and 14 kg of S to enable the biological process to occur (Kirkby et al. 2014).

An increase in soil OC is also important for the nutrient holding capacity of the soil. Sandy soils can have very low (< 2 cmol(+)/kg) CEC and an increase in OC by 1% can increase CEC by approximately 2.2 cmol(+)/kg which can contribute as much as 85% of the CEC (Hoyle 2013) improving the buffering capacity of the sandy soil. Furthermore, a 1% increase in OC can increase the available water-holding capacity by 1.4 to 1.9 mm per 10 cm with greater response in a sandy than clayey soil (Minasny and McBratney 2018).

However, for increases in productivity to be realised, it is critical to identify and address all key soil constraints.

Many inherent properties of sandy soils can be addressed or alleviated in agricultural systems such as better crop rotation selections to improve nutritional or disease issues and overcoming some constraints to root growth. Some properties are only partly alleviated (e.g. nutrient supply and low OC), whilst others deteriorate further due to management systems and practices used (e.g. water repellence and acidification).

AMENDMENTS FOR SANDY SOILS

Mitigation strategies

Improvements in the performance of sands have been achieved using mitigation practices (deep ripping, liming, zero tillage) however they are still only achieving 30–40% of water-limited yield potential (Hall et al. 2010; Macdonald et al. 2019).

Improved yields of 5–15% on sandy soil can occur using mitigation options including winged and paired-row seeding points, on-row seeding and soil wetting agents as observed in a Western Australian study (Davies 2016). These are low-cost options when compared to one-off, long-lasting amendment options such as clay amendment that are of higher cost but higher yielding (30–40%).

Mitigation practices do not permanently improve the reactive surface area of sandy soils.

Addition of organic amendments

Organic matter is considered critical for soil health and successful plant production. Application of organic amendments to sandy soils can improve the reactive surface area and nutrient and water use efficiencies.

Fertilisers derived from organic sources are often nutrient-rich but vary in chemical and stoichiometric properties (Chen et al. 2018) with nutrient content highly dependent on the source and quality of the amendment (Quilty and Cattle 2011). Farrell et al. (2017a) identified that generally only the nutrient-rich composts and manures enhanced nutrient availability for wheat compared to unamended control soils. They found a general lack of evidence for efficacy of other biological inputs such as microbial, humates and biostimulants within rain-fed, broad-acre systems.

Biochar produced from manure, greenhouse waste, and grasses were more effective in providing nutrients than wood-based products that were better for carbon sequestration (Singh et al. 2014). The authors also found that increased yield was more likely in acidic rather than alkaline soil, and that the high reactive surface area of biochars can decrease herbicide and pesticide efficacy. Pre-loading biochar with nutrients may prevent the adsorption of herbicides and pesticides, and provide a source of nutrients whilst increasing the nutrient-use efficiency of future fertiliser applications (Singh et al. 2014).

An understanding of the major soil constraint and chemistry of the organic amendment is critical to make an informed prediction about the impact of the amendment on soil properties (Farrell et al. 2017a) and plant productivity.

Effect of organic amendments on yield

Addition of biochar and compost to sandplain soils of WA increased crop yield to a maximum of 8% in the first three years with no significant difference attributed to organic amendments thereafter (Hall and Bell 2015). They concluded that increases in yield were largely due to direct nutrient addition with the organic amendment and this dissipated over time (by three years).

Chen et al. (2018) found that among the waste-derived organic fertilisers:

- Biosolids had a very strong effect on crop yield but were associated with high contaminant loads making them more suitable for nutrient recovery than direct application.
- Poultry litter had high nutrient load and pathogenicity but did not significantly increase crop yield when compared to addition of inorganic fertiliser. However, composting poultry litter decreased the pathogenicity and enabled direct application to crops, producing yields comparable to inorganic fertiliser addition.
- Cattle manure resulted in crop yield comparable to inorganic fertiliser addition and was suited to direct crop application without composting.

In these cases, waste-derived fertilisers yielded as well as conventional inorganic fertilisers (Chen et al. 2018). In contrast to other soils, there is evidence that the addition of organic amendments to sands increases crop response above that of inorganic fertilisers alone (Chen et al. 2017; Hijbeek et al. 2017; Loveland and Webb 2003). In the sandy soils of northeast Thailand, the response to inorganic fertiliser was poor unless organic materials were also added (Ragland and Boonpukdee 1987). The addition of organic matter has been suggested to increase the buffering function of soil, decrease the demand for mineral fertilisers (if organic inputs and inorganic fertilisers are combined), and reduce the variability in yield (Hijbeek et al. 2017).

Careful consideration needs to be given to the selection of organic amendments to ensure that nutrient-use efficiencies are maximised while minimising risk to the environment by leaching of nutrients or risk to human health through contamination of the food chain.

Effect of organic amendments on OC

The low nutrient- and water-holding capacity of sandy soil makes it difficult to increase OC content (Hall et al. 2010) as low reactive surface areas of sandy soils enables only minor amounts of OC to be stabilised and protected. The remaining OC inputs are readily broken down and lost as CO_2 via microbial decomposition.

To ensure a consistent supply of benefits from organic amendments, frequent applications of organic amendments may be required (Farrell et al. 2017a; Oldfield et al. 2019). However, even with the addition of organic amendments, sandy soils do not have the reactive surface area to retain nutrients, moisture, or the ability to stabilise OC. Permanently increasing the reactive surface area of these soils will ensure sustained benefits. There might also be merit in deep incorporation of organic amendments to slow their rate of decomposition.

Addition of clay amendments

Clay addition to sandy soil can offer a long-term solution to increasing the reactive surface area thereby improving the supply of resources to plant roots. In Australia, subsoil clay addition to sandy soil has been used as a farm management practice since the 1970s (Cann 2000). It is a practice commonly used in South Australia, Western Australia, and Victoria, and was first used to overcome water repellence (Harper et al. 2000; Ma'shum et al. 1989; Ward and Oades 1993) but a number of other benefits have been realised.

In Australia there are approximately 7.5 M ha of sands used for agriculture that are suitable for clay addition: 4.5 M ha in WA; 2.5 M ha in SA; and 0.5 M ha in Vic and NSW. Of this, it is estimated that 0.2 M ha of sandy soils have already been amended with clay (Bell 2016). The most common methods of clay amendment are addition of clay-rich subsoil to the surface of the sand (spreading), elevation of in situ clay-rich subsoil throughout the soil profile (delving), or inversion (mouldboard plough) of the topsoil and clay-rich subsoil layers (Davenport et al. 2011). Selection of the appropriate method is determined by the depth to clay-rich subsoil and the available machinery (for further details see Appendix 1). The amount of clay-rich subsoil added, its clay percentage, and the depth of incorporation into the sandy profile determines the clay concentration, distribution of clay clods, and OC stabilisation capacity of the engineered soil.

Due to the low buffering capacity of sands, the complex chemical, physical, and biological processes that influence plant growth can be quickly altered with management practices.

Soil pH of subsoil clay added to sands can also influence nutrient availability. In South Australia, subsoils are often alkaline due to the presence of calcium carbonate, and application often raises the pH of the clay amended sands. In acidic sands this can increase productivity due to the liming effect (B. Hughes, personal communication), but the application of too much calcium carbonate can reduce yield through induced nutrient deficiency of Zn, Fe, Cu, and Mg. In Western Australia, subsoils are often acidic and application of low pH subsoil to sand can induce aluminium and manganese toxicities and deficiencies of P, Ca, Mg and Mo.

In clay-amended sands, water-limited yield increased to about 70% of the potential based on rainfall (Hall et al. 2010). Hall et al. (2020) argued that subsoil compaction may remain as a yield limitation after surface clay-amendment of sands at Esperance, WA. The tillage processes required for clay amendment can overcome physical limitations such as high bulk density and soil strength caused by compaction (Usowicz and Lipiec 2017). Increased root growth following clay amendment has been reported (Bailey et al. 2010; Hall et al. 1994) and this should lead to improvements in productivity.

Effect of clay addition on soil water

Clay addition to sandy soil has been reported to increase water retention (Betti et al. 2015; Ogunniyi 2017; Schapel et al. 2018a) and decrease saturated hydraulic conductivity (Betti et al. 2016). Added subsoil clay in the field is not homogenously mixed, but distributed as clods ranging in size from a few mm up to greater than 200 mm (Schapel et al. 2019) in a sandy matrix.

Betti et al. (2016) found that clods less than 6mm in size added to sand retained more water than clods greater than 6mm as an intimate mixture of smaller pores was created compared to a bimodal mixture where clods existed as discrete entities in a sand matrix.

Boldt-Burisch et al. (2013) demonstrated that clay clods embedded in sandy soil act as water and nutrient ‘hot spots’, improving pea plant and root development. They found sandy soil had many large pore spaces and very few small pores due to insufficient OM to bind sand grains into larger aggregates. Conversely the compacted, clay clod had many small pores and few large pores.

Modelling of water movement in sandy soil with the addition of various sized clay clods demonstrated that water uptake by plant roots occurred from the sandy soil (Schapel et al. 2018b). The size of the clay clod affected the speed of water flow with higher velocities for small clods (5 cm) than for the large clods (10 cm) because of the number of connected flowpaths. Clod size did not affect transpiration or drainage rates.

This discontinuous, stop/start flow of water and nutrients to plant roots in sandy soils is different to the continuous flow of water in loam or clay soils and could affect a number of properties including plant productivity.

Effect of clay addition on yield

Internationally, improved yields have been reported in Thailand with the addition of bentonite to sandy soil for forage sorghum (Noble et al. 2001) and Turkey with the addition of pumice to increase water-holding capacity (Ozhan et al. 2008). The addition of 60–120 t bentonite (montmorillonite) per hectare to a sandy soil in Poland was found even after 37 years to increase OC, total N, water, microbial activity, and structure (Czaban et al. 2014; Czaban and Siebielec 2013). Field trials comparing the effectiveness of bentonite and kaolin addition to sandy soil in the United Kingdom determined that both amendments increased crop growth and yield, increased CEC, OC, C:N ratio, microbial activity, nutrient efficiency, water retention and soil pore characteristics (Ogunniyi 2017).

In Australia, yield increases between 20–130% (Davenport et al. 2011; Hall et al. 2010) have been reported following addition of clay-rich subsoil to sandy soil. Consistent and significant yield increases around 50% were obtained from clay amendment of deep sands after 15 years following the addition of 200–300 t of subsoil clay per hectare at Esperance, Western Australia (Hall et al. 2017). In South Australia, yield increases (68–97%) were obtained eight years following 200-250 t clay concentration per hectare (Schapel et al. 2018a). Similar yield increases across three trial sites in South Australia (60–95%) were recorded five years following clay additions of 450-600 t subsoil clay per hectare. A doubling of yield in the fifth year demonstrated the longevity of the treatments (M. Fraser, personal communication, 2019). Nevertheless, similar yield responses were obtained at a number of sites where soil mixing occurred to 30 cm without added clay.

A number of studies have reported decreases in crop yield, due to the addition of clay or clay and OM to sandy soil (Bell 2016; Ogunniyi 2017; Schapel 2018). High levels of early biomass growth ‘hay off’ during critical spring periods with limited rainfall. This generally occurs on sites where clay addition and incorporation depth are not suited to the rainfall or farming system. Decreased yield can be attributed to unsuited clay addition rates, particularly in the surface 10 cm, that can lead to changes to soil properties that negatively affect plant growth. These include decreased plant available water, increased bulk density, surface sealing, and high pH (Davenport et al. 2011; Schapel et al. 2018a), and nutrient deficiencies.

Effect of clay addition on OC

The addition of clay to sandy soil (clay amendment) can increase OC storage through binding to clay surfaces (Baldock 2007; Skjemstad et al. 1993) and by occlusion in aggregates formed by clay (Tisdall and Oades 1982). Subsoil clay should have high potential for OC stabilisation as saturation of the mineral particles surfaces by bound C is unlikely to have occurred (Lützow et al. 2006).

In field studies, OC was compared after subsoil clay addition to an untreated sandy soil. Hall et al. (2010) reported a 0.2% OC increase in the top 10 cm, eight years after clay addition. Bailey and Hughes (2012) found a 0.4% increase in OC in the bleached A2 horizon up to seven years after addition of subsoil clay. Schapel et al. (2017) reported OC increases of 0.1 to 0.5% in the surface 30cm equating to an increase between 1 to 22 t ha^{-1} (average 10 t ha^{-1}) in OC stock three to nine years after addition of subsoil clay.

A meta-analysis of 49 clay-amended sites in South Australia demonstrated an average increase of 4.9 t C ha^{-1} above that of comparable unamended sandy soils (Schapel et al. 2018b). Annual rainfall influenced the size of the OC stock change with the largest increase of 8.2 t C ha^{-1} at 350–400 mm rainfall, and a decrease of 1 t C ha^{-1} where rainfall was greater than 600mm.

Incorporation of additional organic matter during the clay amendment process led to higher OC stock compared to treatments without OM addition (Schapel et al. 2018a) and may offset the loss of OC resulting from soil disturbance. Olchin et al. (2008) observed that the negative disruption to OC through tillage appeared to be offset by slower decomposition of residues when they were incorporated to 30 cm compared to 15 cm.

Modelling has shown that sandy topsoils are often close to OC saturation and practices that enable OC to be stored deeper in the soil profile are needed to increase OC storage (Hoyle et al. 2013). There is potential for additional OC storage at 20–30 cm (Schapel et al. 2018a) in clay-amended, particularly delved, soil. Plant roots have an important role increasing OC at depth through increased root biomass, root exudates, and sloughing of cells. The OC in the area surrounding the root (rhizosphere) is much higher compared to the bulk of the soil. The root exudates encourage microbes deeper into the soil and, in doing so, transforms OC through the fractions from particulate to the more recalcitrant humic form. This is important for increasing reactive surface area and hence nutrient and water storage.

Physical inaccessibility of OM is an important factor to consider in sandy soils. The rate of sorption to minerals and occlusion in aggregates is determined by the mineral surface area (Woolf and Lehmann 2019). Microbial produced OM is preferentially associated with the clay mineral (Sokol et al. 2019) so adding clay to sand will benefit by providing more sorption sites and creating an environment that is more conducive to microbial activity. It could be important to provide a continual source of OM (e.g. through repeated OM application or increased root growth) because even in clay-amended sandy soils the clay concentration is low (often less than 10%) and hence the physical accessibility of OM to microbes is high.

Stabilisation of OC will depend on many factors including sesquioxide, calcium and clay concentrations, clay mineralogy, and formation of complexes and stable aggregates (Rasmussen et al. 2018). In acidic soils, chemical stabilisation can occur through binding of OC to hydroxyl groups of iron and aluminium (Saidy et al. 2012). Iron oxides improve aggregation that can limit access to microbes to OC within aggregates (Singh et al. 2018). In alkaline soils, chemical stabilisation is largely through formation of stable aggregates and complexation with calcium carbonate (Fernandez-Ugalde et al. 2011; Rasmussen et al. 2018; Rowley et al. 2018).

Field trials comparing the effectiveness of clay with different mineralogy found that kaolin is as, if not more, suitable than bentonite to improve sandy soil characteristics (Ogunniyi 2017). They found that kaolin amendment increased nutrient uptake and anion retention compared to bentonite, and when kaolin was combined with OM produced higher CEC, available water and spring wheat yield than combined bentonite and OM at the same application rate. The low pH in kaolin was found to reduce soil microbial activity and resulted in less carbon mineralisation than bentonite with a higher pH.

Although kaolinitic clay may have lower capacity for OC stabilisation than other clay minerals due to low CEC and surface area, addition to siliceous sand could result in higher OC stabilisation capacity and crop growth than other clay types by addressing water repellence and plant available water limitations. Kaolinite and illite clays are more effective than smectite or vermiculite clays in alleviating water repellence (Ma'shum et al. 1989) as the kaolin spreads more readily over sand grains and remains evenly distributed after drying (Ward and Oades 1993). To counteract the low CEC and water retention of kaolin, it is recommended to apply it with 20% OM (Ogunniyi 2017). Consideration of the pH of the applied subsoil will also be important to optimise soil microbial activity and OM mineralisation.

This demonstrates that sandy soil amendments cannot be chosen on a single characteristic but need to encompass an array of features. Identification of the sandy soils key constraints to production (e.g. water repellence, soil pH, annual rainfall) is critical to ensure that a suitable product is chosen to optimise yield and mineralisation and stabilisation of OM.

Mechanisms to improve yield following clay addition

Clay addition to sandy soil can have positive productivity and OC impacts through mechanisms including (Figure 1):

1. Overcoming water repellence – increasing the clay content to over 3% in the topsoil overcomes water repellence, leading to more plant numbers with greater early vigour.
2. Reducing frost damage – due to the low heat and water retention of sands, crops on sands are prone to frost. A reduction in frost damage through higher heat storage has been reported to increase yields on clay-amended sands (Rebbeck et al. 2007) and may improve resilience in areas that experience more frequent and severe frosts due to climate change.
3. Provision of plant essential nutrients – applied subsoil clay can act as a medium to long-term pool to supply nutrient to plants when concentrations are high (Bell 2016). This can correct a deficiency and help achieve the yield potential of sandy soils with initial low fertility. Conversely, where subsoil clays are low in an important nutrient such as potassium, the nutrient deficiency can limit yield potential and financial return from clay additions. The chemical composition of the subsoil clay amendment must be determined to understand its effect on nutrient supply and plant growth.

4. Increase nutrient-holding capacity – clay amendments have been reported to increase soil fertility, CEC, OC, extractable S, Colwell P, and Colwell K, (Bailey and Hughes 2012; Hall et al. 2010; Schapel et al. 2018a). This can be through increased retention of nutrients via increased CEC and OC.
5. Increase water-holding capacity – clay addition to sandy soil has been reported to increase water retention (Betti et al. 2015; Ogunniyi 2017; Schapel et al. 2018a) and decrease saturated hydraulic conductivity (Betti et al. 2016). Increasing water storage capacity in sandy soils can improve plant productivity where low and seasonal rainfall limits growth (Usowicz and Lipiec 2017). Grain yield has been found to be more strongly correlated with water-holding capacity than OC stock (Schapel et al. 2018a) and can be specifically linked to soil moisture at grain filling (Ogunniyi 2017). Betti et al. (2016) found that the addition of as little as 10% clay-rich subsoil to sand significantly decreased saturated hydraulic conductivity but plant available water only increased when more than 20% clay-rich subsoil was added.
6. Improve flow of nutrients and water to roots – sandy soils have a discontinuous, stop/start supply of water and nutrients to plant roots due to poor connectivity of pore water channels. The addition of clay can exacerbate the problem, creating water and nutrient ‘hot spots’ in the clay clods and low concentrations in the sand. The addition of smaller clay clods (< 5cm) has the potential to increase the number of connected flowpaths (Schapel et al. 2018b, Boldt-Burisch et al. 2013) improving the supply of water and nutrients to plant roots.
7. Address higher nutrient demands of amended soil – it is critical to address the increased nutrient demands of a higher yielding soil. An increase in nitrogen supply is predicted in clay-amended soil, but further research is needed to clarify how to modify nitrogen fertiliser practices to achieve yield potential while minimising the risks of haying off (Bell 2016).
8. Create an improved environment for biological transformation of OC – enhance soil conditions to improve the transformation rate of particulate OC to the more stable humus fraction. Ensure soils have sufficient nutrition, if necessary through supplementation, to perform the biological process of transforming particulate OM to humus, thereby stabilising soil OC.

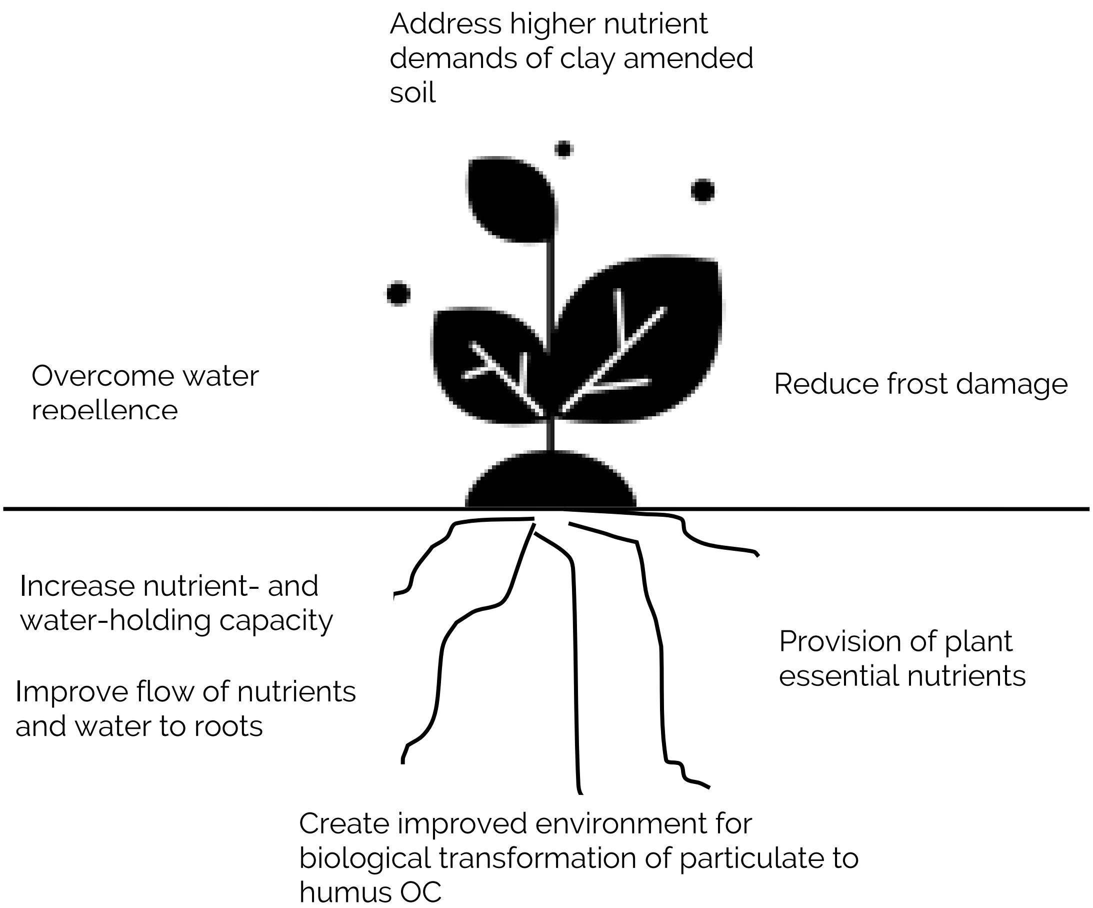


Figure 1. Mechanisms to improve plant productivity and soil OC following clay addition

Summary of clay amendments

Even with substantial improvements of sands after clay addition they are often still not high performing sands, achieving a maximum of 70% of the water-limited yield (Hall et al. 2010, Hall et al. 2020).

With current practices the addition of subsoil clay to sandy soil will largely be restricted to systems with suitable in situ subsoil clay, and availability of appropriate machinery. As suitable subsoil clay can be difficult or expensive to find at the high rates required to overcome limitations, novel products are required.

NOVEL PRODUCTS

Currently, amendments for sandy soils are limited to using in situ clays, on-farm OM, or importing materials from waste sources. Products that are applicable at lower rates, are readily- or locally-available, are as or more effective than current methods, and have the potential to greatly increase the use of amendments. Products that increase reactive surface area of sands when applied at low rates whilst being economic and deliver the same or better benefits of clay and OM will be attractive for commercialisation.

A review of national and international literature identified novel products for consideration in this project.

Industrial waste products

Application of fly ash from Kwinana Power Station in Western Australia to a sandy soil effectively increased soil water-holding capacity, hydraulic conductivity, turf plant nutrition and growth (Pathan et al. 2001; Pathan et al. 2003). Additions of fly ash (~10% clay and 50% silt) were added by weight (0, 5, 10, 20 and 100%) to sand (~4% clay and 2 % silt) and incorporated to 15 cm. Whilst nutrient and water retention increased with fly ash addition, water infiltration was progressively reduced and defined the maximum application rate at between 10 and 20% (Pathan et al. 2001).

Churchman et al. (2014) reported increases in OC in the surface 30 cm ranging between 0.10 to 0.65% resulting in increased stock of about 12 t ha^{-1}, 29 years after addition of fine-textured bauxite processing waste (85% silt, 11% clay and 4% sand) to sand.

Minerals

Most of the research on clay amendment of sandy soil in southern Australia has used locally sourced, low activity (kaolinitic) clay. While these have improved productivity of sands in many cases, greater benefits may be realised from the use of high-activity clay minerals (bentonite), minerals (zeolite, hydrotalcite), and clay-organic mixes (clay-fortified compost).

Hydrotalcite (HT) is a synthetic clay with high structural positive charge (~400 cmolc/kg) (Gillman 2006; Gillman et al. 2008; Jobbágy and Regazzoni 2005). The HT clays could be used in slow-release formulations of fertilisers alone or in mixtures with local clay to adsorb leached nutrient anions. Pre-loading phosphorus on HT could be explored to increase root proliferation in and around the HT granules.

A review by Nakhli et al. 2017 found that natural and surface modified zeolites have a large surface area, and can hold nitrogen, phosphate, potassium and sulphate within their structure and can act as slow-release fertilisers. Zeolites have a larger effect in sands compared to clay soils and decreased hydraulic conductivity whilst increasing nutrient retention.

Organic products

Based on the review by Chen et al. (2018), compost appears to be a promising organic material that could be used to enhance the water and nutrient supply to plant roots on sands.

C-Wise and Peats Soils currently make compost mixes with bentonite and zeolite clays. These products require assessment for their suitability as sand amendments and investigation of a greater range of rates and clay types (HT, bentonite, kaolin, Fe/Al oxides). Their effects on cation and anion exchange capacity, water-holding capacity, and decomposition rates in sands need to be determined. These organic materials also need to be tested in granulated formulations, along with unamended clays and composts, initially under leaching conditions for nutrient retention, and then in plant growth experiments.

Biochar is variably charged, with a high surface area and high porosity. When incorporated into soil, biochar has been shown to increase CEC and enhance the availability of macronutrients such as N and P (Kookana et al. 2011). Biochars produced from manure, greenhouse waste, and grasses were more effective in providing nutrients than wood-based products that were better for carbon sequestration (Singh et al. 2014). Loading biochar with nutrients or products such as goethite (L Van Zwieten, personal communication) can further improve its use as a novel sandy soil amendment.

Hydrolysed wool added to a loamy sand increased zinc and iron uptake and doubled yield and grain protein by wheat plants grown in a pot experiment (Gogos et al. 2013).

Kallenbach et al. (2019) evaluated 'lactobionate' a dairy-industry by-product added at a rate of 1.7% w/w to fine sandy loam in a laboratory experiment. They reported increased OC, water, and microbial content.

Super absorbent polymers

Hydrogels (super absorbent polymers) in agriculture are used to increase the amount of available moisture and nutrients in the rootzone in a controlled release formulation (Rajakumar and Sankar 2016). The effect is greater in sandy than clay textured soils. Reported benefits include increased CEC, reactive surface area water storage, fertility, microbial enzymatic activity, and decreased pH, bulk density, macro-porosity (Rajakumar and Sankar 2016).

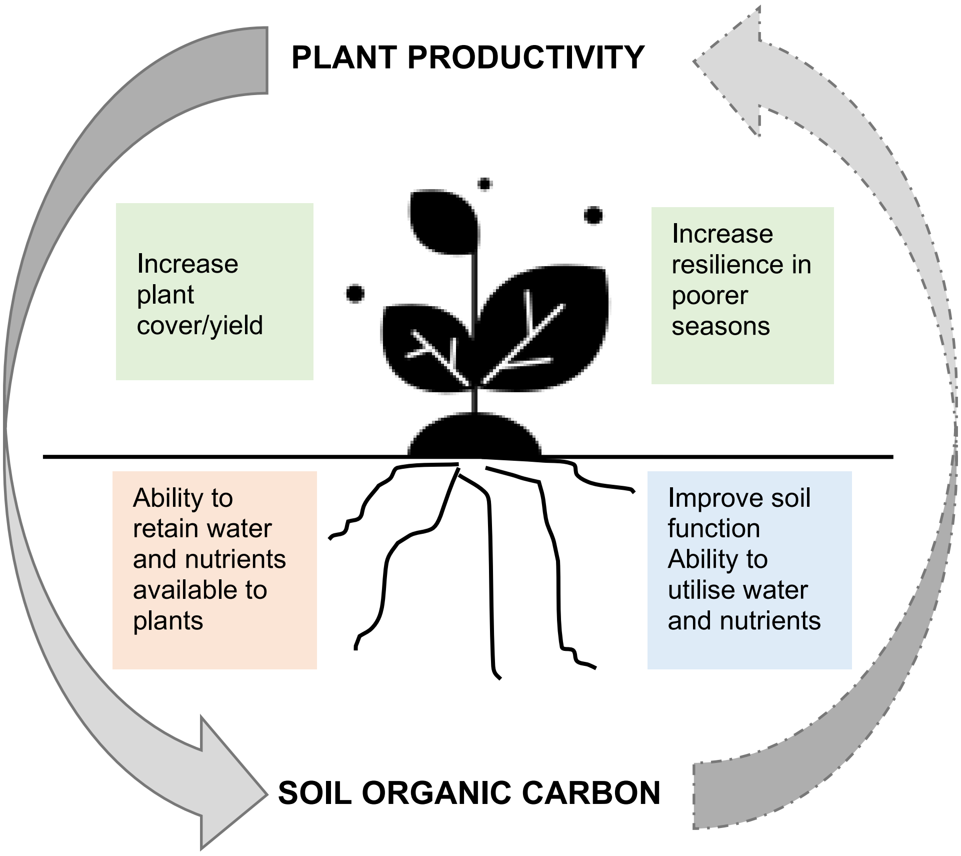
Zhou et al. (2016) reported that application of an amendment with a formulation of Na-bentonite (91%), humic acid (6%), Na_2CO_3 (2%) and plant cellulose (1%) at 30 t ha^{-1} to the soil prior to incorporation to 25 cm, increased maize yield by 23-41% over the five year monitoring period. Soil enzymatic activity also improved over time with increases in soil water storage that peaked in year 3 but were still persistent in year 5.

Youssef et al. (2018) reported that application of 1% w/w biochar with 0.7% w/w superabsorbent polymer was the best treatment to alleviate yield decreases in response to water deficit in a green pea crop.

'Rescaype' is a micronised polymer concentrate in powder form that is water soluble for application through irrigation or sprayer equipment (https://www.rescaypeuk.com/). This product is under assessment in the United Kingdom and Australia and has shown promise for crops, increasing water and nutrient availability.

IDEAL AMENDED SANDY SOIL

There are a number of key factors in creating a high-performance sand for improved plant productivity and soil organic carbon (Figure 2). These include soil limitations that can be practically and economically addressed or overcome, nutrient and water efficiencies above and below ground, and best ways to support biological functioning of the soil.



Increased plant biomass production Address identified soil limitations Grow more on the same area Increase efficiencies for water and nutrients Decrease land degradation issues, leaching	**Increased 'resilience' in poor seasons** Keep ground covered to reduce evaporation and erosion Reduce variability in yield between good and poor seasons
Retention of plant available water Hold water in crop rooting zone with the majority in the plant available range Increase rooting depth to increase water storage Increase AMF fungi to increase accessibility of water and nutrients	**Retention of nutrients in the profile** Increase reactive surface area to hold nutrients in rooting zone Improve N, P mineralisation efficiency Ensure nutrient supply for biology to transform POC to HOC
Utilisation of water and nutrients stored in the rootzone Increase water, N, and P efficiency	**Improved soil function** Increase OC to improve nutrient mineralisation and associated chemical, physical and biological benefits

Figure 2. Criteria to address to create a high-performing sandy soil

Selection of the most suitable amendment to improve plant productivity and soil OC requires an understanding of the product's properties, mode of operation and duration and how these will affect the soil. Consideration needs to be given to chemical, physical, and biological properties that are changed above and below ground with a focus on nutrient and water availability, microbial activity, and function (Figure 3).

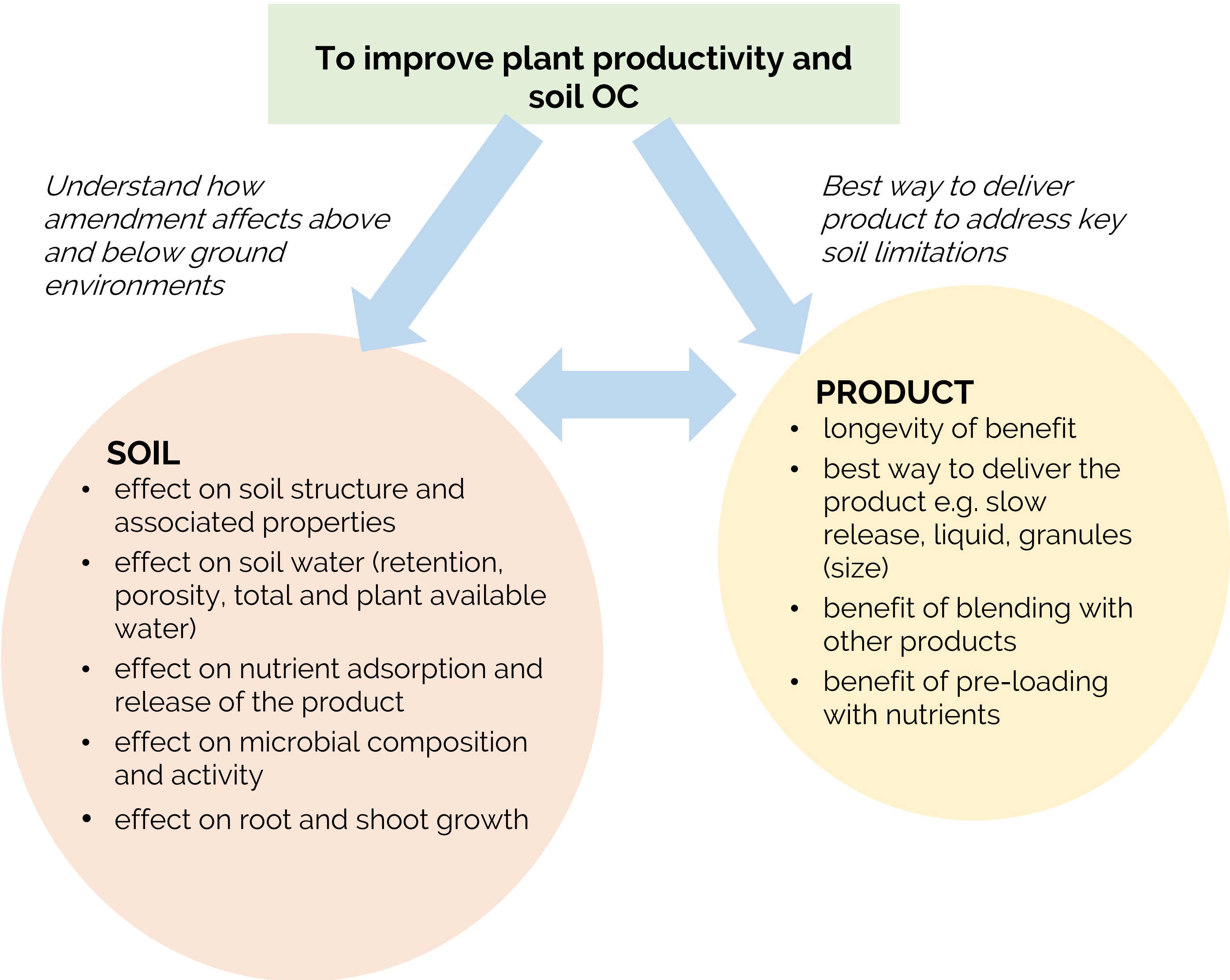


Figure 3. Factors to consider when selecting the most suitable amendment for improving plant productivity and soil OC in sandy soil.

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APPENDIX A CLAY ADDITION METHODS

In South Australia, the most common methods of clay amendment are addition of subsoil clay to the surface of the sand (spreading) or elevation of subsoil clay (delving, spading) throughout the soil profile or inversion (mouldboard plough) of the topsoil and subsoil clay layers (Davenport et al. 2011).

Selection of an appropriate method is determined by depth to clay-rich subsoil and the available machinery. Clay spreading is the only available option for deep sands where clay-rich subsoil is at more than 60cm depth. Clay-rich subsoil is excavated from a nearby pit, spread to the surface of the sandy soil and then incorporated. Spading can be used as a clay amendment method where clay-rich subsoil is within 30–40 cm depth. Clay is elevated and incorporated in one pass using specially designed 'spades' spaced 0.35m apart on a rotary axle. Delving is used where clay-rich subsoil is present within 30-60 cm of the sandy surface (Desbiolles et al. 1997), where specially-designed tynes elevate the clay-rich subsoil into the sand above. After delving, elevated clay clods are spread using bars, dragging clay from the delve line into the area between delve lines (0.7–2 m depending on machine design) and then incorporated. The area between delve lines is modified to the depth of incorporation but below this depth, the sand remains undisturbed. Inversion ploughing differs to spading as it buries rather than mixes the topsoil with the subsoil. Due to this inversion, mouldboard ploughing is best suited to deep sandy soils with increasing clay concentration down the profile and is not suitable where the subsoil is hostile to plant growth.

While inversion ploughing and delving create distinct areas of modification, clay spreading and spading result in a more uniform distribution of subsoil clay clods to the depth of incorporation (**Figure 4**). All clay modification methods result in a mix of clay clods ranging in size from a few mm up to greater than 200 mm (Schapel et al. 2019) in a sand matrix.

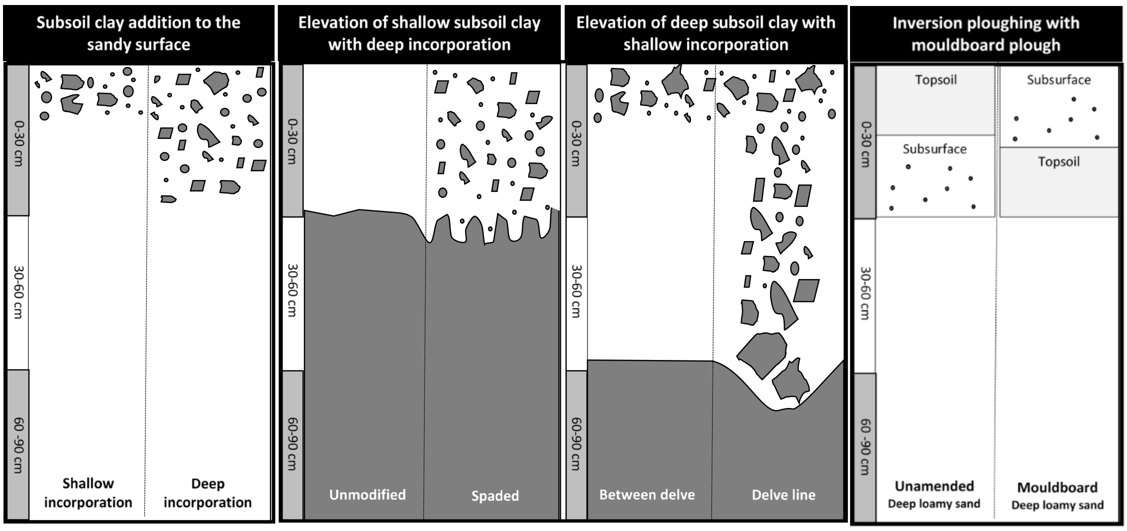

Figure 4. Schematic diagram (not to scale) of distribution of clay clods in the soil profile with clay addition to the surface or elevation from subsoil. Adapted from Schapel et al. 2019

APPENDIX B MODES OF ACTION FOR BIOLOGICAL INPUTS

Table 3. Summary of major biological input groups and their modes of action. Extracted from Farrell et al. 2017b.

	Mode of action (MoA)	Humic substances	Hydrolysates & AAs	Seaweed derived	Chitosan	Animal manures	Green manures	Composts	Vermicomposts	Teas / brews	Wood-based biochar	Manure-based biochar
	DIRECT NUTRIENT VALUE											
	macro			✓		✓	✓	✓	✓			✓
	micro			✓		✓		✓				✓
	PLANT PHYSIOLOGICAL RESPONSES											
	signal molecules / hormones	✓	✓	✓	✓				✓	✓		
	nutrient uptake / use efficiency / metabolism	✓	✓	✓								
	response to drought, salinity, cold stress: osmoregulation	✓	✓	✓			✓		✓			
	heat / temperature stress: membrane stability											
	plant disease responses			✓	✓	✓	✓	✓	✓	✓		
	SOIL QUALITY											
Physical	structure and stability					✓	✓	✓				
Physical	bulk density and porosity					✓	✓	✓			✓	
Physical	hydraulic properties					✓		✓				
Chemical	pH buffering					✓	✓	✓				✓
Chemical	cation exchange capacity					✓	✓	✓			✓	✓
Chemical	chelation	✓		✓		✓	✓	✓				✓
Biological	carbon/energy supply		✓			✓	✓	✓	✓			
Biological	nutrient cycling	✓				✓	✓	✓	✓		✓	✓
Biological	disease supression	✓				✓	✓	✓	✓	✓	✓	
Biological	resistance and resilience	✓				✓	✓	✓	✓	✓	✓	
Dominant FORM	*S = solid; G = granule/prill; L = liquid*	*SGL*	*L*	*L*	*L*	*S*	*S*	*S*	*S*	*L*	*S*	*S*
APPLICATION	*L = Land/soil; F = foliar spray; S = seed;*	*LFS*	*FS*	*LFS*	*FS*	*L*	*L*	*L*	*L*	*LFS*	*L*	*L*