SOIL CRC

Performance through collaboration

MILESTONE REPORT

Project 3.3.003

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

Meta-analysis report

Milestone 9

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INTRODUCTION

The limited capacity of sandy soils to supply resources, water or nutrients, to plant roots is at the core of their low productivity for crops and pastures. Fundamentally, the low reactive surface area of sandy soil causes limitations for agricultural productivity. The addition of materials to sandy soil that can permanently raise the reactive surface area such as clay, and/or recalcitrant organic matter is hypothesised to improve soil carbon and productivity.

A recent meta-analysis of sandy soils by Oldfield *et al.* (2019) examined the relationship between organic carbon (OC) and crop yields from international literature. However, there is still limited published information on this relationship for sands. In the present meta-analysis, we will examine the relationship between productivity and OC and the critical factors that influence them in Australian sandy soils that have had long-term or organic amendments (OAs) applied. It aims to increase the understanding of the benefits of amendments currently applied to sandy soils by analysing a significant body of relevant experiments and demonstration sites across Southern Australia.

It will:

- assess the addition of long-term (clay, biochar and coal) and OAs (composts, manures and residues) in relation to the productivity and carbon concentration of sandy soil
- examine the factors that influence productivity and OC
- understand the effect of these amendments on the physical, chemical and biological properties of sandy soils.

METHODS

An online search in Google Scholar with key words, sandy soil AND Australia AND carbon AND productivity OR crop yield AND clay OR organic identified 65,000 studies. However, the low number of published results with the essential criteria (records on biomass, yield, relative biomass, relative yield, OC (0-10 and 10-30 cm) and relative OC) required further exploration through GRDC Online Farm Trials and directly contacting advisors, and farmers. Suitable data was collated into a dataset from trial, demonstration and audit sites within Southern Australia that had applied amendments to sandy soil. Eighty-nine projects with 270 records were included from South Australia (165), Western Australia (66), Victoria (24) and New South Wales (15).

DATASETS

The dataset comprised many treatments with a wide variety of application methods. Key variables to address productivity and organic carbon (OC) were selected to address the aims of the project. These variables were:

Average yield (t/ha) **N= 149**	where multiple measures of grain yield were recorded over time the average yield was calculated. This value combined all crops including wheat, barley, canola, lupins etc.
Relative yield (%) **N = 180**	At sites where multiple treatments were applied, the relative yield was calculated by *yield of treatment / yield of the nil (control with no addition of amendment) x 100 (%)*
Biomass (t/ha) **N = 69**	for cropping sites, biomass was generally collected at flowering; for pasture sites comparative dry matter cuts were collected.
Relative biomass (%) **N = 74**	Relative biomass was calculated by *biomass of treatment / biomass of the nil x 100 (%)*
Organic carbon (OC) 0-10, (%) **N = 177**	the OC concentration for the 0-10 cm soil depth. OC was tested using the Walkley Black method
OC Cumulative 0-30 cm (%) **N = 131**	the total OC concentration (%) for 0-10 + 10-20 + 20-30 cm depths. This was used to capture changes in OC down the profile following addition of amendments that often were incorporated to depths of 15-30 cm.
Relative OC 0-10 (%) **N = 143**	to minimise climatic effects on OC, relative OC was calculated by *OC of treatment / OC of nil x 100 (%)*
OC stock ESM 4000 (t C/ha) **N = 115**	the OC stock of a standard/equivalent soil mass of 4000 t/ha (~10 percentile of samples that captured bulk density results. Majority of samples were from where clay addition has occurred.
Microbial biomass C (MBC) Cumulative 0-30 cm (mg/kg) **N = 37**	the total MBC concentration (mg/kg) for 0-10 + 10-20 + 20-30 cm depths.
Cation exchange capacity (CEC) (meq/100 g) **N = 141**	total capacity of a soil to hold exchangeable cations and is the sum of exchangeable calcium, magnesium, potassium, sodium and aluminium.

N = number of records

Average yield was selected over yield of a single year as it reflected productivity over several seasons. Hereafter the average yield is simply referred to as yield.

OC Cumulative 0-30 cm would be the preferred OC measure but not all projects collected soil samples deeper than 10 cm. Hence OC of the 0-10 and cumulative 0-30 have been reported.

The absolute values were used to identify factors that influence key variables over a wide range of climatic, soil and management types.

Values relative to the control (Relative) were the preferred productivity and OC measure when comparing across the dataset to minimise climatic and management effects to better understand influencing factors at the site.

Data subsets

The number of treatments with clay addition outweighed other treatments. To ensure that influencing factors for organic amendment application and unamended sands were not overshadowed, subsets of the whole dataset were created. These included Clay only (predominantly for clay rate trials) organic amendments (OA) and unamended (Nil) data subsets.

LINEAR REGRESSION

Treatments and sites were unbalanced so analysis was primarily through linear regression and summary of influencing factors.

Simple linear regression was undertaken for key variables; plant productivity: yield, relative yield, biomass, relative biomass; organic carbon: OC Walkley Black of the 0-10, 10-20 and cumulative 0-30 cm depth, relative OC 0-10 and 10-20, and microbial biomass carbon (MBC) of cumulative 0-30 cm; and cation exchange capacity (CEC) of the 0-10 cm.

In total, 180 factors (Appendix A) were assessed to determine the effect on the key variables. Factors used to calculate a key variable (e.g. Ca in CEC) were excluded from the assessment. Regression coefficients were recorded where $P < 0.05$. The key variables were sorted by highest to lowest R^2 (Table 1) with the top ten factors considered 'influencing factors'.

Data groupings

Due to the continuous nature of the data, when a factor was identified as an influencing factor, values were grouped. A histogram of the influencing factor was used to guide division of the data for analysis into groups of comparable size.

Groups included:

- Long-term amendments (LTA) include subsoil clay (n=121), bentonite (n=13), biochar (n= 2) and coal dust (n = 4).
- OAs have been grouped as addition of organic matter (OM) and can be further separated into compost (animal or plant that has been through a processing stage to increase the recalcitrant OC, n=17), manure (can be stockpiled but not composted, n=39) and residue (plant based can be green, brown or dried, often hay but can be grain, winery waste or grape marc, n=29).
- Annual rainfall (30-year average) 250-350, 350-400, 400-500, 500-550, 550-650 mm.
- Depth of sand over clay: shallow (< 30 cm), moderate (30-60 cm), moderately deep (60-90 cm), deep (> 90 cm) to subsoil clay.
- Depth of incorporation: nil (0 cm), shallow (5-15 cm), deep (15-30 cm).
- Clay concentration of the 0-10 cm: 0-3 %, 3-6%, 6-10%, 10-15% and 15-20%
- Years since amendment applied: 0, 1-2, 2-5, 5-10, 10-15, 15-20 and 20-25 years.

Number of observations, mean, standard error of the mean, minimum, maximum values and quartiles (25, 50 and 75%) were determined to understand the distribution of the data within the selected groups.

Summary statistics and linear regressions were analysed in Genstat Nineteenth Edition (2018).

RESULTS

INFLUENCING FACTORS FROM LINEAR REGRESSION

Analysis of absolute values recorded for yield, biomass and OC were important to assess influencing factors across a spectrum of climatic, soil and management systems. By contrast, analysis of relative values (response compared to the unamended sand of the trial) was critical to assess influencing factors at a site level as the influence of climate and soil type had been removed.

Variance explained by linear regression for the ten most influencing factors of key variables are shown in Table 1.

Productivity

Biomass

Biomass production was strongly influenced by the addition of subsoil clay and climatic factors. The presence of subsoil clay (indicated by increases in potassium K, OC stock and water holding capacity) and the proportion rainfall that fell in summer and winter rainfall were conducive to biomass growth. Mineral nitrogen stock and iron in the subsurface explained about 30% of the variation in productivity.

Yield

Yield was strongly influenced by iron in the 0-20 cm and by biomass. In addition, it was affected by subsurface factors, indicators of presence/absence of clay (OC, C stock and WHC) and sulphur in the 20-50 cm depth.

Rainfall (annual, growing season or seasonal) explained very little of the variation in yield, although there is an indication of yield improvement where annual rainfall is >550 mm (Figure 1). Large variability in relative biomass occurred at the lowest rainfall group (250- 350 mm).

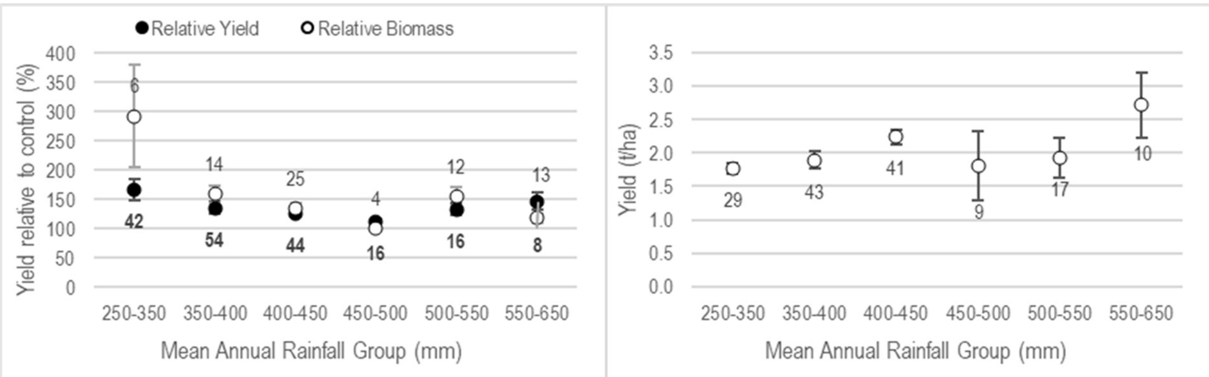

Figure 1. Yield, relative yield and relative biomass by annual rainfall groups. Error bars denote standard error of the mean and labels indicate the number of records.

The depth of sand over clay was negatively related to yield (Figure 2). Grouped data identified the addition of OAs maintained the yield at levels similar to shallow depth of sand (< 30 cm) with a large increase, compared to the unamended sand, where sand depth is > 90 cm. Clay addition improved yield compared to unamended sand where sand depth was between 30-60 cm but had no effect where depth to sand was > 60 cm.

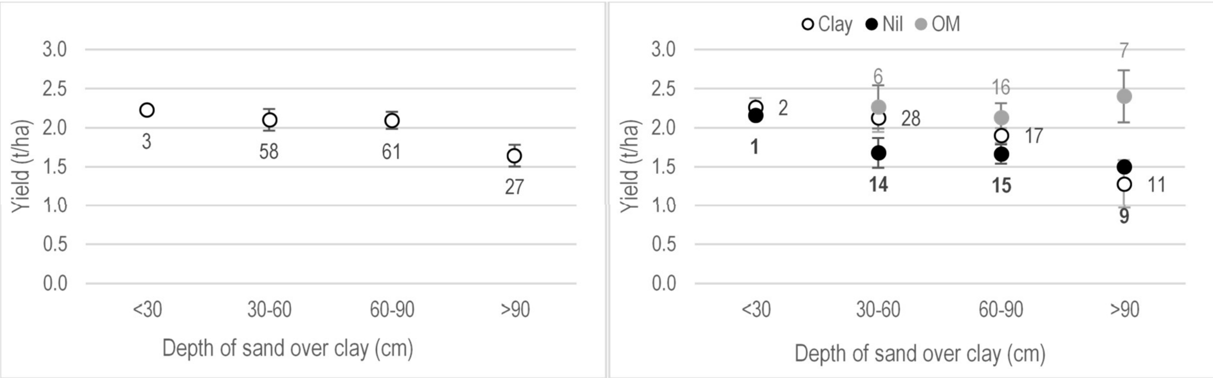

Figure 2. Yield (t/ha) by grouped depth of sand over clay (left) and for individual nil, clay and organic matter (OM) additions (right). Error bars denote standard error of the mean and labels indicate the number of records. Note the decline in yield with increasing sand depth (left) and improvement in yield with the addition of clay and organic amendments depth of sand between 30-60 cm and with OM amendments where depth of sand is >90 cm.

Relative biomass

The variation in relative biomass was largely explained by an inverse correlation with water repellence of the surface soil as measured by Molarity of Ethanol Droplet (MED) test (Figure 3). This is likely associated with overcoming water repellence by application of clay. Relative biomass was strongly influenced by mineral nitrogen in the surface 30 cm and the rate of long-term amendment (LTA) applied to the sand.

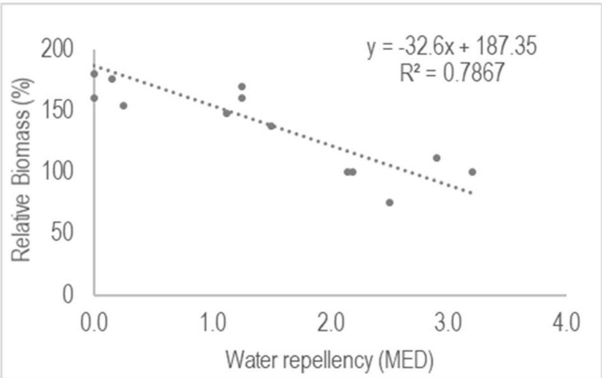

Figure 3.Water repellence of the surface soil as measured by the Molarity of Ethanol Droplet (MED) test. Wettable soils have a MED of zero. Scales of repellency as measured by MED are: low, >0–1.0; moderate, 1.2–2.2; severe, 2.4–3.0; and very severe, MED >3 (King 1981).

Relative yield

Relative yield was strongly influenced by mineral nitrogen of the 0-30 cm depth (Figure 4) and relative biomass.

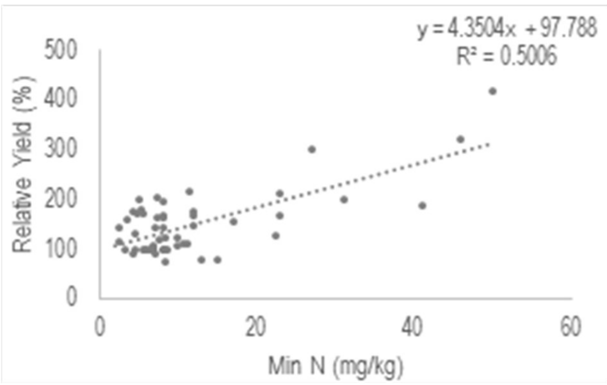

Figure 4. Linear regression of relative yield and mineral nitrogen in the 10-20 cm depth.

When data was grouped by clay concentration in the surface 10 cm, a positive relationship with relative biomass and yield was evident to an upper limit between 10 to 15 % clay concentration followed by a sharp decrease in productivity to the same level as the control when higher rates of clay were added (Figure 5).

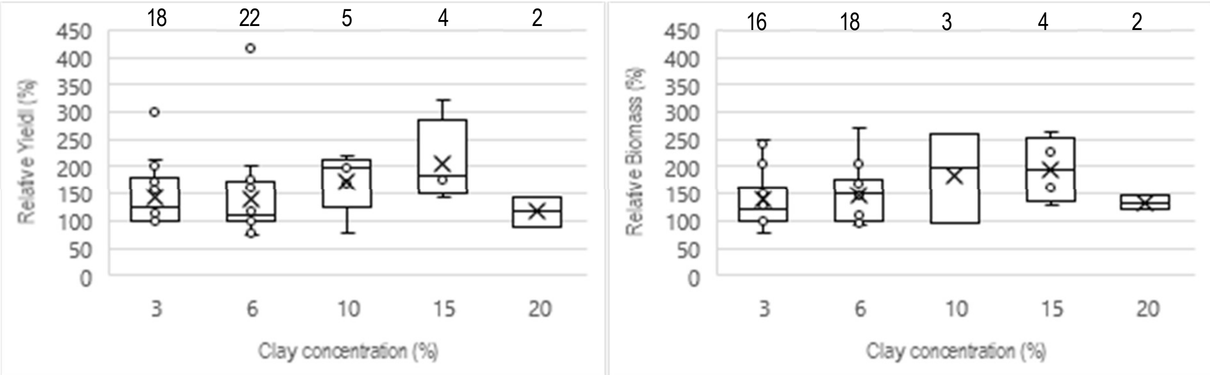

Figure 5. Relative yield (left) and biomass (right) compared to the control by grouped clay concentration. X shows mean of clay concentration class, bars show 5th and 95th quartiles, box denotes 25th and 75th percentile with the bar as the 50th percentile. Labels indicate the number of records. Note similar trends and the decrease in relative productivity after 15% clay concentration.

Grouping data by years since amendment application showed a sharp increase in productivity within 2 years that stabilised and maintained the response for more than 15 years. Most samples in this grouping were from clay amended sites.

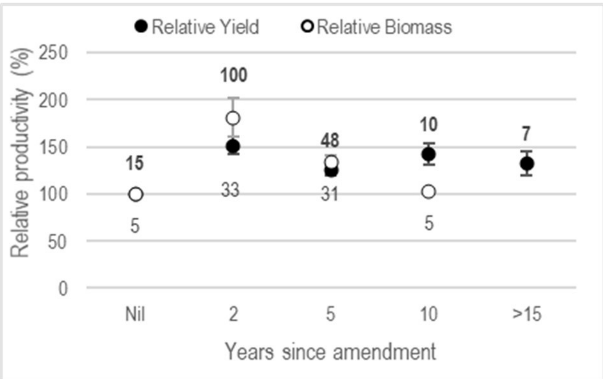

Figure 6. Relative biomass and yield compared to the unamended sand by years since amendment applied. Labels indicate the number of records; relative yield is bolded. Note the sharp productivity increase in the first two years that stabilised by year five and is then maintained for greater than 15 years.

Organic carbon

OC Concentration

OC concentration of the 0-10 cm and cumulative 0-30 cm depth were strongly influenced by iron (Fe) (Figure 7) in the 0-20 cm depth (~70% of variance) and the total annual rainfall (Figure 8), particularly the amount that falls within autumn and winter. An inverse relationship between OC and proportion of summer rainfall indicated a higher turnover of OC with moister, warmer temperatures. This aligned with the inverse relation to evaporation.

OC concentration increased with a shift from arid (0.05 to 0.2) to semi-arid (> 0.2) environment, with a sharp increase in OC at index higher than 0.4 (Figure 9). Aridity index explained more variation in the 0-10 cm dataset than deeper layers which suggests a greater impact of environmental factors on the surface of the soil.

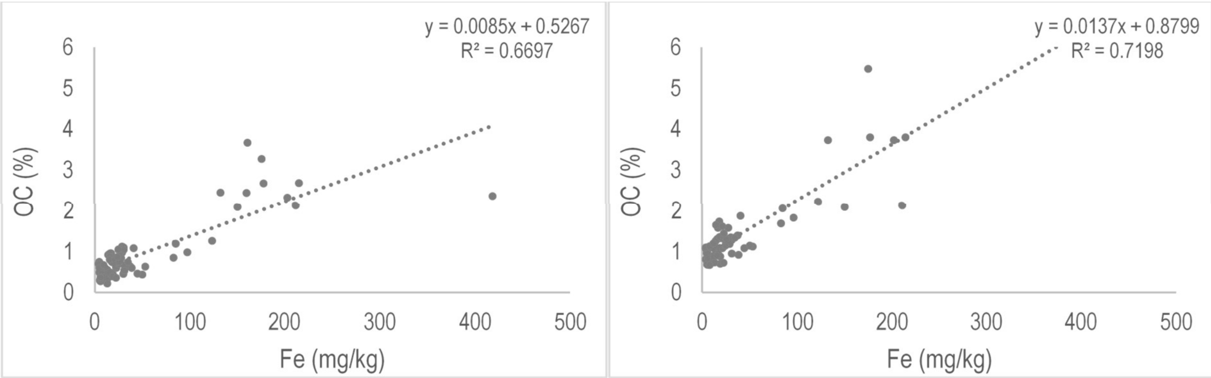

Figure 7. Linear regression OC 0-10 cm (left) and cumulative 0-30 cm (right) by extractable iron.

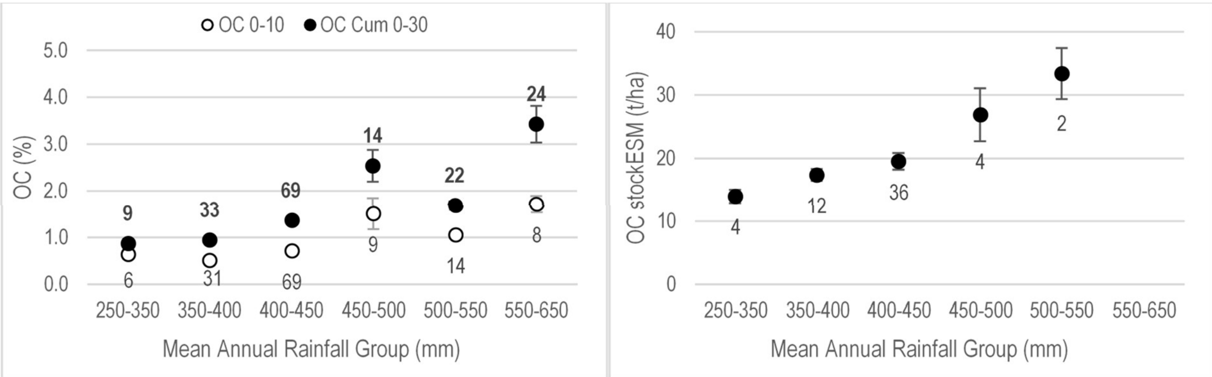

Figure 8. OC 0-10 cm and cumulative 0-30 cm (left) and OC stock$_{ESM}$ (right) by rainfall group. Labels indicate the number of records.

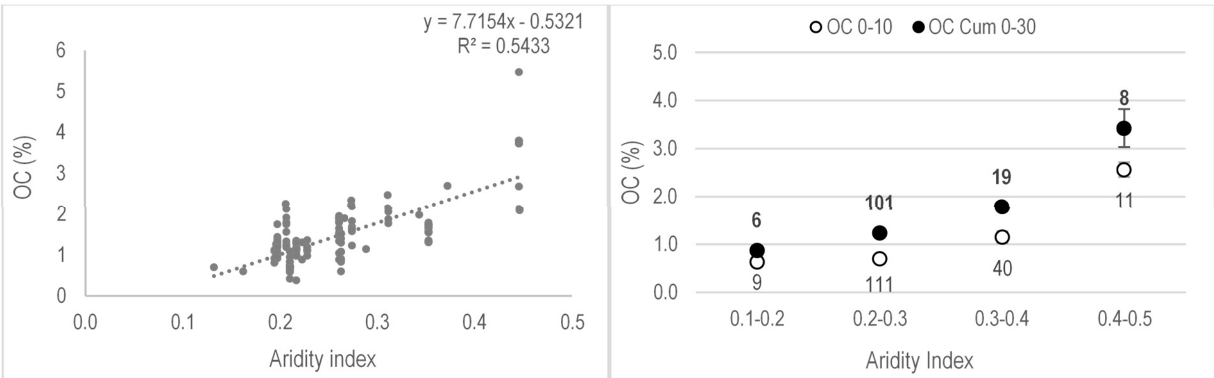

Figure 9. Linear regression organic carbon concentration by aridity index (annual rainfall / evaporation) for the OC cumulative 0-30 cm (left) and OC concentration of the 0-10 cm and cumulative 0-30 cm for aridity index following grouping of data (right). Error bars denote standard error of the mean and labels indicate the number of records; OC cumulative 0-30 cm is bolded. Note the sharp increase in OC concentration where aridity index is > 0.4.

A strong relationship between OC and organic nitrogen, measured as potentially mineralisable nitrogen (PMN), for depths 0-10 cm (Figure 10), 10-20 cm and 20-30 cm. There was no significant linear regression between OC and mineral nitrogen in the surface 10 cm. However, when data in the surface 10 cm was grouped by OC (0-0.75, 0.75-1.5 and > 1.5%), there was an indication of a positive relationship with mineral N when OC concentration was greater than 1.5% (Figure 13). A similar relationship was observed for Sulphur and Phosphorus (data not shown).

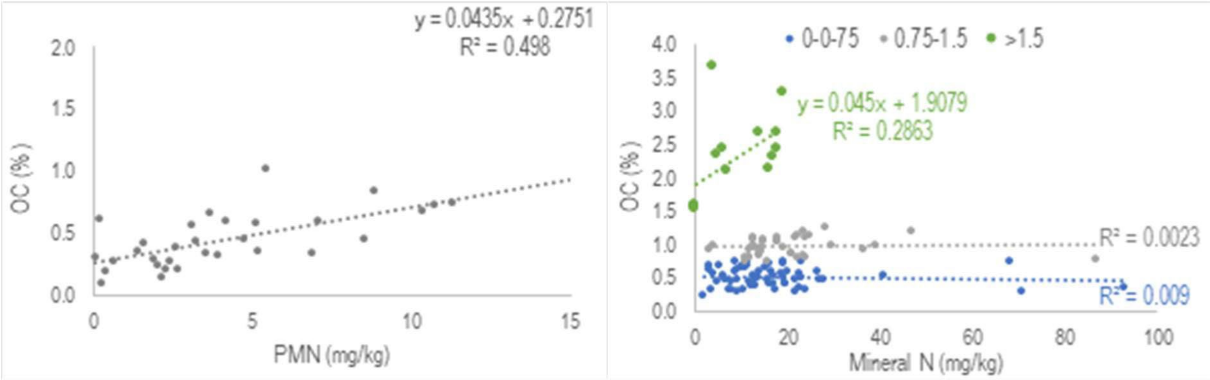

Figure 10. Linear regression of OC 0-10 cm and potentially mineralisable nitrogen (left) and mineral nitrogen grouped by OC categories. Note the non-significant relationship between OC and mineral nitrogen for OC concentrations below 1.5% and significant (P < 0.05) relationship when OC is greater than 1.5%.

There is a negative relationship between cumulative OC 0-30 cm and sand depth (trend not evident in the OC 0-10 cm depth). Clay addition generally improved the cumulative OC 0-30 cm compared to the unamended (Nil) sand particularly when sand is > 90 cm deep (Figure 11).

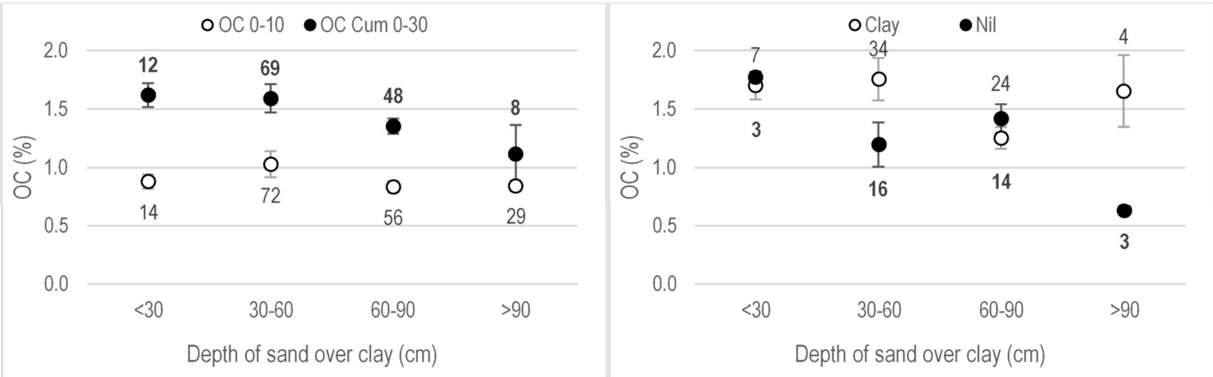

Figure 11. OC concentration (%) in the 0-10 cm and cumulative 0-30 cm depth grouped by depth of sand over clay (left) and for the cumulative OC 0-30 cm for unamended sand (nil) and clay amendment (right). The number of samples addition of organic amendments were low and excluded from the graph. Labels indicate the number of records; OC cumulative 0-30 cm (left) and OC of nil amendment (right) are bolded.

A positive increase in cumulative OC 0-30 cm was evident at clay concentrations higher than 15 % (Figure 12) following grouping by clay concentration in the surface 10 cm. This contrasted with the results for relative productivity where a decrease was observed at clay concentration above 15%.

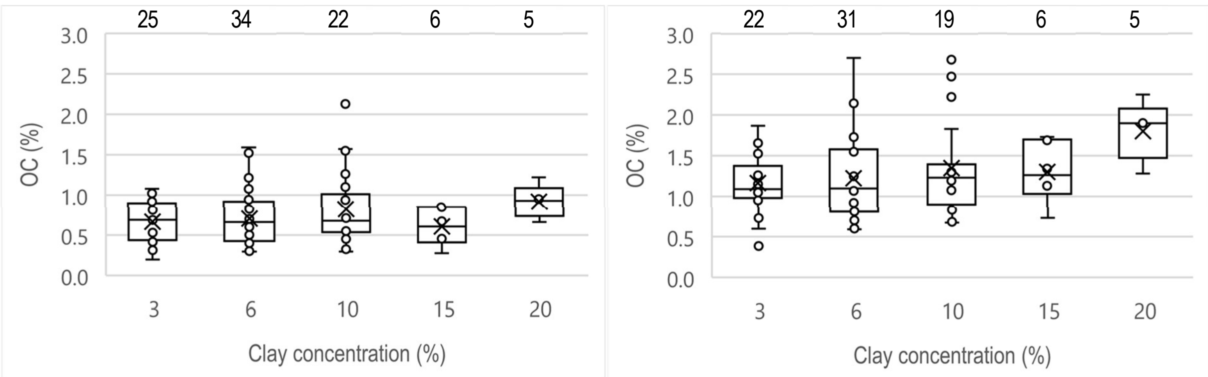

Figure 12. OC concentration of the 0-10 cm (left) and cumulative 0-30 cm (right) by grouped clay concentration of the surface 10 cm of soil. X shows mean of clay concentration class, bars show 5th and 95th quartiles, box denotes 25th and 75th percentile with the bar as the 50th percentile. Labels indicate the number of records. Note the increase in cumulative OC 0-30 cm after 15% clay concentration.

Relative OC

Relative OC for the 0-10 cm depth was influenced by water holding capacity to 50 cm, sulfur below 20 cm, long-term amendment rate and incorporation depth of the long-term and OAs. Relative OC for the 10-20 cm was influenced by PMN of the surface 20 cm (Figure 13) and subsoil clay markers (boron, clay concentration, potassium, water holding capacity).

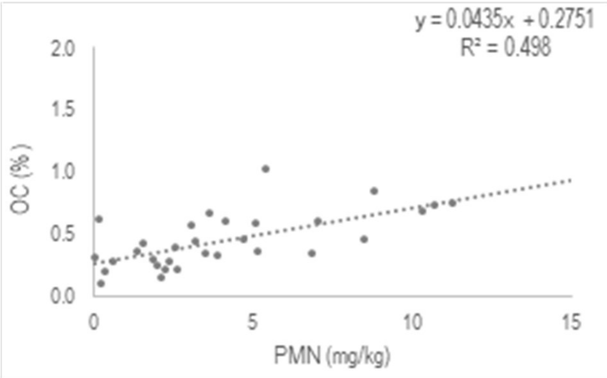

Figure 13. Linear regression of OC 0-10 cm and potentially mineralisable nitrogen.

Grouping data by applied amendment (nil, clay, charcoal and organic) and incorporation depth (nil, shallow and deep) indicated that shallow or deep incorporation without the addition of an amendment decreased relative OC in the surface 10 cm compared to the unamended sand (Figure 14). Deep incorporation decreased relative OC in the surface 10 cm. However, there was a 16% increase in relative OC of the cumulative 0-30 cm depth when clay and/or OAs were applied with no difference between shallow or deep incorporation (data not shown). There was a decrease in relative OC cumulative 0- 30 with shallow or deep incorporation without clay addition.

There was higher relative productivity following deep compared to shallow incorporation. The addition of OM generally resulted in larger increases in relative biomass than yield.

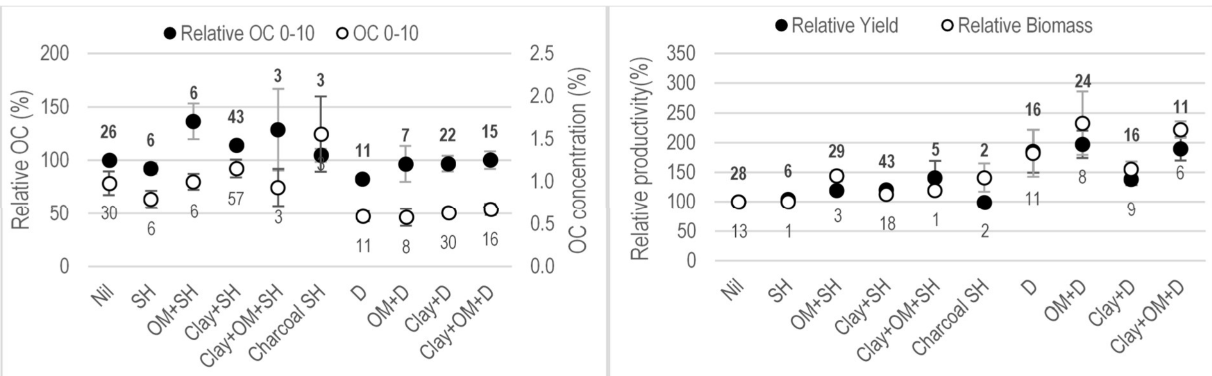

Figure 14. Relative OC and OC concentration of the surface 10 cm (left) and relative productivity (right) by grouped amendment and depth of incorporation. Abbreviations: SH – shallow incorporation, OM – organic matter addition, D – deep incorporation. Labels indicate the number of records; Relative OC 0-10 cm (left) and Relative yield (right) are bolded. Note the contrasting results for OC and productivity.

Grouping data by years since application of amendment showed a slow but gradual increase in relative OC. It can take up to ten years before a change is observed, even in the surface 10 cm.

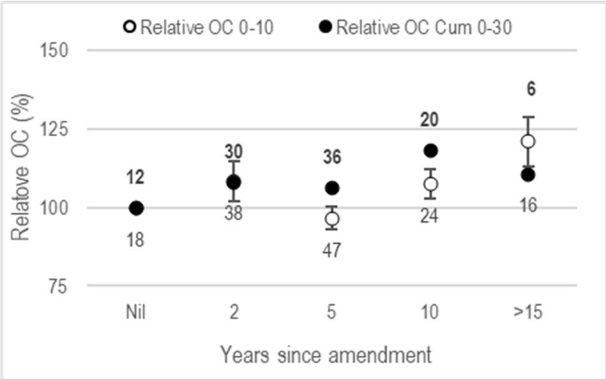

Figure 15. Relative organic carbon of the 0-10 cm and cumulative 0-30 cm depth compared to the unamended sand by years since amendment applied. Note the slow increase in relative OC of the 0-10 cm layer. It can take more than 10 years before a significant change is observed.

Microbial biomass carbon (MBC)

The MBC cumulative 0-30 cm was influenced by potentially mineralisable nitrogen (Figure 16), water holding capacity, carbon and climatic factors including lower proportion of winter and spring rainfall and lower elevations. Clay concentration shows a positive trend and would contribute to the water holding capacity of the surface 10 cm (Figure 16).

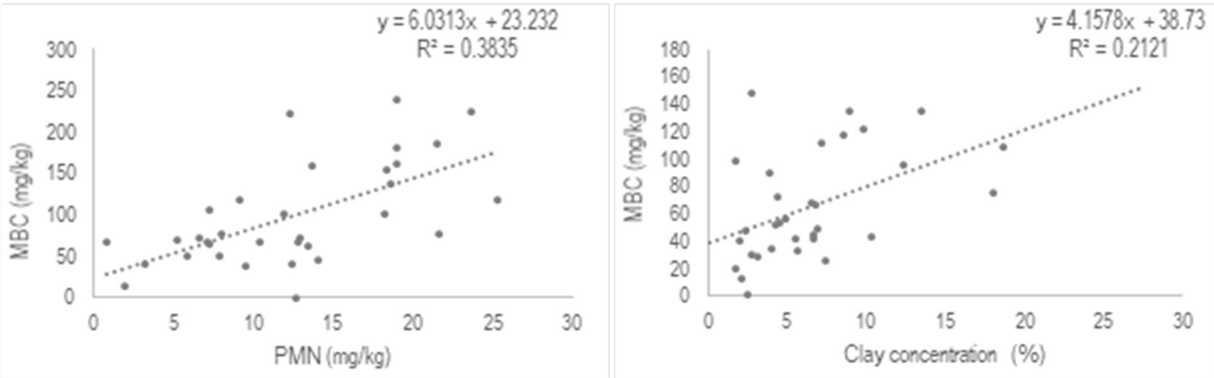

Figure 16. Linear regression microbial biomass carbon of the cumulative 0-30 cm by potentially mineralisable nitrogen (left) and by clay concentration (right) of the surface 10 cm.

Relationship between productivity and OC

There was a positive relationship between yield and soil OC in the surface 10 cm that explained 29% of the variation in yield and 37% for cumulative OC 0-30 cm. Although the number of records above OC 1.5% are low, there was an indication that the relationship between OC and yield was significant only when OC in the surface 10 cm was between 0.75 and 1.5% (Figure 17).

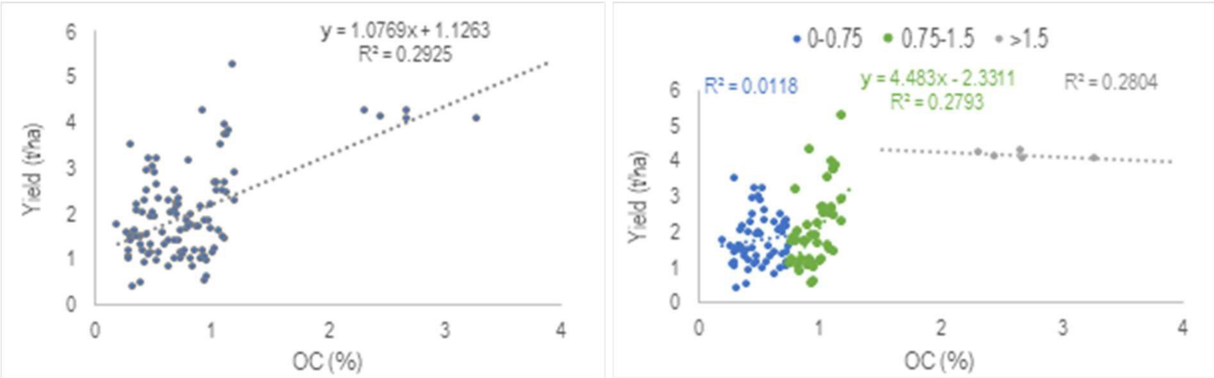

Figure 17. Linear regression of yield and soil organic carbon in the 0-10 cm depth (left) grouped by OC range of the 0-10 cm (right). Note the relationship between yield and OC is when OC is between 0.75 and 1.5%.

Grouping the data by the applied amendment: unamended (Nil), organic (OM), clay (Clay) and clay and organic (Clay+OM); improved the coefficient of regression to 46% for clay addition (Figure 18). However, there is no improvement in yield when clay is compared to the unamended (Nil) sandy soil. In contrast, when OM was added with clay, yield effectively doubled for the same OC concentration. Although there was an increase in yield with the addition of OM without clay there was no relationship between yield and OC.

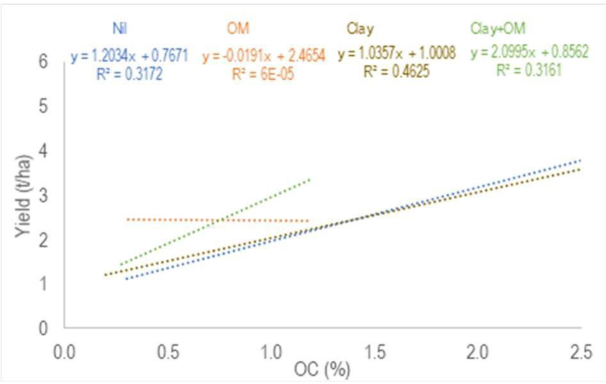

Figure 18. Linear regression of average yield and soil organic carbon in the 0-10 cm depth showing linear trendlines for grouped data by addition of organic material (n=14), clay (n=58), clay and OM (n=19) compared to unamended nil (n=39) (right).

There was no correlation between OC concentration and relative biomass or relative yield.

Cation exchange capacity (CEC)

Factors influencing CEC for the whole dataset were clay concentration, sulphur (S), phosphorus (P), OC and potassium (K) in the 0-10 cm. Clay concentration was associated with the addition of clay to sandy soil.

The increase in CEC from boron (B), P and S are linked to other factors rather than a direct effect. As B, P and S are influencing factors in the OA dataset it is likely to be linked to the addition of OAs (composts, manures, residues). K, EC and B in part were associated with the addition of clay or charcoal.

Clay concentration of the surface 10 cm explained ~ 25% of the CEC variation in the whole and clay dataset. OC 0-10 explained ~15% of CEC variation in the whole and clay only datasets (Figure 19), 23% in the unamended and 84% in the OA datasets.

No data was available for charcoal addition (biochars and coal dust).

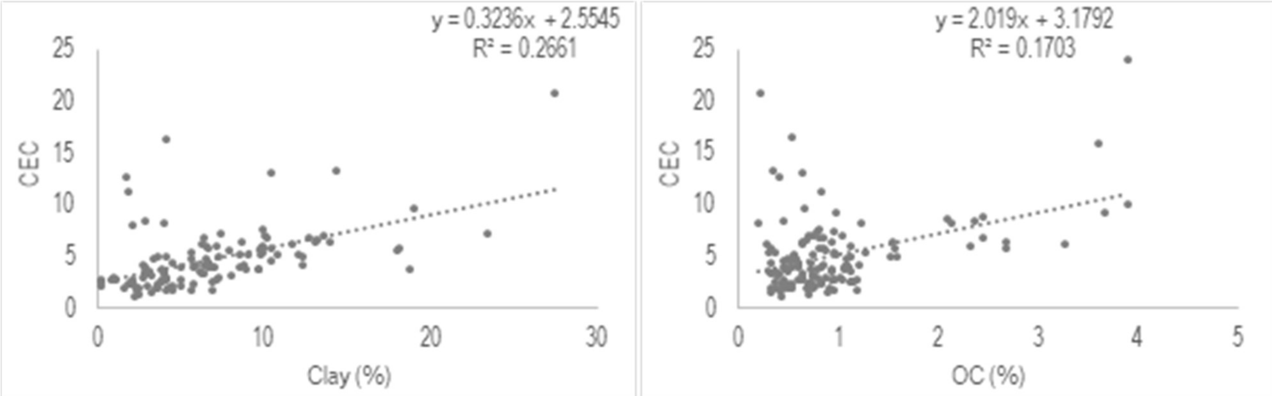

Figure 19. Linear regression of cation exchange capacity (CEC) and clay concentration in the 0-10 cm depth (left) soil organic carbon in the 0-10 cm depth (right).

INDIVIDUAL DATASETS

Clay data subset

The clay data subset included records where clay had been incorporated with/without various OA and the unamended soil for comparison. Similar patterns were observed to those of the whole dataset, but application rate and incorporation depth of the long-term and OAs were important for relative biomass.

A smaller subset specifically assessed effects of different rates of clay application. Many clay-rate trial sites only measured soil characteristics in the surface 10 cm accounting for the lack of subsurface variables. Depth of sand was important to explain the variance in yield and OC, whilst years since amendment was important to explain variation in relative yield. The impact of these factors have been described in the whole dataset above.

Few clay-rate trials measured clay concentration of the amended sands but for the four trial sites that did (3 in WA and 1 in SA), there was an indication of an upper limit to increased yield when clay concentration of the amended sandy soil was above 10%. This is comparable to the effect of clay concentration on relative yield and biomass for the whole dataset (Figure 5) where an upper productivity limit of 10-15% clay concentration before a sharp decrease in productivity occurred where clay concentration is > 20%.

In contrast, OC concentration increased linearly with clay concentration with no detectable upper limit in the clay-rate subset (Figure 21). This was similar to the effect observed in the whole dataset (Figure 12) but without the sharp increase in OC above clay concentration of 15% due to no records in this subset.

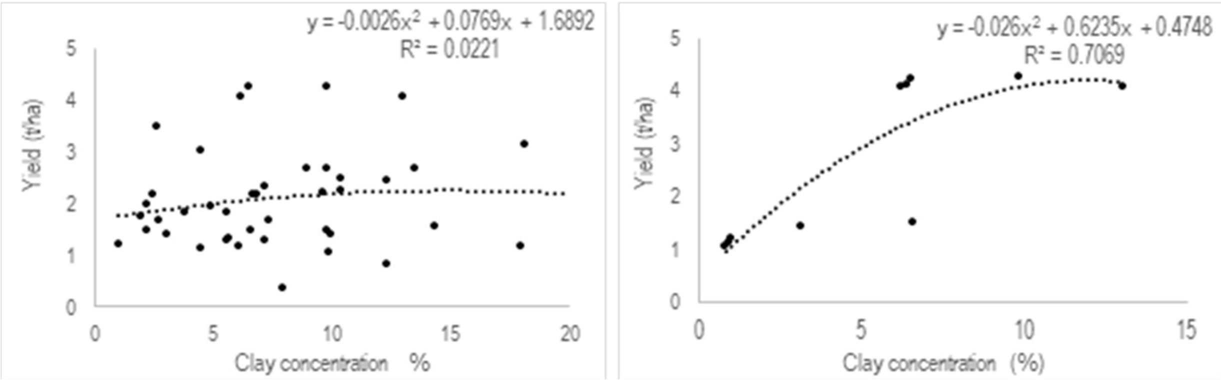

Figure 20. Linear regression of yield and clay concentration in the 0-10 cm depth of the amended soil for the clay data subset (left) and clay-rate trials subset (right). The clay data subset included unamended sandy soil and different incorporation methods resulting in a spread of data points. The clay-rate trial subset consisted of four trials sites (3 in WA and 1 in SA) that compared different rates of clay application with clay concentration of the amended sandy soil measured (not just the rate of clay applied). There is a clear indication that there is an upper limit to increased yield due to clay addition when clay concentration was above 10%.

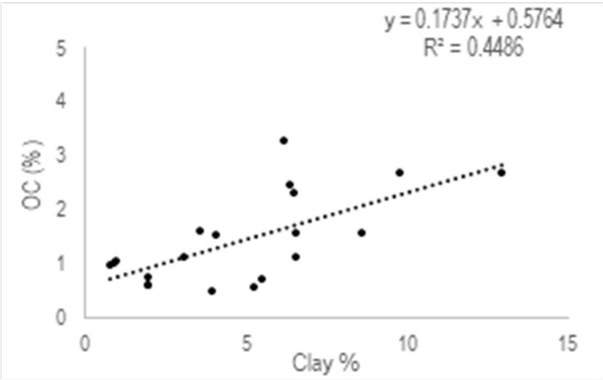

Figure 21. Linear regression of OC and clay concentration in the 0-10 cm depth of the amended soil for the clay-rate trial subset.

Organic Amendment (OA) data subset

The OA data subset included records where OAs (composts, manures and residues) had been applied to sandy soil without the addition of long- term amendments (clay, charcoal) and included unamended sandy soil for comparison.

Similar patterns were observed to those of the whole dataset with influence from nitrogen and subsoil clay markers (between 20-50 cm) for productivity.

Critical factors for OC 0-10 and cumulative 0-30 were cation exchange capacity and the negative effect of subsurface pH_{Ca} (10-50 cm) (Figure 22).

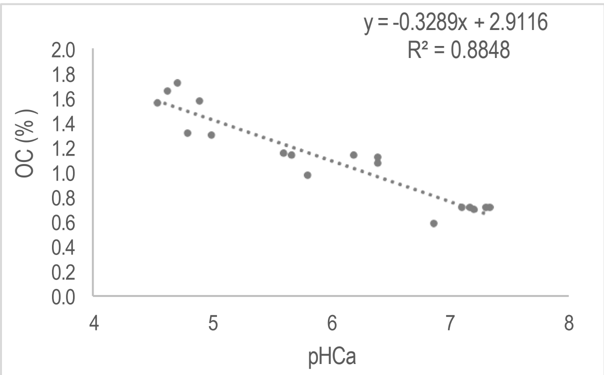

Figure 22. Linear regression of cumulative organic carbon in the 0-30 cm depth with pHCa of the 10-20 cm depth. Note the increase of OC with decreasing pH. This would be associated with the effect of pH on microbial activity. The same trend is observed in unamended and organically amended sands.

Unamended (Nil) data subset

The unamended (Nil) data subset included records where no treatments or tillage/incorporation were applied.

Productivity was influenced by OC concentration in the subsurface 20-50 cm, iron and the depth to subsoil clay particularly in the 30-50 cm depth. Influencing factors for OC included iron, calcium, productivity, nutrients (sulphur, phosphorus) and rainfall. pH_{Ca} of the 10-20 cm had less influence than in the OA data subset which may indicate an acidifying effect with the addition of OA.

For both the OA and unamended data subsets biomass had stronger influence on OC concentration than yield.

Table 1. Variance explained by linear regression for key variables (P < 0.05). Red indicates an inverse correlation, bold indicates a relative value.

		WHOLE DATASET												SUBSETS												
														Clay trials			OA Data						Unamended (Nil)			
		Yield	Biomass	Relative yield	Relative biomass	OC 0-10	OC 10-20	OC Cumulative 0-30	Relative OC 0-10	Relative OC 10-20	OC stock ESM 4000t/ha	MBC Cum 0-30	CEC 0-10	Yield	Relative yield	OC 0-10	Yield	Biomass	Relative yield	Relative biomass	OC 0-10	OC Cumulative 0-30	Yield	Relative yield	OC 0-10	OC Cumulative 0-30
Yield						29	33	36			36					59									29	36
Biomass		53		**57**														**46**	**90**		42		53	**92**	56	74
OC	0-10													59												
	10-20	33				64						**34**	17			88							46		45	
	20-30																	42								
	30-50	24										**28**					42						63			
	Cum 0-30													54												
OC stock	0-10											33														
	20-30		43															40								
	30-50	33															43						63			
OC stock$_{ESM}$4000	0-30																						88			
MBC	0-10										36															
Iron	0-10	65				67	70	72			45			91	78						76	68	82		58	61
	10-20	51	28			66	61	72			43												60		33	43
	20-30						30																			
Mineral N	0-10			19	34									62					29	56						
	10-20			49	48						32								78	70				44		
	20-30		31	40	38												67		37							
Mineral N stock	0-10			28	53														36	60			55			
	10-20			49	45														80	70				70		
	20-30			29													72									
PMN	0-10					38				45	31	36														
Organic N	10-20						48	47		88		30														
	20-30							36																		
Sulfur	0-10					30							23												52	
	10-20																61	41								
	20-30	42							19																	
	30-50	48																26								
Phosphorus	0-10												19			49									40	
	10-20																37									
Calcium	0-10					31					35										81				71	48
	10-20																				62					
	20-30																				79	75				
CEC	0-10															49		21			84	73				
	20-30																				79	75				
	30-50																44									
Clay concentration	0-10									18			26	58				32								
	10-20														44			42							29	30
	30-50																55						48			
Potassium	0-10				29						45		15							46						
	10-20			23	29						43									21						
	20-30			20							46										84	78				
	30-50		43								61						52									
Boron	0-10									48			37	54	69	59			40							
	30-50										61															
WHC	0-10		39				24		28		41	35														
	10-20		33				24		21															87		
	20-30	33																								
	30-50								38								69		43							

Table 2 cont. Variance explained by linear regression for key variables (P < 0.05). Red indicates an inverse correlation, bold indicates a relative value.

		WHOLE DATASET												SUBSETS												
														Clay trials			OA Data						Unamended (Nil)			
		Yield	Biomass	Relative yield	Relative biomass	OC 0-10	OC 10-20	OC Cumulative 0-30	Relative OC 0-10	Relative OC 10-20	OC stock ESM 4000t/ha	MBC Cum 0-30	CEC 0-10	Yield	Relative yield	OC 0-10	Yield	Biomass	Relative yield	Relative biomass	OC 0-10	OC Cumulative 0-30	Yield	Relative yield	OC 0-10	OC Cumulative 0-30
EC	0-10												17							37						
	10-20											29								34		69				
	20-30				60																					43
WR MED				24	77										51					62				37		
pH_{Ca}	0-10																			15						
	10-20																				88	88			25	
	20-30																				85	85				
	30-50																				91	91			15	
LTA Rate					30				15																	
OA Incorp depth									16																	
Depth of sand														65		73										
Years since amended															23											
Aridity index						42	39	50																	37	66
Growing season rainfall 30 yr								48																	33	66
Annual Rainfall ave 30 yr						34	41	51							26										29	70
Annual Rainfall ave 50 yr							41	51																	33	70
Summer mm			29																							
Autumn mm						32	42	53																		66
Winter mm						32	31	40																	29	55
Spring mm							31								28											55
Prop Summer %			35					22																		
Prop Autumn %												30														
Prop Winter %			35									30														
Prop Spring %			26																							
Elevation			37									27														
Evaporation																48										

DISCUSSION

PRODUCTIVITY AND OC RELATIONSHIP

This dataset has shown that in Australian sandy soils the linear relation between yield and OC existed only when OC in the surface 10 cm was between 0.75 and 1.5%. When OC was below 0.75% there was no relationship and above 1.5% the effect on yield had stabilised. This contrasts with a meta-analysis of international literature that demonstrated an initial linear relation between yield and OC that stabilised when OC reached 2% (Oldfield *et al.* 2019).

Whilst the relationship between yield and OC is important, other explanatory variables may be limiting increases in productivity and OC. This meta-analysis has found that:

- Biomass was not directly influenced by OC but climatic and water holding factors were critical.
- Yield was largely explained by biomass and strongly influenced by the presence/absence of subsurface (>20 cm) clay (through depth of sand over clay and/or the addition of clay with amendment of sandy soil).
- Relative yield and biomass were strongly affected by mineral nitrogen, water repellence (biomass more sensitive than yield) and potassium. The rate of clay applied affected relative biomass. Neither were directly influenced by OC.
- OC concentration was strongly influenced by iron concentration and climatic measures; aridity index and rainfall amount (particularly in winter and spring). Relationship with organic nitrogen (potentially mineralisable nitrogen) was important, particularly below 10 cm.
- Relative OC in the surface 10 cm was driven by factors affecting water holding capacity, clay concentration and depth of OA incorporation. In the subsurface, the relationship with organic nitrogen was the primary influence.

Addressing these factors may overcome limitations in productivity or transformation of organic inputs into OC.

CLIMATE

Water has a major influence on Australian agro-ecosystems and was amongst the key influencing factors for biomass (t/ha) and OC concentration. The amount of rainfall (total annual and amount that fell in winter, spring and autumn) was important for OC in the surface 10cm. The influence of autumn rainfall on the cumulative OC 0-30 cm could suggest the timing of rainfall may be important for root growth and hence higher OC in deeper soil layers.

The proportion of rain that fell in each season was important for biomass production. The inverse relationship between OC and proportion of summer rainfall is likely to reflect higher turnover of OC with moister, warmer temperatures. The highest variability in relative productivity occurred where rainfall was most limiting (250-350 mm) as biomass is driven by the reliance on rain. There was no influence of rainfall on yield and relative measures for productivity and OC.

Aridity index was important for OC measures and explained more variation than rainfall alone as it captures the effect of temperature through evaporation. The importance in the 0-10 cm compared to deeper layers reflects the impact of environmental factors on the surface of the soil.

NUTRIENTS

Indications that increased productivity (relative yield and biomass) can be achieved with increased mineral nitrogen (range 2-60 mg/kg), particularly in the 10-30 cm depth.

The importance of OM and its components including organic nitrogen (PMN) throughout the 0-30 cm depth with organic and microbial carbon was demonstrated by a positive relationship.

A positive relationship with mineral nitrogen only occurred when OC concentration was above 1.5% in the 0-10 cm depth. There was no effect of mineral N below this concentration.

IMPROVING RELATIVE SURFACE AREA

Cation Exchange Capacity (CEC)

Clay and OC were key influencing factors to increase CEC. In the absence of clay, the addition of OAs will be pivotal to increase the reactive surface area of sandy soils. Charcoal addition (biochar and coal dust) are assumed to increase CEC but couldn't be confirmed with this dataset as no samples were analysed.

Clay amendment

Application of clay was associated with a number of influencing factors including overcoming water repellence, increased water holding capacity, increased CEC, potassium, boron, and calcium (SA). Clay addition increases the ability of the amended sandy soil to protect OC from turnover by microbes through sorption OC to minerals (Baldock 2007), formation of complexes with iron and aluminium (Saidy *et al.* 2012) and occlusion in aggregates (Tisdall and Oades 1982).

This dataset identified a positive relationship between clay concentration and productivity that stabilised between 10 and 15% clay concentration before productivity declined. Conversely, OC concentration did not increase until clay concentration reached 15%. Whilst clay content in soil is important to hold OC, other properties introduced by the clay including chemical stabilisation by calcium carbonate (Fernandez-Ugalde *et al.* 2011) or changes to pH (Jones *et al.* 2019) appear to have a stronger influence on increasing OC concentration.

These critical limits have implications on how clay-amended sands should be managed.

Iron

In this dataset, iron was influential for productivity (yield and biomass) and OC (concentration and relative) throughout the profile. The higher iron values could reflect a conducive climatic environment (50% variance explained by aridity index) or the type of product applied.

Iron oxides bind OC to hydroxyl groups of iron and aluminium (Saidy *et al.* 2012) and improve aggregation which can limit access to microbes to OC within aggregates (Singh *et al.* 2018).

There is potential to increase OC, and hence the reactive surface area of sands, by using products naturally high or with artificial addition of iron.

MANAGEMENT

Depth of sand to clay

Before any amendments to sandy soil can be selected, the soil type, particularly depth of sand, must be taken into consideration. Where the depth of sand was shallow (< 30 cm), there were little to no yield or OC changes compared to the unamended sand. Whilst clay addition increased cumulative OC when depth to sand was between 30-60 cm and > 90 cm, increased yield only occurred when depth to sand was between 30 and 60 cm. The addition of OAs overcame the reduction in yield with increasing sand depth in unamended soils, especially when depth to sand was > 90 cm. However, the effect on OC was unknown due to low sample numbers.

Depth of incorporation

Large increases in relative productivity were achieved with deep compared to shallow incorporation. Increased relative OC of the 0-30 cumulative depth were seen when clay with or without OAs were applied. Decreases were observed with incorporation without clay addition. The largest change in OC was observed in the 10-30 cm depth with little change in the surface 10 cm.

Acid sandy soil

An inverse relation between OC in the surface 10 cm and subsurface acidity in the OAs data subset highlights a probable limitation to biological activity at low pH (Jones *et al.* 2019). Whilst this did not appear to affect plant productivity, it has long-term consequences for soil health, nutrient turnover, availability and future productivity.

Time to observe changes in productivity and OC

Productivity changes were measured in a short time frame with a large response in the first 2 years that stabilised by 5 years. In the clay amended soils, the productivity response was maintained for 15 years. The limited dataset for OAs indicated that productivity increases were maintained for 4 years but generally declined thereafter.

For OC, it can take more than 10 years before a noticeable change in relative OC was observed.

There appears to be a lag time, of approximately 5-8 years, when changes in OC can be measured following increased productivity. To be able to assess the stability and longevity of applied amendments, measurements should be made for a minimum of 5 but preferably 10 years post application.

Soil sampling depth

It is critical to assess and monitor soil parameters to a depth of at least 30 cm to fully capture influences on productivity and carbon. The majority (70%) of influencing factors identified in this meta-analysis were below 10 cm and if these weren't included only a partial picture would have been presented.

CONCLUSION

In Australian sandy soils, there is a positive relation between OC concentration and yield when OC of the surface 10 cm is between 0.75 and 1.5%. Below OC 0.75% there is no relationship and above 1.5% the yield relation has stabilised. It is probable that other factors may be limiting productivity or transformation of organic inputs into OC.

The amount of rainfall; total annual and amount that fell in winter, spring and autumn; affected OC. The inverse relationship between OC and proportion of summer rainfall likely reflects higher turnover of OC with moister, warmer temperatures. The proportion of rain that fell in each season was important for biomass production.

Mineral nitrogen was important to improve relative productivity whereas organic nitrogen was associated with OC and MBC. There was an indication that the addition of mineral nitrogen, sulphur and phosphorus could increase OC but only when OC in the surface 10 cm was above 1.5%.

Iron and calcium complexes can directly bind OC and improve aggregation which can limit decomposition of OC by microbes. There is potential to increase OC, and hence the reactive surface area of sands, by using products naturally high or with artificial addition of iron and maybe calcium.

The overall soil properties must be taken into consideration when selecting the appropriate amendment as there were implications for increasing yield and OC. Differing responses were observed for water repellence, water holding capacity, low pH, rate of amendment applied, selection of incorporation depth and the depth of sand over clay.

A surface clay concentration between 6-10% of the amended sand will ensure optimal productivity. When clay concentration increased above 15% a yield penalty was observed. By contrast, the greatest increase in OC occurred when clay concentration was above 15%.

This meta-analysis has demonstrated that sandy soil amendments cannot be chosen on a single characteristic but need to encompass an array of features to address limitations to productivity and OC. Climatic parameters cannot be changed but management practices can enhance local water and nutrient efficiencies. It has highlighted the importance of collecting soil samples to at least 30 cm and include repeat sampling over long periods (5-20 years) to enable changes in properties and variables to be assessed especially considering the lag time for OC following productivity increases.

LESSONS LEARNT / RULES OF THUMB

Clay concentration of the amended sand between 6-10% will ensure the best productivity. When clay concentration increases above 15% there is likely to be a decrease in yield, but OC concentration will increase.

Mineral nitrogen was important to improve relative productivity whereas organic nitrogen was important for OC and MBC. Indication that the addition of mineral nitrogen, sulphur and phosphorus could increase OC but only when OC in the surface 10 cm was above 1.5%.

From this dataset, a number of variables can be considered markers for specific characteristics and can be grouped into

- OC stability – iron, calcium and clay concentration (where measured)
- Subsoil clay markers – potassium, boron, calcium, water holding capacity (WHC) generally deeper than 30 cm.
- When clay has been added to the surface 10 cm of the sand – boron, calcium, potassium, WHC, electrical conductivity, cation exchange capacity

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APPENDIX A – VARIABLES AND FACTORS

Factors used in building the understanding of what influenced the selected key variables

Key variables

Factor	Description	Factor	Description
Biomass	Biomass (t/ha)	OC 0-10	Organic carbon concentration - Walkley Black analysis (%)
Relative biomass	Biomass compared to the Nil (%)	Relative OC 0-10	OC compared to the Nil (%) 0-10 cm
Average Yield	Average Yield over time (t/ha)	OC Cum 0-30	OC WB of the cumulative 0-30 cm
Relative yield	Yield compared to the Nil (%)	Relative OC Cum 0-30	OC of the cumulative 0-30 cm compared to the Nil (%)
ECEC 0-10	Effective cation exchange capacity	MBC 0-10	Microbial biomass carbon (mg/kg) 0-10 cm

Factors

Factor	Description	Factor	Description
CARBON		**CLIMATIC**	
OC 10-20	Organic carbon Walkley Black analysis	Elevation	
OC 20-30		Evap	
OC 30-50		AnnRF 30yr	Average over 30 yrs
OC A0-30		Ann RF50yr	Average over 50 yrs
OC Cum 0-50		Autumn mm 30yr	Average amount for each season over 30 yrs
Relative OC 10-20	OC compared to the Nil (%)	Winter mm 30yr	
Relative OC 20-30		Spring mm 30yr	
Relative OC 30-50		Summer mm 30yr	
Relative OC A0-30		Autumn % 30yr	Proportion of rain for the season compared to the total average annual rainfall 30 years
Δ OC 0-10 Control	Change in OC concentration compared to the Nil (%)	Winter % 30yr	
Δ OC 10-20 Control		Spring % 30yr	
Δ OC 20-30 Control		Summer % 30yr	
Δ OC 30-50 Control		GSRF 30 yr	Growing season rainfall, average of 30 or 50 years
C STK 0-10	Carbon stock (t/ha)	GSRF 50 yr	
C STK 10-20		Min Temp 30yr	Average Minimum Temp
C STK 20-30		Max temp 30yr	Average Maximum Temp
C STK 30-50		Aridity Index	Average Annual rainfall / evaporation for average 30 years
C STK A0-30		No El Nina past 10yrs	Number of El Nina/Nino events for the 10 years prior to sampling of the site
C stock ESM 40	Carbon stock in the 0-30 cm depth for the equivalent soil mass of 4000 t/ha (~10th percentile)	No El Nino past 10yrs	
C stock ESM 45	Carbon stock ESM of 4500 t/ha (~50th percentile)	**PRODUCTIVTY**	
C stock ESM 51	Carbon stock for ESM of 5100 t/ha (~90th percentile)	Yield	Yield of the current year (t/ha)
C stock fixed		Total yield	Cumulative yield over time (t/ha)
C:N 0-10	C to N ratio	Protein	Grain protein (%0
C:P 0-10	C to P ratio	Screenings	Grain screenings (%)
C:S 0-10	C to S ratio	**CHEMICAL**	
MBC 10-20	Microbial biomass carbon (mg/kg)	B 0-10	Boron (mg/kg)
MBC 20-30		B 10-20	
MBC 30-50		B 20-30	
MBC A0-30		B 30-50	
MBC Cum 0-30		B A0-30	Average of the 0-30 cm
MBC/OC 0-10		Ca 0-10	Exchangeable Calcium (meq/100g)
DOC 0-10	Dissolved organic carbon (mg/kg)	Ca 10-20	
DOC 10-20		Ca 20-30	
DOC 20-30		Ca 30-50	
DOC 30-50		Ca A0-30	
DOC A0-30		EC 0-10	Electrical conductivity (dS/m)
DOC Cum 0-30		EC 10-20	
TC 0-10	Total Carbon (%)	EC 20-30	
Tot C/TotN	Total Carbon to Total Nitrogen ratio	EC 30-50	
		EC A0-30	

Factors (continued)

Factor	Description	Factor	Description
SOIL DESCRIPTIVE		**CHEMICAL (Cont)**	
Clay 0-10	Clay concentration from particle size analysis (%)	Fe 0-10	DTPA Iron (mg/kg)
Clay 10-20		Fe 10-20	
Clay 20-30		Fe 20-30	
Clay 30-50		Fe 30-50	
Clay A0-30		Fe A0-30	
Clay stock Cum 0-30	Clay stock cumulative for the 0-30 cm depth	K 0-10	Colwell potassium (mg/kg)
Clay+Si 0-10	Clay plus silt fraction from particle size analysis	K 10-20	
Clay+Si 10-20		K 20-30	
Clay+Si 20-30		K 30-50	
Clay+Si 30-50		K A0-30	
Clay+Si A0-30		MinN 0-10	Mineral nitrogen (NO3 + NH4) mg/kg
Fine sand 0-10	Fine sand fraction from particle size analysis	MinN 10-20	
Fine sand 10-20		MinN 20-30	
Fine sand 20-30		MinN 30-50	
Coarse Sand 0-10	Coarse sand fraction from particle size analysis	MinN A0-30	
Coarse Sand 10-20		NH4-N 0-10	Ammonium nitrogen (mg/kg)
Coarse Sand 20-30		NO3 0-10	Nitrate-Nitrogen (mg/kg)
SAND 0-10	Sand fraction from particle size analysis	Total N (Leco)	Total Nitrogen Leco analysis
SAND 10-20		Total N Leco 10-20	
SAND 20-30		Min N Stk 0-10	Mineral N stock (t/ha)
ECEC 10-20	Effective cation exchange capacity	Min N Stk 10-20	
ECEC 20-30		Min N Stk 20-30	
ECEC 30-50		Min N Stk 30-50	
ECEC A0-30		Min N Stk A0-30	
BD 0-10	Bulk density (g/cm3)	PMN 0-10	Potentially mineralisable nitrogen (mg/kg)
BD 10-20		PMN 10-20	
BD 20-30		PMN 20-30	
BD 30-50		PMN 30-50	
BD A0-30	Average of the 0-30 cm	PMN A0-30	
pH 0-10	pH CaCl2 test	P 0-10	Colwell Phosphorus (mg/kg)
pH 10-20		P 10-20	
pH 20-30		P 20-30	
pH 30-50		P 30-50	
pH A0-30		P A0-30	
MED	Water repellence - Molarity of Ethanol Droplet test	DGTP 0-10	Available phosphorus by diffusive gradient in thin-films
SM 0-30	Mass of soil in the 0-30 cm depth (t/ha)	DGTP 10-20	
Subsoil Depth	Depth to subsoil clay (cm)	DGTP 20-30	
WHC 0-10	Water holding capacity - measured by gravimetric water (%)	DGTP 30-50	
WHC 10-20		DGTP A0-30	
WHC 20-30		S 0-10	Sulfur (KCl) mg/kg
WHC 30-50		S 10-20	
WHC A0-30		S 20-30	
AMENDMENT APPLICATION		S 30-50	
LTA incorp depth	Long-term amendment depth of incorporation	S A0-30	
LTA Rate (t/ha)	Long-term amendment rate of application		
OA incorp depth	Organic amendment depth of incorporation		
OA No. applications	Organic amendment number of applications		
OA Rate	Organic amendment rate of application		
Year amended	Year amendment applied		
Yrs since amended	No of years since treatment was amended		

Abbreviations: 10-20 indicates the soil depth, A0-30 is the average value across the 3 depths (0-10, 10-20, 20-30 or equivalent), Cum 0-30 is the cumulative or sum of the value over the 3 depths

APPENDIX B – SUMMARY TABLES FOR INFLUENCING FACTORS

Productivity

	Yield								Relative Yield								Relative Biomass							
	Count	Mean	SE Mean	Minimum	25%	50%	75%	Maximum	Count	Mean	SE Mean	Minimum	25%	50%	75%	Maximum	Count	Mean	SE Mean	Minimum	25%	50%	75%	Maximum
ANNUAL RAINFALL 30 year average																								
250-350	29	1.77	0.07	1.00	1.44	1.74	2.06	2.46	42	167	18	100	112	129	161	642	6	293	88	100	100	240	505	571
350-400	43	1.90	0.13	0.38	1.39	1.61	2.53	3.74	54	136	9	26	100	111	144	418	14	160	15	96	100	160	176	270
400-450	41	2.24	0.10	1.00	1.74	2.18	2.68	4.27	44	126	5	86	100	106	160	211	25	134	10	61	100	120	153	247
450-500	9	1.80	0.51	0.82	0.98	1.11	1.93	5.26	16	112	4	88	100	106	126	143	4	101	4	93	93	101	108	108
500-550	17	1.93	0.29	0.53	1.00	1.60	2.94	3.96	16	133	10	90	100	113	170	202	12	155	17	76	106	152	192	259
550-650	10	2.71	0.48	1.06	1.22	2.78	4.11	4.28	8	147	14	101	110	147	179	203	13	118	7	85	100	107	134	166
ARIDITY INDEX																								
Arid 0.1-0.2	29	1.77	0.07	1.00	1.44	1.74	2.06	2.46	42	167	18	100	112	129	161	642	6	293	88	100	100	240	505	571
Semi arid 0.2-0.3	88	2.14	0.09	0.38	1.53	2.06	2.71	4.27	106	129	5	26	100	106	144	418	43	140	8	61	100	126	161	270
Semi-arid 0.3-0.4	27	1.49	0.19	0.53	1.00	1.15	1.57	5.26	32	134	6	88	101	125	170	203	12	155	17	76	106	152	192	259
Semi-arid 0.4-0.5																								
DEPTH OF SAND OVER CLAY (CM)																								
<30	3	2.23	0.04	2.16	2.18	2.24	2.27	2.28	4	99	1	97	97	99	100	100	0							
30-60	58	2.10	0.14	0.38	1.41	1.72	2.68	5.26	55	135	9	26	100	111	163	418	43	142	7	85	100	129	166	270
60-90	61	2.09	0.11	0.53	1.50	2.00	2.65	3.96	90	145	9	90	100	112	157	642	29	166	23	61	100	120	167	571
>90	27	1.64	0.14	0.82	1.11	1.42	2.00	3.74	31	132	5	94	106	126	143	203	2	106	6	100	100	106	112	112
CLAY CONCENTRATION (%)																								
0-3	21	1.77	0.18	1.00		1.13	1.50	2.10	18	145	13	100	100	124	172	300	16	139	13	76	100	120	160	247
3-6	24	1.60	0.13	0.49		1.18	1.45	2.01	22	139	16	74	100	110	171	418	18	146	12	92	100	151	176	270
6-10	8	1.54	0.24	0.38		1.04	1.59	2.17	5	173	25	78	147	197	207	218	3	184	48	96	121	198	243	259
10-15	4	1.88	0.42	0.84		1.21	2.03	2.55	4	207	39	142	160	182	254	320	4	195	30	129	146	194	244	262
15-20	4	2.49	0.80	0.53		1.27	2.59	3.72	2	117	27	90	90	117	144	144	2	134	12	122	122	134	146	146
ORGANIC AMENDMENT																								
Nil	99	1.84	0.09	0.38	1.16	1.62	2.24	4.28	111	126	6	26	100	106	129	642	54	132	9	61	100	106	154	505
Compost	4	2.13	0.57	1.48	1.53	1.61	2.74	3.83	11	109	4	88	100	105	112	143	3	130	11	112	117	129	144	149
Manure	21	2.59	0.14	1.67	1.94	2.64	3.01	3.74	37	153	9	97	113	129	182	264	3	132	10	120	121	126	145	152
Residue	25	2.22	0.19	1.00	1.58	2.00	2.52	5.26	21	197	27	79	127	169	202	624	14	231	29	111	170	215	259	571
LONG-TERM AMENDMENT																								
Nil	68	1.89	0.10	0.49	1.34	1.71	2.22	4.11	103	142	9	88	100	110	145	642	36	158	19	76	100	111	158	571
Subsoil clay	79	2.08	0.11	0.38	1.41	1.85	2.64	5.26	68	139	6	26	107	125	170	320	32	147	9	61	106	138	186	262
Bentonite	0								7	104	3	93	99	104	110	111	2	94	9	85	85	94	103	103
Biochar	2	3.85	0.11	3.74	3.74	3.85	3.96	3.96	2	99	0	99	99	99	99	99	0							
Coal	0								0								4	140	11	117	123	139	157	165
AMENDMENTS (LTA AND OM) X INCORPORATION DEPTH																								
Nil	22	1.50	0.16	0.49	1.00	1.39	1.93	4.11	28	100	0	100	100	100	100	100	13	100	0	100	100	100	100	100
SH	5	2.14	0.48	0.82	1.48	2.00	2.79	3.71	6	104	3	100	100	100	110	116	1	100		100	100	100	100	100
OM+SH	12	2.16	0.21	1.48	1.63	1.92	2.55	3.83	29	119	4	88	102	115	129	189	3	144	9	126	133	152	154	155
Clay+SH	37	1.95	0.17	0.38	1.17	1.75	2.58	4.28	43	120	5	26	104	111	129	203	18	113	8	61	94	106	122	192
Clay+OM+SH	5	2.86	0.14	2.51	2.61	2.89	3.03	3.35	5	141	29	100	105	114	160	253	1	120		120	120	120	120	120
Charcoal SH	2	3.85	0.11	3.74	3.74	3.85	3.96	3.96	2	99	0	99	99	99	99	99	2	141	24	117	117	141	165	165
D	12	1.70	0.18	1.00	1.19	1.44	2.20	2.88	16	186	36	94	103	129	174	642	11	182	40	76	103	148	161	505
OM+D	17	2.27	0.19	1.19	1.68	2.00	3.03	3.74	24	197	23	97	132	167	216	624	8	233	53	111	125	206	258	571
Clay+D	21	1.82	0.14	0.84	1.39	1.68	2.25	3.16	16	138	10	74	108	143	164	218	9	155	13	96	124	160	185	207
Clay+OM+D	16	2.47	0.28	1.00	1.59	2.39	3.04	5.26	11	190	20	79	169	187	226	320	6	222	14	176	204	215	259	262
YEARS SINCE AMENDMENT APPLIED																								
Nil	12	1.55	0.23	0.95	1.03	1.29	1.77	3.71	15	100	0	100	100	100	100	100	5	100	0	100	100	100	100	100
2	61	1.98	0.10	0.38	1.48	1.93	2.49	3.74	100	151	9	78	100	116	167	642	33	181	20	61	109	149	230	571
5	42	1.95	0.15	0.68	1.16	1.60	2.68	4.27	48	125	5	26	100	118	153	203	31	134	7	76	100	126	160	207
10	27	2.42	0.23	1.12	1.43	2.18	3.30	5.26	10	142	11	109	115	127	173	203	5	103	2	96	99	105	107	108
15	7	1.99	0.09	1.70	1.78	2.00	2.18	2.28	7	133	13	101	106	116	163	185	0							

Organic Carbon

	OC 0-10								OC Cum 0-30							
	Count	Mean	SE Mean	Minimum	25%	50%	75%	Maximum	Count	Mean	SE Mean	Minimum	25%	50%	75%	Maximum
ANNUAL RAINFALL 30 year average																
250-350	9	0.64	0.10	0.30	0.47	0.55	0.78	1.20	6	0.88	0.09	0.60	0.70	0.87	1.10	1.12
350-400	33	0.51	0.04	0.22	0.32	0.45	0.65	1.10	31	0.95	0.06	0.42	0.71	0.89	1.20	1.75
400-450	69	0.72	0.03	0.20	0.53	0.69	0.90	1.26	69	1.37	0.05	0.38	1.08	1.26	1.66	2.34
450-500	14	1.51	0.34	0.56	0.69	0.96	1.22	3.90	9	2.54	0.34	1.14	1.85	2.14	3.68	3.90
500-550	22	1.06	0.06	0.73	0.81	1.02	1.15	1.59	14	1.69	0.09	1.31	1.55	1.66	1.73	2.70
550-650	24	1.72	0.18	0.80	1.01	1.11	2.40	3.67	8	3.43	0.39	2.09	2.41	3.73	3.80	5.47
ARIDITY INDEX																
Arid 0.1-0.2	9	0.64	0.10	0.30	0.47	0.55	0.78	1.20	6	0.88	0.09	0.60	0.70	0.87	1.10	1.12
Semi arid 0.2-0.3	111	0.70	0.03	0.20	0.46	0.64	0.89	1.59	101	1.24	0.04	0.38	0.95	1.15	1.50	2.34
Semi-arid 0.3-0.4	40	1.15	0.12	0.56	0.82	0.96	1.08	3.90	19	1.79	0.08	1.31	1.56	1.73	1.96	2.70
Semi-arid 0.4-0.5	11	2.57	0.15	2.09	2.18	2.44	2.68	3.67	8	3.43	0.39	2.09	2.41	3.73	3.80	5.47
DEPTH OF SAND OVER CLAY (CM)																
<30	14	0.88	0.06	0.56	0.71	0.85	1.10	1.26	12	1.62	0.10	0.89	1.45	1.67	1.81	2.22
30-60	72	1.03	0.11	0.22	0.45	0.68	1.02	3.90	69	1.59	0.12	0.59	0.98	1.25	1.92	5.47
60-90	56	0.84	0.05	0.20	0.56	0.78	1.06	2.13	48	1.35	0.07	0.38	1.05	1.31	1.69	2.68
>90	29	0.85	0.04	0.30	0.69	0.94	1.02	1.20	8	1.12	0.25	0.42	0.60	0.92	1.50	2.47
CLAY CONCENTRATION (%)																
0-3	25	0.67	0.05	0.20	0.45	0.69	0.89	1.08	22	1.17	0.08	0.38	0.98	1.09	1.32	1.87
3-6	34	0.70	0.06	0.30	0.42	0.66	0.91	1.59	31	1.22	0.09	0.59	0.84	1.10	1.57	2.70
6-10	22	0.82	0.10	0.29	0.55	0.68	0.98	2.13	19	1.35	0.13	0.67	0.94	1.23	1.39	2.68
10-15	6	0.61	0.09	0.28	0.46	0.61	0.85	0.85	6	1.30	0.15	0.73	1.13	1.26	1.69	1.73
15-20	5	0.92	0.09	0.66	0.77	0.93	1.02	1.22	5	1.80	0.16	1.28	1.57	1.90	1.99	2.25
ORGANIC AMENDMENT																
Nil	137	0.95	0.06	0.20	0.56	0.80	1.03	3.90	108	1.54	0.08	0.38	1.04	1.27	1.79	5.47
Compost	2	2.41	1.26	1.15	1.15	2.41	3.67	3.67	0							
Manure	9	0.86	0.11	0.31	0.56	0.95	1.10	1.20	8	1.30	0.18	0.42	0.89	1.43	1.72	1.89
LONG-TERM AMENDMENT									21	1.28	0.10	0.64	0.95	1.31	1.41	2.25
Nil	61	0.84	0.07	0.30	0.48	0.70	0.95	3.90	46	1.24	0.09	0.42	0.92	1.11	1.55	3.73
Subsoil clay	103	0.86	0.05	0.20	0.55	0.74	1.03	3.27	87	1.52	0.08	0.38	1.08	1.34	1.78	5.47
Bentonite	3	3.21	0.55	2.13	2.50	3.60	3.83	3.90	1	2.13		2.13	2.13	2.13	2.13	2.13
Biochar	2	1.12	0.01	1.11	1.11	1.12	1.12	1.12	0							
Coal	2	3.06	0.62	2.44	2.44	3.06	3.67	3.67	0							
AMENDMENTS (LTA AND OM) X INCORPORATION DEPTH																
Nil	30	0.98	0.14	0.30	0.54	0.76	0.96	3.90	25	1.43	0.18	0.59	0.92	1.15	1.74	3.90
SH	6	0.79	0.10	0.50	0.63	0.72	1.05	1.13	2	1.44	0.40	1.04	1.04	1.44	1.83	1.83
OM+SH	6	1.00	0.09	0.58	0.95	1.05	1.15	1.20	2	1.34	0.45	0.89	0.89	1.34	1.79	1.79
Clay+SH	57	1.15	0.10	0.20	0.69	0.97	1.18	3.90	41	1.84	0.17	0.38	1.14	1.53	2.16	5.47
Clay+OM+SH	3	0.93	0.22	0.49	0.64	1.10	1.18	1.20	3	1.44	0.29	0.89	1.05	1.54	1.80	1.89
Charcoal SH	3	1.56	0.44	1.11	1.11	1.12	2.11	2.44	0							
D	11	0.59	0.06	0.31	0.45	0.60	0.79	0.85	10	1.14	0.11	0.59	1.05	1.12	1.32	1.69
OM+D	8	0.58	0.10	0.31	0.35	0.46	0.80	1.10	8	1.03	0.14	0.42	0.73	1.03	1.31	1.65
Clay+D	30	0.63	0.04	0.22	0.46	0.62	0.80	1.13	30	1.35	0.08	0.68	1.00	1.20	1.73	2.47
Clay+OM+D	16	0.67	0.06	0.28	0.49	0.69	0.82	1.19	16	1.38	0.12	0.64	1.04	1.34	1.60	2.25
YEARS SINCE AMENDMENT APPLIED																
Nil	21	0.97	0.17	0.30	0.56	0.81	0.96	3.90	16	1.40	0.21	0.60	0.94	1.12	1.64	3.90
2	40	1.07	0.15	0.28	0.47	0.80	1.10	3.90	36	1.43	0.12	0.42	0.89	1.33	1.76	3.90
5	52	0.72	0.03	0.30	0.53	0.72	0.93	1.17	41	1.37	0.08	0.59	1.05	1.27	1.67	2.70
10	36	1.00	0.12	0.22	0.49	0.76	1.11	3.27	32	1.75	0.20	0.60	0.95	1.33	2.10	5.47
15	22	0.95	0.07	0.20	0.70	0.96	1.20	1.57	12	1.42	0.15	0.38	1.14	1.38	1.72	2.22