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Capacity for increasing soil organic carbon stocks in dryland agricultural systems

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Abstract. Assessment of the potential for soil carbon sequestration based on soil type, land use, and climate scenarios is crucial for determining which agricultural regions can be used to help mitigate increasing atmospheric CO_2 concentrations. In semi-arid and Mediterranean-type environments, soil organic carbon (SOC) storage capacity is rarely achieved under dryland agricultural systems. We aimed to assess both actual (measured) and attainable (modelled) SOC stock values for the dryland agricultural production zone of Western Australia. We measured actual SOC storage (0–0.3 m) and known constraints to plant growth for a range of soils types (3–27% clay) and land uses (continuous cropping, mixed cropping, annual and perennial pastures) on the Albany sand plain in Western Australia ($n = 261$ sites), spanning a rainfall gradient of 421–747 mm. Average actual SOC stocks for land use–soil type combinations ranged from 33 to 128 t C/ha (0–0.3 m). Up to 89% of the variability in actual SOC stock was explained by soil depth, rainfall, land use, and soil type. The scenarios modelled with Roth-C predicted that attainable SOC values of 59–140 t C/ha (0–0.3 m) could be achieved within 100 years. This indicated an additional storage capacity of 5–45% (7–27 t C/ha) depending on the specific land use–soil type combination. However, actual SOC in the surface 0–0.1 m was 95 to >100% of modelled attainable SOC values, suggesting this soil depth was 'saturated'. Our findings highlight that additional SOC storage capacity in this region is limited to the subsoil below 0.1 m. This has implications for management strategies to increase SOC sequestration in dryland agricultural systems, as current practices tend to concentrate organic matter near the soil surface.

Additional keywords: carbon farming, carbon modelling, carbon sequestration, climate variability, farming systems, Roth-C.

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Introduction

Sustainable management of soil, and in particular soil organic carbon (SOC), is widely regarded as beneficial to soil functions that support plant productivity (e.g. nutrient cycling) and has been associated with the continued viability of the agricultural sector (Hoyle *et al*. 2011). Sequestering carbon in agricultural soils is also seen as one way of decreasing atmospheric carbon dioxide (CO_2) concentrations and mitigating climate change. Consequently, land managers, industry, and government are interested in identifying land uses that increase net plant/animal organic carbon inputs to the soil and then understanding how these changes will impact soil function (Cookson *et al*. 2005; Hoyle and Murphy 2006; Murphy *et al*. 2011) and carbon sequestration (Álvaro-Fuentes *et al*. 2012; Sauer *et al*. 2012). Although more than half of organic carbon inputs to soil return to the atmosphere as CO_2 via microbial decomposition (Lynch 1983; Hoyle *et al*. 2008), a component of the remaining carbon is sequestered in more stable soil organo-mineral complexes (Baldock and Skjemstad 2000; Six *et al*. 2002). Thus, the potential for increased carbon storage could be achieved via greater inputs, and improved retention of plant/animal residues and associated organic carbon in the soil.

Fundamental studies of the potential for storage of SOC have identified key soil attributes and climate factors that determine the upper and lower thresholds for SOC (Ingram and Fernandes 2001). These include soil depth, texture (i.e. proportion of clay, silt, and sand), and degree of aggregation, which effectively determine the *potential* SOC storage of a soil if climate is not limiting inputs of organic matter from plant growth. For example, increasing clay content can increase the amount of SOC that is physically protected from microbial breakdown (Hoyle *et al*. 2011). Climate parameters (temperature and rainfall) affect SOC levels indirectly by affecting plant growth and net primary productivity (Grace *et al*. 2006), and directly by regulating the rate of microbial soil organic matter (SOM) decomposition (Hoyle *et al*. 2006), thus determining the *attainable* SOC storage capacity (Ingram and Fernandes 2001). With the exception of soil engineering (e.g. soil inversion, claying; Hall *et al*. 2010) there is little scope to significantly influence either the inherent physical or climatic influences on carbon storage in soils. The *actual* SOC storage capacity measures the current status of SOC values and is regulated by both historical climatic conditions and also agronomic, soil, and livestock management decisions made *in situ* (Ingram and Fernandes 2001). Agronomic choices such as crop or pasture selection, fertiliser application rates, net organic matter removal (e.g. burning), management of the soil (e.g. tillage practices), and removal of soil constraints to plant growth (e.g. liming to increase soil pH) alter plant biomass production, contributing to whether or not the actual SOC storage is as high as the attainable SOC capacity (Hoyle *et al*. 2011). Therefore, actual SOC stock values depend not only on soil type (the potential of the soil to protect SOM) but also on the land use and management (determining net primary productivity).

Semi-arid and arid soils constitute a third of the global land area and are widely used for agricultural production (Harrison and Pearce 2000). The Western Australian grain-growing region consists of 18 million ha of semi-arid land and is responsible for ~40% of Australia's annual grain production (Australian Bureau of Agricultural and Resource Economics, www.abareconomics.com). The region is characterised by cool, wet winters and hot, dry summers. Only one crop (e.g. wheat, oats, lupin, canola) or annual pasture can be grown during the winter months (with no plant cover in summer), while growth of perennial pastures is possible over summer by utilising stored water and in response to infrequent summer rainfall. Studies often report that increasing the frequency and longevity of pasture phases will increase SOM (Dalal and Chan 2001). This increase occurs at a faster rate than changes in SOM resulting from the implementation of crop management practices such as zero tillage and stubble retention, which aim to increase the amount of crop residue returned to soil (Murphy *et al*. 2011). This increase does not seem specific to pasture type (Guo and Gifford 2002; Sanderman *et al*. 2010; Chan *et al*. 2011), although for permanent perennial pastures, those with spreading growth (e.g. kikuyu, *Pennisetum clandestinum*, as assessed in this study) can have higher SOC stocks than plants that clump (e.g. Rhodes grass, *Chloris gayana*), where bare soil remains between plants (Sanderman *et al.* 2013*b*). One option to increase actual SOC in this region may be to promote land-use systems which support greater net primary productivity and have potential to increase allocation of SOC to depth (e.g. perennial pasture systems; Jackson and Roy 1986; Nie *et al*. 2008). This concept was evaluated for the Albany Sand Plain in Western Australia, an area of 2250 km^2 which typifies common land uses representative of semi-arid and Mediterranean-type agricultural production systems: cereal-dominated cropping (continuous cropping), mixed crop–pasture rotational systems (mixed cropping), and either permanent annual or perennial pastures for livestock grazing.

In the past, management changes have been a result of commodity prices, but future changes could potentially result from changes in annual rainfall patterns. The Albany Sand Plain catchment was also chosen because the distribution of each land use is likely to change as the climate continues to become drier (i.e. more crop and less pasture). From 1950 to 2003, the south-west of Australia is estimated to have experienced a 15% decrease in heavy winter rainfall (Nicholls 2010), which, combined with larger temperature anomalies (Nicholls 2003), has theoretical implications for net primary productivity and associated SOC sequestration. Mpelasoka *et al*. (2008) projected continued increases in soil-moisture drought frequency in the south-west of Western Australia. A continuing decline in rainfall pattern is likely to influence not only the suitability of the environment to particular land uses but also the attainable SOC targets associated with declining net primary productivity. Although the movement from pasture systems to continuous cropping could have a significant impact on carbon storage, the declining rainfall is likely to be a primary driver of changes in SOC and profit in the Albany Sand Plain catchment and other dryland farming areas.

In order to assess land-use and climate impacts on changes in SOC, the aims of this study were to (*i*) determine which climatic and soil physio-chemical variables helped explain actual SOC levels; (*ii*) quantify actual SOC storage under continuous cropping, mixed cropping, and both annual and perennial pasture based farming systems; and (*iii*) model attainable SOC levels for these soils to determine whether there is further capacity in these soils to sequester carbon under current land-use and future climate scenarios.

Materials and methods

Region description

The Albany Sand Plain, in the south-west of Western Australia (Fig. 1), comprises a level to very gently undulating landscape, internally drained to the east and dissected by the Kalgan River to the west. Deep sands, sandy duplex (i.e. texture-contrast) soils, and shallow sand overlying sodic clay (Tenosols, Podosols, Sodosols; Isbell 1996) dominate the region and typify common soil groups throughout the Western Australian agricultural region (Schoknecht 2002). Dominant land uses, defined by the previous 5–10-year paddock history, include continuous cropping (predominantly barley, canola, and lupin), mixed cropping in rotation with annual pasture, permanent annual pasture (with the livestock enterprise mainly sheep-based), and permanent perennial pasture. Closer to the coast, beef production dominates, with most producers using a perennial pasture base to feed livestock during summer and autumn. Annual pastures are grass-dominated swards comprising ryegrass (*Lolium* spp.), brome grass (*Bromus* spp.), and barley grass (*Hordeum* spp.), with either clover (*Trifolium* spp.) or serradella (*Ornithopus* spp.) as the legume component. Perennial kikuyu pastures have also been used to a limited extent for the past 35 years, typically as a mixed sward of kikuyu with either clover or serradella. Perennial pastures have longer survival, deeper rooting, and greater plant biomass during summer.

Site selection and soil sampling

Sampling sites were distributed over an area of 2250 km^2, spanning a rainfall gradient ranging from 421 to 747 mm (Fig. 1). In total, 261 sites that were determined in the field to be either Tenosol (i.e. deep sand >0.9 m) or Sodosol (shallow duplex, depth to clay <0.4 m, sodic subsoil) were targeted under four primary land uses: (*i*) continuous cropping, (*ii*) mixed cropping, (*iii*) permanent annual pasture, or (*iv*) permanent perennial pasture systems (Table 1). After subsequent soil

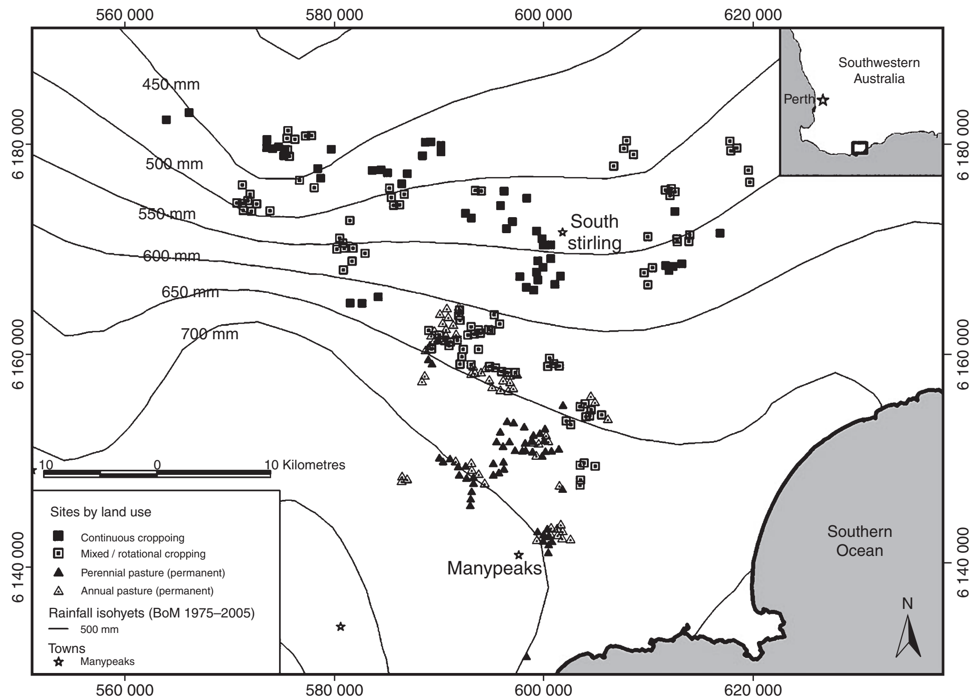

Fig. 1. Albany Sand Plain sampling locations ($n = 261$), land use, and average annual rainfall (1976–2005) isohyets (contours).

Table 1. Comparative site numbers for Western Australian Soil Group (WASG)–land use combinations (total 261 sites)

WASG	Continuous cropping	Mixed crop and livestock	Annual pasture	Perennial pasture
Deep sand	25	49	29	28
Sandy duplex	24	45	22	20
Loamy duplex	2	7	6	4

textural analysis in the laboratory, 19 sites were reclassified as loamy duplex and retained as a separate group (Table 1). Sampling was undertaken to provide a random representation of the management–soil type combination ($n = 25$) under investigation.

Soil collection occurred during the dry summer period (2010–11) while fallow and before a crop or annual pasture was established. As the soil was naturally field-dry (<2% gravimetric water content), soils could be stored without chilling (Gonzalez-Quiñones *et al.* 2011). Therefore, sampling at this time of the year avoided problems associated with (*i*) biological activity resulting in SOM decomposition, and (*ii*) plant roots passing through the sieve and confounding the analysis of soil carbon fractions.

Sites representing a specific soil type–land use combination were selected, and a grid 25 m by 25 m orientated north–south and east–west was laid out and subdivided into grid cells 5 m by 5 m (Sanderman *et al.* 2011). Soil was collected to a depth of 0.3 m in 0.1-m increments using a hand-held sand auger (0.05 m diameter) at 10 randomly selected grid nodes. The 30 samples per site (three depths, 10 profile locations) were kept separate for 5% of the sites (to enable an assessment of the within-site variance); at the remaining sites, the samples were composited by depth. A soil pit was dug at the south-west corner of the grid and described in detail, and soil was classified according to the Australian Soil Classification (Isbell 1996) and Western Australian Soil Group (WASG) (Schoknecht 2002); a marker was buried for future relocation.

Soil analyses

For each separate soil sample, buried plant residue (BPR), root material, and gravel >2 mm retained on the sieve were collected and their percentages determined (data not presented). Total carbon was determined on oven-dried, finely ground soil (<2 mm) by total combustion using a Vario EL Elementar analyser (Elementar Analysensysteme, Hanau, Germany) and total SOC stock adjusted on a volumetric basis using bulk density (BD) and percentage gravel values for each 0.1-m soil increment. Soil BD (g/cm^3) was determined for each of the three soil depths using a gamma-neutron density meter (Blake and Hartge 1986), which has been shown for Western Australian soils to result in the same SOC stock estimates as found with use of traditional BD ring or clod methods (Holmes *et al.* 2011).

Because the primary net productivity of a given site influences SOC, other soil properties known to constrain plant production for the region were also measured (Table 2). Electrical conductivity (EC, used to indicate dry land salinity) and soil pH were determined in 1 : 5 (v/v) soil : water $CaCl_2$ extracts, respectively. Water repellence of soil was measured using the molarity of ethanol droplet test (MED; King 1981). Particle size analysis (sand, silt, clay percentage) was determined by sedimentation (McKenzie *et al.* 2002).

Table 2. Western Australian Soil Group (WASG) properties (adjusted means) averaged across land use classifications for each 0.1-m depth increment (0–0.3 m) on the Albany Sand Plain of Western Australia

BD, Bulk density; EC, electrical conductivity; MED, molarity of ethanol drop test for water repellency (King 1981)

Sampling depth (m)	WASG	*n*	BD (g/cm^3)	Clay (%)	Sand (%)	EC (µS/cm)	MED (mol)	pH
0.0–0.1	Deep sand	131	1.34	3.7	94.8	115.1	3.1	4.7
	Loamy duplex	19	1.33	12.0	83.7	199.0	2.2	4.5
	Sandy duplex	111	1.37	5.0	92.8	150.8	2.8	4.5
0.1–0.2	Deep sand	131	1.51	1.7	96.9	50.7	2.3	4.2
	Loamy duplex	19	1.68	20.6	76.5	126.1	0.1	4.7
	Sandy duplex	111	1.63	8.0	90.3	68.4	0.4	4.4
0.2–0.3	Deep sand	131	1.37	1.2	95.9	40.5	1.7	4.2
	Loamy duplex	19	1.65	27.2	70. 5	168.8	0.0	5.1
	Sandy duplex	111	1.54	18.5	79.9	89.3	0.1	4.7
l.s.d. ($P = 0.05$)			0.05	2.4	3.0	25.8	0.34	0.2

Soil organic carbon stock is a measure of the mass of carbon per area over a specified thickness of soil (Ellert *et al*. 2001), calculated as:

$$\mathrm{SOC}stock = dC\%BD_{fe}(1 - \mathrm{CF}) \tag{1}$$

where SOC*stock* is the SOC stock (t/ha of carbon), d is the sampling thickness (cm), $C\%$ is the total SOC concentration (%), BD_{fe} is the BD of the fine earth fraction (g/cm^3), and CF is the soil coarse fraction so that (1 – CF) is the fine earth fraction (unitless). The SOC stock was calculated in two ways: (*1*) total stock over 0–0.3 m (SOC*stock*), and (*2*) total stock over a soil thickness equivalent to a soil mass of 0.4 t/m^2 (SOC*eq*). The equivalent mass method provides the most accurate baseline possible for assessing differences in stocks between soil types of different BD (Gifford and Roderick 2003; Allen *et al*. 2010), but it was not significantly different from the SOC*stock* for this dataset. This paper reports actual SOC values as determined by SOC*stock*, as the 0–0.3 m volume relates directly to attainable SOC values derived from Roth-C modelling.

Statistical analyses

Linear mixed models using the restricted maximum likelihood (REML) procedure in GENSTAT for Windows (Edition 14, www.genstat.com) were fitted to evaluate the absolute and relative importance of depth, land use, ASC, and WASG on actual SOC stock values. REML allows for estimation of variance components and adjusted mean effects of the factors of interest and can handle unequal numbers of sites in the various strata in the study design. After preliminary analysis of the data the variation of residuals was not uniform. Hence, $\log_{10}$ transformations were used to stabilise the variance. The total (0–0.3 m) actual SOC stock variance was estimated across sites (composite samples) and within site (the 5% of sites where samples were not composited). REML was used to predict data group means, the standard error of the difference, and the least significant difference (l.s.d.) detectable $P = 0.05$.

After fitting the initial model and calculating diagnostics, REML models were fitted to the transformed ($\log_{10}$) actual SOC data for assessment of statistical significance using log-likelihood ratio tests. Group mean values and l.s.d.s were calculated (for the fixed effects in the model). We assumed that *Rainfall*, *Land use*, and *Depth* were fixed terms in the model; ASC and WASG were considered as random terms to compare the methods of classification as assessed by the change in deviance terms or changes in the REML log-likelihood as discussed in Payne *et al*. (2011).

The covariates (EC, pH, MED, sand percentage) taken at each depth were also examined once the base model of *Rainfall*, *Land use*, and best soil classification (WASG) was fitted. These were added as random effects in the model and tested in a similar way using changes in deviance with a chi-square test. The detailed GENSTAT code used is presented in Appendix 1.

Soil carbon modelling

The Roth-C model (version 26.3) operating in Excel© was used to model attainable SOC values in non-waterlogged soils as described by Jenkinson (1990). Roth-C has previously been validated for use in dryland agricultural systems by Janik *et al*. (2002) and, more recently, for use with perennial pastures (Sanderman *et al*. 2013*a*) in southern Australia. To initiate the model, SOC is partitioned into six pools (Janik *et al*. 2002): decomposable plant material (DPM), resistant plant material pool (RPM), fast and slow microbial biomass pools (BIOF and BIOS), humified organic matter (HUM), and inert carbon (IOM, which includes the char fraction). Reported allocations for SOC pool values within Roth-C for Australian soils (Janik *et al*. 2007) were used—1%, 20%, 2%, 0.2%, 60%, 17% for DPM, RPM, BIOF, BIOS, HUM, and IOM, respectively. Janik *et al*. (2002) report that errors in estimates of the IOM, HUM, and RPM pools contribute to uncertainty in the modelled total soil carbon, with the RPM pool demonstrating most sensitivity in model outputs.

Climate data (lat. –34.91, long. 117.99) used to initiate the Roth-C model for the Albany Sand Plain included long-term (1889–2005) average monthly rainfall (mm), open-pan evaporation (mm), and temperature (°C). Other site-dependent variables included plant residue inputs (net removal of dry matter (DM) from paddock via grazing; percentage of stubble retained), measured actual SOC stock (SOC, t C/ha), and clay content (%) (Table 2). We also ran model scenarios to determine likely changes in attainable SOC stocks over a 100-year period based on a projected 30% decline in rainfall (Crimp *et al*. 2008).

Representative land-use scenarios were constructed to initialise Roth-C to determine the attainable SOC storage. Permanent perennial pasture systems were modelled to determine the maximal attainable SOC storage value for each soil type assuming 12 months of DM production, no grazing, and the retention of all plant residues. A root to shoot ratio of 1 : 1 (determined from the average of seven perennial grass species grown over two seasons; Bolinder *et al*. 2002) was used with an above ground DM production of 16 kg/mm available water. In this example, available water was calculated as annual rainfall minus a nominal loss of 50 mm. Four further land-use scenarios were modelled to reflect attainable SOC values for each representative land-use category:

1. Perennial pasture—root to shoot ratio 1.1, 33.5% net removal of DM, 100% water-use efficiency (WUE), slope 16 kg DM/mm available water, 12 months DM production, 95% stubble retention; available water as above.
2. Annual pasture system—root to shoot ratio 1.1, 33.5% net removal of DM, 100% WUE, slope 20 kg DM/mm available water, 7 months DM production from May, 95% stubble retention. In this scenario, available water was calculated as growing season rainfall (GSRF, April–October) minus a 50-mm loss.
3. Continuous cropping—barley, root to shoot ratio 0.5, harvest index 0.4, 60% WUE, slope 17.5 grain and 30 kg DM/mm available water, 7 months DM production from May; available water calculated as GSRF – (0.33 × GSRF).
4. Mixed crop and livestock—barley (as above), canola, annual pasture (as above) rotation; canola as per barley but with a slope 10 kg grain and 20 kg DM/mm available water.

Results

Actual SOC stock values

The main factors of *Depth*, *Land use*, and *Rainfall* were all significant ($P < 0.001$) in the determination of the $\log_{10}$ actual SOC stock values (Table 3). *Depth* × *Land use* and *Depth* × *Rainfall* interactions were also significant in the REML analysis. Using the $\log_{10}$ of actual SOC stock values (0–0.3 m) as the response variate, and with land-use scenarios and long-term average rainfall terms in the statistical model, the WASG classification (Schoknecht 2002) was found to better explain the variation of the actual SOC stock values than did ASC (deviance test: 14.01 on 6 d.f., $P < 0.03$; 0.00 on 6 d.f., $P > 0.99$, for WASG and ASC, respectively). Further examination of the $\log_{10}$ actual SOC stock values by fixed depth with the base model of WASG, land use, and rainfall terms showed a significant linear decrease in actual SOC with depth and interactions with land use and rainfall. The spatial distribution of sites showed a stronger relationship with average annual rainfall (calculated from 1975 to 2005) and land use (Fig. 1) than with WASG.

The other soil properties (sand content (%), EC, soil pH, and severity of non-wetting (MED)) were examined but did not improve the base model (data not presented).

Actual SOC stock was consistently highest in the perennial pasture systems across all soil types (Table 4). Annual pasture systems also had greater actual SOC stock values than either mixed cropping or continuous cropping systems ($P < 0.001$). The REML analysis of $\log_{10}$ actual SOC stock (0–0.3 m) for the base model (Table 4) showed that land use and soil classification (WASG) significantly ($P < 0.001$) influenced SOC stock, with depth and rainfall being the dominant drivers of changes in SOC stock. A significant ($P < 0.001$) interaction in actual SOC storage between land-use systems and soil depth was observed. Actual SOC values under perennial pasture (average rainfall 650 mm) were 60, 22, and 12 t C/ha for the 0–0.1, 0.1–0.2, and 0.2–0.3 m depths, respectively. The corresponding values under annual pasture (average rainfall 625 mm) were 52, 18, and 11 t C/ha; continuous cropping (average rainfall 500 mm) 26, 11, and 6 t C/ha; and mixed cropping systems (average rainfall 500 mm) 26, 10, and 6 t C/ha. The 0–0.1 m soil depth contains on average 63% (61–65%) of the actual SOC stock within the top 0.3 m of the soil. This concentration of SOC in the surface layer was consistent across all land uses and soil types. The 0.1–0.2 m depth contained on average 24% (21–27%) of the actual SOC and the 0.2–0.3 m depth 13% (11–15%).

Modelled attainable SOC values

Comparative differences in actual SOC stocks between land use and soil type were also reflected in long-term (100-year) attainable SOC model simulations (Table 4). For the majority of sites, actual SOC storage (0-0.3 m) was less than the attainable SOC values modeled of 59 t C/ha (deep sand, CC) to 140 t C/ha (loamy duplex, PP) within 100 years (Table 4, Figs 2–4). Modelling realistic management scenarios over 100 years suggested that, on average, the soils under historical cropping systems have greater capacity to store additional SOC (24 t C/ha); the equivalent of 35% of the attainable SOC stock value is still to be sequestered. Depending on the specific land use–soil type combination, the additional storage capacity ranged between 5 and 45% (7–27 t C/ha). Annual and perennial pasture systems had reached 83 and 88% of their attainable SOC stock, respectively (averaged across soil types), with a further 15–18 t C/ha still able to be sequestered. Across all land uses, modelling suggests that ~78% of the attainable SOC could be captured by the next generation of landholders (i.e. over 50 years). This means that at these sites, a theoretical increase in actual SOC stock values of 5–22 t C/ha is possible over 50 years

Table 3. Tests for fixed effects after sequentially adding terms to fixed model from the REML analysis of the $\log_{10}$ SOC stock

Approximate *F*-tests with n.d.f. (numerator degrees of freedom) and d.d.f. (denominator degrees of freedom) are more accurate than the chi-square using the Wald statistic. If *P*-values are <0.001 then *F*-tests will not change the interpretation for the fixed effects

Fixed term	Wald statistic	n.d.f.	*F*-statistic	d.d.f.	*F*-pr
Depth	525.60	2	262.80	4.0	<0.001
Land use	195.98	3	65.32	251.6	<0.001
Rainfall	67.02	1	67.02	231.7	<0.001
Depth.Land use	24.90	6	4.15	627.9	<0.001
Depth.Rainfall	19.54	2	9.77	627.2	<0.001
Land use.Rainfall	0.94	3	0.31	88.5	0.816
Depth.Land use.Rainfall	7.00	6	1.17	628.8	0.322

Table 4. REML analysis of log_{10}-transformed actual soil organic carbon (SOC) stocks with the back-transformed means (t C/ha, 0–0.3 m) reported in parentheses for a rainfall gradient on the Albany Sand Plain in Western Australia for primary Western Australian Soil Groups (WASG) under perennial pasture (PP), annual pasture (AP), mixed crop and livestock (MC), or continuous cropping (CC)
Also presented are modelled attainable SOC stock means (t C/ha, 0–0.3 m after 100 years at annual rainfall of 559 mm). Average l.s.d. ($P = 0.05$) = 0.19 on log_{10}-transformed data

WASG	Land use	Annual rainfall (mm) 500	550	600	650	Modelled SOC stock
			0–0.1 m			
Deep sand	PP	1.41 (26)	1.52 (33)	1.62 (42)	1.72 (53)	41
	AP	1.27 (19)	1.41 (26)	1.54 (35)	1.68 (47)	30
	MC	1.30 (20)	1.40 (25)	1.50 (31)	1.59 (39)	21
	CC	1.30 (20)	1.41 (26)	1.52 (33)	1.63 (42)	20
Sandy duplex	PP	1.52 (33)	1.63 (42)	1.73 (54)	1.83 (68)	39
	AP	1.38 (24)	1.52 (33)	1.65 (45)	1.79 (61)	34
	MC	1.42 (26)	1.51 (32)	1.61 (40)	1.70 (50)	23
	CC	1.41 (26)	1.47 (29)	1.52 (33)	1.58 (38)	21
Loamy duplex	PP	1.61 (41)	1.66 (46)	1.72 (52)	1.77 (58)	46
	AP	1.47 (30)	1.54 (35)	1.61 (40)	1.67 (47)	40
	MC	1.50 (32)	1.55 (36)	1.60 (40)	1.65 (44)	26
	CC	1.50 (32)	1.55 (36)	1.61 (41)	1.67 (46)	25
			0.1–0.2 m			
Deep sand	PP	1.08 (12)	1.16 (15)	1.24 (17)	1.32 (21)	39
	AP	0.92 (8)	1.02 (11)	1.13 (13)	1.24 (17)	30
	MC	0.93 (8)	0.98 (10)	1.03 (11)	1.08 (12)	20
	CC	0.96 (9)	1.03 (11)	1.09 (12)	1.16 (14)	20
Sandy duplex	PP	1.13 (13)	1.21 (16)	1.28 (19)	1.36 (23)	37
	AP	0.96 (9)	1.07 (12)	1.17 (15)	1.28 (19)	35
	MC	0.97 (9)	1.02 (11)	1.07 (12)	1.13 (13)	24
	CC	1.01 (10)	1.07 (12)	1.14 (14)	1.20 (16)	22
Loamy duplex	PP	1.23 (17)	1.30 (20)	1.38 (24)	1.46 (29)	47
	AP	1.06 (11)	1.17 (15)	1.27 (19)	1.38 (24)	42
	MC	1.07 (12)	1.12 (13)	1.17 (15)	1.23 (17)	27
	CC	1.10 (13)	1.17 (15)	1.24 (17)	1.30 (20)	27
			0.2–0.3 m			
Deep sand	PP	0.68 (5)	0.78 (6)	0.87 (7)	0.97 (9)	39
	AP	0.67 (5)	0.76 (6)	0.85 (7)	0.93 (9)	29
	MC	0.66 (5)	0.72 (5)	0.79 (6)	0.85 (7)	20
	CC	0.65 (4)	0.66 (5)	0.67 (5)	0.68 (5)	19
Sandy duplex	PP	0.83 (7)	0.93 (8)	1.03 (11)	1.12 (13)	36
	AP	0.82 (7)	0.91 (8)	1.00 (10)	1.08 (12)	37
	MC	0.81 (6)	0.87 (7)	0.94 (9)	1.00 (10)	26
	CC	0.80 (6)	0.81 (6)	0.82 (7)	0.83 (7)	23
Loamy duplex	PP	0.89 (8)	0.99 (10)	1.09 (12)	1.19 (15)	47
	AP	0.89 (8)	0.97 (9)	1.06 (11)	1.15 (14)	42
	MC	0.87 (7)	0.93 (9)	1.00 (10)	1.06 (12)	28
	CC	0.86 (7)	0.87 (7)	0.88 (8)	0.90 (8)	27

if this carbon can be sequestered. This represents a small annual increase in soil carbon storage of 0.1–0.3 t C/ha.year over this period.

The additional SOC storage capacity (i.e. attainable SOC – actual SOC) over a 0.3 m soil profile was 54–56 t C/ha when assessed by WASG (Fig. 2) and 16–25 t C/ha when assessed by land use (data not shown). However, when each depth (0.1-m increment) was modelled independently using actual clay content and BD values, data suggest that the upper 0.1 m is largely saturated (Fig. 3*a, b*) in terms of its additional SOC storage capacity. In many cases, there is more carbon in this depth than can be theoretically maintained (i.e. >100%), with the additional capacity for SOC sequestration located in the 0.1–0.2 m layer (currently at 50% capacity) and the 0.2–0.3 m depth (currently at 29% capacity) for all land uses and soil types. The pasture systems appear closer to their theoretical carbon saturation than cropping systems (Fig. 3*a, b*).

Actual and attainable SOC stock values were plotted against the long-term average annual rainfall for individual sites (using SILO interpolation of latitude and longitude for climatic data, www.longpaddock.qld.gov.au/silo/) in the Albany Sand Plain region (Fig. 4). This comparison emphasises (*i*) the dominance

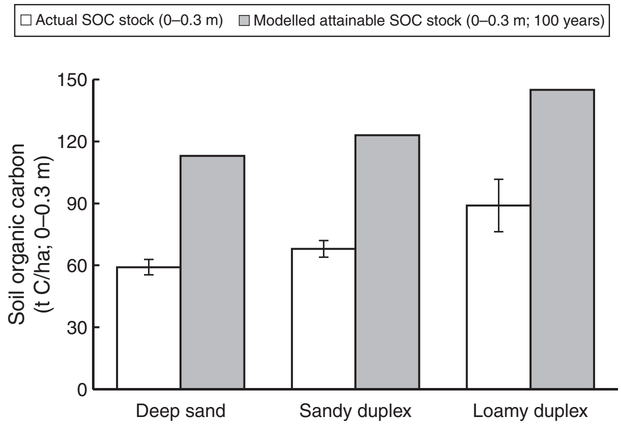

Fig. 2. Actual soil organic carbon stocks (t C/ha, 0–0.3 m) and modelled attainable soil organic carbon stocks after 100 years with an average annual rainfall of 550 mm. Data are the average of all land uses. Capped lines on the actual SOC stocks represent standard errors on measured data.

of pasture systems in the high-rainfall area, some of which are nearing (or in some cases beyond) their theoretical storage capacity; and (*ii*) that the greatest gain in future SOC sequestration is in soils currently under continuous and mixed cropping, even though these sites are located towards the lower end of the rainfall gradient.

Decreasing annual rainfall by 30% to reflect predicted future climate change brings a moderate decline in attainable SOC stock values (Fig. 5*a*, *b*) associated with decreasing net primary productivity. This decline in attainable SOC was double in the higher input pasture system (~20 t C/ha) compared with the cropping systems (~10 t C/ha).

Discussion

Our findings highlight the need for new management practices or land-use options that enable SOC to be stored deeper in the soil profile. Annual legume-based pasture in rotation with cereal production that includes widespread adoption of minimal soil disturbance (reduced/zero tillage cultivation; Cookson *et al.* 2008) and retention of stubble (instead of burning; Hoyle *et al.* 2006) is currently considered the most practical management approach to mitigate SOC decline (Grace *et al.* 1998) in the south-west of Western Australia, but it targets inputs to the soil surface. This is reflected in SOC stocks measured to depth, where 85% of SOC in the upper 1.0 m of soil was in the top 0.3 m (data not presented). Within this uppermost layer (0–0.3 m profile), we found that about two-thirds of actual SOC is within the top 0.1 m in these agricultural systems, as this is where plant residue returns are concentrated. By modelling the attainable SOC stock value for each depth of soil separately (in 0.1-m increments), it was determined that for the majority of sites there is only limited capacity in the soil 0–0.1 m layer to sequester further carbon, whereas further storage capacity was possible in the subsoil (Fig. 3*a*, *b*), especially of gradational/duplex soils where clay content increases with depth. Increased clay content at depth supports a higher potential SOC capacity, while rates of SOM decomposition decline exponentially with soil depth (Murphy *et al*. 1998; Kemmitt *et al*. 2008). However, there are limitations to delivering organic matter to the subsoil cost-effectively (Kragt *et al*. 2012).

Approaches currently being investigated by the agricultural sector include: (*i*) the adoption of high root biomass crop and pasture species; (*ii*) inversion of soil to bury the original carbon-saturated surface soil layer, providing a new surface of soil from depth with additional carbon-sequestration capacity; and (*iii*) injection of organic materials including compost and biochar to depth. Many of these approaches are based on increasing the proportional allocation of organic matter below ground, where it is more likely to remain protected. In exploring these solutions, care must be taken to define any potential negative outcomes (e.g. yield decline, cost of technology adoption).

Improving the capacity of plants to increase their below-ground biomass allocations while maintaining harvest index (i.e. grain yields) provides a viable approach to carbon storage in soils without negatively affecting the profitability of the farming system. An alternative approach may be achieved via genetic solutions to environmental constraints that result in an increase in net primary productivity. Engineered soils, and in particular soil inversion, offer landholders an effective method for the management of weed seed-banks and surface non-wetting. As a result, changes in both the distribution and amount of organic carbon in soils can be observed. This study suggests that the

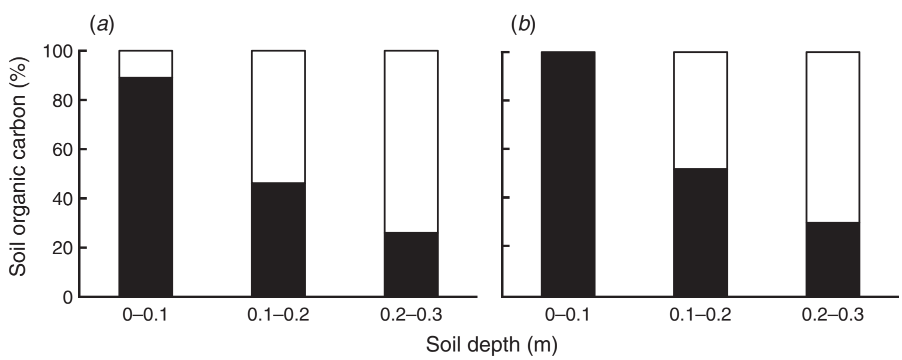

Fig. 3. Measured actual soil organic carbon (filled bars) as a percentage of long-term modelled attainable SOC stocks (after 100 years) (open bars) for each soil depth for (*a*) continuous cropping on a deep sand at 550 mm annual rainfall (i.e. low plant biomass input), and (*b*) perennial pasture systems on a sandy duplex at 650 mm (i.e. high plant biomass input).

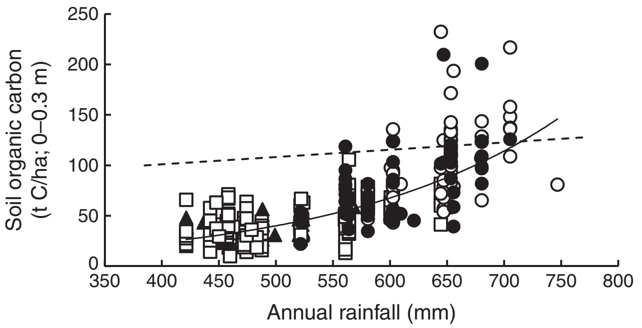

Fig. 4. Actual soil organic carbon stocks (t C/ha, 0–0.3 m) for continuous cropping (▲), mixed crop/livestock (□), annual pasture (○), and perennial pasture (●) on the Albany Sand Plain of Western Australia (average annual rainfall 559 mm). Data are the average of all soil groups. The curvilinear line represents the relationship between data points. The dashed line represents the modelled SOC stock after 100 years assuming optimal utilisation of rainfall for a sandy textured soil as determined by Roth-C.

surface layer of soils is largely saturated and it has limited potential to sequester further organic carbon stores. Therefore, it is conceivable that creating a 'new' soil layer lower in SOC might increase the potential for building SOC stocks. Risks associated with this type of approach include increased erosion on exposed soils with little or no cover, the possibility of bringing up 'sour' soils (e.g. subsoil acidity), or effectively repositioning the barrier to production at depth. Amendment of soils with organic materials including, but not limited to, compost and biochar requires consideration of product composition, rate of application, and resulting changes in soil function. In many instances, the rate of application is insignificant against background SOC stocks and while some amendments may provide a nominal change in measurable organic carbon, the cost of application is such that additional benefits are also required to underpin a profitable production system. To date the agronomic benefits of many of these amendments is highly variable and relatively small compared with the cost of application.

Modelled attainable SOC values were not constrained by practical limitations to plant growth (i.e. subsoil constraints such as soil acidity, toxicities, compaction, nutrient deficiency), which can restrict the ability of a plant root to access soil resources and thus constrain biomass production. Within the agricultural zone of the south-west of Western Australia, 32% of the total land area is classed as having multiple constraints including low soil pH, poor soil water storage, subsurface compaction, erosion, and, in the higher rainfall zones, waterlogging (van Gool 2011). Therefore, to increase carbon storage in soil it is important that management practices remove these constraints to plant growth, where it is cost-effective to do so. For example, on transitional soils in the high-rainfall environment, transient waterlogging can influence grain yields by 20–50% (McFarlane and Cox 1992; Zhang *et al*. 2004). Our modelling (data not shown) suggests that removal of waterlogging could increase the long-term (100-year) carbon sequestration potential by 27%. In addition, the low soil pH measured on many of the soil profiles reported in this study suggest a subsoil constraint on net primary productivity associated with acid soils (and possibly aluminium toxicity). Management of these constraints would assist with 'closing the gap' between actual and potential SOC stock values under cropping based systems, which are further from their attainable SOC target than the pasture systems (Fig. 4).

We predicted a theoretical attainable SOC increase of 0.07–0.27 t C/ha.year (over 100 years) in these soils if additional organic matter was sequestered. Extrapolating this rate across the 18 Mha of semi-arid land within the grain-growing region of Western Australia, a potential storage of ~1.3–4.9 Mt organic carbon/year is indicated. This rate of potential for accumulation of SOC through land-management practices that maximise conversion of rainfall to net primary production (i.e. 100% WUE) and preserve existing SOM is similar to that estimated for Australia (0.35 t C/ha.year; Luo *et al*. 2010).

An average wheat yield in Western Australian of 2 t/ha and harvest index of ~40% produces 5 t/ha of total above-ground plant biomass. Assuming a root/shoot ratio for grain crops of 0.5 and a plant carbon content of 45%, this means that a wheat plant in this environment currently grows 3.4 t C/ha.year. Improving WUE for wheat in this environment (currently 40–60%) through

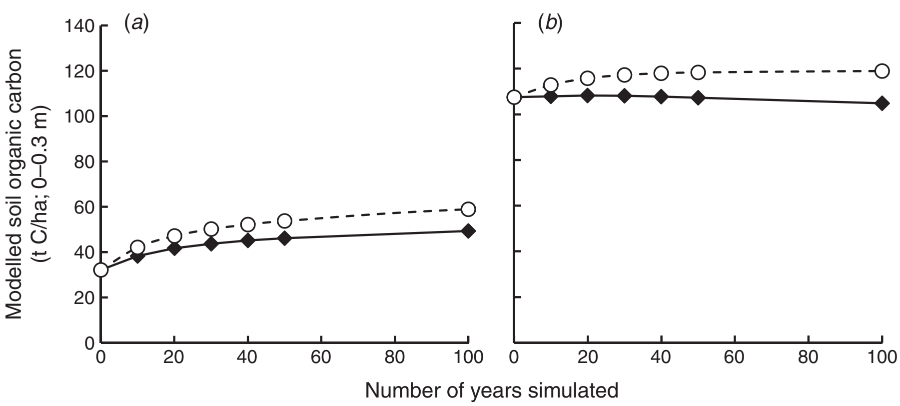

Fig. 5. Attainable soil organic carbon (t C/ha, 0–0.3 m) modelled for 100 years for (*a*) continuous cropping and (*b*) perennial pasture systems on a deep sand on the Albany Sand Plain of Western Australia using the current average 30-year annual rainfall of 559 mm (○) and modelling a 30% decline in annual rainfall (♦) using actual SOC values at time 0 as initialising values for modelling.

a combination of agronomic management and genetic improvement to capture and utilise water more effectively (i.e. improved water infiltration and storage, removed soil constraints to plant growth, plant breeding to improve root architecture for water and nutrient capture) would result in greater net primary productivity. Grace *et al*. (2006) defined the extent of organic carbon that is retained in soil as a function of cation exchange capacity (CEC, used as an analogue to clay). For low CEC soils (<25 mmol/kg), which are typical for the Western Australian agricultural region (see fig. 4 in Gonzalez-Quiñones *et al*. 2011), this function would indicate that, at most, 20–25% of applied organic carbon could be retained in the soil. Using these estimates, sufficient additional plant inputs to meet the modelled theoretical attainable increase of 0.1–0.3 t C/ha.year could be achieved where subsoil constraints are managed.

Based on forecast climate variability (Crimp *et al*. 2008), modelled declines in attainable SOC for this region could be in the order of 5–10 t C/ha over the next 100 years (average 0.075 t C/ha decline per year; Fig. 5). Assuming that WUE can be increased (as discussed above), the loss of SOC from declining rainfall can be offset through an increase net primary productivity. However, while Western Australia has experienced a decline in winter rainfall (Allan and Haylock 1993), trend analysis suggests that summer rainfall events that occur outside of the period of crop and annual pasture growth are increasing (Alexander *et al*. 2007). Higher and more frequent summer rainfall is likely to increase SOM mineralisation rates and associated CO_2 emissions (Hoyle *et al*. 2006), as surface soil temperatures are high (30–40°C). A shift from winter to more summer rainfall was not included in current carbon modelling scenarios but warrants further consideration; especially given that these summer rainfall events cause approximately half of the nitrous oxide (N_2O) emissions from this region (Barton *et al*. 2008).

Conclusions

By gaining a quantitative understanding of the *actual* (measured) and *attainable* (modelled upper limits) SOC stock values for these typical agricultural systems, we can provide a moderate level of confidence for future soil carbon scenarios and manage landholder and industry expectations appropriately. Comparison of actual *v.* attainable SOC stock values highlight that: (*i*) the additional carbon sequestration capacity in these soils is below the surface 0.1 m depth, and (*ii*) the gap between actual and attainable SOC stock values decreases as rainfall increases. This has major implications for future management of carbon inputs to these agricultural systems, which currently concentrate plant residue returns at or close to the soil surface.

Acknowledgements

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Appendix 1.

In GENSTAT notation, we can describe the linear mixed model in the following manner: For the *y*-variate of interest, we compute the spline term first denoted by *splineRainfall* (Sue Welham, VSN International, pers. comm.), and then add that to the random effects model below, where: the sites are represented by the variable *SCWA*; the samples within a site are represented by the variable *Samplept*; the depth factor represented by the variable *Depth*; the soil classification factor represented by the variable *WASG*; the land use factor represented by the variable *Land-use*. Interactions of these terms and factors are shown as combinations of these factors separated by the dot (.) symbol

```
NCSPLINE X = Rainfall; BASIS = splineRainfall; SCALE = scRainfall
CALCULATE splineRainfall [] = splineRainfall []/scRainfall
vcomp [fixed = Depth * Land-use * Rainfall;fact = 9] \
random = SCWA/Samplept/ Depth + WASG + splineRainfall +\
WASG.(Depth + Land-use + Rainfall + splineRainfall)+\
WASG. Land-use.(Depth + Rainfall + splineRainfall)+\
WASG. Land-use. Depth.(Rainfall + splineRainfall)\
;con = positive remL [print = wald,dev,comp] y
```