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ORIGINAL ARTICLE

The potential for enhancing soil carbon levels through the use of organic soil amendments in Queensland, Australia

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Abstract
Application of organic amendments such as livestock manures and compost is commonly listed amongst strategies with potential to sequester soil organic carbon (SOC) in agriculture and contribute to climate change mitigation. However, quantifying this potential is hampered by the paucity of data on amounts and characteristics of organic amendments applied to land, and limited understanding of the carbon dynamics during storage, processing and following land application. The objective of this study was to evaluate this potential for the State of Queensland, Australia, by collating and analysing information on organic amendments and modelling SOC sequestration in illustrative cropping locations. An estimated 2.7 million tonnes (Mt) dry matter (dm) of organic amendments has likely been land applied in Queensland in 2015/16, supplying significant quantities of carbon (C) to the soil. Simulations with Australia's national inventory modelling tool predicted that, in a favourable location, high annual applications of manure and compost (10 t / 15 t fresh matter (fm) per hectare and year (ha^{-1} yr^{-1}) could result in SOC increases of 0.9% and 0.55%, respectively, per year averaged over 20 years of continuous cropping, exceeding the aspirational goal of the United Nations Framework Convention on Climate Change *4 per 1000* Initiative. In less favourable conditions, C stocks may continue to decline but at a slower rate than without organic amendments. Based on regional analysis and review of current understanding of the dynamics of organic matter in soils, we identified a set of research priorities to enable more accurate assessments of the C sequestration potential to support development of policies and frameworks for use of organic amendments in agricultural soils for climate, food security and waste management benefits.

Keywords Organic soil amendments · Soil carbon sequestration · Manure · Compost · Models

Introduction

Soil organic carbon (SOC) sequestration was defined by Olson (2013) as the process of transferring CO_2 from the atmosphere into the soil through plants, plant residues and other organic solids, which are stored or retained as part of the soil organic matter. The sequestrated SOC process should increase the net SOC storage during a given period

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for a defined land unit and result in a net reduction in the atmospheric CO_2 levels. Consequently, the Intergovernmental Panel on Climate Change (IPCC) and many non-government organisations consider SOC sequestration as a key mechanism for countering increasing greenhouse gas (GHG) emissions (Teske 2019). Yet, only a handful of countries specifically address SOC sequestration in their Nationally Determined Contributions (NDCs) as part of their emission reduction commitments in the Paris Agreement (Wiese et al. 2019). NDCs currently do not reflect well the level of activity globally to increase or maintain C stocks in soils, and it is difficult to assess the area of land subject to improved practices and the subsequent climate abatement potential from C sequestration in these soils. In Australia, the national greenhouse gas inventory reports changes in soil C stocks in net agricultural sector emissions. The key climate change policy instrument, the Emissions Reduction Fund (ERF), which provides a crediting, purchasing and compliance framework, enables farmers and other land managers to be issued with C credits for eligible activities, including practices that aim at sequestering C in soils. Since 2014, associated legislation has allowed voluntary participants in the ERF to earn income from sale of C credits. Rules and requirements for quantifying soil C credits by modelling or measurement techniques are set out in methodology determinations (Australian Government undated).

Australia has experienced substantial (40–60%) loss of SOC stocks together with soil nitrogen, phosphorous and sulphur reserves (Kopittke et al. 2017) associated with the conversion of native vegetation to European style farming (Sanderman et al. 2010). Significant SOC losses occur within short time spans (20–50 years) after the onset of soil cultivation (Dalal and Mayer 1986), providing for potential increase in SOC estimated to be about 36.3 million tonnes (Mt) C annually under a medium sequestration scenario for the Australia/Pacific region (Zomer et al. 2017). Other studies in Queensland found SOC stocks decreased by 20–49% (0–30 cm) following conversion from native vegetation to cropping (Dalal and Mayer 1986). Furthermore, a semi-arid subtropical cropping site in central Queensland lost 38% (0–30 cm) in SOC stocks over 33 years from 1965 to 2014 (Dalal et al. 2021). The authors attributed the decline to insufficient C inputs to maintain SOM at steady state. This is consistent with the global meta-analysis study conducted by Kopittke et al. (2017) which showed a median decrease of 46% in SOC stocks. These results and the observation that conversion from cropping to ley pasture in the final 4 years of monitoring arrested the decline (Dalal et al. 2021) indicate the potential for adding exogenous organic materials to overcome the shortfall on inputs relative to losses, and to re-build SOC stocks.

The potential for reversing SOC losses has contributed to the Australian Government's identification of soil C sequestration as a priority measure for offsetting the country's GHG emissions, but there remains uncertainty and debate in Australia, and globally, regarding (a) the total potential of agricultural soils to store additional C; (b) the possible rate of accumulation; (c) the permanence of this sink; and (d) how best to monitor changes in SOC stocks (Sanderman and Baldock 2010; Sanderman et al. 2010; Powlson et al. 2014; White and Davidson 2016; Paustian et al. 2019). From 2009 to 2015, significant government investment resulted in major scientific, data and technological advances (e.g. Australian Government 2015) aimed at supporting action to realise the potential for C sequestration in managed lands. However, cultural and economic barriers limiting participation of farmers in C sequestration schemes remain largely unaddressed (Amundson and Biardeau 2018). A contributing factor to farmer reluctance is the relatively low average price being paid per Australian Carbon Credit Unit (ACCU), both in voluntary commercial markets and the Australian Government's ERF reverse auction mechanism. Since 2014, the average auction price paid for ACCUs has been only AU\$12.20 t^{-1} CO_2-e, with the most recent auctions in 2020 seeing prices reach almost AU\$16.00 t^{-1} CO_2-e. In contrast, SOC monitoring costs are relatively high. Even if the Australian Government reaches its 'stretch goal' of reducing monitoring costs from around AU\$30 to AU\$3 ha^{-1} (Australian Government 2020), the low price currently being offered for C credits and the fact that farmers carry much of the risk as to whether they will achieve and maintain expected increases in SOC stocks over a time frame of at least 25 years will likely remain barriers to uptake. A better understanding of the co-benefits of increased SOC in terms of soil health, productivity and resilience has been proposed to incentivise adoption (Macintosh et al. 2019) since income from C sequestration programs alone is currently too low to make practice changes financially viable.

Amongst practices with the greatest theoretical potential for SOC sequestration in existing Australian agricultural systems is thought to be large additions of organic materials such as animal manures and other organic soil amendments (Sanderman et al. 2010). Australian farmers use a wide variety of organic soil amendments, commonly to improve physical, chemical and biological soil properties, and supply plant nutrients. The lack of adequate characterisation of organic amendments and reliable evidence for their long-term effects on soil C stocks, along with restrictions on eligibility of materials are the most likely reasons for very low uptake of organic amendment projects in the ERF. The ERF currently allows use of 'non-synthetic fertilisers' if they have been generated from a dedicated waste stream and if their use represents a new or significantly different management practice. Moreover, the ERF currently (early 2021) precludes projects using annual applications of organic amendments since reporting must be delayed for a period of 24 months following application to manage the risk of 'leakage', i.e. the risk of negative effects on SOC stocks outside the project area due to bringing in exogenous organic materials to the project.

Organic amendments may still contribute to GHG abatement, even though the activity is not covered by government-sponsored C credit programs. Organic amendments directly supply external C and nutrients to the soil, and through possible improvements to soil health and higher microbial and plant biomass may also contribute indirectly to longer-term storage of SOC. Actual rates of SOC sequestration will be defined by the amount and frequency of materials added and their degradability, and also depend on local climatic and soil edaphic conditions (Sanderman et al. 2010).

Despite their obvious contribution to SOC turnover and stocks, no quantitative and qualitative assessment of organic amendments has been conducted in Australia. Chenu et al. (2019) also noted the lack of appropriate assessment concerning the contribution of organic soil amendments towards maintaining and enhancing SOC in other countries.

This paper aimed to estimate the potential contribution of using organic amendments for maintaining or increasing soil C stocks in the State of Queensland (Australia). This analysis requires data on amounts and characteristics of organic amendments that are applied to land, and on having an understanding of carbon dynamics in organic amendments during storage, processing and following land application. We collated, for the first time, data on the use of organic amendments that allowed an estimation of total organic C supplied to soil through these products. We reviewed and discuss in depth the state of knowledge on the potential for soils to sequester carbon, and prevailing hypotheses concerning organic amendments and soil organic carbon dynamics. Exemplary modelling of the longer-term effects of applying organic amendments at different rates and frequencies on SOC stocks in local sorghum cropping systems in variable soils and climatic conditions provided the basis for considering the potential to enhance soil C levels in Queensland through the use of organic soil amendments.

Materials and methods

Background—agriculture in Queensland

Queensland, the second largest of Australia's eight states and territories, covers a total area of around 1.72 million (M) square kilometres and is home to approximately 5 M people. Agricultural land in Queensland occupies around 84% of the state, most of which is used for grazing cattle on native or naturalised vegetation, and 4.25 M ha (2.47%) is used for agricultural and horticultural cropping, including perennial crops (Table 1).

Table 1 Land used in Queensland in 2013 (source: Queensland Government 2018)

Land use	Area (ha)	Percent of state
Broadacre cropping	3,547,778	2.06
Sugar cane	565,162	0.33
Perennial horticulture	87,829	0.05
Annual horticulture	47,166	0.03
Grazing (native pasture)	147,926,860	85.87
Sown pasture	16,041,166	9.31
Intensive livestock	37,856	0.02
Aquaculture	4548	0.00
Other land use (non-agricultural, may include forestry)	20,060,748	11.64
Total	**172,277,977**	**100.00**

Livestock production contributes around 40% of total agricultural farmgate value in the state (Queensland Government 2019). Over the past 20 years, Queensland's dairy herd declined by more than 50% while pig and poultry numbers increased substantially (see Table OR-1, Online Resource 1). The total number of meat cattle remained relatively constant during that period, although there was a threefold increase in the number of feedlot cattle 'on feed' from around 200,000 to more than 600,000, which equates to an annual throughput of about 2.4 M cattle (ALFA [Australian Lotfeeders Association] 2020). Intensive livestock units have therefore significantly increased in Queensland over the past 20 years, resulting in more feedlot manure also being produced over the same period.

Exogenous organic soil amendments

This investigation specifically considered potential effects of bulk external organic soil amendments originating from agriculture, food, fibre and wood processing and the urban waste stream that are applied to land with or without prior processing on soil carbon stocks. Hence, other materials such as crop residues and green manure crops, animal dung excreted in pastures, and products such as microbial stimulants or humates were excluded. Carbon contained in individual organic residues as excreted or generated was accounted for. Due to lack of appropriate quantitative and qualitative data, we were unable to take account of losses during storage or processing (composting) or consider organic amendments comprised of several C-containing raw materials, such as chicken litter or urban-derived compost. Consequently, C quantities presented here overestimate the amount of C supplied to land with organic soil amendments, particularly for organic residues that contain a large proportion of easily degradable C fractions and that were composted prior to land application.

Quantitative and qualitative data for organic amendments used in Queensland

Data collated for the Australian Biomass for Bioenergy Assessment (ABBA) project (Queensland Government undated-2) were used to obtain baseline data for 2015/16 on the location (local government areas), volumes and availability of organic residues (biomass) in Queensland. The main groupings of organic residues included animal manures (dairy, feedlot cattle, pigs, poultry), residues from food and fibre processing (cotton ginning, sugar milling, meat processing), wood processing and urban waste materials (biosolids, green and food waste, timber). The ABBA data provided total dry matter (dm) quantities that could potentially be utilised for bioenergy generation, and included, for example, organic waste that was still landfilled in 2015/16, and total quantities of wood processing residues, rather than only the proportion that was utilised for land management. Therefore, all ABBA baseline data except for most animal manures had to be modified to obtain estimated quantities of organic residues that were used for land management. Details on these modifications and additional background information are provided in the supplementary information (Tables OR-2 and OR-3).

Literature data were used to assign C and N values for each of the 17 organic residues (Table OR-4). The assumed C values were subsequently used to estimate the quantity of C contained in the organic residues at the point of excretion or generation for all organic amendments and local government areas considered (Table OR-6).

Queensland is comprised of 78 local government areas, many of which are sparsely populated. Only local government areas in which more than 1000 t (dm) of organic residues were generated were included in this study. This amounted to 42 local government areas generating 17 different organic residues (Table OR-5).

Cropland simulation modelling

A process-based ecosystem model, the Full Carbon Accounting Model (FullCAM, Richards and Evans 2004), was used to simulate the long-term soil C stock change in selected Queensland agricultural soils following the application of composted and raw organic amendments. Within FullCAM, the CAMAg sub-model for cropping and grazing systems simulates the impact of management practices on soil C accumulation and partitioning between plants, debris and soil. CAMAg incorporates a version of Roth-C (Rothamsted Soil Carbon Model, Jenkinson et al. 1991; McGill 1996) to model temporal changes as decomposition rates of soil C pools (decomposable and resistant material).

FullCAM is used in Australia's National Greenhouse Gas Accounts and has been extensively parametrised, tested and validated against field data by independent agencies (Commonwealth of Australia 2020). The embedded data builder function generates spatially explicit model inputs of climate and initial soil condition for any latitude and longitude. Specifically, the soil data, including soil type and clay content, are derived from *The Soil and Landscape Grid of Australia-wide Soil Attribute* (Viscarra Rossel et al. 2015). In the Roth-C sub-model, the soil clay content determines the ratio at which added exogenous C is either released as CO_2 or maintained in SOC pools. Climate data are obtained from the interpolated climate grids (1 km resolution) based on weather station observations of the Australian Bureau of Meteorology. Crop growth is simulated as a sigmoidal curve and the rate of growth is based on rainfall availability during the growth period (Unkovich et al. 2009).

Simulations of annual sorghum cultivation (from 2000 to 2020), as an illustrative cropping system, were performed in continuous sequential mode to account for the carry-over effect of organic amendment applications from 1 year to the next. Similar to other simulation models, FullCAM does not have specific functions for the transformation of organic soil amendments. In FullCAM, the transformation dynamics of all exogenous organic materials is based on the percentage of decomposable and resistant C fractions of the organic material added. The Roth-C sub-model parametrisation (percentage of decomposable and resistant C fractions) does not differentiate between different categories of organic soil amendments, i.e. whether they are crop residues or exogenous amendments. Characterisations of organic residues usually do not provide this kind of information. Therefore, generic C fractions for manure and compost obtained from Farrell (2015) were used. Specifically, for manure products, the C content was assumed to be 38% (dm) with an average water content of 52%, and C fractions were assumed to be 24% and 76% for fast and slow decomposable pools, respectively. For composted material, the C content was 26% (dm) with an average water content of 32%, and assumed C fractions were 11.4% and 88.6% for fast and slow decomposable pools, respectively.

The scenarios simulated (with application rates as t fresh matter (fm)) were:

1. Annual application of manure at 3 t/ha and 10 t/ha
2. Annual application of compost at 5 t/ha and 15 t/ha
3. Manure application at 3 t/ha and 10 t/ha at 3-year intervals (triennial)
4. Compost application at 5 t/ha and 15 t/ha at 3-year intervals (triennial)
5. No compost or manure application.

To assess the influence of soil and climatic conditions on the effect of organic amendment applications on soil C dynamics, the selected scenarios were simulated across three different bioclimatic zones of Queensland:

1) Central Queensland (Central QLD), near Rockhampton: characterised by a subtropical climate with average annual rainfall of 800–1000 mm and a summer/wet season temperature of 32 °C max 22 °C min and winter/dry season of 23 °C max 9 °C min. Average soil clay content is 46.3% and soil total C is 54 t ha^{-1} at 0–20 cm depth.
2) Eastern Downs, near Toowoomba: characterised by a semi-arid subtropical climate with average annual rainfall of 600–800 mm. Summer maximum temperature range 28 to 34 °C; winter maximums 13 to 19 °C. Average soil clay content is 50.9% and soil total C is 46 t ha^{-1} at 0–20 cm depth.
3) Maranoa, near Roma, has a semi-arid climate with very hot summer and warm, dry winters. Average summer temperature is 27 °C and winter average 13 °C. Annual average rainfall 550 mm. Average soil clay content is 30.6% and soil total C is 36 t ha^{-1} at 0–20 cm depth.

Tables OR-7 and OR-8 provide an overview of dominant soil types, including clay and C content, and climatic conditions in local government areas where the majority of organic amendments are utilised in Queensland.

Results

Types and quantities of organic amendments

The ABBA project estimated that around 17 Mt (dm) biomass from forestry, cropping, intensive livestock, food and fibre processing and urban waste was generated and potentially available for bioenergy generation in Queensland in 2015/16 (Queensland Government undated-2). About 50% of these materials were comprised of crop residues that usually remain in the field and are not used as organic soil amendments elsewhere, and hence were disregarded for the purpose of this investigation. Further adjustments of the available data for dairy manure, sugar milling and wood processing residues, biosolids and other urban-derived organic residues resulted in an estimated 2.7 Mt (dm) of organic residues that were utilised for soil management purposes in Queensland (Table 2), not accounting for around 36,000 t (dm) of grease trap waste.

Agricultural residues made up 74% of C contained in organic residues, with the main contributors being poultry manure (234,000 t dm), sugar milling residues (174,000 t dm) and feedlot and dairy manure (each about 115,000 t dm) (Table 2). The manures are the largest grouping

Table 2 Total quantities (tonnes dry matter, t dm) of organic amendments used in Queensland for land management purposes in 2015/16, and amount of carbon contained therein

Organic residues		Quantity (t dm)	Carbon / nitrogen (% dm)	Carbon (t dm)
Manure	Dairy (as excreted)	283,296	40.30 / 5.08	114,168
	Feedlot cattle	349,850	33.48 / 2.32	117,130
	Pigs (as excreted)	113,330	41.52 / 7.28	47,055
	Poultry (as excreted)	645,250	36.32 / 5.32	234,355
Food/fibre processing	Cotton ginning	67,270	12.65 / 1.28	8510
	Sugar milling (Filter cake + ash)	638,332	26.50 / 1.00	174,249
	Meat processing	62,763	45.02 / 1.54	28,256
Wood processing	*Cypress*			
	Bark	6638	53.99 / 0.17	3584
	Sawdust	11,997	"	6477
	Softwood			
	Bark	40,926	"	22,096
	Sawdust	36,218	"	19,554
	Shavings	21,731	"	11,732
	Hardwood			
	Sawdust	42,480	50.39 / 0.16	21,405
Urban residues	Biosolids	99,319	29.67 / 3.31	29,468
	Green waste	202,931	40.39 / 0.91	81,964
	Timber	93,452	53.99 / 0.17	50,455
	Food	16,128	47.71 / 2.92	7695
Total		**2,731,911**		**978,153**

of products currently utilised in agriculture, delivering around 513,000 t C annually.

Many agricultural residues in Queensland are applied to land directly without composting, though they can be stored in large piles for some time before use. Cotton gin trash is one exception since virtually all are composted to ensure elimination of the fungal pathogen *Fusarium* prior to land application by cotton growers. Close to 20% of feedlot manure is composted. No data was available for poultry and dairy manure although a certain proportion of these products is known to be composted.

Total urban waste–derived C, including biosolids, made up about 17% (171,000 t dm) of the total amount of C contained in organic residues. While over 95% of biosolids generated in Queensland are land applied, there is still significant potential for diverting urban organic residues from landfill and utilising them as organic soil amendments. Across Queensland, there was potential for diverting another 106,000 t (dm) of green waste, 609,000 t (dm) of timber and 224,000 t (dm) of food waste from landfill. However, as complete diversion of organics from residual waste is unlikely, for the purpose of this study it was assumed that 50,000, 150,000 and 100,000 t (dm) of green waste, timber and food, respectively, can be diverted from landfill and utilised as organic soil amendments in the future. If achieved, this will add 150,000 t of C in organic residues, or 15% of 2015/16 levels, that can potentially be used for land management purposes, being comprised of 20,000 t from green waste, 82,000 t from wood waste and 48,000 from food waste. Most of the additional urban waste–derived C would become available in South-East Queensland, where 70% of Queensland's population resides. In 2015/16, 49% of the total C quantity was generated and utilised in greater South-East Queensland, which comprises about 300,000 ha of cropped agricultural land (OR-7), with Toowoomba (130,000 t), Scenic Rim (57,000 t), Moreton Bay (49,000 t) and Sunshine Coast (49,000 t) local government areas showing the highest quantities of C generated.

Modelling soil organic carbon dynamics associated with the use of organic amendments in agriculture

The potential for organic amendments to contribute to soil health, agricultural productivity and soil C sequestration depends on the quantity and quality of material applied and the local soil and climatic conditions, as modified by the agricultural production system employed. Soil C stocks in cropping lands vary regionally, with temperature and soil texture likely key factors (Fig. 1).

After 20 years of continuous sorghum cultivation, highest predicted losses of soil C occur without the use of organic amendments. These losses ranged from 11% for the Maranoa location and up to 25% for the Central Queensland scenario (Table 3). The highest annual application rate of compost (15 t fm ha^{-1}) or manure (10 t fm ha^{-1}) resulted in the smallest reduction of soil C content for the Central Queensland site and net increases in the Maranoa and Eastern Downs sites. The 3-year interval compost and manure application showed proportional reduction of soil C content when compared to the annual application. Marked differences were observed between locations. The Central Queensland region, with the highest temperatures amongst the selected locations and an intermediate level of soil clay content (46%), showed a higher decline of soil C while only small differences were predicted between Maranoa and Eastern Darling Downs locations.

Discussion

Use of exogenous organic amendments

Despite utilisation of a wide variety of organic amendments to improve production on Australian farms over many years, and more recent proposals for their potential contribution to climate change mitigation through soil C sequestration, reliable data and robust evidence is very limited. Information on the characterisation of various organic amendments, their availability and extent of use, and their effectiveness in enhancing soil properties and as a source of nutrients and C in Australia is generally lacking. The best possible use of organic amendments is likely constrained by availability, quality, costs, knowledge about and confidence in their benefits and risks relative to using synthetic fertilisers (Quilty and Cattle 2011).

The use of organic amendment products like manure may not yield a direct net sink for C in soils since it essentially involves a transfer of C from one location to another (Schlesinger and Andrews 2000) and should therefore not be considered in SOC sequestration accounting (Olson 2013). This applies to all external organic soil amendments considered here, regardless of their origin. Nevertheless, indirect C storage and net GHG removal may occur when soil properties are changed to result in more of the SOC in resistant forms (Sanderman and Baldock 2010). Substituting use of mineral fertiliser to supply macro nutrients with application of organic amendments provides key environmental and financial benefits to farmers, and is considered the main determinant for potential GHG emission reductions in the manure supply chain (Rowlings and Biala 2016).

Outside of C credit schemes, improvements could still be made to current practice thereby increasing soil health and potentially C sequestration efficiency. For example, Poulton et al. (2018) point out that the use of organic amendments could be better targeted for use on soils where there is greater potential to improve C stocks (e.g. in heavy soil

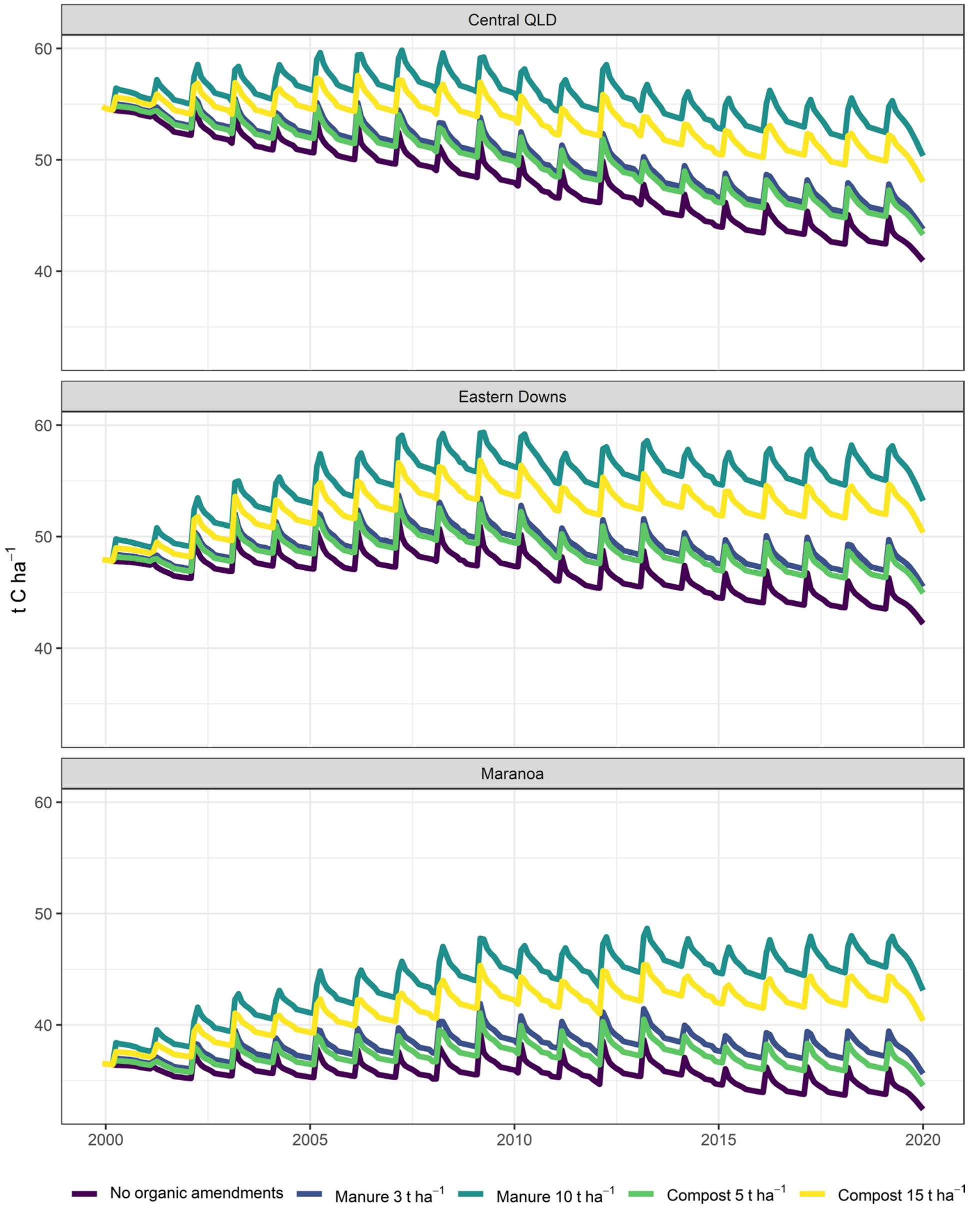

Fig. 1 Changes in simulated soil organic carbon (C) stocks (0–20 cm) in response to annual manure and compost application at different rates at three locations in Queensland (QLD) during continuous sorghum cropping

Table 3 Predicted changes in soil organic carbon (C) stocks in response to manure and compost applied at different rates and frequencies at three locations in Queensland (QLD) during 20 years of continuous sorghum cropping

Organic amendment	Application frequency	Application rate t fm ha^{-1}	Modelled change in C stocks		
			Central QLD	Eastern Downs	Maranoa
None		0	−25%	−12%	−11%
Manure	Annual	3	−20%	−5%	−2%
Manure	Annual	10	−8%	+11%	+18%
Compost	Annual	5	−21%	−6%	−5%
Compost	Annual	15	−12%	+5%	+11%
Manure	Every 3 yrs	3	−24%	−10%	−8%
Manure	Every 3 yrs	10	−19%	−4%	−1%
Compost	Every 3 yrs	5	−24%	−10%	−9%
Compost	Every 3 yrs	15	−21%	−6%	−4%

of low SOC content or for re-building soils A-horizons after laser levelling). Recent developments such as variable rate applicators for mill mud are promising technologies in this regard. As more than 80% of cultivated land in Queensland is affected by land degradation, including horticultural and sugarcane lands on the coast and land in the Darling Downs and Western Downs regions (Department of Primary Industries 1994, cited in Queensland Government 2015), most applications of organic amendments to cultivated land in Queensland should be beneficial. Realistic environmental gains from improved organic amendment utilisation efficiency may be small unless it results in more organic waste streams being diverted from landfill. The imperative to reduce organic waste disposal in landfill is recognised by governments at all levels in Australia (DAWE [Department of Agriculture, Water and the Environment] 2019).

Greater overall gains in organic waste utilisation could be achieved if manures were combined with lignocellulosic forestry-processing residues or urban organic waste streams like green waste and recycled timber as a feedstock for co-composting, particularly in regional areas (Biala 2003). However, integration of organic waste streams from agriculture with those from urban and forestry sectors in Queensland may be difficult to achieve in reality since most manures (and sugar milling residues) are already applied directly to land. Any attempt to improve resource utilisation efficiency and net greenhouse gas abatement for organic amendments across urban areas, forestry and agriculture would therefore need to consider issues associated with increased handling, transport and processing, including costs and resultant greenhouse gas emissions.

The commercial urban composting industry in Queensland, as in the rest of Australia, is based on green waste processing. Green waste is currently co-composted with a wide range of municipal and commercial solid and liquid residues, including for example food, food processing residues and grease trap waste. Urban-derived composted products are typically applied back in urban areas rather than in agriculture, although there is a push to supply more product to agricultural markets.

Losses of C as carbon dioxide and methane during storage or processing have not been accounted for in the above estimates due to lack of reliable data. Carbon levels in wood-processing residues may not be greatly affected during short-term storage, delivering 'as generated' C to soil when these products are used as mulch in landscaping applications or agricultural production. The situation can be similar with some urban-derived organic residues. An unknown proportion of green and timber waste was milled and then used without further processing as mulch, delivering 'as generated' C to the soil. On average, about 50% of carbon contained in the raw materials is released as CO_2 during composting, and 50% is retained, mostly in recalcitrant organic compounds (Biala 2011), although values can range considerably, depending on feedstock and also composting conditions and duration (Tiquia et al. 2002; Larney et al. 2005; Chang et al. 2019).

Potential for soils to sequester carbon

Depleted and degraded soils have a high theoretical potential for sequestering soil C (Lal et al. 2015), although the realistic C sink in many regions is likely to be, at best, 10–30% of the long-term loss (Sanderman et al. 2017). As Australian landscapes have lost 30–60% of their soil C since conversion from natural landscapes to agricultural production, they now represent significant biophysical potential as C sinks (Eady et al. 2009). Minasny et al. (2017) estimated that a 0.4% increase in soil C across Australia's agricultural land (assumed to be 470 million hectares), consistent with the objectives of the *4 per 1000* Initiative (Rumpel et al. 2020), was equivalent to sequestering an average of 0.22 t C ha^{-1} yr^{-1}. There is intensive debate globally on the achievability of the goal of the *4 per 1000* Initiative with acknowledgement that 0.4% annual increase in SOC is not realistic in all agricultural soils (Rumpel et al. 2020). The difficulty in achieving and maintaining increased C stocks in Australian soils through improved management practices has been emphasised in a number of studies (Sanderman et al. 2010; Robertson et al. 2016; White and Davidson 2016). The Australian ERF (2018) soil C measurement method (Australian Government undated) recognises the use of organic soil amendments (non-synthetic fertilisers) as an eligible activity, as long as it represents a new or significantly different management practice. It restricts the use of non-synthetic fertilisers, i.e. organic amendments, to those generated using a dedicated waste stream (thus excluding crop residue, hay or straw) or from within the area being sampled for change in C stocks. These restrictions aim to ensure gains and losses are both included in the average change for the project and only genuine abatement is credited. In assessing the climate change mitigation benefits associated with the application of exogenous organic amendments, it is the overall net impact on all greenhouse gas fluxes that must be assessed (Smith et al. 2008), not just their contribution to C stocks.

Globally, published results for measured SOC sequestration with addition of organic amendments vary widely from 0.24 to as high as 1.00 t C ha^{-1} yr^{-1} (e.g. Bhogal et al. 2011; Maillard and Angers 2014; Minasny et al. 2017). Authors note that soil texture and type are factors affecting the variability of C sequestration potential when modelling long-term sequestration dynamics and that initial SOC levels, climate and available moisture also strongly affect to what degree this potential can be achieved (Page et al. 2013; Luo et al. 2013; Godde et al. 2016). Sanderman and Baldock (2010) note that understanding the baseline SOC dynamics, i.e. whether initial C stocks are at steady state or declining due to past management, is critical in predicting net sequestration when improved practices are implemented.

Queensland's large land mass, widespread degradation of cultivated soil and generally low soil C stocks provide a theoretically large potential for soil C sequestration (Viscarra Rossel et al. 2015). Soils in Queensland are highly diverse. Kandosols, Sodosols and Vertosols have been reported to constitute 50% of the State's land area and have significant potential for C sequestration due to their biophysical properties (Karoly et al. 2009). Of the State's agricultural lands, 20 M ha of cropping land and sown pastures are considered to have C sink potential due to degradation and high clay contents. As these soils constitute a large proportion of local government areas where the majority of organic amendments are generated and utilised (Tables OR-7 and OR-8), there is good potential for increasing soil C relative to baseline levels.

In estimating SOC sequestration potential, research must realistically reflect actual farming practices. Research projects often use high annual application rates to demonstrate C sequestration potential or they may investigate other aspects of using these products (e.g. Chan et al. 2007; Adani et al. 2009). In reality, farmer decision-making is usually guided by practical and economic constraints, which frequently result in relatively low and infrequent application of organic amendments. Our modelling shows that, while high annual application of organic amendments can result in increased C stocks, low and less frequent applications will not achieve this goal (Table 3). The use of biosolids provides another example where theoretical and practical sequestration diverge significantly. Although the Biosolids Emissions Assessment Model (Sylvis 2009) assumes a default sequestration value of 0.068 t C t^{-1} biosolids, Goh (2017) demonstrated for South Australian conditions that SOC sequestration at annual biosolids application rates of 5 t (dm) ha^{-1} yr^{-1} (equal to 30–40 t (fm) ha^{-1} yr^{-1}) is not technically and financially viable. Because regulations stipulate that biosolids can be applied only once every 5 years in Queensland (NSW Epa [New South Wales Environment Protection Authority] 2000), direct C sequestration through the use of biosolids is practically ruled out.

Our own modelling of SOC change in response to use of organic amendments over 20 years for three sites in Queensland indicates that C sequestration of up to 18%, equivalent to 0.9% per year on average, is possible with high annual application rates of organic amendments in cropping soils in some regions of Queensland (Maranoa, Table 3). This exceeds the *4 per 1000* goal of 0.4%, but results for the warmer, more tropical site (Central QLD, Table 3) and for lower and non-annual applications indicate that the potential to achieve any net gain in SOC stocks under continuous cropping can be low. However, reducing the rate of decline in C stocks through application of organic amendments should not be overlooked as a real contribution to climate change mitigation and soil health.

Organic amendments and soil organic carbon dynamics

The capacity for models to reliably assess the potential for organic amendments to contribute to soil C sequestration and climate change mitigation is limited by how accurately they simulate what happens to these materials when added to soil and how the dynamics of organic matter is influenced by soil, climate and management factors.

Much insight into C and nutrient cycling in agricultural systems has been gained from long-term field trials involving the use of organic amendments (manures) in Europe (e.g. Rothamsted and Woburn (UK), Askov (Denmark), Bad Lauchstädt (Germany)) and the USA (Sanborn Field) (Johnston and Poulton 2018). Amongst other things, these experiments demonstrate the soil quality and productivity benefits associated with managing soil organic matter (SOM) by various means. Even small increases in SOM can have disproportionately large and beneficial effects on soil function and quality (Poulton et al. 2018), although it has also been suggested that manures may only have a benefit on soil productivity, over and above their nutrient content, when large inputs are applied over many years (Edmeades 2003).

Some researchers have called into question assumptions underlying the predominant conceptual model of SOM cycling (Stockmann et al. 2013; Lehmann and Kleber 2015). Soil C models such as Roth-C and Century are built on the premise that organic matter can be divided into pools that have different rates of turnover, and that microorganisms preferentially utilise labile pools of organic matter (e.g. in applied plant litter or manure) over those forms of SOM that are resistant to decomposition ('slow' and 'passive' pools). The labile portion consists of easily converted C compounds such as proteins and amino acids which undergo rapid mineralisation. They also have increased mobility through the soil profile via processes such as leaching of dissolved organic C (Zhang et al. 2017; Maltas et al. 2018). This model of SOM dynamics does not imply that more recalcitrant pools do not undergo decomposition, but microorganisms will preferentially decompose forms of organic matter that are energetically more favourable (De Nobili et al. 2020). Both the labile and recalcitrant pools are influenced by the initial soil C stock levels and the C saturation capacity of the soil with studies indicating that long-term storage of C is affected by protection from abiotic and biotic degradation. This protection can be through association with soil minerals, recalcitrant structures such as humic substances, lignins, tannins and fats, or through occlusion within microaggregates (Kong et al. 2005; Gulde et al. 2008; Yu et al. 2012; Hua et al. 2014).

While evidence for preferential decomposition of SOM can be supported (De Nobili et al. 2020), exceptions to this general rule have also been demonstrated. For example, lignin has long been thought to be resistant to decomposition, yet recent studies have demonstrated that it can be degraded rapidly early on, if easily accessible and if other sources of bioavailable C are present to help mineralise it (Klotzbücher et al. 2011). This is also the case for a range of other presumably persistent materials like polycyclic aromatic hydrocarbons, alkanes, fire-derived C and even polyethylene (Gramss et al. 1999; Wiesenberg et al. 2004; Hamer et al. 2004; Yang et al. 2014).

The resistance of some SOM pools to decomposition has been thought to be the result of 'humification', that is, the synthesis of complex, recalcitrant compounds following microbial degradation of SOM (Schlesinger 1977). However, the mechanisms underlying humification are poorly understood and 'humic substances' (HS) are ill-defined (Lehmann et al. 2008). Analytically, HS are separated from soils and other environments by alkali extraction, but Lehmann and Kleber (2015) claim that the HS extracted by alkali have never been observed as components of organic matter that actually exist in soil environments. In contrast, proponents of humification theory state that the most advanced techniques increasingly favour classical views on the structure and origin of HS (De Nobili et al. 2020), and that alkali-extracted HS can be successfully used as a proxy of SOM (Olk et al. 2019). Gleixner (2013) points out that the persistence of a C atom does not necessarily mean that the atom itself is still in the original molecule in which it was originally added to the soil. Carbon may persist in soil simply by its continued recycling as a component of substrate (for energy) and cell architecture (e.g. bacterial cell wall), rather than because of its chemical make-up, per se.

Microorganisms are fundamental to SOM cycling, yet mechanistic models regard the microbial biomass in all soils as a single, uniform 'black box' compartment (De Nobili et al. 2020). Despite the complexity of the microbial biomass, there is evidence that remarkably similar patterns govern SOM decomposition in all soils. It is therefore unclear whether increased complexity of mechanistic models would actually improve the modelling of SOM dynamics (Stockmann et al. 2013). Increasing model complexity would proportionally increase the site-specificity of the calibrated model and therefore when upscaling, it would increase the uncertainty of the model estimates linked to the spatial variability that characterises soil systems. However, more complex models with site-specific parameterisation may be better suited for project-scale accounting while simplified modelling better suits quantifying soil C changes at larger regional, national or continental scales.

Humification theory is also dominant in the field of composting science. According to a review by Wichuk and McCartney (2010), labile C in compost feedstock is converted into more stable HS over the course of composting. Fulvic acids (FA) are thought to be formed as an intermediate step in the formation of humic acids (HA) and, finally, water-insoluble, non-phytotoxic HS (Wichuk and McCartney 2010). The observed increase in HS with composting is closely correlated with a decrease in microbial respiration over time. As a result, the HA:FA ratio has been proposed as a measure of compost stability, especially for composts derived from high lignocellulosic feedstocks (Mathur et al. 1993).

Carbon retention efficiency is defined as the proportion of input C that is transformed or stabilised into SOM (Maillard and Angers 2014). Accumulation of soil C is thought to be slower in warmer climates where decomposition rates are faster (Schulze and Freibauer 2005), and the efficiency of C retention decreases as soil C stocks increase (Jiang et al. 2018). Climatic conditions (e.g. annual precipitation and ambient temperature) have a major bearing on what level of SOC content is achievable (as opposed to theoretically possible) in any given land management system (Stockmann et al. 2013). Accordingly, simulation results in our study showed C loss was fastest at the Central Queensland location—a site which is characterised by a clay content of 46% and the highest average temperature and highest annual rainfall amongst the locations studied.

Carbon retention is correlated with the quantity and quality of the product applied (Hao et al. 2003; Gerzabek et al. 1997; Maillard and Angers 2014) up to the point of saturation which is mainly determined by soil texture (Hassink 1997). For instance, dairy cow manure was found to retain a higher proportion of added C in soil compared to pig and horse manure (Jiang et al. 2018). In performing a linear regression with data from 42 long-term studies (average duration 18 years), Maillard and Angers (2014) estimated a global manure-C retention efficiency of 12% ± 4. This represents an additional 9.6 t C ha^{-1} or 0.53 t C ha^{-1} yr^{-1} retained in soil as a result of manure application. Fan et al. (2014) found that compost applications over a 20-year period resulted in C sequestration at 0.58 t C ha^{-1} yr^{-1} with a C retention efficiency of 14.1%. This is consistent with a higher sequestration rate for composted compared with fresh manure found by Xia et al. (2017) in their meta-analysis.

A large increase in the proportion of the labile C pool, for example by using organic soil amendments, accelerates soil C and nutrient cycling, resulting in an improvement of soil fertility. In a meta-analysis comparing C and nutrient cycling following the use of composted and non-composted manures, Liu et al. (2020) found that compost had a greater impact on microbial C and all enzyme activities compared to non-composted manure. Soil C and nutrient cycles are coupled to the extent that while microbial C:N and C:P ratios may be altered drastically with the application of organic amendments, non-microbial C:nutrient ratios can remain unaffected. Stable soil C:nutrient ratios probably reflect the stability of mineral-associated organic matter, which responds more slowly to management practices compared to the microbial biomass (Cotrufo et al. 2019).

Although stable compost may contain higher levels of HS, raw materials such as feedlot manure (and immature compost) contain higher levels of total C and polysaccharides which may actually improve soil aggregation more effectively than stable compost (Sela et al. 1998). During the composting process, significant levels of C are volatilised, reducing C content compared to the raw, uncomposted material. The overall C mass balance should therefore be considered when comparing composts and manures, but few studies with reliable long-term field trial data also factor in C losses during composting or storage (Helgason et al. 2005). A global meta-analysis of 141 studies using either synthetic N fertiliser or an equivalent N application using manure as either fresh material or compost indicated that manure substitution increased the rate of SOC sequestration relative to synthetic fertiliser by, on average, 699.6 kg C ha^{-1} yr^{-1} in upland (non paddy) cropping systems, attributed mainly to the addition of exogenous C in manure (Xia et al. 2017). Moreover, from this meta-analysis, Xia et al. (2017) found that the increase in SOC was higher for composted manure (18 observations) than for raw manure (38 observations).

Recent Australian research involving incubations of sand with various organic amendments for 18 months at 22 °C suggests that the half-life of urban compost-derived C is probably of the same order as manure and biosolids, at around 10–15 years (Farrell 2015). Other incubation studies with compost suggest that the stability of the compost product may be a good predictor of C retention efficiency. For example, in an incubation study spanning 100 days duration with 3 soils amended with composted manure of differing levels of stability, cumulative CO_2 emissions were found to decrease as compost stability increased (Lim et al. 2012). However, the value of short-term incubation studies for predicting C retention efficiency is limited because mineralisation of SOM proceeds at a much slower rate than the decomposition of the plant and animal residues from which it is derived. Carbon quality may, therefore, explain short-term decomposition of exogenously applied organic matter better than long-term SOM decomposition (Stockmann et al. 2013; Miller et al. 2015). Still, long-term trials in Woburn in the UK suggest that C retention efficiency can be marginally higher in soils treated with composted materials compared to raw materials, with the rate at which saturation is reached occurring earlier in compost amended soils (Poulton et al. 2018).

Other researchers have noted increased degradation of the soil C pool upon applications of exogenous organic matter due to the priming effect (Kuzyakov et al. 2000). De Rosa et al. (2017) observed that the application of an easily degradable C source such as raw manure in an intensively cultivated soil system can promote native soil C degradation as a consequence of a priming effect. In soils where a source of easily available energy for microbial activity is a limiting factor, the addition of readily degradable exogenous C sources stimulates native soil C degradation due to increased microbial activity scavenging for nutrients (Kuzyakov et al. 2000). This might offset the beneficial effect on soil C storage of application of raw organic amendments. Since the priming effect is commonly associated with the applications of readily degradable organic matter (Fontaine et al. 2007), many propose that the most suitable organic amendments for C sequestration are those that exhibit high structural and functional similarity with native SOM (Daouk et al. 2015). Incubation studies by Lerch et al. (2019) showed that addition of raw vegetation residues resulted in a priming effect, while that was not observed when the same material was composted prior to soil incorporation.

Organic amendments may also be applied to the soil surface with little or no incorporation. While there has been little research on C dynamics following applications of exogenous material as mulch, the effects of using crop residues for mulching have been examined in several cropping systems and found to result in increased soil C levels, e.g. in a bamboo forest (Zhang et al. 2013), a citrus orchard (Gu et al. 2016), in pasture (Mitchell et al. 2018) and in broadacre cropping without straw removal (Kahlon et al. 2013). A review of studies that investigated the effects of crop residue mulches on SOC stocks in the topsoil (0–20 cm) for periods between 3 and 28 years by Ranaivoson et al. (2017) found that SOC stocks increased with increasing amounts of residues, but that annual gains of SOC were relatively low, with a mean of 0.50 t C ha^{-1} $year^{-1}$ for residue levels of 1.5 to 16 t ha^{-1}. The maximum SOC gain corresponded to 1.75 t C ha^{-1} $year^{-1}$ with 16 t ha^{-1} of residues. Findeling et al. (2007) point out that various models, including Century, Roth-C, APSIM and EXPERT-N simulate the decomposition of crop residues under various conditions with varying degrees of accuracy. Findeling et al. (2007) aimed to better capture the effect of abiotic factors (mulch temperature, mulch water content, nitrogen limitations and contact between mulch and soil) on the dynamics of decomposing microorganisms in their model, $PASTIS_{mulch}$. They showed that the total mulch dry mass and the proportion of this dry mass in contact with the soil are decisive parameters and that mulch decomposition was not a continuous process but occurred in the form of successive pulses that correspond to favourable hydric conditions. It is expected that the same principles and mechanisms apply when organic amendments rather than crop residues are used for mulching, but research on this subject is limited.

Conclusions

Modified Australian Biomass for Bioenergy Assessment data indicated that 2.7 Mt (dm) of organic materials were most likely used for land application in Queensland in 2015/16. These materials contained about 1.0 Mt (dm) of organic C when generated, but the data were insufficient to estimate both the actual amount and stability of C that was applied to land through the use of organic amendments and the potential for increasing soil carbon stocks. Exemplary FullCAM simulations over 20 years of continuous cropping predicted that, in favourable conditions, high annual applications of manure and compost can result in SOC increases above the *4 per 1000* Initiative's aspirational goal. Yet, in less favourable conditions (lower/infrequent application, soil with lower clay content, higher temperatures and more rainfall), C stocks may continue to decline but at a lower rate than without organic amendments. Regionally explicit data that characterise these amendments (raw and composted) and provide information on application rates and frequencies are needed to scale-up field measurements and to parameterise models to assess the potential using organic amendments has for reducing C losses and improving SOC stocks in Queensland.

While robust quantification of the potential climate change abatement and agricultural productivity gain from application of organic amendments is not currently possible for Queensland or for Australia as a whole, available data shows that investment in research to fill knowledge gaps is warranted. This will support long-term agricultural and environmental goals, including sustainable food production, climate change mitigation and resilience and organic waste reduction. Research needs include:

- Appropriate analytical characterisation of organic soil amendments that allows parametrisation, testing and validation of crop/soil simulation models, and their subsequent use in predicting the likely effects of using organic amendments on SOC and crop performance
- Improved material flow data across all organic residue supply chains
- Carbon losses during storage and co-composting of various (mixed) organic residues and the allocation of C losses to various blended raw materials according to their C degradability characteristics
- The fate of C when organic amendments are not or only minimally incorporated in minimum till farming operations and pastures, or applied as surface mulch in landscaping, site remediation or perennial and tree cropping operations
- Quantified agronomic and economic benefits of application of organic amendments in a range of cropping, soil and climatic conditions in Queensland
- Validated models for use in ERF methods to estimate SOC sequestration following use of raw and composted organic amendments
- Development of a user-friendly C calculator to inform farmers on the likely impacts of their current or future farm management practices, including use of organic amendments, on SOC levels

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