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ORIGINAL ARTICLE

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Stock change accounting overestimates the potential climate benefit of soil carbon storage

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Abstract

Agriculture is being called upon to increase carbon (C) storage in soils to reduce greenhouse gas (GHG) accumulation in the atmosphere. Cropping systems research can be used to support GHG mitigation efforts, but we must quantify land management impacts using appropriate assumptions and unambiguous methods. Soil C sequestration is considered temporary because it can be re-emitted as carbon dioxide (CO_2) if the effecting practice is not maintained and/or the soil–plant system is disturbed, for example, as the result of changing climate. Because of this, the climate benefit of soil C sequestration depends on the time that C is held out of the atmosphere. When assessing the net GHG impact of management practices, soil C storage is often aggregated with non-CO_2 (N_2O and CH_4) emissions after converting all components to CO_2 equivalents (CO_2e) and assuming a given time horizon (TH), in what is known as *stock change accounting*. However, such analyses do not consider potential re-emission of soil C or apply consistent assumptions about time horizons. Here, we demonstrate that *tonne-year* accounting provides a more conservative estimate of the emissions offsetting potential of soil C storage compared to stock change accounting. Tonne-year accounting can be used to reconcile differences in the context and timeframes of soil C sequestration and non-CO_2 GHG emissions. The approach can be applied post hoc to commonly observed cropping systems data to estimate GHG emissions offsets associated with agricultural land management over given THs and with more clearly defined assumptions.

1 | INTRODUCTION

The agricultural and soil science communities produce a wealth of data assessing the greenhouse gas (GHG) impacts of land use change and cropping system management at the field- and farm-scales. These analyses sometimes include soil organic carbon (SOC) stock change data, while other times it is absent (Liebig et al., 2023). Without clear guidance, methods for including biogenic C storage, such as soil organic C (SOC), into GHG inventories vary widely. Given that agricultural management has a large impact on soil C dynamics, this inconsistency can result in inaccurate characterizations of the GHG impacts of agricultural systems and the products they produce.

In the context of finite-term emissions mitigation, there are two main ways to account for the GHG emissions offset of biogenic C storage: stock change and tonne-year accounting (Cacho et al., 2003). Stock change accounting assigns a GHG emissions offset equal to the total mass of CO_2 stored

Abbreviations: CO_2e, carbon dioxide equivalents; GHG, greenhouse gas; GWP, global warming potential; IRF, impulse response function; SOC, soil organic carbon; TH, time horizon.

during the period over which the stock change occurred, that is, a tonne of CO_2 stored offsets a tonne of CO_2 emitted. Conversely, tonne-year accounting uses a time integrated value of soil CO_2 storage to assign a partial GHG emissions offset for warming that is moved beyond a given time horizon (TH) as the emission is delayed.

These accounting frameworks make differing assumptions about the permanence of biogenic C. Analyses that use stock change accounting implicitly assume that an increase in SOC storage is permanent, or at least will continue for the entire TH over which the radiative forcing impacts of GHGs are considered, often 100 years. This assumption neglects uncertainties associated with potential release of SOC due to changes in management and/or climate (Bernal et al., 2016; Bradford et al., 2016). This contrasts with tonne-year accounting, which uses a time-integrated approach to quantify the GHG emission offsets from SOC storage.

The objectives of this paper are to describe the assumptions and details of the stock change and tonne-year accounting methods and apply the methods to existing datasets representing a range of climate, crop, and management regimes. Through these examples, we aim to (1) demonstrate how the underlying assumptions used to quantify the net GHG impact of soil C storage can influence findings and (2) promote informed representation of SOC stock changes within broader sustainability analyses.

Core Ideas

- Changes in soil carbon are not consistently accounted for in greenhouse gas accounting exercises.
- The two main methods used to quantify the climate impact of additional soil carbon rely on differing assumptions.
- Stock change accounting assigns a climate benefit equal to the mass of additional C in the year of sequestration.
- Tonne-year accounting assigns a climate benefit annually using a time integrated approach.

2 | METHODS

2.1 | Background

THs are common in GHG accounting exercises. A TH represents a finite period during which the warming impacts are considered, and beyond which further impacts are not. The use of a TH allows the comparison of emission scenarios by integrating the warming impacts of GHGs during the specified timeframe. This is the underlying concept of the commonly used global warming potential (GWP) framework, which equates the warming impact of multiple GHGs as carbon dioxide equivalents (CO_2e) (Smith & Wigley, 2000). In choosing a TH, we prioritize near-term GHG impacts, but because we cannot objectively weigh the cost-benefit of present and future warming, the choice is subjective. The decision on the considered timeframe, therefore, may be determined in response to specific policy objectives or climate goals.

Atmospheric CO_2 is utilized and absorbed by natural processes, such as photosynthesis and ocean dissolution (Lord et al., 2016). The utilization of a given emission of CO_2 by these processes occurs on timescales that range from tens to hundreds of thousands of years. The net drawdown over this period has been described using an impulse response function (IRF) consisting of a series of exponential decay functions representing atmospheric CO_2 removal by these global carbon sinks. A current version of the IRF for CO_2 (IPCC AR6) expresses the proportion of the initial pulse emission of CO_2 remaining in the atmosphere after t years as follows (Gasser et al., 2017):

$$\text{IRF}\ (t) = 0.2033 + a_1 e^{-\left(\frac{t}{b_1}\right)} + a_2 e^{-\left(\frac{t}{b_2}\right)} + a_3 e^{-\left(\frac{t}{b_3}\right)}, \tag{1a}$$

which can be written more concisely as:

$$\text{IRF}\ (t) = 0.2033 + \sum_{i=1}^{3} a_i \times e^{-\left(\frac{t}{b_i}\right)}, \tag{1b}$$

where a_i and b_i are constants given by $a_{1,2,3} = 0.3016$, 0.2836, 0.2115 and $b_{1,2,3} = 2.376$, 30.14, 490.1.

It is important to note that Equation (1) represents a ratio of the mass of CO_2 remaining in the atmosphere following a pulse CO_2 emission occurring at time zero ($t = 0$, or T0). Thus, any set of mass units can be used and scaled to the mass of the initial emission. An example of Equation (1) is shown in Figure 1 using mass units of tonne (Mg = 1000 kg); therefore, the curve in Figure 1 represents Mg of CO_2 remaining in the atmosphere following a 1 Mg emission of CO_2 at $t = 0$.

Because CO_2 and other GHGs persist in the atmosphere over decadal and longer timescales, the total warming impacts of an emission accumulate over time. These cumulative impacts can be estimated by integrating the IRF over the period of interest. For the period from t_1 to t_2 years, the general solution of the integral of Equation (1) is given by (Forster et al., 2021):

$$\int_{t_1}^{t_2} \text{IRF}\,(t)\,dt = 0.2033\left(t_2 - t_1\right) - \sum_{i=1}^{3} a_i b_i \left[e^{-\left(\frac{t_2}{b_i}\right)} - e^{-\left(\frac{t_1}{b_i}\right)}\right] \tag{2a}$$

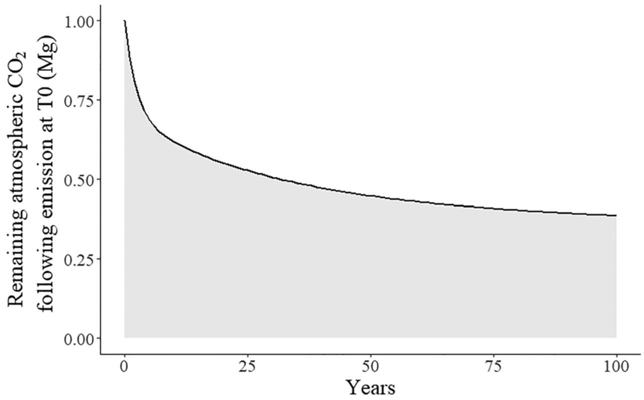

FIGURE 1 Example of the CO_2 impulse response function (IRF). The black curve shows the mass of CO_2 (Mg) remaining in the atmosphere after a 1 Mg CO_2 emission occurring at T0. The shaded area under the curve represents the cumulative 100-year impact (Mg-year) of the initial CO_2 emission.

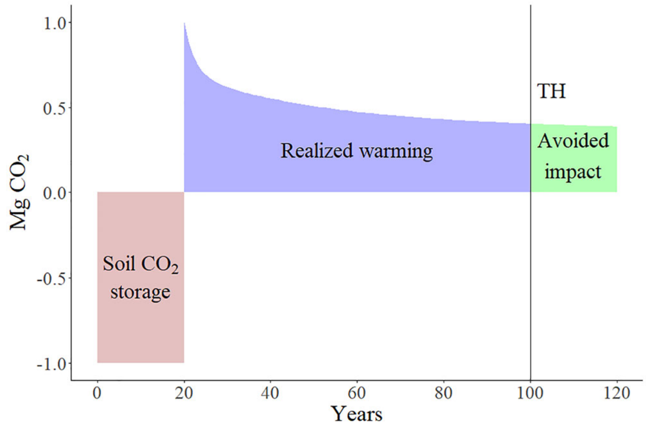

FIGURE 2 Simplified example of the tonne-year accounting approach assuming a 100-year time horizon (TH) and where 1 Mg CO_2 is stored for 20 years before being re-emitted. Following emission, the first 80 years of warming are represented by the impulse response function (IRF) integral up to the TH, while warming that occurs beyond the TH represents the avoided climate impact of the soil CO_2 storage.

and when $t_1 = 0$, this simplifies to:

$$\int_{o}^{t_2} \mathrm{IRF}\,(t)\,dt \;=\; 0.2033\,(t_2) \;-\; \sum_{i=1}^{3} a_i b_i \left[e^{-\left(\frac{t_2}{b_i}\right)} \;-\; 1 \right], \tag{2b}$$

where a_i and b_i are the same as in Equation (1). Thus, the shaded area under the curve in Figure 1 can be used to represent the cumulative (100-year) warming impact of a 1 Mg CO_2 emission occurring at $t = 0$, the numerical value of which (52.3 Mg CO_2-year) can be determined from Equation (2b) where $t_2 = 100$ years.

The cumulative warming impact of an emission from T0 to a given TH can be referred to as the GWP (Lashof & Ahuja, 1990). The GWP is often used to equate the warming impacts of non-CO_2 GHGs with different atmospheric lifetimes and radiative efficiencies, although the physical basis of the GWP values for different GHGs is not often described. Using the time-integrated warming impact of CO_2 as our reference, we can integrate the respective IRFs and correct for the increased relative radiative efficiencies of non-CO_2 GHGs. The resulting mass-time value relative to our reference gas determines CO_2e, and using a TH of 100 years, the GWP_{100} values of N_2O and CH_4 are 296 and 23 CO_2e, respectively (Gasser et al., 2017). For the current analysis, a 100-year TH is also assumed.

Tonne-year accounting calculates the warming impact that is avoided when CO_2 is removed from the atmosphere and stored within soil or biomass (Fearnside et al., 2000). This method is illustrated in Figure 2, where SOC equivalent to 1 Mg CO_2 is stored for 20 years as represented by the area below the horizontal (x) axis. An equivalent emission is delayed while this CO_2 is stored in the soil. The IRF for CO_2 is therefore shifted to the right on the x axis during the storage period, and the avoided warming impact is represented by the area of the "tail" of the shifted IRF that extends beyond the initial 100-year TH. The GHG offset of temporary CO_2 storage can be calculated as the difference between the tonne-year impact of a CO_2 emission at $t = 0$ and the tonne-year impact that is realized when CO_2 is held for t years, as follows:

$$\mathrm{GHG\ offset} \;=\; \int_{0}^{100} \mathrm{IRF}\,(t)\,dt - \int_{0}^{100-t} \mathrm{IRF}\,(t)\,dt\,, \tag{3a}$$

which simplifies to the following equation:

$$\mathrm{GHG\ offset} \;=\; \int_{100-t}^{100} \mathrm{IRF}\,(t)\,dt, \tag{3b}$$

where t is the period of soil C storage and the avoided emissions have units of Mg CO_2-year, or more specifically Mg CO_2-year offset per Mg CO_2 stored as soil C for t years.

According to the IRF used in the IPCC AR6, the CO_2e of 1 Mg CO_2 emission is equal to 52.3 tonne-years. We can calculate the cumulative emissions offset of temporary CO_2 storage as the quotient of the GHG offset (tonne-years; Equation 3) and the tonne-year impact of 1 Mg CO_2e (Equation 4) as follows:

$$\mathrm{Cumulative\ emissions\ offset}\;(t) \;=\; \frac{\int_{t_1}^{t_2} \mathrm{IRF}\,(t)\,dt}{52.3} \tag{4}$$

This equation can be applied to annual SOC stock change data, where the mass CO_2 storage is multiplied by the cumulative emissions offset function when CO_2 is stored for t years. As t approaches the 100-year TH, the cumulative

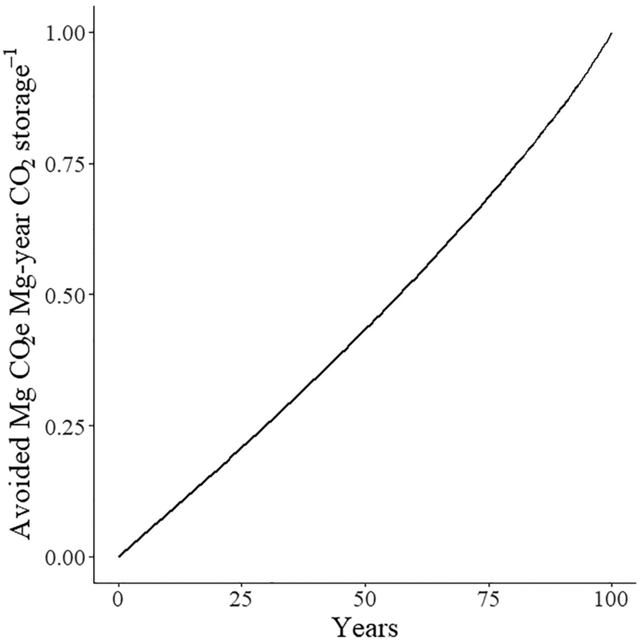

FIGURE 3 Cumulative offset (Mg CO_2e) per Mg CO_2 storage for *t* years when assuming a time horizon of 100 years.

Mg CO_2e emission offset per Mg CO_2 stored approaches 1 (Figure 3).

2.2 | Example applications

We applied the tonne-year accounting methods to data reported in Mosier et al. (2005), who analyzed the net CO_2e impact of three agroecosystems (Peterson et al., 1993; Robertson et al., 2000; Sherrod et al., 2003). We re-analyzed two of the reported datasets from that manuscript that represent farming systems local to Michigan and Colorado. The datasets reported emissions associated with energy use from farm operations, irrigation, liming, N fertilizer production and application (Follett, 2001), soil emissions of N_2O and CH_4, and the average annual SOC stock change over an 11-year monitoring period for treatments in each cropping system. They calculated the net impact of management practices and non-CO_2 GHG emissions to sum each source or sink using CO_2e as the equivalent term, where the CO_2e impact of non-CO_2 GHGs was converted according to the IPCC Third Assessment Report (Ramaswamy et al., 2001).

Mosier et al. (2005) set the average annual SOC stock change equivalent to CO_2e, where positive values represent soils as a net source of CO_2, and negative values represent SOC sequestration. They accounted for the GHG mitigation of SOC storage in the year of sequestration, which represents a stock-change accounting approach that assumes sequestered C is maintained to the TH. They concluded that "whether the system is a sink or source of CO_2 was controlled by the rate of SOC storage." We will explore the tonne-year accounting methods using example data and results from Mosier et al. (2005) using a 100-year TH.

The first example dataset measured SOC content under Michigan cropping systems that were studied between 1988 and 1999. We, like the original authors, made the simplifying assumption that the SOC stock change was constant during the 11-year experiment. The cumulative emissions offset from SOC storage realized during the study period were calculated by multiplying the average annual SOC stock change (kg CO_2 ha^{-1} year^{-1}) by Equation (4) for each year of the experiment (11 years), where *t* equals the number of years that the CO_2 was stored by end of the study. The results of those calculations were averaged, and the reported annual CO_2e emissions sources and sinks, including the cumulative emissions offset estimated using the tonne-year approach, were summed to recalculate the net CO_2e emissions for each treatment.

The second example dataset measured SOC content under Colorado dryland cropping systems over the period from 1986 to 1997. The cumulative emissions offset and the net CO_2e emissions from management treatments during the study period were calculated as in Example 1. We then divided the reported crop biomass yield data by the average annual net CO_2e emissions of each cropping system (kg biomass kg CO_2e^{-1}) to determine the CO_2e efficiency of each treatment.

3 | RESULTS AND DISCUSSION

Example 1. Net CO_2e in Michigan agroecosystems.

This dataset details the net GHG emissions from corn–soybean–wheat rotations (CSW) managed under no-till (NT) or conventional tillage (CT) with a continuous alfalfa comparison. Results calculated using the tonne-year approach differed substantially from the original published values (Table 1). The original study reported that SOC accrual over the study period completely offset emissions from continuous alfalfa production, while the CSW-CT and CSW-NT treatments were a net source of CO_2e. This contrasts with the values calculated using the tonne-year approach, which report that alfalfa was the largest source of net CO_2e over the study period while CSW-CT was the smallest.

The difference between these results follows from the differing assumptions associated with SOC sequestration. Stock change accounting implicitly assumes permanence of sequestered C for the complete duration of the TH and awards the full CO_2e offset in the year of sequestration. This contrasts with tonne-year accounting, which makes no assumptions beyond the temporal boundaries of the data, and calculates the cumulative benefit of C storage relative to the 100-year

TABLE 1 Sources of carbon dioxide equivalents (CO_2e) from Michigan agroecosystems.

Treatment	Farm operations (kg CO_2e ha^{-1} year^{-1})	Lime (kg CO_2e ha^{-1} year^{-1})	N fertilizer[a] (kg CO_2e ha^{-1} year^{-1})	N_2O (kg CO_2e ha^{-1} year^{-1})	CH_4 (kg CO_2e ha^{-1} year^{-1})	Total non-SOC (kg CO_2e ha^{-1} year^{-1})	ΔSOC[b] (kg CO_2e ha^{-1} year^{-1})	Net CO_2e (kg CO_2e ha^{-1} year^{-1})	ΔSOC[c] (kg CO_2e ha^{-1} year^{-1})	Net CO_2e (kg CO_2e ha^{-1} year^{-1})
	Mosier et al. (2005)						**Stock change**		**Tonne-year**	
CSW-CT	160	230	270	520	−40	1140	0	1140	0	1140
CSW-NT	120	340	270	560	−50	1240	−1100	140	−54	1186
Alfalfa	80	880	0	590	−60	1490	−1610	-200	−79	1411

Note: Adapted from Mosier et al. (2005); data from Robertson et al. (2000). ΔSOC values represent CO_2e emissions attributed to a change in SOC content. A negative ΔSOC represents an increase in SOC content, which results in a CO_2e emissions offset. Net CO_2e is the sum of CO_2e sources and sinks represented in the table.

Abbreviations: Alfalfa, continuous alfalfa; CSW, corn–soybean–wheat rotation; CT, conventional tillage; NT, no-tillage; SOC, soil organic carbon.

[a]45.5 kg CO_2 ha^{-1} for application + 3.0 kg CO_2 per kg N applied (Follett, 2001).

[b]Values are equal to the average annual SOC stock change in the 0- to 7.5-cm depth increment during the experimental period (1988–1999).

[c]Values represent to the average annual CO_2e offset calculated using the tonne-year approach with a 100-year time horizon. Values were calculated using Equation (4) and assume that SOC stocks increased linearly during the experimental period. CO_2 storage time (*t*) is equal to the years of storage before the termination of the experiment. Nothing is assumed beyond the temporal boundaries of the original data.

TH. This means that if SOC storage is maintained to the TH, the cumulative offset is as large as the stock change, and the average annual offset is 1/100 of that amount.

Example 2. Climate efficiency of Colorado dryland production.

This dataset details the response of soil C and crop biomass by crop rotation and field slope position. Wheat–corn–fallow (WCF), opportunity cropping (OC), which aims to minimize fallow times by planting crops based on soil moisture levels (Burton et al., 2009), and perennial grass rotations, were sampled at the midslope (M) and toeslope (T) landscape positions. Once again, results derived with the tonne-year approach differed from the original stock change results (Table 2). Mosier et al. (2005) originally concluded that the WCF treatment was a net source of CO_2e emissions, while OC and Grass treatments were a net sink. With tonne-year accounting, results indicate that OC and WCF treatments have similar net CO_2e emissions, but higher yields in the OC treatment increased the annual biomass per CO_2e emission by 47% relative to WCF. Low yields in the Grass treatments were accompanied by significant emissions reductions, which increases the emissions efficiency of the Grass system above all other treatments.

By scaling the net CO_2e emissions of the system by yield, we determine the per unit impacts of a management system. We can suggest two main conclusions from the example results: (1) increasing yield without increasing inputs improves the emissions efficiency of the system, and (2) a system that realizes reduced relative yields can also reduce emissions from other sources to maintain or increase its emissions efficiency. By integrating these values, we can weigh the cost-benefit of management interventions that influence both emissions impacts and crop yield (Murray et al., 2007).

3.1 | Implications

Stock change accounting awards emission offsets in the year of sequestration without accounting for the maintenance of additional C. Given the uncertainty around long-term maintenance of agricultural SOC stocks, the stock change approach likely represents an overly optimistic, or at least a best-case, assessment of the benefits of short-term CO_2 storage because these benefits may never be realized to the full estimated extent. By using tonne-year accounting, we remove the permanence requirement from the offset, which allows us to sum the effect of SOC storage with non-SOC sources of CO_2e under a GWP framework using non-conditional and equivalent terms.

Our applications of tonne-year accounting indicate that emission offsets from SOC storage can be small in comparison to non-SOC sources of CO_2e. This suggests that

TABLE 2 Sources of carbon dioxide equivalents (CO_2e) from Colorado dryland agroecosystems.

Treatment	Annualized biomass[a] (kg ha^{-1} year^{-1})	Farm operations kg CO_2e (ha^{-1} year^{-1})	N fertilizer[b] (ha^{-1} year^{-1})	N_2O (ha^{-1} year^{-1})	CH_4 (ha^{-1} year^{-1})	Total non-SOC (ha^{-1} year^{-1})	ΔSOC[c] (ha^{-1} year^{-1})	Net GWP (ha^{-1} year^{-1})	ΔSOC[d] (ha^{-1} year^{-1})	Net GWP (ha^{-1} year^{-1})	Climate efficiency (kg biomass kg CO_2e^{-1})
	Mosier et al. (2005)						Stock change		Tonne-year		
WCF-M	2060	85	383	334	25	827	−476	311	−23	804	2.56
WCF-T	2705	85	383	334	25	827	−590	197	−29	798	3.39
OC-M	2880	85	383	334	25	827	−1100	−313	−54	773	3.73
OC-T	3790	85	383	334	25	827	−1467	−683	−72	755	5.02
Grass-M	803	0	0	165	11.4	176.4	−653	−480	−32	144.4	5.56
Grass-T	1569	0	0	165	11.4	176.4	−968	−803	−47	129.4	12.13

Note: Adapted from Mosier et al. (2005); data from Peterson et al. (1993) and Sherrod et al. (2003). ΔSOC values represent CO_2e emissions attributed to a change in SOC content. A negative ΔSOC represents an increase in SOC content, which results in a CO_2e emissions offset. Net CO_2e is the sum of CO_2e sources and sinks represented in the table.

Abbreviations: M, midslope field position; OC, opportunity cropping; SOC, soil organic carbon; T, toeslope field position; WCF, wheat–corn–fallow crop rotation.

[a]Annualized biomass is the average annual biomass production from management treatments between 1986 and 1997 (Sherrod et al., 2003).

[b]45.5 kg CO_2 ha^{-1} for application + 3.0 kg CO_2 per kg N applied (Follett, 2001).

[c]Values are equal to the average annual SOC stock change in the 0- to 5-cm depth increment during the experimental period (1986 to 1997).

[d]Values represent the average annual CO_2e offset calculated using the tonne-year approach with a 100-year time horizon. Values were calculated using Equation (4) and assume that SOC stocks increased linearly during the experimental period. CO_2 storage time (t) is equal to the years of storage before the termination of the experiment. Nothing is assumed beyond the temporal boundaries of the original data.

increasing SOC stocks will not necessarily mitigate the GHG footprint of land management. While SOC-based CO_2e offsets take time (e.g., 100 years) to be fully realized, emissions reductions, including emissions associated with inputs, management, and in-field N_2O and CH_4 flux (Venterea et al., 2012), can reduce the CO_2e impact of agricultural production systems annually. These findings were not necessarily apparent using a stock change approach.

The mathematical framework for tonne-year accounting is also used within other approaches that incorporate modeling-based estimates of future soil C dynamics (Leifeld, 2023). The Climate Benefit of Sequestration (CBS), developed by Crow and Sierra (2022) and Sierra et al. (2021), models future SOC dynamics using litter retention coefficients for annual C inputs. They estimate the SOC that remains after annual biomass inputs, and, like tonne-year accounting, integrate SOC storage over time to determine the avoided warming impact over a fixed TH. CBS can be used to answer specific questions about projected impacts from land management, while tonne-year accounting concepts can be used more generally to quantify net GHG offsets directly from SOC stock change data derived from field measurements or other modeling programs.

We have provided descriptions and context for the tonne-year accounting method and compared its assumptions to those of the stock change approach. This analysis does not imply that tonne-year accounting is the most appropriate method, nor is it our intention to endorse the generation of emissions offsets from agricultural land. The examples do highlight the contrasting results obtained using tonne-year versus stock change accounting, and how the latter approach represents a best-case, if not overly optimistic, scenario regarding soil C storage. We hope that our application of alternative methods to cropping system research inspires further discussion regarding the integration of SOC into more holistic analyses of agroecosystem sustainability.

AUTHOR CONTRIBUTIONS

Jonathan R. Alexander: Conceptualization; formal analysis; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Joshua D. Gamble**: Conceptualization; investigation; project administration; supervision; writing—review and editing. **Rodney T. Venterea**: Conceptualization; formal analysis; methodology; writing—review and editing.

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