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The climate benefit of sequestration in soils for warming mitigation

Susan E. Crow · Carlos A. Sierra

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Abstract Soils are an enticing reservoir for nature-based climate solutions, but long timescales are required to store amounts of C of relevance to mitigate warming acknowledging its impermanence. Scientific clarity on the controlling factors in soil C persistence should help to disambiguate debates related to permanence in the climate policy domain. However, another contributing factor that is lacking in this debate is a way to compute the climate benefits of C in terrestrial ecosystems over time in the same units as greenhouse gas emissions. We use a case study approach here to demonstrate the use of the metrics of carbon sequestration (CS) and climate benefit of sequestration (CBS) with the aim of assessing the contribution of simultaneous emissions and uptake on radiative forcing. We show how this new computational framework quantifies the climate benefit achieved in two different agricultural systems, one a managed tropical perennial grass system in Hawai‘i, USA and the other a boreal (cold-temperate, semi-humid) agricultural soil from long term amendment trials in Sweden. Using a set of computations, we show how C inputs and persistence interact to produce different levels of radiative forcing at relevant time frames, which could greatly help to clarify issues of carbon permanence discussed in climate policy. Temporary soil C storage could help to decrease peak warming provided that ambitious emission reductions are part of the portfolio of solutions; the CS and CBS framework gives us a way to quantify it based on biogeochemical understanding of soil C persistence.

Keywords Carbon dioxide removal · Sustainable development goals · Climate policy · Peak warming · Carbon accounting

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S. E. Crow (✉)
Department of Natural Resources and Environmental Management, University of Hawai‘i Mānoa, Honolulu, HI, USA
e-mail: crows@hawaii.edu

C. A. Sierra
Max Planck Institute for Biogeochemistry, Jena, Germany

C. A. Sierra
Swedish University of Agricultural Sciences, Uppsala, Sweden

Introduction

Meeting climate objectives set in the Paris Agreement requires achieving net-zero CO_2 emissions by mid-century. Carbon dioxide removal (CDR) options, including nature-based climate solutions that aim to preserve or enhance storage in terrestrial and marine systems, may be critical to achieving net-zero objectives by offsetting unavoidable non-renewable emissions elsewhere in the global system (Rogelj et al. 2021). Soils are an enticing reservoir for nature-based CDR and mediation of greenhouse gas emissions (Lal 2013; Chabbi et al. 2017; Bossio et al. 2020). However, long timescales are required to store amounts of carbon in soils of relevance to mitigate climate change. In addition, uncertainty in the magnitude and relevant timeframe for soil carbon management remains high across ecosystems (Lu et al. 2018; Cai et al. 2022). Carbon is stored impermanently in soils, thus it is challenging to know how long new C inputs from the implementation of climate-smart practices or mitigation strategies will stay belowground and thereby provide quantifiable climate benefits (Xiao et al. 2022). An approach that can quantifies both how much and for how long C inputs will remain stored can advance the valuation of protecting or improving soil C in a climate change mitigation portfolio.

Permanence—a policy term for when credits are traded as part of a climate change mitigation project and the buyer seeks assurance that the C will remain in the system for a contracted period—is an issue that remains highly debated in policy making. In contrast, the scientific concept of persistence—an ecosystem property resulting from physicochemical and biological influences in the soil environment that cause organic matter to remain longer in soil than outside it—has been well studied in soil science and biogeochemistry (Torn et al. 1997; Schmidt et al. 2011; Sierra et al. 2018; Cotrufo and Lavallee 2022; Heckman et al. 2022). These concepts both seek to introduce the aspect of time into their frameworks to assess how much and for long C resides in soils.

The debate over permanence and related uncertainties in how long soil C remains belowground is creating a barrier to incentive programs surrounding nature-based solutions that include soils and terrestrial ecosystems (Bradford et al. 2019; Dynarski et al. 2020). These debates distract from the diversity of potential climate, environmental, and societal co-benefits to the actions that increase C drawdown into terrestrial landscapes (Smith et al. 2015; Keesstra et al. 2016; Lal et al. 2021). The balance between C inputs and outputs determines the size of the soil C reservoir (Olson 1963), with the outputs depending strongly on how fast microbes can access and consume organic matter (Schimel and Schaeffer 2012; Wieder et al. 2013). The slower their rate of consumption and release, the longer C persists in soils (Sierra et al. 2018). Scientific clarity on soil C persistence should help to disambiguate debates related to permanence in the climate policy domain. However, another contributing factor in this debate, is that there has not been a way to compute the climate benefits of C in terrestrial ecosystems over time, even when there is a mathematical model for that system, in the same units as GHG emissions are expressed in global warming potentials (GWP).

Currently, the Intergovernmental Panel for Climate Change (IPCC) use annual GHG inventory reporting as the metric of the GHG contribution of ecosystems (Intergovernmental Panel on Climate Change 2006; IPCC 2019). This approach requires reporting of GHG emissions by sources and removal by sinks, but treats all removals equally regardless of their fates over time (Sierra et al. 2021). Other policy frameworks continue to rely on measures of organic C storage and/or annual GHG flux, but do not apply an appropriate accounting mechanism for time and ignores potential effects of disturbance (Anderson-Teixeira and DeLucia 2011; Körner 2017).

Approaches to consider multiple year time frames in valuing the full GHG implication of ecosystems have been put forward, but each remain problematic. For example, the ton-year accounting methods took a first step to address the issue of temporary C storage in valuations for offset markets (Fearnside et al. 2000 and references therein), but they mostly focus on contrasting the warming effects of emissions (fluxes in units of mass per year) to static stocks in ecosystems (units of mass). This inconsistency in units remains problematic and does not reflect the potential impacts of emissions versus sequestrations on the radiative forcing effect of GHG in the atmosphere. Another example is the concept and metric of greenhouse gas value (GHGV), which accounts for storage, flux, and probable disturbance over multiyear timeframes and is sensitive to the timing of emissions (Anderson-Teixeira and DeLucia 2011). These methods effectively track the radiative forcing effects expected due to losses as emissions upon a major disturbance or land use change such as deforestation, and account for all sources from soil organic matter and burning, etc. versus maintenance of the ecosystem through protective measures. However, the metric does not allow for simulation of scenarios that include a valuation of the uptake, or sequestration, of C in soil.

Other recent work that focused on C markets and trading rather than soil processes prioritize valuing time in the contractual agreement at the expense of accurately portraying the biophysical controls on C cycling over time. For example, Leifeld and Keel (2022) oversimplify the biophysical processes that control cycling of C in the ecosystem to permanent versus impermanent soil C. Therefore, the simultaneous emission and uptake calculation presented assumes that all C gained during the contracting period (i.e., "hold time") is lost immediately after it is over, which is not representative of how ecosystems function. Nonetheless, the conclusion that non-permanent soil C sinks can make a significant contribution to cooling is appealing.

We can quantify the degree of permanence of soil C using existing frameworks of soil C stabilization and its persistence. But we need to connect the concepts of permanence and persistence to the amount of warming that is avoided while C is stored in ecosystems, including soils (Fig. 1) to achieve meaningful climate benefits.

Here, we will conceptually and computationally join the policy-oriented concept of "permanence" and biogeosciences-oriented concept of "persistence" to the amount of potential warming that is avoided while C is stored in ecosystems, including soils. The connection is made through the metrics of carbon sequestration (CS) and climate benefit of sequestration (CBS), developed with the aim of assessing the contribution of simultaneous emissions and uptake, from and to C reservoirs, on radiative forcing (Sierra et al. 2021; Sierra and Crow 2021). These metrics are consistent with the concept of global warming potential previously developed to assess the contribution of different GHGs to warming (Lashof and Ahuja 1990; Rodhe 1990). Because different gases stay for different times in the atmosphere after their emission, their contribution to warming depends on how much gas is emitted and how long it remains in the atmosphere. Similarly for the CS and CBS concepts, different ecosystems drawdown different amounts of C and retain it for different amounts of time, thus avoided warming through C sequestration in ecosystems must quantify how much C is stored and for how long. Our new insight is the explicit accounting for how much time new inputs spend in an ecosystem, grounded on process-based understanding of soil C persistence, and the resulting atmospheric response.

The CBS computational structure moves beyond current approaches to allow ecosystems to be treated with different values for C sequestration and help address the issue of permanence more explicitly. Here, we aim to clearly communicate the computation of these benefits using a case study of two agricultural systems in very different bioclimatic zones. We demonstrate how CBS could be used to plan management strategies. Then, we discuss how the computational framework can be deployed to determine whether a nature-based solution will provide meaningful climate benefits on appropriate time frames.

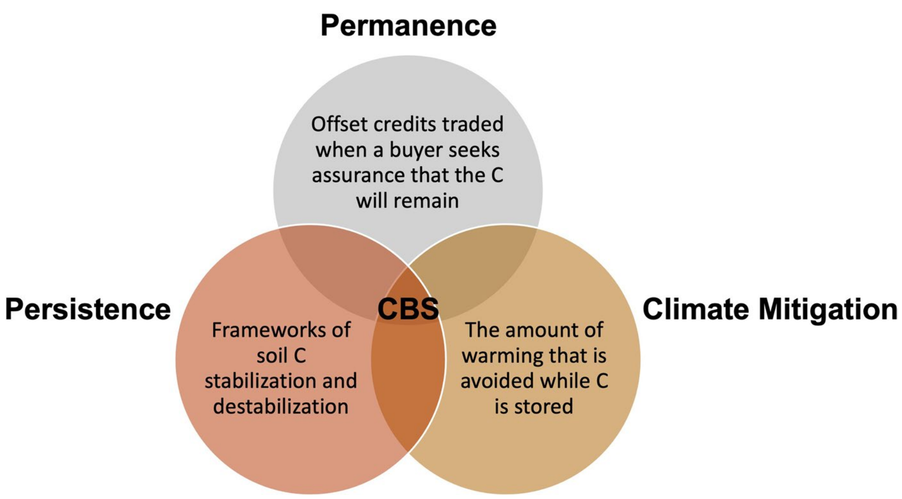

Fig. 1 The climate benefit of sequestration (CBS) metric, which quantifies the radiative effect of removing CO_2 from the atmosphere and retaining it temporarily, connects concepts of permanence, persistence, and the amount of warming that is avoided while C is stored in ecosystems, including soils

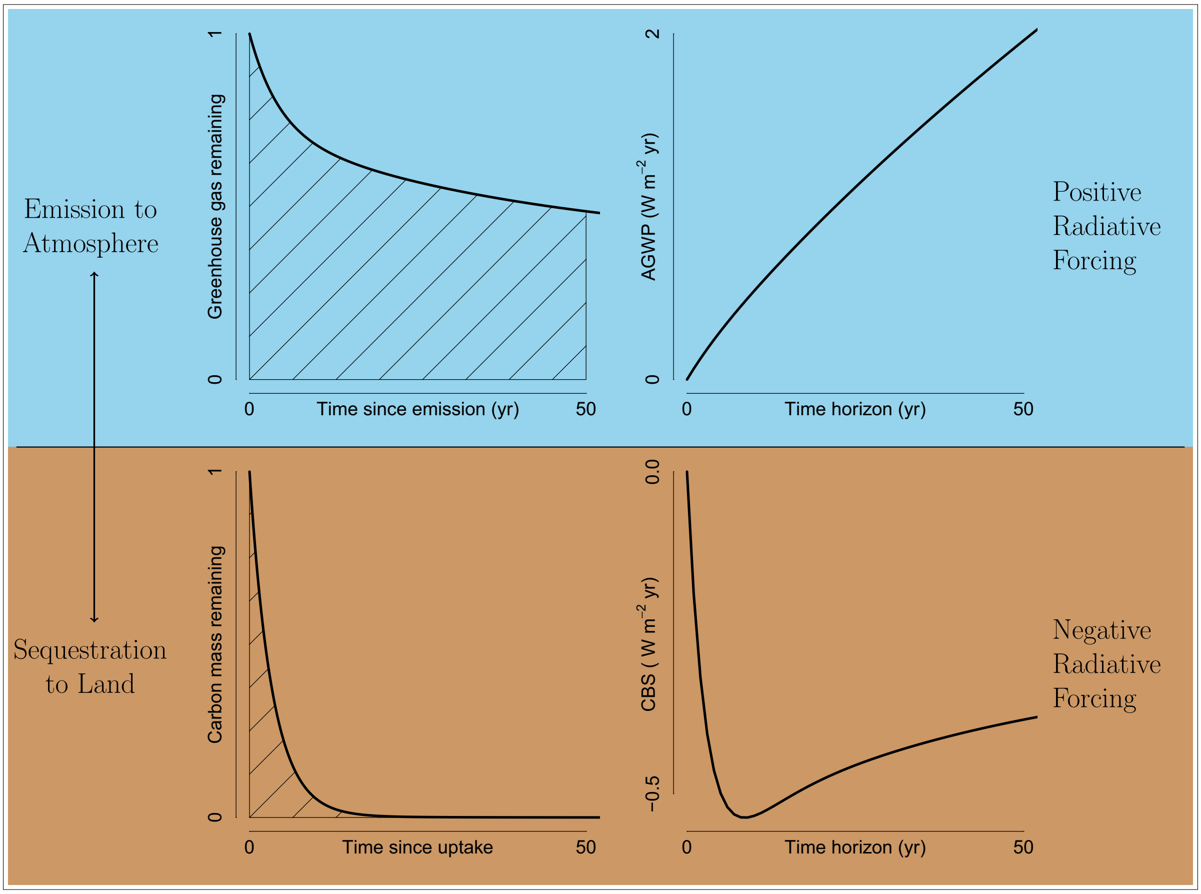

Fig. 2 Conceptual representation of absolute global warming potential (AGWP), carbon sequestration (CS) and climate benefit of sequestration (CBS). The concept of AGWP considers the fate of an emission (e.g., one year of emission is represented in this figure) of a greenhouse gas and computes the area under the curve of the amount of gas remaining after the emission occurs until a certain time horizon of interest. Then, AGWP is computed by multiplying this area under the curve by the radiative effect of the gas during the time it stays in the atmosphere. CS and CBS follow a similar approach; CS is the area under the curve of an amount of sequestered carbon (e.g., 1 year of uptake is represented in this figure) and its fate over time until a certain time horizon. CBS is computed as the radiative effect in the atmosphere of the sequestration pulse. From the point of view of the atmosphere, a sequestration pulse is a negative emission, and therefore CBS is expressed in negative numbers. Note that the units of CS are mass of C per hectare times year. This is because, as an area under a curve, it results from the multiplication of the mass per hectare and time

Computational approach summarized

To better understand the concepts of CS and CBS, it is important to review the concept of absolute global warming potential (AGWP) of an emission. For an amount of emitted C (Fig. 2, upper left), AGWP quantifies potential warming as the area under the curve of the amount of C remaining in the atmosphere for a given time horizon (Fig. 2, upper right). Many people are more familiar with the GWP of multiple greenhouse gases, presented relative to one another in CO_2 equivalents. The absolute value of these are AGWP, and the AGWP of 1 Mg CO_2-C to the atmosphere is 3.4×10^{-10} W m^{-2} year on a 100 year time horizon (Joos et al. 2013). Most CO_2 stays in the atmosphere for 300–1000 years, but some molecules stay shorter and some remain longer (Archer et al. 2009).

A similar approach can be taken to quantify the effects of CO_2 uptake on land. We quantified the area under the curve of an amount of C uptake over a given time frame since the initial uptake (Fig. 2, lower left). We defined this area under the curve as

C sequestration (or CS) because it is a metric that considers both the amount of C uptake and the time it remains stored in an ecosystem. In addition, we computed the amount of avoided warming of C uptake during the time of storage. We called this metric climate benefit of sequestration (or CBS), and it is similar to AGWP, but it considers C uptake as a negative emission that eventually returns to the atmosphere (Fig. 2, upper right). Details on the computational approach and equations are presented in detail in the Online Resource.

CS and CBS can be computed for any ecosystem over any time frame of interest. It only requires a model that describes how C is transferred and decomposed within an ecosystem, expressed in compartmental (matrix equation) form (Luo and Weng 2011; Luo et al. 2017; Sierra et al. 2018, Luo et al. 2022). The approach works regardless of whether there is simple linear model or a complex nonlinear model (Sierra and Crow 2021). AGWP and CBS can be added together to obtain the net climate effect of simultaneous emissions (which are +) and sequestration (which are −) in a particular system. The main insight of the CS metric is that it combines mass of C and the time it remains in soils, therefore directly addressing challenges of quantifying permanence. Every year that some portion of the initial input remains in the soil means that warming may be avoided as a result (and quantified by the CBS computation). The critical aspect is that the user may choose any time frame of interest and sum the areas under the curve for all uptake during that time. We now use a case study approach to demonstrate the computations.

Case study: Hawai‘i and Sweden

We explored the fate of one year's worth of new C inputs in two different agricultural systems, one a managed tropical perennial grass system in Hawai‘i, USA (Fig. 3 left) (Sumiyoshi et al. 2016; Crow et al. 2018; Crow and Sierra 2018) and the other a boreal (cold-temperate, semi-humid) agricultural soil from long term amendment trials in Sweden (Fig. 3 right) (Andrén and Kätterer 1997; Crow et al. 2018). For both sites, simple two or three-pool mathematical models for soil C were previously developed (Andrén and Kätterer 1997; Crow et al. 2018) but a more complex ecosystem model such as CLM or Daycent may also be adapted into matrix forms of the equations if available (e.g., Huang et al. 2018). In a series of experimental sets, we track an annual pulse of new inputs into the case study systems at steady state to effectively demonstrate how long fresh C remains in the different soils, how much warming it avoids while stored, and how this compares to warming produced by emissions of fossil fuels over the same time frame.

CS as a metric computed from any compartmental model, regardless of complexity, is the storage of a certain amount of C input over a time period as it flows through an ecosystem (see Online Resource for the model parameters and equations). The areas

Fig. 3 Experimental tropical managed perennial grass system on a Mollisol soil in Hawai‘i, USA (Crow et al. 2018) (left, photo credit Susan Crow) boreal agricultural Cambisol soils from long term amendment trials in Sweden (Andrén and Kätterer 1997) (right, photo credit Jenny Svennås-Gillner/SLU).

under the curves until a specific time horizon are used to compare how much C has remained until a certain time (e.g., a contracting period). First, we considered the fate of the same amount of input (1 Mg C ha^{-1}) in a tropical perennial grass system on a Mollisol in Hawai'i versus an arable Cambisol in Sweden. Considering one unit of input allows us to focus on differences in C cycling between the soils independent of productivity of the sites. On a 5-year time horizon, more C remained from 1 Mg of C input in Hawai'i than in Sweden, therefore CS was higher for the tropical Mollisol (Fig. 4, top). However, at a 20-year time horizon CS was higher for the Swedish Cambisol. Although one unit of C decomposed relatively fast first in the Swedish soil, because of differences in the processes that control

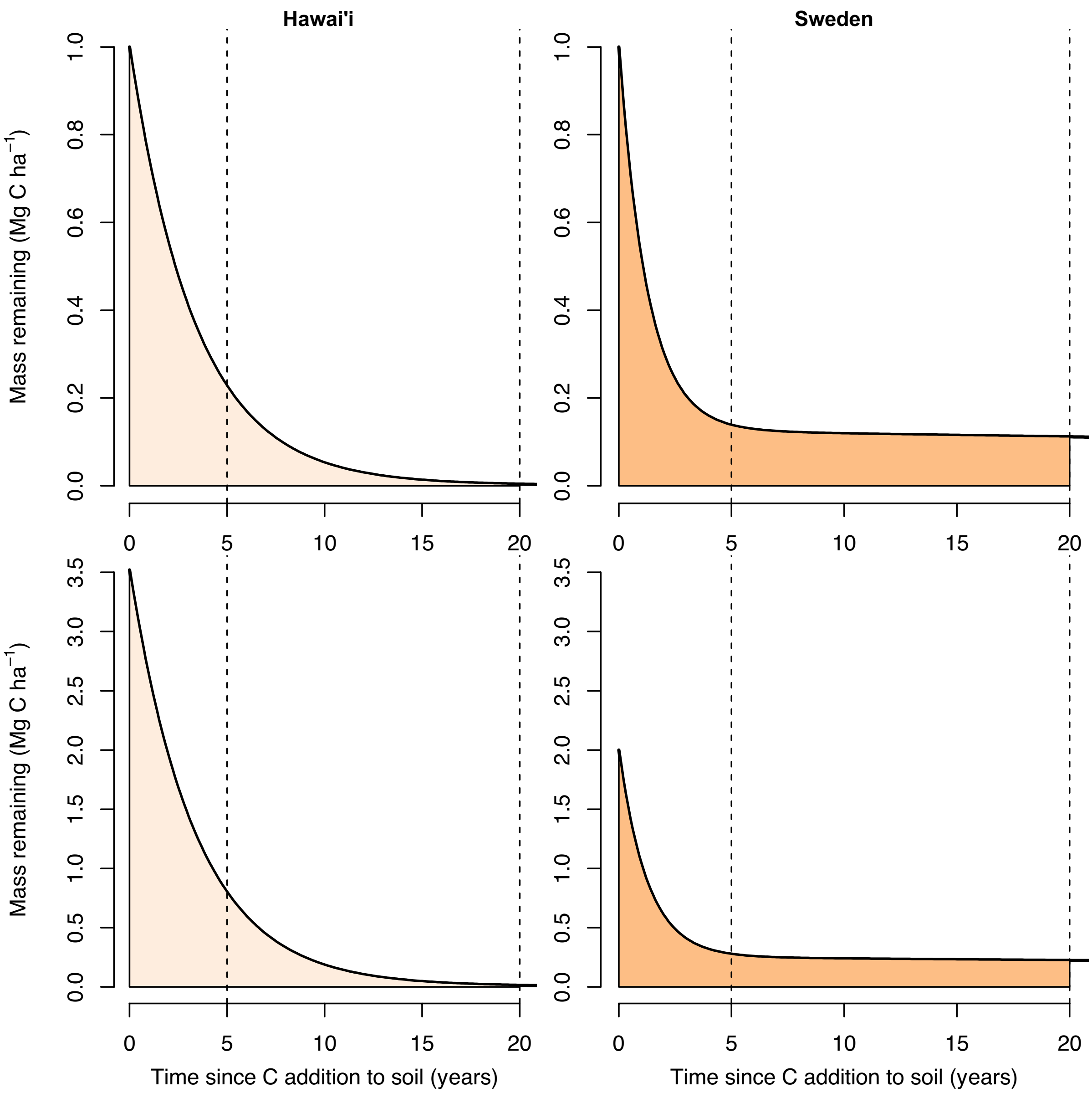

Fig. 4 Carbon sequestration (CS) of one unit of C input (top) or one year of productivity (bottom) over time as it flows through managed ecosystems in Hawai'i (left) and Sweden (right)

organic matter dynamics of the systems, more C remained after 20 years in comparison with the Hawai'i soil.

Then, the differences in plant productivity and C input between the two sites were compared together with the inherent difference in C cycling between the soils. The more productive tropical perennial grasses (annual inputs of 3.5 Mg C ha^{-1} $year^{-1}$) (Crow et al. 2018) had a larger CS for all time horizons compared to the less productive Swedish cropland (annual inputs of 2.0 Mg C ha^{-1} $year^{-1}$) (Andrén and Kätterer 1997). Because soil from Hawai'i has higher inputs (from higher crop productivity), the areas under the curve were higher for Hawai'i at all time horizons shown here. At the 20-year time horizon, CS was 11.9 Mg C ha^{-1} year for the tropical Mollisol, which was more than in the Swedish Cambisol (6.9 Mg C ha^{-1} year). These values are the sum of all the mass remaining in the pools from 1 year pulse integrated over the 20-year time frame. Each year that the C remains in the soil is a year where the potential radiative effects are mitigated, therefore these values increase monotonically with increases in time horizon. In a real soil situation, each annual pulse would be integrated to calculate the stored C over time, thereby providing cumulative potential climate benefit (see example below).

The soil in Hawai'i had almost twice as much CS from one year of inputs on a 20-year timeframe in comparison with the Swedish soil. Notice that the units of CS are mass of C per hectare times year. This is because, as an area under a curve, it results from the multiplication of the mass per hectare and time. Therefore, CS tells us about the amount of C stored over a time period, but it tells nothing about the greenhouse effect the C avoids while stored in soil.

The next step of the computation is the CBS, i.e., the radiative forcing effect avoided by C inputs to the soil stored over a period of time. Because most C that enters the soil returns to the atmosphere as heterotrophic respiration, CBS accounts for the temporary effect of storing C that enters at a particular time and returns to the atmosphere over a time horizon. We demonstrate the utility of this metric by using the productivity-based computation to compare the potential amount of avoided warming between the two soils for different time horizons. Values are negative because the system is pulling CO_2 out of the atmosphere and the more negative the higher the avoided warming and greater the climate benefit.

Our computations revealed that for our case study systems, the tropical soil had a larger climate benefit (or, more negative CBS) on short time horizons under about a decade (Fig. 5, top). On a 20-year time frame, the climate benefit starts to decline. Because inputs are larger in the tropical Mollisol, more warming is avoided for time horizons below ~40 years. But, beyond this time point, the temperate soil has a larger climate benefit. Because a larger proportion (albeit a small amount) of the original input stays in the Swedish Cambisol for a longer time than the tropical Mollisol, CBS is greater in the Cambisol for time horizons longer than 40 years. It is important to note that—as this example is just tracking one pulse of inputs—these curves all go back up to zero eventually. In reality, each year gets a pulse, and it gets summed up over time.

As a next step, we can now make the direct comparison between the radiative forcing effects of

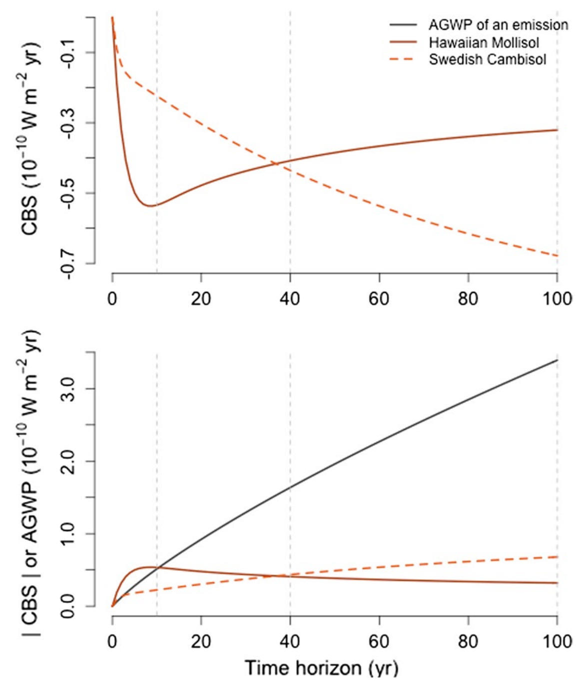

Fig. 5 Climate benefit of sequestration (CBS) of one year of productivity (top) over time as it flows through managed ecosystems in Hawai'i (dark, solid line) and Sweden (light, dotted line). The absolute value of CBS over time compared directly to the absolute global warming potential (AGWP) of one Mg C of CO_2 emission (lower)

emissions and uptake in our case study soils. Generally speaking, the AGWP of CO_2 is much larger for 1 unit of emissions than for one unit of uptake for any timescale because fossil fuel emissions stay for much longer in the atmosphere–biosphere–ocean system (Sierra et al. 2021). The emission of one Mg C to the atmosphere leads to 3.4×10^{-10} W m^{-2} year on a 100 year time horizon; one order of magnitude higher than the potential warming avoided in either soil (Fig. 5, bottom).

The case study demonstrated that new C inputs to the soil do not remain for long timescales, and only small proportions are stabilized to provide warming mitigation using agricultural soils from Hawaiʻi, USA and Sweden as examples. Until now, there hasn't been a way to compute the climate benefits of C in terrestrial ecosystems, even when there is a model for that system, in the same units as GHG's emissions are expressed in global warming potentials (GWP). This series of experimental sets demonstrate how AGWP and CBS can be added together to obtain the net climate effect of simultaneous emissions and sequestration in a particular ecosystem and assists with fundamental policy-oriented questions surrounding permanence and soil C solutions (Table 1).

Computational exercise to demonstrate informed management options

The amount of input is affected by land use and management changes such as deforestation, afforestation, conversion of pasture to conservation, removal of crop residues, etc. The amount of time C inputs remain in the system is also affected by management choices that influence persistence such as site selection for climate/environmental factors or soil mineralogy, application of soil amendment such as biochar. Management decisions that factor in both inputs and persistence can maximize climate change mitigation potential, to the point that the warming benefits of a land-based action can be equal to or greater than emissions avoidance elsewhere. This way, one can select the most promising management techniques to enhance soil carbon at the same level of tackling the paramount issue of reducing fossil fuel combustion (Schlesinger and Amundson 2019).

Table 1 Policy-oriented questions concerning permanence using the CS and CBS computations in our case study soils in Hawaiʻi and Sweden

Question	Metric (unit)	Hawaiʻi	Sweden
How long do new C inputs stay in the soil on average?	Transit time (mean, year)	3.41	21.9
How long does half of the C in new inputs stay in the soil?	Transit time (median, year)	2.33	1.06
How much of one unit of C (1 Mg C ha^{-1}) remains in soil after 5 years?	Mass remaining (proportion)	0.23	0.14
How much of one unit of C remains in soil after 20 years?	Mass remaining (proportion)	0.004	0.11
What is the amount of one unit of C stored over 5 years?	CS-1 unit (Mg C ha^{-1} year)	2.60	1.69
What is the amount of one unit of C stored over 20 years?	CS-1 unit (Mg C ha^{-1} year)	3.38	3.47
What is the amount of ecosystem C inputs stored over 5 years?	CS-productivity (Mg C ha^{-1} year)	9.17	3.39
What is the amount of ecosystem C inputs stored over 20 years?	CS-productivity (Mg C ha^{-1} year)	11.9	6.93
What is the amount of warming mitigated by soil C storage in the ecosystem after 20 years?	CBS-productivity (absolute value, W m^{-2} year)	4.78×10^{-11}	3.03×10^{-11}
What is the amount of warming mitigated by soil C storage in the ecosystem after 40 years?	CBS-productivity (absolute value, W m^{-2} year)	4.08×10^{-11}	4.36×10^{-11}
What is the amount of warming mitigated by soil C storage in the ecosystem after 100 years?	CBS-productivity (absolute value, W m^{-2} year)	3.21×10^{-11}	6.78×10^{-11}

To consider whether we could potentially manage these soils to achieve values of CBS at least as large as AWGP of a unit of emissions, we performed a simple simulation experiment by modifying the decomposition rates of the two pools in the underlying compartmental models. For both soils, CBS was almost insensitive to changes in the decomposition rate of the slow pools because most of the C is lost early after it is added to the soil. Therefore, slowing down decomposition (i.e., it takes longer for the recent inputs to be processed by microorganisms) of the very small proportions of C inputs that can remain for longer time horizons makes no difference in terms of avoided warming. However, we observed important effects of modifying the decomposition rate of the fast pools, which is equivalent to slowing down decomposition of the fresh material before it is lost. In this case, we observed large avoided-warming potentials by slowing the decomposition rate of the fast pools (Fig. 6).

This analysis showed that slowing down the decomposition rate in the fast pool by about a decade in the Hawaiian case study soil may avoid a warming effect larger than the warming effect that could be generated by an emission over the course of a century. In both the Hawaiian and Swedish soils, when decomposition of the fast pool is slowed by a 100th of their original values (C remains on a century timescales), CBS is much larger than AGWP and the avoided warming of the NPP inputs to the soil is much larger than the warming produced by the emission of a ton of CO_2 at all time scales. This shows that managing soil C can be very effective to mitigate the effect of emissions, but efforts should concentrate on avoiding the quick losses from the decomposition of the fast pools. This implies that more C stays for much longer. However, care must be taken in implementing some types of management that may have other unintended impacts. For example, if decomposition of OM from the fast pools is slowed down, there would be less microbial activity and nutrient mineralization, which can negatively impact plant growth in nutrient limited ecosystems.

In this series of experiment sets and computations, the existing C stock was excluded because we focused on the fate of new C inputs for simplicity. Our aim was to provide a rigorous definition of C sequestration: the act of taking CO_2 from the atmosphere and keeping it in an ecosystem or a soil for a defined period of time. It is important to have this definition

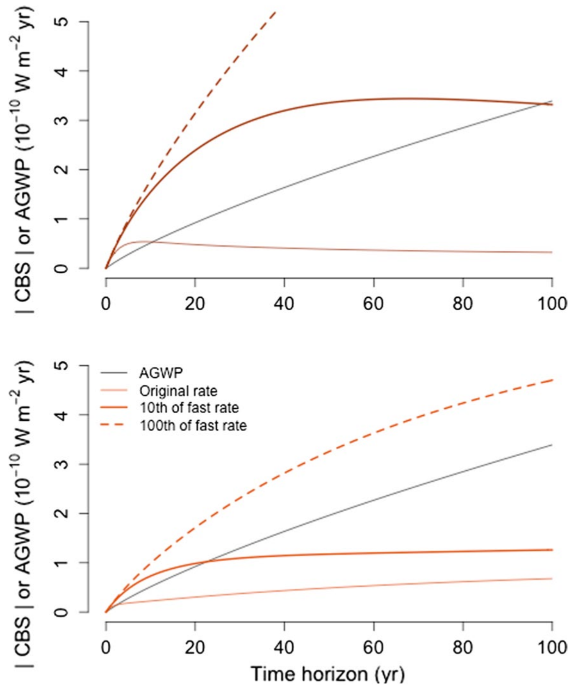

Fig. 6 For the Hawaiian (top) and Swedish (bottom) soils, AGWP (black line) and the absolute value of CBS (light line) obtained from the original productivity-based models. The thick lines represent the simulation in which the fast pool was slowed down by a 10th of its original value, i.e., the decomposition rate of the fast pool multiplied by 0.1, which is equivalent to retarding decomposition by about a decade. The dashed lines are the CBS obtained by multiplying the decomposition rate of the fast pool by 0.01, or, slowing down decomposition of this pool by a century

because previous approaches did not take into consideration the time new C is stored in an ecosystem and instead focused mostly on quantifying the effects of emissions from ecosystems. In this sense, these previous approaches provide an appropriate framework to quantify the effect of emissions of existing carbon stocks. For example, to quantify the value of conserving standing C stocks in ecosystems, an avoided emissions framework provides the best approach to quantify the effect of decomposition of existing carbon. The framework provided by Anderson-Teixeira and DeLucia (2011) is an example of an approach that is perfectly suitable for this application. However, this framework does not account for the fate of new inputs and for how long they stay in an ecosystem being restored or put into an improved practice. The CBS concept (not CS) as defined here can address the simultaneous effects of emissions and sequestration. One can add the effect of emissions from standing C stocks and balance it with the effect of new inputs, and then quantify the atmospheric response in terms of radiative forcing. The existing soil C maybe added into the computational structure if desired. Mostly this change would increase the amount of C in respiration going back to the atmosphere; however, the amount respired from existing soil pools is small relative to losses from the new inputs, particularly from autotrophic respiration. An example of this case could be found in Sierra et al. (2021).

Exploring changes in steady state conditions allows us to understand the dynamics of soil C including transit time of new inputs and how that affects total C storage. Critically this is the starting point for assessing how a system might change with disturbance or land use/management change. This starting point is dependent on the system of interest and any potential management strategy under consideration. It is also important to establish the analog steady state in an undisturbed or restored system to understand the potential gains/benefits if an implementation is undertaken.

Transient, non-steady states in between the current and desired outcome are also important. The CS and CBS computational framework allows running dynamic simulations to better understand how long it may take and along what trajectory the system will follow to reach a desired, improved state. Implementation contracts will require this transient state computational prediction to know how much climate benefit will be achieved because of the contractual action. For example, assume you have a degraded agricultural system where you want to change from conventional tillage to zero-tillage ratoon harvest management (e.g., Crow et al. 2020). If a 20-year contract is desired, you would need to understand how much of the new C inputs will stay as a result of the alternative management system.

For non-steady-state cases with transient accumulation of C, the approach to computing CS and CBS is to consider a series of individual pulses (Fig. 7). The areas under the curve of each pulse accumulate the amount of C and the time it is retained in an ecosystem, providing a comprehensive quantification of CS that can reveal important differences between ecosystems or management strategies. In our case study, we can see how the individual pulses for the soil in Hawai‘i tend to reach a maximum faster than the soil in Sweden, mostly due to the differences in inputs and soil processes controlling decomposition and C cycling between the two soils. For time horizons of 20, 40, and 100 years, CS for the soil in Hawai‘i would be 203.3, 442.0, and 1160.8 Mg C ha^{-1} year, respectively. For the soil in Sweden, CS under continuous inputs would be 92.7, 276.3, and 1265.9 Mg C ha^{-1} year for time horizons of 20, 40, and 100 years, respectively. Notice that in the short term, CS is higher during the first 40 years in Hawai‘i while at longer time horizons CS is higher in Sweden.

A similar non-steady-state computation can be performed for CBS. For time horizons of 20, 40, and 100 years, CBS in Hawai‘i was estimated as -0.9, -1.8, and -3.9×10^{-9} W m^{-2} year, respectively. For the soil in Sweden, CBS was estimated as -0.4, -1.2, -4.6×10^{-9} W m^{-2} year respectively. Again, the climate mitigation potential for the soil in Hawai‘i is more important in the short term than for the soil in Sweden, but the roles reverse for longer time horizons (> 80 year).

Our case study shows how CDR and storage in soils is amenable to timeframes suitable for contracting periods of implementation (permanence) and represents the biophysical soil processes controlling decomposition and stabilization (persistance) of C inputs to the ecosystem. In Hawai‘i, a short contract period (e.g., 20 years) achieves maximum climate benefits, while longer periods do not have a marginal increase in benefits. In Sweden, longer contracting terms are required (~ 80 year) to achieve equal climate benefits in soil than in Hawai‘i.

These examples show how CS and CBS integrate biogeochemical understanding of soil carbon persistence with the policy-related concept of permanence. By selecting specific time horizons where known amounts of inputs stay for a known amount of time, less ambiguous contractual agreements can be developed in carbon trading markets. In particular, CBS can more directly estimate the temporary nature of C storage in natural reservoirs and can be contrasted with warming potential of emissions. It builds on the well-established framework of global warming potentials and allows comparisons of different management strategies in different ecosystems with different levels of productivity and soil carbon persistence.

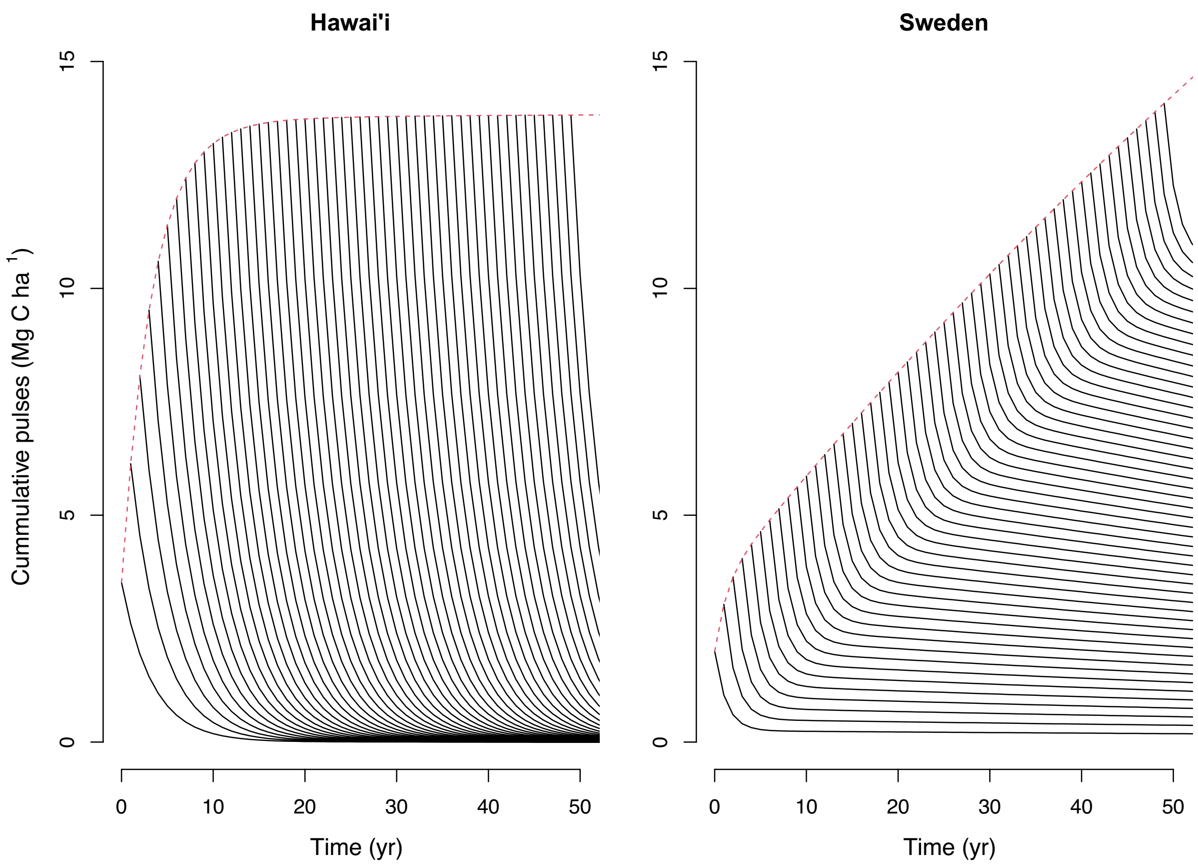

Fig. 7 Example of a trajectory of accumulated annual pulses for the two study case soils. In each case, the areas under the curve of individual pulses can be summed over the time period of interest to obtain CS. Similarly, the individual values of CBS obtained for each pulse can be summed over the period of interest. For this example, the soil in Hawai'i reaches a steady-state faster because decomposition is fast, while the Swedish soil continues accumulating carbon pulses after a 50 year time period because of the slow decomposition of the carbon pulses

Conclusion

Even though temporary storage in ecosystems has the potential to decrease peak warming if aggressive emission reductions are also pursued simultaneously (Matthews et al. 2022), soils are not yet included in nature-based climate solution policies and economic incentives (Smith et al. 2015; Amelung et al. 2020). Now, we have a computational framework to represent soils in a more accurate way and reduce uncertainty about how much and for how long C may remain in soil. This framework quantifies the climate benefit, specific to each system and adaptable to different models (simple or complex) available for a location regardless of scale. Further, there is often a need to directly compare the benefit of CDR to that of direct emission avoidance elsewhere in a system. CS allows you to compute how much carbon remains and for how long it stays in a soil. CBS allows you to assess how radiative forcing in the atmosphere responds to C drawdown and release in natural and managed lands. Then, CBS can facilitate direct, detailed comparisons of potential climate change mitigation and tradeoffs (e.g., soil C sequestration in improved management strategies, avoided import of food and fertilizer in a sustainable food system, and all aspects of bioenergy/fuel production and fossil offsets). Thus, geopolitical units and institutions may add rigor and clarity to their net-zero targets (Rogelj et al. 2021).

The CBS computational framework provides a critical missing piece that quantifies climate benefits of sequestration alongside avoided emissions within complex systems. Food systems account for 1/3 of global emissions, with energy and transportation accounting for most of the rest (Crippa et al. 2021). This computational advance is critical to achieving multiple sustainability goals that include the food and energy sectors (Lal et al. 2021). Many soils will not achieve marketable levels of warming benefits from sequestration, but some will, especially in ecosystems with high productivity with potential to slow down decomposition through management. More importantly, with implementation of climate-smart practices and land-management decisions comes a multitude of co-benefits to the environment and society (including soil health, reduced dependance on imports, clean water, and local jobs) (Smith et al. 2015; Adhikari and Hartemink 2016; Amin et al. 2020). Investments back into the community build viable social-ecological-economic systems (Löbmann et al. 2022) that policy and incentives programming can support (Amelung et al. 2020).

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Data availability Original study data may be found in the references cited for each site, code for the analysis presented here may be downloaded at https://doi.org/10.5281/zenodo.6861402.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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