



Photosynthetic limits on carbon sequestration in croplands

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ABSTRACT

How much C can be stored in agricultural soils worldwide to mitigate rising carbon dioxide (CO₂) concentrations, and at what cost? This question, because of its critical relevance to climate policy, has been a focus of soil science for decades. The amount of additional soil organic C (SOC) that could be stored has been estimated in various ways, most of which have taken the soil as the starting point: projecting how much of the SOC previously lost can be restored, for example, or calculating the cumulative effect of multiple soil management strategies. Here, we take a different approach, recognizing that photosynthesis, the source of C input to soil, represents the most fundamental constraint to C sequestration. We follow a simple “Fermi approach” to derive a rough but robust estimate by reducing our problem to a series of approximate relations that can be parameterized using data from the literature. We distinguish two forms of soil C: ‘ephemeral C’, denoting recently-applied plant-derived C that is quickly decayed to CO₂, and ‘lingering C’, which remains in the soil long enough to serve as a lasting repository for C derived from atmospheric CO₂. First, we estimate global net C inputs into lingering SOC in croplands from net primary production, biomass removal by humans and short-term decomposition. Next, we estimate net additional C storage in cropland soils globally from the estimated C inputs, accounting also for decomposition of lingering SOC already present. Our results suggest a maximum C input rate into the lingering SOC pool of 0.44 Pg C yr⁻¹, and a maximum net sequestration rate of 0.14 Pg C yr⁻¹ – significantly less than most previous estimates, even allowing for acknowledged uncertainties. More importantly, we argue for a re-orientation in emphasis from soil processes towards a wider ecosystem perspective, starting with photosynthesis.

1. Introduction

“How many piano tuners are there in Chicago?” Enrico Fermi famously posed this question to illustrate how seemingly intractable problems can be resolved, crudely but reliably, by parsing them into a series of estimable entities (Von Baeyer, 1993). The population of Chicago was then about three million, he said; if average family size was four, and one in three families had pianos, the city had about 250,000 pianos. Assuming that pianos were tuned every five years, and each tuner serviced four pianos per day for 250 days each year, then Chicago must have about 50 tuners.

Ecology has many such “Fermi problems”, seemingly impenetrable quandaries for which inventive back-of-the-envelope algorithms can be instructive (Harte, 1988; Weinstein and Adams, 2008). A notable example in soil science today is the amount of carbon (C) that could be

withdrawn from the atmosphere by adopting soil C-building practices on croplands globally (Lal, 2019). Clearly, defensible estimates of achievable C gains would inform policies urgently needed to reduce the serious buildup of atmospheric CO₂: if soils can be induced to mop up a large fraction of fossil C-derived CO₂, then assertive policies promoting this avenue are warranted (Zomer et al., 2017); conversely, if augmented stores of persisting C are modest relative to emissions, then such policies may distract from more effectual strategies (Schlesinger and Amundson, 2019).

1.1. Past approaches for estimating global C sequestration potential in soils

Potential soil C sequestration rates have been estimated in several ways. One approach, perhaps the simplest Fermi computation, is to

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assume that existing C stocks can be incrementally increased by a constant fraction per year (Approach 1, Table 1). For example, the widely-publicized “4 per 1000” initiative proposed that “An annual growth rate of 0.4% in the soil carbon stocks ... in the first 30 to 40 cm of soil, would significantly reduce the CO₂ concentration in the atmosphere ...” (<http://www.4p1000.org/>). If applied only to agricultural soils (not to all soils), it would “effectively offset 20–35% of global anthropogenic greenhouse gas emissions” (Minasny et al., 2017), although underlying assumptions in this estimate have been questioned (De Vries, 2018; VandenBygaart, 2018; White et al., 2018). Zomer et al. (2017), using a slightly modified approach from Sommer and Bossio (2014), estimated that soil C sequestration in croplands worldwide could amount to 0.90 to 1.85 Pg C yr⁻¹, or 26 to 53% of the “4 per 1000” target. Although commendably straightforward, the “4 per 1000” approach begs the question: Does this rate – 0.4% per year – have any empirical foundation? And is it reasonable to assume, as this approach implies, that absolute C gain per ha will be greater in soils already high in C (Batjes, 2019; Franko and Ruehlmann, 2018)? Perhaps for these reasons, the ‘4 per 1000’ value has increasingly been framed more as ‘aspirational target’ than as quantitative estimate (Amelung et al., 2020; Minasny et al., 2018; Soussana et al., 2017).

A second approach, among the earliest, is to estimate potential soil C gains based on partial recovery of soil C previously lost (Approach 2, Table 1). Cole et al. (1996, 1997), for example, proposed that if half to two thirds of historical losses (about 55 Pg C) could be recovered over 50–100 years, then soil C sequestration would amount to 0.4 – 0.6 Pg C yr⁻¹ for 50 yr. Recent studies propose that cumulative soil C losses have exceeded 100 Pg C (Lal, 2018; Sanderman et al., 2017b), implying greater potential for C gain using this approach. But projecting future gains from past losses poses several questions: Is the pre-cultivation C stock a defensible measure of maximum C storage under conditions and land use vastly different from those under which the soils developed? Can we know reliably the amount of soil C lost, since original soil C was never measured? And how do we estimate the fraction of past losses that can realistically be restored (Powlson et al., 2022)?

In a third approach (Table 1), potential C sequestration is estimated

Table 1

Summary of mathematical approaches to estimate potential rate of soil C gain in cropland soils globally.

Approach	Equation	Examples
1	$C_r = S * F_s$ <p>where: C_r = C sequestration rate (Pg C yr⁻¹); S = global C stock (Pg C) F_s = fractional increase in C_r (Pg C Pg C⁻¹yr⁻¹)</p>	https://www.4p1000.org/ ; Minasny et al. (2017)
2	$C_r = L * F_L / t$ <p>where: C_r = C sequestration rate (Pg C yr⁻¹); L = accumulated loss of global C stock (Pg C) F_L = fraction of past loss recoverable (Pg C / Pg C) t = time over which recovery occurs (yr)</p>	Cole et al. (1996, 1997)
3	$C_r = \sum_{i=1}^n \sum_{j=1}^m (A_{ij} * r_{ij})$ <p>where: C_r = C sequestration rate (Pg C yr⁻¹); A_{ij} = area of adopted C-conserving practice i (10⁹ ha) in region j r_{ij} = C sequestration rate for practice i (Mg C ha⁻¹ yr⁻¹) in region j</p>	Smith et al. (2007, 2008)

using complex bottom-up calculations, wherein predicted responses to individual C-promoting practices (Mg C ha⁻¹ yr⁻¹) are multiplied by the potential area (ha) over which such practices can be applied. One such calculation yielded a technical potential of about 1.3 Pg C yr⁻¹ on agricultural lands globally, of which 0.4 – 0.7 Pg C yr⁻¹ was estimated to be economically feasible (Smith, 2008; Smith et al., 2007). Paustian et al. (2016) elevated these estimates, by including additional potential gains from enhanced inputs of root-derived C (about 0.3 Pg soil C yr⁻¹) and biochar (about 0.4 Pg C yr⁻¹). More recently, Lal (2018) proposed a ‘technical potential’ on arable lands of 0.5 to 1.2 Pg C yr⁻¹ with additional amounts on degraded lands and on lands under pasture, permanent crops, or urban management for a total of 1.45 to 3.44 Pg C yr⁻¹. Such bottom-up estimates, however, are almost intractably complex, with expected C gains from individual practices prohibitively uncertain. To cite one example: reduced tillage is among the most widely-advocated options for sequestering C on croplands throughout the world (Bruce et al., 1999; Minasny et al., 2017; Pacala and Socolow, 2004; Post et al., 2004; Smith et al., 2007; Sperow, 2016; Thomson et al., 2008; World Bank, 2012; Zhang et al., 2014; Zomer et al., 2017). But despite decades of research, questions remain about the extent to which such practices actually increase soil C stocks rather than merely rearranging C in the soil profile (Angers and Eriksen-Hamel, 2008; Baker et al., 2007; Chatterjee, 2018; DeLuca and Zabinski, 2011; Manley et al., 2005; Meurer et al., 2018; Paustian et al., 2016; Powlson et al., 2014). For no-till and all other C-conserving practices, rates of soil C gain are highly variable, reflecting complex interactions of land history, soil properties, climatic conditions, and agronomic setting (Virto et al., 2012; Yang et al., 2013). Notably, soil C gain is not a function of the current practice alone, but rather of the *change* in practice and therefore depends on land use history. Thus, for example, land now under no-till practices might be *gaining* C if recently converted from a degradative system (Nicoloso et al., 2020), but might be *losing* C if recently converted from grassland (DuPont et al., 2010). To estimate C gains, therefore, it is not enough to know the area of land under given practices; you also need to know the preceding practices, and how long the new practice has been in place, because any C accrual wanes with time (Poulton et al., 2018). And when multiple practices are implemented together, their effects are not always additive, but subject to inscrutable interactions (Alhameid et al., 2017; Triberti et al., 2016). Predicting global C gains via this approach therefore involves staggering complexity with commensurate uncertainty.

1.2. Input of photosynthetically-derived C as primary driver of soil C change

The preceding approaches are soil-focused, implying that C sequestration is dictated by the capacity of soil to store additional C. But soil C storage is a product of the entire ecosystem, not of soil processes alone; indeed, it is plants, not soils, that pull CO₂ from the air. For a given area of land, net storage of atmospheric C in soil is the difference between input to soil of C from photosynthesis on that land and loss of C as CO₂ or CH₄ from biotic metabolism of accumulated C (including respiration of re-located C in erosional deposits or leachates):

$$\Delta C_{\text{soil}} = C_i - C_m \quad (1)$$

where:

ΔC_{soil} = change in soil C storage (Mg C ha⁻¹yr⁻¹).

C_i = input of C to soil from photosynthesis occurring on that land area (excluding input of imported C from photosynthesis elsewhere)

C_m = losses of C to atmosphere via metabolism (mostly CO₂), including respiration of C translocated via erosion or leaching. Soil C

eroded or leached from a given unit of land but stored elsewhere is not lost to the atmosphere.

The primary driver of soil C gain, therefore, is input of photosynthetically-fixed C from net primary productivity (NPP). Rate of decay (C_m), of course, also affects net soil C change, but it generally follows C input: as C stocks build with higher C input, microbial activity tends to intensify in response so that, in time, rates of C loss and gain converge and C stocks reach a quasi-steady state. An increase in soil C stock, therefore, simply reflects the temporary lag between plant-derived C inputs and the eventual catch-up of the slowly-accelerating decay rate (Odum, 1969). Management can influence rate of decay temporarily – for example, reducing tillage may slow decay in semi-arid lands by suspending residues in desiccated layers (Helgason et al., 2014) – but as available C accumulates, decay eventually catches up to input.

Not surprisingly, therefore, early studies showed a strong linear relationship between plant-derived C input and management-induced changes in soil C content (Larson et al., 1972; Paustian et al., 1992). A sampling of recent studies confirms that this direct relationship holds in diverse settings throughout the world (Table S1). For example, in a comprehensive review of soil C dynamics in tropical croplands (214 cases in 48 studies in 13 countries), Fujisaki et al. (2018) concluded that “the SOC accumulation rates increased linearly with C inputs, and the conversion rate of C inputs to SOC was $8.2 \pm 0.8\%$ ”.

Although soil properties such as texture and mineralogy affect C retention by influencing stabilization processes (Krull et al., 2003), such mechanisms are evidently subservient to the dominant effects of C inputs. According to some hypotheses, soils may reach ‘saturation’, beyond which soil C stocks are no longer responsive to variations in residue input (Chen et al., 2019; Stewart et al., 2007), but this typically occurs only at C concentrations exceeding those in most cropland soils. In an oft-cited example, Campbell et al. (1991) found no significant relationship between estimated residue C input and C stocks, but the soil already had high C reserves (61 to 67 Mg C ha⁻¹ to 0.15 m), perhaps concealing small responses. A recent modeling study (Martin et al., 2021) concluded that approximately 95% of croplands in France are unsaturated. In the end, regardless of the protection of organic substrate by a soil, any increase in soil C depends ultimately on how much photosynthetically-derived C is added. Even ‘stabilized’ C is not perfectly inert, and is subject to gradual decay (Parton et al., 1988).

The substantial loss of soil C after converting natural ecosystems to cropland – the alleged gap available for future ‘sequestration’ (in Approach 2; Table 1) – largely reflects the sharply-reduced inputs of biotic C to soil (Crews and Rumsey, 2017; Janzen, 2004; McLauchlan, 2006; Nyawira et al., 2017). In ‘natural’ ecosystems, most of the C trapped by photosynthesis – about 90% – escapes herbivory and fire (Coleman et al., 2004; Gessner et al., 2010), eventually reaching the soil where it quickly decays, leaving behind the persisting remnants that comprise the bulk of soil organic matter. In croplands, by comparison, a large fraction of the NPP is harvested and exported from the system (Barnosky et al., 2012); that, after all, is the point of farming: to direct photosynthate into products for use elsewhere. The impressive yield increases in cereals in recent decades, for example, have been achieved largely by improving harvest index, the fraction of above-ground biomass destined for harvest (Parry et al., 2011). Typically, now, about one third of total NPP is removed from the ecosystem (Bolinder et al., 2007). Furthermore, croplands usually have lower NPP than ‘natural’ ecosystems despite agronomic developments in recent decades (Haberl et al., 2002; Krausmann et al., 2013). With lower total NPP, of which a large share is removed, return of biomass C to soil is much lower in croplands than in the systems they replaced, leading inevitably to lower soil C stocks. Therefore, merely re-tuning practices in a system fundamentally designed for massive C removal seems unlikely to restore the substantial troves of C once lost.

The main factor preventing restoration of SOC lost in croplands is not constraints in soil properties but limits in C input dictated by necessary

removal of plant C (Bruni et al., 2021; Riggers et al., 2021). With burgeoning demands for food, fiber, and fuel, a large share of NPP from croplands must be exported. Removal of crop residues has approximately tripled in the last century (Krausmann et al., 2013), a trend unlikely to be reversed, given expanding demands for biofuel and other uses (Cherubin et al., 2018; Karlen et al., 2015; Karlen and Johnson, 2014). Thus, C stocks will likely never approach pre-cultivation levels on many croplands, regardless of the efforts to store more C in soil, so that pre-cultivation C stocks are a dubious benchmark for potential re-accumulation (Approach 2, Table 1) (Poulton et al., 2018). Similarly, the estimates of soil C accrual based on improved practices (Approach 3, Table 1) will remain elusive without enhanced plant-derived C return to soil. Merely dampening decay of existing reserves cannot compensate for the relentless siphoning of plant C to urgent uses outside the ecosystem. In short: if we are to increase soil C stocks, where will the additional C come from?

2. An alternative: estimating potential C sequestration from plant C inputs

As an alternative to earlier approaches, we propose that management-induced gain in soil C can be roughly estimated from amounts of photosynthetically-derived C available to replenish soil organic matter. In this approach, we distinguish two forms of soil C: ‘ephemeral C’, denoting recently-applied plant-derived C that is quickly decayed to CO₂, and ‘lingering C’, which remains in soil long enough to serve as lasting repository for atmospheric C. Much of the ‘lingering’ C may be comprised of microbial necromass, stabilized by interaction with soil minerals (Liang et al., 2020) (we use ‘lingering’ in place of ambiguous terms such as ‘recalcitrant’ and ‘stable’, which erroneously imply a pool that is inherently inert or refractory (Kleber, 2010)). ‘Ephemeral C’ consists of incompletely-processed plant debris and accounts for much of the short-term fluctuations in soil C; it is quickly replenished but just as quickly depleted. Because this fraction turns over quickly, releasing nutrients and energy, it is crucial for soil productivity and biodiversity but it cannot be a reliable, enduring storehouse for excess atmospheric C. It is ‘lingering’ C that we hope to augment as a store of excess atmospheric CO₂.

On the premise that building enduring soil C is fundamentally a function of C inputs, potential C sequestration in cropland soils globally can be approximated using the following two simple steps (Fig. 1):

Step 1: Estimate net C inputs to ‘lingering’ soil organic matter.

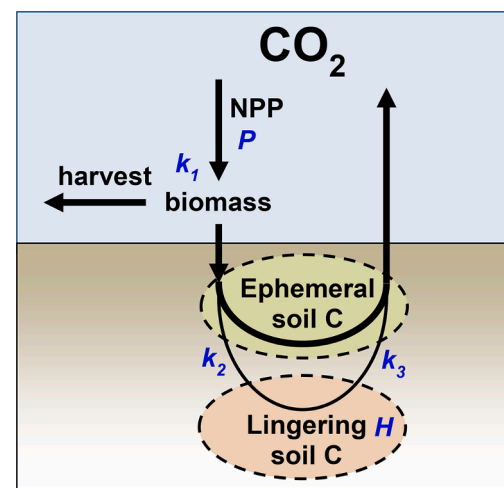


Fig. 1. Schematic overview of carbon flows in agroecosystems, depicting pools and coefficients used in our approach to estimate annual change in global carbon stocks in cropland soils, as presented in Equation [3].

Table 2

Estimated parameters for our approach, as used in Equations 1–4 as well as in our Monte Carlo simulation (Fig. 2, Suppl. Fig. 1). For rationale and references, see description in text.

Parameter	Description	Unit	Estimate	s.d.	Limits
P	Global net primary productivity	Pg C yr ⁻¹	5.25	0.46	> 0
k ₁	Net fraction of NPP exported	Pg C Pg C ⁻¹	0.44	0.044	0–1
k ₂	Fraction of added plant C that persists in soil for >5 yrs	Pg C Pg C ⁻¹	0.15	0.015	0–1
H	Global stock of soil C in croplands (0–30 cm)	Pg C	140	14	> 0
R	Mean residence time	yr	500	200	> 0

$$C_{iL} = P * (1 - k_1) * k_2 \quad (2)$$

where:

C_{iL} = net C input to ‘lingering’ soil C (Pg C yr⁻¹). ‘Lingering C’ here refers to plant-derived C which persists in soil for > 5 years.

P = net primary productivity on all cropland, globally (Pg C yr⁻¹)

k_1 = net fraction of NPP exported (Pg C exported / Pg C NPP). ‘Exported’ C refers to C in harvested products not returned to cropland, directly or indirectly (e.g., in manure)

k_2 = fraction of added plant C that persists in soil for > 5 yrs (Pg C retained / Pg C added)

The three parameters in equation [2] can be readily approximated from the literature. Estimates of annual net photosynthesis (P) on croplands globally vary somewhat, but typically amount to about 10% of global terrestrial NPP. A rigorous recent study estimated global cropland NPP to be 5.25 ± 0.46 Pg C yr⁻¹, including below-ground C (Wolf et al., 2017; Wolf et al., 2015). This is the amount of C removed annually from the atmosphere by photosynthesis in all croplands worldwide, and represents the source of new soil C.

A large share of the NPP, however, is removed from croplands and quickly respired or combusted back to CO₂ (Poeplau et al., 2017). According to Wolf et al. (2015), about 2.59 Pg C is removed annually from croplands, 2.05 in products and 0.54 in residues. Some of this, however, is returned to cropland in manure. We estimate, based on Wolf et al. (2015) and discussions with Oene Oenema, that manure production from cropland harvest is about 0.4 Pg C yr⁻¹. Allowing for storage losses and other uses for manure, we assume manure C recycled to cropland globally is about 0.3 Pg C yr⁻¹. Thus, net removal is about 2.29 Pg C yr⁻¹, k_1 is approximately 0.44, and annual return of photosynthetically-derived C to croplands is about 2.96 Pg C yr⁻¹.

Plant residue added to soil is transient and most of its C is quickly returned to CO₂. Studies using isotopic tracers find consistently, across different climates and soils, that about 80 to 90% of added C is lost from soil within a few years of application. For our approximation, we assume that 15% of the added litter C is ‘lingering’, remaining in soil for >5 years ($k_2 = 0.15$). The use of 5 yrs duration is arbitrary, but recovery of applied C generally follows 1st-order kinetics, with rapid initial decay, waning after several years (Gregorich et al., 2017; Jenkinson and Ayanaba, 1977). Thus, plant-derived C retention changes only slowly after 5 years; for example, C recovery is not much less after 10 years than after 5 years.

Based on these assumptions, the net C input to ‘lingering’ soil organic matter in croplands (C_{iL} in equation [1]) is about $5.25 * (1 - 0.44) * 0.15 = 0.44$ Pg C yr⁻¹ (Table 2). As with all Fermi solutions, this estimate is approximate, and carries a significant confidence interval. But it seems unlikely, based on simple Monte Carlo simulation, that reasonable coefficients in Equation [1] would yield estimates much > 0.6 Pg C yr⁻¹ (Suppl. Fig. 1).

Step 2: Account for turnover of C previously stored in soil.

Our estimate (0.44 Pg C yr⁻¹), however, represents an unattainable upper bound of potential soil C sequestration because it does not yet account for the slow decay of previously-stored ‘lingering’ C; that is, equation [2] assumes that C already stored in soil is inert. To illustrate how the decomposition of this indigenous soil C further limits net SOC gain, we can append an additional term, which crudely estimates its gradual turnover:

$$C_g = C_{iL} - H * k_3 \quad (3)$$

$$= [P * (1 - k_1) * k_2] - (H * k_3) \quad (4)$$

where:

C_g = net annual gain in global soil C stocks on croplands (Pg C yr⁻¹)

H = global stock of soil C in cropland soil (Pg C to 30 cm), conservatively assumed to be all ‘lingering C’

k_3 = fraction of SOC stock decayed per yr in surface 30 cm (Pg C decayed yr⁻¹ Pg SOC⁻¹)

$$= 1/R$$

where R = mean residence time (MRT) of C in surface 30 cm (years).

The C stock of all cropland soils is about 140 Pg C to a depth of 30 cm (Zomer et al., 2017). Additional amounts occur at lower depths, but this C turns over only slowly (Balesdent et al., 2018), and can be assumed (erring on the side of over-estimating net sequestration) to be almost inert on scales of years to decades. The mean residence time (MRT) of C in surface soil varies widely, depending on climate, soil properties, soil depth, organic matter composition, and how MRT is defined (Baisden and Parfitt, 2007; Balesdent et al., 2018; Chen et al., 2013; Mills et al.,

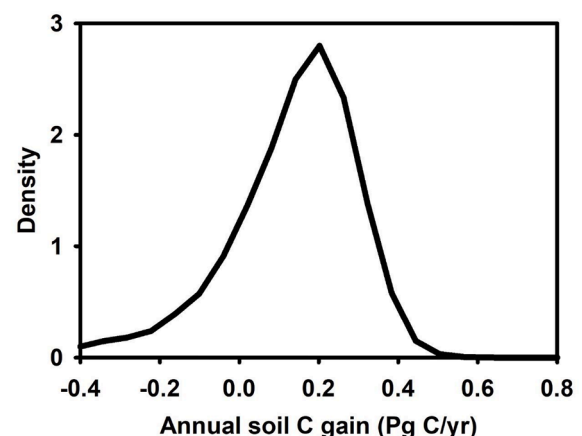


Fig. 2. Distribution of annual C gain (C_g) estimates from Monte Carlo analysis of Equation [4]. The X-axis was truncated to eliminate very small density values for $x < -0.4$ and $x > 0.8$. For parameter estimates see Table 2, for a detailed explanation of the Monte Carlo analysis, see the Supplementary Information.

2014; Paul, 2016; Sierra et al., 2018; Trumbore, 1993). Chen et al. (2013) estimated a MRT of the global C pool of 21.0 to 23.2 years for the 1960 to 2008 period, but that was for a depth of 20 cm; the MRT of the C in the 0–30 cm layer is likely longer, owing to increasing residence time with depth (Balesdent et al., 2018).

By definition, the MRT of ‘lingering’ C equals total stock (Pg C) divided by the annual rate of decay (Pg C yr⁻¹) (Carvalhais et al., 2014). If the ‘lingering’ C stock is at steady state (i.e., annual decay = annual input), then MRT of this ‘lingering’ C is equal to C stock divided by annual input. Assuming for simplicity that C stock of ‘lingering’ C is 140 Pg C (Zomer et al., 2017) and input to ‘lingering’ C is 0.44 Pg C yr⁻¹, then MRT = 140 Pg C / 0.44 Pg C yr⁻¹ = 318 years. The actual value will be slightly smaller because a small portion of global C stocks at any given time is composed of ‘ephemeral’ C.

To estimate annual indigenous soil C turnover, we assume a MRT of 500 years, longer than that of most measured values, both to err on the side of over-estimating possible soil C gain and to allow for any slowing of decay through adoption of practices such as no-till. Then, if the total organic C stock of cropland soil to 30 cm depth = 140 Pg C (Zomer et al., 2017), annual loss of ‘lingering’ soil C amounts to about 0.3 Pg C yr⁻¹, and potential soil C sequestration in cropland soils world-wide is in the order of about 0.44 – 0.3 = 0.14 Pg C yr⁻¹ (Fig. 2). The relationship between assumed MRT and estimated C sequestration is asymptotic (Fig. 3). At MRT values less than approximately 320 yr, turnover of global C stocks negates any benefits from incoming C inputs, and net change is zero or even negative. Even if our estimate of MRT is too low, or if MRT is increased by practices such as no-till, this will only have limited effect on net C storage; for example, at MRT = 1000 years, the estimated annual soil gain increases only to about 0.3 Pg C yr⁻¹.

Any increase in SOC in response to higher C input, of course, cannot increase indefinitely (Johnston et al., 2017; Schiefer et al., 2018). As the pool of ‘lingering’ soil C increases, C loss from decay also increases, both because of 1st order kinetics (Caruso et al., 2018) and because protective mechanisms are progressively less effective as soil C builds up (Lehmann and Kleber, 2015). In time, therefore, the value of the second term in equation [3] approaches that of the first term, and soil C gain subsides to zero. To phrase it another way, soil C responds only to a *change* in amount of plant C added; if there has been no change in residue additions in recent decades, soil C attains a quasi-steady state and changes only gradually, if at all.

3. Summary of proposed estimate

Our approach suggests that about 0.44 Pg C yr⁻¹ can be added to lingering soil C stocks in croplands globally. But allowing for the slow turnover of existing C stocks, the potential *net* accumulation is much

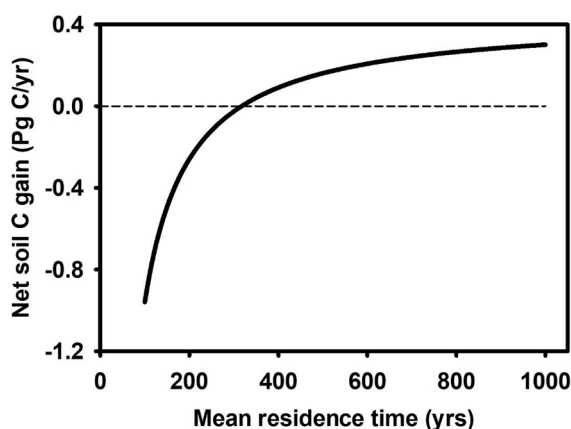


Fig. 3. Relationship between estimated annual soil carbon gain and mean residence time (yrs) of soil carbon, excluding recent additions. Mean residence time = $1/k_3$ (see Equation [4]).

less, perhaps about 0.14 Pg C yr⁻¹. This estimate, like all Fermi algorithms, is crude but, based on our tentative assumptions, the amounts of biomass C available for SOC replenishments will likely constrain annual global C sequestration in cropland soils to 0.14 (± 0.1) Pg C yr⁻¹ (Fig. 2), roughly 1.5% of current anthropogenic emissions (which are about 10 Pg yr⁻¹; Friedlingstein et al. (2021)).

Based on our rough Fermi estimate, soil C sequestration in croplands is a laudable, worthy goal as part of a phalanx of other measures, but it cannot supplant drastic reduction in fossil fuel emissions to suppress rising CO₂ concentrations. It is indeed an opportunity that “should be neither dismissed nor exaggerated” (Bossio et al., 2020). We need every feasible strategy to combat the threat of climate change; but overly optimistic projections for soil C gains may dilute the urgency of other strategies, notably of reducing fossil C emissions.

Additional C may be sequestered in soils on grazing lands, which could also be estimated using the approach described above. Achieving discernible soil C gains may be more difficult in these lands than in croplands, however, because many grazing lands are comparatively arid (with modest C inputs), not amenable to management change, and spatially variable, hampering verification (Briske et al., 2013). Soil C gains from organic inputs such as biochar could also be readily incorporated into our approach, but these gains count as atmospheric C removal on croplands only if the biochar was derived from photosynthesis on those lands, or if biochar amendment promoted photosynthesis (Equation [1]).

Like all Fermi solutions, our proposed framework yields only rough estimates, but may help establish reasonable bounds of C sequestration potential. As understanding develops and new insights emerge, the coefficients in the framework can be easily updated to generate progressively more robust estimates. At this stage, perhaps, the precise value of potential C sequestration is less important than the approach for deriving it.

4. Implications

The approach described here, while furnishing approximate estimates, also offers several directions for continuing research towards augmenting soil C. Firstly, it justifies rigorous efforts to promote photosynthesis (total plant yield) in agricultural ecosystems. The higher the NPP, the more C is available for both harvest *and* replenishment of soil organic matter. One strategy, for example, is continued research toward greater use of perennial crops, including forages, which maintain photosynthesis for longer durations, and allocate more C to plant parts not subject to harvest and removal, notably in rooting systems (Glover et al., 2010). Where perennial systems are not feasible, their benefits can be mimicked by extending and enhancing photosynthesis through measures such as cover cropping, diversified cropping schemes, judicious crop nutrition, and promoting perennials in unharvested landscape areas (Asbjornsen et al., 2014; King and Blesh, 2018). A small increase in NPP across all croplands globally (increasing P, equation [4]) might offer greater lasting benefit for soil C accrual than merely redirecting new plant C to more stable soil C fractions (increasing k_2 , equation [4]). Moreover, enhanced C input allows for higher soil C accumulation *and* more benefits from decay, thereby circumventing the C dilemma of having to choose between accumulating soil C or using it to promote soil functions through its decomposition by biota (Janzen, 2006; Sanderman et al., 2017a).

If augmenting soil C depends on promoting NPP, then availability of other nutrients, notably nitrogen (N), becomes important (Albrecht, 1983; Loveland et al., 2014; Van Groenigen et al., 2017; Zaehle, 2013). For example, if soil C is to be increased by 0.14 Pg C yr⁻¹ and the C:N ratio of soil organic matter is 12:1, then that C gain requires an additional 12 Tg N yr⁻¹, either from increased N input or reduced N losses. When a soil is a sink for C, it is also a sink for N, which may limit N fertility without compensatory measures.

Our calculation also emphasizes the importance of maximizing

return of plant C to soil (k_1 in Equation [4]), either directly or as recycled by-products, such as animal manure, biochar, and ‘wastes’ from industrial processing of cropland harvests. The growing demands for agricultural biomass as a feedstock for renewable fuels (Karlen et al., 2015) and other uses amplifies the importance of k_1 in dictating potential soil C gains. Equation [4], therefore, provides a framework for navigating the inevitable trade-offs arising from limitations of available plant biomass. Every tonne of biomass C trapped by photosynthesis can be removed or returned to replenish soil organic matter – never both. In some cases, societal demand may favor removal of plant biomass for different use rather than returning it to soil for soil C replenishment. For that reason, our estimates of soil C sequestration represent an upper bound (a technical potential), not a projected rate of soil C accrual.

The Fermi approach we outline also upholds the view that biological C stock is a product of interwoven ecosystem processes – notably photosynthesis – rather than of soil processes alone. Any effort to measure and maximize soil C storage must therefore adopt an ecological perspective including all biota within and upon the soil in their myriad interactions. This means tracing more fully and cohesively the fate and flows of plant C into and through entire cropland ecosystems. Perhaps the greatest uncertainty resides in rhizospheric C fluxes; because below-ground measurements are laborious, the amounts and fate of C entering the soil via roots and their exudates remain inadequately quantified (Amos and Walters, 2006; Kramer et al., 2012; Paul, 2016; Pausch and Kuzyakov, 2018; Pett-Ridge and Firestone, 2017). For example, some studies suggest that retention of root C in soil organic matter is greater than that of above-ground residues (Berti et al., 2016; Ghafoor et al., 2017; Jackson et al., 2017; Menichetti et al., 2015; Xu et al., 2021); but others report the converse (Tahir et al., 2016) or no discernible difference (Hu et al., 2018). Such calculations obviously depend on reliable estimates of root C inputs to soil organic matter. Unlike above-ground parts, roots are always decaying; hence any one-time measure captures only a fraction of the C allocated annually to roots. If current estimates of root-derived C input are conservative, then the estimate of potential C gain from equation [4] might increase slightly (increased P, decreased k_1). A recent synthesis, however, suggests that only 5–6% of NPP in croplands is allocated to net rhizodeposition (Pausch and Kuzyakov, 2018) – substantially less than in grasslands, and well within the uncertainty associated with the assumed NPP in our calculations.

Our estimate of potential cropland C sequestration is almost an order-of-magnitude below current emissions from land use change (currently $\sim 0.9 (\pm 0.7)$ Pg C yr⁻¹; (Friedlingstein et al., 2021)). Therefore, policies and research efforts to preserve C already stored in the biosphere deserve at least as much attention as efforts to sequester new stores, especially in light of projected expansion of cropland area (Molotoks et al., 2018). Many of these, such as reducing food waste or shifting food preferences, extend outside the usual purview of soil science, demanding a trans-disciplinary approach.

Plant biomass, a repository of solar energy and plant nutrients, is an increasingly valuable commodity, in demand for many uses beyond soil C sequestration for climate mitigation. The growing shortage of this resource dictates careful thought on how best to invest this precious material, recognizing inevitable trade-offs.

5. Conclusions

Our approach suggests that the maximally achievable rate of C sequestration in arable lands globally is most likely in the order of 0.1–0.2 Pg C yr⁻¹, around 1.5% of current annual anthropogenic CO₂ emissions. Soil C sequestration on croplands, therefore, offers significant but modest benefits, insufficient to forestall drastic efforts to reduce emissions from fossil C and degradative land use change.

More important than the numerical value of our estimate, perhaps, is the change in orientation: what matters in projecting soil C change is not past losses but future C inputs. This reorientation shifts the emphasis from a myopic focus on soil processes, intent on stashing away soil C, to

a wider ecosystem perspective of C cycling, encompassing the role of plants as agents of atmospheric CO₂ withdrawal, with photosynthesis at its core.

Our approach offers a quantitative reminder that preserving existing stores of C in ecosystems is at least as important as accumulating new stores of C. Despite past losses, agricultural ecosystems still hold large reserves of C. Prudent farming practices, by avoiding expanded cultivation, may help to hold in place even larger pools of C in grasslands, forests, and other non-arable lands. Leaving grasslands unplowed, wetlands undrained, and forests uncut surely is as important as leaving coal unburnt.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

HJ derived the basic approach presented in this study, which was further refined based on discussions with JWVG, DP and KJVG. TS conducted the Monte Carlo uncertainty analysis and produced the associated figures. Most of the writing was done by HJ and JWVG, with significant inputs of DP and KJVG. JWVG oversaw and directed the iterative writing process. All co-authors reviewed and edited the text.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geoderma.2022.115810>.

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