

Soil carbon saturation: concept, evidence and evaluation

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Abstract Current estimates of soil C storage potential are based on models or factors that assume linearity between C input levels and C stocks at steady-state, implying that SOC stocks could increase without limit as C input levels increase. However, some soils show little or no increase in steady-state SOC stock with increasing C input levels suggesting that SOC can become *saturated* with respect to C input. We used long-term field experiment data to assess alternative hypotheses of soil carbon storage by three simple models: a linear model (no saturation), a one-pool whole-soil C saturation model, and a two-pool mixed model with C saturation of a single C pool, but not the whole soil. The one-pool C saturation model best fit the combined data from 14 sites, four individual sites were best-fit with the linear

model, and no sites were best fit by the mixed model. These results indicate that existing agricultural field experiments generally have too small a range in C input levels to show saturation behavior, and verify the accepted linear relationship between soil C and C input used to model SOM dynamics. However, all sites combined and the site with the widest range in C input levels were best fit with the C-saturation model. Nevertheless, the same site produced distinct effective stabilization capacity curves rather than an absolute C saturation level. We conclude that the saturation of soil C does occur and therefore the greatest efficiency in soil C sequestration will be in soils further from C saturation.

Keywords Agroecosystems · Carbon saturation · Soil carbon sequestration · Soil carbon modeling · Tillage

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Introduction

Soil organic C (SOC) constitutes a large pool of C in the global C cycle representing a dynamic balance between C inputs through photosynthesis and deposition and losses via respiration, erosion and leaching. In agroecosystems, the SOC balance is influenced by management practices such as organic matter additions, tillage intensity, fertilization, irrigation, and crop rotation. Soil organic C storage may be increased directly by increasing C returns to the soil

as crop residue, manure, or other organic amendments. Carbon inputs to the system also may be increased indirectly by fertilization or irrigation treatments that increase crop productivity, biomass and root production.

Interest has grown in promoting C sequestration in soils to help mitigate increasing CO₂ levels in the atmosphere because most agricultural soils have been previously depleted with respect to organic matter (CAST 2004). This interest is also coincident with the desire to increase soil C contents to improve soil sustainability (Follett and Delgado 2002). Key questions include: what is the relative C storage efficiency (i.e., C stock increase per unit C added) for different soils and is there an upper limit to the capacity for soils to store organic C?

Most current SOC models employ first-order kinetics for decomposition processes, and therefore the models predict linearity between C input level and SOC level at equilibrium (i.e., steady-state; Paustian et al. 1997a). This linearity means that soil C storage 'efficiency' (i.e. $\Delta\text{SOC}/\Delta\text{C}$ input) is constant and that equilibrium soil C levels could increase continuously and without limit as steady-state C input levels increase. Many long-term agroecosystem field experiments, in which treatments give different levels of C inputs, show soil C stocks that appear linearly related to the average amount of C returned to the system (e.g. Huggins et al. 1998b; Kong et al. 2005; Paustian et al. 1997a). This linear relationship between steady-state C inputs and soil C levels is consistent with the behavior predicted by soil C models based on first-order kinetics.

However, some long-term agroecosystem experiments show little or no change in SOC stocks in response to varying C input levels. After 30 years of continuous corn (*Zea mays* L.) at Morris, MN, neither varying levels of fertilization nor removal of crop stover had a significant effect on SOC content of the upper 20 cm of soil (Reicosky et al. 2002). At Lamberton, MN, greater residue additions in corn versus corn-soybean (*Glycine max* L.) crop rotations over 10 years (Huggins et al. 1998a) and differences in N-fertilizer rates and residue inputs over 19 years (Huggins and Fuchs 1997; Huggins et al. 1998b) did not significantly affect SOC levels. Other field studies have shown decreased SOC stabilization efficiency in high-C compared to low-C soils under the same treatments. For example after 31 years of fertilizer and crop rotation treatments,

Campbell et al. (1991b) found that SOC content was not significantly different as a function of C input level (1.4–2.2 Mg C ha⁻¹ year⁻¹) at Melfort, Saskatchewan, whereas SOC increased as a function of C input level (0.9–2.0 Mg C ha⁻¹ year⁻¹) at Indian Head, Saskatchewan. They attributed this difference in response of SOC to carbon input, in part, to the lesser SOC content of Indian Head (36–42 Mg C ha⁻¹) compared to Melfort (61–67 Mg C ha⁻¹, 0–15 cm). After 11 years, Nyborg et al. (1995) found less stabilization of new C in a Typic Cryoborol (Ellerslie, Alberta) with a greater C content (86.7 Mg C ha⁻¹, 0–15 cm) compared to a paired site at Breton, Alberta (Typic Cryoboralf) (33.2 Mg C ha⁻¹, 0–15 cm) under straw addition and N-fertilization treatments. This lack of response in SOC levels to varying levels of C input, over many years, and the apparent dependency between C stabilization efficiency and soil C content, suggests the possibility of an upper limit or 'saturation level' for soil carbon (Six et al. 2002).

Saturation limits to individual SOC pools have been proposed by other researchers, due to silt + clay protection (Hassink 1996, 1997), soil structure (physical protection within aggregates), and the biochemical complexity of the organic compounds (Baldock and Skjemstad 2000). Six et al. (2002) proposed a whole-soil C saturation limit with respect to soil C input levels at steady-state comprised of all the above C pools, including a non-protected C pool. Soil C saturation is then defined as a soil's unique limit to C stabilization as a function of C input levels (at steady state) based on the cumulative behavior of these four C pools (i.e., chemically-, physically-, biochemically-protected, and non-protected pools). Across 11 agroecosystems, Six et al. (2002) found that an asymptotic curve fit the SOC content and C input level data better than a linear relationship. They suggested that the smaller increase in SOC content with increased C input level was due to the decreased capacity of a high C soil to store added C. Their conceptual model implies that the further a soil is from saturation (i.e., the greater the saturation deficit), the greater its capacity and efficiency to sequester added C, whereas a soil approaching saturation will accumulate a smaller amount of SOC at a slower rate and efficiency (Hassink and Whitmore 1997).

As our ability to increase SOC stocks (even beyond native levels) through greater C inputs and improved management practices advances, it is

crucial to know what, if anything, limits the amount and rate of SOC stabilization. Results from long-term experiments are ambiguous, with many sites showing a linear response of SOC to C input levels that is consistent with first-order decomposition processes and other experiments that suggest saturation dynamics. Our objective was to analyze previously published data to test three simple C accumulation hypotheses: the common (first-order) ‘linear’ model, a one-component whole-soil C saturation model (representing a simplification of the Six et al. (2002) hypothesis of C saturation), and a two-pool mixed model with assumptions of C saturation of a single C pool, but not the whole soil. The latter model is analogous to Hassink and Whitmore (1997) where the single saturated pool is represented by the silt and clay associated C. We explored the steady-state dynamics of each simplified model and using information theory, we then ranked the performance of models against experimental data from long-term agroecosystems to test whether C saturation influenced whole SOC accumulation.

Theory

The distinction between the concepts of equilibrium soil C content and soil C saturation is illustrated in Fig. 1. Soil organic matter dynamics are typically viewed in terms of changes in stocks over time. If

changes in agricultural management practices increase (or decrease) C input levels, then over time, soil C content will increase (or decrease) until a new *equilibrium* soil C content is reached. Multiple equilibrium levels of C input will produce multiple equilibrium SOC levels because equilibrium soil C levels are achieved where C additions are balanced by C losses—if C input rates are held constant, soil C contents approach an equilibrium level over time (Fig. 1a, c). With no saturation, there is no limit to soil C content as steady-state C input rates increase (Fig. 1b). The soil C saturation concept proposes that there is a maximum equilibrium C level that will be attained when C input is maximized (Fig. 1d). Hence, under the C saturation model, equilibrium SOC also increases with greater C input rates, but the incremental increase in SOC declines as the rate of C addition increases (Fig. 1c). Hence the storage efficiency decreases towards zero as the soil C content approaches the saturation level.

Complex simulation models for SOC, when analyzed at steady-state, can be simplified to mathematical expressions that illustrate general conclusions (Bolker et al. 1998). Here, we present the simplest form of a linear (first-order decay) model which forms the basis of simulation models such as Century, RothC, and many others (Paustian et al. 1997b) and we compare this to simple models that include a C saturation component. It is important to note that here

Fig. 1 Theoretical relationship between C input level and soil organic C (SOC) contents at steady-state, with and without C saturation. Steady-state SOC accumulation dynamics expressed over time (a) produces a linear relationship when expressed over C input level (b) Under the conditions of C saturation, SOC stabilization with increasing input rates (at steady state) is not proportional (c) resulting in an asymptotic relationship when expressed over C input level (d)

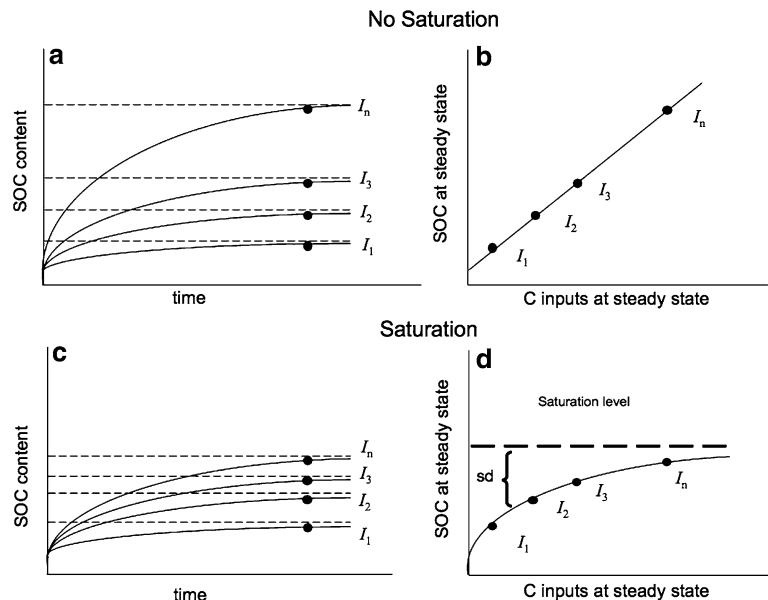
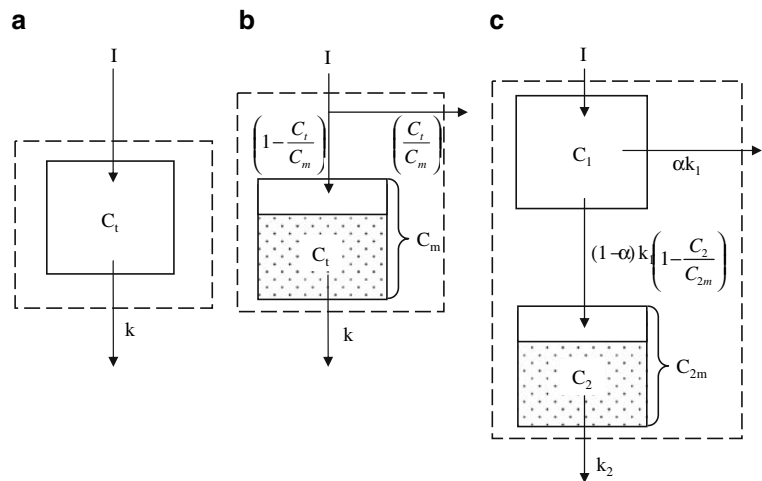


Fig. 2 Graphical representations of the linear (no saturation) model (a), the one-pool whole-soil C saturation model (b) and the two-pool mixed model with C saturation of a single C pool, but not the whole soil (c)



we use the models not to simulate the dynamic behavior of SOM pool(s) over time, but rather to evaluate the fundamental relationship between C addition levels and soil C levels at steady-state.

The boundaries of the proposed models are soil organic matter rather than the soil itself (Fig. 2). This places an important distinction on how C inputs (I) to the system are defined; they do not represent residues entering the soil system as a whole, but rather organic materials entering the pool of soil organic matter, which is usually operationally defined as organic materials <2 mm in size that are intimately associated with the soil matrix.

Linear model

The simple first-order decay model (proposed by Jenny (1941) and other early workers) assumes that the amount of C entering a C pool is independent of the pool size and that decomposition rates are directly proportional to the size of the pool (Fig. 2a).

$$\frac{dC_t}{dt} = I - kC_t \quad (1)$$

where the rate of change in SOC at time t (dC_t/dt) is dependent on the level of C input (I) and losses through first-order decomposition kinetics of the SOC pool (C_t) with a specific decay constant (k).¹ If C

¹ For simplicity, losses via respiration are included in the term k , and losses through other pathways (e.g., leaching) are assumed to be zero.

input level (I) added to the soil pool is increased by a constant proportion (n) in the manner $I_n = I_i \cdot n$, SOC will accumulate until a new steady-state level is achieved (Fig. 1a).

However, for the present analysis we are only concerned with the relationship at steady-state ($dC_t/dt = 0$),

$$C_t^* = \frac{I^*}{k} \quad (2)$$

where SOC content (C_t^*) is directly proportional to C input level (I^*). If I is increased, SOC content at steady-state will increase by the same proportion, without limit (Fig. 1b). Most current models are based on first-order decomposition kinetics and hence show a linear relationship between C input levels and SOC content at steady-state (Paustian 1994; Paustian et al. 1997c). This relationship holds even for simulation models with multiple pools (and k 's) of SOC (e.g. Bolker et al. 1998; Jenkinson 1990; Parton et al. 1988) and simulation models where the specific decomposition rates (k) is treated as a variable (e.g. Bosatta and Agren 1999) rather than a constant (Paustian et al. 1997c).

Carbon saturation model

The C saturation model has a whole soil saturation limit (C_m) (Fig. 2b) due to inherent physicochemical limitations. In contrast to the linear model, the fundamental relationship between C addition levels and soil C levels at steady-state is asymptotic. While

many first-order based simulation models use texture to modify soil stabilization of C inputs between soils of differing silt + clay content (e.g. CENTURY), there is no explicit limit to soil C stabilization. Another simulation model (Hassink and Whitmore 1997) assumed C saturation of a single C pool, but not the whole soil. Our simplified C saturation expression differs from previous models in that the stabilization of C input into soil organic matter is *explicitly limited* and the mechanism of physico-chemical stabilization is implied rather than directly modeled as a specific process.

Over time, the soil C saturation concept may be expressed as a simple modification to the C input term in Eq. 1:

$$\frac{dC_t}{dt} = I \left(1 - \frac{C_t}{C_m} \right) - kC_t \quad (3)$$

where C_m is the maximum amount of C that can be stabilized by the soil. In this model, soil C storage is limited by a saturation deficit (sd) which we define as:

$$sd = 1 - \frac{C_t}{C_m} \quad (4)$$

As a soil approaches C saturation level, the proportion of new C input stabilized by physico-chemical mechanisms is reduced by the proportion of SOC present (C_t) to the maximum C level (C_m), i.e., the SOC stabilization efficiency decreases. The remaining C inputs (I^*C_t/C_m) are not stabilized as soil organic matter. As in the non-saturated case, if the amount of C added to the soil pool is increased by a constant proportion $I_n = I_i \cdot n$, SOC will accumulate until a new steady-state level is achieved (Fig. 1c). However in the C saturation case, relative SOC stabilization decreases with increasing I , rather than remaining proportional as in the linear model (Fig. 1c vs. 1a).

Solving Eq. 3 for steady-state SOC concentration (C_t^*) results in an asymptotic relationship between C inputs (I^*) and SOC (e.g., Fig. 1d):

$$C_t^* = \frac{I^*}{k + \frac{I^*}{C_m}} \quad (5)$$

The asymptotic relationship between C input levels and SOC content at steady-state is a key

attribute to the C saturation model (Fig. 1d vs. 1b). Direct corollaries of this asymptotic relationship are that (1) the further a soil is from saturation (i.e., the greater the saturation deficit), the greater its efficiency in sequestering added C, and (2) as a soil approaches saturation, the rate and amount of SOC accumulation decreases due to a smaller saturation deficit.

Mixed model

The C saturation model above assumes that the amount of C that can be stabilized is limited and that once saturation is reached any additional C input will be not be stabilized but will be lost from the system. Hence, we can visualize a mixed C saturation model comprised of a labile residue C pool (C_1) that is not saturatable and a second more stable C pool with saturation behavior (C_2), (Fig. 2c):

$$\frac{dC_t}{dt} = \frac{dC_1}{dt} + \frac{dC_2}{dt} \quad (6)$$

where

$$\frac{dC_1}{dt} = I - \alpha k_1 C_1 - (1 - \alpha) \left(1 - \frac{C_2}{C_{2m}} \right) k_1 C_1 \quad (7)$$

and

$$\frac{dC_2}{dt} = (1 - \alpha) \left(1 - \frac{C_2}{C_{2m}} \right) k_1 C_1 - k_2 C_2 \quad (8)$$

with decomposition constants k_1 and k_2 , respectively. The term α is a partitioning coefficient for the losses from C_1 between respiration (α) versus the transfer of decomposition products to the more stable pool ($1 - \alpha$). We assign a value of 0.55 to α , similar to respiration coefficients used in simulation models for SOM dynamics (e.g. Parton et al. 1987). The remaining microbial products that are not incorporated into the stable pool (i.e. $(1 - \alpha) k_1 \left(\frac{C_2}{C_{2m}} \right) C_1$) are retained implicitly in C_1 , the labile fraction, and represent processed organic materials unable to be protected due to the saturation of the stable pool. Carbon stabilization in C_2 is limited by the saturation limit of C_2 (C_{2m}). As C_2 approaches C_{2m} , the amount of decomposition products from C_1 transferred into C_2 decreases

until C_2 reaches its saturation level (i.e. $C_2 = C_{2m}$). At this point, C transfer into C_2 ceases, and SOC accumulation in C_1 proceeds according to the linear model (Eq. 1).

Solving Eqs. 6, 7 and 8 for steady-state expressed as a function of a single C pool (with C_1 solved in terms of C_2),

$$C_t^* = \frac{I^* C_{m2}}{k_1(C_{m2} - C_2 + \alpha C_2)} + \frac{(\alpha - 1)I - k_2 C_{m2} \pm \sqrt{((\alpha - 1)I - k_2 C_{m2})^2 - 4Ik_2 C_{m2}(\alpha - 1)^2}}{2(k_2\alpha - k_2)} \quad (9)$$

illustrates the relationship between C input level (I) and whole-soil SOC (C_t). Although there are two solutions, the only relevant one produces C_t in positive space (positive root). At low to moderate C input levels, this model produces slightly curvilinear whole soil C accumulation dynamics, but under high C input levels, SOC accumulation is linear. Theoretically, SOC will increase indefinitely in this model as SOC input levels are increased, however at a slower rate than in the linear model. Assuming $k_1 > k_2$, the turnover rate of the total soil C increases as the recalcitrant pool approaches saturation because C is retained in the labile (unprotected) state, which is subject to a faster rate of decomposition.

The three steady-state models described above (Eqs. 2, 5 and 9) provide three contrasting scenarios, or hypotheses of SOC accumulation: (1) no saturation (i.e., linear, Eq. 2), (2) whole-soil C saturation (i.e., C saturation model, Eq. 5), and (3) soil C saturation of a stabilized C pool, but not the whole soil (i.e., mixed model Eq. 9). By using likelihood-based methods and information theory (small sample Akaike's Information Criterion, AIC_c), we were able to quantify the relative explanatory power of these models, given the long-term agroecosystem (Anderson et al. 1998; Burnham and Anderson 2001, 2004).

Analysis methods

We compiled the most recent SOC contents and average C input levels (as crop residues and organic amendments) from a data set compiled from long-term agricultural sites around the world (see Ogle et al. 2005). Required data included SOC stocks,

soil bulk density, depth of measurement, and C input levels. We estimated crop residue C inputs based on reported crop yield (and in some cases total aboveground biomass production), using regression models to estimate total C inputs from roots plus aboveground residues (Table 1) or published values from the experiment. Long-term

agricultural sites were only included if the experimental duration was greater than 12 years in age and had been under conventional cultivation at least 10 years prior to the initiation of the current treatment. This criterion was to exclude sites where soil C stocks may be far from steady-state. Additionally, sites were required to have four or more C input levels (e.g., differences in crop rotations or organic matter addition treatments) on which to base a regression line. Sites with multiple treatments (e.g., tillage and crop rotation) were split as tillage could confound the C input effect.

An additional factor in the analysis is that the long-term experiments do not, strictly speaking, represent a true steady-state condition with respect to SOM levels as a function of C input level, because of the very long residence time of some recalcitrant SOC and the variability in carbon inputs. For example, when C inputs are totally eliminated (e.g., bare fallow experiments), a substantial fraction of the SOC persists over many decades (Paustian et al. 1992; Plante et al. 2004). The true steady-state condition for all three models under the condition of zero C inputs, however, is zero SOC. An intercept term (R) was added to the linear model in Eq. 2 to account for the residual SOC that is not affected over the course of the agroecosystem experiment:

$$C_t^* = \frac{I}{k} + R \quad (10)$$

Due to the composite nature of the mixed model, there is no unique steady-state solution in terms of C_t , so a sensitivity analysis was performed to determine the

Table 1 Regression equations for above- and belowground C input from grain dry weight (GDW) for common crops in long-term agroecosystems experiments based on long-term crop yield data from US agroecosystem experiments (IPCC Guidelines 2006)

	Aboveground residue (AGR) (Mg dry wt. ha ⁻¹)	Belowground residue (BGR) (Mg dry wt. ha ⁻¹)
Alfalfa	0.325 * GDW [‡]	0.43 * (GDW [‡] + AGR)
Oat	1.09 * GDW + 0.387	0.26 * (GDW + AGR)
Soybean	1.712 * GDW + 0.795	0.24 * (GDW + AGR)
Corn	1.03 * GDW + 0.610	0.21 * (GDW + AGR)
Wheat		
Winter	1.61 * GDW + 0.389	0.21 * (GDW + AGR)
Spring	1.29 * GDW + 0.715	
Barley	0.95 * GDW + 0.625	0.20 * (GDW + AGR)

[‡] GDW = grain dry wt. (Mg ha⁻¹); for alfalfa GDW = aboveground biomass dry weight

sensitivity of the proportions of C_1 and C_2 on the model parameter estimates. To determine the effect of the proportion of C_1 versus C_2 on the steady-state solution, we ran the model iteratively with fixed proportions of C_2 (0.1–0.9). We found that the parameter estimates varied only slightly across all proportions of C_2 and produced less than nine percent variation in AIC_c value.

Traditional statistics lack a formal method of incorporating the uncertainty of the data into the model. However, information-theory integrates model-selection uncertainty by penalizing models with poor predictor choice, errors in structure, or poor explanation of the given data. Information theory also allows a set of competing models to be tested and a “best” model or models (if there is high uncertainty) to be determined based on the data (Anderson et al. 1998). Akaike information criterion (AIC) is an estimate of the relative distance between the fitted model and the unknown true equation (or process) that produced the observed data (Burnham and Anderson 2001).

$$AIC = -2 \log L(\theta_i | Y) + 2K \quad (11)$$

with $L(\theta_i | Y)$ as the maximized likelihood, a function of the unknown parameters θ_i , given the data Y and the model. However, to account for the extremely small sample sizes, we used small sample Akaike information criterion (AIC_c) for model selection which is modified by the number of parameters (K) and sample size (n), i.e.,

$$AIC_c = AIC + \frac{2K*(K+1)}{n-K-1} \quad (12)$$

An advantage of AIC_c is that models may be ranked according to best-fit. To compare models,

AIC_c values were rescaled as differences (Δ_i) between the AIC_c of model i and the best approximating model ($\Delta_i = AIC_{ci} - AIC_{c\min}$). The relative likelihood of a model, given the data and the set of models, or its ‘probability’, is expressed by weights.

$$w_i = \frac{e^{-1/2\Delta_i}}{\sum_i e^{-1/2\Delta_i}} \quad (13)$$

We used this method to test the likelihood of the linear (Eq. 10), C saturation (Eq. 5), and mixed (Eq. 9) models given the C input level and SOC data. All models were fit using PROC NL MIXED in SAS/STAT (SAS Institute, Cary NC) to normalize for the treatment of variance in model fits, and to obtain AIC and AIC_c values. A model was considered to be best fit if differences in $\Delta_i < 2$ (Burnham and Anderson 2001).

Results

We found that by incorporating a simple proportional C saturation limit $\left(1 - \frac{C}{C_m}\right)$ to the C input term of the first-order decomposition model, that steady-state SOC versus C input level produced an asymptotic function and allowed us to explicitly estimate the value C saturation for a given soil. The expression in the two-pool model, incorporating C saturation of a single pool, produced a slight curve at low to moderate C input levels but produced linear SOC accumulation under high C input levels. The 2-pool model is analogous to the Hassink et al. (1997) hypothesis of C saturation of the silt + clay protective

capacity, but not the whole soil. This occurs because C is retained in the labile (unprotected) state, which is subject to a faster rate of decomposition as the recalcitrant pool approaches saturation. This model does not simulate whole-soil saturation because SOC will increase indefinitely in this model as SOC input levels are increased.

We found 14 sites that matched our criteria from a variety of temperate agroecosystems in the U.S. and Canada (Table 2). They varied in SOC contents from 7.7 to 121.9 Mg C ha⁻¹ and C input levels from 0.17 to 7.42 Mg C ha⁻¹ year⁻¹. To assess the relative support in the compiled agroecosystem data for non-saturating (linear) versus C saturating (asymptotic relationship) behavior between C input level and SOC content, we ranked the models by $\Delta_i < 2$ (Burnham and Anderson 2001). Using this criterion, only five sites had a clear best-fit model (Table 3); the linear model for Lancaster 2, Pendleton, Sanborn CT,

and Sterling, and the C saturation model for Sanborn NT (Fig. 3). The linear and C saturation models were indistinguishable at 11 sites, but both had better fits than the mixed model. The large Δ_i for the mixed model at all sites indicated that it is the worst-ranked of the three proposed models and reflected the penalty of additional parameters (versus the other two models) on AIC_c. There was no evidence in the Morrow corn-soybean rotation data to distinguish between any of the models (Table 3).

To overcome the small sample size within sites and minimize the effect of the AIC_c penalty term, we also fit our three models against the combined site data. Combining site data could confound the C saturation analysis if C input level (*I*) co-varied with decomposition rate (*k*), resulting in an apparent saturation response of less SOC accumulation at high input levels because of faster decomposition rates due to optimal temperature and moisture conditions. We

Table 2 Long-term agroecosystem sites selected for use in comparative model analyses

Site	Treatment duration (years)	Treatments	Reference
Breton, AB	51	Crop rotation Fertilizer addition Manure addition	Izaurre et al. 2001
Indianhead, SK	30	Crop rotation	Campbell and Zentner 1997
Lamberton, MN	22	Fertilizer addition	Darmody and Peck 1997
Lancaster2, PA	14	Tillage	Karlen et al. 1994
Lancaster1, PA	14	Residue management	Vanotti et al. 1997
Mandan, ND	12	Tillage Fertilizer addition	Halvorson et al. 2002
Melfort, SK	30	Crop rotation	Campbell et al. 1991c
Morrow, IL	27	Crop rotation	Darmody and Peck 1997
Pendleton, OR	17	Tillage	Rasmussen and Albrecht 1997
Sanborn, MO	CT 96 NT 25	Tillage Manure addition	Buyanovsky et al. 1998
Sterling, CO	12	Crop rotation Topographic location	Sherrod et al. 2003
Stratton, CO	12	Crop rotation Topographic location	Sherrod et al. 2003
Swift Current, SK	13	Crop rotation Fertilizer addition	Campbell et al. 1999
Walsh, CO	12	Crop rotation Topographic location	Sherrod et al. 2003

Conventional tillage = CT and no-tillage = NT. Equations are based on IPCC Guidelines (2006)

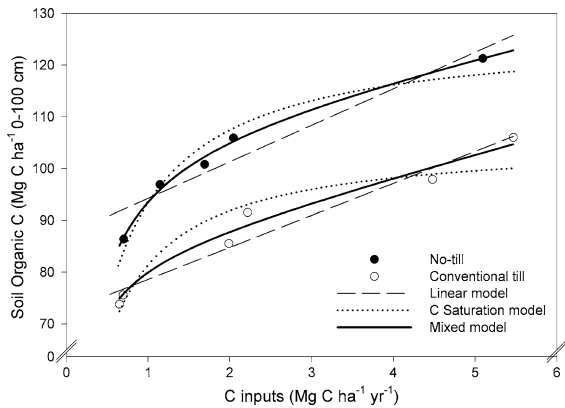


Fig. 3 Linear, C saturation, and mixed model fits of soil organic C content (Mg C ha^{-1}) as a function of C input levels ($\text{Mg C ha}^{-1} \text{ year}^{-1}$) in the manure plots at Sanborn in no- (NT) and conventional-tillage (CT) treatments (25 and 96 years, respectively)

found no significant relationship, however, between decomposition (k calculated using the linear model fit) and C input level (I) (data not shown). Although

there is great variability in the data, when the three models were tested against all the sites combined, the C saturation model had greater support ($\Delta_i = 0$) in the data than either the linear ($\Delta_i = 8.78$) or the mixed model ($\Delta_i = 6.3$) (Fig. 4 and Table 3). Combining Akaike weights (w_i) as an estimation of probability, that there is a 99% probability either the C saturation or mixed model is the best approximation of these data.

Discussion

Of our three hypotheses of SOC accumulation: no saturation limit (i.e., linear), whole-soil C saturation (i.e., C saturation model), and soil C saturation of a stabilized C pool, but not the whole soil (i.e., mixed model), the C saturation model best fit the combined site data, supporting the hypothesis that whole soil C accumulation is limited with respect to C input level.

Table 3 Model fit statistics of the linear model (no saturation), whole-soil C saturation model (CSAT) and the two-pool mixed model (C saturation of a single C pool, but not the whole soil)

Site	<i>n</i>	AIC			AICc			Δ_i			w_i		
		linear	CSAT	Mixed	linear	CSAT	Mixed	linear	CSAT	Mixed	linear	CSAT	Mixed
Breton, AB	6	31.3	32.8	33.7	43.3	44.8	93.7	0.0	1.5	50.4	0.68	0.32	0.00
Indianhead, SK	7	29.2	30.2	29.9	37.2	38.2	92.0	0.0	1.0	54.8	0.63	0.37	0.00
Lamberton, MN	4	23.6	23.4	27.4	47.6	47.4	87.4	0.1	0.0	40.0	0.48	0.52	0.00
Lancaster2, PA	4	26.6	29.5	30.0	50.6	53.5	90.0	0.0	2.8	39.4	0.81	0.19	0.00
Lancaster1, PA	5	34.0	34.3	38.3	58.0	58.3	98.3	0.0	0.0	40.0	0.50	0.50	0.00
Mandan, NE	17	74.7	75.5	78.2	76.5	77.4	83.6	0.0	0.8	7.1	0.59	0.39	0.02
Melfort, SK	8	37.2	37.2	41.1	43.2	43.2	71.2	0.2	0.0	28.0	0.47	0.53	0.00
Morrow, IL													
Corn	4	28.0	29.0	31.2	52.0	53.0	71.2	0.0	1.0	39.5	0.62	0.38	0.00
Corn–soybean	4	27.3	29.1	13.2	51.3	53.1	91.6	0.0	1.7	38.7	0.70	0.30	0.00
Corn–oat–hay	4	26.1	27.5	27.5	50.1	51.5	90.1	0.0	1.5	39.1	0.67	0.33	0.00
Pendleton, OR	4	9.4	15.5	7.5	33.4	39.5	89.2	0.0	6.1	46.7	0.95	0.05	0.00
Sanborn, MO													
Conventional-till	6	34.8	38.8	33.8	46.8	50.8	80.1	0.0	3.9	46.9	0.88	0.12	0.00
No-till	5	32.7	29.6	22.7	56.7	53.6	93.7	14.9	0.0	29.0	0.00	1.00	0.00
Sterling, CO	12	60.3	62.8	62.1	63.3	65.8	82.5	0.0	2.6	9.2	0.78	0.22	0.01
Stratton, CO	12	66.6	65.0	69.0	69.6	68.0	72.5	1.5	0.0	10.9	0.32	0.68	0.00
Swift Current, SK	7	33.6	34.4	36.2	41.6	42.4	78.9	0.0	0.8	55.3	0.59	0.41	0.00
Walsh, CO	10	59.8	60.5	64.5	63.8	64.5	96.9	0.0	0.7	15.8	0.59	0.41	0.00
Combined Sites	119	1057.3	1048.5	1052.5	1057.5	1048.7	1055.0	8.8	0.0	6.3	0.01	0.95	0.04

AIC = Akaike Information Criterion, AICc = Akaike Information Criterion corrected for small sample size, $\Delta_i = \text{AIC}_{ci} - \text{AIC}_{c \text{ min}}$, and w_i is the relative weight given each model based on AICc

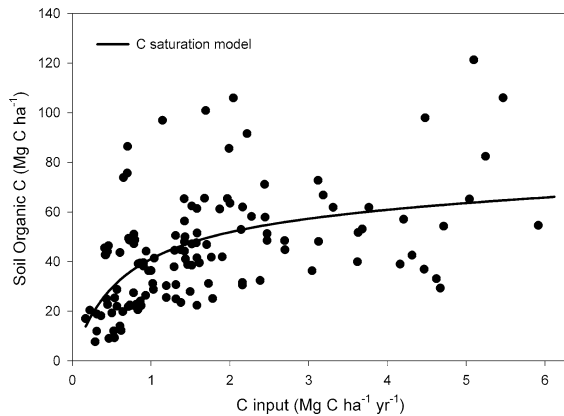


Fig. 4 Soil organic C content (Mg C ha^{-1}) expressed as a function of C input levels ($\text{Mg C ha}^{-1} \text{ year}^{-1}$) for the 14 long-term agroecosystem experiments reported in Table 1

This corresponds to the 11 site analysis of Six et al. (2002) who found an asymptotic model explained more variability than a linear model. C saturation of a whole soil, presumably including a non-protected pool, suggests that even relatively labile soil C approaches a maximum level.

This best fit of the whole soil C saturation model is only corroborated by the single C saturation best model fit in the individual site data of Sanborn. Namely, the NT treatment at Sanborn (including grass cover crops) had substantial support for the C saturation model. However, the penalty of adding parameters to the model is illustrated by the good fit of the mixed model's AIC value in both tillage treatments, but lack of substantiation when compared by AIC_c to the linear and C saturation models (Fig. 3).

The observed best linear model fits as well as the lack of model differentiation may be due to the small sample size within a site (n of four input levels in six sites). The Akaike value for small sample sizes (AIC_c), greatly penalizes models with both small sample size and a larger number of parameters. The additional parameter in the mixed compared to the linear and C saturation models greatly increased the AIC_c value and subsequently decreased support for the model given the small amount of data.

According to the C saturation concept, an asymptotic relationship would better fit the data than the linear model, but if C input levels are low, the asymptotic trend in SOC accumulation will not be

evident. The conjecture that C input levels were too small to exhibit C saturation dynamics within a given site is supported by three of the four linear best-fit models (Lancaster, Pendleton, and Sterling), where inputs were less than 3.5 Mg C ha^{-1} . Furthermore, smaller sections of an asymptotic curve can appear linear in the range being observed. Within each site, a small range of C input levels will not necessarily capture the full range of linear to asymptotic behaviors expected from a soil subject to C saturation. In our data set, differences between the highest and lowest input levels were $<2 \text{ Mg C ha}^{-1}$ at eight sites.

Soil C saturation versus effective C stabilization capacity

Evidence of C saturation has been suggested using data from long-term agroecosystem experiments that show little response in SOC accumulation to increasing C input level (e.g. Campbell et al. 1991a; Solberg et al. 1997). Data from the Sanborn experiment suggest that saturation behavior does occur, but that tillage influences the level of effective soil C stabilization that can be attained (Fig. 3). According to the original C saturation concept, each soil has a single, unique C saturation level dictated by, for example, textural and mineralogical properties. However, the conventional (CT) and no-tillage (NT) treatments imposed at Sanborn fit two distinct curves. How can the same soil appear to be approaching two apparently distinct C stabilization levels with increasing C input level? The C saturation model in Eq. 5 shows that the SOC content (C_t) is dependent on both C input level (I) and decay constant k . Within a site, k is influenced by micro-environmental and disturbance factors such as tillage-induced changes in porosity, water retention, heat flux, etc. The factor k alters the slope of the SOC and C input level relationship in the models. Factors that influence decomposition rate thus also influence SOC storage and its relationship to C input level at steady-state. Consequently, a soil under a management regime with an increased inherent decomposition rate (e.g., CT) may therefore show a different asymptotic SOC response to C input levels at steady-state (CT curve in Fig. 5). At the greater addition levels, the soil may appear to be approaching SOC saturation due to little or no SOC accumulation as C input levels are increased further (Fig. 5). However, a change in management (e.g.,

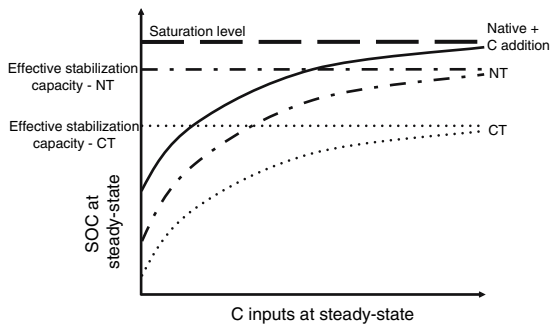


Fig. 5 Soil C accumulation dynamics under theoretical decomposition regimes produced by management scenarios. Since no-tillage (NT) has a reduced specific decomposition rate compare to conventional tillage (CT), steady-state SOC content will be greater under the same C input level. Effective stabilization capacity is the upper limit to C storage as a function of differing specific decomposition rates (i.e., CT vs. NT). These systems may appear to illustrate soil C saturation, but are not considered saturated due to C decomposition conditions dominating C stabilization. Soil C saturation is imposed by physical and chemical properties of a soil under conditions when C input levels are maximized and disturbance minimized

reduction or elimination of tillage) can decrease decomposition and thereby increase steady-state SOC content over the same range of C input levels. We propose the term “effective stabilization capacity” to denote these asymptotic relationships between SOC content and C inputs at levels smaller than the soil C saturation level, due to factors other than the physicochemical properties of the soil. If disturbance dominates SOC content such as in tilled agroecosystems, a soil cannot achieve the saturation level, but could reach an effective stabilization capacity commensurate with the input level. Although these soils are not approaching C saturation level, the asymptotic relationship between C input level and SOC content in these soils is indicative of C saturation dynamics.

The theoretical distinction between effective stabilization capacity and C saturation level explains why, over similar ranges of C additions, the different treatments established on the same Sanborn soil can be approaching two asymptotes even though they have the same theoretical C saturation level. This also implies that none of the soils included in our present analyses are approaching their absolute saturation level, but rather are approaching their effective stabilization capacity because of tillage-induced disturbances.

Summary

Soils that show no increase in SOC stock with increasing C input levels as well as high C content soils having decreased C stabilization efficiency suggest an upper limit, or saturation limit to whole-soil C. This hypothesis is contrary to the models that assume linearity between C input level and C stocks at steady-state. We used hypothesis-based model testing to assess the relative support in long-term agroecosystem data for C saturating (asymptotic) versus non-saturating (linear) behavior between C input level and SOC content at steady state. The C saturation model was the best approximation of the data pooled across all sites, suggesting that across a wide range of C input levels, C stabilization efficiency decreased in soils with high SOC content. Given our data, there was less than 1% “probability” that the linear model was the best. However, within individual sites, only Sanborn showed a C saturation best-fit, whereas four sites had a linear model best-fit. All other sites had both a small range in C input levels and a small sample size, which greatly penalized AIC_c support for the model given the small amount of data. These results underscore a lack of range in C input level as well as a general scarcity of data with which to explicitly test these hypotheses.

The fact that the C saturation model fits the pooled site data suggests that not only the silt + clay pool saturates with respect to C, but other, less-protected C pools (i.e. the non-protected pool) do as well. However, we do suggest, based on data from Sanborn, that agroecosystems under disturbance may never approach an absolute C saturation level, due to the effects of tillage disturbance accelerating SOC decomposition although within treatments, asymptotic SOC dynamics are observed. We propose the term effective stabilization capacity, which defines the maximum C sequestration possible with increasing C input level under a particular management scenario.

The true soil C saturation level may be of small practical importance, as large organic C inputs must be maintained over long time periods to sequester large quantities of C. Of more practical interest is the behavior of soils as they approach their effective stabilization capacity as well as the influence of C saturation deficit on the efficiency of SOC accumulation in non-saturated soils. Although current

simulation models are fairly successful in explaining SOC accumulation in degraded agricultural soils, the validity of these models need to be further examined under scenarios of increasing C input levels and increasing SOC contents, where decreasing SOC stabilization efficiency due to saturation effects will be manifested. However, additional research is needed to firmly establish the validity of the saturation concept and better quantify the controls on SOC kinetics for C-rich soils.

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