Carbon accumulation in a bare fallow Chernozem soil with high carbon input rates

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Abstract
A multitude of models for soil organic carbon (SOC) dynamics are available to predict management impacts on SOC dynamics in its interaction with environmental factors. Most models include one SOC pool that has no or a very slow, negligible turnover. For this pool of long-term stabilized (LTS) organic matter, we assumed a dynamic physical protection, whereby organic matter is protected in micropores and exposed to microbial access due to soil structure dynamics. Dynamics of the LTS pool is of special interest because of its very long turnover time. Therefore, it is of special importance whether the size of this pool is unlimited or if it reaches a saturation state. We investigated this topic by applying the CCB (CANDY Carbon Balance) model on a dataset from a long-term experiment that started in 1983 in Bad Lauchstädt, Germany on a Haplic Chernozem and includes bare fallow treatments with the application of farmyard manure at different rates from 5 to 20 kg m⁻² year⁻¹. Observations of SOC development over time supported our hypothesis about the existence of a saturation effect and were used to calibrate the CCB model with the hypothetical assumption of a limited LTS pool size. The model results suggest an upper limit of the LTS pool of 1.07 M% (percent of dry soil mass) SOC for the Bad Lauchstädt site. Furthermore, model calibration of LTS turnover revealed that organic matter in this pool is released from its protected state at a very low rate of 0.003 year⁻¹.

Highlights
• Long-term bare fallow field experiment with FYM input rates up to 20 kg m⁻²
• Predicted long-term SOC dynamics reflect observations
• Proof of non-linear relationship between SOC storage and carbon input rate
• Evidence for limited protection capacity for SOC (saturation effect)

KEYWORDS
bare fallow, farmyard manure, modelling, saturation, soil organic carbon

1 INTRODUCTION
Soil organic carbon (SOC) is a well-established indicator to assess soil functions, especially for carbon (C) sequestration, which is currently being focused on as a possible means to counteract greenhouse gas emissions (Minasny et al., 2017; Smith et al., 2018; Tang, Kragt, Hailu, & Ma, 2016). SOC changes develop very slowly.
Therefore, long-term field experiments have to provide the essential experimental background for the modelling that is required to predict the effect of potential actions that change the C cycling in soil (Fan et al., 2019; Farina et al., 2018; Karhu et al., 2012). Many well-proven models use first-order kinetic approaches to describe C turnover in soils (Smith et al., 1997; Stockmann et al., 2013) giving reasons for the generalized model of Sierra, Müller, and Trumbore (2012). The turnover rates in these models are proportional to pool sizes and are further moderated by environmental conditions in the pore space due to soil texture. Approaches of this type predict, over the whole time course, a linear relationship between the input rate of fresh organic C and SOC accumulation (Sierra, Ceballos-Núñez, Metzler, & Müller, 2018) in soil, whereby the increase of C stocks is only limited by the availability of fresh organic matter (OM).

In contrast to the hypothesis of linearity between C input and C storage in soil, Kolbe (2010) observed decreasing SOC retention with increasing application rates. Based on an analysis of 471 treatments with farmyard manure (FYM) application from 240 long-term field experiments, he applied this successfully in the STAND approach (Kolbe, 2010) for the calculation of SOC balance. Similarly, Tan, Fan, He, Luo, and Peng (2014) found a non-linear relation between C input and SOC accumulation and concluded that the proportion of external carbon that is integrated into SOM decreases with increase of the SOC content.

These empirical findings imply an indication of possible non-linearity between C input and C storage in soil but do not allow a mechanistic explanation for this behaviour. Obviously, this detected non-linearity is reducing the rate of SOC accumulation. Qin and Huang (2010) assumed an upper limit for accumulation of total SOC stock and used a global dataset of long-term field experiments to quantify this amount, depending on parameters of climate (temperature and rainfall, including irrigation input) and soil (clay content and pH value).

The exclusion of microbes and enzymes from pores was identified as a key protection mechanism for occluded soil organic matter (SOM) in microaggregates (Sollins, Homann, & Caldwell, 1996; von Lützow et al., 2008). Similarly, Carrington, Herness, Dyda, Plante, and Six (2012) concluded that physical and chemical protection mechanisms govern long-term C storage and control C saturation. This can be connected to the hypothesis of Hassink (1997) about a potential C saturation in soils that is controlled by the number of particles <20 μm.

Explaining the nature of physical protection, Du, Wu, Zhang, Guo, and Meng (2014) supposed an aggregation effect. They found that the non-protected coarse particulate OM was still increasing with higher manure application rates, whereas C in micro- and small macro-aggregates exhibited no additional accumulation with higher manure application. Moreover, emphasizing aggregation as the key process for long-term protection of SOC requires taking into account soil aggregate turnover as well (Plante & McGill, 2002).

With the development of X-ray microtomography to analyse soil structure it is possible to change the view that aggregates are the building blocks of soil in the soil pore system to the more general view of soil structure dynamics (Rabot, Wiesmeier, Schlüter, & Vogel, 2018). Currently, the potential of the soil pore system to control C stabilization (Kravchenko & Guber, 2017) gets more and more consideration (Bradford et al., 2019) as the physical location of organic molecules can exclude them from microbial turnover (Lehmann & Kleber, 2015). Here we have to take into account that soil structure dynamics is not necessarily changing pore size distribution when microscopic destruction and formation of pores are in balance (Diel, Vogel, & Schlüter, 2019).

Campbell and Paustian (2015) concluded from their literature review that there is much evidence to characterize SOM as a complex mixture of smaller biopolymers distributed across the soil matrix and place an emphasis on physical protection, including mineral associations that reduce microbial accessibility to organic matter. The results of McCarthy et al. (2008) imply that OM preservation arises from the evolution of the architectural system of microaggregates during their formation and stabilization, where pores at the submicron scale within micro-aggregates may become completely filled with OM. Similar “pore filling” mechanism effects were described by Zimmerman, Goyne, Chorover, Komarneni, and Brantley (2004). However, Mayer, Schick, Hardy, Wagai, and McCarthy (2004) propose that not only enclosure within pores but also the structure of the pore network contribute to protection of OM.

Stewart, Paustian, Conant, Plante, and Six (2007) did show that the assumption of a saturation level of SOC leads mathematically to a reduced C retention with increasing application rates. Following this line of reasoning, we hypothesize that long-term stabilization of SOC is controlled by physical protection related to soil structure dynamics from formation and destruction of pores, which is similar to formation and destruction of soil aggregates, and moreover, that the capacity to protect C within the soil pore system may be limited. Furthermore, it can be expected that growth of the protected part of SOC will be dependent on OM input to soil. Therefore, a protection limit will be reached first in treatments with higher C input rates. This will appear as an increase of the overall SOC turnover rate or a decrease of the humification rate, because a greater part of the added C is
excluded from protection and allocated to microbial accessible pools.

Acknowledging the conclusion of Stewart et al. (2007) that in many long-term field experiments the range of C input rates was too small to show saturation behaviour, we selected a dataset from a long-term field experiment with very high C input rates. We tested the hypothesis that an increasing C input rate leads to a decreasing SOC retention and aimed to explain the observations as limited C protection within a continually changing soil pore system that is comparable to a dynamic reformation of aggregates.

2 MATERIAL AND METHODS

2.1 Experimental data

The empirical basis for the study was the field experiment High Manure Doses Bad Lauchstädt (HMBDL), Sachsen-Anhalt, Germany (51°24'N, 11°53'E). This long-term field experiment was initiated in 1983 in order to investigate the effects of extreme input rates of organic amendments on crop yield, crop quality and soil fertility. The soil type in this experiment is Haplic Chernozem (FAO) (USDA: Mollisol), consisting of 21.0% clay, 67.8% silt and 11.2% sand. The mean annual temperature and precipitation of the last three decades at the site are 8.9°C and 481 mm, respectively. The field experiment was laid out as a two-factorial block experiment in two replicates, with factor 1 being FYM application and factor 2 land use (cropped or bare fallow). The total area of the experiment is 800 m², with individual areas of 64 m² for cropped plots and 32 m² for the bare fallow plots. In order to reduce errors from unknown C inputs from roots and plant residues, we restricted this study to the bare fallow treatments (b1, b2, b3 and b4) of the experiment and ignored the cropped treatments. FYM was applied every year in autumn before ploughing at rates of 0, 5, 10 and 20 kg m⁻² fresh matter for the treatments b1, b2, b3 and b4, respectively. The FYM from cattle farming had an average dry matter content of 25.2%, 37.2% carbon, and 2.9% nitrogen concentration in dry matter. This results in annual C addition rates of 0, 0.47, 0.94 and 1.87 kg m⁻², respectively.

Soil samples were taken from the plough horizon (0–30 cm) every year in October. Approximately 25 single cores were taken with an auger (1 cm diameter). The pooled soil samples of each plot were sieved to <2 mm and air-dried. Stones and visible plant residues were removed. Total carbon (TC) was determined via combustion in a C/H/N analyser (Vario El III, Elementar-Hanau). No inorganic C was detected, so the reported TC values represent the total SOC.

2.2 Calculation of SOC stocks and SOC accumulation

Calculations of SOC stocks were based on the “equivalent soil mass” method suggested by Wendt and Hauser (2013). As no bulk density observations were available, we used the approach of Ruehlmann and Körschens (2009) to calculate bulk densities for each year according to the experimentally determined SOC concentration and used the minimum value of these bulk densities as the reference to calculate C stocks for a constant soil mass of 350.4 kg m⁻². This corresponds to a calculated virtual soil depth from 24 to 30 cm within the actual sampling depth according to the varying bulk density. The SOC accumulation was then calculated as the difference between the SOC stock in a given year and the initial SOC stock in 1983 when the experiment started. Assuming a linear behaviour between C input and C storage in soil, we used the treatment with low FYM input (5 kg m⁻²) as the reference, extrapolated the SOC accumulation to the treatments with higher FYM input rates, and calculated the difference between the expected and observed SOC accumulation as apparently “missing” SOC accumulation. The used data set is given in Table S1 as supporting information. For further analysis we used the dataset from 1990 to 2016. Seven of 99 data records were excluded from further analysis because:

- treatment b2 had negative SOC accumulation in 2012 and extremely high SOC accumulation in 2015, leading to unreasonable differences between b3 and b4 (four records);
- treatment b3 had a negative SOC accumulation in 2005 (one record); and
- treatment b4 had extremely low SOC accumulation in 2005 and 2013 (two records).

2.3 Statistical analysis

We investigated if there exists a certain amount of SOC stock above which the SOC accumulation becomes nonlinear in relation to the C-input with FYM and used the R package segmented as described by Muggeo (2017) for segmented linear regression analysis to identify the breakpoint, where the system is no longer behaving linearly. Further, we applied an ANOVA with the HSD test from the R package agricolae to show that the average
values for the apparently “missing” SOC accumulation before and after the breakpoint are significantly different.

### 2.4 Model approach with limited physical protection

The CCB model (CANDY Carbon Balance), a derivative of the CANDY model (Carbon And Nitrogen Dynamics), has been applied successfully in a number of field experiments (Franko, Kolbe, Thiel, & Ließ, 2011; Franko & Spiegel, 2016). A special feature of the CCB model is the state variable biologic active time (BAT) to express the effect of site conditions on SOM turnover (Franko & Oelschlägel, 1995). Recently, the model was extended to predict also the changes of the physically stabilized OM in relation to SOC-driven changes of soil structure (Franko & Merbach, 2017). This approach allowed a first interpretation of the role of soil structure in C stabilization but has a very static character as any C that is protected within the fine soil pores will never be released if SOC remains constant or is further increasing. Refining that approach, the CCB model was reconfigured and we hypothesized that processes that change the soil pore network (like destruction and reformation of aggregates in soil) may be responsible for an exchange of SOM between protected and unprotected states, thus leading to a limited capacity for this protection in a steady state where the same amount of carbon is released and re-protected.

CCB distributes all SOM over an active (A-SOM), a stabilized (S-SOM) and a long-term stabilized (LTS-SOM) pool (Figure 1). We considered the LTS pool related to the space of micropores (associated with the permanent wilting point). Along with the microbial-driven matter dynamics in the easily decomposable pools (A-SOM and S-SOM), a matter transfer between A-SOM and LTS pools is considered. A part of the newly formed SOM (Crep) is captured inside micropores and thus shielded from decomposition, whereas a part of C-LTS is released from protection and exposed to microbial turnover. This exchange is modelled in annual timesteps. The annual change of C_{LTS} (ΔC_{LTS}) is given by:

\[
ΔC_{LTS} = k_d \cdot (\lambda \cdot C_{rep} - C_{LTS})
\]

with \( \lambda = \frac{C_{LTS}(\infty)}{C_A(\infty) + C_S(\infty) + C_{LTS}(\infty)} \), \( k_d, k_m \): turnover constants of unprotected SOM pools, \( k_d \): part of the inner soil surface released from soil micropores. At the end of each timestep the matter balance is completed by

\[
C_A(t_1) = C_A(t_0) - ΔC_{LTS} \quad \text{and} \quad C_{LTS}(t_1) = C_{LTS}(t_0) + ΔC_{LTS}
\]

Furthermore, the growth of the LTS pool is limited to a site-specific value \( C_{sat} \) by the condition \( C_{LTS} = \text{MIN}(C_{LTS}, C_{sat}) \). If the saturation level is reached, \( ΔC_{LTS} \) is set to zero, with the consequence that all Crep is available for microbial turnover, which results in a decreasing rate of SOC accumulation.

The value of the parameter \( \lambda = 3,038 \) was determined using a version of the CCB model, where the LTS accumulation is controlled only by the change of permanent wilting point (Franko & Merbach, 2017), to drive the soil to a steady state with different C inputs. This parameter has a time dimension that relates to BAT, as explained above, to be compatible with the other turnover processes of the model. The product \( k_d \cdot \lambda \) quantifies the part of newly formed SOC that is protected by soil structure, whereas \( k_d \) alone controls the release of C into an unprotected state due to changes of the inner soil surface comparable to a degradation of soil aggregates, where parts of the soil from micropores without considerable biological activity are transformed to larger pores with better potential for microbial turnover. The parameters \( k_d \) and \( C_{sat} \) were fitted to the observed SOC concentrations of all four treatments using the downhill simplex method of Nelder and Mead (1965) to minimize root mean square error (RMSE).

### 3 RESULTS

As a first step, we calculated the average SOC accumulation for the first 10 years, with annual SOC observations from 1990 to 1999, and compared these results with the data from 2007 to 2016. In Figure 2 the accumulation data are plotted against the FYM input rate. The broken
line is the average effect of the treatments with lower FYM input rates, which is extrapolated and compared with the SOC accumulation at the maximum FYM input rate. In the theory of a linear relationship between C input and C storage in soil, one would expect all data for each time interval to be on one line. This may be valid for the first time interval from 1990 to 1999, where it is still reasonable that the small differences between point and line are caused by the variability of SOC determination. Looking at the second time interval from 2007 to 2016, it is obvious that the observed accumulation in the treatment with the maximum FYM input rate is far below the result expected from the assumption of linearity. This supports the hypothesis that the non-linear relation between C input and C storage in soil is not directly related to the input rate, but it is rather a consequence of a limited protection capacity after a certain level of SOC accumulation.

We explored this effect in more detail by comparing the expected SOC accumulation for a system with linear behaviour with the observed SOC accumulation using the treatment with the lowest FYM input rate as reference. Accordingly, the expected SOC accumulation is given by the observed reference value multiplied by the relationship between the FYM input rate of a given treatment and the reference. A linear system would accumulate with 10 kg m$^{-2}$ annual FYM input, double the amount of the reference treatment of 5 kg m$^{-2}$. The difference between the expected and the observed relationship between the FYM input rate of a given treatment and the reference. A linear system would accumulate with 10 kg m$^{-2}$ annual FYM input, double the amount of the reference treatment of 5 kg m$^{-2}$. The difference between the expected and the observed accumulation.
accumulation is referred to as apparently “missing”, which is zero as long as the system behaviour is linear. Segmented regression provided an estimation of a breakpoint at an SOC accumulation of 4.6 ± 0.9 kg m\(^{-2}\), where the slope of the second segment above this breakpoint is significantly different from zero (Figure 3). In a second step we grouped the data according to this breakpoint for an ANOVA that did confirm a different behaviour if SOC accumulation is below or above the critical SOC stock of 4.6 kg m\(^{-2}\) (Figure 4).

Assuming the SOC is internally structured into pools of different turnover times, this can be explained with the hypothesis that the pool with lower turnover time gets saturated (meaning it cannot store any more C) and further C input is stored in the pool with faster turnover times, thus apparently reducing the C retention in soil.

The discrepancy between observations and expected results assuming a linear relation between C-input and C-stock gave a reason to use a model with dynamic physical protection of SOC in soil micropores to possibly explain the experimental results.

The model results (Figure 5) indicate better performance particularly for treatments b3 and b4. It is obvious that the observed approach of a steady state cannot be explained by the model configuration without a limited LTS pool. Along with the initial SOC value in the experiment, the model parameters \(k_d\) and \(C_{sat}^{LTS}\) were fitted to the complete dataset, and this resulted in the estimation of an initial SOC value of 2.09 ± 0.02 M%. The \(k_d\) parameter (0.003 ± 0.002 year\(^{-1}\)) shows that the exchange rate between protected and unprotected SOM at this site is very low. The maximum amount of C that is protected in the LTS pool was determined to be 1.07 ± 0.02 M% SOC.

**FIGURE 5** Comparison of observed soil organic carbon (SOC) values (dots) and simulation results assuming a saturation effect (continuous line) and without saturation effect (broken line). Vertical lines indicate the standard deviation of the observed SOC value.
The modelled initial value of SOC is higher than the observation of 1.86 M% SOC, but this may be explained by the generally high variability observed in this experiment. The average standard deviation of the observed SOC values (in M%) is 0.2 for treatment b1 and increases to 0.41, 0.31 and 0.3 for treatments b2, b3 and b4, respectively. We assessed the model performance using the relationship between RMSE of the model calibration and the experimental error as given by their average standard deviation. If limited LTS storage is assumed, the first three treatments show a similar performance, where the model error is about 25% higher than the observation error (Figure 6). Allowing unlimited storage of SOC in the LTS pool increases model errors for treatments with annual FYM input rates higher than 5 kg m\(^{-2}\). However, for the highest FYM input rate in treatment b4, even the approach with limitation of C storage results in a model error that is still higher than in the first three treatments. This suggests there may be other processes besides the assumed interplay of protection and exposure that require additional consideration in modelling.

The results of this study allow the assumption of a limited protection capacity of C in the LTS pool of the CCB model. So far it is not clear how this limitation will affect the overall SOC storage in the soil of this experiment. At the Bad Lauchstädt site, the very high FYM input rates over a time interval of three decades led to an SOC concentration of more than 4%, representing an estimated stock of about 14 kg m\(^{-2}\). Despite the required C input being beyond reasonable limits, the results show a huge theoretical sequestration potential that exceeds the value of 7.12 kg m\(^{-2}\) predicted by the model from Qin and Huang (2010) for the site conditions of our experiment.

Although discussion of limited carbon protection will lead to an improved understanding of SOC dynamics in general, this has admittedly little importance for model predictions in conditions where management follows good agricultural practice with application rates that are usually limited (mainly due to restrictions on the amount of nitrogen) and clearly below the application rates of this experiment.
DATA AVAILABILITY STATEMENT
The data that support the findings of this study are included as supplementary material (Table S1).

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REFERENCES
Bradford, M. A., Carey, C. J., Atwood, L., Bossio, D., Fenichel, E. P., Gennet, S., ... Wood, S. A. (2019). Soil carbon science for policy and practice. Nature Sustainability, 2, 1070–1072. https://doi.org/10.1038/s41893-019-0431-y

Campbell, E. E., & Paustian, K. (2015). Current developments in soil organic matter modeling and the expansion of model applications: A review. Environmental Research Letters, 10, 123004. http://dx.doi.org/10.1088/1748-9326/10/12/123004

Carrington, E. M., Hernes, P. J., Dyda, R. Y., Plante, A. F., & Six, J. (2012). Biochemical changes across a carbon saturation gradient: Lignin, cutin, and suberin decomposition and stabilization in fractionated carbon pools. Soil Biology and Biochemistry, 47, 179–190. https://doi.org/10.1016/j.soilbio.2011.12.024

Diel, J., Vogel, H.-J., & Schlüter, S. (2019). Impact of wetting and drying cycles on soil structure dynamics. Geoderma, 345, 63–71. https://doi.org/10.1016/j.geoderma.2019.03.018

Du, Z.-I., Wu, W.-I., Zhang, Q.-z., Guo, Y.-b., & Meng, F.-q. (2014). Long-term manure amendments enhance soil aggregation and carbon saturation of stable pools in North China plain. Journal of Integrative Agriculture, 13, 2276–2285. https://doi.org/10.1007/S11218-014-0802-6

Fan, J., McConkey, B. G., Liang, B. C., Angers, D. A., Janzen, H. H., Kröbel, R., ... Smith, W. N. (2019). Increasing crop yields and root input make Canadian farmland a large carbon sink. Geoderma, 336, 49–58. https://doi.org/10.1016/j.geoderma.2018.08.004

Farina, R., Testani, E., Campanelli, G., Leteo, F., Napoli, R., Canali, S., & Tittarelli, F. (2018). Potential carbon sequestration in a Mediterranean organic vegetable cropping system. A model approach for evaluating the effects of compost and agro-ecological service crops (ASCs). Agricultural Systems, 162, 239–248. https://doi.org/10.1016/j.agsy.2018.02.002

Franco, U., Kolbe, H., Thiel, E., & Ließ, E. (2011). Multi-site validation of a soil organic matter model for arable fields based on generally available input data. Geoderma, 166, 119–134. https://doi.org/10.1016/j.geoderma.2011.07.019

Franco, U., & Merbach, I. (2017). Modelling soil organic matter dynamics on a bare fallow Chernozem soil in Central Germany. Geoderma, 303, 93–98. https://doi.org/10.1016/j.geoderma.2017.05.013

Franco, U., & Oelschlägel, B. (1995). Einfluss von klima und textur auf die biologische aktivität beim umsatz der organischen bodensubstanz. Archives of Agronomy and Soil Science, 39, 155–163. https://doi.org/10.1080/0365034909365898

Franco, U., & Spiegel, H. (2016). Modeling soil organic carbon dynamics in an Austrian long-term tillage field experiment. Soil and Tillage Research, 156, 83–90. https://doi.org/10.1016/j.still.2015.10.003

Hassink, J. (1997). The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant and Soil, 191, 77–87. https://doi.org/10.1023/a:1004213929699

Karhu, K., Gärdnäss, A. I., Heikkinen, J., Vanhala, P., Tuomi, M., & Liski, J. (2012). Impacts of organic amendments on carbon stocks of an agricultural soil — Comparison of model-simulations to measurements. Geoderma, 189–190, 606–616. https://doi.org/10.1016/j.geoderma.2012.06.007

Kolbe, H. (2010). Site-adjusted organic matter–balance method for use in arable farming systems. Journal of Plant Nutrition and Soil Science, 173, 678–691. https://doi.org/10.1002/jpln.200900175

Kravchenko, A. N., & Guber, A. K. (2017). Soil pores and their contributions to soil carbon processes. Geoderma, 287, 31–39. https://doi.org/10.1016/j.geoderma.2016.06.027

Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. Nature, 528, 60–68. https://doi.org/10.1038/nature16069

Mayer, L. M., Schick, L. L., Hardy, K. R., Wagai, R., & McCarthy, J. (2004). Organic matter in small mesopores in sediments and soils. Geochimica et Cosmochimica Acta, 68, 3863–3872. https://doi.org/10.1016/j.gca.2004.03.019

McCarty, J. F., Ilavsky, J., Jastrow, J. D., Mayer, L. M., Perfect, E., & Zhuang, J. (2008). Protection of organic carbon in soil microaggregates via restructuring of aggregate porosity and filling of pores with accumulating organic matter. Geochimica et Cosmochimica Acta, 72, 4725–4744. https://doi.org/10.1016/j.gca.2008.06.015

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., ... Winowiecki, L. (2017). Soil carbon 4 per mille. Geoderma, 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Muggeo, V. M. R. (2017). Interval estimation for the breakpoint in segmented regression: A smoothed score-based approach. Australian & New Zealand Journal of Statistics, 59, 311–322. https://doi.org/10.1111/ansz.12200

Nelder, J. A., & Mead, R. (1965). A simplex method for function minimization. The Computer Journal, 7, 308–313. https://doi.org/10.1093/comjnl/7.4.308

Plante, A. F., & McGill, W. B. (2002). Soil aggregate dynamics and the retention of organic matter in laboratory-incubated soil with differing simulated tillage frequencies. Soil and Tillage Research, 66, 79–92. https://doi.org/10.1016/S0167-1987(02)00015-6

Qin, Z. C., & Huang, Y. (2010). Quantification of soil organic carbon sequestration potential in cropland: A model approach. Science China Life Sciences, 53, 868–884. https://doi.org/10.1007/s11427-010-4023-3

Rabot, E., Wiesmeier, M., Schlüter, S., & Vogel, H. J. (2018). Soil structure as an indicator of soil functions: A review. Geoderma, 314, 122–137. https://doi.org/10.1016/j.geoderma.2017.11.009

Ruehlmann, J., & Körschens, M. (2009). Calculating the effect of soil organic matter concentration on soil bulk density. Soil Science Society of America Journal, 73, 876–885. https://doi.org/10.2136/sssaj2007.0149

Sierra, C. A., Ceballos-Núñez, V., Metzler, H., & Müller, M. (2018). Representing and understanding the carbon cycle using the theory of compartmental dynamical systems. Journal of
Advances in Modeling Earth Systems, 10, 1729–1734. https://doi.org/10.1029/2018ms001360
Sierra, C. A., Müller, M., & Trumbore, S. E. (2012). Models of soil organic matter decomposition: The SoilR package, version 1.0. Geoscientific Model Development, 5, 1045–1060. https://doi.org/10.5194/gmd-5-1045-2012
Smith, P., Lutfalla, S., Riley, W. J., Torn, M. S., Schmidt, M. W. I., & Soussana, J.-F. (2018). The changing faces of soil organic matter research. European Journal of Soil Science, 69, 23–30. https://doi.org/10.1111/ejss.12500
Smith, P., Smith, J. U., Powlson, D. S., McGill, W. B., Arah, J. R. M., Chertov, O. G., … Whitmore, A. P. (1997). A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma, 81, 153–225. https://doi.org/10.1016/S0016-7061(97)00087-6
Sollins, P., Homann, P., & Caldwell, B. A. (1996). Stabilization and destabilization of soil organic matter: Mechanisms and controls. Geoderma, 74, 65–105. https://doi.org/10.1016/S0016-7061(96)00036-5
Stewart, C. E., Paustian, K., Conant, R. T., Plante, A. F., & Six, J. (2007). Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry, 86, 19–31. https://doi.org/10.1007/s10533-007-9140-0
Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., Henakaarachchi, N., Jenkins, M., … Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems & Environment, 164, 80–99. https://doi.org/10.1016/j.agee.2012.10.001
Tan, B., Fan, J., He, Y., Luo, S., & Peng, X. (2014). Possible effect of soil organic carbon on its own turnover: A negative feedback. Soil Biology and Biochemistry, 69, 313–319. https://doi.org/10.1016/j.soilbio.2013.11.017
Tang, K., Kragt, M. E., Hailu, A., & Ma, C. (2016). Carbon farming economics: What have we learned? Journal of Environmental Management, 172, 49–57. https://doi.org/10.1016/j.jenvman.2016.02.008
von Lützow, M., Kögel-Knabner, I., Ludwig, B., Matzner, E., Flessa, H., Ekschmitt, K., … Kalbitz, K. (2008). Stabilization mechanisms of organic matter in four temperate soils: Development and application of a conceptual model. Journal of Plant Nutrition and Soil Science, 171, 111–124. https://doi.org/10.1111/j.1365-3091.2008.01070.x
Wendt, J. W., & Hauser, S. (2013). An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. European Journal of Soil Science, 64, 58–65. https://doi.org/10.1111/ejss.12002
Zimmerman, A. R., Goyne, K. W., Chorover, J., Komarneni, S., & Brantley, S. L. (2004). Mineral mesopore effects on nitrogenous organic matter adsorption. Organic Geochemistry, 35, 355–375. https://doi.org/10.1016/j.orggeochem.2003.10.009

SUPPORTING INFORMATION
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