



A simple method for estimating the influence of eroding soil profiles on atmospheric CO₂

S. A. Billings,¹ R. W. Buddemeier,² D. deB. Richter,³ K. Van Oost,⁴ and G. Bohling²

Received 7 May 2009; revised 8 September 2009; accepted 21 October 2009; published 2 April 2010.

[1] Although soil erosion has often been considered a net source of atmospheric carbon (C), several recent studies suggest that erosion serves as a net C sink. We have developed a spreadsheet-based model of soil organic C dynamics within an eroding profile (Soil Organic Carbon, Erosion, Replacement, and Oxidation (SOrCERO)) that calculates effects of soil organic carbon (SOC) erosion and altered SOC oxidation and production on the net exchange of C between the eroding profile and atmosphere. SOrCERO suggests that erosion can induce a net C sink or source, depending on management practices, the extent to which SOC oxidation and production characteristics change with erosion, and the fate of eroded SOC. Varying these parameters generated a wide range of C source and sink estimates (maximum net source and sink of 1.1/3.1 Pg C yr⁻¹ respectively, applying results globally), highlighting research needs to constrain model estimates. We invite others to download SOrCERO (http://www.kbs.ku.edu/people/staff_www/billings/index.html) to test conceptual models and eroding soil profiles of interest in a consistent, comparable fashion.

Citation: Billings, S. A., R. W. Buddemeier, D. deB. Richter, K. Van Oost, and G. Bohling (2010), A simple method for estimating the influence of eroding soil profiles on atmospheric CO₂, *Global Biogeochem. Cycles*, 24, GB2001, doi:10.1029/2009GB003560.

1. Introduction

[2] Until recently, soil erosion has often been considered to be a net source of carbon (C) to the atmosphere [Lal, 2003]. Certainly, soil erosion can induce significant declines in the soil organic carbon (SOC) content within an eroded profile, and some fraction of eroded SOC likely is oxidized in transit or upon deposition [Schlesinger, 1990, 1995]. The degree to which soil erosion influences the size of the atmospheric C pool, however, depends on a multitude of factors in addition to the movement of organic C across a landscape and the fate of that material. Erosion can induce changes in soil-atmosphere C exchange via altered patterns of oxidation of SOC remaining at the eroding site and of the SOC originally present at the depositional site, as well as via SOC production in both locations. Oxidation of eroded SOC, whether in transit or at a depositional site, is therefore only one component of the total change in soil-atmosphere CO₂

flux. The concept of SOC production at an eroding site offsetting oxidation of eroded SOC (“dynamic replacement”) was first introduced by Stallard [1998] and has been explored in several modeling and measurement studies [Harden *et al.*, 1999; Smith *et al.*, 2001; Liu *et al.*, 2003; Fang *et al.*, 2006; Rosenbloom *et al.*, 2006; Berhe *et al.*, 2007; Jenerette and Lal, 2007; Quine and Van Oost, 2007; Van Oost *et al.*, 2007]. Many of these studies question the role of soil erosion as a globally significant C source of 0.8 to 1.2 Pg yr⁻¹ [Lal, 2003]; recent work, based on multiple eroding profiles, indicates that the net effect of erosional processes may represent a C sink of up to ~0.12 Pg C yr⁻¹ [Van Oost *et al.*, 2007].

[3] Studies suggesting that soil erosion may induce a net C sink typically use a combination of empirical and modeling approaches, as reviewed by Berhe *et al.* [2007]. For example, the radioisotopes ¹³⁷Cs and ¹⁴C have permitted refined assessments of SOC fluxes across well defined landscapes, and accompanying models have generated estimates of the net influence of these fluxes and related processes on the atmospheric C pool size [Harden *et al.*, 1999; Fang *et al.*, 2006; Van Oost *et al.*, 2007]. Liu *et al.* [2003] adapted an ecosystem process model to consider C dynamics at erosional and depositional sites described in an earlier study [Harden *et al.*, 1999]. These and other recent studies, in conjunction with the recent review of the issue [Berhe *et al.*, 2007], help clarify the importance of “dynamic replacement” [Stallard, 1998] in contributing to the potential net C sink induced by soil erosion.

¹Department of Ecology and Evolutionary Biology and Kansas Biological Survey, University of Kansas, Lawrence, Kansas, USA.

²Kansas Geological Survey, University of Kansas, Lawrence, Kansas, USA.

³Nicholas School of the Environment and Earth Sciences, Duke University, Durham, North Carolina, USA.

⁴Department of Geography, University of Louvain, Louvain-la-Neuve, Belgium.

[4] There remains significant controversy about the net effect of landscape-scale soil erosion on the atmospheric C pool, for two key reasons. First, current models exploring how erosion influences soil-atmosphere C fluxes rely on fairly detailed parameterization of the relevant soil profiles. The site-specific properties of eroding profiles and depositional areas make applying these models to broader, heterogeneous landscapes challenging (however, see *Smith et al.* [2001, 2005]).

[5] A second key reason for the controversy motivated the current work. Investigators have invoked widely varying assumptions about eroding and depositional profiles, as well as the fate of eroded SOC, rendering comparisons among studies extremely challenging. For example, *Van Oost et al.* [2007] indicate that approximately 26% of eroded SOC is replaced at the eroding site, based on historical data from agricultural sites. In contrast, *Smith et al.* [2001, 2005] implicitly assume that all eroded SOC is replaced via SOC production at the eroding site. *Harden et al.* [1999] address the influence of soil erosion on SOC dynamics by amending a biogeochemistry process model with an external, subsoil compartment. In contrast, *Liu et al.* [2003] introduce multiple subsoil layers into an adapted model to account for altered SOC dynamics with erosion. Assumptions about oxidation of eroded SOC in transit and upon deposition also range widely, from 0% to 100% [*Lal*, 1995; *Schlesinger*, 1995; *Jacinthe and Lal*, 2001; *Smith et al.* 2001; *Berhe et al.* 2007]; we know that the fate of this material is a critical determinant of the influence of erosion on atmospheric CO₂ [*Harden et al.*, 1999]. These variations in assumptions and approaches make study comparisons difficult if not impossible and magnify the controversy surrounding the ultimate influence of soil erosion on the size of the atmospheric C pool.

[6] To address these concerns, we developed a spreadsheet-based model of SOC dynamics within an eroding soil profile (Soil Organic Carbon Erosion, Replacement, and Oxidation (SOrcERO)). Use of SOrcERO requires quantification of model parameters in a way that documents assumptions and will simplify the task of comparing or integrating diverse studies to elucidate key patterns and results. SOrcERO calculates the combined effects of progressive SOC erosion and concurrent SOC oxidation and production on the net exchange of C between the eroding soils and the atmosphere. This net C exchange can be readily assessed as a function of the oxidative fate of eroded SOC. A novel and critical feature of the model is its inclusion of SOC oxidation and production mixing coefficients. These inputs permit the user to define the extent to which each layer retains its originally defined oxidation and production characteristics versus having these rates determined by the layer's new, shallower depth. We developed this model to provide a tool to help determine conditions under which erosion can induce a net atmospheric C source or sink, and the magnitude of that soil-atmosphere C exchange. The model is particularly useful at the hectare to regional scale; we acknowledge that at larger spatial scales, a greater understanding of SOC dynamics at depositional sites is needed to perform a full accounting of the influence of erosion on atmospheric CO₂. However, the model permits

investigators to assess C dynamics within eroding profiles of interest across known time periods or depths of erosion. Equally important, the model highlights the parameters apparently critical for performing a full accounting of the influence of soil erosion and related SOC dynamics on the size of the atmospheric C pool and provides a conceptual framework with which to compare assumptions and results of other studies.

[7] Here we illustrate the operation and capabilities of the model by applying it to two contrasting soil profiles as they experience multiple erosion rates, invoking a wide range of assumptions about SOC dynamics of the profile remaining at the eroding site and eroded material in transit or at depositional sites. Our objectives are to demonstrate (1) how this easily accessible model functions as a tool for evaluating effects of erosion in any soil of interest on the atmospheric C pool and (2) the degree to which commonly used assumptions govern the net C source or sink strength of erosional processes in two soil profiles that contrast in their land use history and SOC content.

2. Model Description and Structure

[8] SOrcERO is a spreadsheet-based (Microsoft Excel™) model that depicts soil layers of user-specified thickness, SOC content, and oxidation and production rates. As currently configured, SOrcERO contains 984 layers, each of which can contain a unique quantity and quality (i.e., reactivity) of SOC. Thus the model avoids the limitations imposed by modeling SOC profiles as homogenous units or as a relatively small number of stacked, homogenous units. The user specifies values for SOC content of each layer, the erosion rate, initial rates of oxidation and production of SOC in each layer, and mixing coefficients (see section 2.4) that determine how the rates of SOC oxidation and production change as erosion progresses. The erosive removal of successive layers, commonly but not necessarily treated as an annual event, is accompanied by recalculation of layer SOC contents according to the specified parameters. The amount of SOC in each remaining layer is defined by the SOC in that layer at the end of the previous time step plus the SOC produced during that year, minus the SOC oxidized during the year (Figures 1 and 2). The model reports incremental and cumulative changes in profile SOC pools and profile C exchange with the atmosphere over time, in units of kg C m⁻². The user is able to view all model outputs at all time steps, as well as excerpted outputs representing user-specified times and/or depths of interest. The model is available for use at http://www.kbs.ku.edu/people/staff_www/billings.

2.1. SOC Content of Each Layer

[9] The user can input SOC content of known depths directly (kg C m⁻²) or as a function of other variables; the model is set up to calculate SOC content from bulk density (g cm⁻³) and SOC concentrations (unitless fractions), both commonly available data sets. All other layers of the profile can then be populated by interpolation between known values.

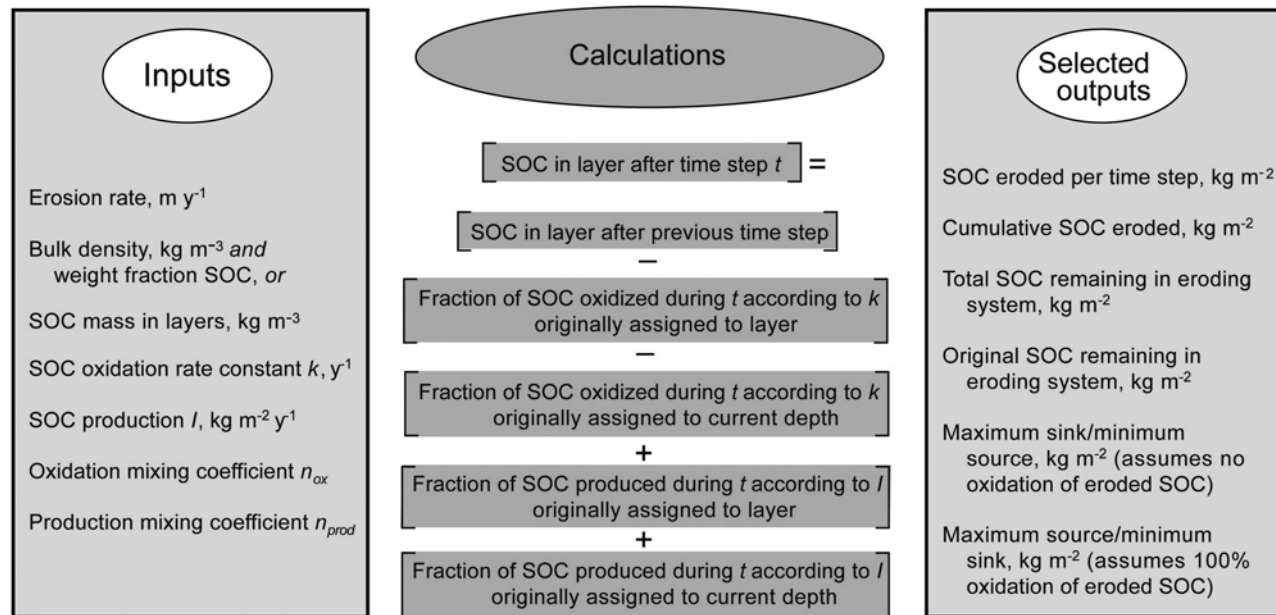


Figure 1. Depiction of required model inputs, the equation that iteratively calculates soil organic C (SOC) content of each layer in a soil profile as erosion proceeds, and selected outputs of the SORCERO model. Oxidation and production mixing coefficients (n_{ox} and n_{prod} , respectively) depend on the assumed changes in SOC oxidation and production throughout the profile as erosion proceeds. See text (sections 2.4, 2.5, and 2.6) for a detailed description of n_{ox} and n_{prod} , function details, and further explanation of output calculations. See Table 1 for a depiction of how n_{ox} and n_{prod} can change with erosion.

2.2. Erosion Rate

[10] The user specifies the erosion rate (e.g., $m\ yr^{-1}$), which defines the thickness of each layer and thus the initial depth of the bottom layer of the profile. As one layer is removed from the eroding surface, the model recalculates SOC contents and associated parameters across the redefined layers. Because the erosion rate defines layer thickness, for comparative studies the user must specify either a common time period or erosion to a common depth to make relevant comparisons between model outputs that represent different erosion rates. The model can be defined as using time steps other than annual and can readily be modified to include nonuniform time or erosion steps. This may be particularly useful for profiles experiencing relatively short-term, episodic erosion.

2.3. SOC Oxidation and Production in Each Layer

[11] The model requires that the user provide a SOC oxidation rate constant (k_{ox} , yr^{-1}) and an amount of SOC produced over the time step of interest (I , $kg\ C\ m^{-2}$; we employ a yearly time step) for each layer. The model version described considers oxidation a first-order process, but this can be replaced to reflect other functions. SOC production I includes the in situ formation of SOC from organic detritus, but it can also represent the arrival of SOC from a source external to the layer (i.e., overland flow or vertical percolation, mechanical or biological disturbance, or organic amendments). Use of I therefore conveys only physical

arrival of SOC in each layer and does not imply assumptions about the productivity or function of the surface ecosystem. We provide details on approaches for populating these values below (section 3).

2.4. Mixing Coefficients for SOC Oxidation and Production

[12] Oxidation and production of SOC are also defined according to mixing coefficients (n_{ox} and n_{prod} , respectively) that are assigned by the user. Values of n_{ox} and n_{prod} , which are independent of each other, depend on the assumed changes in SOC oxidation and production throughout the profile as erosion proceeds. SOC in each layer can retain its originally defined oxidation and production characteristics (termed absolute oxidation and production, n_{ox} and $n_{prod} = 0$), have rates defined as those originally assigned to the current depth in the profile (termed relative oxidation and production, n_{ox} and $n_{prod} = 1$), or exhibit any combination of these two end-members (Table 1). For example, if n_{ox} is assigned a value of 0 in each layer of the eroding profile, k_{ox} of each layer is the value originally assigned to that depth. Alternatively, if n_{ox} is 1 in each layer of the eroding profile, k_{ox} of each layer is the value originally assigned to the depth where the current layer resides: e.g., the current surface layer always retains the original surface value for k_{ox} regardless of its original depth and SOC content. Values of n_{prod} function in an analogous manner. In this way, the user determines the degree to which SOC in an eroding profile experiences reduction in oxidation

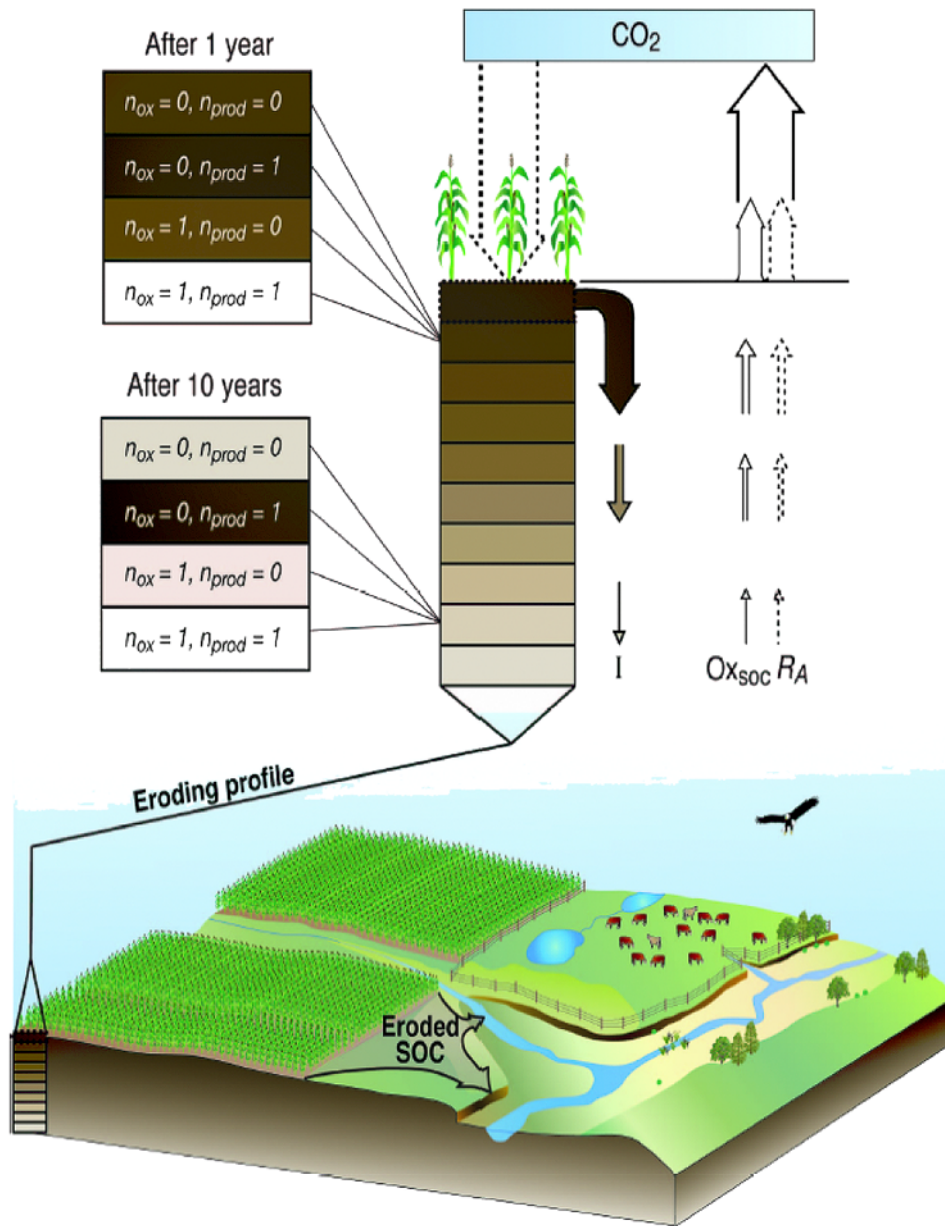


Figure 2. Generalized depiction of major C fluxes into and out of a landscape, with features of the C cycle addressed by SOrCERO highlighted. Each year of erosion removes one surface layer of the profile, which is limited to ten layers for simplicity. Box color qualitatively corresponds to varying soil organic C (SOC) content, with darker colors indicating greater content. Offset boxes depict various possible SOC contents after 1 or 10 years of erosion, dependent on assumptions about SOC oxidation and production characteristics of each layer as erosion proceeds in the SOrCERO model (see text for model details). Ox_{soc} , oxidation of SOC; R_a , autotrophic respiration; n_{ox} , SOC oxidation mixing coefficient; n_{prod} , SOC production mixing coefficient. See section 2 for detailed description of n_{ox} and n_{prod} . Figure 2 depicts only binary (0,1) options for n_{ox} and n_{prod} , but each of these values can be any fraction (Table 1). White boxes are uncolored because assumptions of $n_{ox} = 1$ and $n_{prod} = 1$ can result in many possible SOC contents.

and production with erosion (i.e., low values of n_{ox} and n_{prod} govern relatively low values of oxidation and production, respectively) versus maintenance of rates of these processes more similar to the original values in spite of erosion.

2.5. Model Equation

[13] SOC eroded per time step is calculated simultaneously for every layer as each layer’s original SOC content modified by SOC oxidation and production during the time

Table 1. Depiction of the Influence of Assigned Values of Soil Organic Carbon Oxidation and Production Mixing Coefficients on the SOC Oxidation Rate Constant and Production Rate in the Soil Erosion Model SOrCERO^a

Before Erosion		After Erosion	
Layer	k_{ox}, I	Layer	k_{ox}, I
<i>Relative Assignment of k_{ox} and I Values to the Layers ($n_{ox} = n_{prod} = 1$)</i>			
1	$k_{ox1}, I1$	–	–
2	$k_{ox2}, I2$	–	–
3	$k_{ox3}, I3$	–	–
4	$k_{ox4}, I4$	–	–
5	$k_{ox5}, I5$	5	$k_{ox1}, I1$
6	$k_{ox6}, I6$	6	$k_{ox2}, I2$
7	$k_{ox7}, I7$	7	$k_{ox3}, I3$
8	$k_{ox8}, I8$	8	$k_{ox4}, I4$
<i>Absolute Assignment of k_{ox} and I Values to the Layers ($n_{ox} = n_{prod} = 0$)^a</i>			
1	$k_{ox1}, I1$	–	–
2	$k_{ox2}, I2$	–	–
3	$k_{ox3}, I3$	–	–
4	$k_{ox4}, I4$	–	–
5	$k_{ox5}, I5$	5	$k_{ox5}, I5$
6	$k_{ox6}, I6$	6	$k_{ox6}, I6$
7	$k_{ox7}, I7$	7	$k_{ox7}, I7$
8	$k_{ox8}, I8$	8	$k_{ox8}, I8$
<i>Mixed Assignment of k_{ox} and I Values to the Layers ($n_{ox} = n_{prod} = 0.5$)^a</i>			
1	$k_{ox1}, I1$	–	–
2	$k_{ox2}, I2$	–	–
3	$k_{ox3}, I3$	–	–
4	$k_{ox4}, I4$	–	–
5	$k_{ox5}, I5$	5	$(0.5 \times k_{ox1} + 0.5 \times k_{ox5}), (0.5 \times I1 + 0.5 \times I5)$
6	$k_{ox6}, I6$	6	$(0.5 \times k_{ox2} + 0.5 \times k_{ox6}), (0.5 \times I2 + 0.5 \times I6)$
7	$k_{ox7}, I7$	7	$(0.5 \times k_{ox3} + 0.5 \times k_{ox7}), (0.5 \times I3 + 0.5 \times I7)$
8	$k_{ox8}, I8$	8	$(0.5 \times k_{ox4} + 0.5 \times k_{ox8}), (0.5 \times I4 + 0.5 \times I8)$

^aMixing coefficients allow model users to determine the relative versus absolute SOC oxidation and production as erosion proceeds. Mixing coefficient values for relative oxidation and/or production (n_{ox} and $n_{prod} = 1$) dictate that these rates are determined completely by a layer's current depth in the profile; absolute values (n_{ox} and $n_{prod} = 0$) dictate that each layer retains its originally defined rates. Values between 0 and 1 reflect fraction of layer's SOC with relative oxidation or production characteristics. See text for details of model and assigning mixing coefficient values. The SOC oxidation rate constant is k_{ox} (yr^{-1}); SOC production rate is I ($\text{kg C m}^{-2} \text{yr}^{-1}$).

(e.g., years) between erosion onset and the erosion of this specific layer using equation (1):

$$C_t = C_{t-1} - ((n_{ox} \times C_{t-1}) \times e^{-k_{ox,R}t} + (1 - n_{ox}) \times C_{t-1} \times e^{-k_{ox,A}t}) + n_{prod} \times I_R + (1 - n_{prod}) \times I_A \quad (1)$$

where C_t is the amount of SOC in the layer at the end of time step t , $k_{ox,R}$ is the new SOC oxidation rate constant assigned to the layer (relative), $k_{ox,A}$ is the SOC oxidation rate constant originally assigned to the layer (absolute), t is the time step, I_R is the SOC production rate newly assigned to the layer (relative), and I_A is the SOC production rate originally assigned to the layer (absolute). Note that our usage of I differs from that of Jenny [1941], who presents the differentiated form in equation (2):

$$\frac{\delta C}{\delta t} = I - kC \quad (2)$$

[14] In Jenny's equation, at steady state, $I = kC$. Our version of steady state is defined by equation (3):

$$I = Ce^{-k_{ox}t} \quad (3)$$

because the model changes each layer's inventory by a specified, finite increment or decrement, necessitating use of the integrated, not differential, mode. This approach requires values of I in units of kg m^{-2} , with inferred units of $\text{kg m}^{-2} \text{yr}^{-1}$ if we use an annual time step. The user can change the time step and alter relevant model units accordingly.

2.6. Model Outputs

[15] Model output consists of spreadsheet columns representing parameter values of eleven variables across each layer within the soil profile. We describe them here, in order of presentation in the model file. Negative values represent a C sink, while positive values represent a C source to the atmosphere.

[16] 1. SOC eroded per yearly time step is calculated simultaneously for every layer according to the above equation.

[17] 2. Cumulative SOC eroded is the cumulative sum of item 1 over all layers from layer 1 to the most recently eroded.

[18] 3. Total SOC remaining in the eroded system is the sum of the original SOC contents of all remaining (not yet

eroded) layers as they have been modified by ongoing oxidation and production.

[19] 4. Net loss of SOC (oxidized SOC – SOC input) prior to layer's erosion is the difference between the current (item 1) and original content of the specified layer at the time of erosion (positive value indicates a net gain of SOC; in this case the sign convention is relative to the layer and not the atmosphere).

[20] 5. Cumulative net loss of SOC (oxidized SOC – SOC input) prior to erosion of layers is the cumulative value of item 4 from the start of erosion to the current time step. This value reflects the source or sink behavior of original profile layers now removed by erosion, but does not address any changes in the SOC content of the eroded material after it leaves the profile, or in the original material not yet eroded (see item 7).

[21] 6. Original C content of remaining system is the amount of SOC that would exist in the as yet uneroded layers if there were no oxidation or production as erosion proceeds.

[22] 7. Cumulative, preerosion net loss of SOC in remaining layers (oxidized SOC - SOC input) is the sum of the difference between the current (item 3) and original (item 6) contents of the eroded layers at their individual times of erosion.

[23] 8. Cumulative, original SOC eroded is the amount of SOC that would have been eroded in the absence of any oxidation or production.

[24] 9. System C source (minimum) or sink (maximum) is the total of all oxidation and production in the original system, eroded and uneroded layers combined, assuming no oxidation of eroded SOC after it leaves the eroding profile (sum of items 5 and 7).

[25] 10. System C source (maximum) or sink (minimum) is the total of all oxidation and production in the original system, eroded and uneroded layers combined, when all eroded SOC is oxidized after it leaves the eroding profile (sum of items 9 and 2).

[26] Subsequent output columns are excerpted from those described above for user-specified times or depths of erosion of particular interest.

3. Populating Model Input Parameters

[27] To explore how SOC erosion and multiple assumptions about associated SOC processes influence the atmospheric C pool, we applied our model to two contrasting soil profiles in the Calhoun Experimental Forest in South Carolina, United States. One profile has experienced significant erosion during its ~150 year history of cultivation of cotton, corn, and wheat (from ~1810 to 1955), and the other is a less disturbed profile in an adjacent hardwood stand that is generally considered to have never been cultivated [Richter and Markewitz, 2001]. Cultivation resulted in loss of the A horizon and significant soil compaction at the eroded site. At the less disturbed hardwood stand, there was no such soil degradation [Richter and Markewitz, 2001]. We obtained bulk density and SOC concentration distributions from several biogeochemical studies based at this research site [Markewitz and Richter, 1998; Richter et al., 1999; D. Richter, unpublished data, 2009].

[28] We employed curve fitting of bulk density and SOC concentration distributions to generate smoothed values of these parameters and associated SOC contents throughout the profile (Figures 3a and 3b). We used multiple functions throughout the profile where data could not be smoothed using a single function. If applied functions generated unreasonable values in spite of otherwise good fits (i.e., extremely high values for surface SOC concentrations), we constrained values to reflect known site characteristics. We restricted solutions of the equation to ensure constant values at the base of both profiles. This approach generated equations useful for relatively rapid parameterization of the profile for the model's multiple layers. The smoothed nature of these curves also mitigated discontinuities in graphical outputs induced by abrupt transitions in the SOC profile.

[29] We estimated first-order oxidation rate constants (k_{ox} , yr^{-1}) based on estimated values of mean residence times (MRT) at the surface of and deep within both profiles (Figures 3c and 3d). We assumed MRT values ranged from 100 years at the surface to 1500 years at depth at the relatively eroded site. These values are reasonable given the MRT calculated from $\Delta^{14}C$ values of multiple soil horizons in 1962, likely before the bulk of ^{14}C "bomb carbon" was significantly incorporated into the soil profile [Richter et al., 1999]. We assumed MRT values ranged from 10 years at the surface to 1500 years at depth in the less disturbed profile, given that the surface layer in this forest likely contained a greater proportion of relatively recently fixed C exhibiting a faster turnover time [Harrison et al., 1995]. We let the vertical distribution of SOC concentration govern remaining k_{ox} values, given known variation in labile versus refractory SOC characteristics with depth [Trumbore, 2000]. We developed a linear regression between two points (depth and SOC fraction for surface and deep layers) to relate k_{ox} values to SOC concentration. We used this equation to populate the remainder of the profile's k_{ox} values.

[30] Soil organic C production is defined in the profile at the beginning of the model run assuming a steady state, such that the constant value I ($kg\ C\ m^{-2}$) for each layer at time zero is given by equation (3) above. The steady state assumption can be changed at the user's discretion as can the first-order oxidation assumption, the approach for determining k_{ox} values, and/or the depth distribution of k_{ox} .

4. Model Application

[31] We applied the model to the two soil profiles described above to explore how erosion rates, assumptions about n_{ox} , n_{prod} , and the quality of the eroding profile may influence the size of the atmospheric C pool. We model C exchange with the atmosphere only at the eroding sites, and unlike studies that focus on redistribution and fate of eroded C [Rosenbloom et al., 2006], we do not explicitly track the distribution or dynamics of the eroded C. Thus, we examine model results across the entire range of possible oxidation fates of eroded SOC, from complete preservation (none is oxidized during transit or upon deposition, generating a maximum C sink) to complete oxidation (all is oxidized during transit or upon deposition, generating a maximum C source). Neither extreme of this range is likely, but these

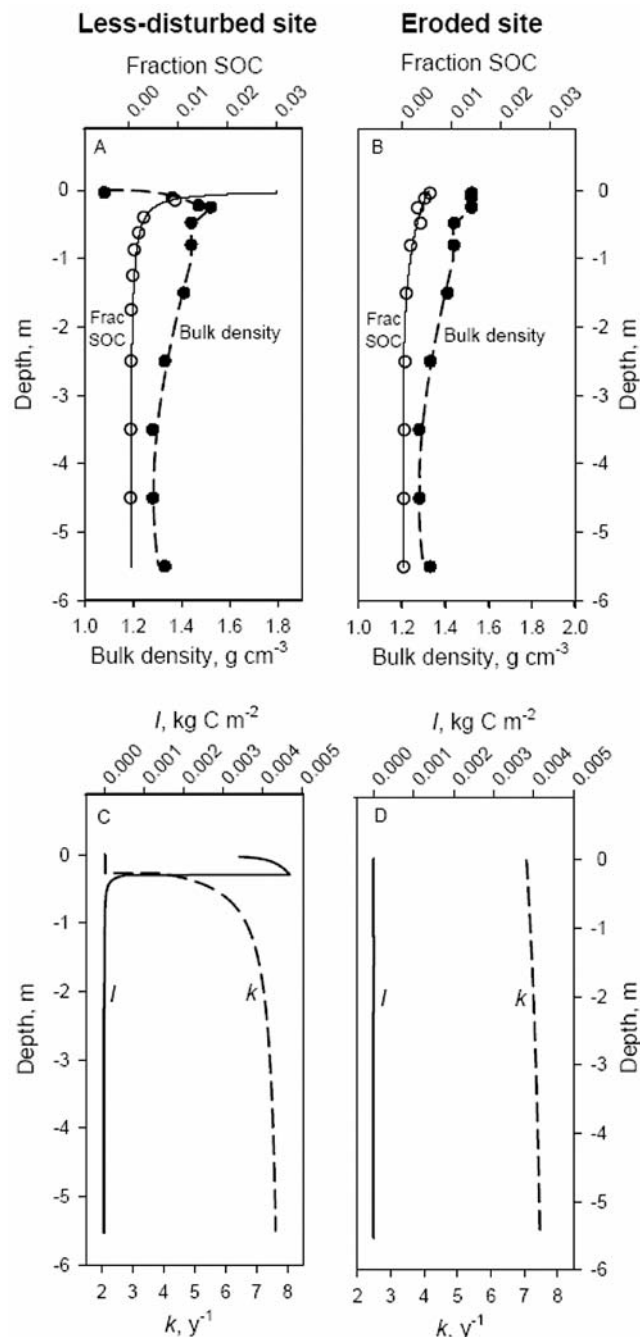


Figure 3. (a, b) Bulk density (solid lines) and soil organic C (SOC; dashed lines) concentration profiles and (c, d) SOC production I (solid) and decomposition rate constant k (dashed) at relatively undisturbed and previously eroded sites. Points represent observations as reported by Markewitz and Richter [1998], Richter et al. [1999], Richter and Markewitz [2001], and unpublished data of D. Richter, 2009; lines represent smoothed values derived from functions as described in sections 2.5 and 3. We restricted function solutions for the near-surface layers in the relatively undisturbed profile to reflect observed values, and deep within both profiles to ensure constant values near profile bases.

analyses permit us to determine what fraction of eroded SOC must be oxidized in transit or upon deposition to generate a net C sink or source. First, we conduct sensitivity analyses by applying multiple erosion rates, spanning 3 orders of magnitude (0.1 , 1.0 , and 10.0 mm yr^{-1}), to the two contrasting soil profiles for 150 years. We selected these erosion rates to represent values well within the range of geologic erosion (0.1 mm yr^{-1}) and at the high end of geologic and agriculture erosion (10 mm yr^{-1}) [Montgomery, 2007]. We apply these rates using extreme values of n_{ox} and n_{prod} (0 and 1 for both parameters) to demonstrate how assumptions about changing erosion rates and SOC oxidation and production within an eroding profile can govern estimates of C source or sink strength. Second, we explore how 150 years of agricultural use at the historically eroded site may have influenced the atmospheric C pool by applying a best estimate of the mean erosion rate experienced by the site, and more realistic values of n_{ox} and n_{prod} , to the less disturbed site. Third, we develop model scenarios to represent how two contrasting soil management regimes may influence C exchange between the eroding profile and the atmosphere at both sites. Finally, we use model output to highlight future research needs for constraining the influence of SOC erosion on biosphere-atmosphere C exchange.

5. Model Results

5.1. Influence of Mixing Coefficients, Erosion Rates, and SOC Levels on C Fluxes at Eroding Sites

[32] The effect of n_{prod} on net C sink or source strength is stronger than the effect of n_{ox} . As n_{prod} increases, source strength decreases, or sink strength increases. The effect of n_{ox} is qualitatively opposite and somewhat weaker. As n_{ox} increases, sink strength decreases, or source strength increases. These trends, using end-member values of n_{prod} and n_{ox} , are summarized in Table 2; Figure 4 illustrates the source and sink strengths as functions of the fraction of eroded SOC oxidized following erosion. Increasing the erosion rate amplifies the differences in net C sink or source strength caused by the mixing coefficients. Maximum values of source strength are relatively consistent (~ 5 to 7 kg C m^{-2} , all at the highest erosion rate), whereas maximum sink strengths are much more variable in magnitude (up to almost 30 kg C m^{-2}) and occurrence (controlled more by mixing coefficients than by erosion rate).

[33] The net C fluxes at eroding sites are usually modest sources when SOC content and/or production are low (compare Figures 4a, 4b, and 4d). However, high SOC content and n_{prod} values generate greater variability in the magnitude of C fluxes, with high sink values possible (Figure 4c).

5.2. Assessing Maximum Net C Sinks and Sources Across Time

[34] We assessed how maximum C sink and source strengths varied with erosion rate by assuming 0% and 100% oxidation of eroded SOC, respectively, and plotting these C flux values across time (Figure 5). At both sites, annual C exchange with the atmosphere at the eroding profile increases with erosion rate and is enhanced relatively sooner in the erosional scenario as erosion rate increases. These

Table 2. Modeled Maximum Net C Sink and Source Strength of Soil Profiles Experiencing Erosion Rates of 0.1, 1.0, and 10.0 mm yr⁻¹ Using Binary End-Member Values of the Soil Organic C Oxidation and Production Mixing Coefficients for Two Soil Profiles Exhibiting Contrasting SOC Contents at the Calhoun Experimental Forest^a

Mixing Coefficient Scenario	Erosion Rate		
	0.1 mm yr ⁻¹	1.0 mm yr ⁻¹	10.0 mm yr ⁻¹
<i>Low Soil Organic Carbon Content</i>			
$n_{ox} = 1; n_{prod} = 0$	0.0, 0.1, +	0.0, 1.1, +	0.0, 5.0, +
$n_{ox} = 0; n_{prod} = 0$	0.0, 0.1, +	0.0, 1.1, +	-0.1, 5.0, 5%
$n_{ox} = 0; n_{prod} = 1$	0.0, 0.1, +	-0.1, 1.0, 20%	-0.4, 4.8, 10%
$n_{ox} = 1; n_{prod} = 1$	0.0, 0.1, +	0.0, 1.1, +	-0.4, 4.9, 10%
<i>High Soil Organic Carbon Content</i>			
$n_{ox} = 1; n_{prod} = 0$	0.4, 0.9, +	2.0, 3.8, +	2.1, 6.9, +
$n_{ox} = 0; n_{prod} = 0$	0.0, 0.5, +	0.0, 3.3, +	-0.4, 6.9, 2%
$n_{ox} = 0; n_{prod} = 1$	-2.7, -2.3, -	-24.9, -2.5, -	-28.4, 6.3, 81%
$n_{ox} = 1; n_{prod} = 1$	-0.1, 0.3, 60%	-2.8, 2.0, 55%	-20.7, 6.4, 75%

^aMaximum net C sink is the first number in the top line in each cell; maximum net C source is the second number in the pair. Negative values indicate a net C sink; positive values indicate a net C source. Units are kg C m⁻². Percent that follows within each cell is the percent of eroded SOC that must be oxidized to generate a net C source at the eroding profile. Plus signs indicate a net C source across all nonzero results of possible oxidation fates of the eroded SOC; minus signs indicate a net C sink across all possible oxidation fates of the eroded SOC. See section 2.4 for detailed explanation of mixing coefficients (n_{ox} and n_{prod}).

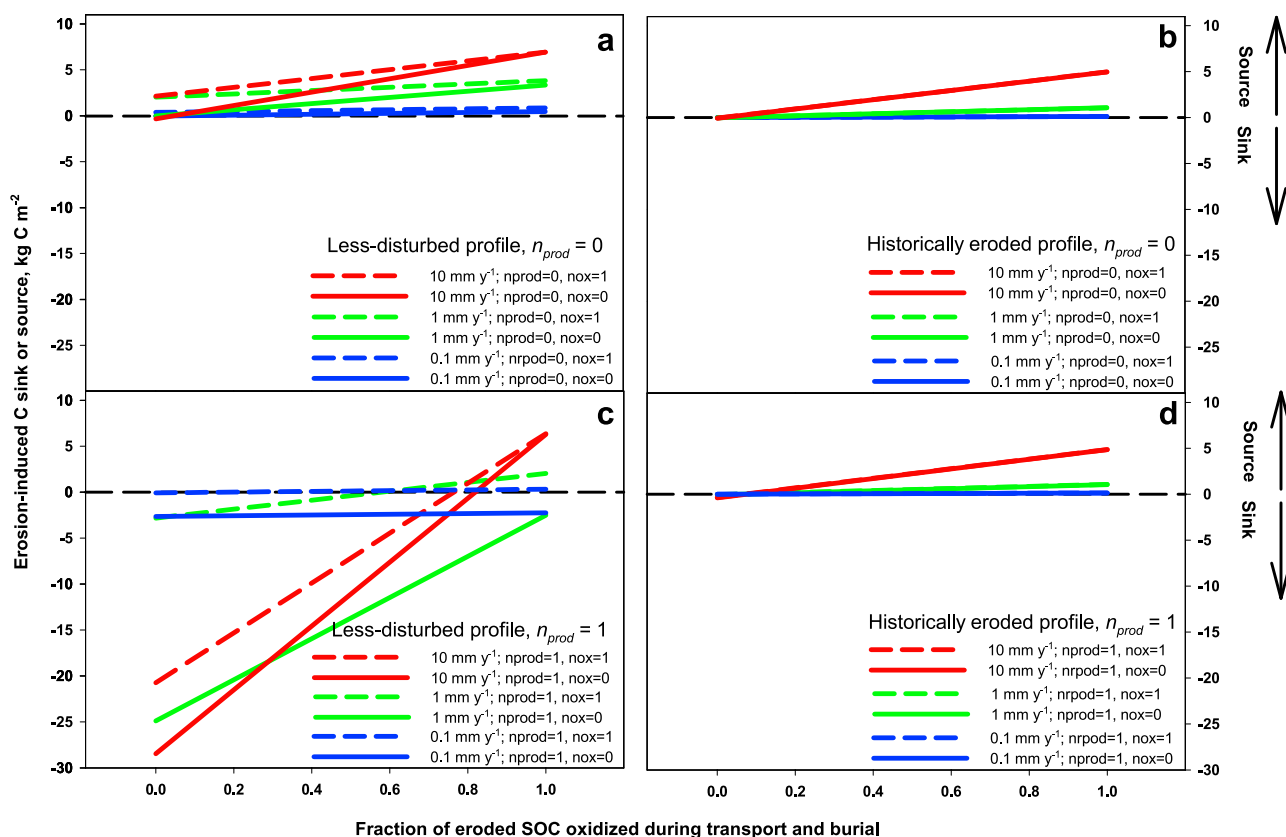


Figure 4. Net C flux between an eroding soil profile and the atmosphere after 150 y of erosion at three erosion rates (0.1, 1, and 10 mm yr⁻¹). (a, b) Net C fluxes resulting from erosion when $n_{prod} = 0$ in a relatively undisturbed and a historically eroded profile, respectively. (c, d) Net C fluxes when $n_{prod} = 1$ in these same two profiles, respectively. Fluxes are depicted as a function of the fraction of SOC oxidized (complete preservation at $X = 0$, complete oxidation at $X = 1$). See section 2.4 for definitions and explanation of assigned values for n_{ox} and n_{prod} . Positive values indicate a net flux of C to the atmosphere; negative values indicate a net flux of C into the soil.

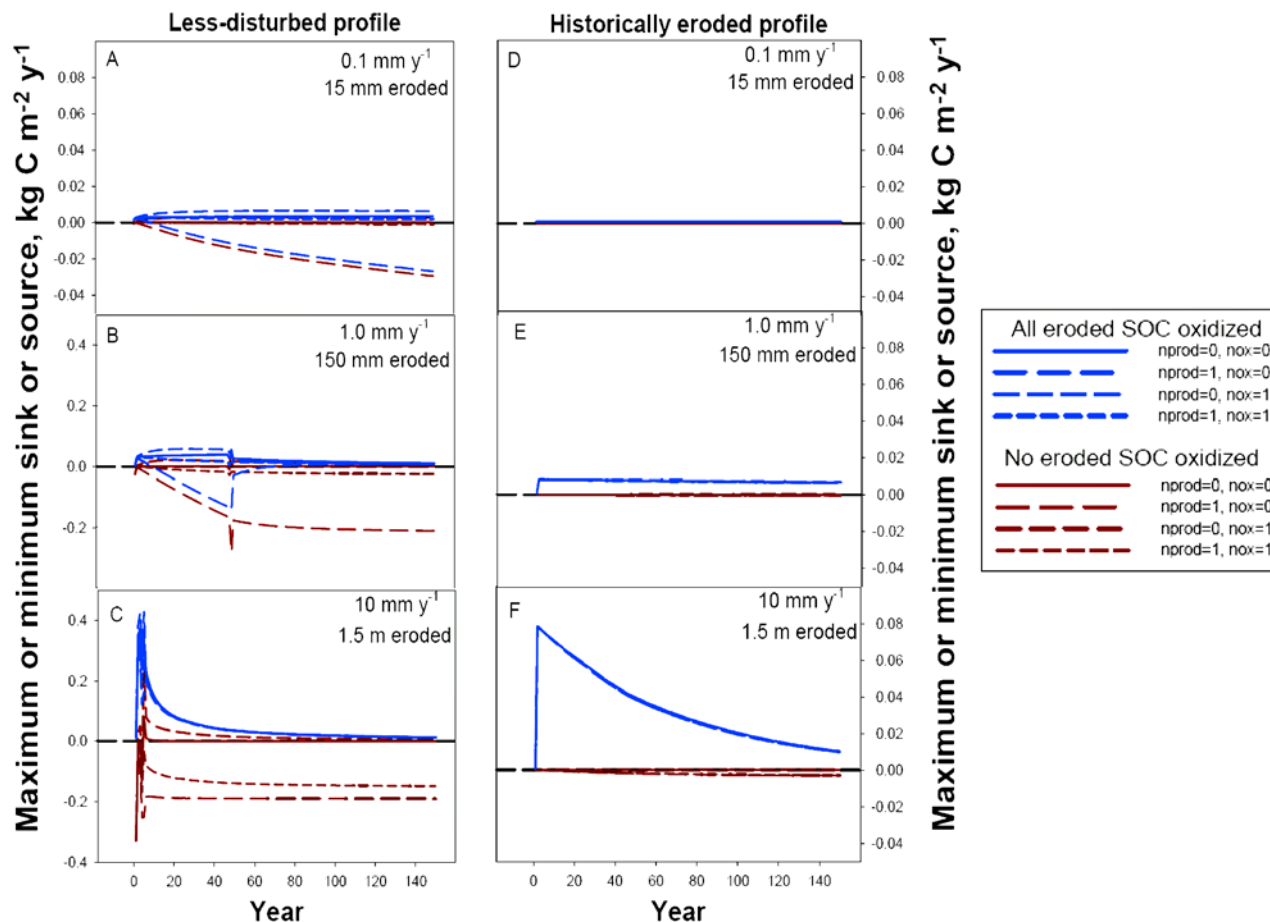


Figure 5. Maximum C sink or source strength at soil profiles eroding for 150 years at specified rates, in a (a, b, c) less disturbed and (d, e, f) historically eroded profile with lower SOC content. Maximum C sink strength (brown lines) assumes none of the eroded SOC is oxidized during transit or upon deposition; maximum C source strength (blue lines) assumes that all eroded SOC is oxidized. Only extreme end-member values for n_{ox} and n_{prod} are depicted. See section 2.4 for definitions and explanation of assigned values for n_{ox} and n_{prod} . Note different y axis scale for Figures 5b and 5c. Positive values indicate a net flux of C to the atmosphere; negative values indicate a net flux of C into the soil.

patterns are associated with the more rapid removal of relatively SOC-rich profile layers at higher erosion rates. Abrupt shifts correspond to changes in eroding layer SOC content. These functions become smoother over time as deeper soil layers (those containing relatively low SOC content) are eroded.

5.3. Estimating the Influence of Historical Erosion on the Atmospheric C Pool

[35] We investigated how 150 years of agricultural use at the historically eroded site may have influenced net C exchange with the atmosphere. If we assume this site's soil profile prior to erosion was similar to that of the less disturbed site [Richter and Markewitz, 2001], the loss of the A horizon suggests a mean erosion rate of at least 1 mm yr^{-1} during its 150 year agricultural history. We applied this erosion rate to the less disturbed site for 150 years to mimic the erosional processes that likely occurred at the relatively disturbed site (Figure 6). Instead of applying extreme values for n_{ox} and

n_{prod} as in section 5.1, we applied multiple midrange values for these parameters to generate more realistic scenarios.

[36] Equivalent values of n_{ox} and n_{prod} , regardless of the value (black, blue, and brown lines in Figure 6), result in similar C flux magnitudes and a net C sink if less than 45% to 60% of the eroded SOC is oxidized in transit or upon deposition. The fraction of eroded SOC that must experience oxidation to generate a net C source deviates from this range when n_{ox} and n_{prod} differ from each other. When $n_{ox} = 0.25$ and $n_{prod} = 0.75$, model results indicate that the historically eroded site generated a maximum net C sink of 9.0 kg C m^{-2} across 150 years, or an average of $60 \text{ g C m}^{-2} \text{ yr}^{-1}$ (see green line in Figure 6). In contrast, reversing values of n_{ox} (0.75) and n_{prod} (0.25) generates a maximum net C source to the atmosphere of 3.2 kg C m^{-2} across 150 years, or an average of $21 \text{ g C m}^{-2} \text{ yr}^{-1}$ (see turquoise line in Figure 6). Overall, when $n_{prod} < n_{ox}$, a net C source results for almost all oxidation scenarios of eroded SOC (Figure 6).

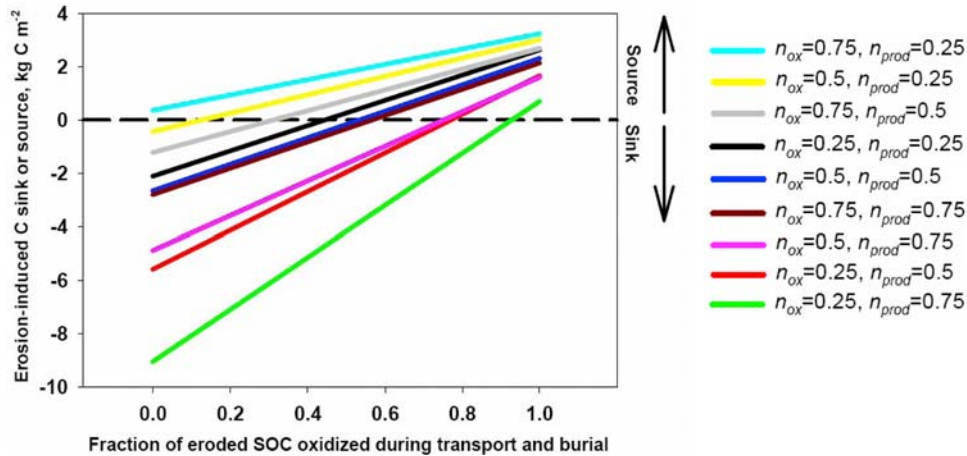


Figure 6. Net C flux to or from the atmosphere resulting from 150 years of modeled soil erosion (1 mm yr^{-1}) at the less disturbed site, mimicking what likely occurred during the agricultural history at the historically eroded site. Assigned values of n_{ox} and n_{prod} reflect relatively moderate assumptions of the influence of erosion on SOC oxidation and production within the profile. See section 2.4 for definitions and explanation of assigned values for n_{ox} and n_{prod} . Positive values indicate a net flux of C to the atmosphere; negative values indicate a net flux of C into the soil.

In contrast, if $n_{prod} > n_{ox}$, a net C sink results even if ~75% to 96% of eroded SOC is oxidized.

5.4. Contrasting Influences of Soil Management Practices on the Atmospheric C Pool

[37] We compared two contrasting sets of assumptions about erosion rate and values of n_{ox} and n_{prod} to assess how

varying soil management practices may influence exchange of atmospheric C with an eroding site. We applied these assumptions for 150 years to the historically eroded and less disturbed profiles (Figure 7). Where soil management practices result in relatively low erosion and maintenance of system productivity, we assumed an erosion rate of 0.1 mm yr^{-1} . We assigned a n_{prod} value of 0.8, a reflection

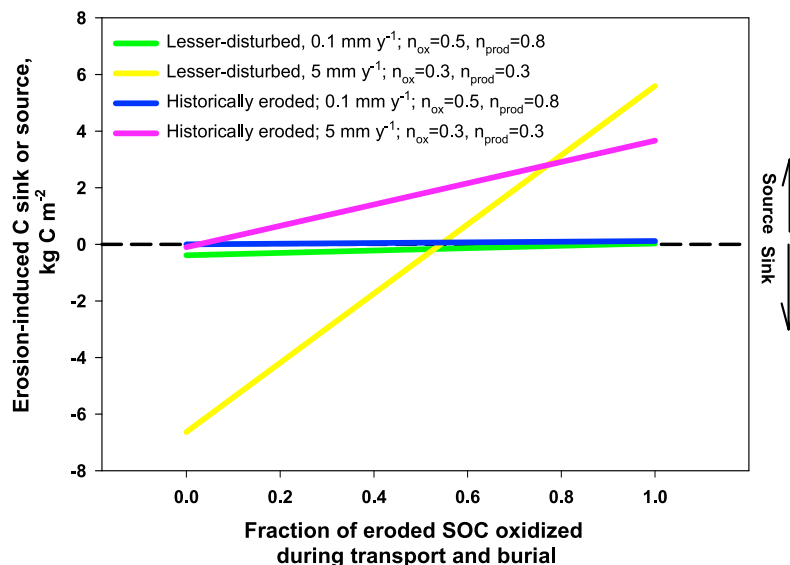


Figure 7. Net C flux to or from the atmosphere after 150 years of soil erosion and associated dynamics of soil organic C (SOC) for two different soil management scenarios. Carbon fluxes are depicted over the range of oxidation fates for the eroded SOC (complete preservation at $X = 0$, complete oxidation at $X = 1$). Values of n_{prod} and n_{ox} reflect assumptions associated with soil management strategies that limit soil erosion to 0.1 mm yr^{-1} and maintain site productivity versus those that permit an erosion rate of 5 mm yr^{-1} and declining site productivity. See section 2.4 for definitions of n_{ox} and n_{prod} . Positive values indicate a net flux of C to the atmosphere; negative values indicate a net flux of C into the soil.

of relatively high productivity at the site. The n_{ox} value was set at 0.5. In contrast, to represent a site experiencing poor soil management, we assumed an erosion rate of 5 mm yr^{-1} and a n_{prod} value of 0.3. We also set n_{ox} at 0.3, reflecting an increasing proportion of recalcitrant SOC in the soil profile with low production rates of newer, labile SOC.

[38] After 150 years of erosion, the assumptions we invoked as representative of good soil management practices at the already eroded site (see blue line in Figure 7) result in no C exchange with the atmosphere across a wide range of fates of the eroded SOC, and a maximum C source to the atmosphere of 0.1 kg C m^{-2} when all eroded SOC is oxidized. This same management scenario results in a greater magnitude of C exchange with the atmosphere at the less disturbed site (see green line in Figure 7). The maximum C sink is 0.4 kg C m^{-2} ; there is no net exchange of C with the atmosphere when all eroded SOC is oxidized. Applying a higher erosion rate and n_{ox} and n_{prod} values reflective of poorer soil management practices for 150 years results in a maximum C sink of 0.1 kg C m^{-2} and a maximum C source of 3.7 kg C m^{-2} at the already eroded site. An even wider range of potential atmospheric C exchange occurs at the less disturbed site, with a maximum C sink of 6.6 kg C m^{-2} and a maximum C source of 5.6 kg C m^{-2} . Under these conditions, at least 55% of the eroded SOC must be preserved to induce a net C sink at the less disturbed site. These patterns and trends are consistent with the results using extreme value of n_{prod} and n_{ox} (Figure 4 and Table 2).

6. Discussion

[39] Model outputs indicate the potential for wide variations in C sink or source strength at eroding sites. The magnitude and direction of modeled C flux is dependent on profile characteristics, erosion rate, assumptions about SOC oxidation and production within the profile as erosion proceeds, and the actual flux in nature will also depend on the degree to which eroded SOC is oxidized during transit or upon deposition. Some of these variables are relatively straightforward to characterize (profile characteristics) or apply (erosion rates). However, appropriate values for n_{ox} , n_{prod} , and the proportion of eroded SOC oxidized are more challenging to constrain.

6.1. Sensitivity Analyses

[40] SOrCERO results indicate that increasing the SOC production of each layer with erosion, increasing values of n_{prod} , increases potential C sink strength at the eroding site. Increasing n_{prod} and the associated increase in potential C sink strength are consistent with an enhanced degree of “dynamic replacement” [Stallard, 1998] and the significant C sinks estimated when complete replacement of eroded SOC is assumed [Smith *et al.*, 2001, 2005]. Model results also show that increasing the reactivity of SOC in each layer as it becomes progressively shallower with erosion, increasing values of n_{ox} , reduces potential C sink strength at the eroding site. The degree to which erosion can induce a net C source or sink for given values of n_{ox} and n_{prod} depends on the erosion rate and the quality of the soil profile in

question, as evidenced by the marked variation in C source or sink strength at the less disturbed site (Figures 4c, 5a, 5b, and 5c). The stronger effect of n_{prod} on net C source or sink strength relative to the effect of n_{ox} (Table 2) indicates that the input rate of organic material to the soil profile is a more important driver of organic matter accumulation than decomposition rates for the modeled system. This result contrasts with studies suggesting that soil organic matter accumulation is governed more by decomposition processes than by input rates [Schlesinger, 1977; Cebrian and Duarte, 1995], although the cited studies were conducted over a wide range of spatiotemporal scales and ecosystems.

6.2. Mimicking Past Erosional History

[41] Compared to the end-member n_{ox} and n_{prod} values discussed above (sections 5.1 and 6.1), relatively moderate values are more likely to reflect SOC oxidation and production characteristics of the eroding profile at the Calhoun Experimental Forest during its 150 year agricultural history. With more moderate values of n_{ox} and n_{prod} , estimates of C sink or source strength range from a sink of $60 \text{ g C m}^{-2} \text{ yr}^{-1}$ with $n_{ox} = 0.25$ and $n_{prod} = 0.75$ to a source of $21 \text{ g C m}^{-2} \text{ yr}^{-1}$ with $n_{ox} = 0.75$ and $n_{prod} = 0.25$. This range encompasses published estimates of C sink strength associated with erosion: 3 to $10 \text{ g C m}^{-2} \text{ yr}^{-1}$ [Van Oost *et al.*, 2005], 10 to $20 \text{ g C m}^{-2} \text{ yr}^{-1}$ [Harden *et al.*, 1999] and $1.9 \text{ g C m}^{-2} \text{ yr}^{-1}$ [Yoo *et al.*, 2005].

[42] To estimate the magnitude of C fluxes across a broader region, we apply model results across the $\sim 0.85 \times 10^{12} \text{ m}^2$ of southeastern United States that currently supports secondary forest [Powell *et al.*, 1993]. We make the simplifying assumption that the Calhoun soil profile characteristics are broadly representative of the well-drained, upland Ultisols of the southeastern region [Richter and Markewitz, 2001] and that this area was subjected to similar erosional processes as the Calhoun for 150 years. Under such conditions, model results indicate that erosion for 150 years in the region might have generated C fluxes ranging from a net C sink of up to 7.7 Pg C ($60 \text{ g C m}^{-2} \text{ yr}^{-1} \times 150 \text{ years} \times 0.85 \times 10^{12} \text{ m}^2$), up to a net C source of up to 2.7 Pg C ($21 \text{ g C m}^{-2} \text{ yr}^{-1} \times 150 \text{ years} \times 0.85 \times 10^{12} \text{ m}^2$).

[43] We cannot know the fate of eroded SOC from Calhoun during its time of cotton production, but given the large quantities of soil that can be deposited into river systems [Trimble, 1983, Smith *et al.*, 2005] and more recent deposits into rivers and impoundments [Smith *et al.*, 2001], it seems reasonable to assume that some fraction of eroded SOC has been protected from oxidation. If we assume that 50% of eroded SOC was protected from oxidation, all but three of the historic erosional scenarios we consider plausible for the Calhoun Experimental Forest result in a net C sink or almost no net exchange of C with the atmosphere (Figure 6). Assuming a smaller fraction of eroded SOC was oxidized increases the probability that erosion during the 150 years of agriculture at Calhoun induced a net C sink.

6.3. Influence of Soil Management on C Fluxes

[44] SOrCERO results depicting contrasting soil management practices applied for 150 years indicate that good

management generates relatively small net fluxes of C to and from the atmosphere, regardless of the quality of the soil profile or the fraction of organic C material that is oxidized posterosion (Figure 7). In contrast, relatively poor soil management practices can generate a wide range of potential C source and sink strengths, depending on the SOC content of the eroding soil profile. Assuming the erosion rates and values of n_{ox} and n_{prod} in our analyses are reasonable, the model indicates that relatively low quality soil profiles subjected to poor management generate a net C source to the atmosphere if more than ~2% of eroded SOC experiences oxidation. However, results also indicate that those same soil management practices applied to relatively high quality soil profiles can induce a significant C sink if less than 50% of the eroded SOC was oxidized. Such conditions may occur if a significant fraction of eroded SOC is redeposited in environments where oxidation is relatively limited, as is postulated by several studies [Harden *et al.*, 1999; Smith *et al.*, 2001; Berhe *et al.*, 2007].

[45] Extrapolating SOrCERO results beyond the region examined in this study, though fraught with simplifying and likely incorrect assumptions, can inform us about the potential relevance of the C fluxes the model predicts and permits us to compare our results with other global-scale estimates. If we apply our modeled net C fluxes at Calhoun, assuming the relatively moderate values of n_{ox} and n_{prod} described in section 6.2, across the global area subjected to agricultural practices ($5.0 \times 10^{13} \text{ m}^2$, the mean of Stallard's [1998] estimate of $5.1 \times 10^{13} \text{ m}^2$ and Goldewijk's [2001] summed estimate of $4.9 \times 10^{13} \text{ m}^2$ for cropland and pastureland), we obtain C flux values at eroding sites ranging from a sink of 3.1 Pg C yr^{-1} ($60 \text{ g C m}^{-2} \text{ yr}^{-1} \times 5.0 \times 10^{13} \text{ m}^2$) to a source of 1.1 Pg C yr^{-1} ($21 \text{ g C m}^{-2} \text{ yr}^{-1} \times 5.0 \times 10^{13} \text{ m}^2$). This range encompasses Harden *et al.*'s [1999] estimate of a C sink resulting from erosion of 1 Pg C yr^{-1} , derived from extrapolating their model results with the same Stallard [1998] reference. If we apply our modeled SOC flux estimates at Calhoun to estimates of cropland only, omitting pasture ($1.7 \times 10^{13} \text{ m}^2$, averaging estimates from Ramankutty and Foley [1998] and Goldewijk [2001]), we obtain C flux values at eroding sites ranging from a sink of 1.0 Pg C yr^{-1} to a source of 0.4 Pg C yr^{-1} . The significant range of these estimates is generated by the variation in parameter input values for SOrCERO and the unknown oxidation fate of eroded SOC. Although such extrapolations oversimplify the global-scale complexities of diverse soil profiles and varied erosional histories, they provide a starting point for further constraining these values.

6.4. Future Research Needs

[46] SOrCERO highlights what variables require further study to better constrain the net C source or sink strength in eroding soil profiles. For example, model results highlight how SOC production and oxidation characteristics within a soil profile are critical determinants of C fluxes into and out of the eroding profile. Variation in SOC production and oxidation as erosion proceeds is likely, but we currently have little information on which to base our selection of values for n_{ox} and n_{prod} . Further study of the distribution of inherently

recalcitrant SOC throughout soil profiles (SOC that resists decomposition regardless of its environment) would aid us in better constraining n_{ox} . Values of n_{prod} are equally challenging to predict. Recent work reveals that approximately 26% of eroded SOC can be replaced in high-input agricultural fields [Van Oost *et al.*, 2007], but such estimates do little to constrain how SOC "production" (input, in SOrCERO) in each layer of an eroding soil profile changes relative to its preeroded state. Although modern agricultural techniques strive to maintain high levels of crop (ecosystem) productivity independent of changing soil properties, the relationship between ecosystem productivity and rates of SOC production is unclear. Quantifying isohumification coefficients [Six and Jastrow, 2006] for multiple ecosystems is thus critical.

[47] As highlighted in multiple studies, the fate of eroded SOC is also a key feature that governs the net C source or sink strength of an eroding profile [Stallard, 1998; Harden *et al.*, 1999; Smith *et al.*, 2001, 2005; Berhe *et al.*, 2007; Van Oost *et al.*, 2007], but about which we know little. Because SOrCERO models only the eroding profile and does not consider the fate of eroded SOC, we have depicted model output across all possible SOC fates. Although this is a useful approach, further research assessing the post-erosion fate of eroded SOC across a wide range of time scales and settings is critical for our efforts to further constrain the net influence of erosion on atmospheric C. Modeling the influence of deposition of eroded SOC on oxidation and production characteristics of extant and newly arrived SOC at depositional sites would also be a valuable contribution to this field, and one that could adapt many of the approaches used in the erosional version of SOrCERO.

[48] In addition to these research needs, we invite the scientific community to employ this model at research sites of interest. SOrCERO affords us the opportunity to compare the influence of contrasting, eroding profiles on C exchange with the atmosphere and to explore how assumptions about oxidation and production within an eroding profile and the oxidation of eroded SOC influence net C fluxes, in a consistent modeling environment. The results of these efforts (multiple studies with transparent assumptions and comparable calculations) will greatly advance our understanding of soil erosion's influence on the atmospheric C pool. These efforts will require the expertise of those familiar with erosional histories and profile data at a multitude of soil research sites.

7. Conclusions

[49] 1. Erosion-related changes in SOC production and oxidation over time and depth, represented in the SOrCERO model by the mixing coefficient n_{prod} and n_{ox} , are critical factors in assessing the exchange of C with the atmosphere. Modeled SOC production that reflects each layer's changing depth with erosion (i.e., the degree to which a layer's production increases at shallower depths) results in significant sink strength, which can increase with erosion rate. Modeled SOC oxidation that reflects each layer's changing depth with erosion (i.e., the degree to which a layer's oxidation increases

at shallower depths) decreases the net C sink strength, or increases the net C source strength. For the specific system modeled, this factor was less of an influence on net C fluxes than modeled SOC production.

[50] 2. Profile SOC content and soil management practices also interact to jointly influence net C exchange between an eroding site and the atmosphere. Soil management practices that maintain low erosion rates and high rates of SOC production (i.e., site productivity is maintained) are likely to result in minimal net exchange of C with the atmosphere at poor quality sites, or a small net C sink at higher-quality sites. Soil management practices that promote high erosion rates and low production of SOC (i.e., low site productivity) can generate a strong C source in poor-quality profiles, particularly if a large fraction of eroded SOC is oxidized during transit or upon deposition. Soil management practices at higher-quality sites can result in either a strong net C sink or source. The direction of the net flow of C between a higher-quality soil profile and the atmosphere depends largely on the fate of the eroded SOC.

[51] 3. Applying relatively moderate values of n_{prod} and n_{ox} at the Calhoun Experimental Forest and assuming that at least 50% of eroded SOC was protected from oxidation suggest that 150 years of agriculture at this site generated a significant net C sink.

[52] 4. Global extrapolation of erosion of a relatively undisturbed soil profile for 150 years results in a maximum net source of C of up to 1.1 Pg C yr^{-1} ($n_{\text{prod}} = 0.25$, $n_{\text{ox}} = 0.75$, all eroded SOC oxidized during transit or upon deposition). In contrast, SORCERO results project a maximum global net C sink of up to 3.1 Pg C yr^{-1} ($n_{\text{prod}} = 0.75$, $n_{\text{ox}} = 0.25$, all eroded SOC protected from oxidation during transit or upon deposition).

[53] 5. SORCERO results (the large modeled range of net C source or sink strength) highlight the importance of clearly defining assumed oxidation and production characteristics of an eroding profile, and assumptions about the fate of eroded SOC. The results also highlight the need for studies developing a more complete understanding of SOC production and oxidation characteristics in eroding profiles, and the fate of eroded SOC.

[54] 6. We emphasize the importance of mitigating erosion as a means of maintaining crop production, water quality, and many other ecosystem characteristics important for ecosystem and human health [Montgomery, 2007; Lal, 2009]. In no way do we mean to suggest that the instances in which soil erosion can apparently induce a net C sink should be used to promote or excuse poor soil management. We invite investigators to download SORCERO (http://www.kbs.ku.edu/people/staff_wwww/billings/index.html) and use it as a tool for testing how varying erosion rate, profile SOC content, and SOC oxidation and production characteristics alter the net flow of C between an eroding profile of interest and the atmosphere after specified time periods or depths of erosion, and across a range of eroded SOC oxidation fates.

[55] **Acknowledgments.** Richard Houghton, William Renwick, William Schlesinger, Richard Slezzer, Stephen Smith, and Eric Sundquist made valuable contributions to the project. We appreciate Mark Schoneweis' assistance with the graphics. Cole Roe and Katie Soldan

assisted with spreadsheet development. Two anonymous reviewers made helpful comments on an earlier version of this manuscript.

References

- Berhe, A. A., J. Harte, J. W. Harden, and M. S. Torn (2007), The significance of the erosion-induced terrestrial carbon sink, *BioScience*, *57*, 337–346, doi:10.1641/B570408.
- Cebrian, J., and C. M. Duarte (1995), Plant growth-rate dependence of detrital carbon storage in ecosystems, *Science*, *268*, 1606–1608, doi:10.1126/science.268.5217.1606.
- Fang, H. J., S. L. Cheng, X. P. Zhang, X. M. Yang, and C. F. Drury (2006), Impact of soil redistribution in a sloping landscape on carbon sequestration in northeast China, *Land Degrad. Dev.*, *17*, 89–96, doi:10.1002/ldr.697.
- Goldewijk, K. K. (2001), Estimating global land use change over the past 300 years: The HYDE Database, *Global Biogeochem. Cycles*, *15*, 417–433, doi:10.1029/1999GB001232.
- Harden, J. W., J. M. Sharpe, W. J. Parton, D. S. Ojima, T. L. Fries, T. G. Huntington, and S. M. Dabney (1999), Dynamic replacement and loss of soil carbon on eroding cropland, *Global Biogeochem. Cycles*, *13*, 885–901, doi:10.1029/1999GB900061.
- Harrison, K. G., W. M. Post, and D. D. Richter (1995), Soil carbon turnover in a recovering temperate forest, *Global Biogeochem. Cycles*, *9*, 449–454, doi:10.1029/95GB02380.
- Jacinte, P. A., and R. Lal (2001), A mass balance approach to assess carbon dioxide evolution during erosional events, *Land Degrad. Dev.*, *12*, 329–339, doi:10.1002/ldr.454.
- Jenerette, G. D., and R. Lal (2007), Modeled carbon sequestration variation in a linked erosion-deposition system, *Ecol. Modell.*, *200*, 207–216, doi:10.1016/j.ecolmodel.2006.07.027.
- Jenny, H. (1941), *Factors of Soil Formation: A System of Quantitative Pedology*, 269 pp., McGraw-Hill, New York.
- Lal, R. (1995), Global soil erosion by water and carbon dynamics, in *Soils and Global Change*, edited by J. M. Kimble et al., pp. 131–141, CRC Press, Boca Raton, Fla.
- Lal, R. (2003), Soil erosion and the global carbon budget, *Environ. Int.*, *29*, 437–450, doi:10.1016/S0160-4120(02)00192-7.
- Lal, R. (2009), Soils and food sufficiency: A review, *Agron. Sustainable Dev.*, *29*, 113–133, doi:10.1051/agro:2008044.
- Liu, S., N. Bliss, E. Sundquist, and T. G. Huntington (2003), Modeling carbon dynamics in vegetation and soil under the impact of soil erosion and deposition, *Global Biogeochem. Cycles*, *17*(2), 1074, doi:10.1029/2002GB002010.
- Markewitz, D., and D. D. Richter (1998), The bio in aluminum and silicon geochemistry, *Biogeochemistry*, *42*, 235–252, doi:10.1023/A:1005901417165.
- Montgomery, D. R. (2007), Soil erosion and agricultural sustainability, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 13,268–13,272, doi:10.1073/pnas.0611508104.
- Powell, D. S., J. L. Faulkner, D. R. Darr, Z. Zhu, and D. W. MacCleery (1993), Forest resources of the United States, 1992. *USDA For. Serv. Gen. Tech. Rep. RM-234*, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.
- Quine, T. A., and K. Van Oost (2007), Quantifying carbon sequestration as a result of soil erosion and deposition: Retrospective assessment using caesium-137 and carbon inventories, *Global Change Biol.*, *13*, 2610–2625, doi:10.1111/j.1365-2486.2007.01457.x.
- Ramankutty, N., and J. A. Foley (1998), Characterizing patterns of global land use: An analysis of global croplands data, *Global Biogeochem. Cycles*, *12*, 667–685, doi:10.1029/98GB02512.
- Richter, D. D., and D. Markewitz (2001), *Understanding Soil Change*, 255 pp., Cambridge Univ. Press, Cambridge, U. K.
- Richter, D. D., D. Markewitz, S. E. Trumbore, and C. G. Wells (1999), Rapid accumulation and turnover of soil carbon in a re-establishing forest, *Nature*, *400*, 56–58, doi:10.1038/21867.
- Rosenbloom, N.A., J. W. Harden, J. C. Neff, and D. S. Schimel (2006), Geomorphic control of landscape carbon accumulation, *J. Geophys. Res.*, *111*, G01004, doi:10.1029/2005JG000077.
- Schlesinger, W. H. (1977), Carbon balance in terrestrial detritus, *Annu. Rev. Ecol. Syst.*, *8*, 51–81, doi:10.1146/annurev.es.08.110177.000411.
- Schlesinger, W. H. (1990), Evidence from chronosequence studies for a low carbon-storage potential of soils, *Nature*, *348*, 232–234, doi:10.1038/348232a0.
- Schlesinger, W. H. (1995), Soil respiration and changes in soil carbon stocks, in *Biotic Feedbacks in the Global Climate System: Will the Warming Feed the Warming?*, edited by G. M. Woodwell and F. T. Mackenzie, pp. 159–168, Oxford Univ. Press, New York.

- Six, J., and J. D. Jastrow (2006), Organic matter turnover, in *Encyclopedia of Soil Science*, vol. 2, edited by R. Lal, pp. 1210–1215, Taylor and Francis, Boca Raton, Fla.
- Smith, S. V., W. H. Renwick, R. W. Buddemeier, and C. J. Crossland (2001), Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States, *Global Biogeochem. Cycles*, 15, 697–707, doi:10.1029/2000GB001341.
- Smith, S. V., R. O. Slezzer, W. H. Renwick, and R. W. Buddemeier (2005), Fates of eroded soil organic carbon: Mississippi basin case study, *Ecol. Appl.*, 15, 1929–1940, doi:10.1890/05-0073.
- Stallard, R. F. (1998), Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial, *Global Biogeochem. Cycles*, 12, 231–257, doi:10.1029/98GB00741.
- Trimble, S. W. (1983), A sediment budget for Coon Creek, the Driftless Area, Wisconsin, 1853–1977, *Am. J. Sci.*, 283, 454–474.
- Trumbore, S. (2000), Age of soil organic matter and soil respiration: Radiocarbon constraints on belowground C dynamics, *Ecol. Appl.*, 10, 399–411, doi:10.1890/1051-0761(2000)010[0399:AOSOMA]2.0.CO;2.
- Van Oost, K., G. Govers, T. A. Quine, G. Heckrath, J. E. Olesen, S. De Gryze, and R. Merckx (2005), Landscape-scale modeling of carbon cycling under the impact of soil redistribution: The role of tillage erosion, *Global Biogeochem. Cycles*, 19, GB4014, doi:10.1029/2005GB002471.
- Van Oost, K., et al. (2007), The impact of agricultural soil erosion on the global carbon cycle, *Science*, 318, 626–629, doi:10.1126/science.1145724.
- Yoo, K., R. Amundson, A. M. Heimsath, and W. E. Dietrich (2005), Erosion of upland hillslope soil organic carbon: Coupling field measurements with a sediment transport model, *Global Biogeochem. Cycles*, 19, GB3003, doi:10.1029/2004GB002271.
- S. A. Billings, Department of Ecology and Evolutionary Biology and Kansas Biological Survey, University of Kansas, Lawrence, KS 66047, USA.
- G. Bohling and R. W. Buddemeier, Kansas Geological Survey, University of Kansas, Lawrence, KS 66047, USA.
- D. deB. Richter, Nicholas School of the Environment and Earth Sciences, Duke University, Durham, NC 27708, USA.
- K. Van Oost, Department of Geography, University of Louvain, B-1348 Louvain-la-Neuve, Belgium.