Calhoun Critical Zone Observatory
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Topographic variability in the influence of soil erosion on the carbon cycle

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SUMMARY

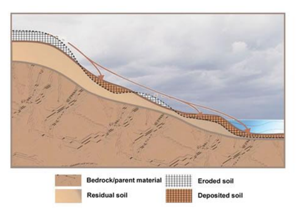
Soil erosion, particularly that caused by agriculture, is closely linked to the global carbon (C) cycle. There is a wide range of contrasting global estimates of soil-atmosphere C exchange partly due to limited understanding of how geomorphology, topography, and land management practices affect erosion and transport of soil organic C (SOC). Here we present a physically-based approach that stresses the fine dynamics and spatial heterogeneity of SOC erosion and atmospheric C sequestration. The methodology was implemented in tRIBS-ECO (Triangulated Irregular Network-based Real-time Integrated Basin Simulator-Erosion and Carbon Oxidation), a spatially-explicit model of SOC dynamics built within an existing coupled physically-based hydro-geomorphic model. We study a region recovering from some of the most serious agricultural erosion in North America. We utilize measurements of biogeochemical characteristics at multiple depths. We found that topographically induced variations of C erosion and replacement can be markedly higher than the variability among reported point estimates globally. We estimated that the net atmospheric C exchange ranges from a maximum source to a sink of 14.5 g m^{-2} yr^{-1} and 18.2 g m^{-2} yr^{-1}, respectively. Applying results globally yields a maximum source and sink of 0.73 Pg yr^{-1} and 0.91 Pg yr^{-1}, respectively. We conclude that the small scale complexity of C erosion and burial driven by topography exerts a strong control on the landscape's capacity to serve as a C sink or a source. We suggest that the significant spatial variability of C fluxes should be explicitly accounted for in regional and global C budgets.

1. Motivation

- Accelerated soil erosion and deposition play an important role in the global Carbon (C) cycle.
- There is controversy over the effect of erosion on soil-atmosphere CO_2 flux in the literature (*Van Oost et al.*, 2007).
- Interacting processes are typically studied in isolation.
- A wide range of assumptions are invoked on the fate of eroded soil organic C (SOC).

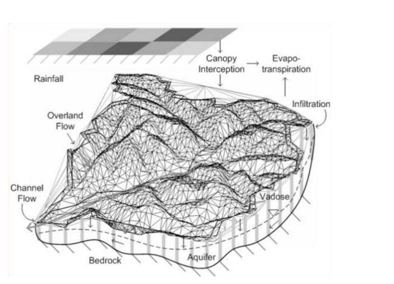
Here we aim to assess the effect of erosion on soil-atmosphere CO_2 flux by:

1) Systematically accounting for feedbacks among coupled processes
2) Explicitly tracking the dynamics of eroded SOC



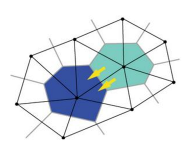
Source: science@berkeley (www2.lbl.gov-Science-Articles-Archive-sabl-2007-Apr-05-erosion)

2. Coupled Physically-Based Distributed Modelling

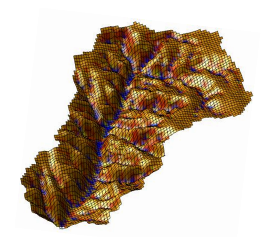


Triangulated Irregular Network Real-Time Integrated Basin Simulator (tRIBS) (*Ivanov et al.*, 2004a, 2004b; *Vivoni et al.*, 2004).

- Hydro-Geomorphic Model (tRIBS-Erosion, *Francipane et al.* 2012)
- Erosion mechanisms include Raindrop Impact Detachment and Overland and Channel Flow



Quantify the Fate of Eroded SOC based on Dynamic Erosion rates



3. tRIBS-ECO: A Spatially-Explicit Biogeochemical Model

$$\left.\frac{\delta SOC}{\delta t}\right|_t = \int_0^{H_t} I_t(z)dz - \int_0^{H_t} k_t(z)\rho(z)C_t(z)dz - \left.\int_0^{h_t} \rho(z)C_t(z)dz\right|_{out} + \left.\sum_i \int_0^{h_{t,i}} \rho_i(z)C_{t,i}(z)dz\right|_{in}$$

where the subscript t is time step [T], z is depth [L], SOC is total soil organic C storage in the soil column [ML^{-2}], $k_t(z)$ is SOC oxidation rate [T^{-1}], $I_t(z)$ is SOC production [ML^{-3}T^{-1}], $\rho(z)$ is bulk density [ML^{-3}], $C_t(z)$ is SOC mass fraction [MM^{-1}], Ht is soil thickness [L], and h_t is the eroded soil layer [L].

tRIBS-ECO
Erosion
Carbon
Oxidation

Dialynas et al., 2014

- *Explicitly tracking the dynamics of eroded SOC*: Eroded SOC can be oxidized upon transport or it can be stored at deeper horizons at depositional sites.

- *Accounting for the effect of management practices on depth-dependent SOC oxidation*:

Assume that by time t_2 soil erosion leads to the removal of a soil layer with the new surface having an oxidation rate $k_{t2}(z=0)$, altered compared to $k_{t1}(z=0)$. Management practices restore the original oxidation at a rate a_k. The framework is also applied to SOC production (*Billings et al.*, 2010).

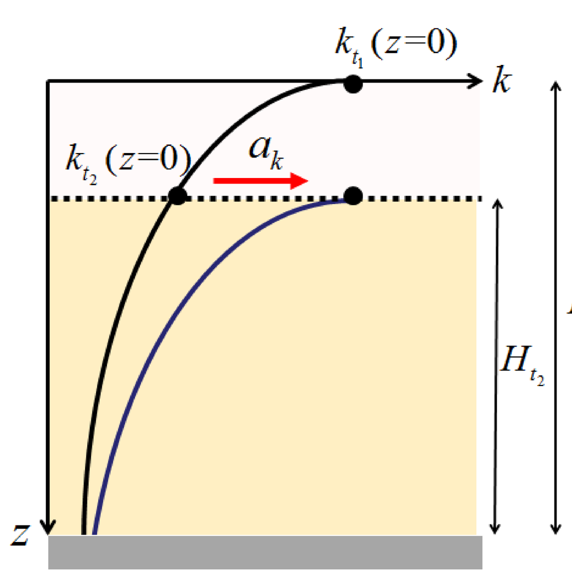
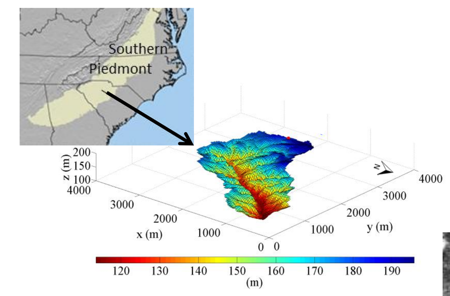


Figure 1. Illustration of the effect of management practices on depth-dependent SOC oxidation.

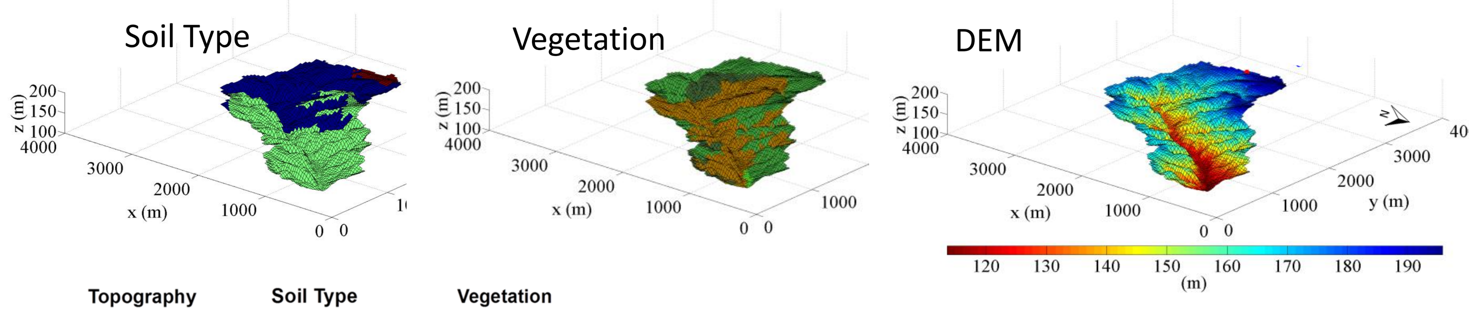
4. Case Study: Calhoun Critical Zone Observatory



- Significant soil erosion up to the mid- 20th century.
- Some of the most serious agricultural land degradation in North America (*Trimble* 1987).

USFS photo, 1950s, Calhoun Experimental Forest — James et al., 2007 — James et al., 2007

- We used a synthetic 100-yr Hydro-climatic Scenario and different surface properties in the spatially-explicit model.



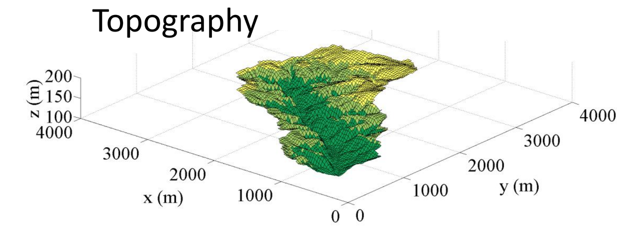
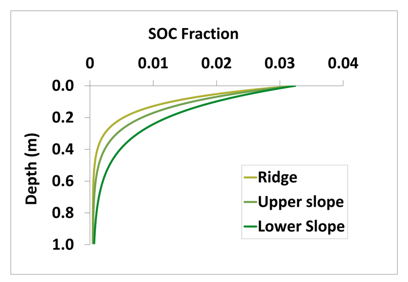


Figure 2. Spatial distribution of vegetation types, soil textural classes, and digital elevation model (DEM), and classification of topography to ridges, upper- and lower slopes.



- We accounted for topographic controls on SOC storage (*Rosenbloom et al.,* 2006): rapid depth attenuation of SOC content was assumed in ridges compared to middle slopes.

Figure 3. Variation of SOC attenuation with depth at different hillslope positions.

- Biochemical inputs were based on observations and on previous studies in the area (*Markewitz and Richter*, 1998; *Richter et al.*, 1999; *Richter and Markewitz*, 2001; *Billings et al.*, 2010).

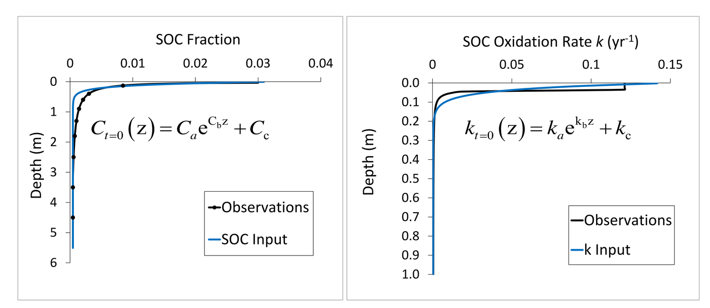


Figure 4. Depth-dependent SOC content and decomposition rate inputs.

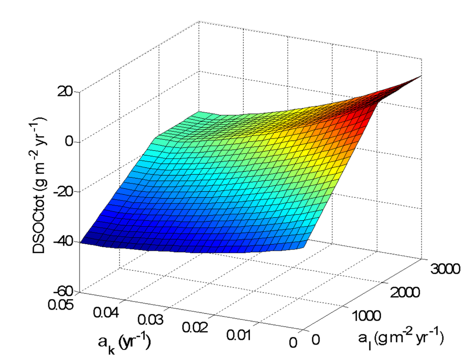


Figure 5. Sensitivity analysis of the effect of management practices on soil-atmosphere C exchange.

- Sensitivity analysis of the effect of management practices on the impact of erosion on soil-atmosphere C exchange. We studied three scenarios:
  1. Maximum Source Scenario
  2. Intermediate Scenario
  3. Maximum Sink Scenario

RESULTS

5. Erosion and deposition

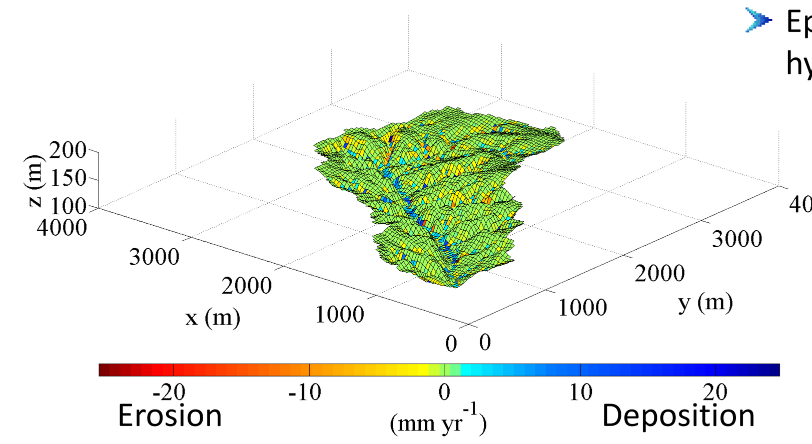
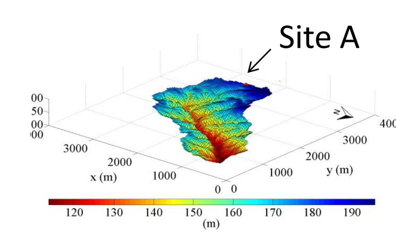


Figure 6. Mean erosion/deposition rates across the watershed. Higher deposition rates are illustrated in blue (e.g., across stream network), while eroding sites (yellow to red) dominate hillslopes.

- Episodic erosion rates result from the watershed's response to the hydrometeorological forcing



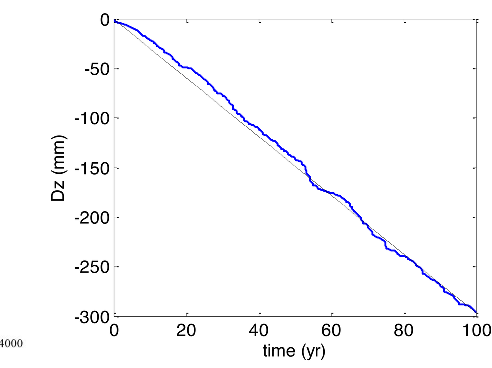


Figure 7. Soil erosion time series at an eroding site (site A). The dynamic character of soil erosion (~ 3 mm yr^{-1}) is evident, as a result from the 100-year hydro-meteorological forcing

6. Effect of episodic erosion rates: Point comparison with SOrCERO

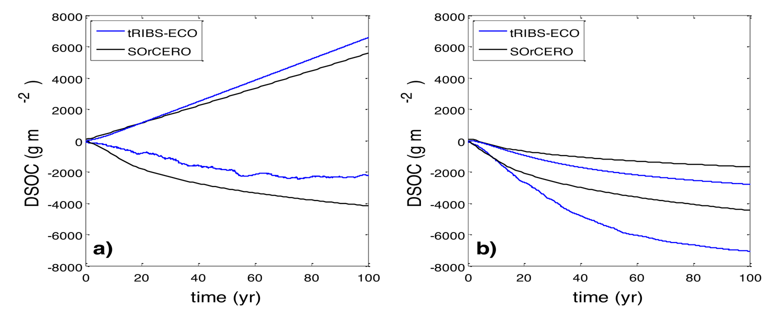
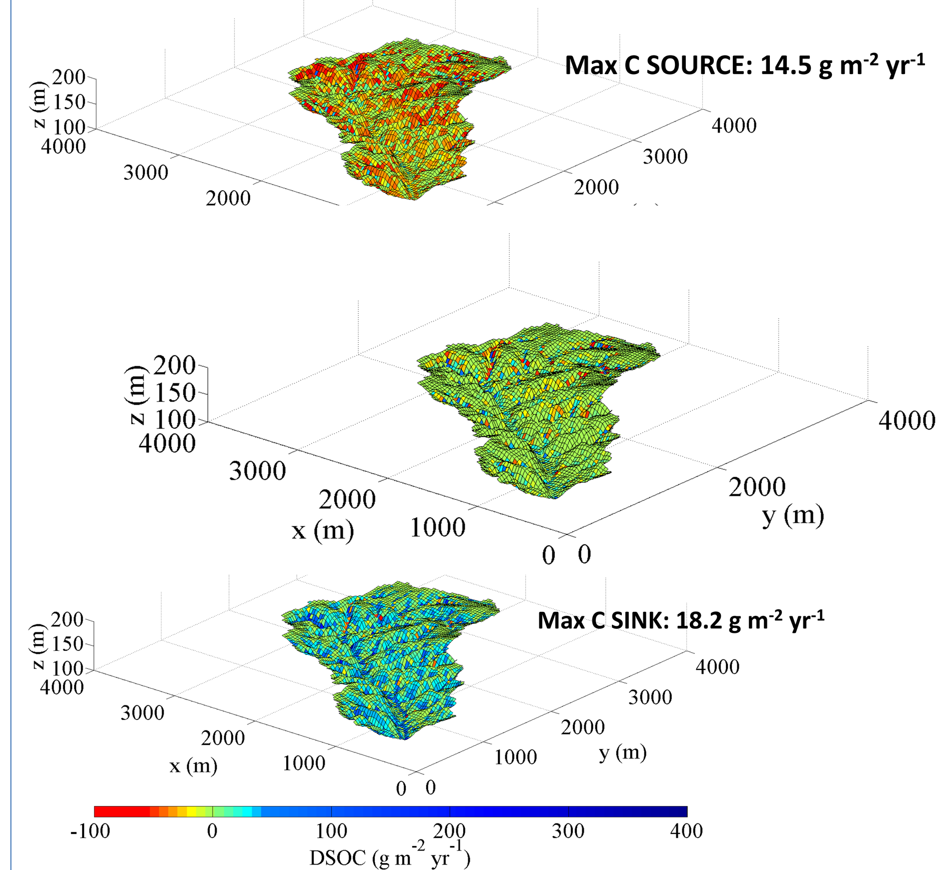


Figure 8. point-based comparison of total SOC difference at site A between tRIBS-ECO (blue) and SOrCERO (black). Panel (a) corresponds to the maximum sink and panel (b) corresponds to maximum source scenario. Positive values of DSOC difference (DSOC) represent a net sink of atmospheric CO_2, while negative values correspond to a net loss of SOC at the eroding site.

- We performed point comparison (site A) between tRIBS-ECO and SOrCERO (Soil Organic Carbon, Erosion, Replacement, and Oxidation), which estimates effects of SOC erosion and altered SOC production and oxidation on CO_2 release in an eroding profile, assuming a constant erosion rate (Billings et al., 2010).
- tRIBS-ECO resulted in a wider range of C flux (Max. Source of 70.7 g C m^{-2} yr^{-1} ÷ Max. Sink of 65.5 g C m^{-2} yr^{-1}) compared to SOrCERO (Max. Source of 44.5 g C m^{-2} yr^{-1} ÷ Max. Sink of 55.2 g C m^{-2} yr^{-1}).
- We found that the episodic character of soil erosion has a significant impact on lateral and vertical SOC fluxes.

7. Watershed-Integrated Results



- We analysed the ratio of vertical (from the atmosphere to the soil) over lateral C flux at eroding sites.

34% of eroded SOC was replaced by C sequestration

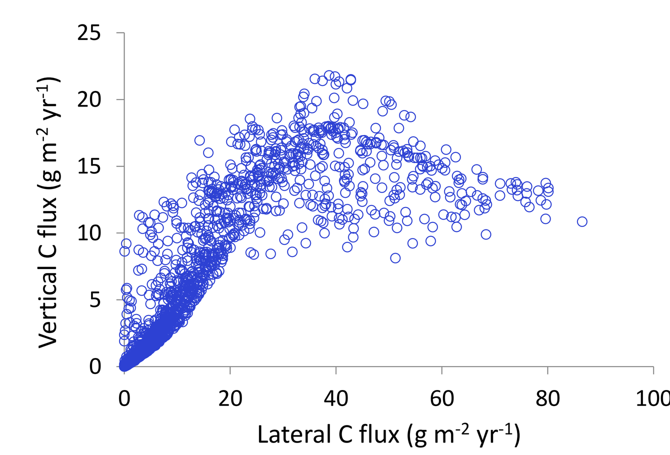


Figure 9. Vertical (soil-atmosphere) C flux from the atmosphere to eroding cells versus lateral C flux (intermediate scenario): on the average, 34% of eroded SOC is replaced at the eroding sites by sequestered CO_2.

Figure 10. Spatially-explicit results: Total erosion-induced SOC fluxes corresponding to the maximum source scenario, the intermediate scenario, and the maximum sink scenario are demonstrated at the top, middle, and bottom panel, respectively. At the intermediate scenario, depositional sites across the stream network are characterized by a net increase of SOC content (blue).

CONCLUSIONS

1. A spatially-explicit biogeochemical model (tRIBS-ECO) was developed to examine whether soil erosion at the landscape scale enhances C sequestration or stimulates oxidation and CO_2 return to the atmosphere. We demonstrate that explicitly accounting for the fate of eroded SOC across the landscape is important on estimating the strength of erosion-induced atmospheric CO_2 flux.
2. Soil erosion is naturally episodic as a result of the watershed's response to hydro-meteorological forcings, and exhibits high spatial heterogeneity influenced by topographic and surface characteristics. We highlight that the spatially-explicit, physically-based representation of erosion and deposition in tRIBS-ECO has an important role for the redistribution of SOC and for the associated atmospheric CO_2 fluxes.
3. In the proposed framework soil erosion alters depth-dependent soil physico-biochemical properties which control lateral and vertical C fluxes. Land management practices, such as fertilization and associated enhancement of system productivity, can have an effect on production and oxidation of SOC at eroding sites. We found that dynamic representation of SOC production and oxidation can significantly impact soil-atmosphere C exchange.
4. Watershed-integrated results ranged from a source strength of 14.5 g C m^{-2} yr^{-1}, to a sink strength of 18.2 g C m^{-2} yr^{-1} which encompasses published estimates. Additional modelling efforts are required to further constrain this range.
5. On the average, 34% of eroded C has been replaced by C sequestration. Hillslope characteristics lead to wide topographic variation of C replacement across the watershed. We suggest that future attempts to quantify the net C exchange with the atmosphere in regional and global C budgets adopt physical representations of C erosion driven by local variation in geomorphological characteristics and hydroclimatic conditions.

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