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Erosional Removal and Redistribution of Soil Organic Carbon in Upland Ecosystems

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Summary

Rivers and streams perpetually dissect the land, creating hillslopes across California and the globe. These soil-covered hillslopes distinguish themselves among terrestrial ecosystems by experiencing active soil erosion and deposition. Nonetheless, hillslope sediment transport has not been rigorously linked to the cycle and storage of soil organic carbon (SOC), a crucial step to gauge the role of hilly uplands in the global C cycle. To tackle this problem, we combined landscape surveys and measurements of plant C inputs and SOC contents with sediment transport models. Field sites included Tennessee Valley (TV) and Black Diamond (BD) in central California. TV is cooler, wetter, and less erodable than BD. Both sites were chosen because the sediment production and transport had been well quantified. We list the major results as follows.

First, erosion removes C on convex slopes at rates of 1.4-2.7 g C m^{-2} yr^{-1} and 5-8 g C m^{-2} yr^{-1} at TV and BD, respectively. Second, depositional slopes have accumulated 15-24 and 15 kg C m^{-2} of SOC with long-term rates of ~1.9 and 1.7-2.8 g C m^{-2} yr^{-1} at TV and BD, respectively. The C accumulation makes the studied hillslopes C sinks with a potential global significance. Third, we conclude that most depositional SOC is oxidized, and that the in-situ plant is the primary C source for the SOC in depositional slopes. Fourth, the soil thickness, a balance of soil erosion and production primarily determines topographic pattern of hillslope SOC storage. In conclusion, the mechanical integration of sediment transport and the soil C cycle provides a novel insight to the spatial and temporal dynamics of hillslope SOC storage. Furthermore, this study showed that factoring sediment transport in SOC cycle is essential in understanding the soil-atmosphere C exchange, a forefront topic of current global climate change.

Keywords: soil, carbon, hillslope, erosion, deposition.

Objectives

Topographic maps of California and the globe reveal that hilly to mountainous landscapes comprise the large part of terrestrial ecosystems. Soil organic carbon (SOC) in these sloping terrains is unique in terms of its exposure to persistent soil erosion or deposition. But this aspect of SOC has been largely ignored or at best qualitatively described. This is not surprising: most SOC cycling studies have focused on level land with agricultural significance, and carbon researchers have avoided hillslopes due to potential complications. We target this knowledge gap and attempt to answer the question, “How does sediment transport affect the spatial and temporal dynamics of hillslope SOC”? Additionally, this study concerns the global implication of results generated from integrating sediment transport and SOC.

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This question is an extension of Stallard's [1998] hypothesis that the combined process of agriculturally accelerated soil erosion and subsequent sedimentation in reservoirs can sequester 1-2 Gt C yr^{-1} globally, the size of the currently debated missing C sink. But this study is unique in three aspects. First, we focus on natural hillslopes instead of agricultural watersheds. Second, we limit the scope of this study to areas above channel heads where sediment transport is not driven by runoff. Third, we quantitatively delve into the mechanisms between sediment transport and the SOC cycle, based on modeling and field measurements.

The nature of this study requires that the hillslopes where sediment transport processes are monitored are well characterized and quantified in an empirical and mathematical manner. We choose two grassland hillslopes in mid California that satisfy these conditions. At these two sites, we achieved the following five objectives:

1. Quantify the rates of SOC erosion loss and depositional gain at the local (individual soil pit of $1m^2$ scale) and zero order watershed (~1ha) scales.
2. Quantify the importance of sediment transport in creating a topographic pattern of SOC storage relative to biological C fluxes.
3. Quantify the temporal trend of hillslope SOC storage on a time scale of ~10k years.
4. Characterize the mechanisms of temporal changes in hillslope SOC storage.
5. Examine the global implication of sediment transport driven hillslope SOC storage.

Below, we list our results for each objective. A Ph.D. dissertation was completed in November on this project (Yoo, 2003), and we are in the stage of preparing two manuscripts for publication.

Approach and Procedure

We developed a SOC mass balance model for hillslope that integrates sediment transport and biological C cycle (*fig. 1*):

$$\frac{dS}{dt} = \int_0^H \left[\frac{I_z}{\Delta z} - k_z \rho_z C_z\right] dz - \rho_\varepsilon C_\varepsilon E \qquad (1)$$

where

$$\frac{dH}{dt} = P - E \qquad (2)$$

where S is soil organic carbon storage [M L^{-2}], I is plant C input [M L^{-2} T^{-1}], k is decomposition rate [T^{-1}], C is the mass fraction of carbon in soil [MM^{-1}], H is soil thickness [L], ρ is soil bulk density [ML^{-3}], z is a soil horizon depth relative to the ground surface [L], the subscript ε stands for erosion, E is soil erosion rate [LT^{-1}], and P is soil production rate [LT^{-1}]. In this model, soil is defined as the transportable materials derived from underlying saprolite. This model is unique in explicitly including the C erosion loss and soil thickness determined by soil erosion and production, in addition to biological C fluxes. At the study sites, the soil erosion is proportional to slope curvature, and the soil production rate exponentially diminishes with soil thickness. We determine the C concentrations of eroded soils by combining the field-specific sediment transport process with the measured soil C profile.

With this model as a guiding principle, we conducted our research on two grass-covered zero order watersheds located at Tennessee Valley (TV) and Black Diamond (BD) Regional Park in

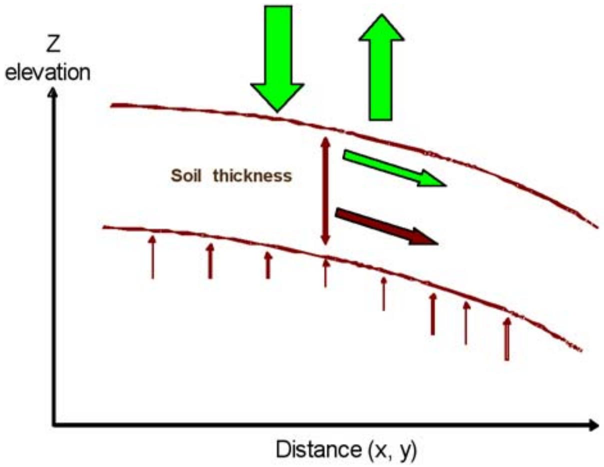

Figure 1. A schematic diagram of processes affecting hillslope soil and SOC.

mid California. Each site is distinct in its soil transport rates and mechanisms: soil is more erodable in BD due to its high clay content (Fernandes and Dietrich 1997; Heimsath et al. 1997; Heimsath et al. 1999; McKean et al. 1993; Reneau and Dietrich 1987; Reneau et al. 1990). The soils accumulate in depositional hollows and footslopes until the next evacuation, and the cycle repeats (McKean 1993; Reneau et al. 1984; Reneau et al. 1986; Reneau et al. 1990). At each site, we sampled soils along a toposequence from erosive convex hillslopes to convergent areas (*fig. 2*). We sampled soils by depth increments to the bedrock boundary. Soil samples were measured for C and N content, bulk density, and particle size distribution. Additionally, the standing biomass was collected at the end of the growing season, for three years, to determine above-ground net primary productivity (ANPP). We also surveyed the areas with a total laser station to calculate the curvature-dependent erosion rates.

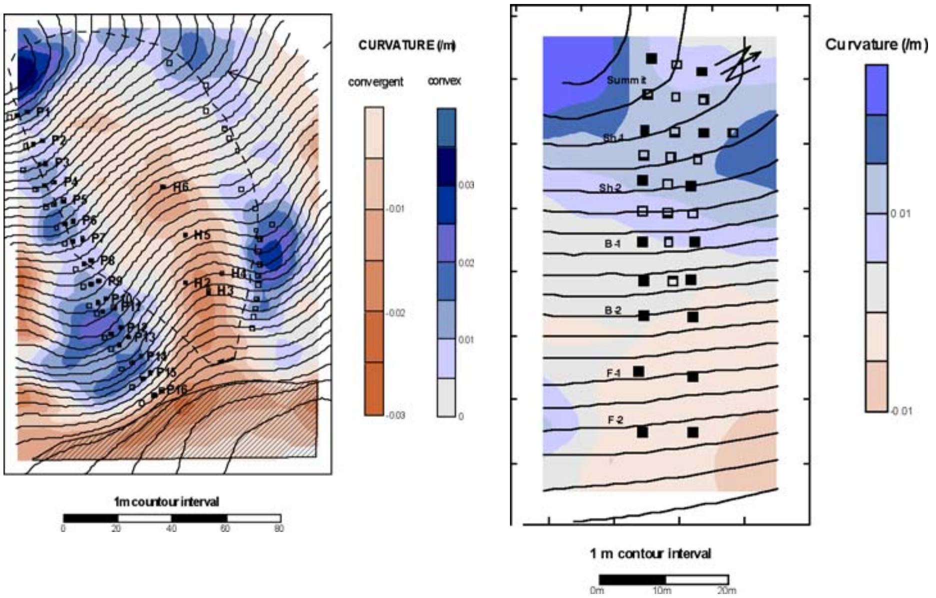

Figure 2. Map of study sites: (a) Tennessee Valley and (b) Black Diamond. The filled dots represent soil pits where samples were taken for various laboratory analyses. The empty dots represent sites where only soil thicknesses were measured.

Results and Discussion

Soil and SOC Erosion and Deposition

At TV, the calculated soil erosion rates are as high as 110 g m^{-2} yr^{-1}, while the deposition rate achieves values up to 110 g m^{-2} yr^{-1} in the hollow axis. Most (~94 %) of the eroded soils are redistributed within the watershed. At BD, the erosion rate for the shoulder is nearly 700 g m^{-2} yr^{1}, while the footslope accumulates sediment at rates of up to 200 g m^{-2} yr^{-1}.

The studied hillslopes represent a wide spectrum of natural hillslope erosion rates (Heimsath 1999). We note, however, that even the highest erosion rates at our California sites are lower than the erosion rate averaged across the conterminous United States (~940 g m^{-2} yr^{-1}) (Smith et al. 2001). Additionally, most of the eroded sediment is redistributed and does not reach the streams. Below, we quantify the amount of C moving with eroded soils. Then, we will analyze how the sediment redistribution and export are linked to watershed soil C storage.

Figure 3 illustrates the calculated SOC erosion rates. At TV, the SOC erosional loss was locally up to 6 g C m^{-2} yr^{-1} with average value of 1.5 g C m^{-2} yr^{-1} over the convex slope. In the hollows, the depositional C input is as high as 3.0 g C $m^{-2}yr^{-1}$ near the hollow axis. At BD, with higher soil erosion rates and lower soil C percentage, the SOC erosional loss is up to 13 g C m^{-2} yr^{-1} with average value of 5-8 g C m^{-2} yr^{-1} on convex slope, while the depositional C input ranges between 0 and 2 g C m^{-2} yr^{-1} on the footslope.

To weigh the importance of the C erosion losses and depositional inputs in the total C budget, we compared them to the measured ANPP. At TV, erosional losses of C are locally as high as 5% of the ANPP. In the adjacent hollow, the depositional C input ranges between 1 and 2% of measured ANPP. At BD, soil erosion removes C at a rate of locally up to 7% of the ANPP. In contrast, the depositional C inputs are ~1% of the in-situ ANPP.

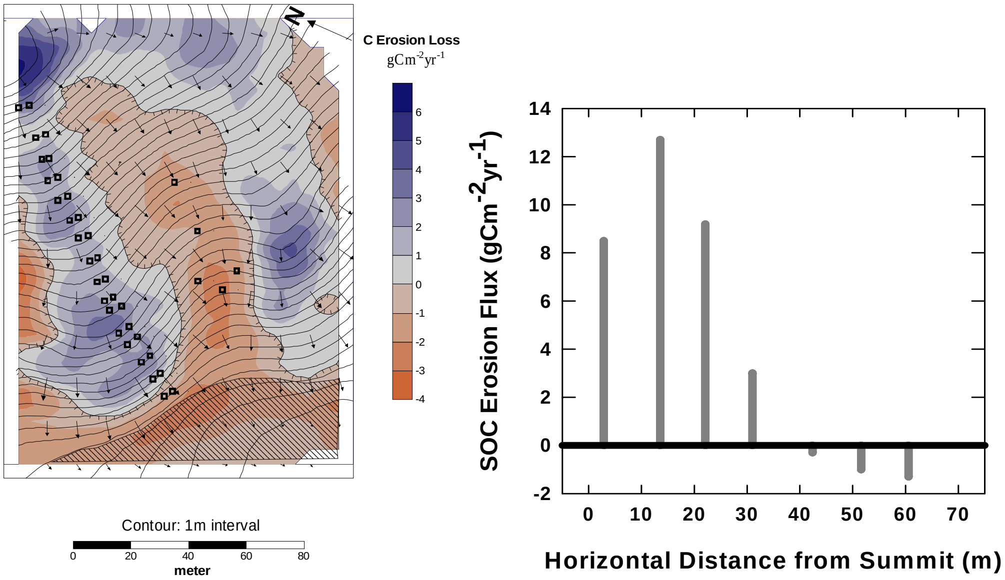

Figure 3. Calculated C erosion rate at (a) TV and (b) at BD.

These are the first quantification of absolute and relative importance of C movement by erosion and deposition on upland hillslopes. Stallard [1995; 1998] presented C yield of 1-5 g C m^{-2} yr^{-1} from undisturbed watershed on a global basis. These estimates were, however, based on stream sediment yield and thus conceal the spatial distribution of erosion and redistribution not only within the studied watershed but also within hillslopes above channels.

Processes Behind the Spatial Patterns of Soil Organic Carbon Storage

We found that the spatial patterns of SOC storage and soil C concentration were decoupled at both sites. Soil C percentage varies independently of slope curvature and gradient but depends on local biological C fluxes. However, SOC storage increased with concavity and decreased with convexity (*fig. 4*). For curvature-dependent SOC storage, we tested the two possible explanations. The first is the curvature-dependent C erosion loss or depositional gain, and the other is soil thickness as a function of soil production and curvature-dependent soil erosion. We found that soil thickness is the major driver of SOC storage spatial distribution.

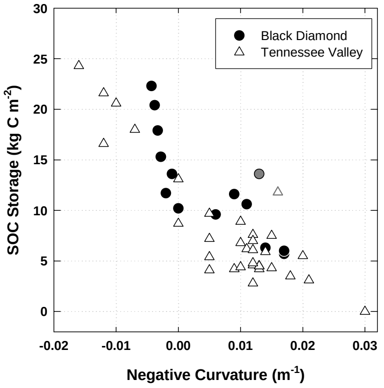

Figure 4. SOC storage versus calculated negative slope curvature at Tennessee Valley and Black Diamond.

In comparing the two sites, soils at the wetter and cooler TV site consistently have higher soil C percentages, while the stored amount of SOC at TV is less than that of BD. These seemingly contradicting results were explained by the higher soil production and erosion rates at BD. Despite the higher erosion rate, the even greater soil production at BD maintains the thicker soil on convex slope. In depositional slope, the greater sediment input from upslope resulted in thicker soils at BD. The thicker soils, despite lower soil C percentage, ended up storing more C.

This is an unexpected result. Traditionally, the topographic pattern of SOC storage is considered to be the result of topographically varying C fluxes by plant C input, microbial decomposition, and erosion. This concept only applies to C percentage in soil surface. We found that the sediment transport and soil production from bedrock are essential in mechanically understanding the spatial pattern of SOC storage in local to regional scales.

Based on the relationships between slope curvature, soil thickness, and SOC storage, we created SOC storage maps at both sites (*fig.5*). From these maps, we calculated that ~70% of hillslope SOC resides in depositional slopes that are susceptible to episodic mass movement, such as landslide and earthflow. With the nearly ubiquitous hillslopes over the globe, we roughly estimated that ~50% of global SOC pool occurs in depositional slope turning over in 1~10kyr scales.

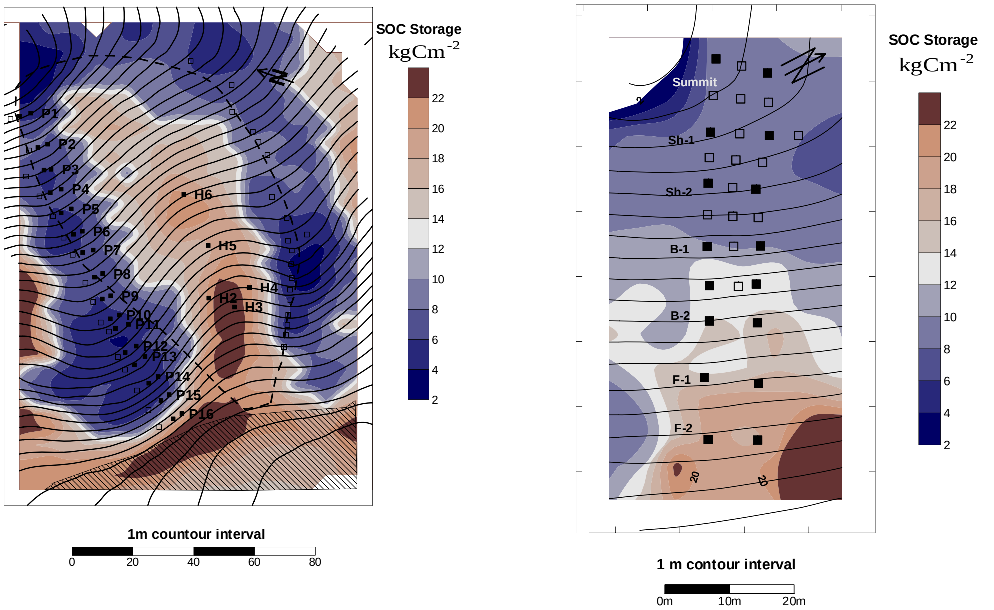

Figure 5. Calculated SOC storage map at (a) Tennessee Valley, and (b) Black Diamond.

Temporal Variation of Hillslope Soil Organic Carbon Storage

In spite of C erosion losses, two sets of data support the likely steady state of SOC storage on convex slopes. By definition, SOC storage equals the depth integration of C profile. We examined the temporal change of soil thickness and soil C concentrations. First, the measured soil thicknesses on the convex slope that reasonably conform to the model-predicted steady state values. Second, the soil C percentage varies independently of slope gradient and curvature, suggesting that the biological C cycle rather than sediment transport determines soil C percentage. While we do not have the record of biological C fluxes in the time scale of 10^3 to 10^4 years, the lack of an irregular sedimentation record in adjacent depositional soils suggests a stable climate during the Holocene. Subsequently, it is likely that SOC storage on the convex slope is at a steady state.

In contrast to convex slopes, convergent areas have thicker soils due to sediment input. Based on the geometry of hollow and known soil erosion rates, we simulated the temporal trend of hollow soil thickness at TV. To reach their current thicknesses, soils have accumulated sediment for the 11-13k years and 5.3-8.8k years at TV (*fig. 6a*) and BD, respectively. These ages agree with the published hollow ages in the area determined by dating basal charcoal (Reneau and Dietrich 1990, 1986; Reneau et al. 1990). At TV, as hollow fills up, sediment spread over expanding depositional area leads to decreasing rates of thickening.

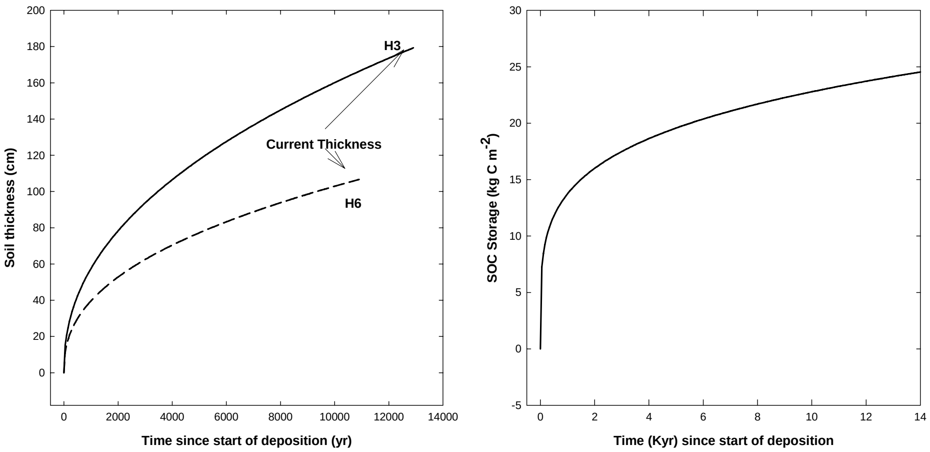

Figure 6. Simulated hollow (a) soil thicknesses and (b) SOC storage at Tennessee Valley.

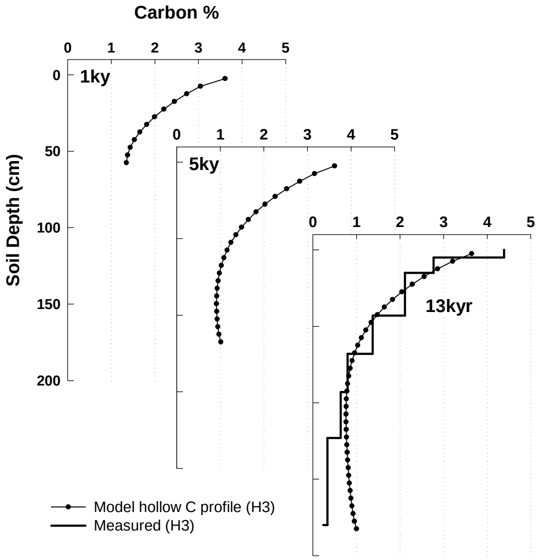

Figure 7. Simulated soil C profiles during hollow infilling at Tennessee Valley.

Sedimentation leads to C accumulation in the depositional soils. The long-term C accumulation rates vary between 1.4 and 2.1 g C m^{-2} yr^{-1} within the TV hollow. In the BD footslope, a rate of 1.7-2.8 g C m^{-2} yr^{-1} was obtained from our calculations. We modeled the hollow SOC storage as a function of time using sedimentation rates and rates of C cycling (*fig. 6b*). The simulation for TV suggests a decreasing C accumulation rate from 14 g C m^{-2} yr^{-1} during the first 1,000 years to 0.3 g C m^{-2} yr^{-1} at present. The current C accumulation rate at BD was calculated to be 0.8 g C m^{-2} yr^{-1}.

To mechanically understand the decreasing temporal trend of SOC accumulation, a C profile was simulated for TV hollow (*fig. 7*). In the model run, the soil surface C concentration, once formed, varies little over time because the site-specific C cycling rates are faster than sediment deposition. As time progresses, the thickening of the deeper soil zones with lower C percentage causes the additional SOC storage. The C cycling, combined with the declining rate of soil thickening, explains why SOC accumulation rate decreases faster than soil thickening rate.

We combined the SOC storage on eroding and depositional components of the TV watershed with estimates of rates of hollow infilling and evacuation (*fig. 8*). From this comparison, it is clear that the watershed SOC storage is largely driven by the hollow, in terms of magnitude and dynamics. The watershed-averaged C accumulation is 9 kg C m^{-2} during the past 12k years, a value close to the globally averaged SOC storage of 10 kg C m^{-2} (Post et al. 1982). We note that the short-term rate of C sink depends on the stage of hollow accumulation. The overall watershed SOC accumulation rate is 0.8 g C m^{-2} yr^{-1}. This is a significant value, which is 5-11% of the current missing C sink strength. On level soils not subjected to erosional/depositional processes, the landscape would be at C steady state on these time scales (Schlesinger 1990).

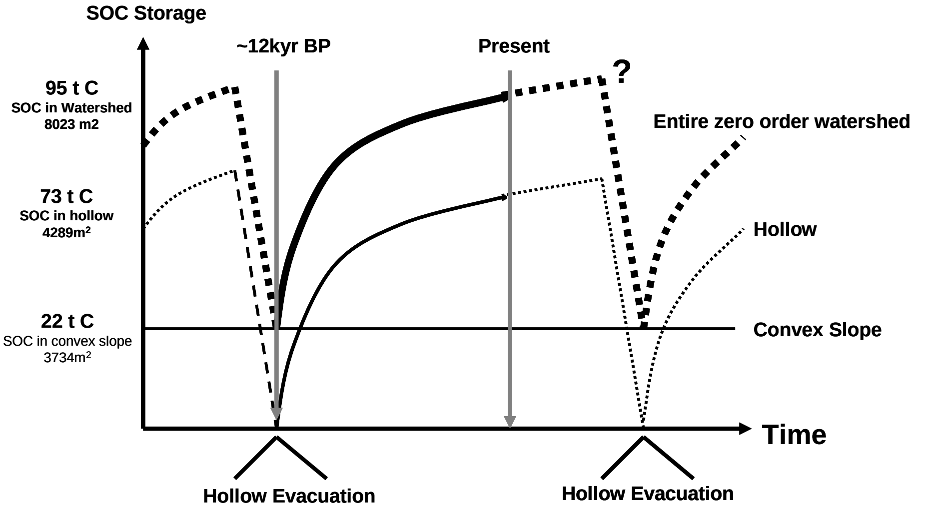

Figure 8. Temporal trends of soil C storage in hillslope components (convex slope and hollow), and of the entire zero-order watershed studied, for Tennessee Valley.

Source of Soil Organic Carbon in Depositional Landscapes

The assumption that eroded C is buried and preserved in depositional areas is the primary reason that soil erosion is viewed as an atmospheric C sink. In spite of the significance of the issue, this assumption has not been closely investigated. Based on the simulation below, we suggest a strongly contrasting situation, in that nearly all eroded C is oxidized in depositional settings, and that the large pool of C in these soils is almost entirely due to plant production and in situ C cycling – combined with the relatively great soil thicknesses.

To examine the fate of eroded SOC once deposited in a hollow, we simulated an empirically constrained TV hollow SOC storage model with and without in-situ plant C inputs. When simulated without plant C inputs, the resulting SOC storage was nearly zero after hollow infilling, meaning that the depositional C input is oxidized. Because this conclusion hinges on the chosen decomposition rate of the deposited C, we used a range of feasible decomposition rates, and similar results were obtained regardless of decomposition rate.

Without preserving deposited SOC, how did depositional soils accumulate SOC? In-situ plant is, based on our simulations, the primary source of C for the hollow soils. This is further supported by following data. First, we multiplied the soil sedimentation rate to the C concentration of sediment. The resulting depositional C input was comparable to current plant C input only during the initial sedimentation, and rapidly declined to the current rate of <2 g C m^{-2} yr^{-1} (~1 % of ANPP). Second, the measured C:N ratios were significantly higher (meaning fresher organic matter) in the hollow than on the convex slopes, supporting the dominance of in-situ net primary productivity (NPP) in hollow SOC pool. In-situ NPP also appears to dominate depositional SOC at BD since depositional C input is currently ~1% of in-situ ANPP.

We conclude that the studied upland watershed C sinks developed due to the sedimentation of in-situ plant C. This is a previously unrecognized process of C sinks. There are likely other geomorphic settings in which eroding materials from convex slopes directly enter the area with greatly reduced decomposition rates. Our research, however, emphasizes that in-situ plant significantly supplements the sediment-driven watershed C sink, regardless of the fate of eroded C.

Conclusion and Future Research Need

To our knowledge, this is the first attempt to study the temporal and spatial dynamics of hillslope SOC by mechanically combining the biological and geomorphic processes. By conducting this study in grassland hillslopes typical in California, we addressed the central Kearney Foundation’s mission: *Understand mechanisms and processes governing the storage and flow of carbon pools in soils that support California's diverse ecosystems.*

The studied hillslopes may lie near one end of the spectrum of erosion vs. biological C cycling rates. Regardless of environmental conditions, however, the fundamentals of the model (a combination of Eq. 1 and 2) are applicable to other areas by substituting appropriate sub-models of soil erosion and production. Additionally, the inclusion of particle sorting during sediment transport will advance the current understanding of hillslope SOC distribution and its temporal trends.

This study shows that individual hillslopes or zero-order watersheds are time-dependent C sinks. This time dependency makes it challenging to estimate the current C sink size in the larger regional to global scales. Depending on the temporal correlation and spatial extent of episodic evacuation of deposited materials, the hillslope C sink in larger scale will vary greatly. There is evidence that hollow evacuation, was concentrated in the beginning of Holocene along the west coast of the United States (Reneau and Dietrich 1990). If this applies to the globe, simple calculation of upland depositional SOC storage suggests that up to half of global soil C pool has accumulated during the Holocene, which must have substantially affected the global C cycle.

In placing the zero-order watersheds in the larger scale of river watersheds, the least-known factor is the fate of SOC exported from the upland hillslopes. The C-bearing sediment continuously leaves the watersheds. More importantly, the hollow episodically evacuates. We know little about where the C in these sediments ends up. If the exported C is completely protected from oxidation, a cumulative C sink occurs. This, when scaled up, has potential to deplete the atmospheric C pool in 10k years, emphasizing the role of C export in the global C cycle. This calculation did not even include the burial of in-situ plant production by sediment, the major process of hollow C accumulation. In the present world, a significant fraction of the C exported may be buried in reservoirs as Stallard (1998) has suggested. On geological time scales, oxidation of exported C may have experienced substantial changes during the sea level change.

The base level variations must have increased the thickness of floodplain sediments, burying in-situ plant and slowing down the oxidation of C export. The fate of C export is presently a poorly constrained question, one that is a key to expand the findings of this study to geological time scales.

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