Erosion and Non-steady State Storage of Soil Organic Carbon on Undisturbed Hillslopes in Coastal California

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Introduction

Most upland ecosystems under natural vegetation are not level; land with < 8% slope comprises only 36% of global soil [*Staub and Rosenzweig*, 1992]. These hilly upland landscapes represent unexplored processes relevant to the global C cycle. In recent years, geomorphic research on the processes of soil transport on soil mantled hillslopes has provided an empirically constrained mathematical framework to explore an unknown aspect of the upland soil C cycle: the rate of soil C erosion and burial within watersheds. We conducted intense soil C studies on two sites where extensive geomorphic research on soil production and transport has been made. In particular, we attempt to achieve two objectives: (1) quantify the C fluxes associated with soil erosion and deposition, and (2) integrate these two processes to determine the C accumulation in typical hillslopes in central California.

Model

In contrast to the traditional soil organic carbon mass balance models that consider soil carbon storage (C) as a balance of plant C inputs (I) and C losses through microbial decomposition (R_h), we included erosional loss (positive) or depositional gain (negative) of soil C (ε) [Stallard, 1998]:

$$\frac{dC}{dt} = I - R_h - \varepsilon \qquad (1)$$

On convex land surfaces, soil transport is driven by a combination of biological and physical processes aided by gravity, which results in curvature-dependent soil C erosion losses:

$$\varepsilon = \rho_\varepsilon f(-K\nabla^2 Z) \qquad (2)$$

where ρ_ε is the bulk density of eroded soils, f is the mass fraction of carbon in eroded soils, K is the diffusivity, and $-\nabla^2 Z$ is the negative curvature of the slope.

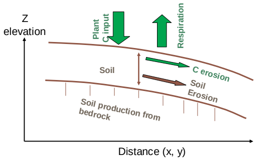


Fig.1 **Cross section view of a convex hillslope soil C mass balance**

On concave slopes ($-\nabla 2z$ is negative), soils continue to thicken due to sediment input until they are eventually evacuated through landslides, and the cycle then repeats. Here, we have simplified hollow geometry (Fig. 2) and analytically modeled how hollow soil thickness varies with time, following the approach of Dietrich et al., [1986]. In this approach, the soil thickness along a hollow axis is described as a function of diffusivity (K), side slope angle (β), convergence angle (γ), and time (t):

$$H = [2Kt\cos\gamma\tan\beta(\frac{1}{\sin^2\beta\cos^2\gamma} - 1)^{-1/2}]^{1/2} \qquad (3)$$

During the soil thickening, the C content at depth z is modeled as the balance of plant C inputs and SOC decomposition:

$$\frac{d(\rho_z C_z)}{dt} = \frac{I_z}{\Delta z} - k_z \rho_z C_z \qquad (4)$$

The depth integration of this C profile yields soil C storage.

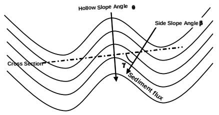


Fig.2 **Simplified geometry of hollow**

In hollows where soil continuously thickens, the depth from the soil surface to a soil layer of interest (z in Eq.4) must be adjusted as deposition occurs. This is important because both plant C inputs and decomposition rates vary significantly with soil depth. Given that the distance of certain soil layer to the soil-bedrock interface (Θ) stays constant in hollows in spite of the soil thickness (H) change, the soil depth z in Eq.4 is adjusted as:

$$Z = H - \Theta \qquad (5)$$

where z is soil depth from ground surface [L], and Θ is distance of that soil layer to bedrock. The distance to bedrock (Θ) does not change, while the soil thickness (H) is dynamic. When Eq.4 is solved with time dependent soil thickness (Eq.3), this depth adjustment is continuously made.

Sites and Measurements

On the following hillslopes at two sites, we made detailed measurements of the spatial variation in soil organic carbon content and above ground net primary productivity (ANPP). The soil %C was combined with the erosion mechanism on the site to determine the %C of eroding soils. We also made detailed topographic survey with total laser station. The resulting data was used to calculate the local slope curvature over the entire hillslopes.

Fig.3

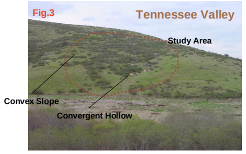


Fig.4

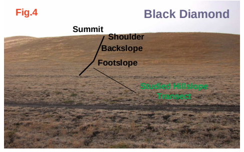


Table 1

	Tennessee Valley	Black Diamond
Climate	Mediterranean MAP: 1200 mm yr^{-1}	Mediterranean MAP: 350 mm yr^{-1}
Bedrock	Sandstone	Clay-rich Shale
Erosion mechanism	Bioturbation and Rainsplash	Soil creep with Soil swelling and shrinking
K (Eq.2)	50cm^{2}yr^{-1*}	360cm^{2}yr^{-1+}
C concentration of eroding soils (f in Eq.2)	Case I (Gopher Induced erosion) 2-5% varying with elevation Case II (Rainsplash induced erosion) 3.5-6% varying with elevation	Decreasing from 2% at summit to 0.7% at footslope

* Heimsath et al., 1997, +McKean et al., 1993

Result 1: Soil C Erosion Flux

1. C erosion flux at Tennessee Valley

Fig.5 **Soil Erosion by Gopher Soil Perturbation**

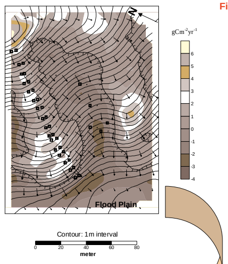
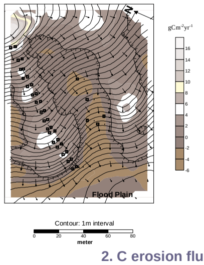


Fig.6 **Soil Erosion by Rainsplash or Root Decay**



We measured the %C of eroding soils and slope curvatures over the entire hillslopes. These measurements allowed us to calculate the soil C erosion flux using Eq.2.

The average C erosion loss from convex slopes was between 1.4 and 2.7 g C m^{-2} yr^{-1} at TV and approximately 8 g C m^{-2} yr^{-1} of at BD. The C erosional flux was locally as high as 5 (case I)-14% (case II) of ANPP at TV and 8% at BD.

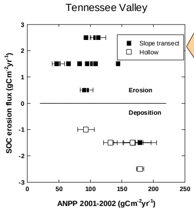


Fig.7 Comparison of soil C erosion flux to measured Above ground Net Primary Productivity (ANPP)

2. C erosion flux at Black Diamond

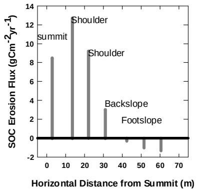


Fig.8 **Calculated soil C erosion flux along hillslope transect**

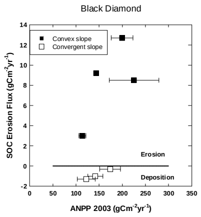
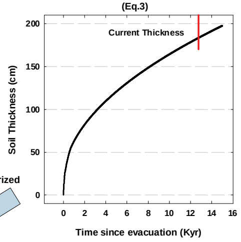


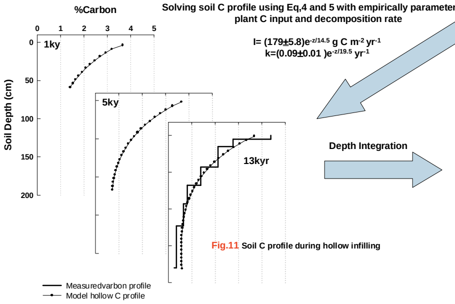
Fig.9 **Comparison of soil C erosion flux to ANPP**

Result 2: C Accumulation in Depositional Slope

Eroded soils accumulated in depositional slopes that were estimated to have residence times of 13 kyrs at TV and 5.3 kyrs at BD. In the TV hollow (depositional slope within a zero order watershed), 15-24 kg C m^{-2} of soil C has accumulated at a long-term rate of 1.6-1.9 g C m^{-2} yr^{-1}. The present rates of C accumulation were calculated to be 0.3 g C m^{-2} yr^{-1} at TV and 0.6 g C m^{-2} yr^{-1} at BD. During the hollow infilling, the depositional C inputs outweigh the C accumulation rates, meaning that much of the incoming eroded C was oxidized to CO_2. Given the higher C:N ratio of soil organic matter in hollows and the model simulation that suggests the present soil C profile can be formed even in the absence of erosional C inputs, most soil C in depositional areas appears to be from in-situ NPP rather than eroded soil C.

Fig.10 **Soil Accumulation in the Tennessee Valley Hollow (Eq.3)**





Solving soil C profile using Eq,4 and 5 with empirically parameterized plant C input and decomposition rate

$$I = (179 \pm 5.8)e^{-z/14.5}\ g\ C\ m^{-2}\ yr^{-1}$$
$$k = (0.09 \pm 0.01)e^{-z/19.5}\ yr^{-1}$$

Fig.11 **Soil C profile during hollow infilling**

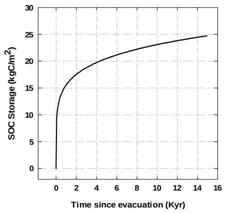


Fig.12 **Model estimated SOC storage during hollow infilling**

Result 3:Long-term Trends in Soil Carbon Storage at Tennessee Valley

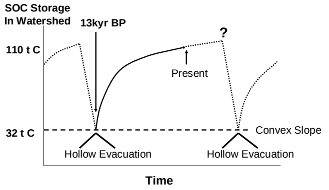


Fig.13 **The total SOC storage within the TV watershed between hollow evacuations**

The empirically obtained relationship between soil C storage and slope curvature was used to create the continuous soil C storage map, which allowed the estimations of soil C storage within convex slope and convergent slope. Here we took an extreme case that entire convergent hollow was excavated at 13 kyrs BP.

The watershed has been accumulating C, and its accumulation rate has been nonlinearly decreasing.

Result 4: The Size of C Sinks and Sources

The convex slopes were C sinks because NPP exceeds respiration by the size of C erosion. During the entire period of hollow infilling, model simulation suggests that the depositional C inputs are far greater than the C accumulation rates, meaning that hollows act as a net C source even though they are large stores of C. However, when all hillslope components are integrated, these hillslopes are continuous atmospheric C sinks currently sequestering up to 0.3 and 3.9 g C m^{-2} yr^{-1}. We suggest that the impact of soil erosion and deposition on upland soil C cycle can play a significant role in the global C balance.

Table 2 **A summary of the C fluxes for different components of the two watersheds.**

Case	Eroding Slope All rates are averaged over the convex slope				Depositional Slope All rates are averaged over the convergent slope				Entire Hillslope All rates are averaged over the entire slope		
	Area or Length	C Erosion Rate gCm^{-2}yr^{-1}	C Accumulation Rate gCm^{-2}yr^{-1}	C Sink gCm^{-2}yr^{-1}	Area or Length	C Deposition Rate gCm^{-2}yr^{-1}	C Accumulation Rate gCm^{-2}yr^{-1}	C Source gCm^{-2}yr^{-1}	C Accumulation Rate^1 gCm^{-2}yr^{-1}	C Export Rate gCm^{-2}yr^{-1}	C Sink gCm^{-2}yr^{-1}
Tennessee Valley Scenario I	3734m^2	1.4	0	1.4	4289m^2	1.0	0.3	-0.7	0.2	0.1	0.3
Tennessee Valley Scenario II		2.7	0	2.7		1.5		-1.2		0.5	0.7
Black Diamond	35m	8	0	8	35m	1.0	0.8	-0.2	0.4	3.5	3.9

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