Where does fluvial transport transition to debris flow failure in the natural landscape?

Jeff P. Prancevic*, Michael P. Lamb, Brian M. Fuller

Geological & Planetary Sciences,
California Institute of Technology, Pasadena, CA

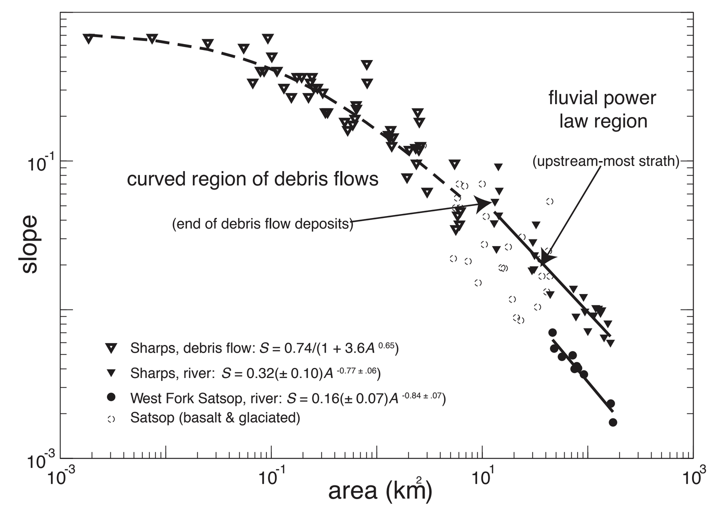
*jprancev@caltech.edu

Summary

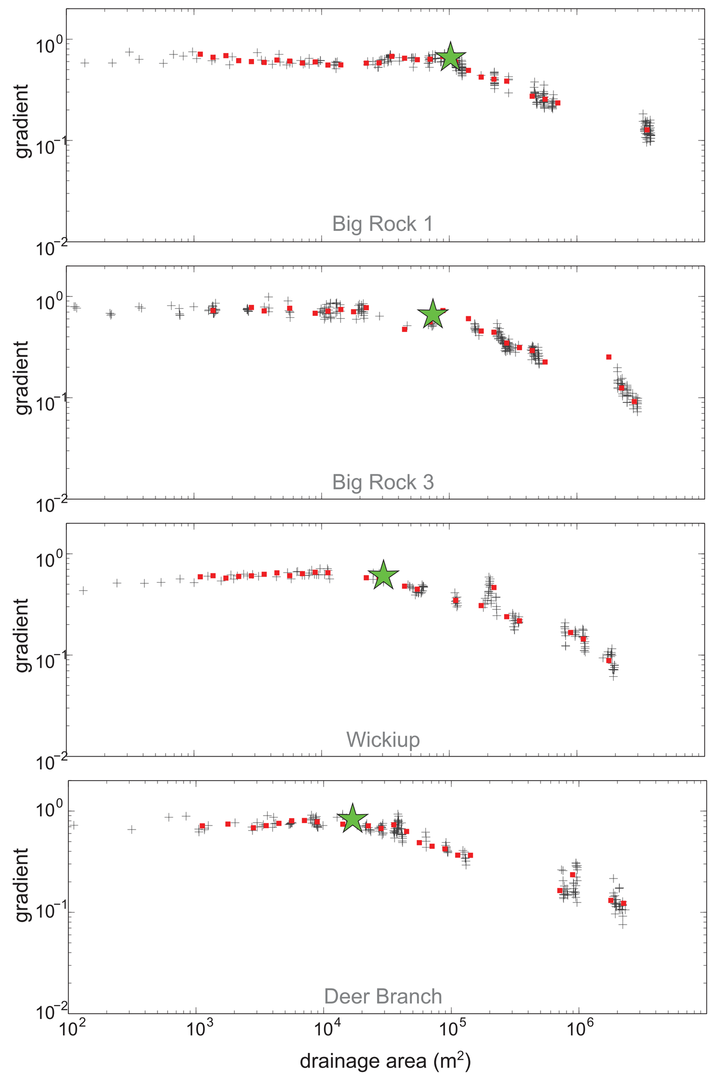
- Two dominant sediment transport regimes are known to occur in mountainous landscapes: dilute fluvial bedload transport and *en masse* bed failure. However, the transition between these two regimes has not been identified.
- We test, for the first time, the transition between fluvial sediment transport and bed failure using laboratory flume experiments.
- The experimental results show that we can accurately predict the onset of bedload transport up to the transitional slope.
- The critical conditions for bed failure, however, do not follow theoretical predictions without introducing a fit parameter that has an unclear physical meaning. We investigate potential explanations for the discrepancy between traditional theory and our experimental results.
- Using this best-fit model we identify a critical slope that represents a maximum slope at which fluvial bedload transport can occur. However, bed failures can likely occur at much lower slopes under extreme flood conditions or grainsize perturbations.

The Landscape Signature of Debris Flows

Olympic Mountains, WA and Oregon Cascades *(Stock et al., GSA Bull., 2005)*



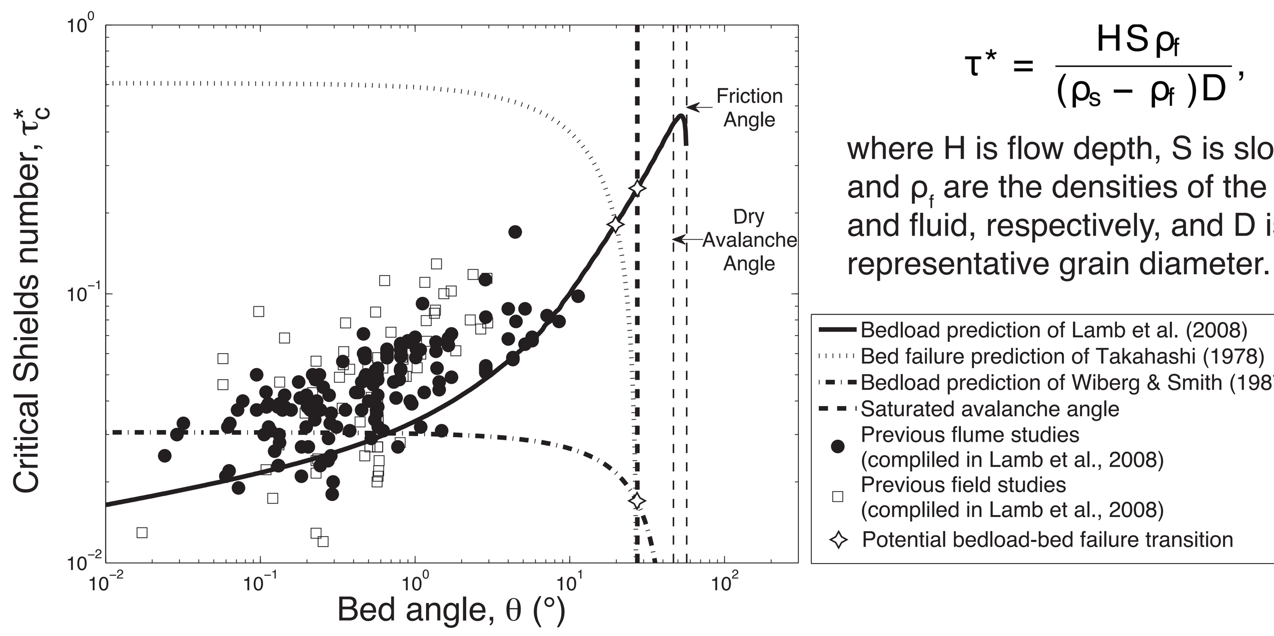
San Gabriel Mountains, CA *(DiBiase et al., ESPL, 2012)*



In plots of topographic gradient vs. total drainage area, researchers have noted that there exists a regime at large drainage areas that follows a power law relation. Above this critical drainage area, the topographic gradient varies less with drainage area. This transition typically occurs between 3% and 10% slope (2° and 6°) (Stock & Dietrich, 2003), but can extend up to much steeper slopes in some landscapes. This transitional slope is typically thought to represent the lowermost extent of debris flow runout, as confirmed by field investigations (Stock & Dietrich, 2003).

But where can we expect these debris flows to initiate?

Theoretical Debris Flow Initiation



$$\tau^* = \frac{HS\rho_f}{(\rho_s - \rho_f)D},$$

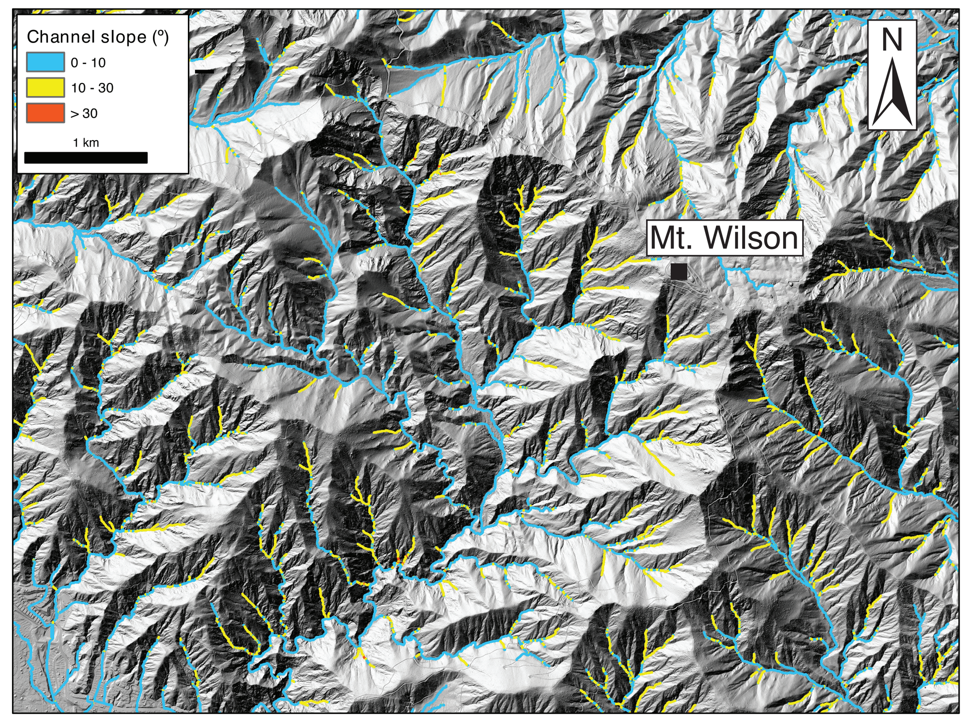
where H is flow depth, S is slope, ρ_s and ρ_f are the densities of the solid and fluid, respectively, and D is the representative grain diameter.

The theoretical transitional slope between bedload transport and channel bed failure varies between 20° and 27° depending on which fluvial transport model is used. Both fluvial transport models perform a similar theoretical force balance on an individual grain, except the Lamb model considers altered flow hydraulics of steep slopes. The Takahashi model is an infinite slope force balance that considers seepage stress and surface flow. Unfortunately, previous fluvial transport experiments extend up to only 10°, while controlled slope stability experiments and field monitoring have only taken place on slopes greater than ~30°.

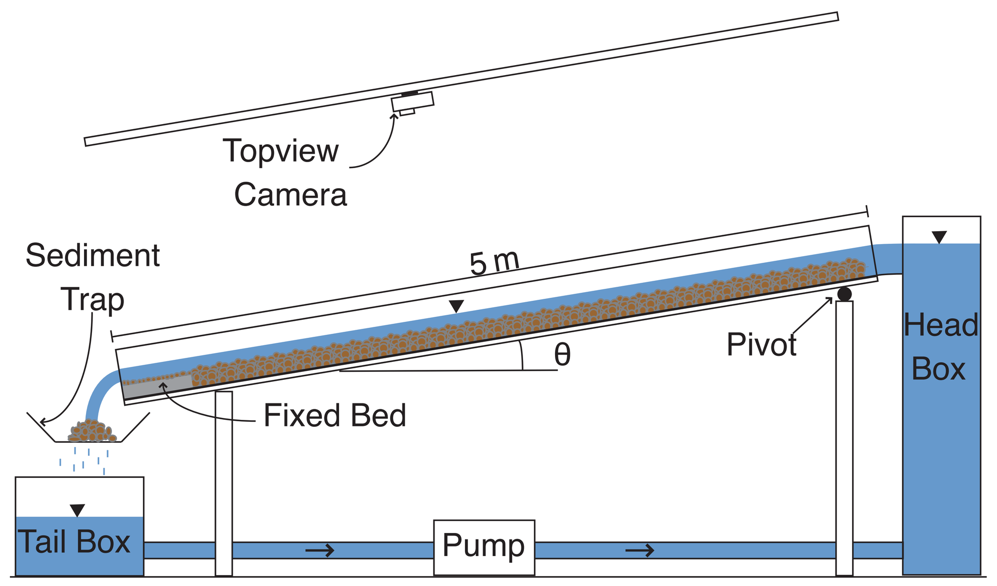
Slope Distribution in Mountainous Terrain

Unfortunately, much of the drainage network in mountainous terrain exists within this untested, yet critical range in slopes (10° to 30°).

San Gabriel Mountains, CA

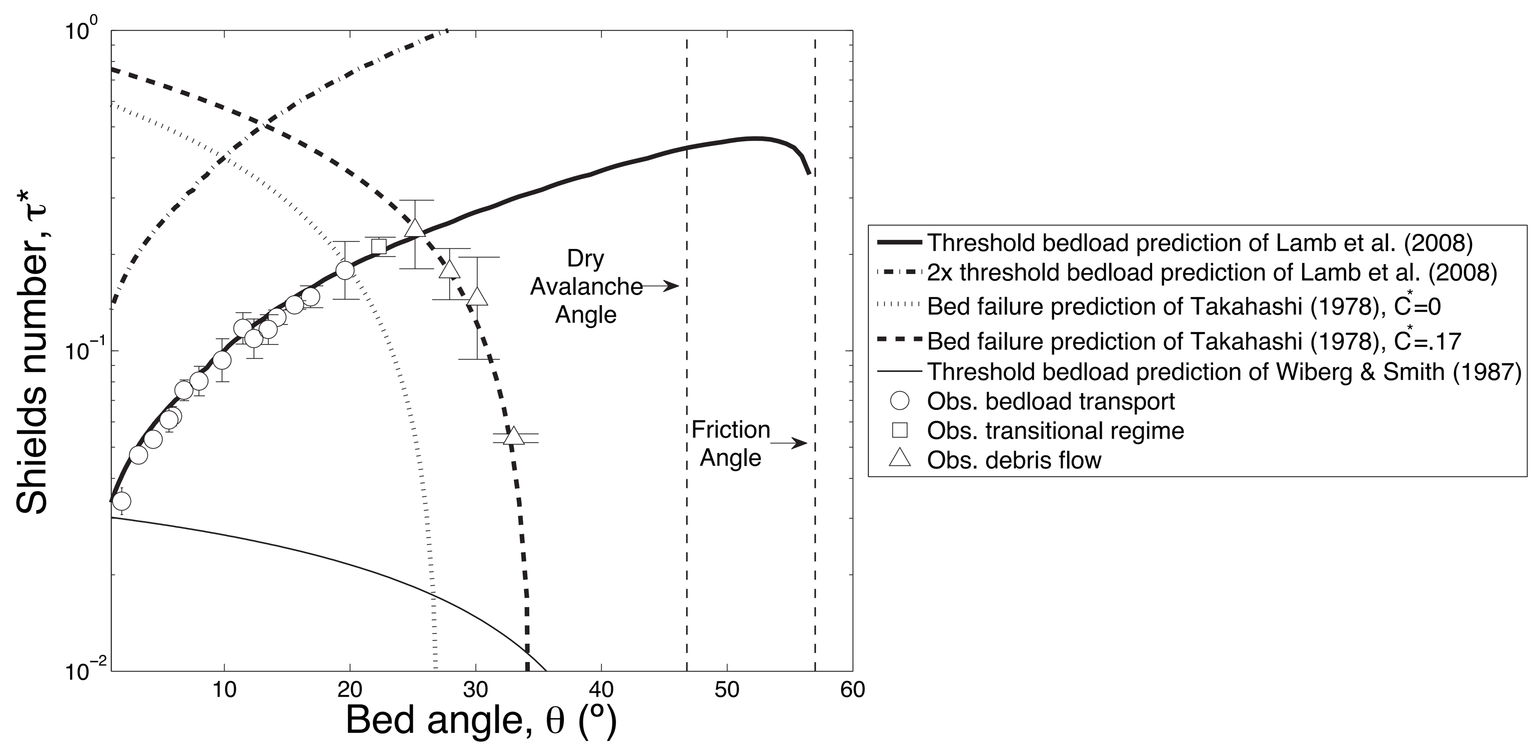


Flume Experiments



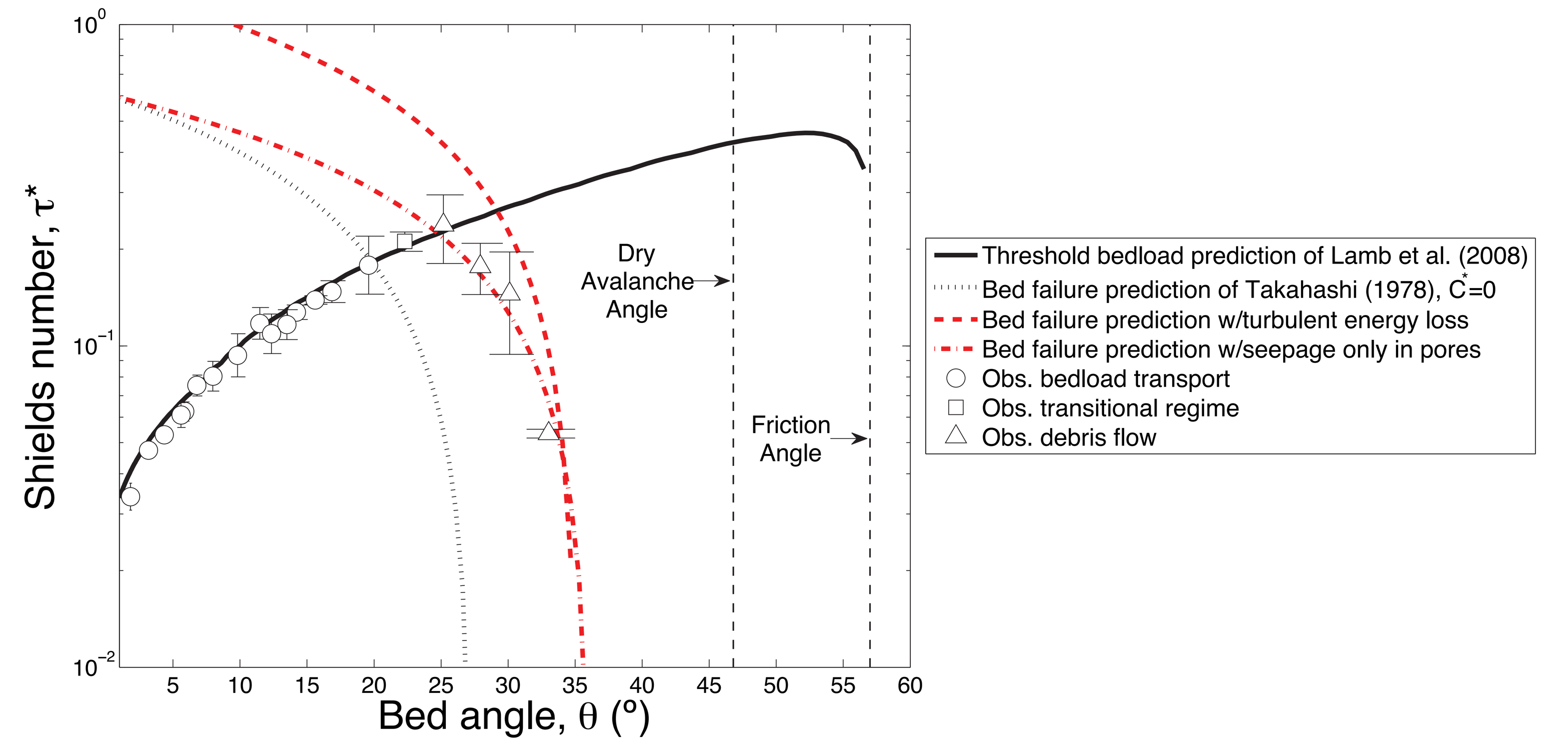
To address this gap in threshold of motion data we conducted laboratory flume experiments at 15 different slopes ranging from 3° to 33°. We used 1.5-cm siliciclastic gravel screed to a planar initial bed topography. Flow discharge was slowly increased until transport conditions were achieved. Flow velocity, discharge, and depth, as well as sediment flux were measured at each discharge in order to calculate the critical conditions.

Experimental Results



- For fluvial bedload transport the data clearly supports the Lamb et al. (2008) model for threshold bedload transport over the traditional Wiberg & Smith (1987) model that was developed for low-sloping rivers.
- Based on this fluvial model and the Takahashi (1978) bed failure model, the expected transition occurs at 20°
- In experiments, patchy bed failure occurred at 22°
- A clear change in sediment transport mechanism did not occur until 25°
- **The bed is more stable than predicted!**
- Adding an effective cohesion term better fits the data but the physical meaning of this term is unclear, given that our grain size is large and doesn't experience the electromagnetic cohesion of clay
- We need an alternative modification to explain the unexpected bed stability for coarse particles.

Modifications to Slope Stability



In an effort to better explain the unexpected stability of the sediment grains within the bed failure regime, we propose two modifications to the traditional Takahashi (1978) model:

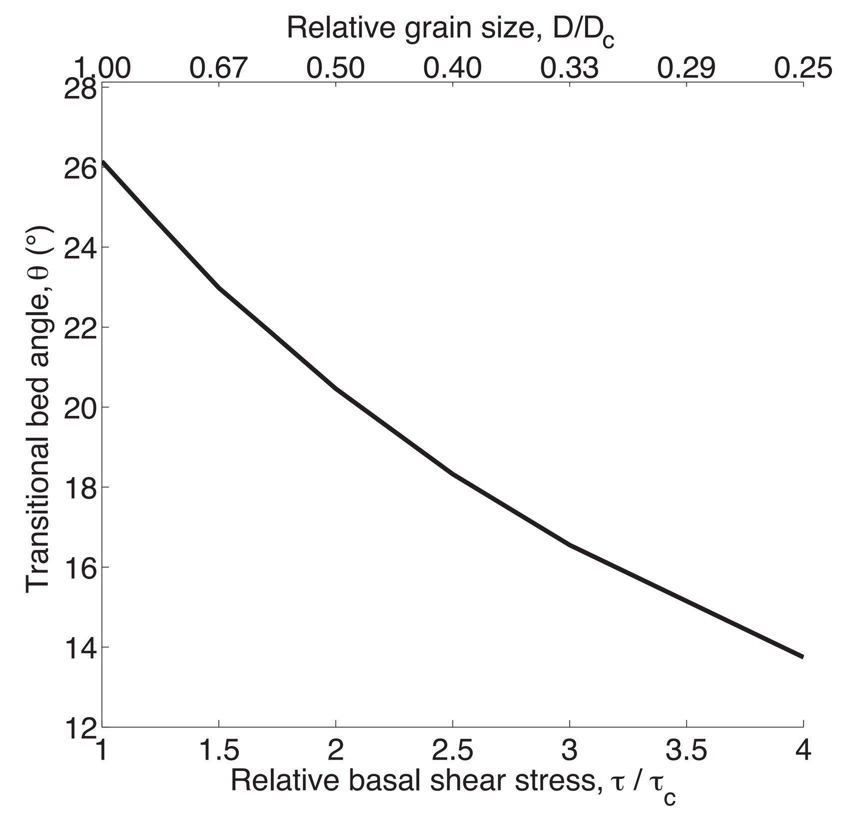
I. At these steep slopes with coarse material, the subsurface flow is turbulent and no longer within the Darcy regime (Re ≈ 700). In this case, some of the energy in the flow is lost turbulent energy rather than stress on the grains. In an attempt to account for this we subtract the nonlinear component of the Forchheimer energy slope ($\nabla h = (1/K)q + \mathbf{B}q^2$) from the slope used in calculating seepage stress.

The resulting model prediction fits the data better, but is still outside of the error bars. Further calibration of the linear Darcy coefficient, K, may improve this fit.

II. Most traditional slope stability models that include seepage stress, including that of Takahashi (1978), consider seepage stress as the downstream component of the gravitational force acting on the fluid, but neglect to include porosity. The reason for this may lie in the treatment of buoyant force relative to seepage force; however, accounting for porosity in the seepage stress here provides a great fit with the data.

The Threshold Slope for Extreme Conditions

The transitional slope presented in the plot to the left (25°) is that expected at the threshold of motion. If the threshold of motion is exceeded, then bed failure could potentially occur at much lower slopes. The plot to the right shows how the critical slope for bed failure changes as the excess shear stress increases. This can be achieved by a large flood event, or by a normal flood event following a grain size perturbation. It is this grain size perturbation that may explain the increased occurrence of debris flows following wildfires and the associated dry ravel.



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