The Transfer of Modern Organic Carbon by Landslide Activity in Tropical Montane Ecoystems

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Landslides- A key geomorphic agent

Sediment Budgets

-***89%:*** sediment generated by a single storm was landslide-derived
North Island, New Zealand (Page et al, 1994-*Geomorphology*)

-***60%:*** road-related sediment production associated to landslides
Clearwater Basin, WA-USA (Reid et al., 1981-*Jrnl of Hydrology*)

-***50%:*** sediment budget attributed to landslides
Issaquah Creek, WA-USA (Nelson & Brooth, 2002-*Jrnl of Hydrology*)

-***77-98%***: long-term sediment released from hillslopes due to landsliding
Puerto Rico (Larsen, 1997)

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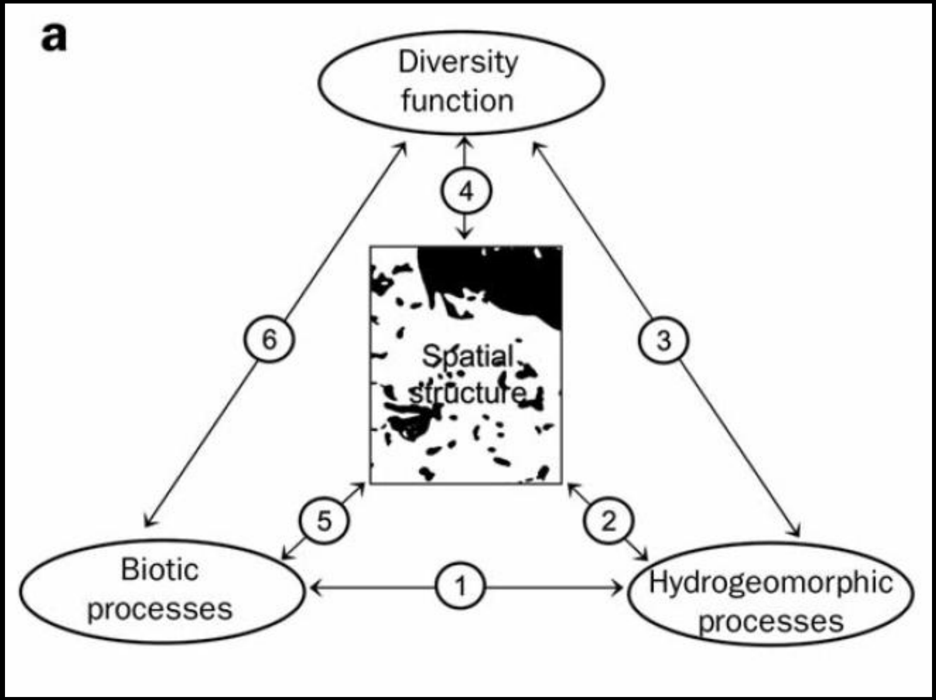
Landslides- A key Eco-geomorphic agent

Two-way interactions:

- *Ecological Diversity*
- *Slope stability (root cohesion, macropores, interception, ET, etc.)*
- *Thickness of detritus*
- *Nutrient and Carbon Cycling*



From: Restrepo et al. 2009. Biosciences

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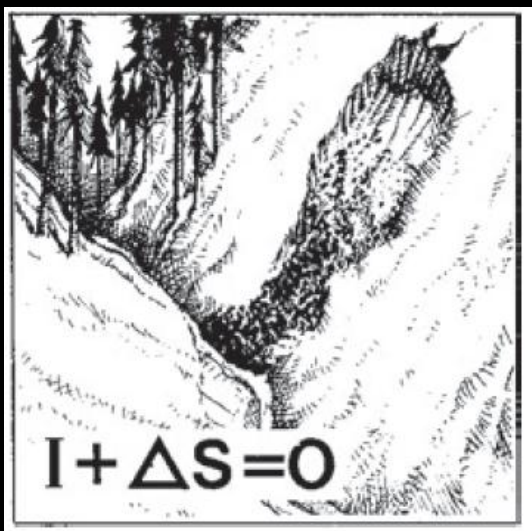
Landslides- Relevant to Carbon Budgets

Watershed- or Regional-scale simple mass conservation approach:

Δ Storage = Inputs – Outputs



From Swanson et al. (1982)-Sediment budgets and routing in forested drainage basins.

What are the landslide-relevant processes controlling inputs/outputs of Carbon?

Outputs

a) Losses associated to direct delivery to the outlet of the control surface (debris flows to watershed outlet)
b) Losses associated to consequent erosion of colluvial compartments and eventual fluvial transport to the outlet of the control surface
c) Losses associated to oxidation of organic components exposed to aeration in colluvial deposits still within the boundaries of the control surface

Inputs

a) Net Primary Production on failed (scared/scoured) surfaces during ecosystem development

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Landslides- Relevant to Terrestrial Carbon Budgets

$$\Delta S = Inputs - Outputs$$

$$\Delta S = Ecosystem\ Recuperation - Losses$$

$$\Delta S = \left[NPP_{landslide} * Area_{landslide}\right] - \left[\sum C_{landslides} * (1 - \%\, C_{retained})\right]$$

$$\Delta S = \left[NPP_l * \sum C_l \big/ C_{\rho\, l}\right] - \left[\sum C_l * (1 - \%C_{retained})\right]$$

$$\Delta S = \sum C_l * \left[\left(NPP_l \big/ C_{\rho\, l}\right) - (1 - \%C_{retained})\right]$$

$$\left(NPP_l \big/ C_{\rho\, l}\right) \sim Recurrence\ Interval\ Landsliding / Time\ for\ Recuperation\ of\ Carbon\ Lost$$

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Objectives

1) Quantify pre-landslide triggering event modern C stocks for the Sierra de las Minas mountain chain in Guatemala [GIS procedure]
2) Quantify the quantity and disposition of C from source to depositional sites based on the population of landslides triggered by Hurricane Mitch (1998) in SLM [GIS procedure]
3) Assess the potential for net C loss/gain associated to landslides based on:

a) Data generated to fulfill Objectives 1-2 (hillslope & 1st order streams vs. higher order streams)
b) NPP rates associated to ecosystem recuperation on landslide scars based on literature reviews
c) Landslide-triggering event recurrence interval from previous studies in Guatemala.

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Introduction to SLM

- Central-eastern Guatemala; Northern sierras of Central America
- NW-SE direction, 130 km long
- Boundary between NA and Caribbean tectonic plates
- Lithology is dominated by metamorphic rocks (gneiss, schists, etc.)
- Wide range of climatic regimes (500-4000 mm yr^{-1} & 5-30 degrees C)
- 12 Ecosystem types (from xerophytic lowland forest to tropical evergreen broad-leaved altimontane forest) and 7 soil series grouped into 3 soil orders

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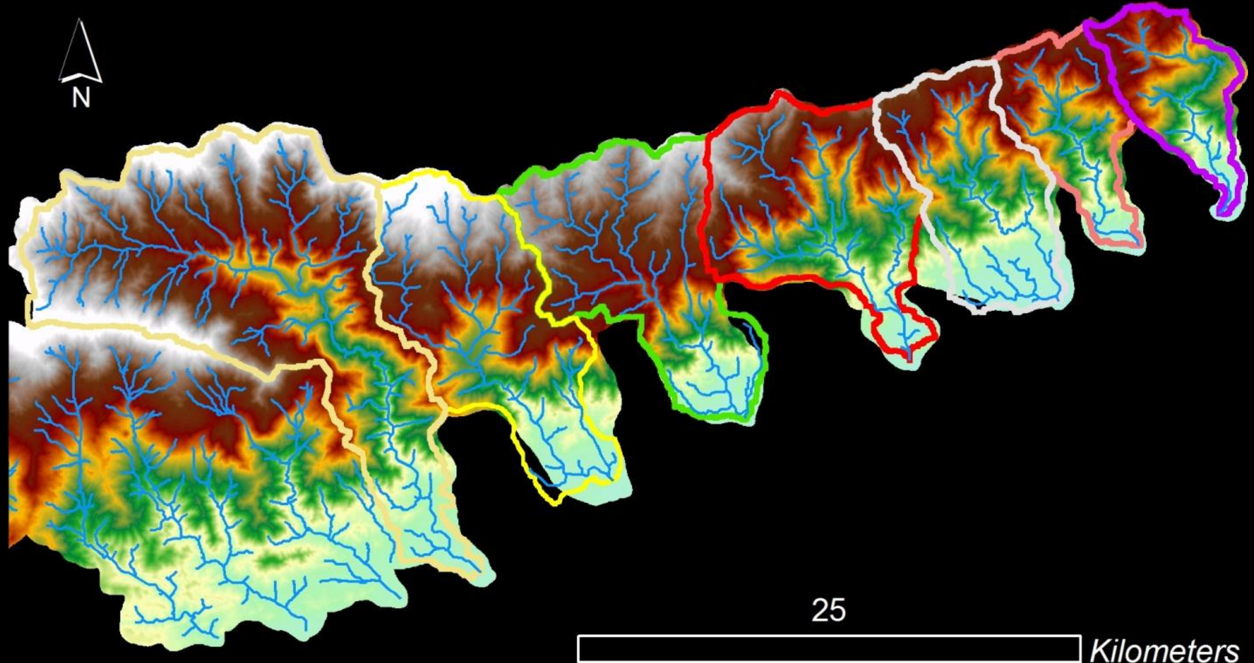
SLM- Seven Study Watersheds

- Southern flank of SLM (657 km^2)
- Watershed areas range from 39 – 207 km^2 (3rd to 5th order streams)
- Average slopes ranging 25 degrees $\pm$ 3 degrees
- Elevation range 140 – 2900 m



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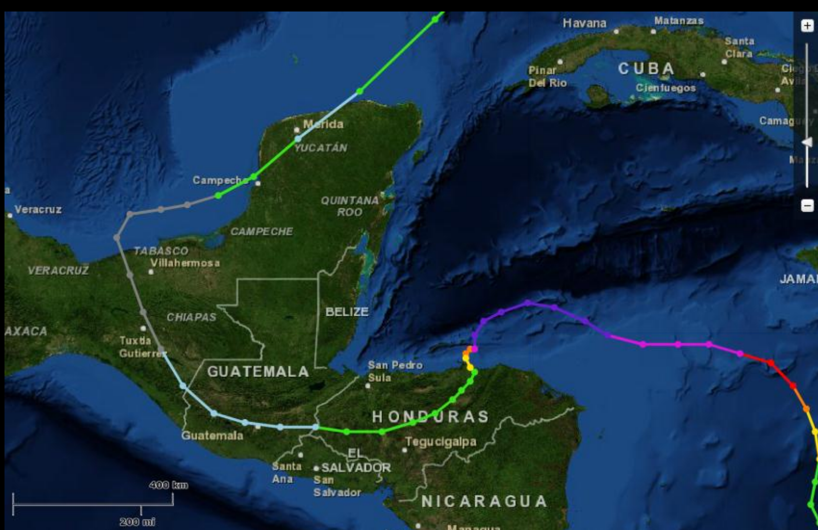
SLM-Hurricane Mitch

- One of the strongest and most devastating tropical storms impacting Central America over the last 250 years
- On 22 October 1998 it became a category 5 Hurricane on the Saffir-Sampson scale
- Reached the Guatemalan border October 31st



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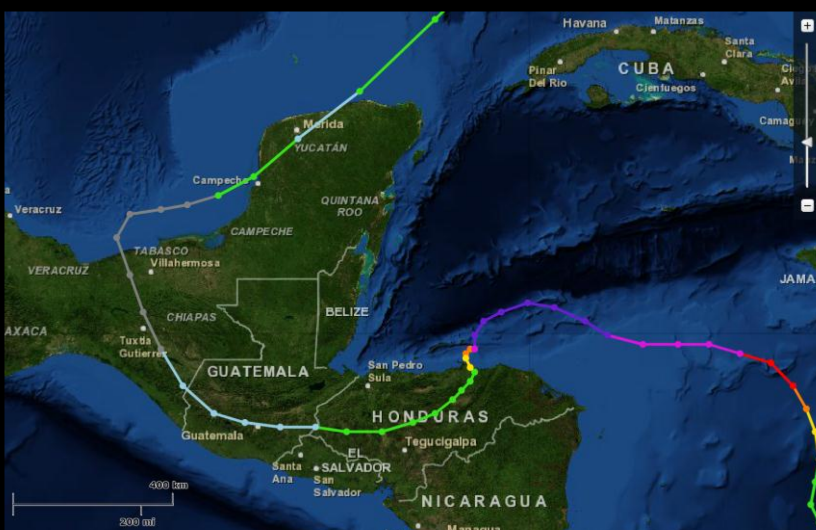
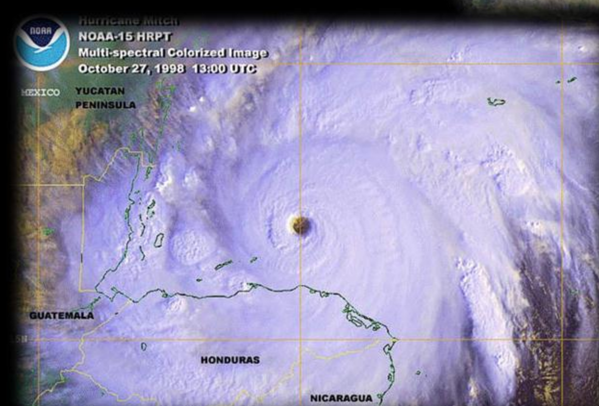
SLM-Hurricane Mitch

- Extreme precipitation experienced between October 27th and November 1st
- Within SLM it was responsible for almost tripling monthly average rainfalls (upwards to 500 mm)
- 11,500 landslides triggered over a 10,000 km^2 area of the SLM (Bucknam et al., 2001; Coe et al., 2004)





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Methods

Database generation

- Pre-existing vegetation and soil maps
- Linked to Carbon density tables generated from literature reviews

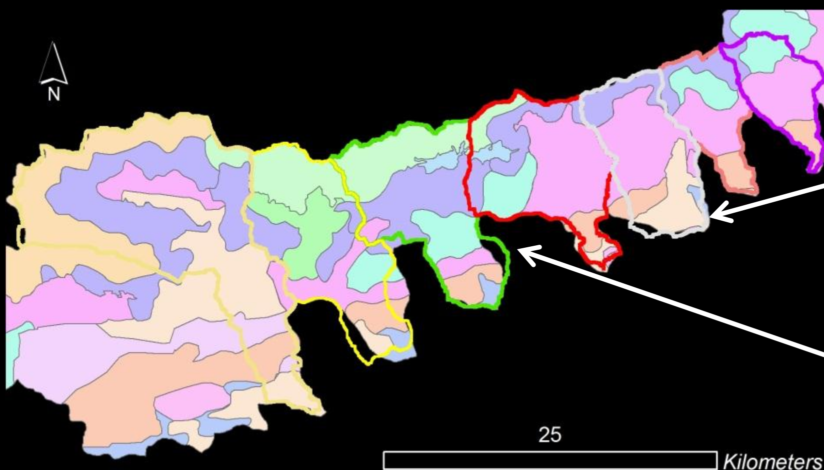

Table 1. Ecosystem types found within the study area in the Sierra de Las Minas arranged according to elevation except pastures and perennial crops.

Ecosystem type	Total area (ha)	Percent area	Carbon density ($Mg\ ha^{-1}$) (mean ± SD)
Tropical deciduous broad-leaved xerophytic lowland forest (1-07)	130	0.2%	16 ± 0[5,8]
Tropical evergreen mixed lower montane forest (1-27)	5300	8.1%	135[6]
Tropical evergreen mixed upper montane forest (1-30)	16500	25%	211 ± 62[2,3,8]
Tropical evergreen broad-leaved altimontane forest (1-32)	5100	7.8%	549 ± 90[8]
Tropical evergreen mixed altimontane forest (1-33)	6700	10%	80 ± 59[3]
Tropical deciduous broad-leaved xerophytic lowland shrubland (2-04)	700	1.1%	24[3,9]
Tropical deciduous broad-leaved lowland shrubland (2-05)	4700	7.1%	18 ± 11[4]
Tropical evergreen mixed shrubland (2-07)	15900	24%	87 ± 79[4,8]
Pastures and shrublands in degraded mountains (3-04)	650	1.0%	3.8 ± 2.3[1,7]
Perennial crops - Cultivated mixed forest (4-02)	2300	3.5%	32 ± 13.4[8]
Perennial crops - Shaded coffee, cacao, and/or cardamom plantations (4-04)	840	1.3%	39 ± 15.0[4,8]
Perennial crops – Cultivated open forest with pastures or shrublands in understory (4-05)	69	11%	3.8 ± 2.3[1,7]

[1] *M Acosta et al.* [2001], [2] *E Castellanos et al.* [2007], [3] *E Catellanos and C Florez* [2006], [4] *Castellanos* unpublished data, [5] *D Clark et al.* [2001], [6] *B H De Jong et al.* [1999], [7] *J Etchevers et al.* [2001], [8] *Fundacion Defensores de La Naturaleza* [2002], [9] *V J Jaramillo et al.*

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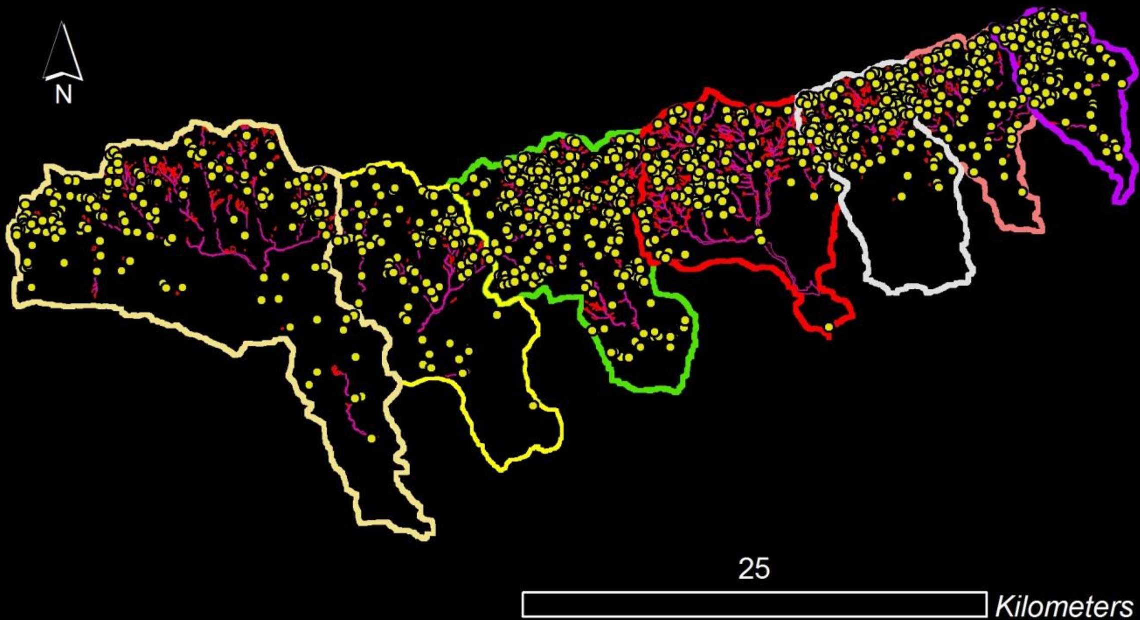
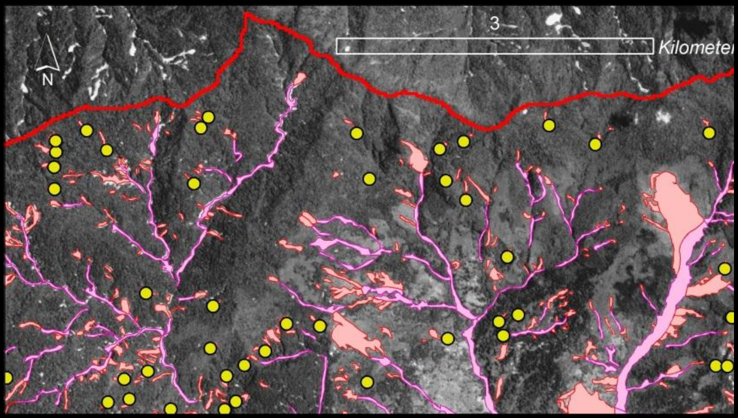
Methods

Database generation

- Landslide maps generated from aerial imagery (scars, debris scours, deposits)
- Linked databases (scars to scours to assumed depositional sites)





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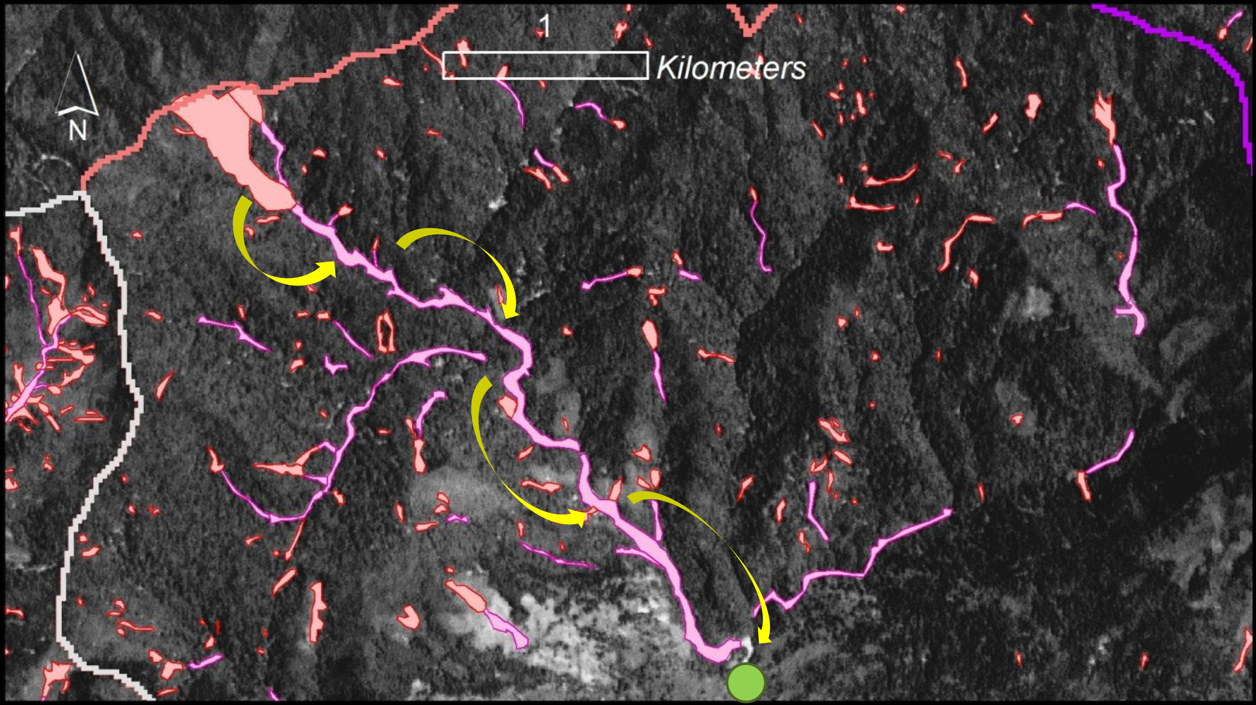
Methods

GIS Procedure-Watershed scale application

- Calculate the total and spatial distribution of Pre-Event C
- Calculate the total C transferred and its downslope transport to deposits
- Tabulate C downslope transfer in terms of elevation and whether C came to rest on hillslopes or streams of varying order



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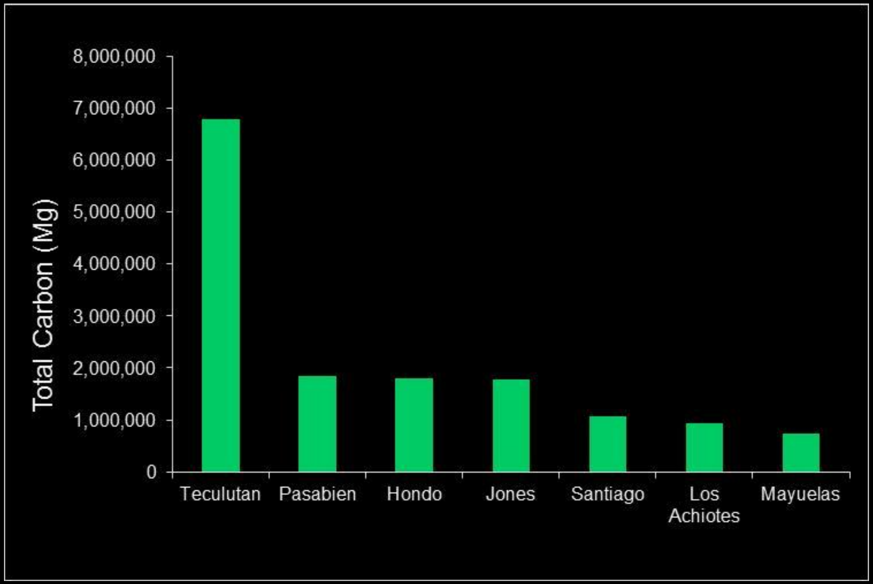
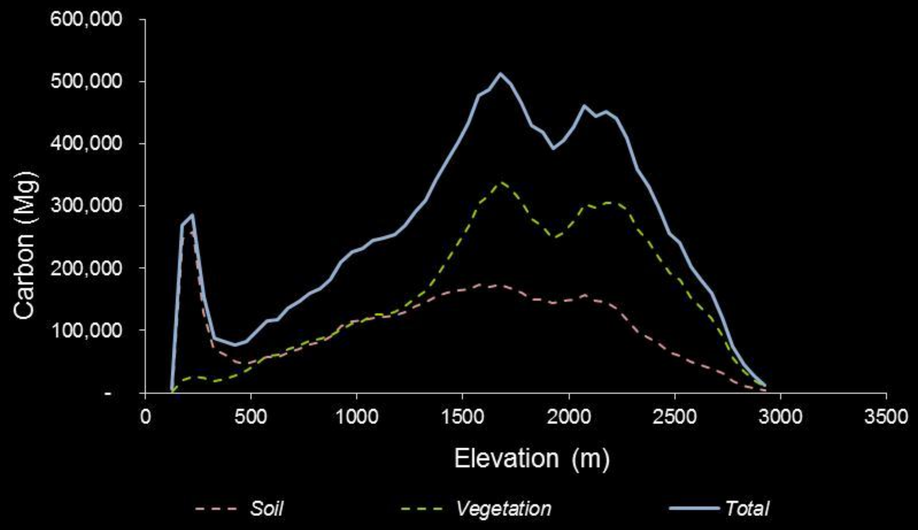
Results

Pre-Event Carbon

- ***15 x 10^6 MgC***: Total Carbon in SLM study area
- ***57% & 43%***: C in above-ground vegetation & soils, respectively
- ***130 MgC ha^{-1}***: Average C density





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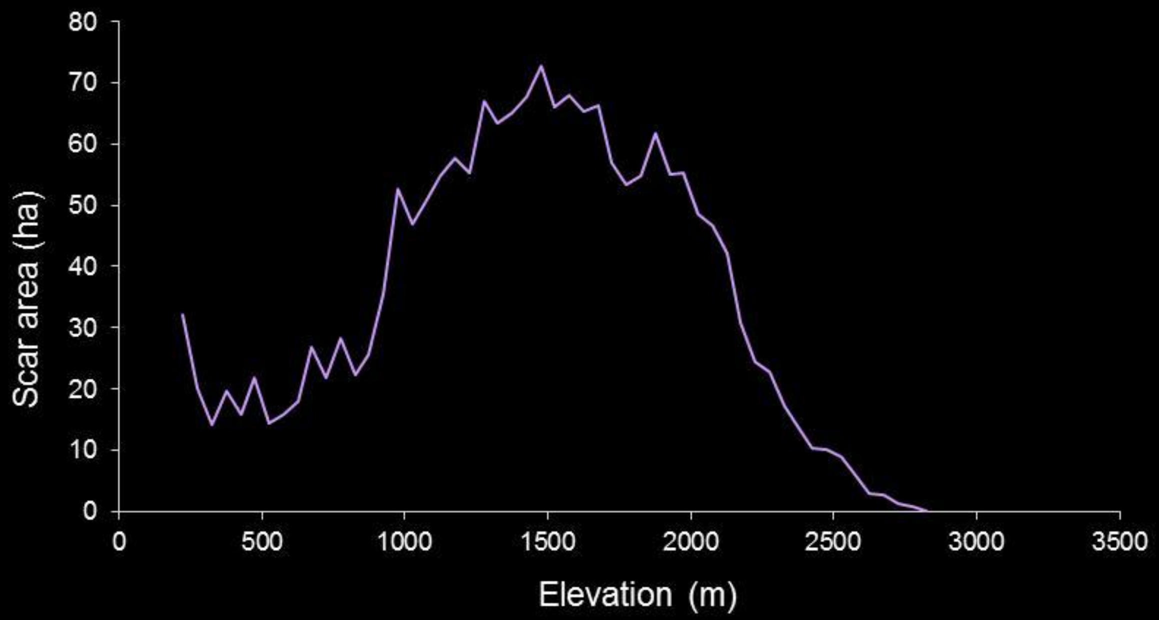
Results

Landslides

- ***2,711***: Total number of landslides in study area
- ***0.04 ha⁻¹***: Number of landslides per unit hectare
- ***1,876 ha***: Total area denuded by landslides
- ***0.3%***: Proportion of total area denuded by landslides



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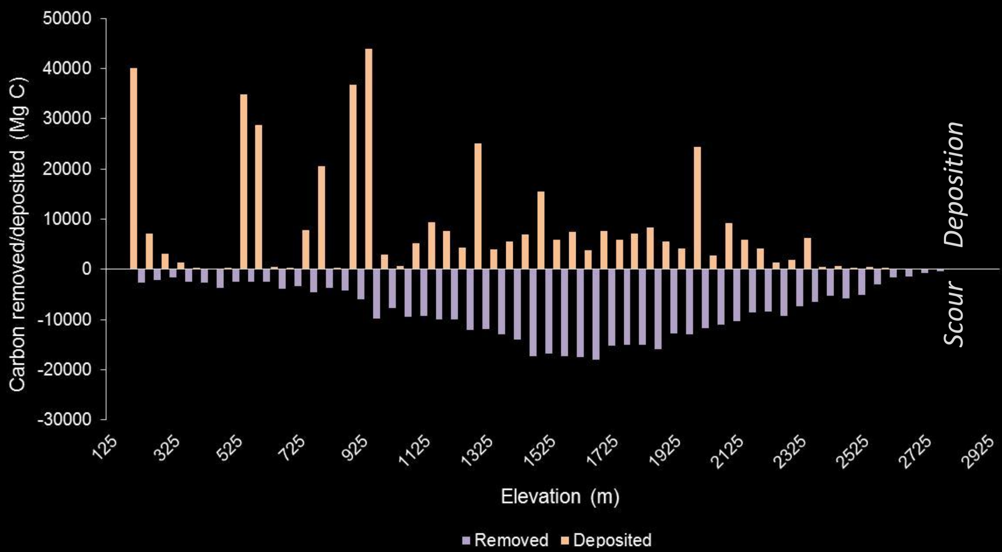
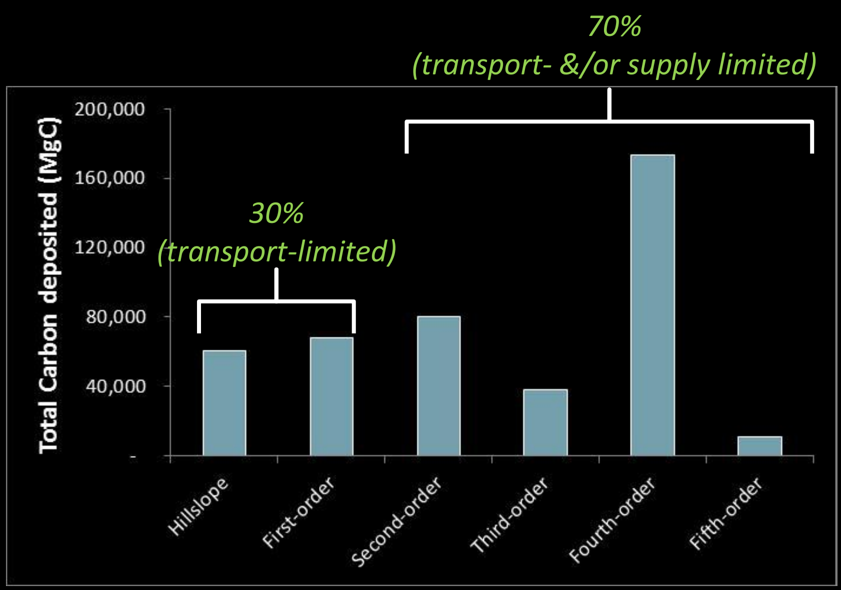
Results

Landslides & Carbon

- ***43 x 10⁴ MgC***: Total amount of Carbon released by landslide activity
- ***6.6 MgC ha⁻¹***: Amount of Carbon released per unit area
- ***3%***: Proportion of total Carbon released by landslides





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Implications

$$\Delta S = \sum C_l * \left[\left({NPP_l}/{C_{\rho\, l}} \right) - (1 - \%C_{retained}) \right]$$

$$\left({NPP_l}/{C_{\rho\, l}} \right) \sim Recurrence\ Interval\ Landsliding / Time\ for\ Recuperation\ of\ Carbon\ Lost$$

0.3 – 1.5 MgC ha^{-1} yr^{-1}: NPP_l Rates from literature review

442 – 2212 MgC yr^{-1}: When applied over the 1475 ha scarred area

-or-

194 to 972 yrs: Time It would take for NPP_l to fully compensate the 43 x 10^4 MgC released by landsliding during Hurricane Mitch

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Implications

$$\Delta S = \sum C_l * \left[\left({NPP_l}/{C_{\rho\, l}} \right) - (1 - \%C_{retained}) \right]$$

$$\left({NPP_l}/{C_{\rho\, l}} \right) \sim Recurrence\ Interval\ Landsliding / Time\ for\ Recuperation\ of\ Carbon\ Lost$$

194 to 972 yrs: Time for recuperation of C lost

20 – 80 yrs: Recurrence interval of rainfall totals similar to H. Mitch in Guatemala

0.02 – 0.41: Recurrence Interval Landsliding / Time for recuperation < 1
Therefore, NPP_l will never recuperate all C transferred in-between landslide-triggering events.

Can NPP_l recuperate the amount that has exited the control area?

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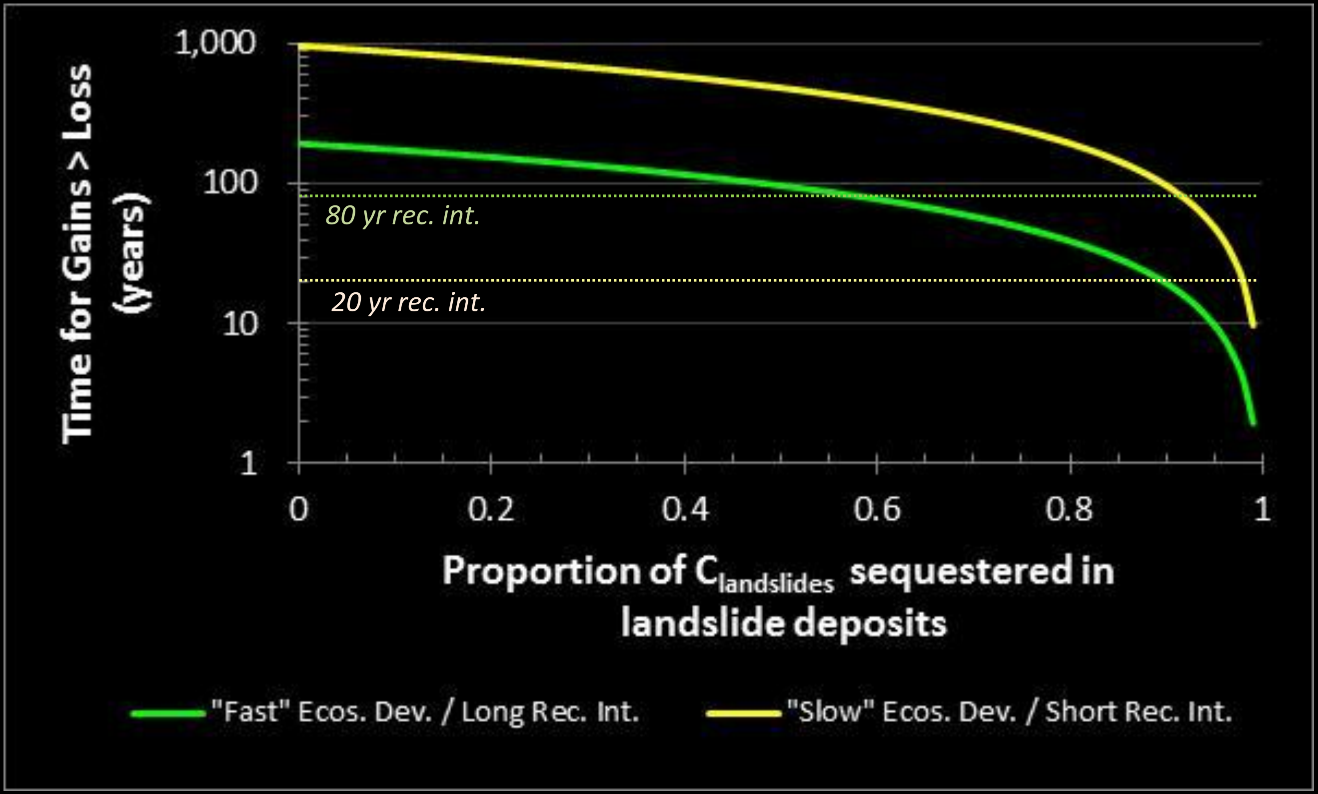
Implications-SLM Scale



Case 1 (yellow):

Slow NPP_l & Short Rec Int.-
~100% of C_l must be retained in order for net C gains to be possible

Case 2 (green):

Fast NPPl & Long Rec. Int.-
>60% of C_l must be retained in order for net C gains to be possible

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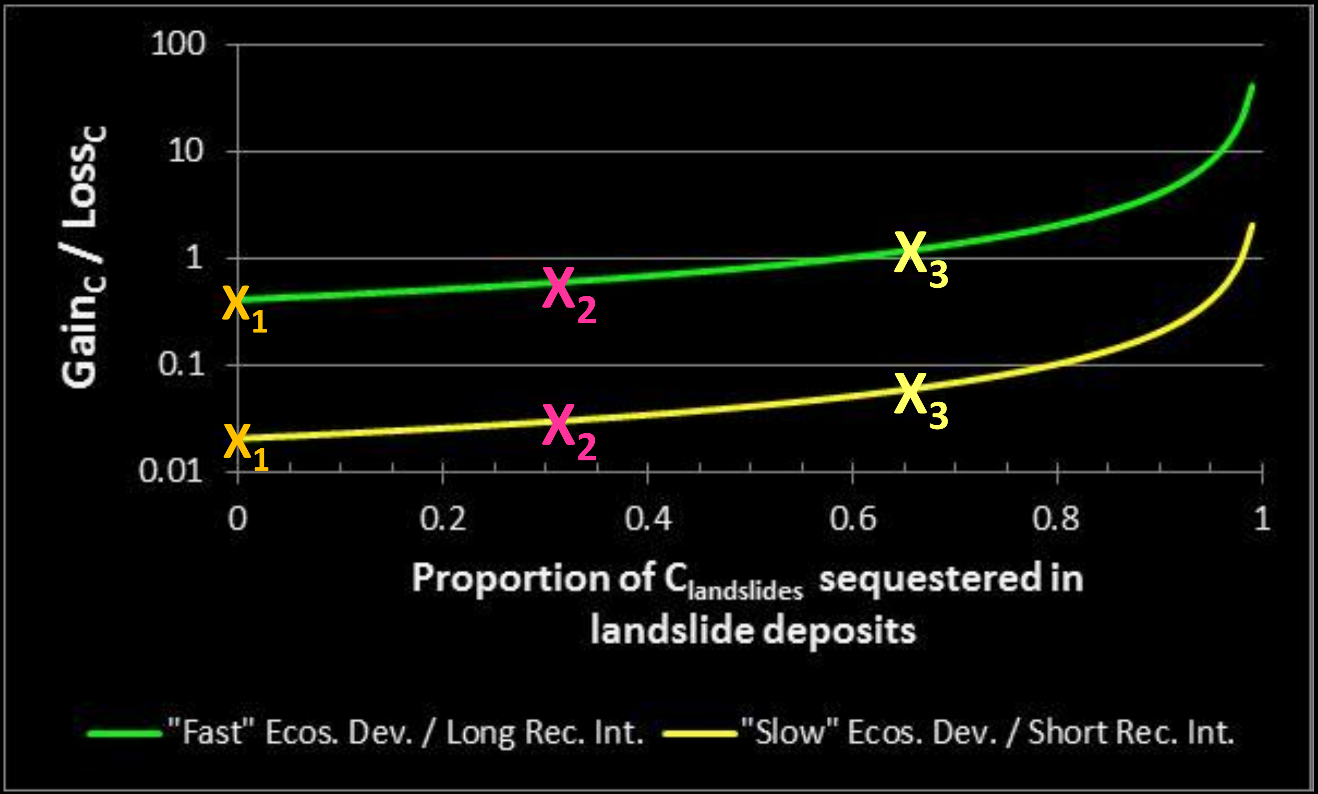
Implications-SLM Scale



SLM Wide Potential for C_l sequestration- *Possible scenarios:*

X_1-0% retention

X_2-30% retention-all C_l delivered to hillslopes & 1st order streams is sequestered

X_3-65% retention- all C_l delivered to hillslopes & 1st order streams and one-half of the C_l delivered to higher order streams is sequestered

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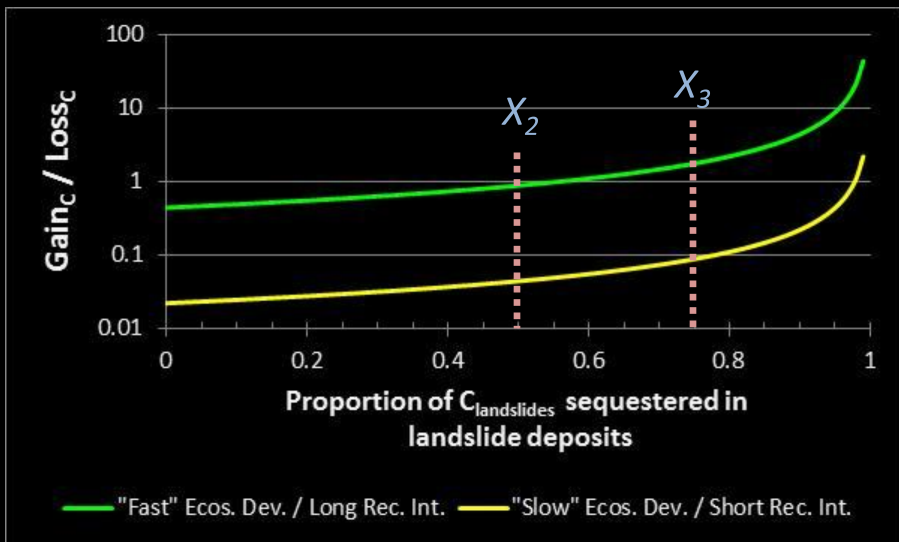
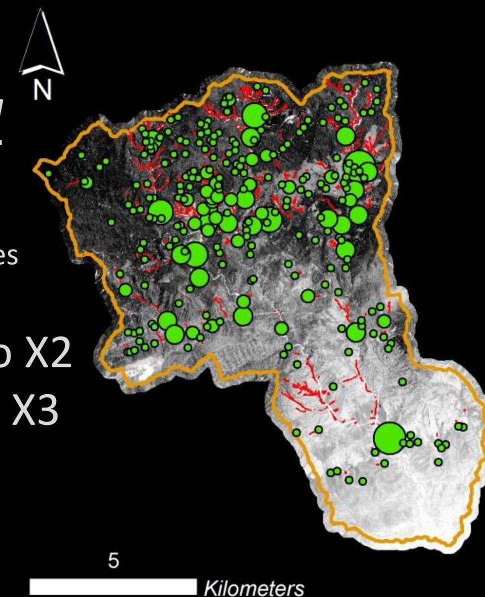
Implications-Watershed Scale





Rio Hondo Watershed

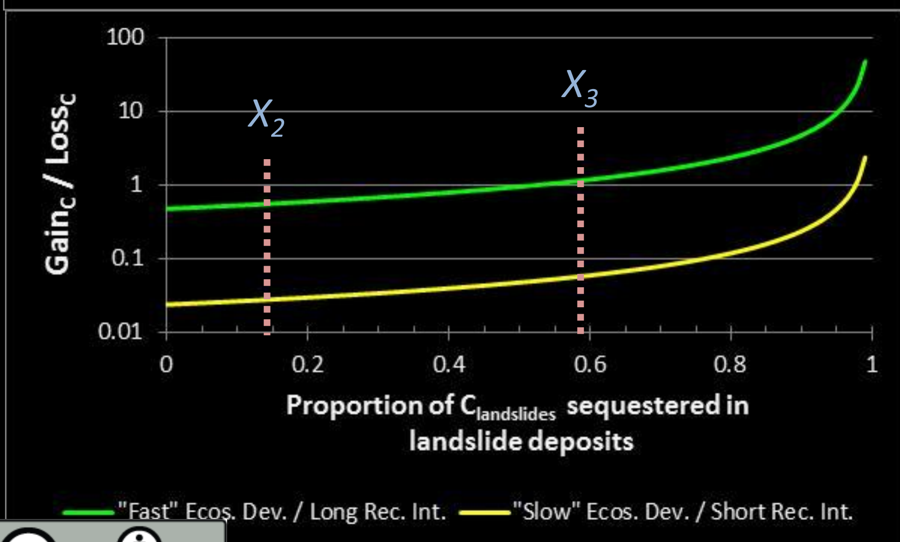
553: No. slides

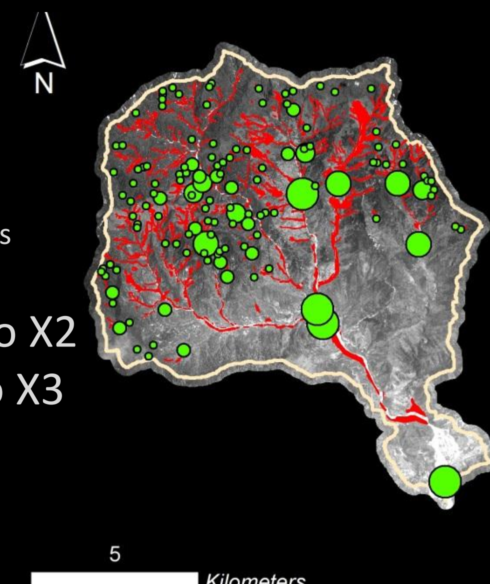
5.0×10^4 MgC: $\Sigma\ C_{landslides}$

184 ha: Denuded area

48% C_l retained: Scenario X2

74% C_l retained Scenario X3





Rio Jones Watershed

594: No. slides

14×10^4 MgC: $\Sigma\ C_{landslides}$

555 ha: Denuded area

13% C_l retained: Scenario X2

59% C_l retained Scenario X3

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Conclusions

1) About *3% of the total organic modern C* in the above-ground biomass and soil compartments in the SLM study area was in-transit as a result of landsliding activity triggered by Hurricane Mitch
2) The potential for landsliding activity in resulting in a net gain/loss of modern organic C depends upon the *proportion of C released that enters long-term storage compartments*, and the *ratio of the recurrence interval* of landslide-triggering events *to the time it takes for ecosystem development* on failed sites to recover C stocks to pre-landslide conditions.
3) Based upon the SLM-Mitch case study and literature reviews:

a) It appears that at least *60%* of the C released by landslides must be sequestered in order for ecosystem development to compensate for C losses

b) Even *contiguous watersheds* display *very different responses* in terms of total C released and perceived retention potential, thus questioning the validity of extrapolation attempts beyond the spatial scale at which observations are made

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