# Mechanisms of Soil Organic Matter Stabilization in Eroding Landscapes

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# Main Message

- Soil erosion imposes significant control on dynamics of soil and Soil Organic Matter.

- Soil erosion and terrestrial sedimentation can account for significant, previously unaccounted carbon sink, due to:
  - *Dynamic replacement of eroded C by NPP*
  - *Stabilization of eroded C in depositional settings*

- Specific mechanisms of SOM stabilization determine sustainability of the erosion induced C sink

# The Erosion Paradox

- **General Understanding**
  - Environmental disaster
    - "Soil erosion is a major global environmental problem"
    - "Soil erosion destroys land resources"
    - "Soil erosion threatens food security"
    - "Soil erosion hampers regional development"
    - Agricultural erosion (⅔ of total) costs $400 billion $yr^{-1}$ *(Pimentel et al., 1995)*
  - Land use change results in transfer of C from land to atmosphere *(Lal 2004, Lal et al 2001, Lal and Pimentel 2008)*
  - Global warming could result in further degradation
    - Projected changes in climate → accelerate soil erosion (*Berc et al., 2003; Commission on Geosciences; Environment and Resources, 1999)*

# The Erosion Paradox

- **General Understanding**
  - Environmental disaster
  - Global warming could result in further degradation

- **Latest Scientific findings**

  ***Soil erosion and terrestrial sedimentation lead to an important, previously unaccounted terrestrial sink for atmospheric $CO_2$.***
  - Damaged Land, Buried Carbon: Can eroding soil store excess $CO_2$?
  - Erosion and Deposition Constitute a Net Carbon Sink
  - The upside of erosion: Yes, it damages hillsides and streams, but erosion is not all bad

  *(Headlines for work of Berhe et al. 2007 as they appeared in Conservation Magazine, California Magazine, View from LBL, Science at LBL, USDA National Research highlight)*

# Erosion is widespread

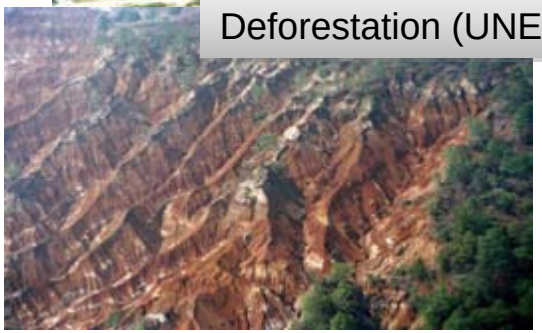
Rainspash (WEPP)

Pocket gophers (wikimedia)

Slope failure (USGS)

Intensive agriculture (FAO)

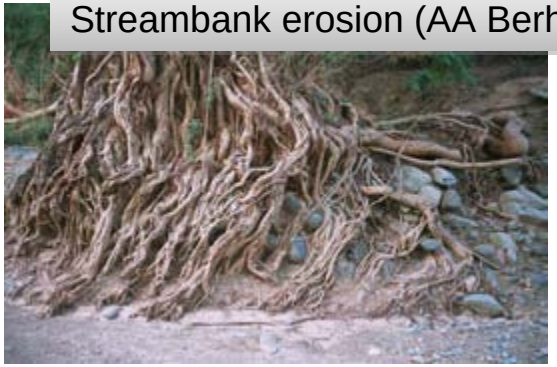
Intensive agriculture (FAO)



Deforestation (UNEP)

Wind Erosion, (Button UI)

Dust bowl (USDA)

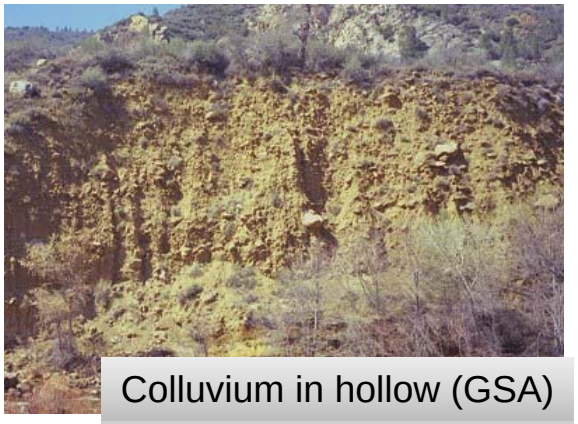


Streambank erosion (AA Berhe)

# Global significance of erosion and deposition

- Soil erosion (wind and water)
  - Affects **1.1 billion ha** of land globally (>13% of total)
  - Redistributes on the order of **75 Gt soil** and **1-5 Gt C** (Gt = $10^{15}$)
  - More than **70%** deposited locally within the same or adjacent toposequences

*Stallard 1998; Harden et al 1999*



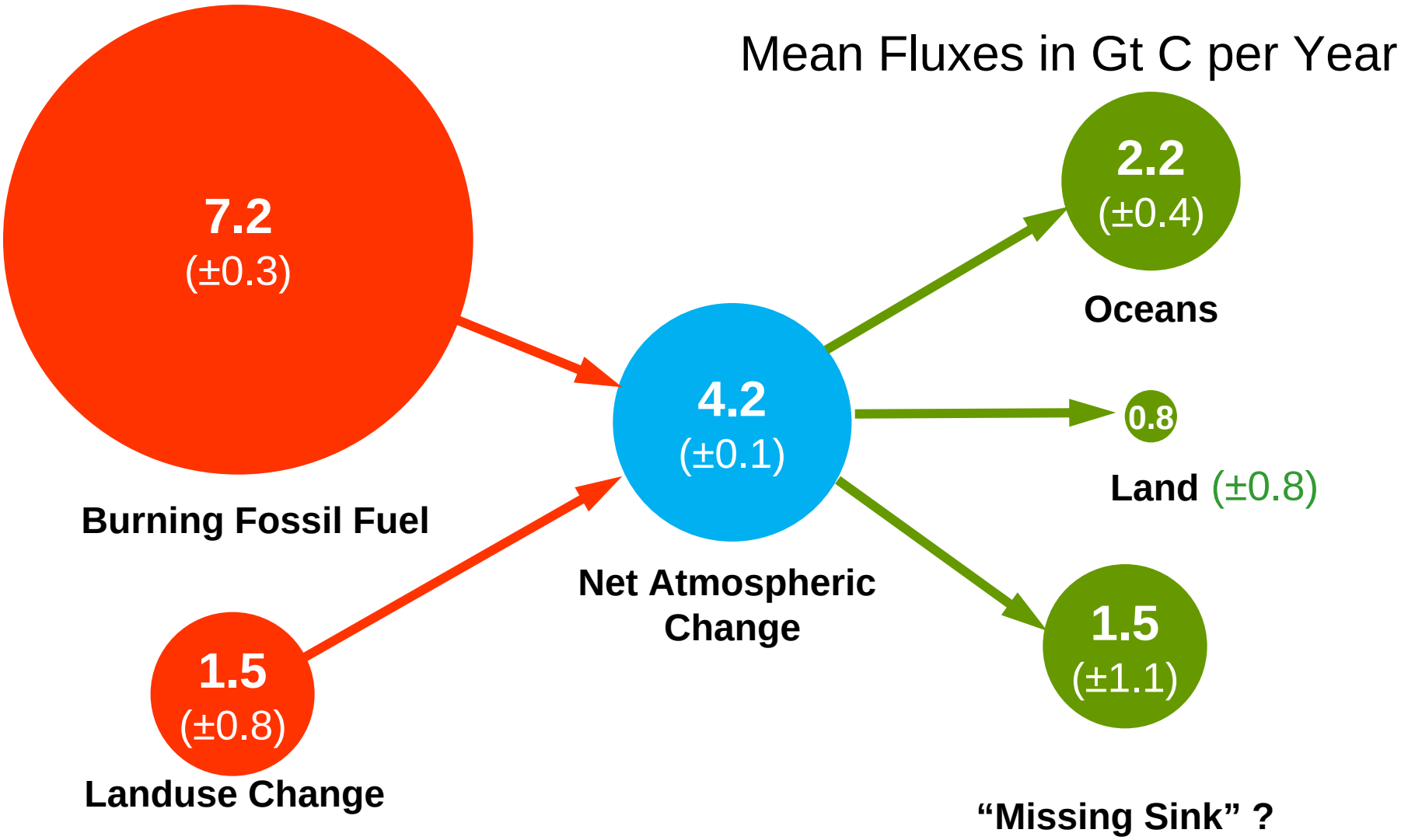
Colluvium in hollow (GSA)

Alluvial/colluvial plain (IUPUI)

Lakes, reservoirs etc. (MSU)

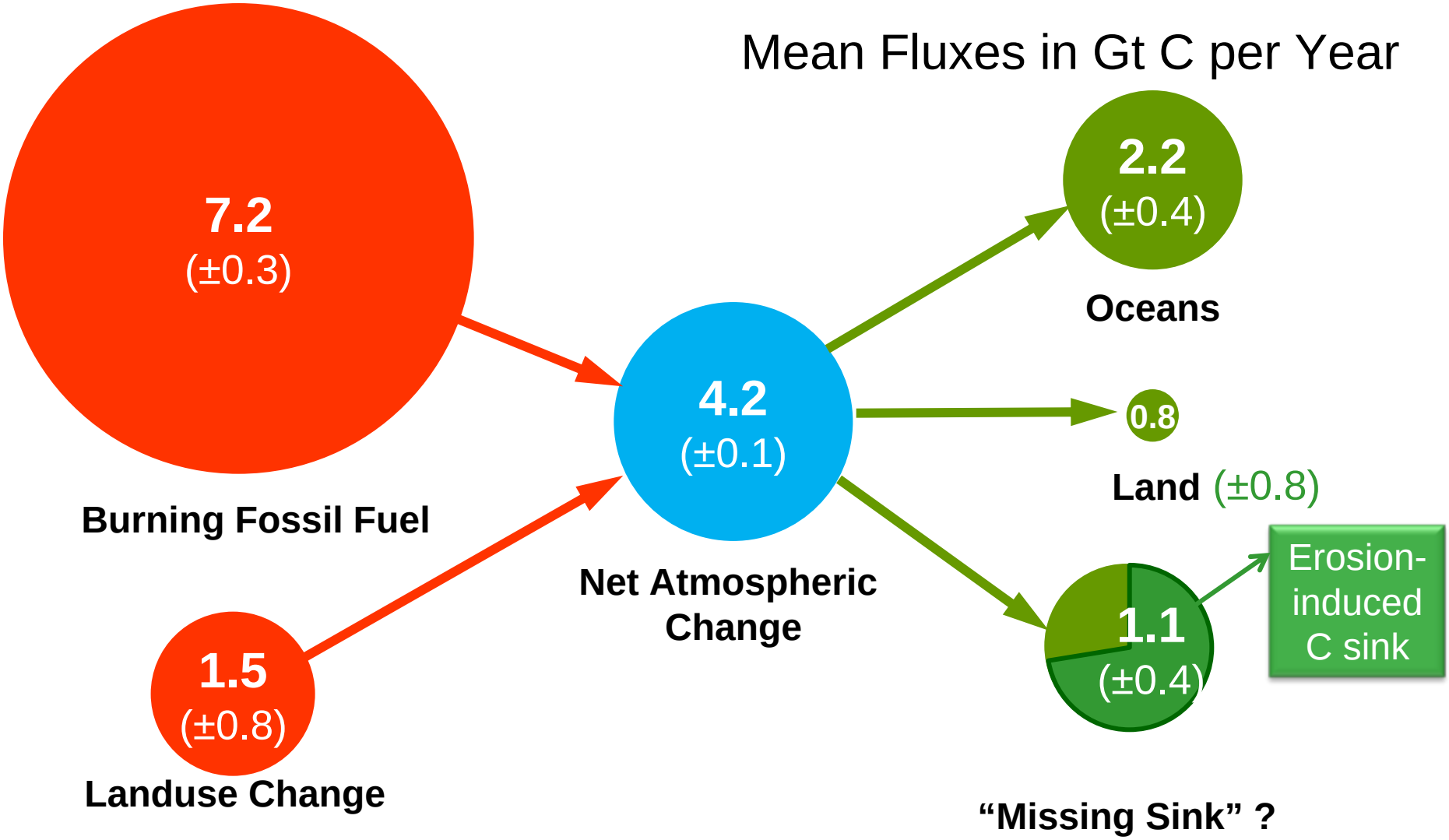
Soil erosion can result in terrestrial carbon sequestration.

# Significance of the erosion-induced C sink




*Houghton, 2007; Berhe et al 2007*

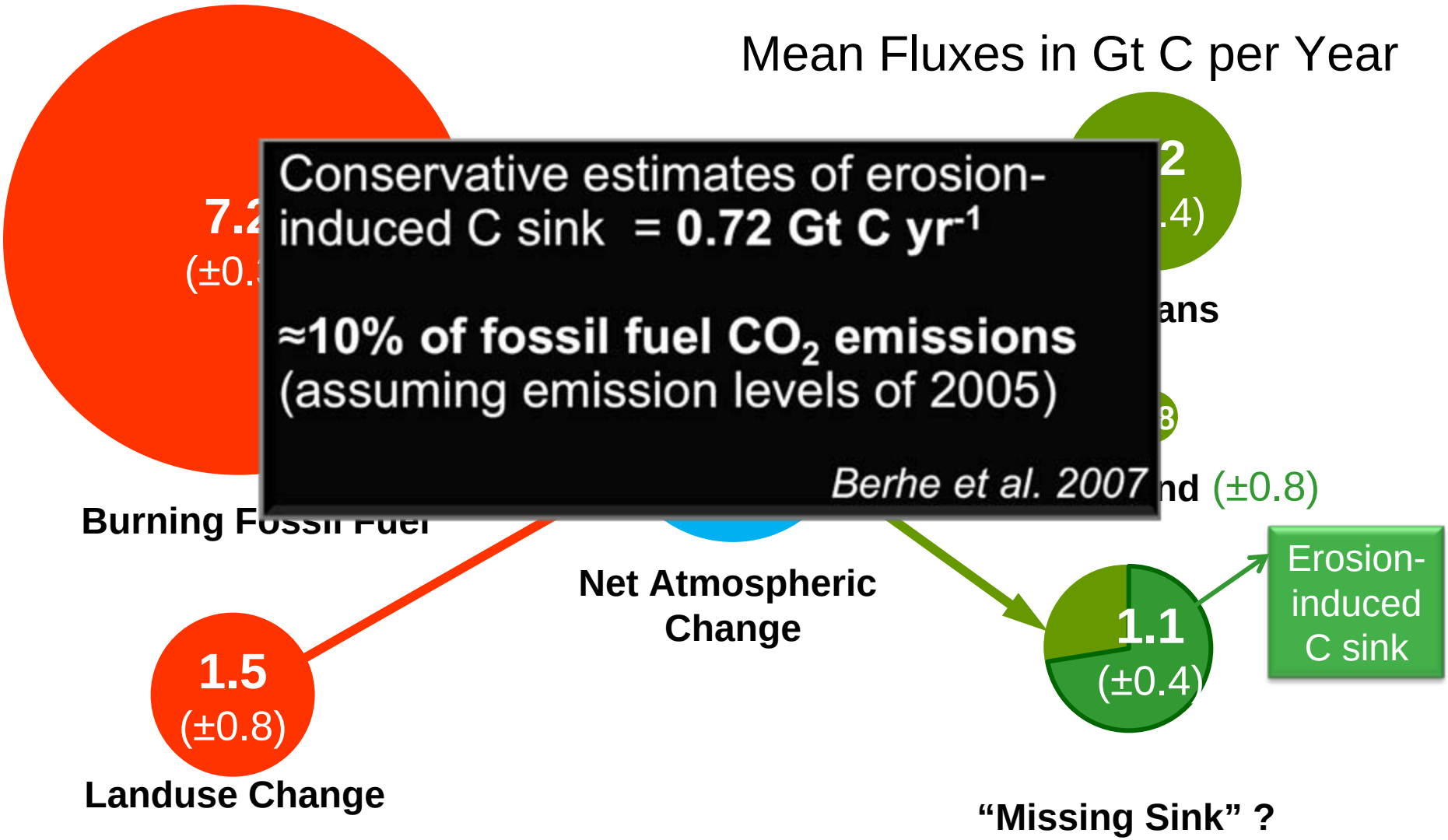
# Significance of the erosion-induced C sink




*Houghton, 2007; Berhe et al 2007*

# Significance of the erosion-induced C sink

Mean Fluxes in Gt C per Year




Conservative estimates of erosion-induced C sink = **0.72 Gt C $yr^{-1}$**

**≈10% of fossil fuel $CO_2$ emissions**
(assuming emission levels of 2005)

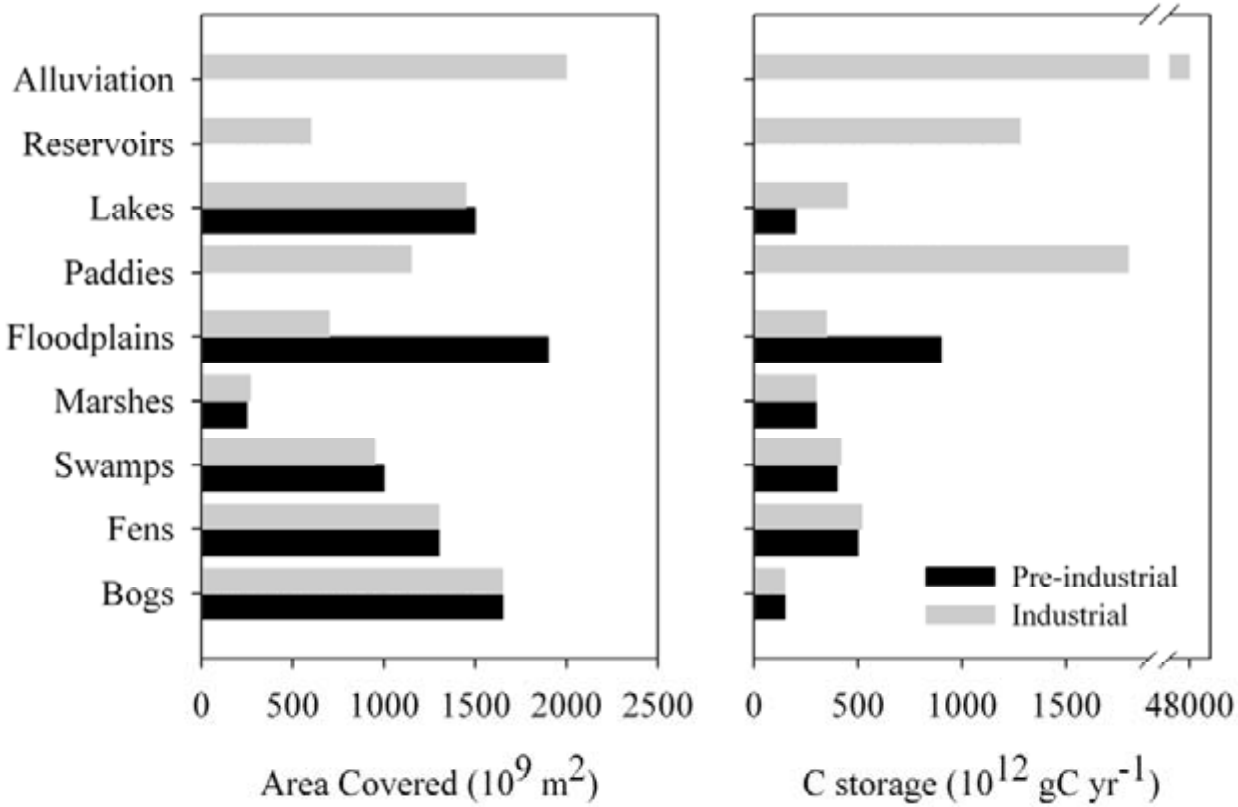
*Berhe et al. 2007*

*Houghton, 2007; Berhe et al 2007*

# Rates of erosion and deposition increasing

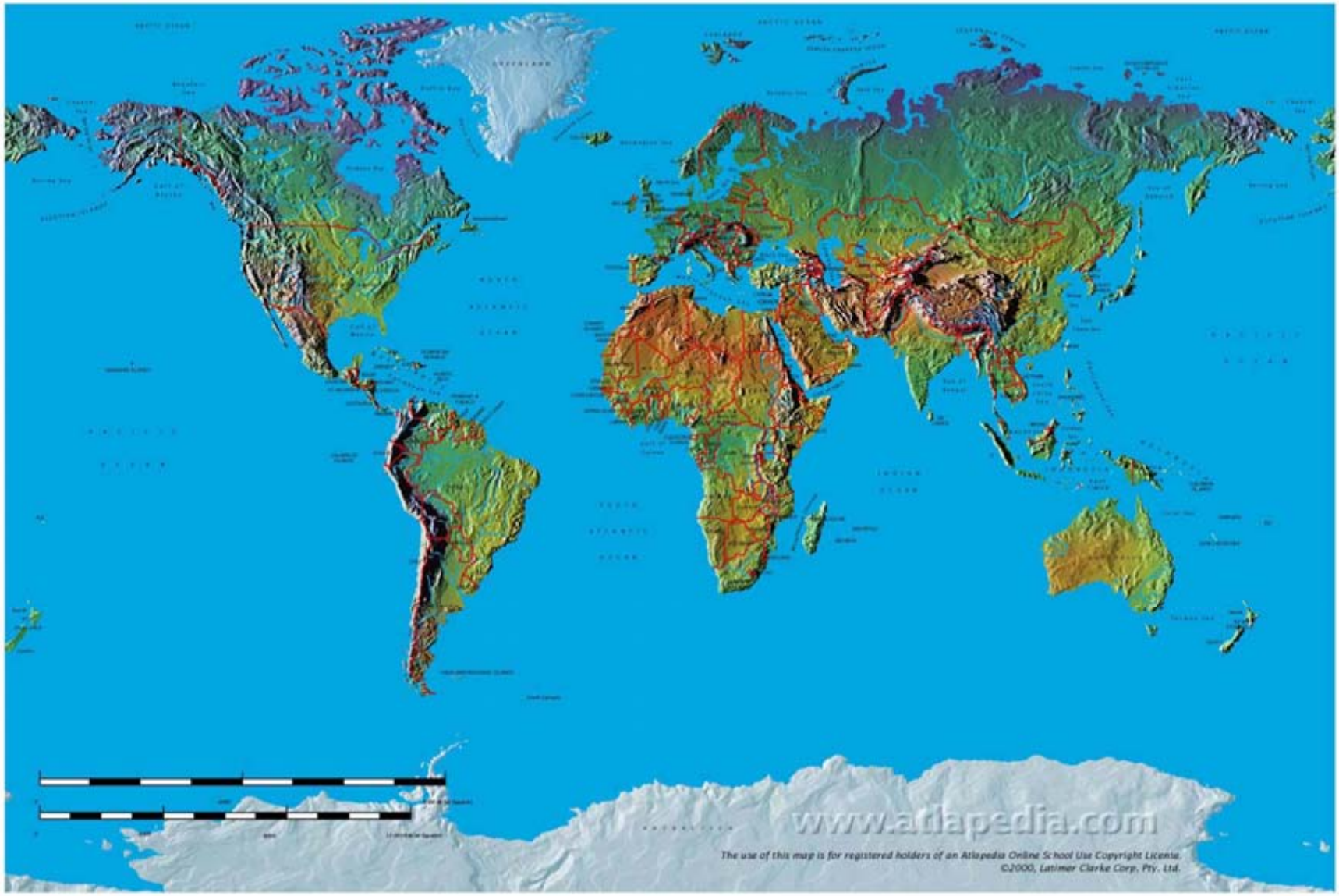
- Global rate of soil erosion is increasing (*Yang et al., 2003*).
- Rates of terrestrial sedimentation increasing more than erosion rates

- Increase in depositional area and storage of C (*Stallard, 1998*).
  - Size increased by **3.5 *$10^6$ km$^2$** *(2% of global land area)*
  - C storage increased by **4.4 Gt C yr$^{-1}$**



Most land is not flat.
Upland ecosystems play important role in terrestrial C sequestration

# Upland Ecosystems



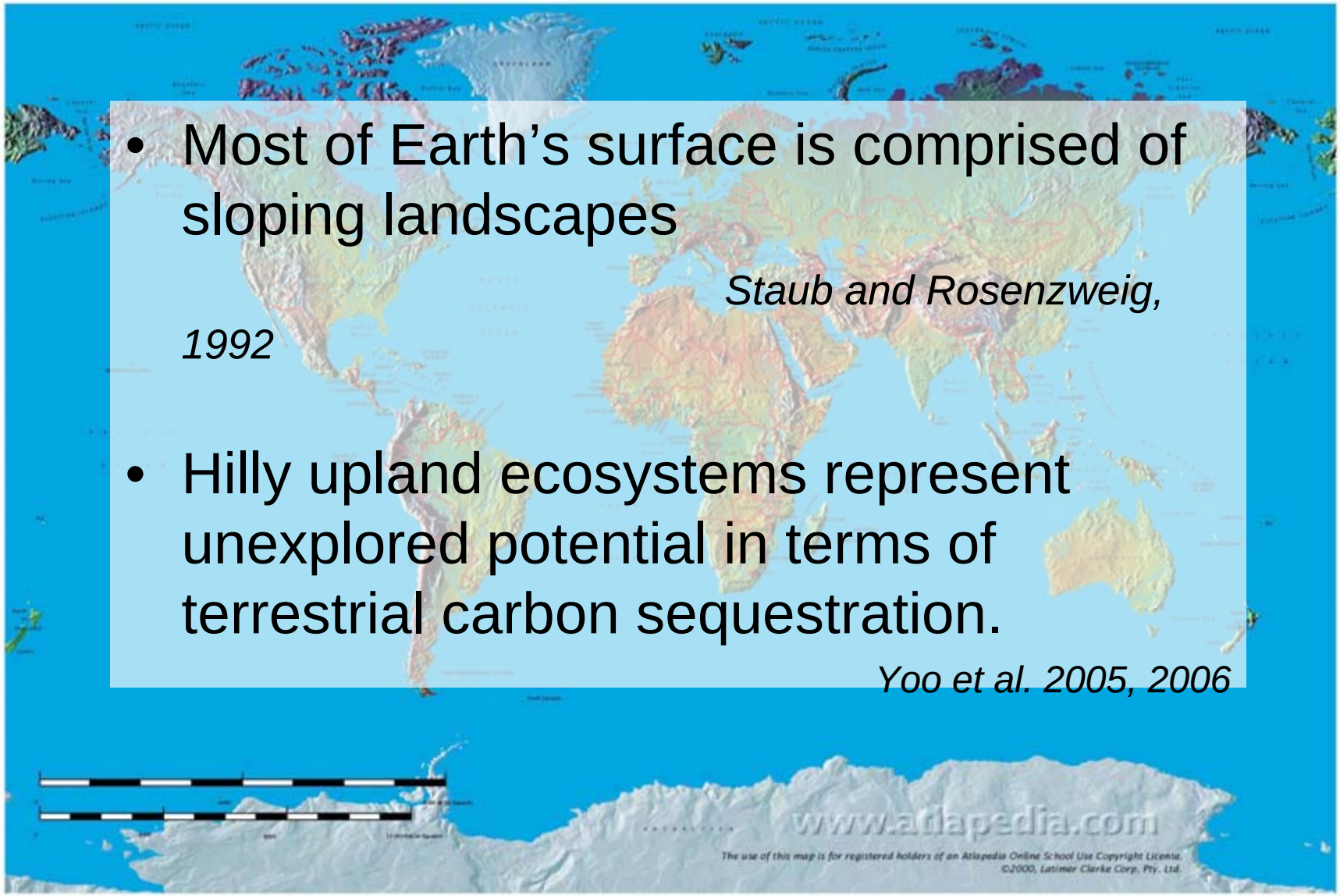
# Upland Ecosystems

- Most of Earth's surface is comprised of sloping landscapes

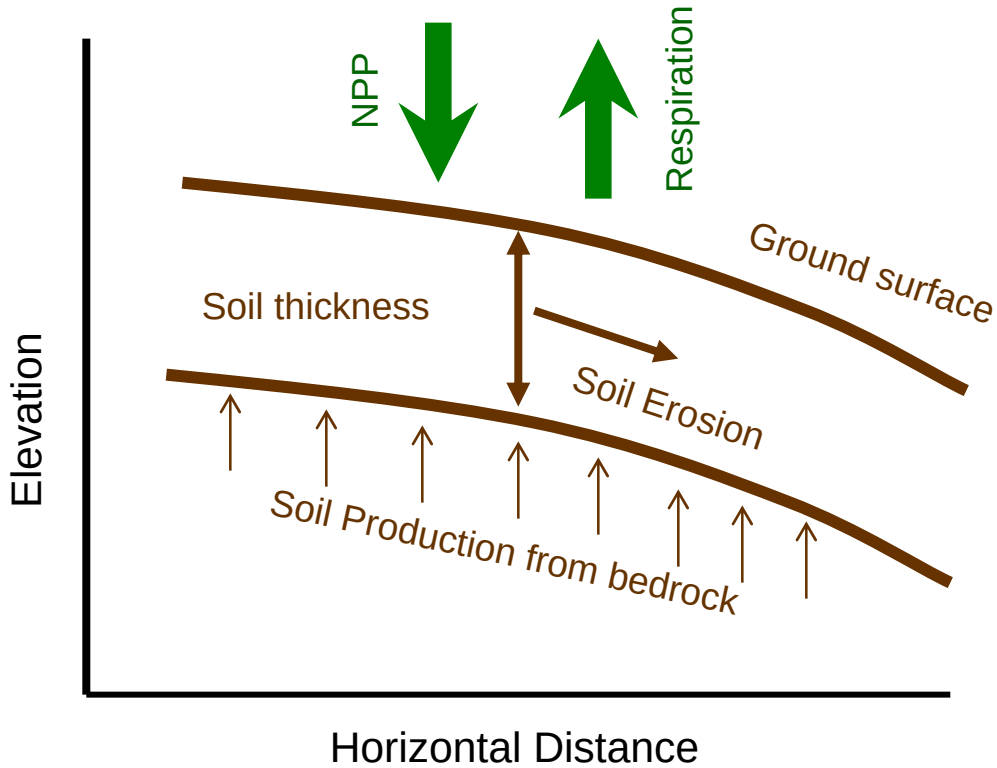
  *Staub and Rosenzweig, 1992*

- Hilly upland ecosystems represent unexplored potential in terms of terrestrial carbon sequestration.

  *Yoo et al. 2005, 2006*



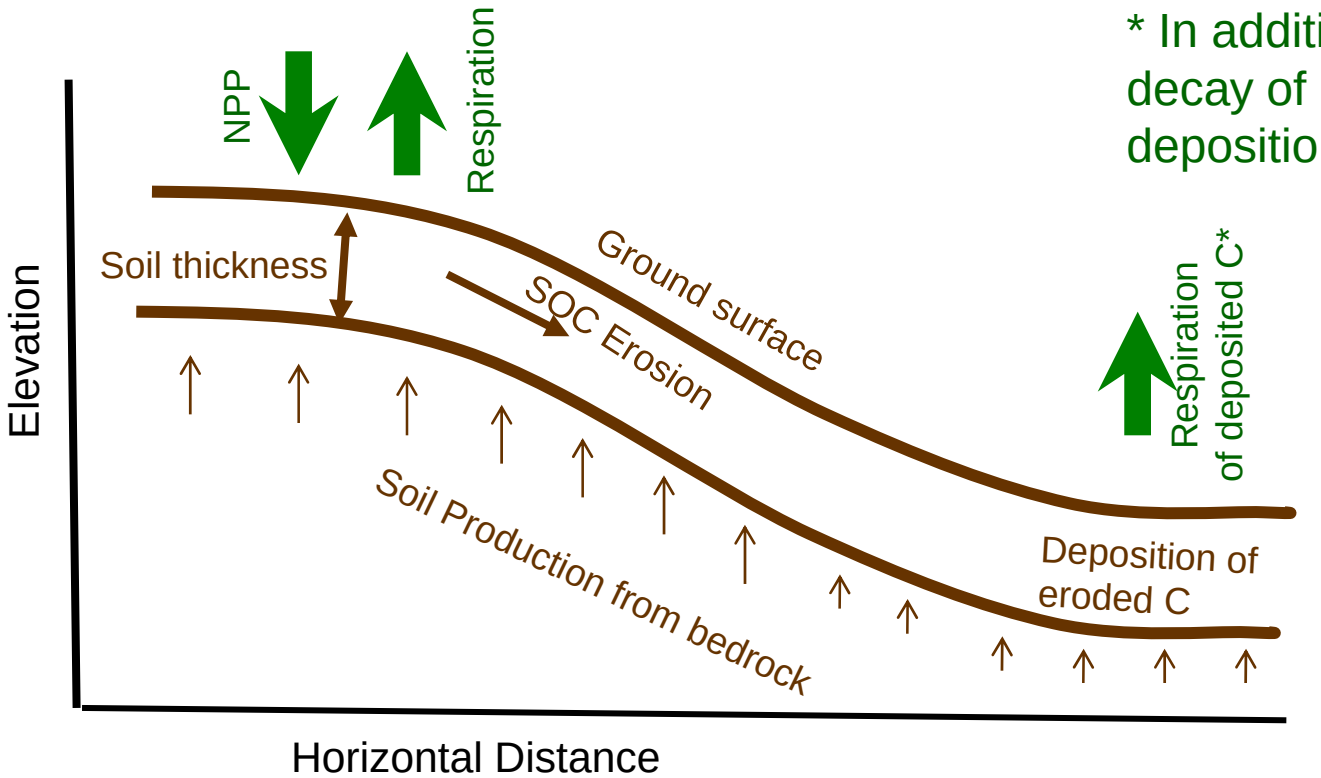
# Geomorphic controls on soil C storage




Soil C assessment at a spot vs. watershed approach

- Watershed C balance = Σ (opposing C fluxes)
  - positive C balance indicates a C sink
  - negative C balance indicates a source term in the C balance

# Erosion and Watershed C balance




* In addition to NPP and decay of in situ C at depositional settings

- Explicit consideration was missing for:
  - Decomposition of eroded C downslope
  - Enhanced NPP downslope (deposition of nutrient-rich topsoil)
  - Stability of the organic matter (mechanisms of stabilization determine change in decay rate of SOM during or after transport)

# Sink or Source?

- Criterion
  - Eroded C replaced, at least partially, by new photosynthate ($P$)
  - Preserved in more passive pools in the depositional basins ($k$)

$$\underbrace{P_D^{'} + P_E^{'} - (K_D^{'} + K_E^{'})}_{\text{Post-erosion}} > \underbrace{P_D + P_E - (K_D + K_E)}_{\text{Pre-erosion}}$$

  - This criterion allows for one of the above conditions to be violated if the other one is strongly observed, meaning
    - $P' >> P$, or
    - $k' << k$

*Berhe et al., 2007*

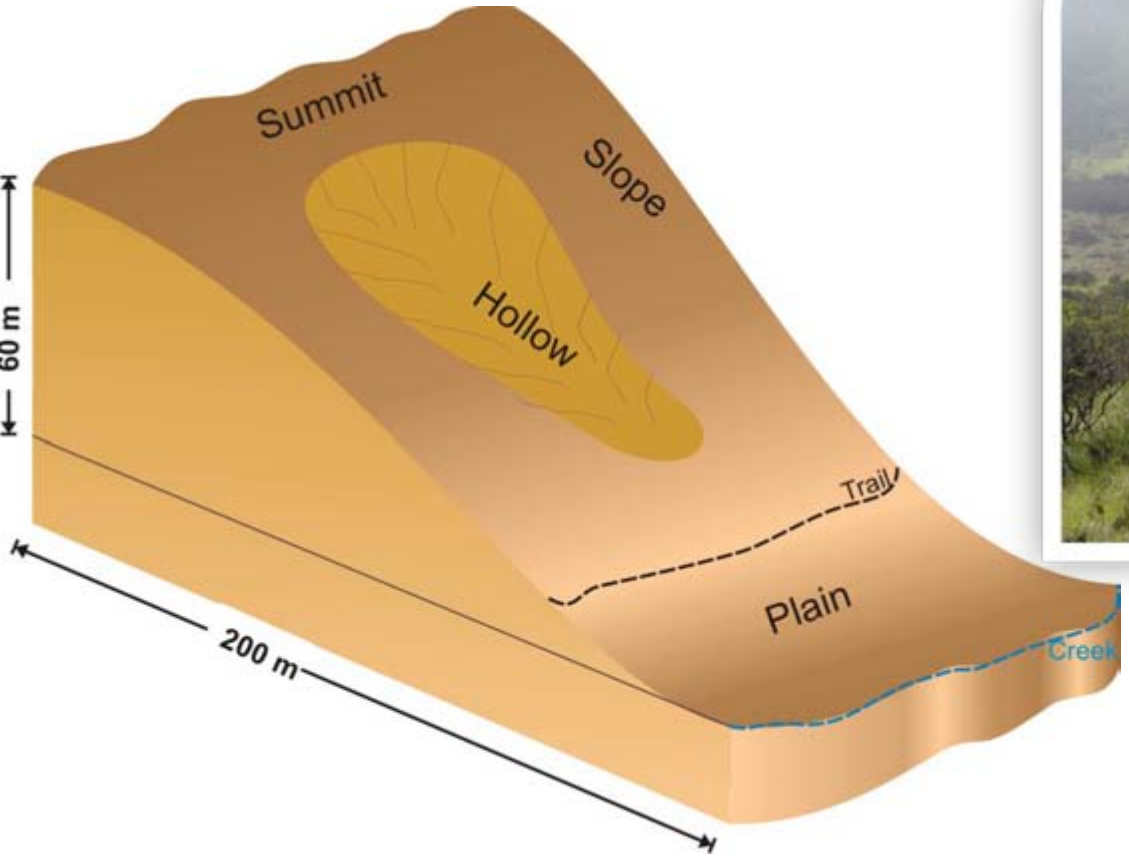
- Erosion becomes a sink if more C is removed from the atmosphere than is emitted.

# Question

What mechanisms are important for stabilization of SOM in eroding landscapes?

1 – Physical, Chemical, and Biochemical
2 –eroding vs. depositional landform positions

# Tennessee Valley



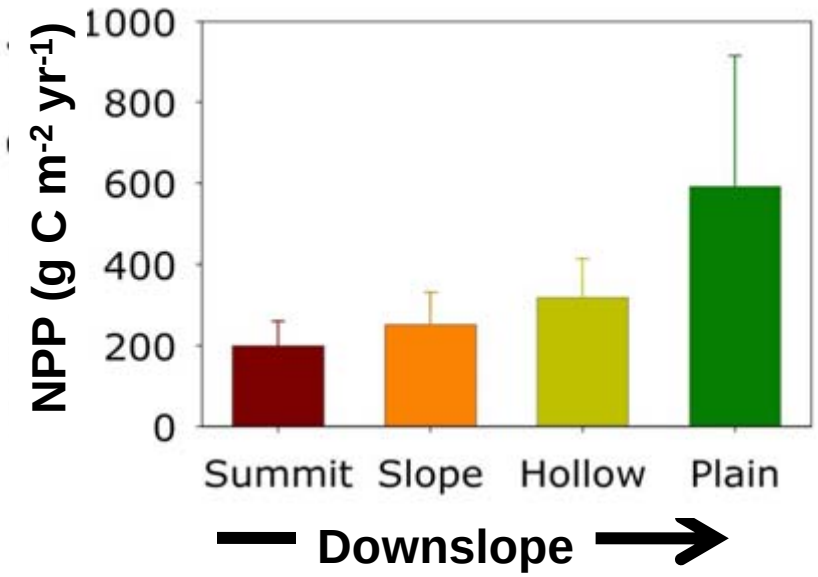
| | Erosion (-) & Deposition (+) ($g\ m^{-2}\ yr^{-1}$) | |
|---|---|---|
| | **Soil ¤** | **C*** |
| **Summit** | -130 | -2.00 |
| **Slope** | -110 | -2.03 |
| **Hollow** | 90 | 1.7 |
| **Plain** | 70 | 1.2 |

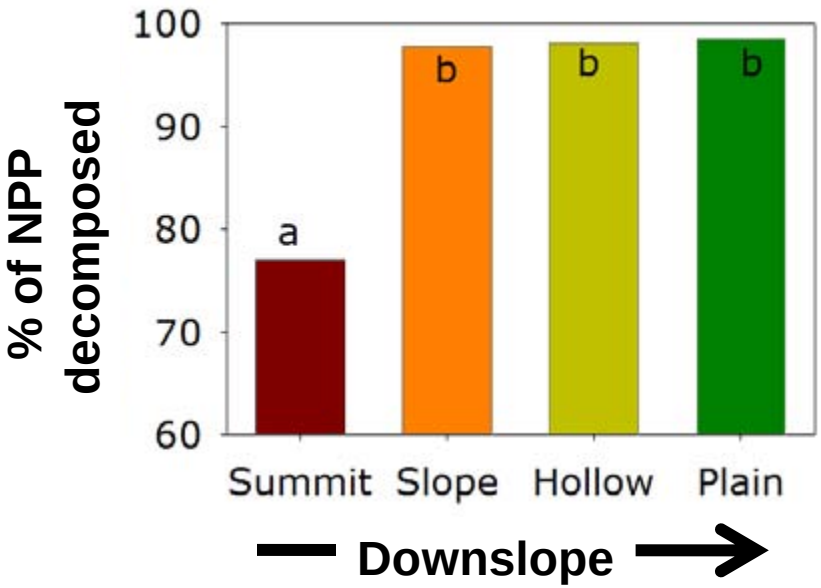
¤ *Heimsath et al 1999; * Yoo et al. 2005*

Undisturbed, naturally eroding (pocket gophers, rainsplash)

Fransciscan Sandstone parent material, Entisols in eroding, Mollisols in depositional; MAP 1200, MAT14

# Replacement of eroded C



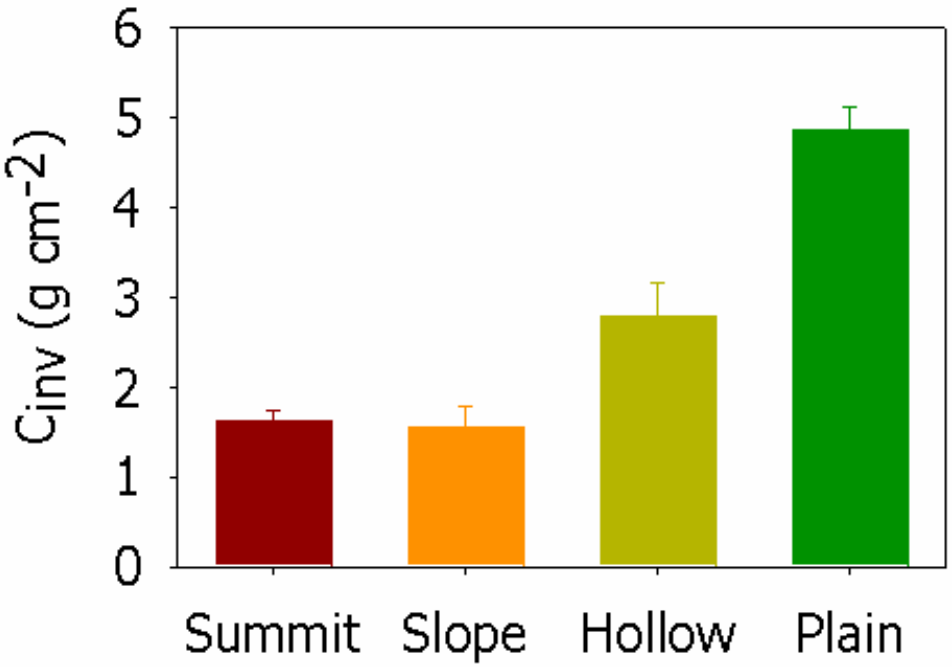




- Plant productivity 2-3 times higher in depositional
- **Humification coefficient -** that fraction of NPP that mineralizes fast and doesn't enter the soil carbon pool
  - 23% NPP enters soil pool of summit (compared to 2-3% in the rest).

- Complete replacement of eroded C (2 g $m^{-2}$ $yr^{-1}$)
  - **16-times** over in summit
  - **4-times** over in slope

*Berhe et al., 2008*

# Stock of Soil Organic Carbon

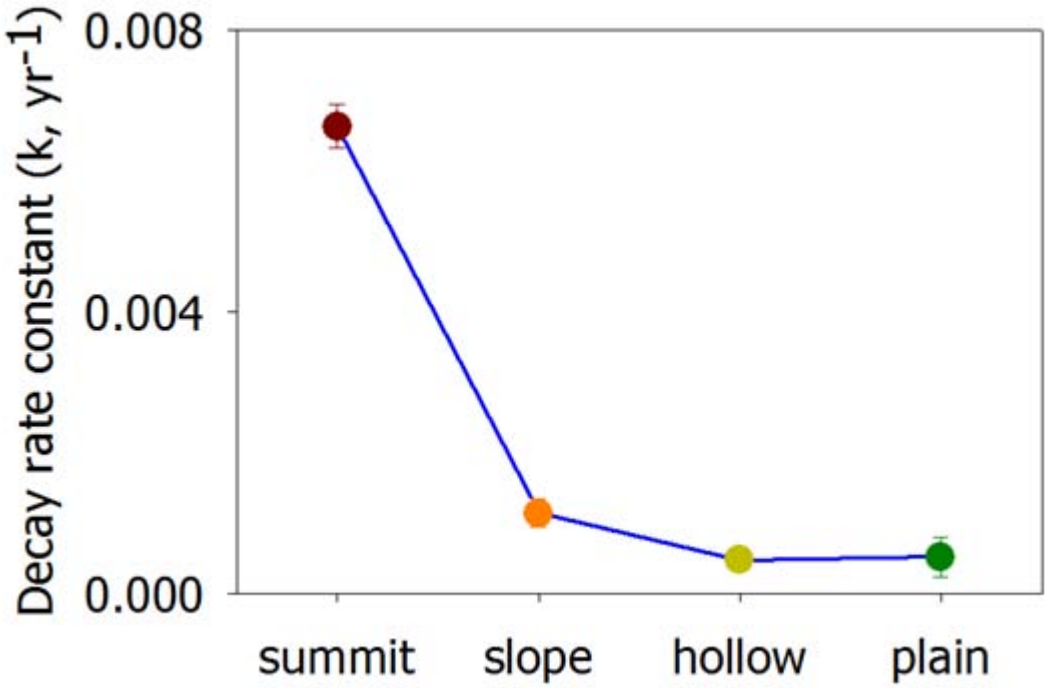



- 2-3 times more C stored in depositional settings, compared to eroding
- Soil thickness
  - 63cm eroding
  - 120cm depositional

Profile Inventory

$$C_{inv} = \sum \Delta Z \cdot \rho_i \cdot (1 - R_i) \cdot [\%OC_i \cdot 100]$$

# Decay rate constant of bulk SOM



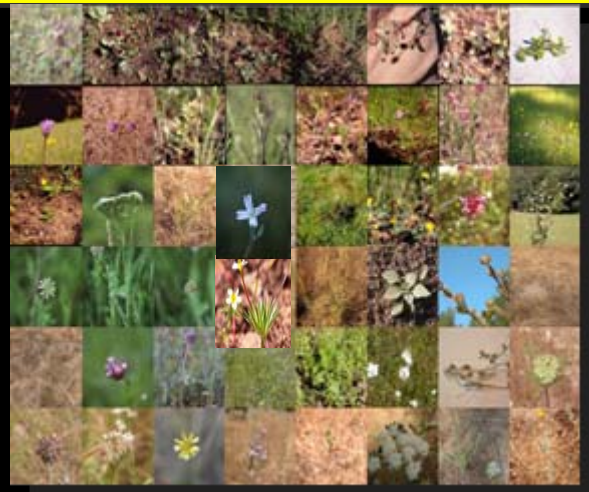

Profile averaged decay rate constant over the entire history of the toposequence

- Decay rate at depositional settings is 2-10 time slower than in eroding slope positions
- A lot of OM that cycles very slowly at the depositional settings
  - high storage effectiveness, Weighted FM, $^{14}C$.

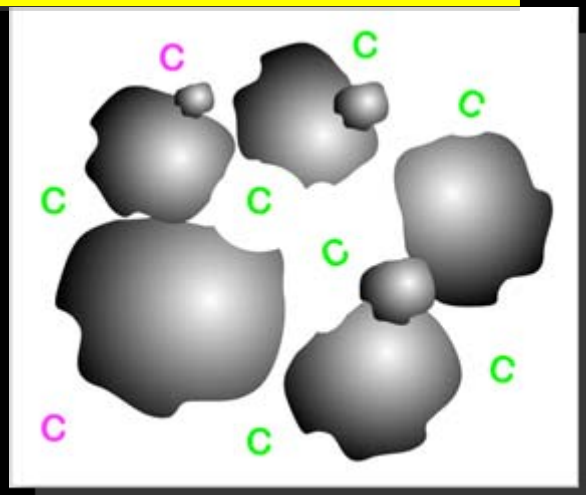
*Berhe et al., 2008*

# Unprotected vs. Stabilized OM

Unprotected

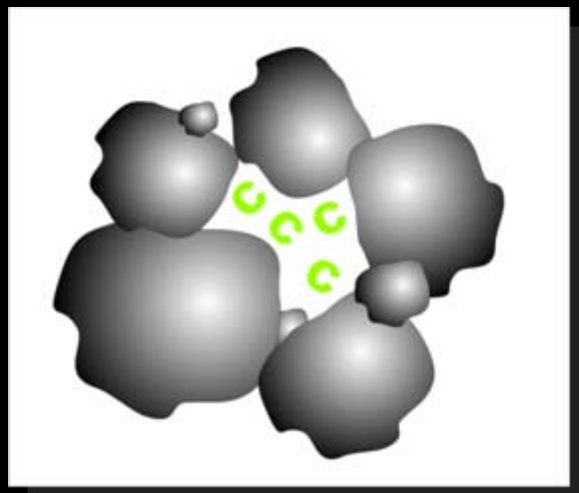


Aboveground biomass

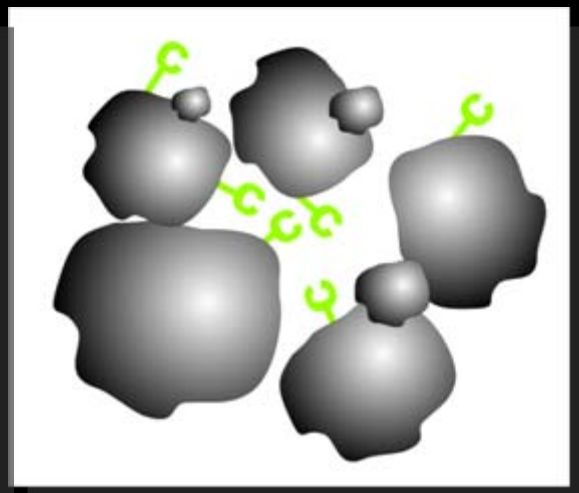



Unprotected, free light fraction (fLF)

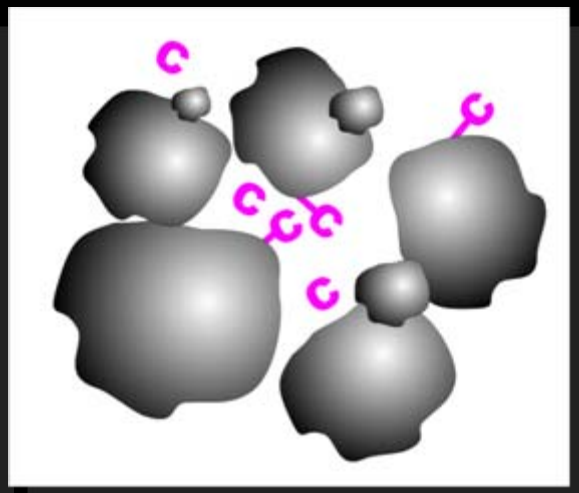
Stabilized



Physically stabilized



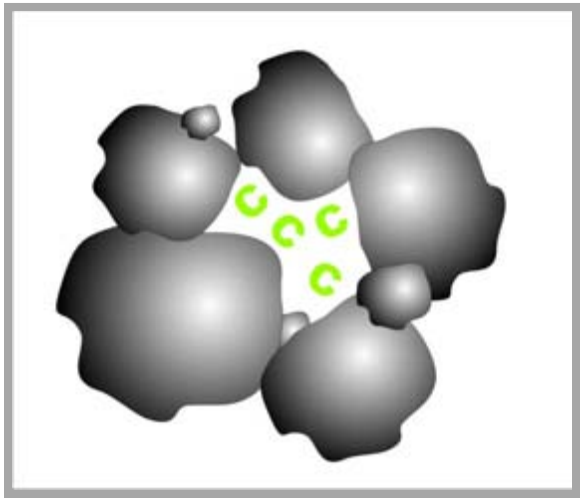
Chemically stabilized



Biochemically stabilized

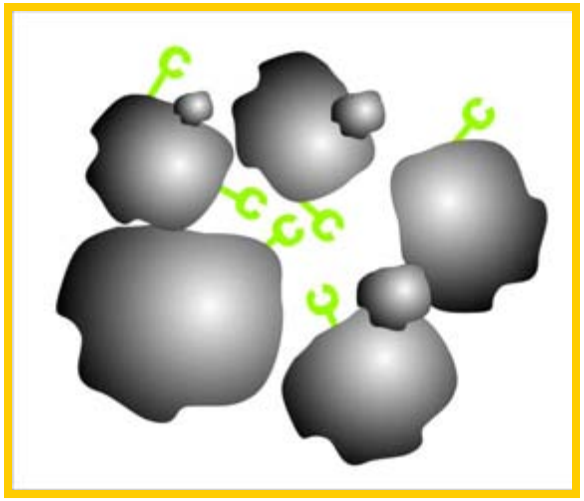
# Mechanisms of SOM stabilization & Erosion

*Krull et al. 2003 and Six et al 2002*



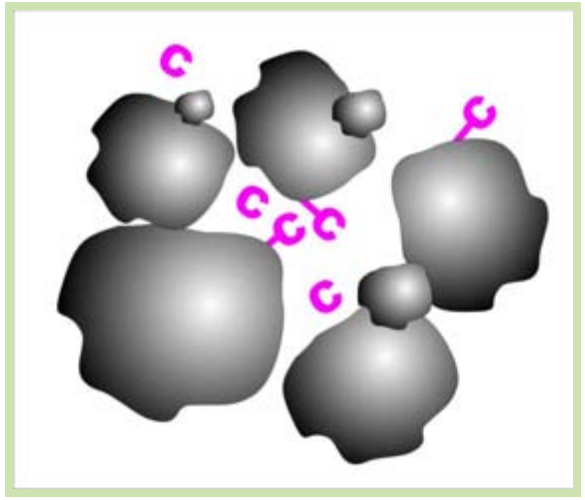
## Physical stabilization

- inside aggregates
- Unstable against erosion
- Density fractionation



## Chemical stabilization

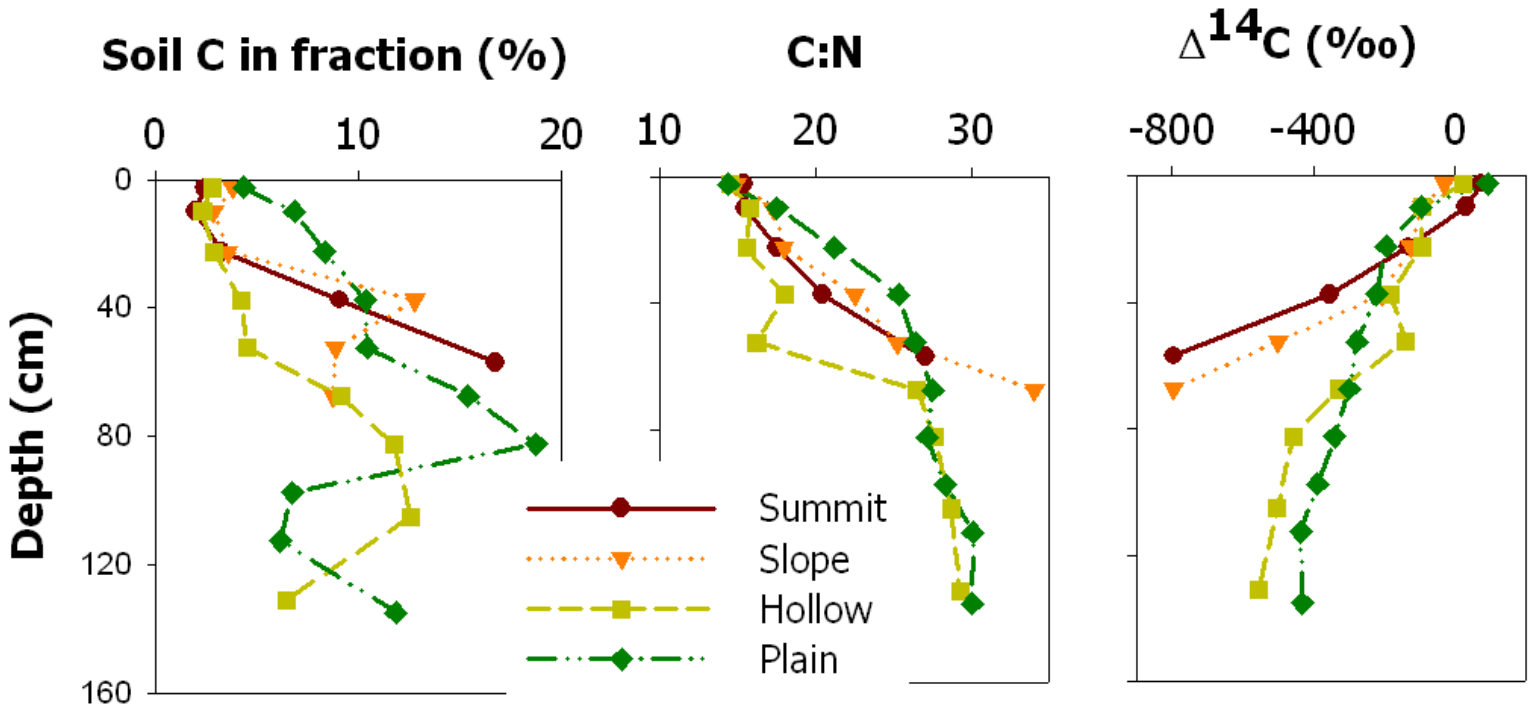
- chemically bound with minerals
- Stable against erosion
- Fe and Al selective dissolutions



## Biochemical stabilization

- Inherently recalcitrant
- Stable against erosion
- $^{13}C$ – NMR

# Physical stabilization due to aggregation




*density fractionation <1.7 g cm$^{-3}$ SPT, occluded light fraction*

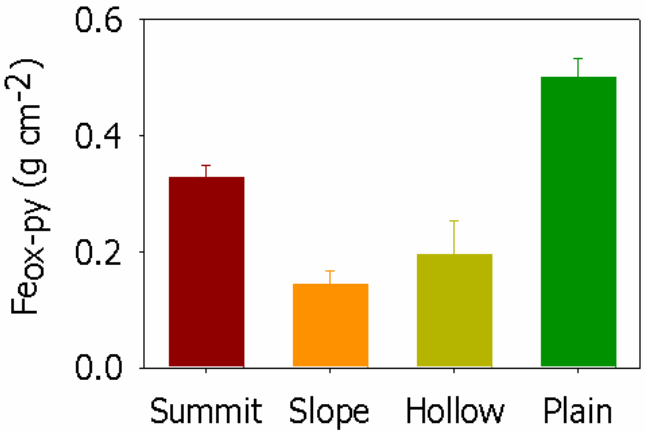
- Plain effective for physical stabilization, but not Hollow
- Deep OM progressively older but higher C:N with small change below 60cm (OM composition)
- Deep soil $\Delta^{14}C$ in depositional sites ≈ mixed layer in eroding

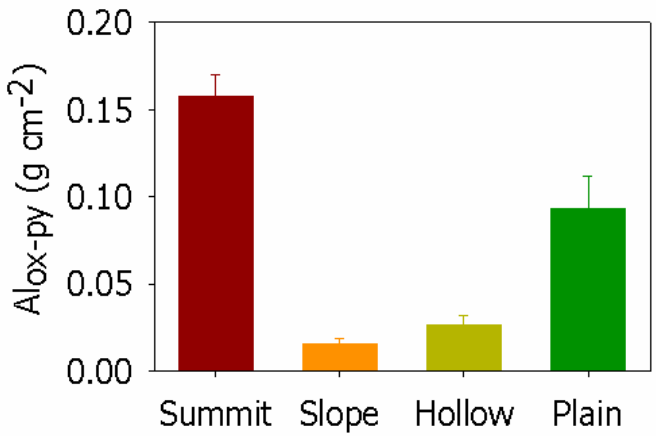
*Berhe et al., In review*

# Chemical stabilization due to bonding of OM w/minerals

## Poorly crystalline oxides

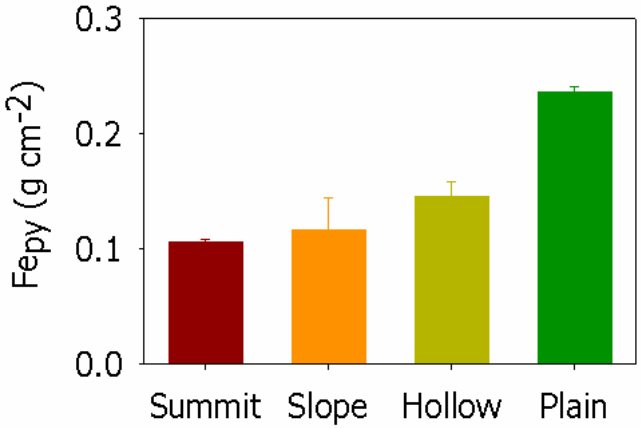
*=weighted FM ($^{14}C$)

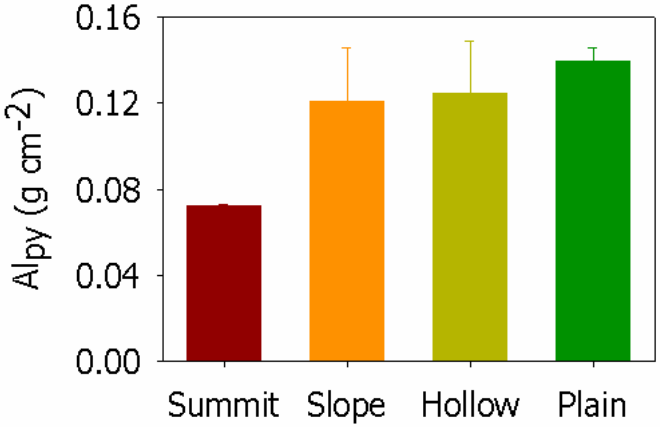



| $R^2$ | $C_{inv}$ | *Storage effectiveness |
|---|---|---|
| $Fe_{ox-py}$ | 0.96 | .04 |
| $Al_{ox-py}$ | .48 | .11 |

## Organo-mineral complexes




| $R^2$ | $C_{inv}$ | *Storage effectiveness |
|---|---|---|
| $Fe_{py}$ | 0.88 | .26 |
| $Al_{py}$ | 0.64 | 0.49 |

- Limited contribution of poorly crystallines due to their lateral distribution
- Stronger contribution of Fe and Al in organo-mineral complexes for SOM stabilization overall

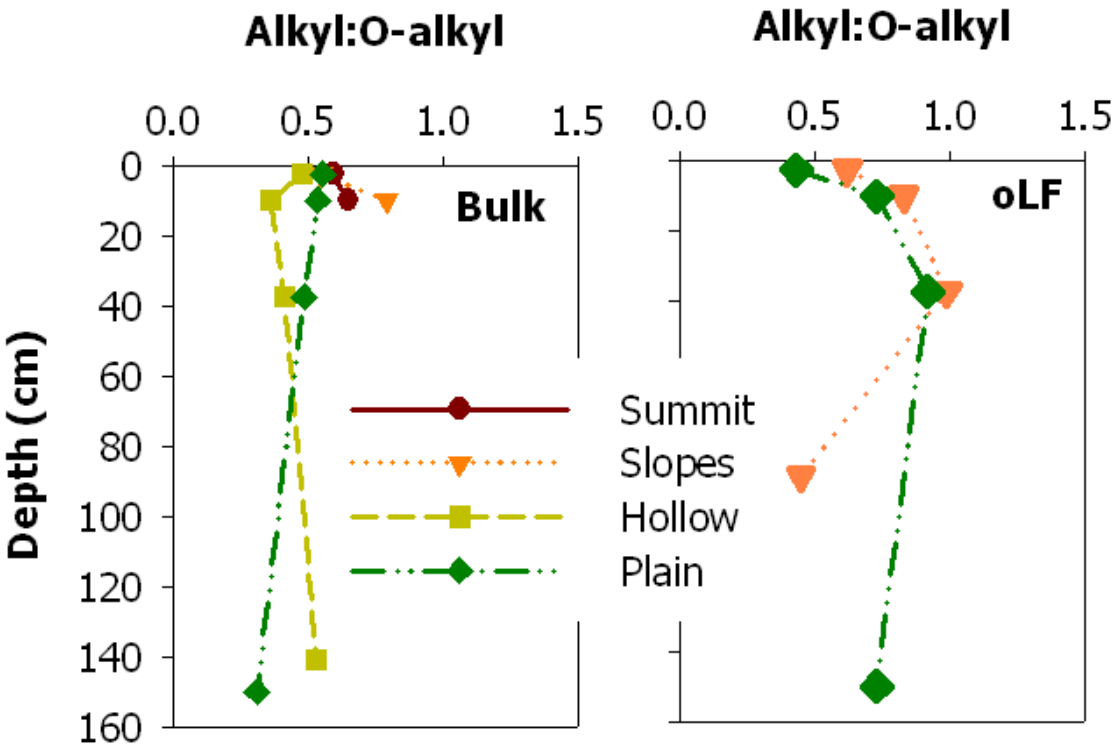
*Berhe et al., In review*

# Biochemical stabilization due to recalcitrance of OM

**As humification progresses**

- proportion of Alkyls increases
- Proportion of O-alkyls decreases

➔ **Increase in A:O-a**




- Less decomposed (transformed, may be labile) OM in depositional sites
  - Except in deepest layers in slopes

→ evidence for preservation of OM after deposition of eroded C

→ Buried SOM is not passive and in situ NPP at depositional settings has important contributions

*Berhe et al., In review*

# Summary

Stabilization of eroded C in depositional settings mainly due to:

1 – Burial and Physical aggregation of carbon within soil mineral particles

2 – Formation of organo-mineral complexes with Fe and Al oxides

# Important Clarification

*This work addresses **proper accounting** of erosion associated terrestrial carbon sink.*

Soil erosion can constitute a C sink, but

- Conservation matters
  - Disturbance of depositional sites can destabilize physically protected SOM in depositional settings
  - Increase or maintenance of NPP can increase carbon sequestration potential of eroding watersheds

- Can we compare the environmental costs of soil erosion to beneficial role it plays in C sequestration?
  - Can we put the costs in some common matrix?

*Berhe et al., 2007, Harden, Berhe et al 2008*

# Conclusions

- Both *natural* and *anthropogenically accelerated* soil erosion result in terrestrial C sequestration
  - Criterion met:
    - Dynamic replacement of eroded C
    - Reduction in decay rates at depositional settings
  - the faster the rate of erosion (the more degraded the land), the higher the sequestration potential

- Effect of land management on soil erosion depends on soil quality

- Landscapes are complex. Important to consider varied landform positions to understand implication of anthropogenic activities on soil quality, sustainability, C sequestration.

# Acknowledgments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# Professional goals

- Informing public discourse
  - Global change science
  - Soil processes and Ecosystem functions of soils
- Viewpoint
  - Disciplinary emphasis on biogeochemistry
  - Interdisciplinary work (political ecology) to understand
    - How soil's regulate provision of important services to human beings
    - How human actions affect land quality/management and people's relations with land (identity)

# Research Focus

**Postdoctoral work**

- Pedogenic responses to changes in amount and seasonality of rainfall
- Nano-biogeochemistry, OM desorption from oxide surfaces

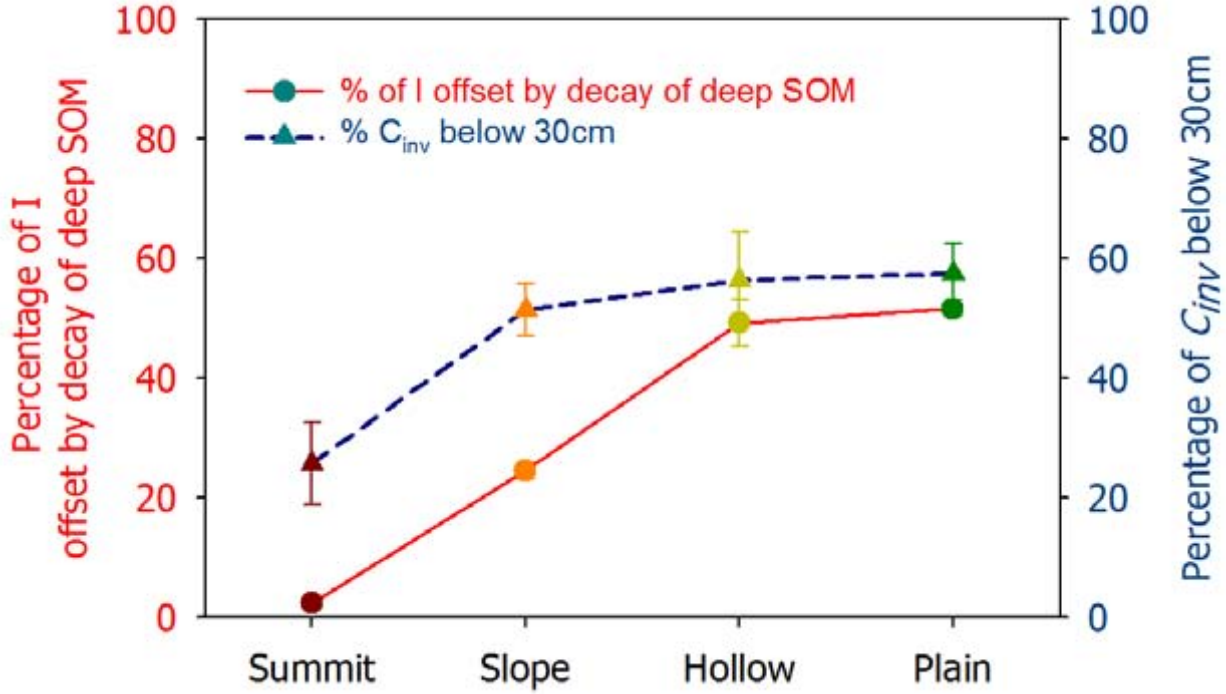
**Continuing work**

- Temporal evolution of the erosion induced C-sink
- Biochemical constraints on decomposition of permafrost SOM in Alaska
- Effect of source material and soil depth on decomposition of black carbon

**Future Work**

- How significant is erosion-induced C sequestration during landuse conversion for biofuels?
- Can we reconstruct climate and vegetation history in the Sahel to understand drivers of climate and vegetation change (over last 200yrs)?
- Does urbanization and associated chemical pollution impose fundamental physiological and/or macroscopic constraints on nutrient cycling (due to changes in stoichiometry, C:N:P:S)?
- What sort of real (land management) and imagined (identity) relationships due war refugees adopt in their settlements?

# Decay of deep SOM

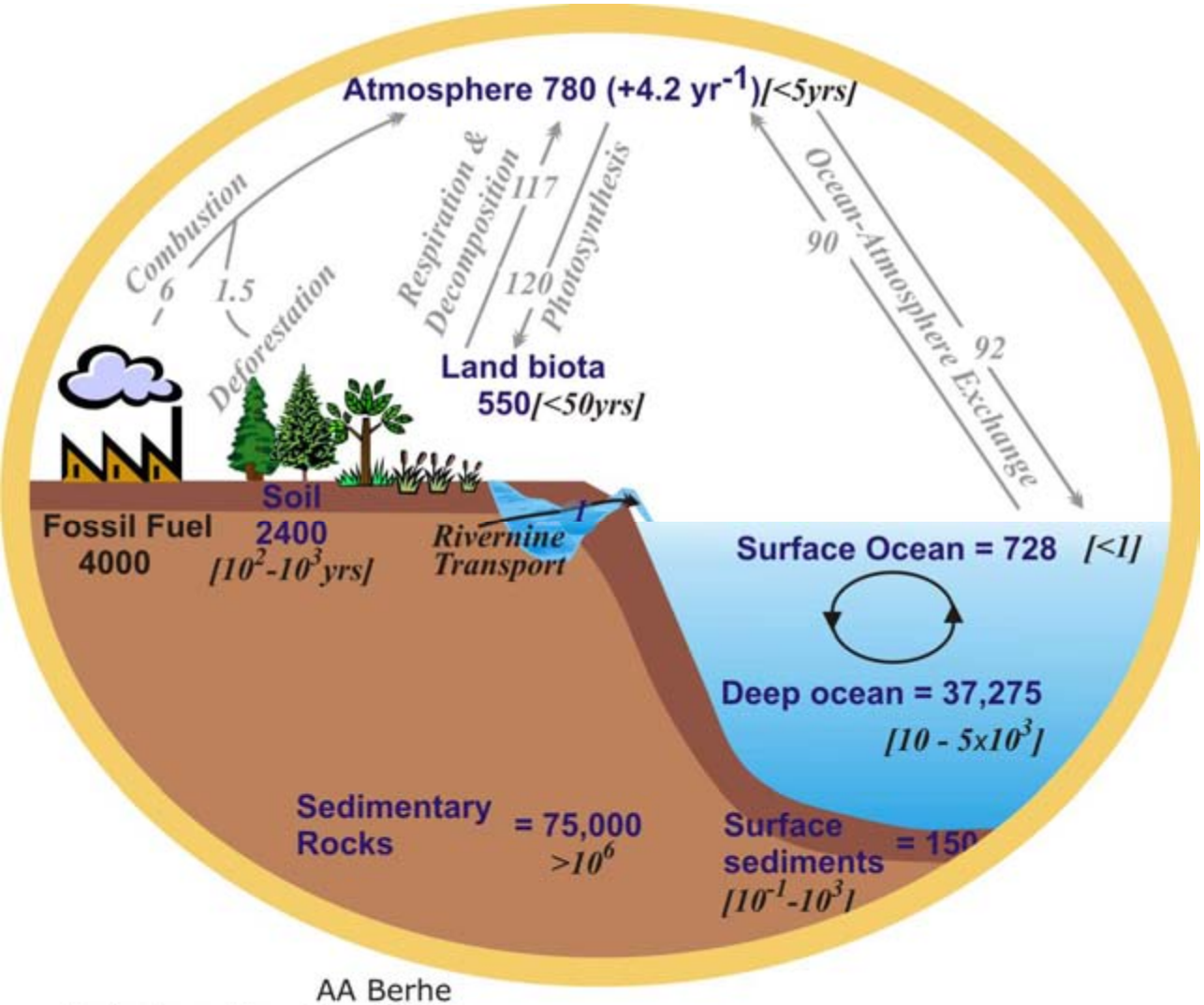



- Subsoil SOM
  - ~50% of total soil C
  - decay of deep SOM offsets half of the fresh input to SOC pool annually

- Buried C is not necessarily stabilized, it continues to receive inputs from top soil layers and release $CO_2$ to the atmosphere

*Berhe et al., 2008*

# The Global Carbon Cycle

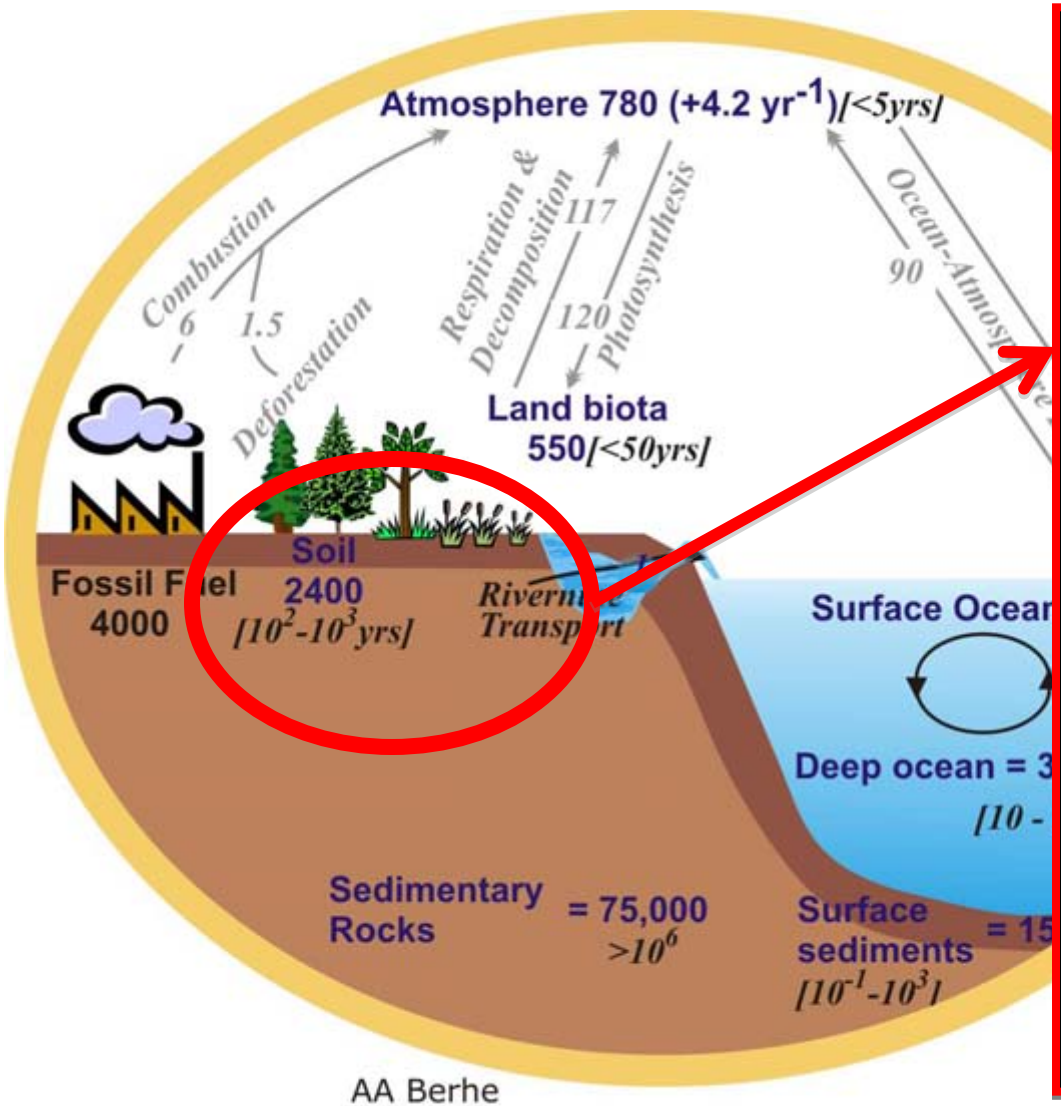



AA Berhe
Data from Houghton 2007

Balancing the C budget

- Understanding the processes responsible for net sources and sinks of carbon is of paramount importance
- Net terrestrial balance: the term with the least agreement among different estimates

# The Global Carbon Cycle




AA Berhe
Data from Houghton 2007

## My work

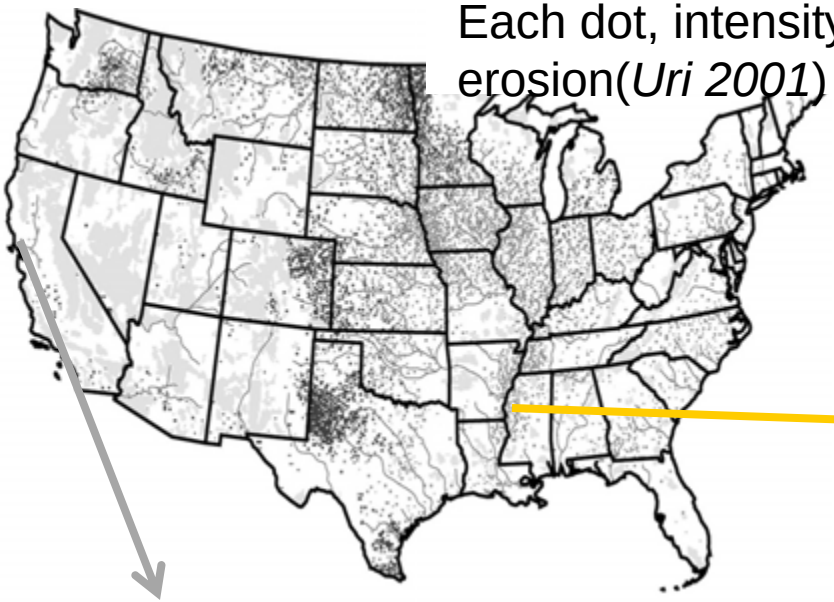
General themes

- Geomorphic and Anthropogenic influences on cycling of essential elements in the critical zone.
- Dynamic two-way relationship between soils and society

Methods

- Soil (bio)chemistry
  - Isotopes,
  - Spectroscopy
- Ecosystem ecology
- Ethnopedology
- Political ecology

# Contrasting causes, forms, & magnitudes of erosion



Each dot, intensity of soil erosion(*Uri 2001*)

Nelson Farm, central MS

Tennessee Valley, Marin headlands, CA

- **Nelson Farm, MS**
  - Cultivated
  - Anthropogenically accelerated intensive soil erosion,
- **Tennessee Valley, CA**
  - Undisturbed grassland (grazed 19th to early 20th century)
  - Natural, Slow rate of erosion (gophers)

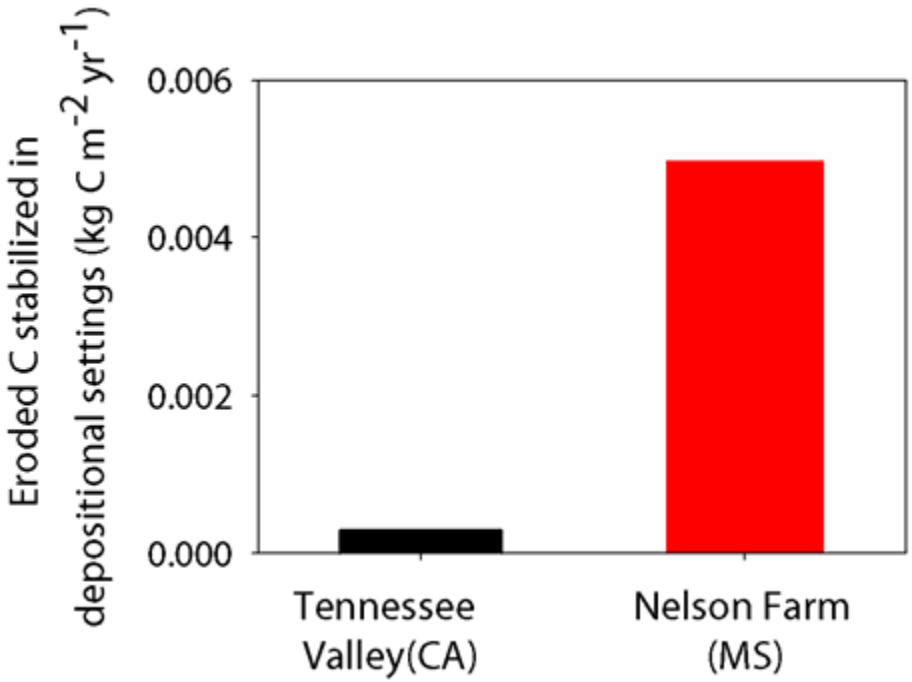
# Study sites

| | Tennessee Valley, CA | Nelson Farm, MS |
|---|---|---|
| Parent Material | Fransc. Sandstone | Peoria Loess |
| Soils | Entisols, Mollisols | Alfisols |
| Mean annual precipitation (mm) | 1200 | 1340 |
| Mean annual temperature (°C) | 14 | 17.3°C |
| Management | Undisturbed | Cultivated |
| Carbon content of eroding soil (%) | 2.2 | 0.7 |
| Rate of erosion (kg $m^{-2}$ $yr^{-1}$) | 0.1 | 4.7 |
| Eroded C deposited within watershed (%) | 77 | 79 |

- Nelson Farm, MS
  - NPP maintained by addition of fertilizers and irrigation
  - Mechanically cultivated with cotton 1800-1950, since then sorghum, wheat, soybean.

*Berhe et al (2007)*

# Regardless of cause, erosion causes a sink




- Both forms of erosion result in terrestrial C sequestration

Cultivated MS site had
- Faster rate of erosion
- Smaller %C in topsoil
- Higher fraction of eroded C stabilized

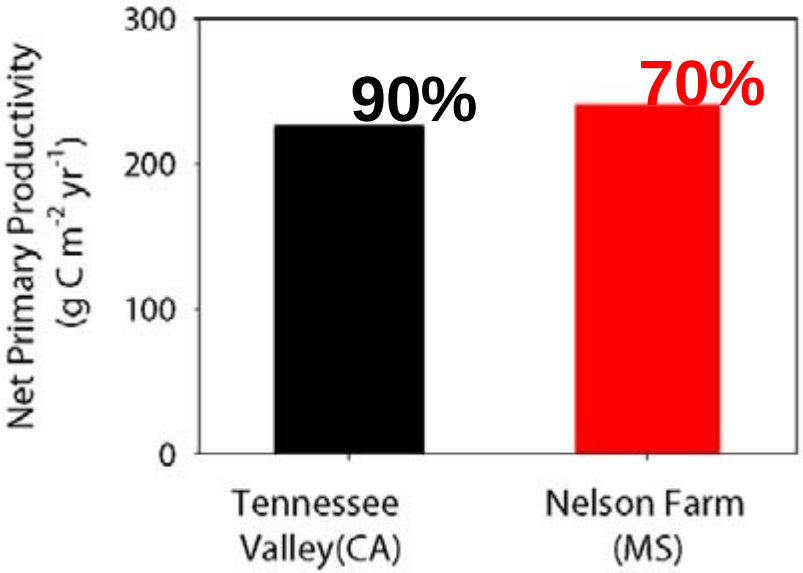
The more degraded a land, theoretically, the furthest it is from its maximum carbon sequestration potential.

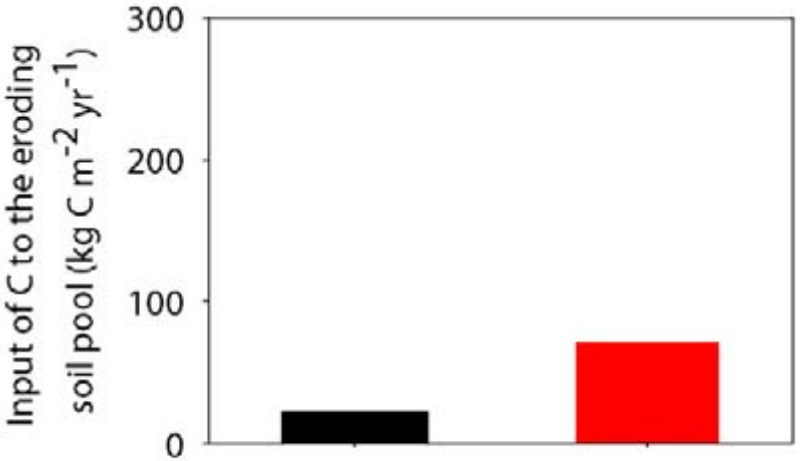
- No C stabilization ($C_s$), only if:
  - Fraction of eroded C arriving at depositional site ($f_{e,d}$) = 0
  - Fraction of C decomposed after deposition ($f_{d,o}$) = 1

*Berhe et al (2007)*

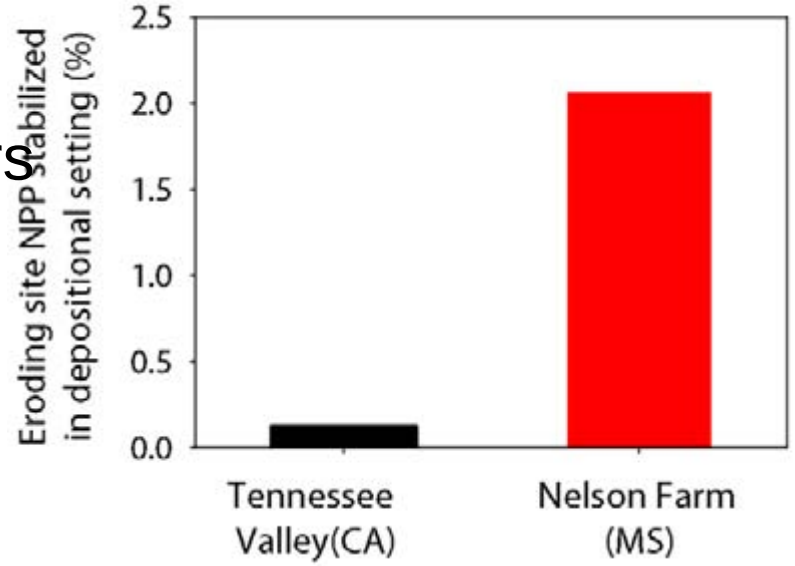
# New photosynthate & its contributions

* Humification coefficient




- Comparable NPP
- Up to 3 times more C enters soil pool at MS
- Erosion-induced C sequestration
  - 0.3% of NPP in CA
  - 2.3% of NPP in MS



# Post-erosion watershed C balance

$$\frac{dC}{dt} = I - kC$$

$$C_T = C_{T,erod} + C_{T,dep}$$

- New (post-erosion) input decomposing at old (eroding site) decay rates
  - Eroding settings
  - Topsoil of depositional settings

$$Then,\ post-erosion$$

$$C_T^{'} = C_{T,erod} + (deposited\ C + in\ situ\ C)$$

$$C_T^{'}(t) = \frac{I^{'}}{k}\left(1 - e^{-kt}\right) + \frac{I}{k}\left(1 + e^{-k^{'}t}\right)$$

- Old (pre-erosion) carbon (little or no fresh input) decomposing at new decay rates
  - Buried in subsoil of depositional settings

## Modeling results

*Berhe 2006*

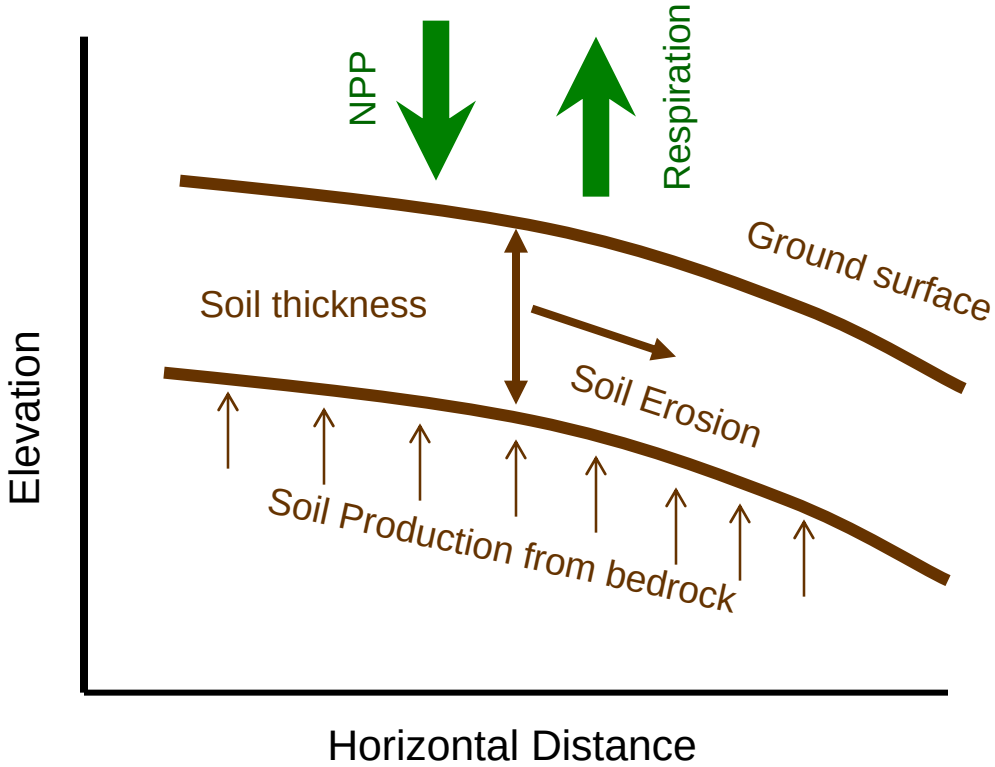
- Changes to rate of C input to soil more important than changes in rate of OM decomposition (unless decomposition is completely stopped)

# 1 – Both constitute net C sequestration

More degraded land has higher potential for C sequestration

Maintenance of NPP

# Geomorphic Controls on C Storage

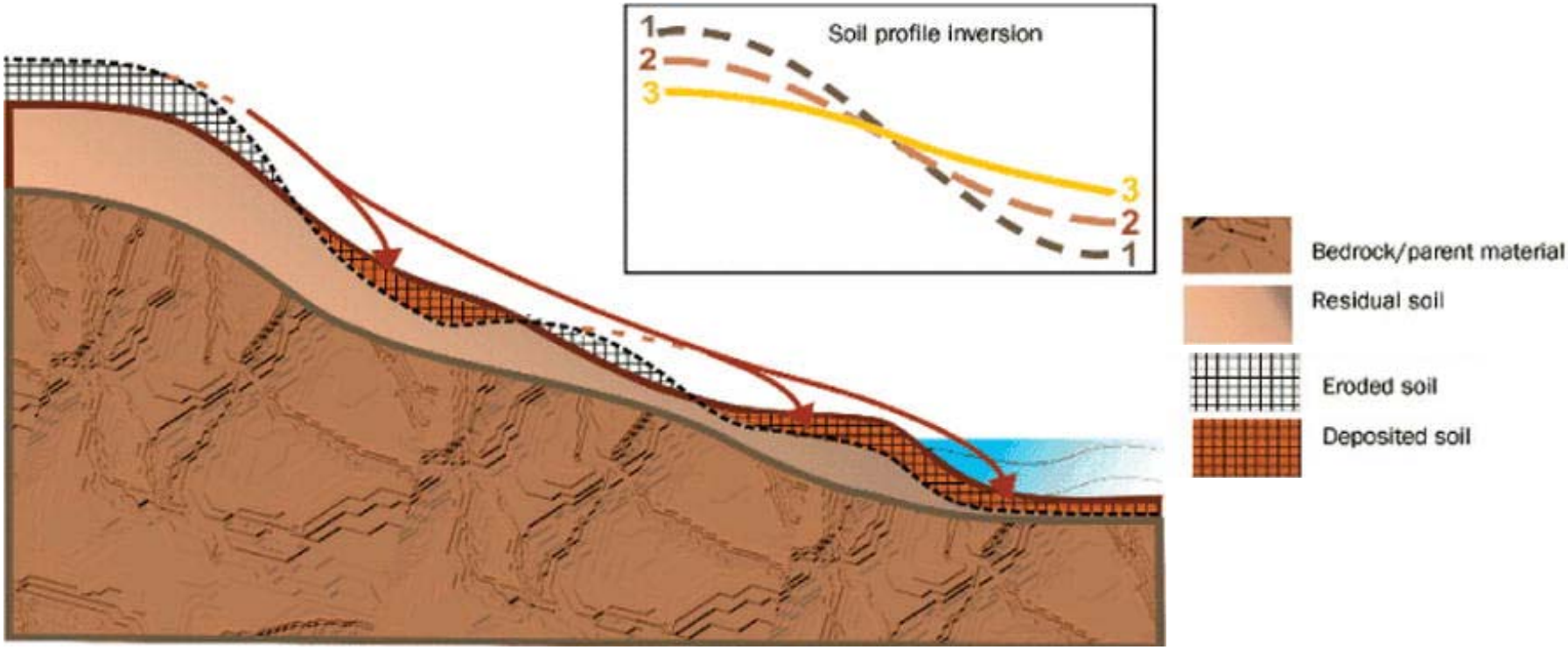



- Erosion affects the stock of
  - Soil
  - Soil carbon

- In flat and undisturbed mature sites:
  soil loss by erosion ≈ soil production.
- In hilly and anthropogenically disturbed landscapes:
  rate of soil erosion >>> rate of soil production

*Figure adapted from Yoo et al. 2005*

# Erosion redistributing C




- Soil erosion
  - Removes topsoil (high SOM), exposes subsoil (low SOM)
  - Transports eroded topsoil downhill
  - Buries transported soil in different depositional settings (hollows, foot-slopes, alluvial/colluvial plains…)
- Until recently, erosion was not included in most global C models