# Towards modelling global soil erosion and its importance for the terrestrial carbon cycle

**Tom Vanwalleghem[1] and Jed Kaplan[2]**

**1 - Group for Rural Hydrology and Hydraulics, Department of Agronomy, University of Cordoba, Spain**

**2 - Athmosphere Regolith Vegetation, EPFL, Switzerland**

# Overview

1. **Soils in Earth System Models**

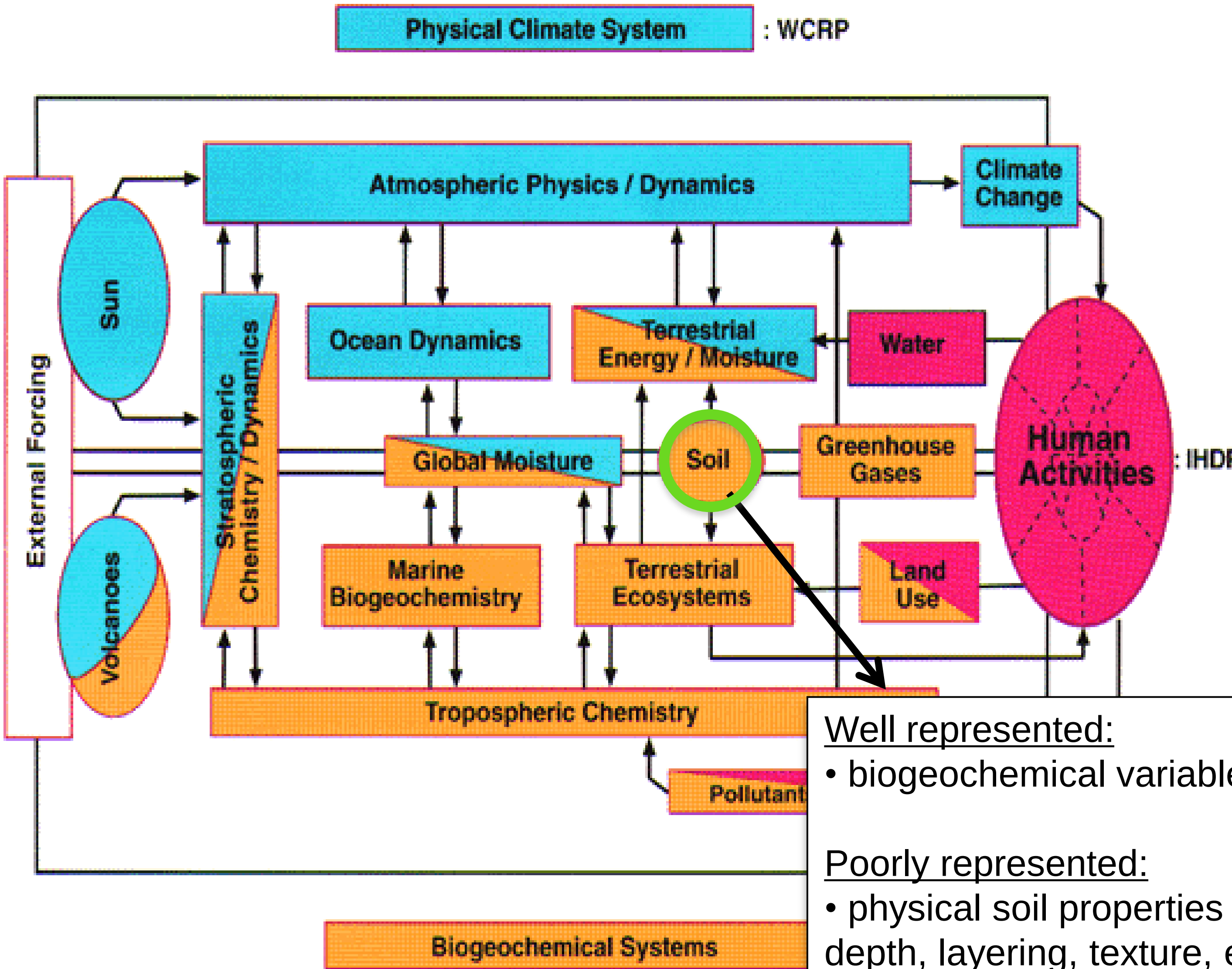
2. **Importance of soil erosion for the carbon cycle**

3. **Holocene soil erosion and modelling soil/carbon erosion**

4. **Scaling topographical properties for global-scale soil erosion modelling**

5. **Conclusions and future perspectives: towards constraining the effect of global-scale soil erosion on the carbon cycle**

# Soils in Earth System Models




Well represented:

- biogeochemical variables/cycling

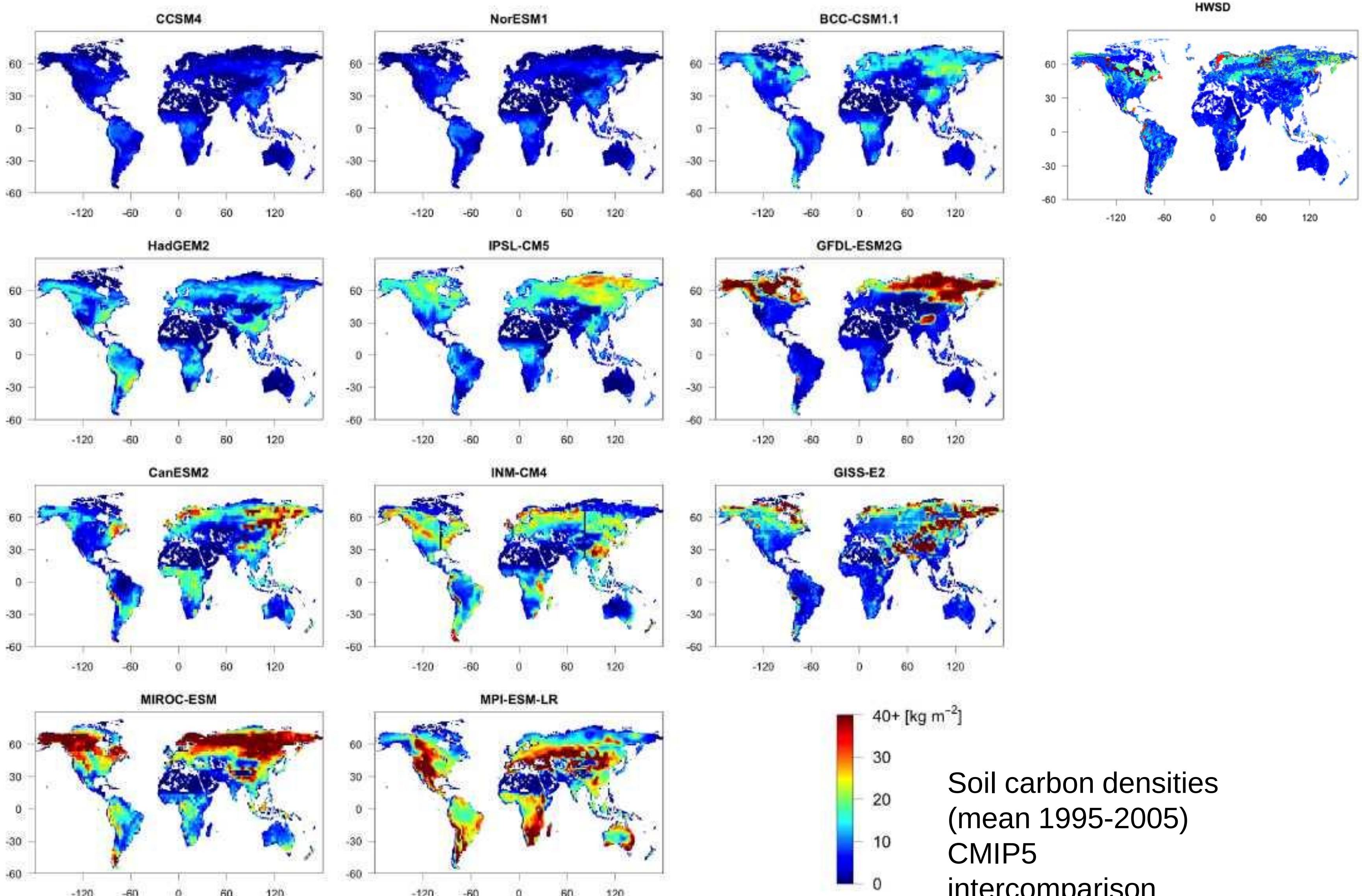
Poorly represented:

- physical soil properties (soil depth, layering, texture, etc.)
- **evolution → static**

Modified Bretherton Diagram (Guy Brasseur, NCAR Atmospheric Chemistry Division)

# Soils in Earth System Models

## How much do we know about soils on a global scale?




Soil carbon densities (mean 1995-2005) CMIP5 intercomparison

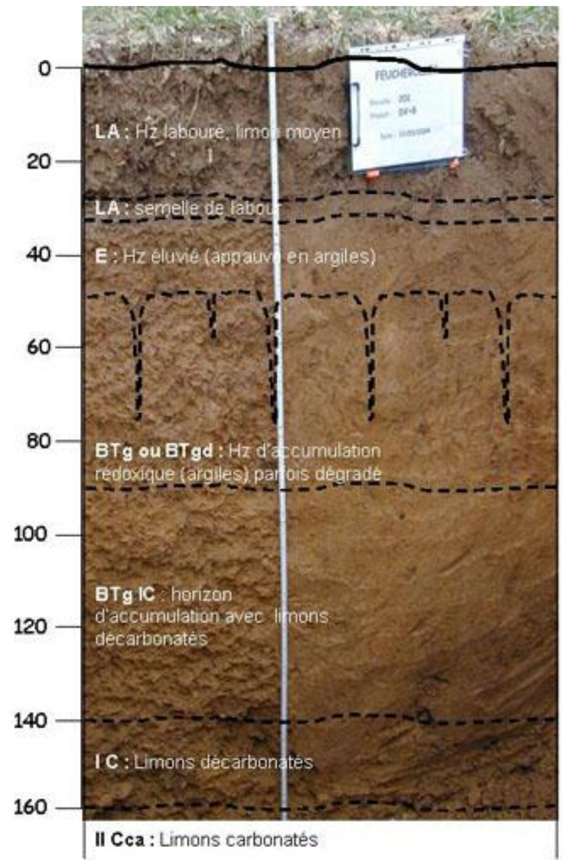
Todd-Brown et al. 2013. *Biogeosciences*

# Soils in Earth System Models

## How much do we know about soils on a <u>global scale</u> and a <u>Holocene timescale</u>?

Static or dynamic soils?

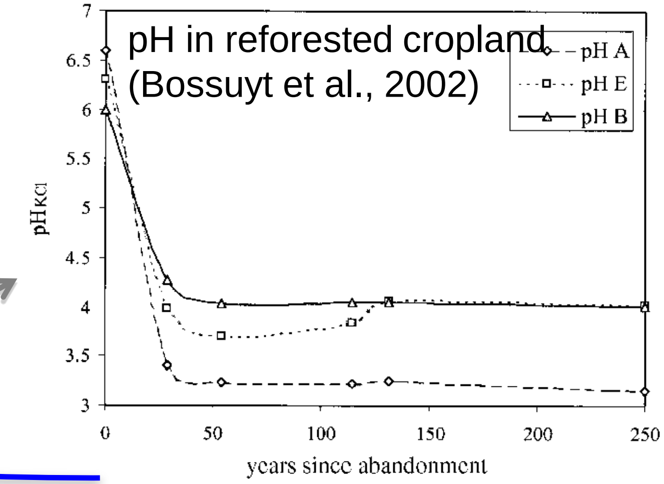

Shallow marls, S Spain

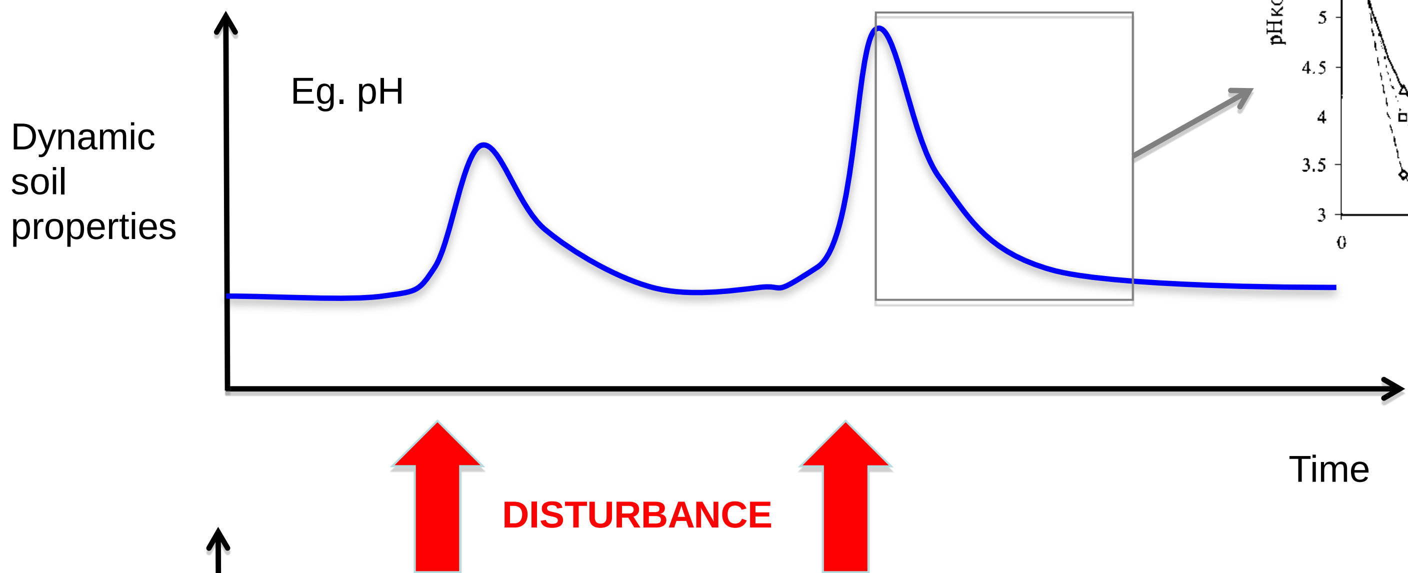


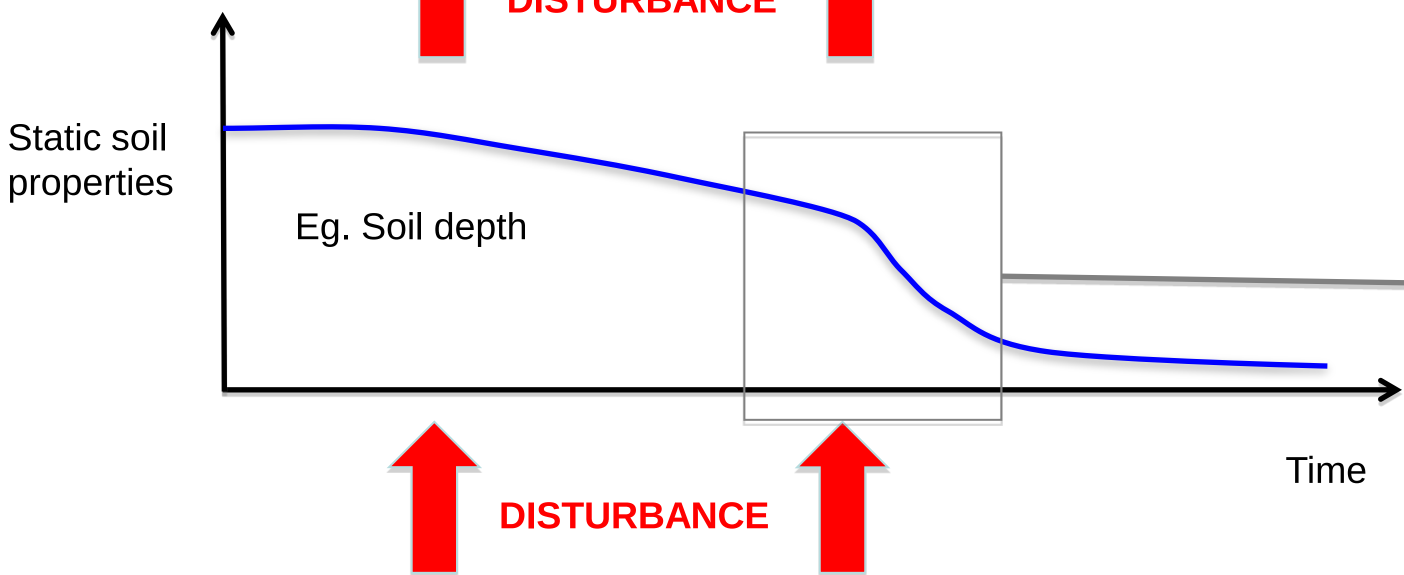

Loess soil profile (INRA, France)

# Relating soil profiles and erosion

- **<u>Static</u> versus <u>Dynamic</u> soil properties**

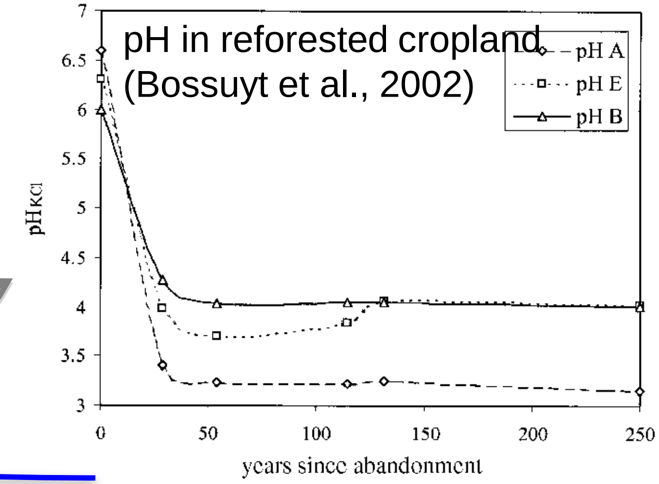


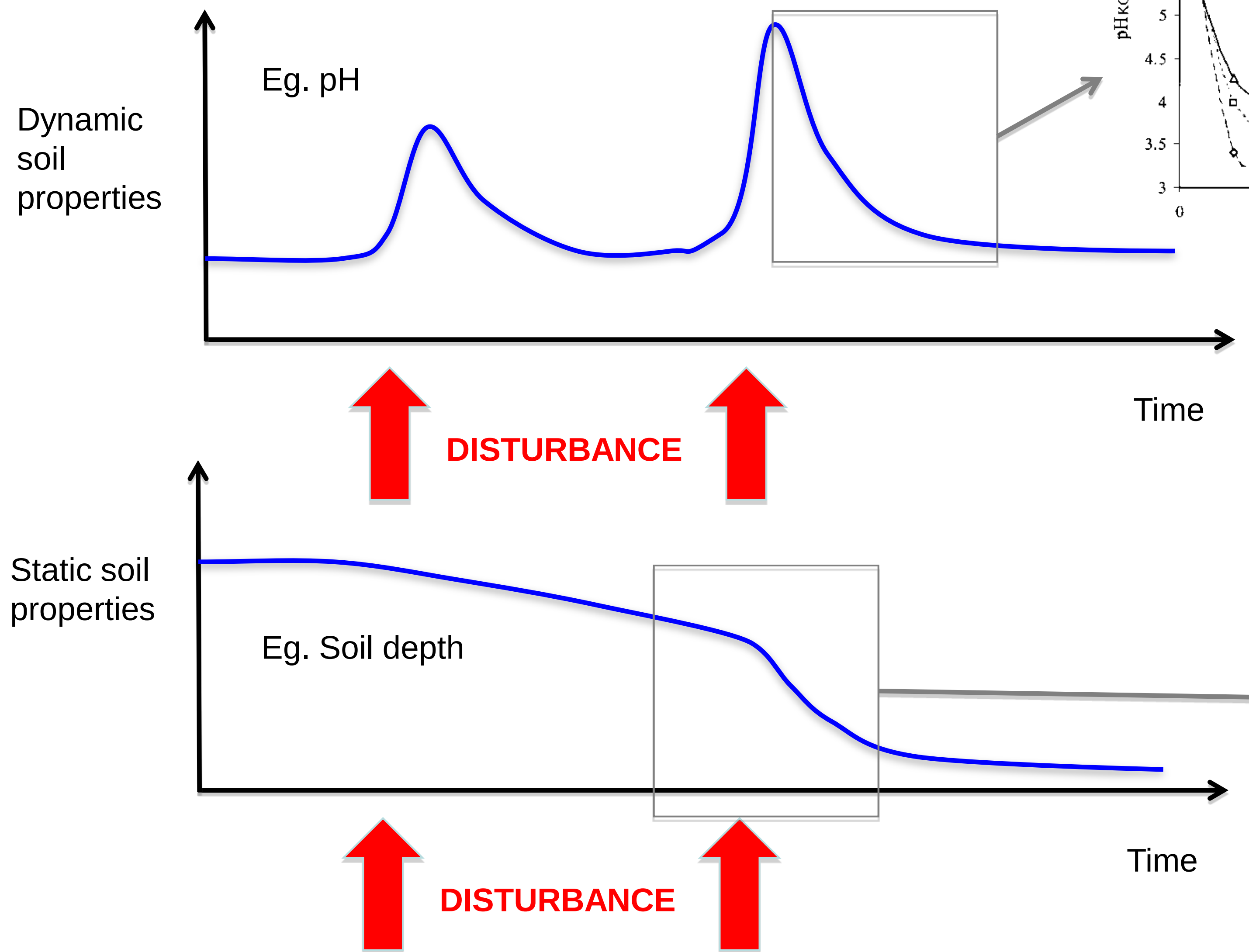




# Relating soil profiles and erosion

- **<u>Static</u> versus <u>Dynamic</u> soil properties**

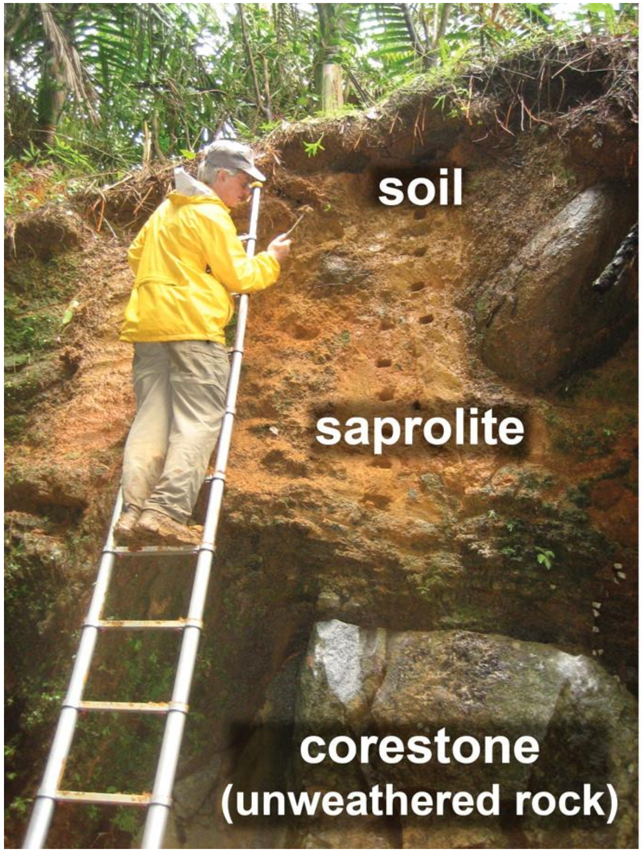


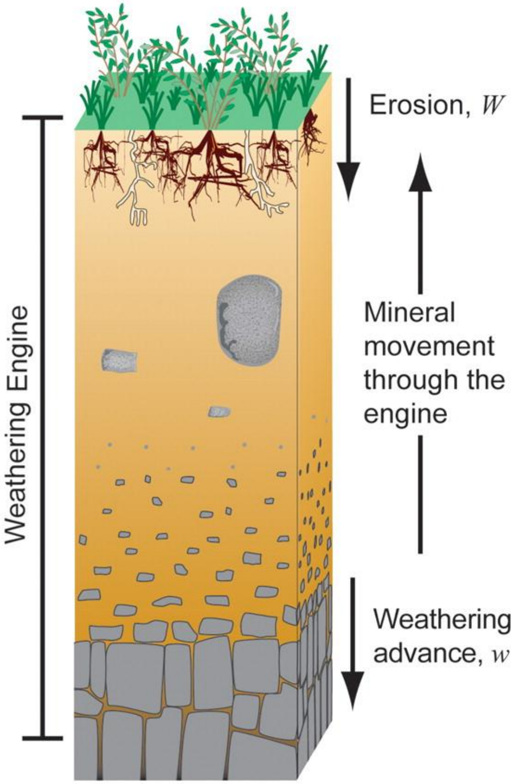




Irreversible ecosystem shifts

# Dynamic soils: modelling

## Evolution of soils

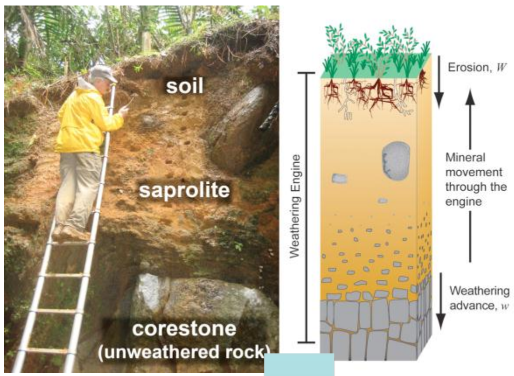


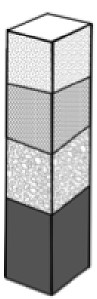

Brantley et al. 2007. *Elements*

# Dynamic soils: modelling

Recent advances in modelling coupled soil-landscape evolution:




**MODEL FOR INTEGRATED SOIL DEVELOPMENT**



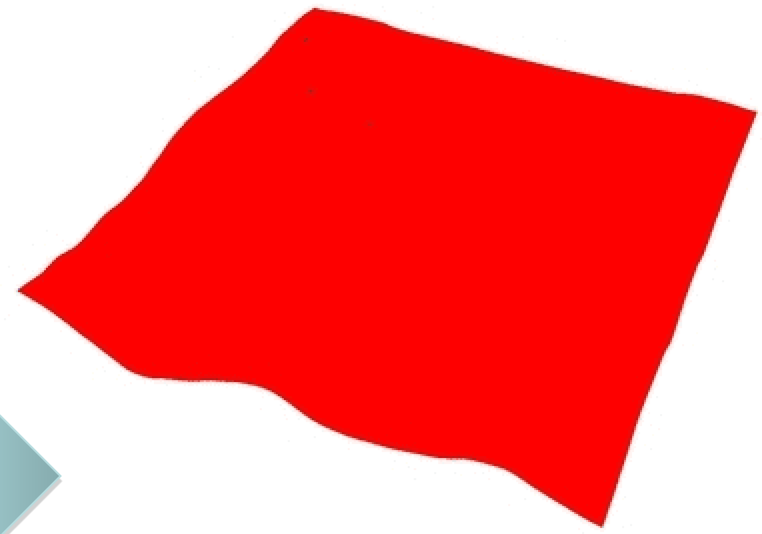
LAYER 1 (A)
LAYER 2 (B)
LAYER 3 (BC)
BEDROCK (C)

SOIL FORMATION

SOIL EROSION & DEPOSITION

4-layer model
5 particle size classes
Different soil formation and erosion processes

**Total soil thickness (m)**

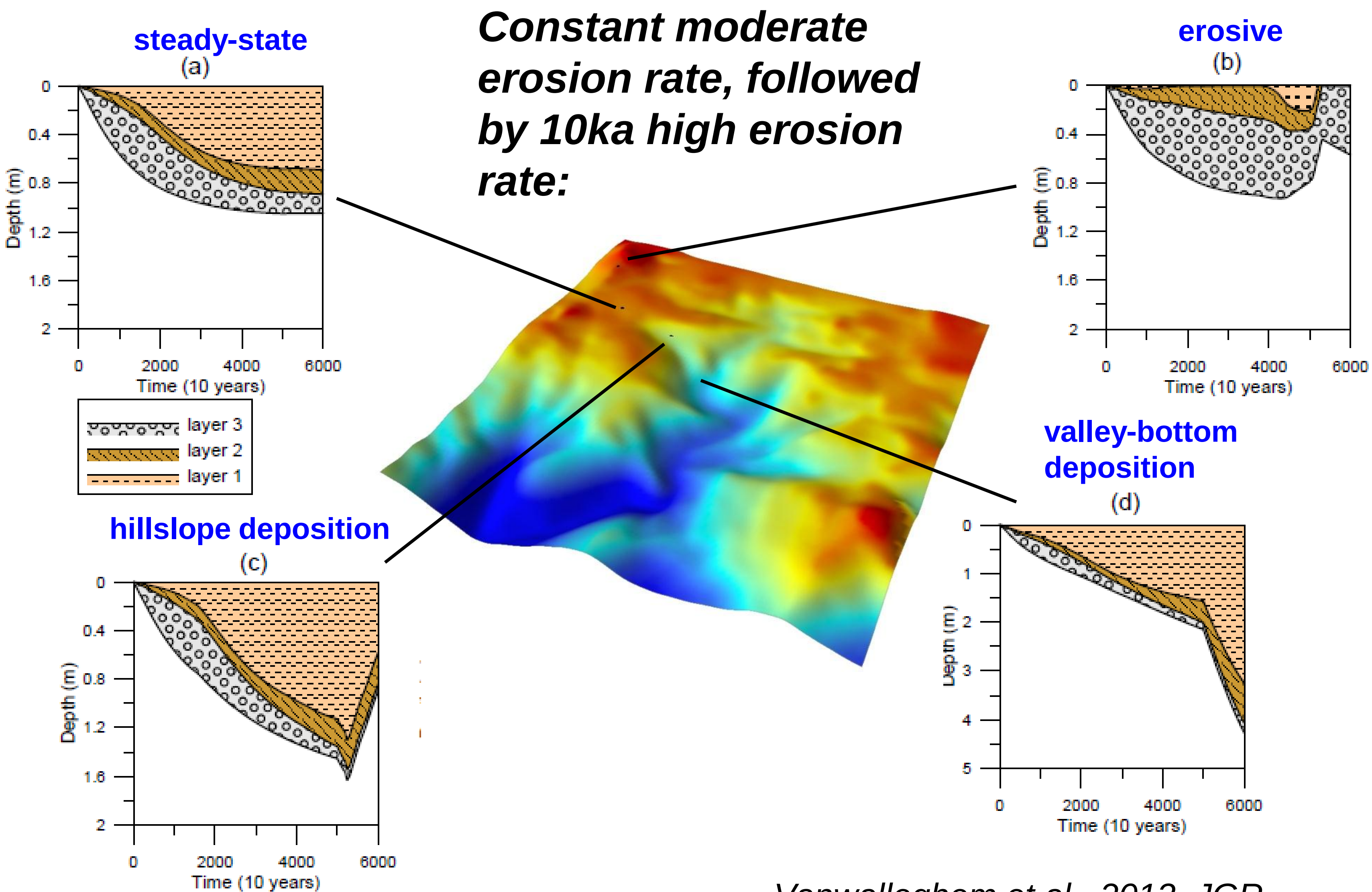


t = 0 ky

Vanwalleghem et al. 2013. *JGR-ES*

# Model for Integrating Landscape and Soil Development

- **Soil thickness, integrating soil formation and soil erosion**

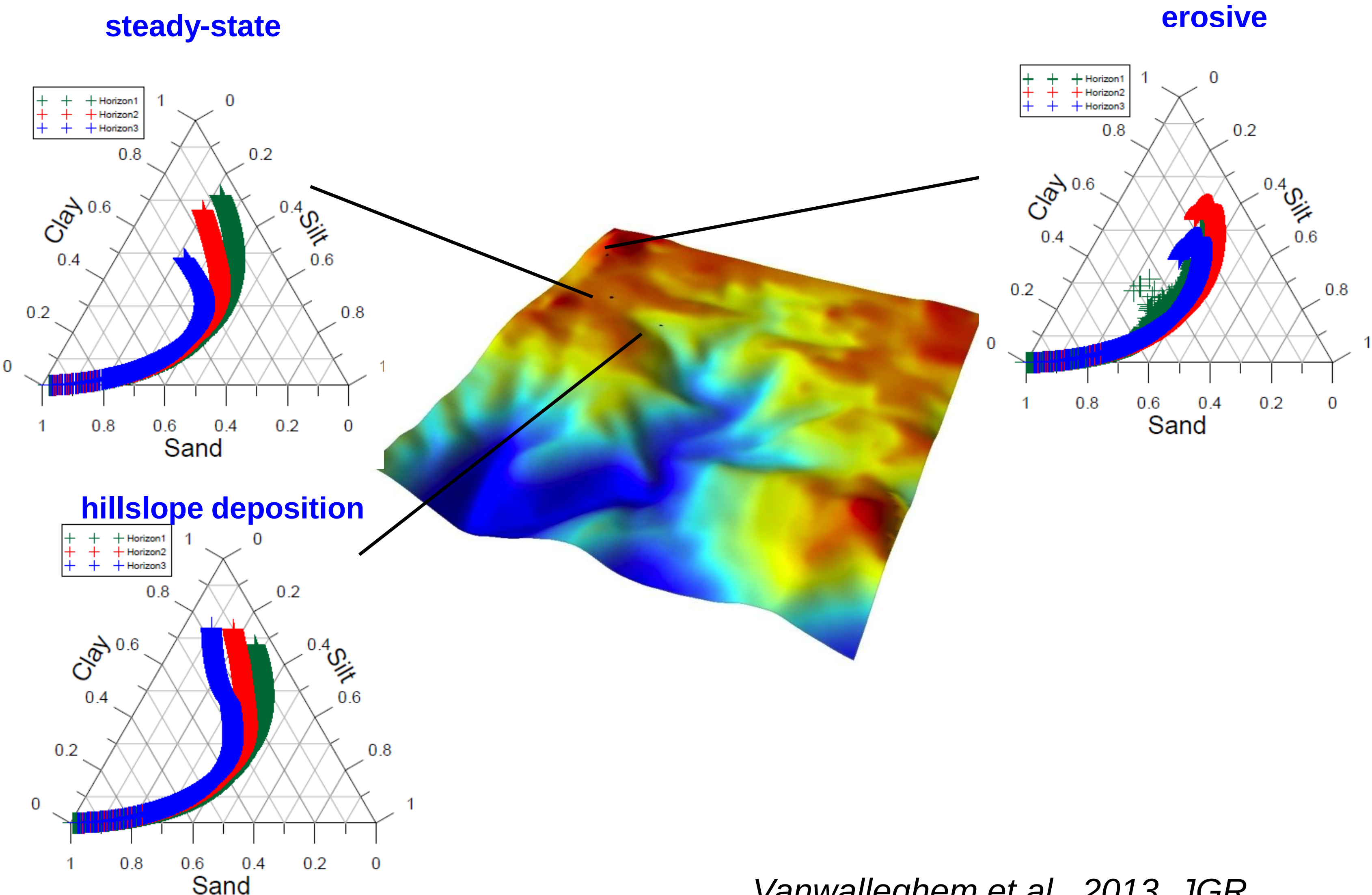



*Vanwalleghem et al., 2013. JGR*

# Model for Integrating Landscape and Soil Development

- **Erosion effect on texture**

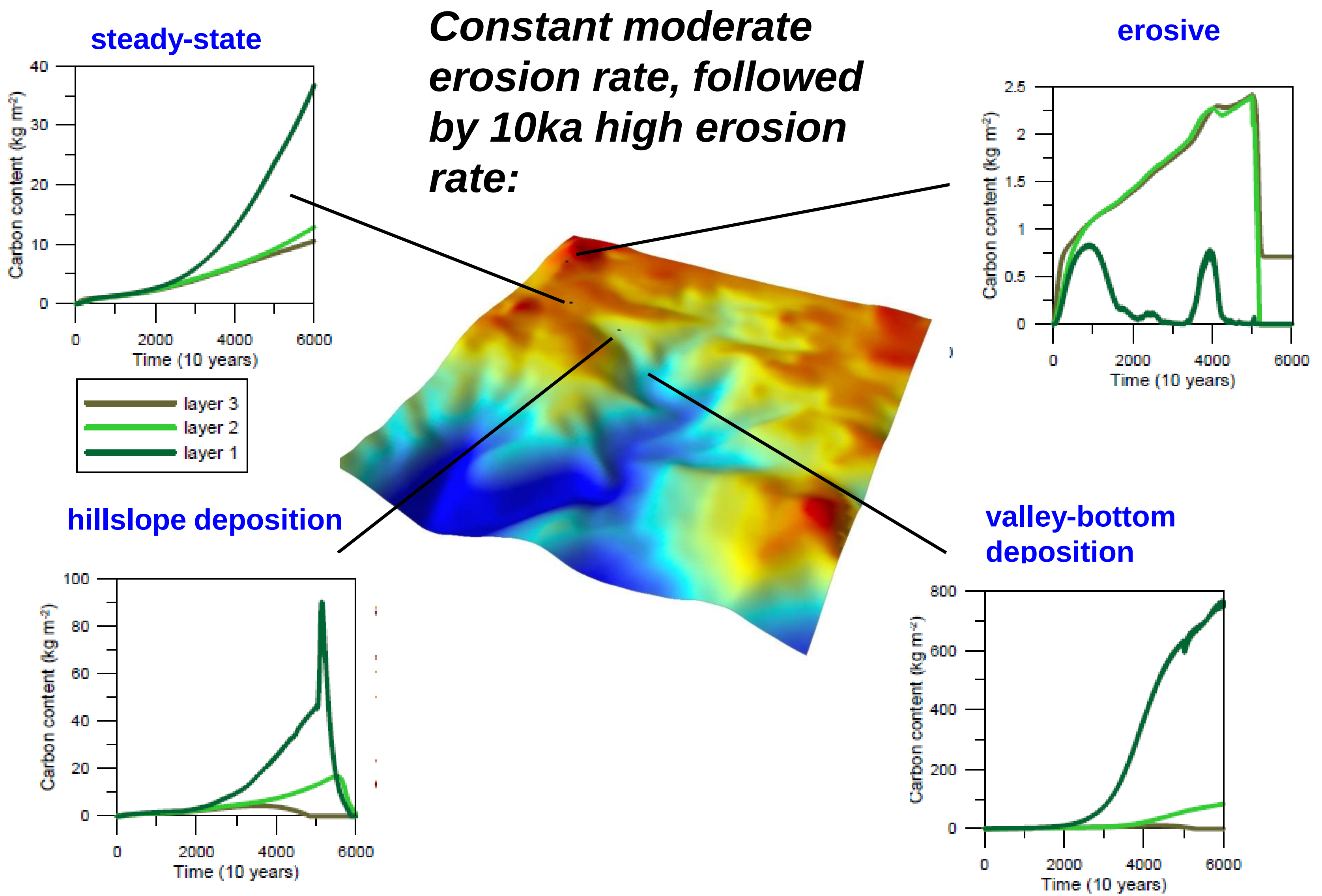
***Scenario with constant moderate erosion rate:***




*Vanwalleghem et al., 2013. JGR*

# Model for Integrating Landscape and Soil Development

- **Soil organic carbon, integrating soil formation and soil erosion**

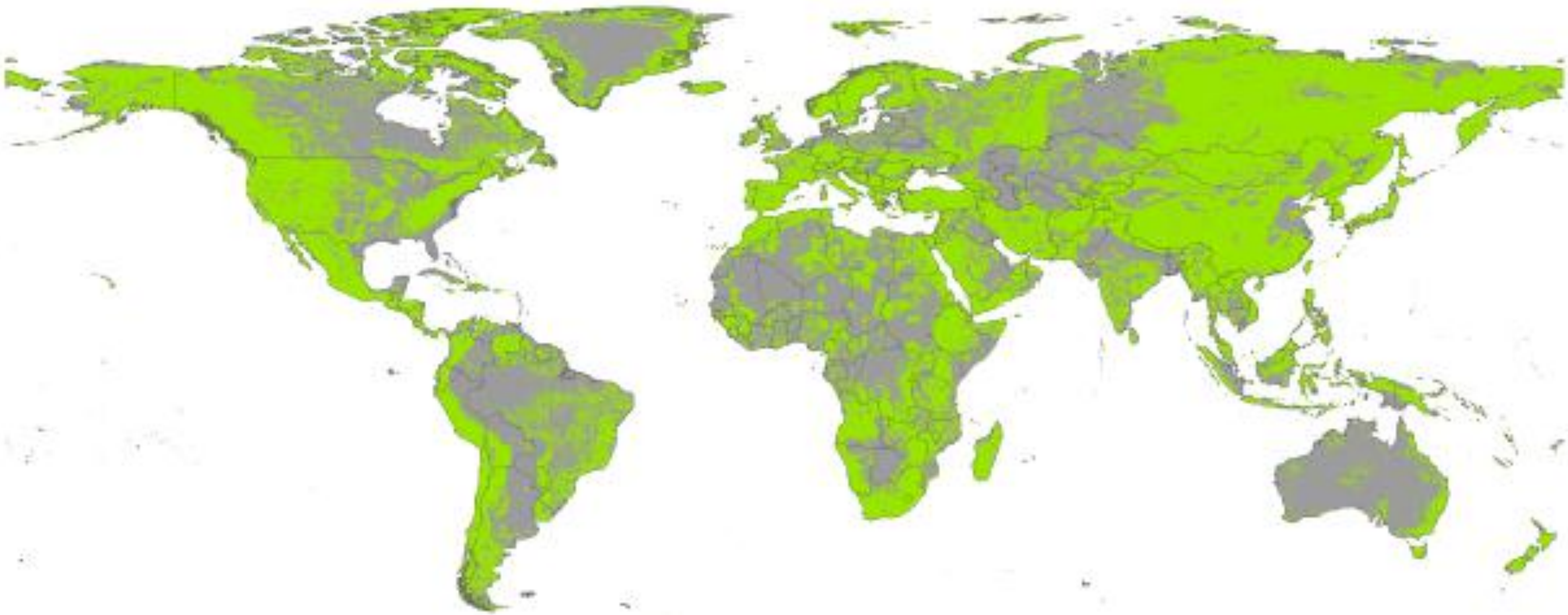


# Importance of erosion for soil profiles

- **Soil erosion has been shaping our land and soils since historic times:**

# Importance of erosion for soil profiles

- > 70% is sloping land



# Relating soil profiles and erosion

- **Soils are not static!**
- **Impact on vegetation**
- **Soil loss rates in Mediterranean**

**Table 5**

Scale document down sion rates (weighted mean and standard deviation) for different land u

| | Other regions | | | |
|---|---|---|---|---|
| Land use | Database entries* | Plot-months | Mean (t ha$^{-1}$ year$^{-1}$) | Std. I |
| Bare | 62 | 7599 | 17.12 | 30.23 |
| Arable | 73 | 6635 | 6.33 | 13.46 |
| Forest | 2 | 60 | 0.003 | 0.00 |
| Grassland | 7 | 1535 | 0.29 | 1.15 |
| Shrub | 3 | 90 | 0.13 | 0.19 |
| Vineyard | 4 | 144 | 23.64 | 26.0 |
| Orchard | 2 | 408 | 20.6 | 19.4 |

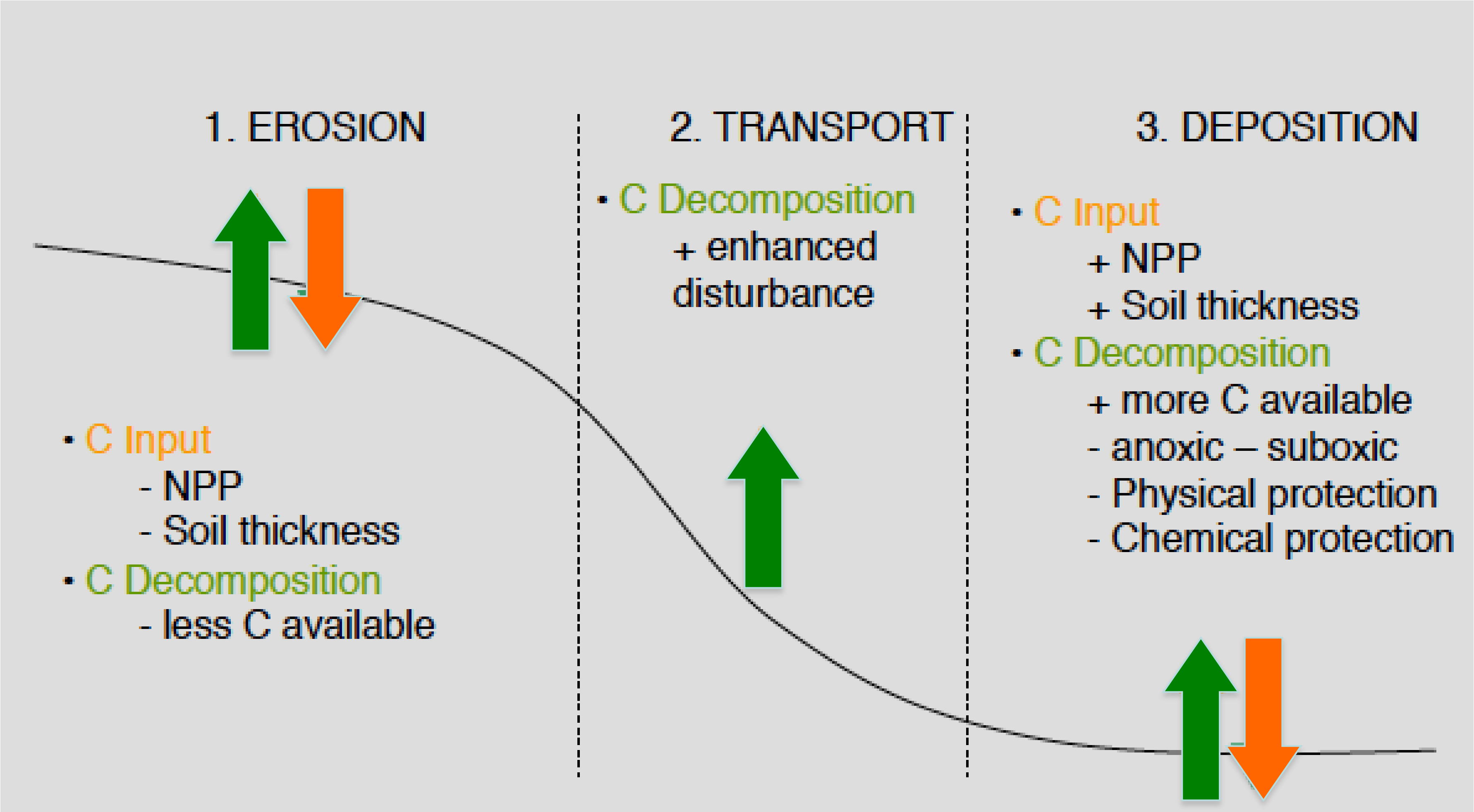
*One entry is the combination of one land use, slope, etc. for one experimental site.

*Cerdan y col., 2010. Geomorphology*


**Fig. 1.** Spatial distribution of soils with a high rock fragment content in Europe. Areas with soils having a rock fragment cover >30% are shown in dark brown. Data derived from the Soil Geographical Database of Europe (European Commission, 2004).

# Importance of erosion for the carbon cycle

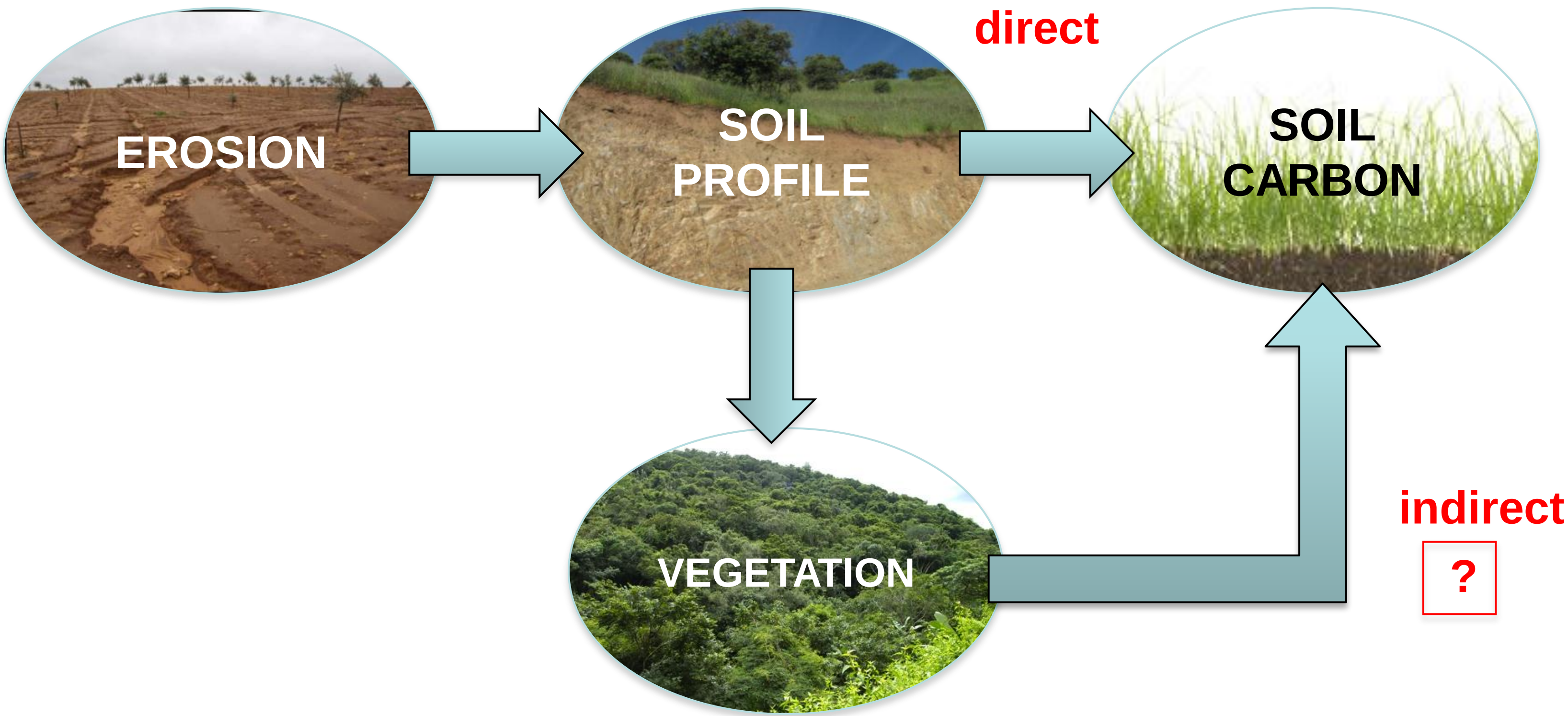
- **General framework**




*Adapted from Van Oost, 2007*

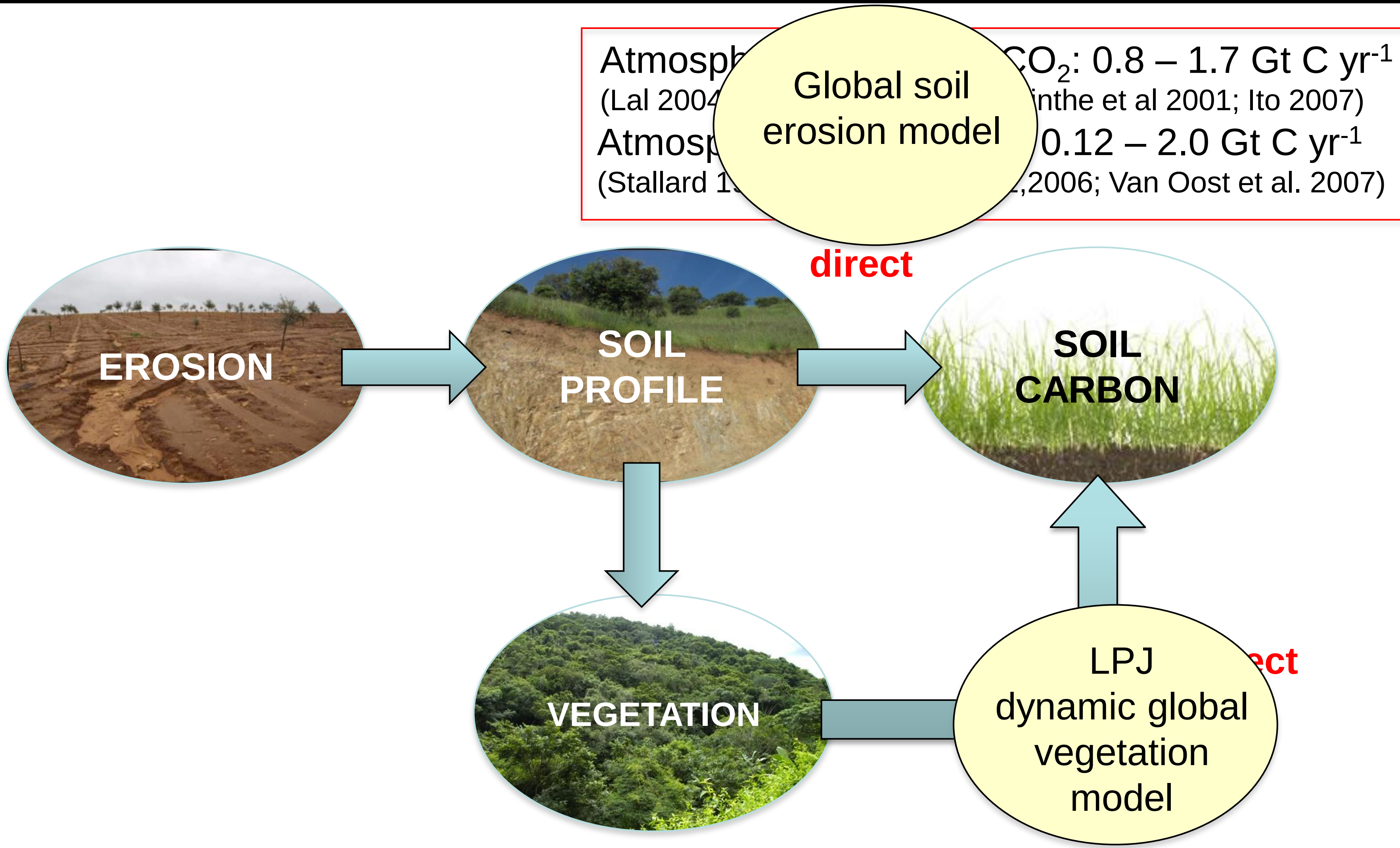
# Importance of erosion for the carbon cycle

Atmospheric ***source*** of $CO_2$: 0.8 – 1.7 Gt C $yr^{-1}$
(Lal 2004; Schlesinger 1995, Jacinthe et al 2001; Ito 2007)
Atmospheric ***sink*** of $CO_2$: 0.12 – 2.0 Gt C $yr^{-1}$
(Stallard 1998; Smith et al. 2001,2006; Van Oost et al. 2007)




- **Unsufficient understanding of interaction erosion-carbon cycling at process level and challenge of upscaling local data to global level**
- **Uncertainty associated with estimate of global soil erosion**

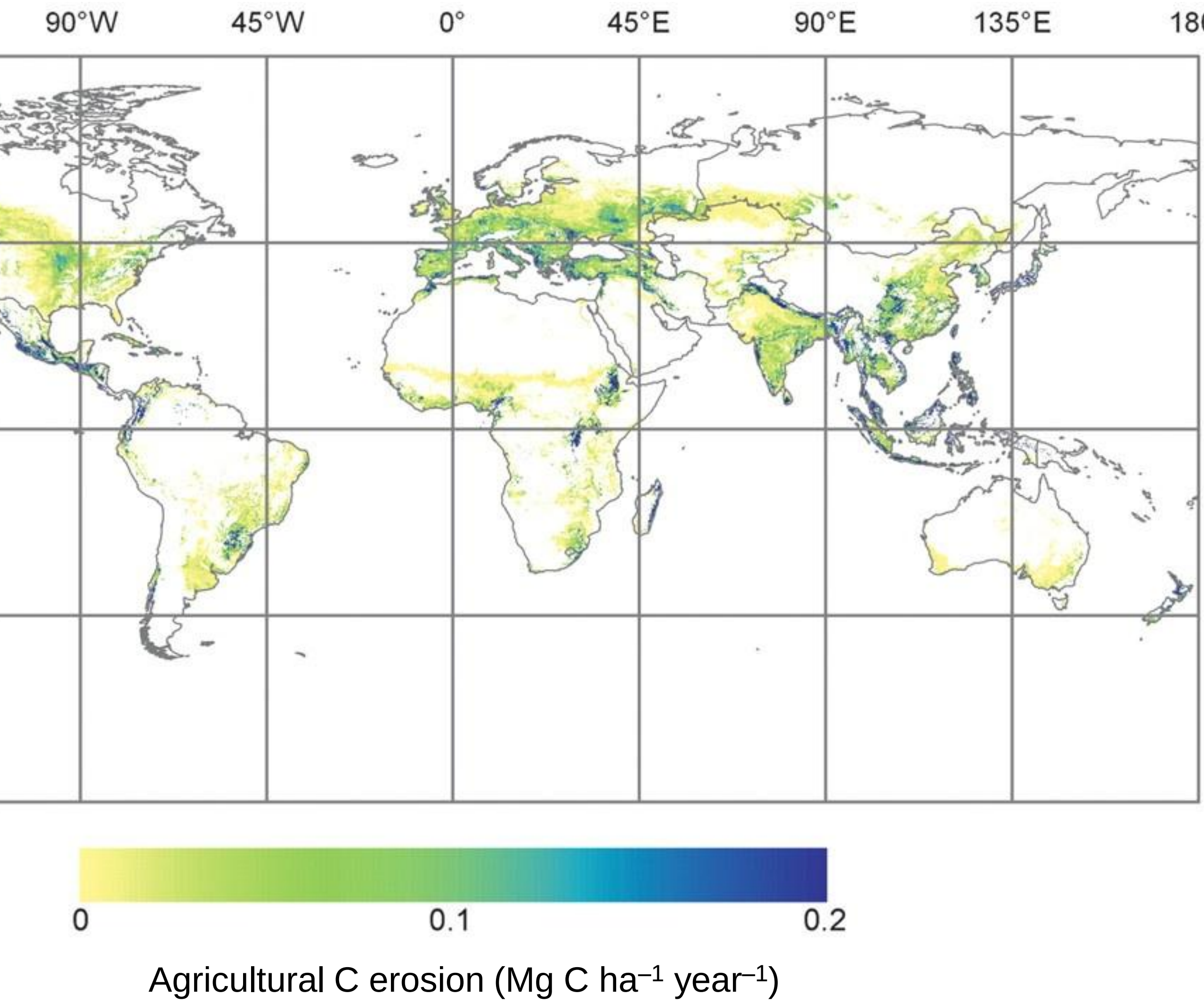
# Importance of erosion for the carbon cycle




- **Unsufficient understanding of interaction erosion-carbon cycling at process level and challenge of upscaling local data to global level**
- **Uncertainty associated with estimate of global soil erosion**

# Soil erosion and carbon cycle

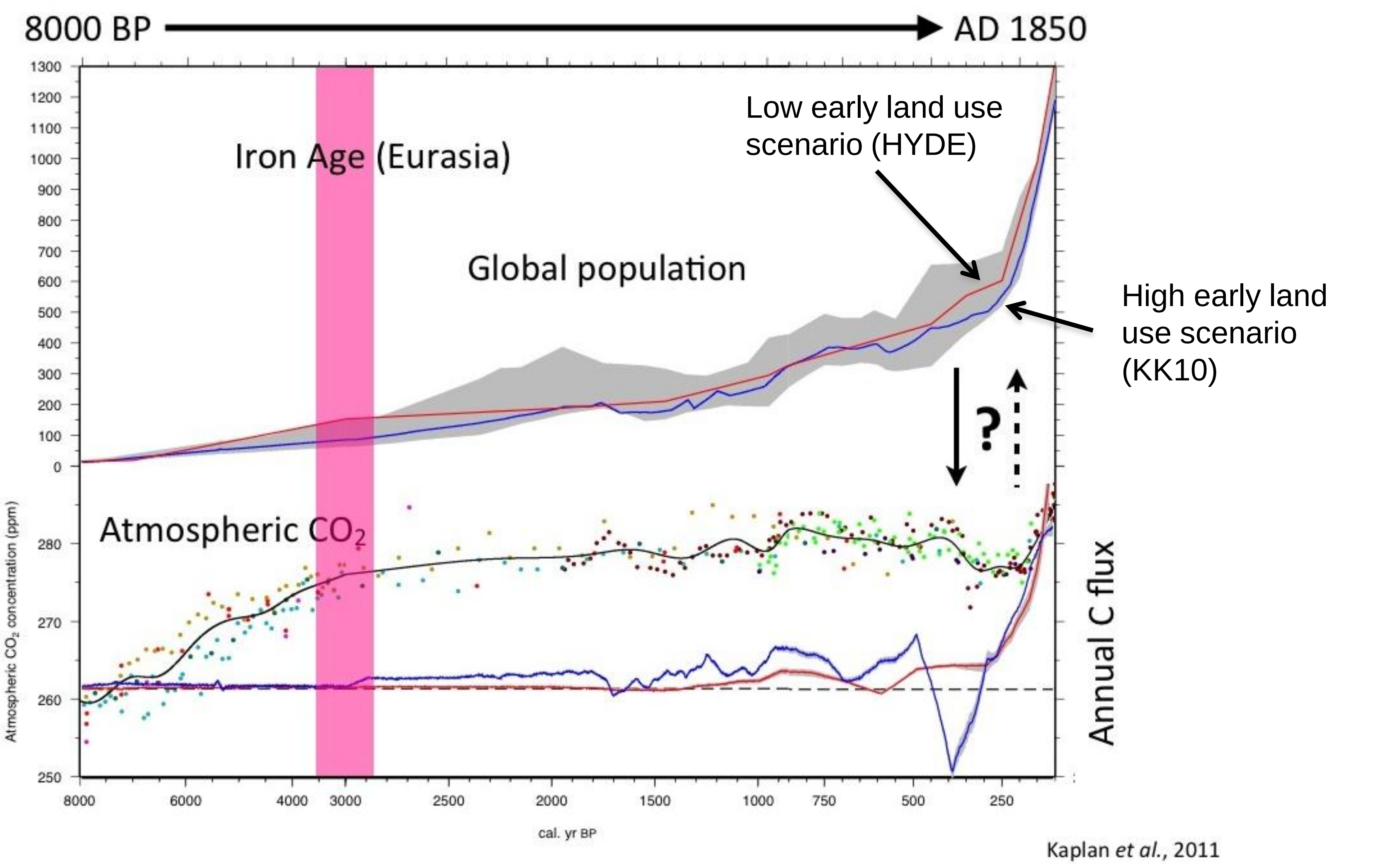
## Importance of *current* soil erosion for the global C cycle




# Holocene soil erosion and carbon cycle

What do we know? What are key model needs?

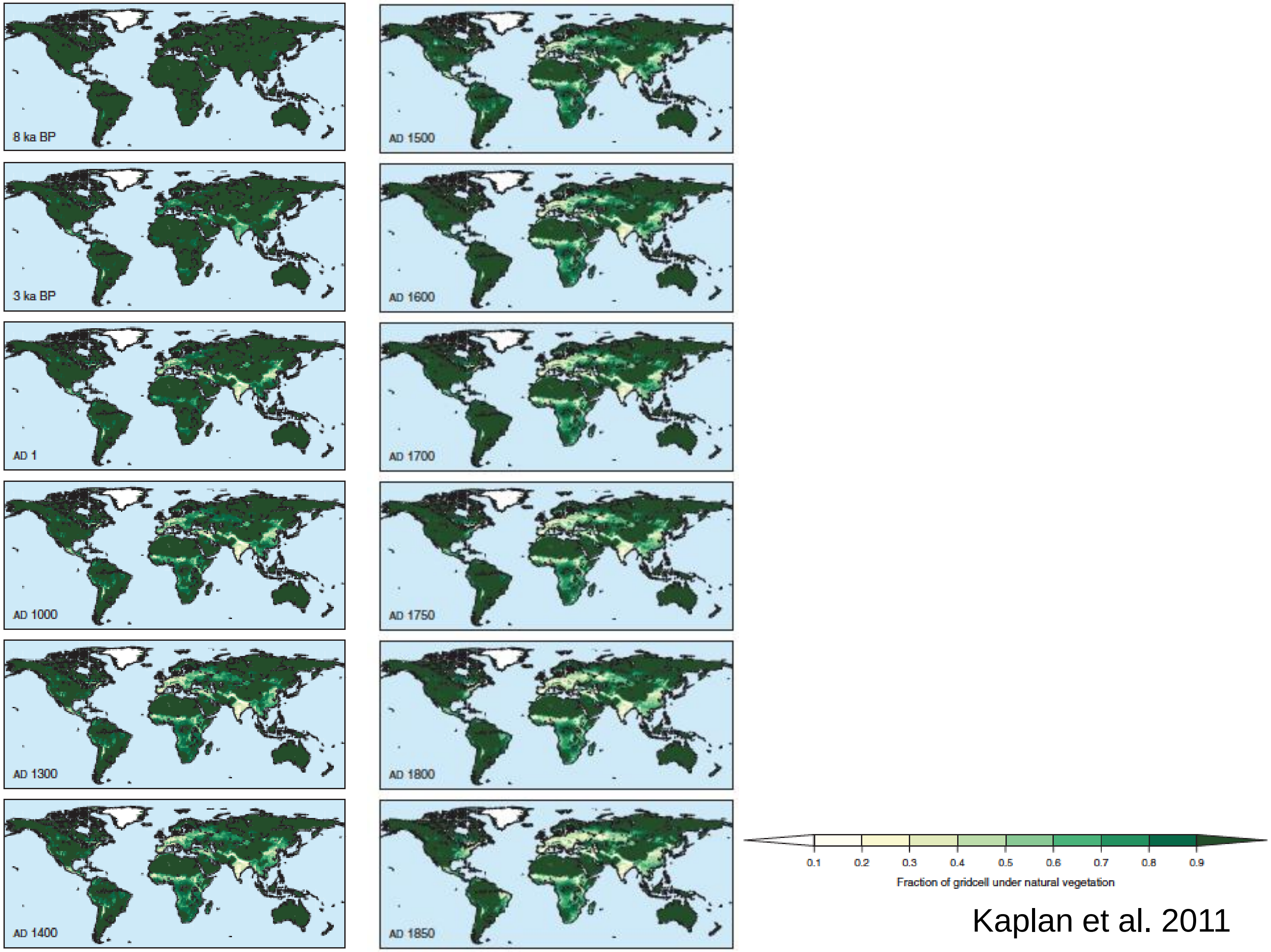
Holocene population and atmospheric CO2



# Holocene soil erosion and carbon cycle

What do we know? What are key model needs?

KK10 Scenario of human-induced land use change

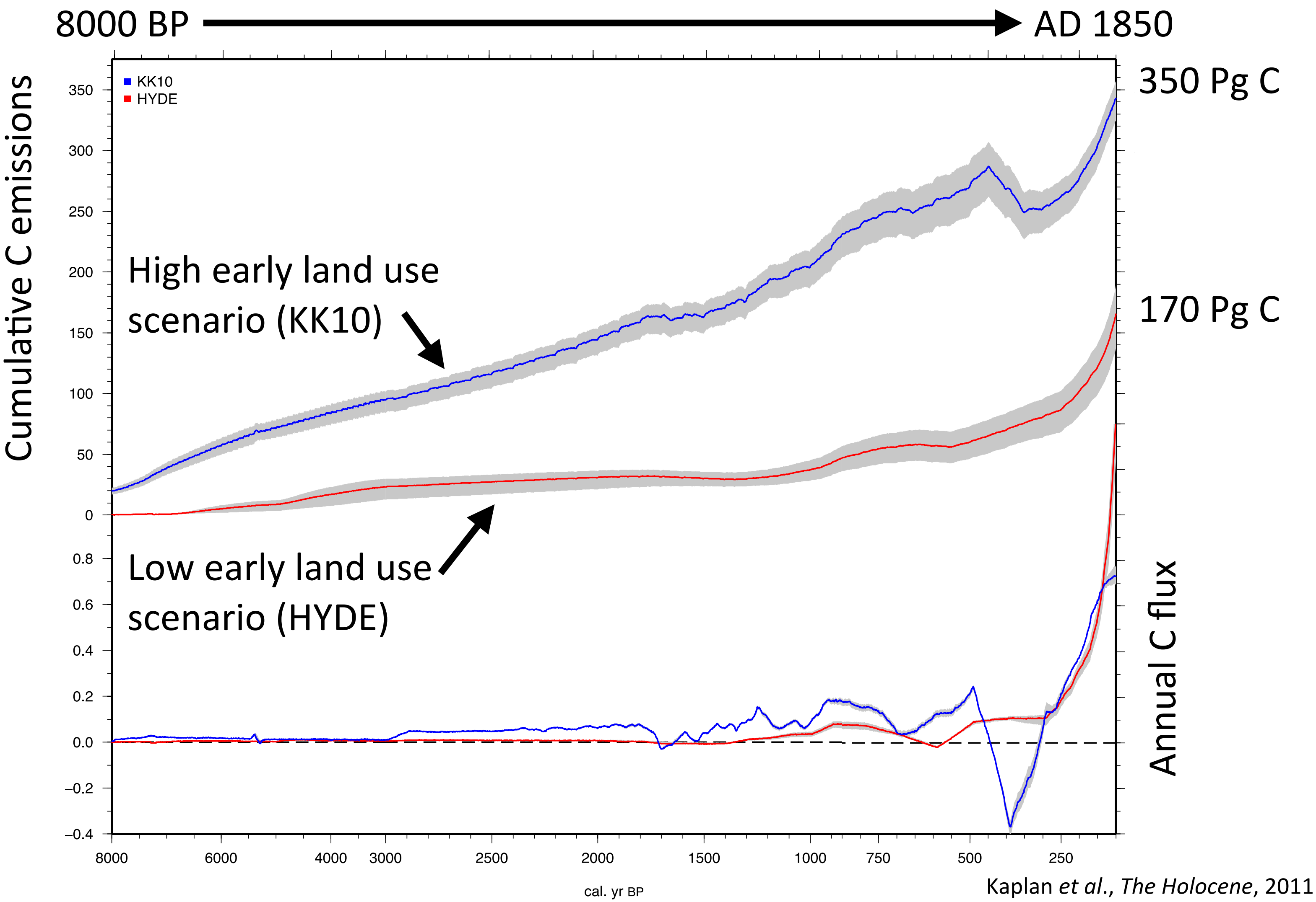



Kaplan et al. 2011

# Holocene soil erosion and carbon cycle

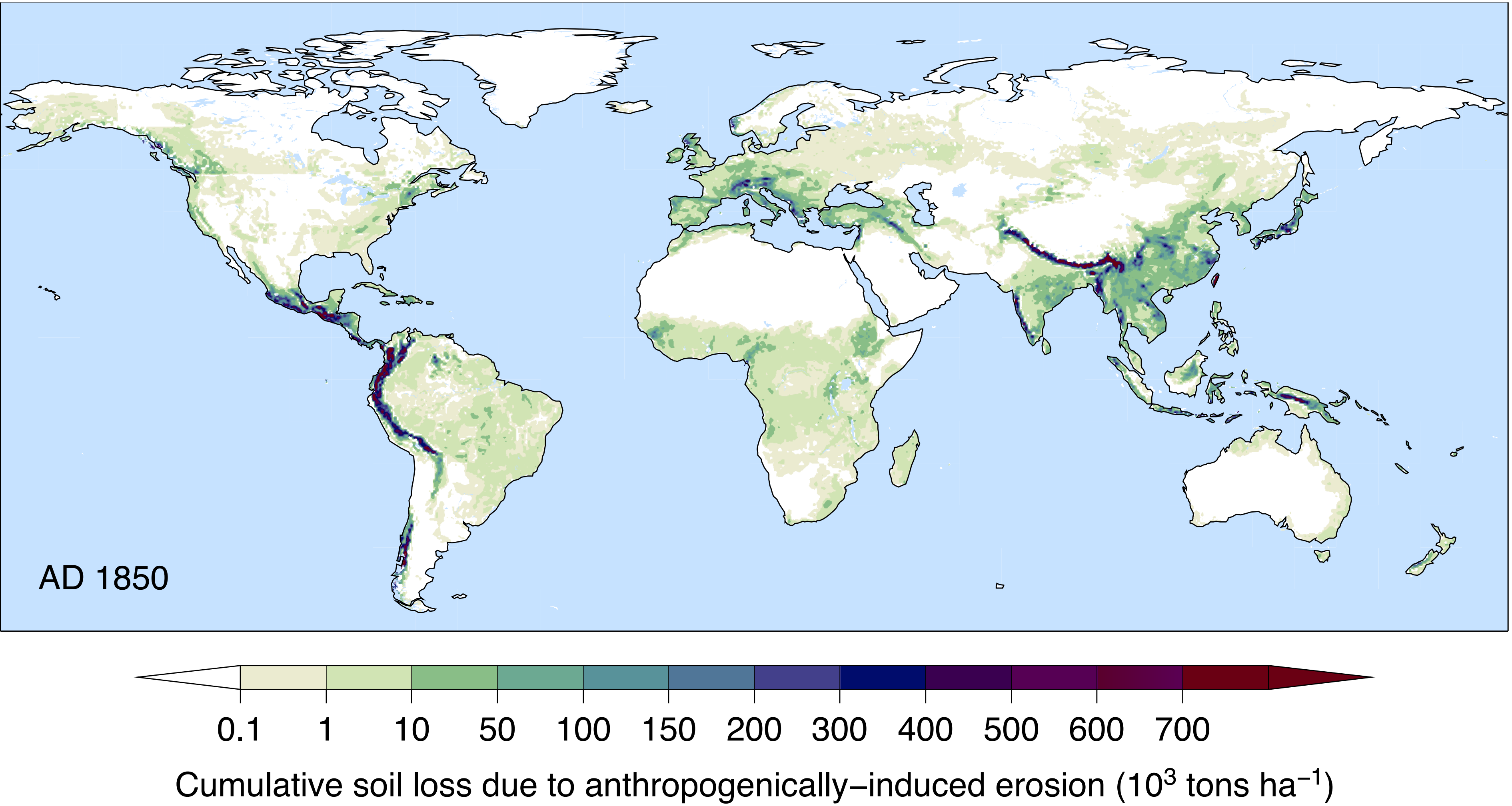
What do we know? What are key model needs?

Carbon emission from land cover change




Kaplan *et al.*, *The Holocene*, 2011

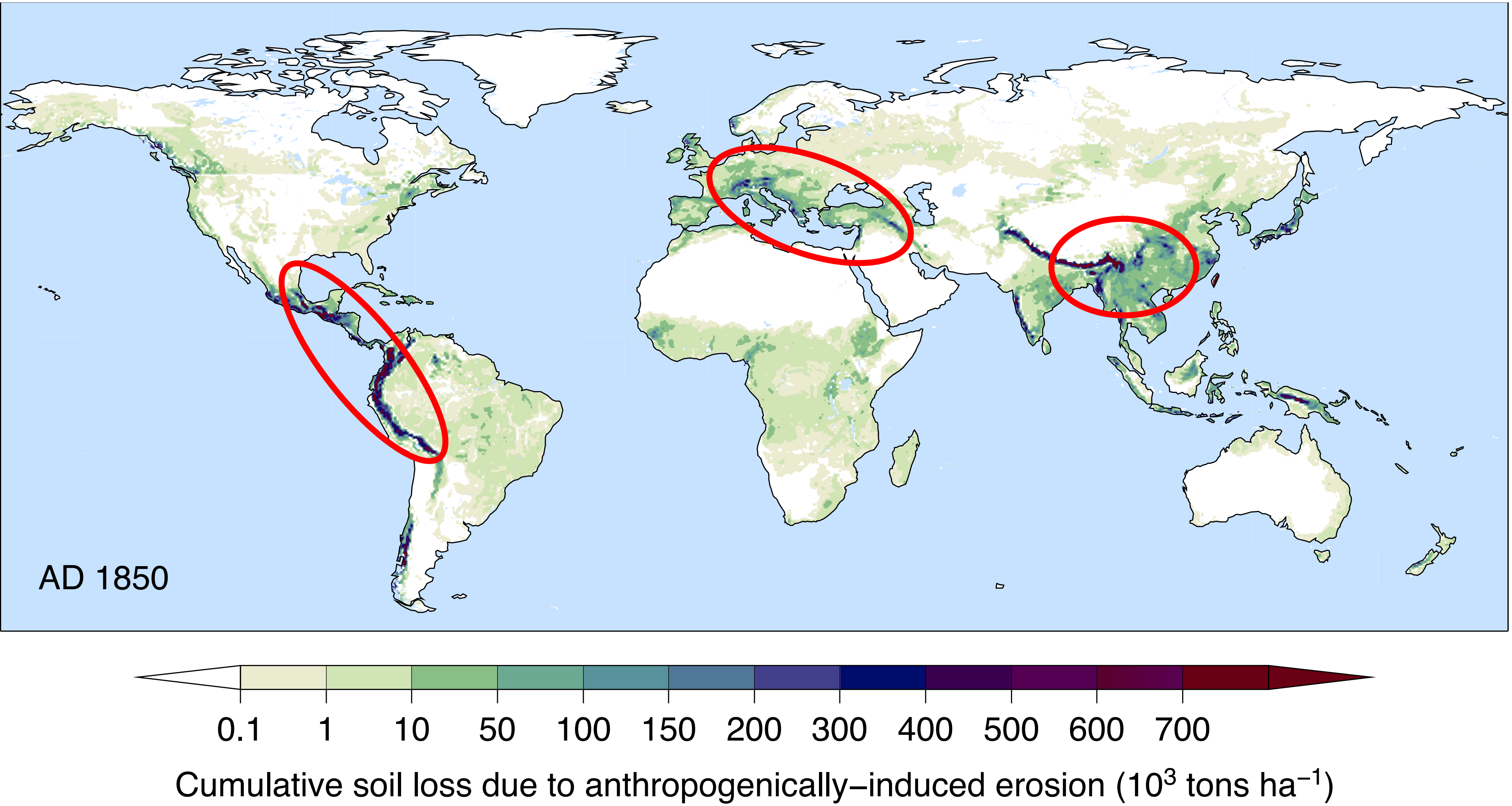
# Cumulative soil erosion at AD 1850




Modelling soil erosion with RUSLE

Kaplan *et al.*, in prep.

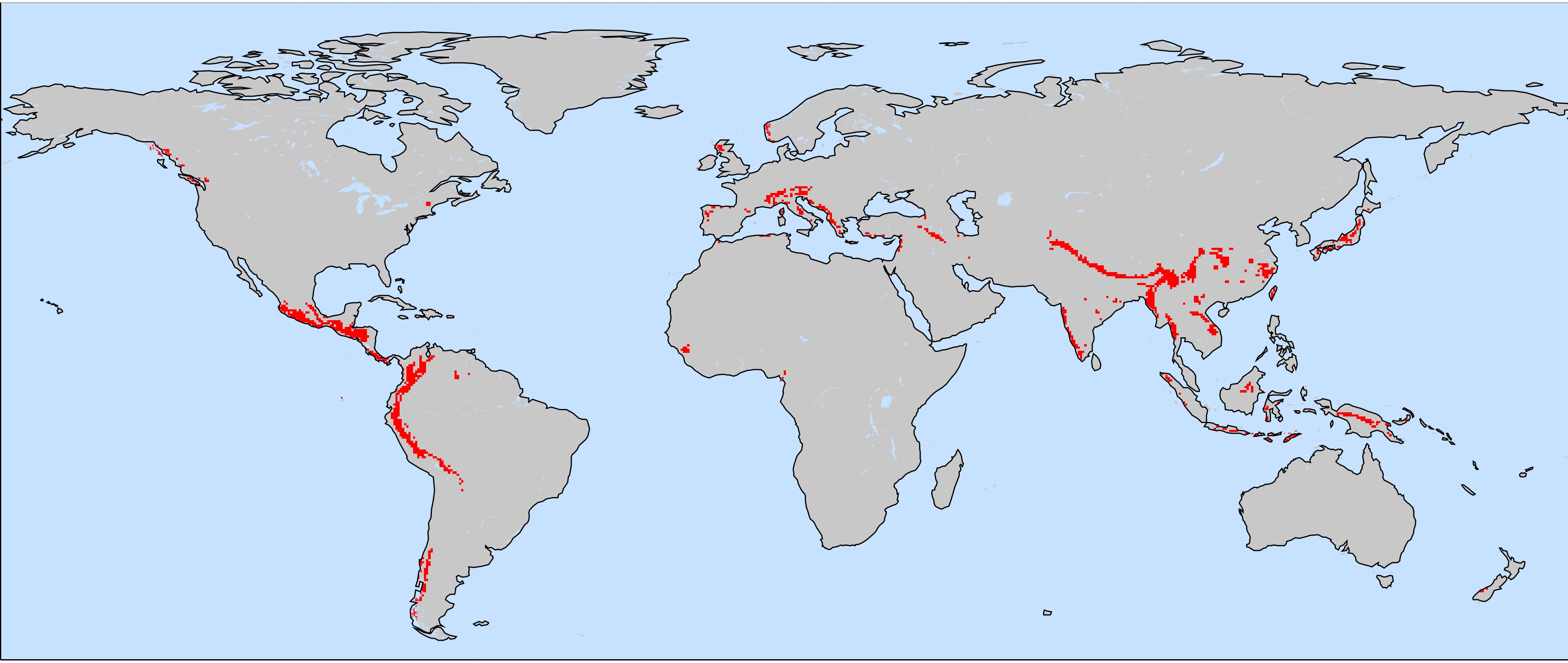
# Cumulative soil erosion at AD 1850




Areas with very long human impact show significant soil degradation

Kaplan *et al.*, in prep.

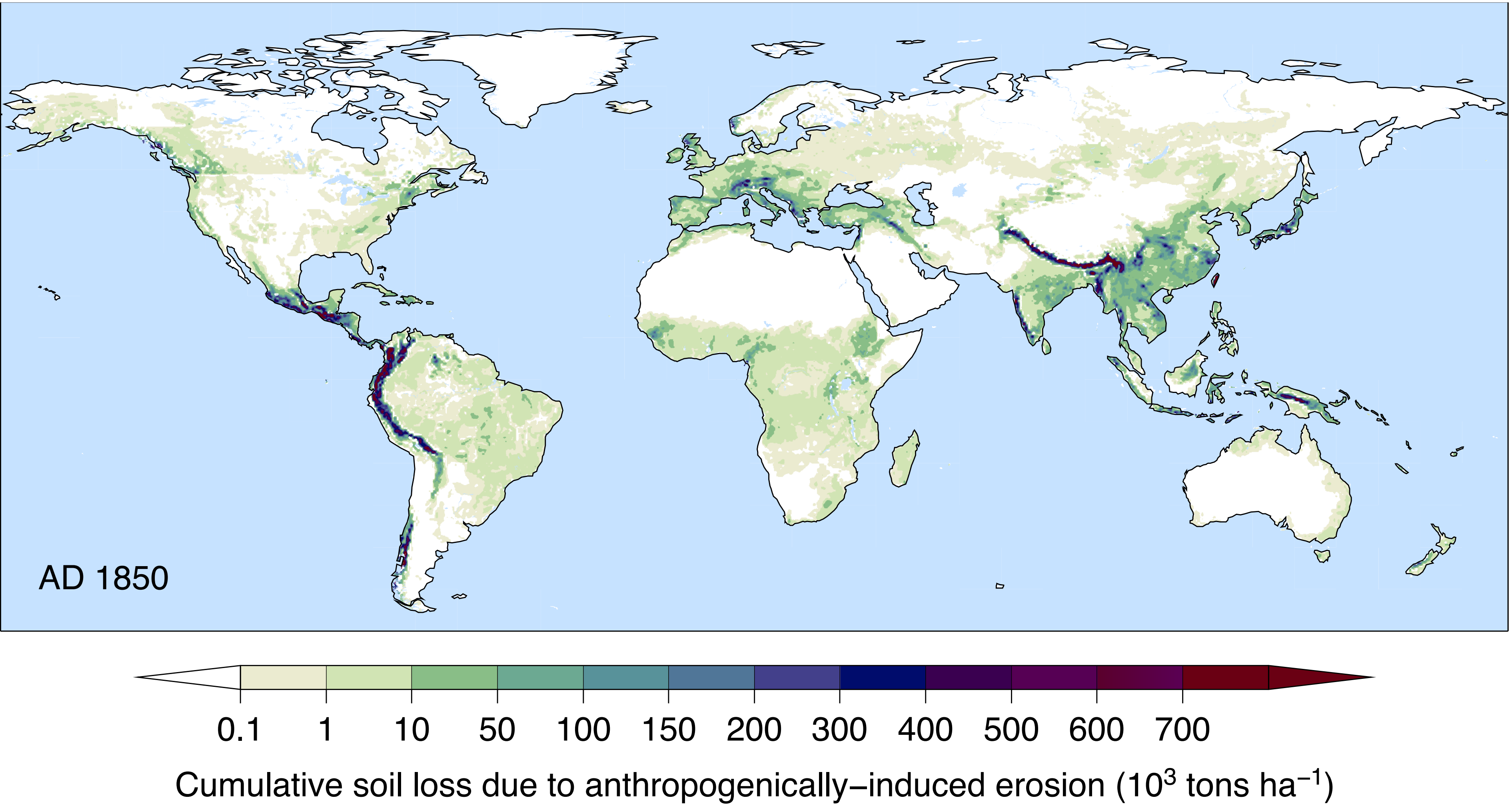
# Irreversibly degraded ecosystems?



Areas with consolidated bedrock and high cumulative erosion (>100kt)

Kaplan *et al.*, in prep.

# Cumulative soil erosion at AD 1850




However…no limit on erosion → overestimation

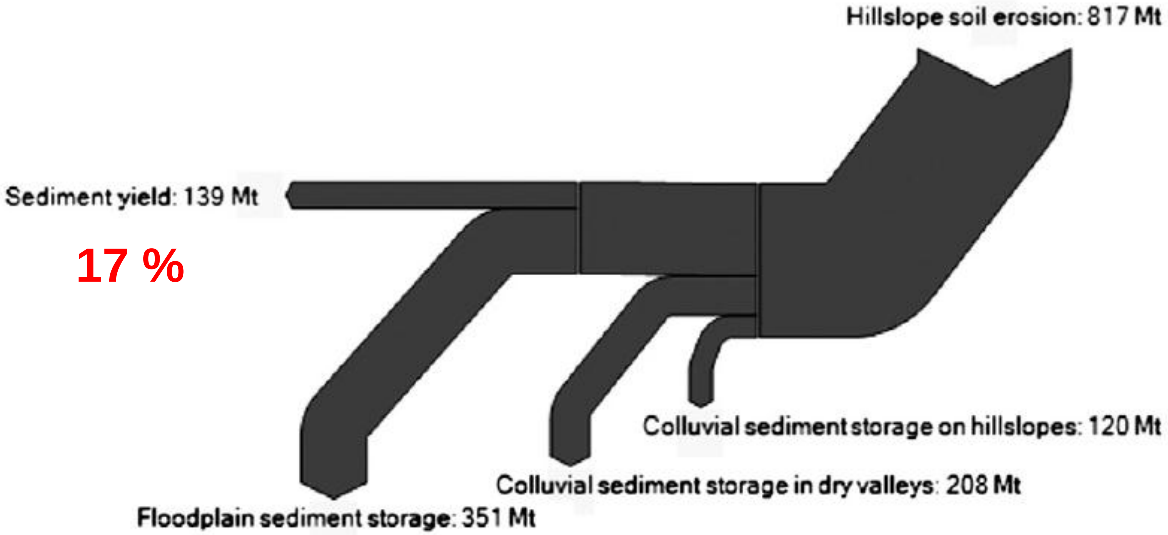
→ how to improve model?

Kaplan *et al.*, in prep.

# Holocene soil erosion

- **Many case studies - regional scale**
- **2 key driving processes:** **1) erosion** **2) deposition**

Holocene sediment budget


**17 %**

**43 %**

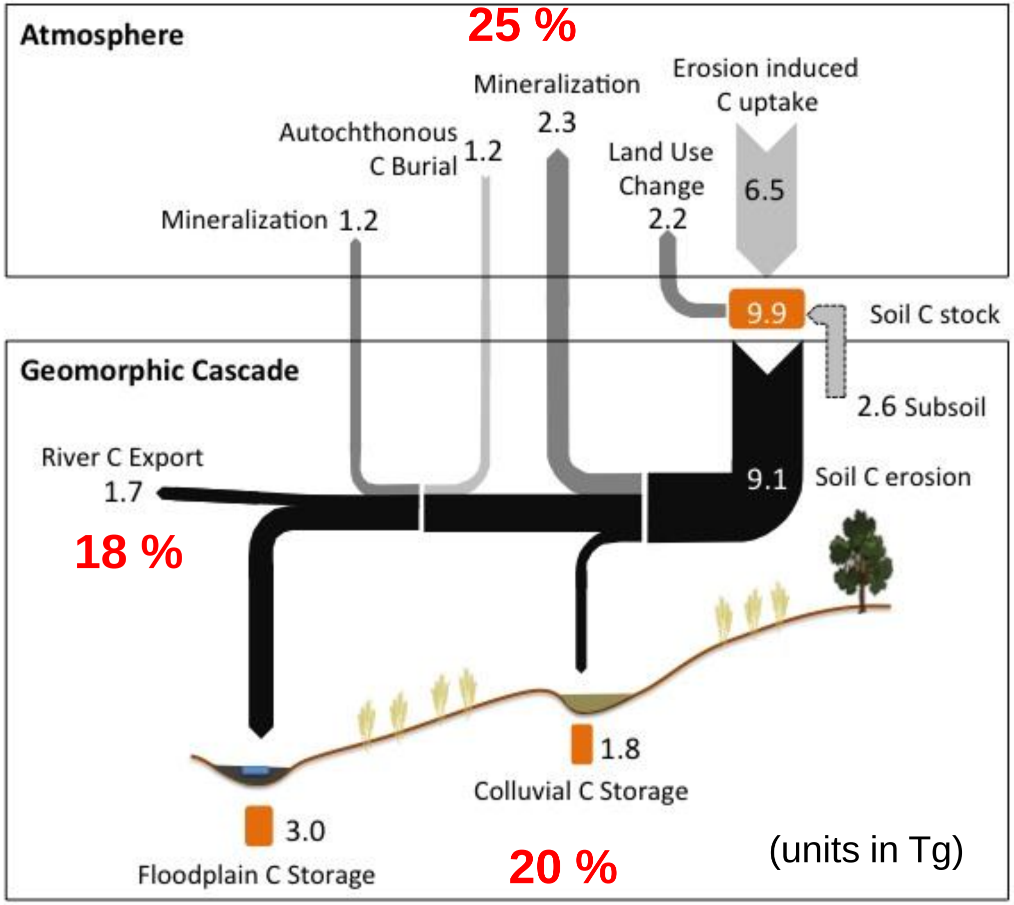
**40 %**

Notebaert et al., 2009. Catena

# Holocene carbon budget

- Many case studies - regional scale
- 2 key driving processes: 1) erosion 2) deposition

photo: Tom Rommens




33 %

Van Oost et al., 2012. PNAS

# Modelling Holocene soil erosion

- **Universal soil loss equation (R)USLE → only part of the story**

USLE = R K LS C P

Rainfall
Soil erodibility
Topography
Land cover
Management practices


- **Deposition: transport capacity**

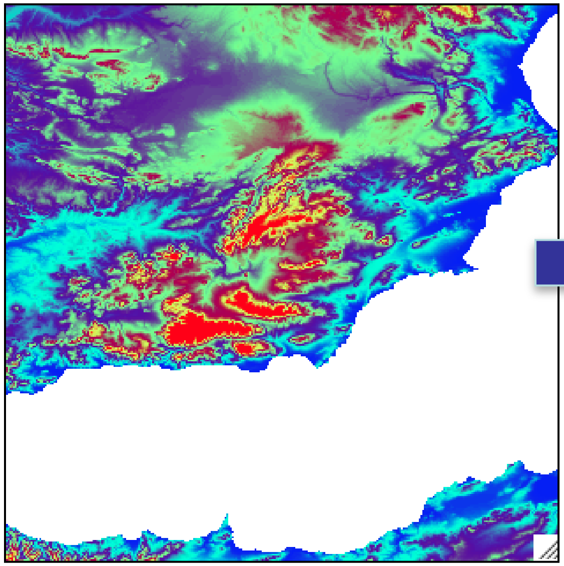
$$TC = \mathrm{ktc}\ R\ K(\mathrm{LS}_{2D} - 4.1 s^{0.8})$$

- **WaTEM/SEDEM model** (Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2002)

# Scaling topographical parameters: methodology

- **Subgrid representation of erosion/deposition processes**

SRTM 5º tile

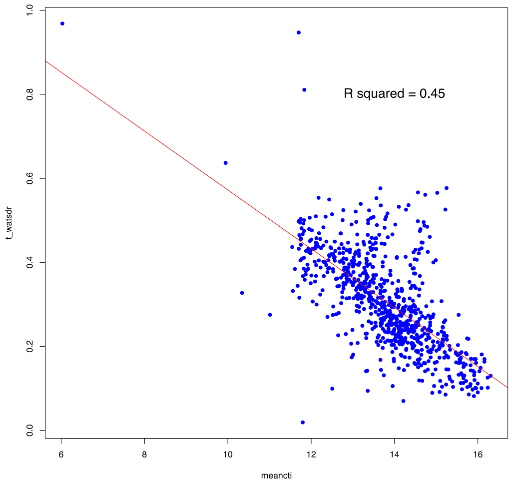


**Detailed subgrid model**

WaTEM/
SEDEM
model

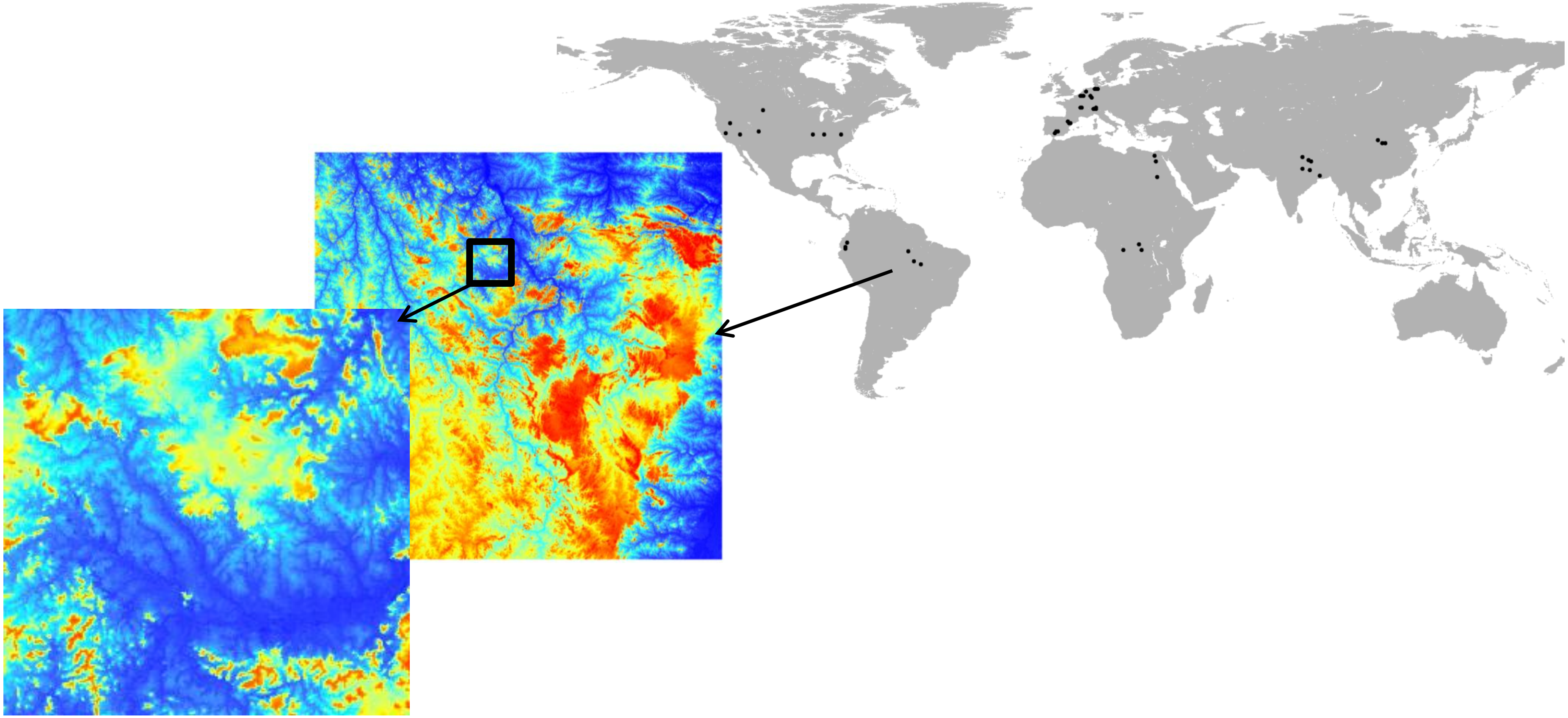
**Generalized model**

Scaling relationships with topographic variables



# Scaling topographical parameters: methodology

- WaTEM/SEDEM: USLE + transport capacity
- 5 land use scenarios: 0 - 25 - 50 - 75 - 100 % cropland (random spatial allocation)
- SRTM: 50 subtiles of 0.5º  (3” resolution)



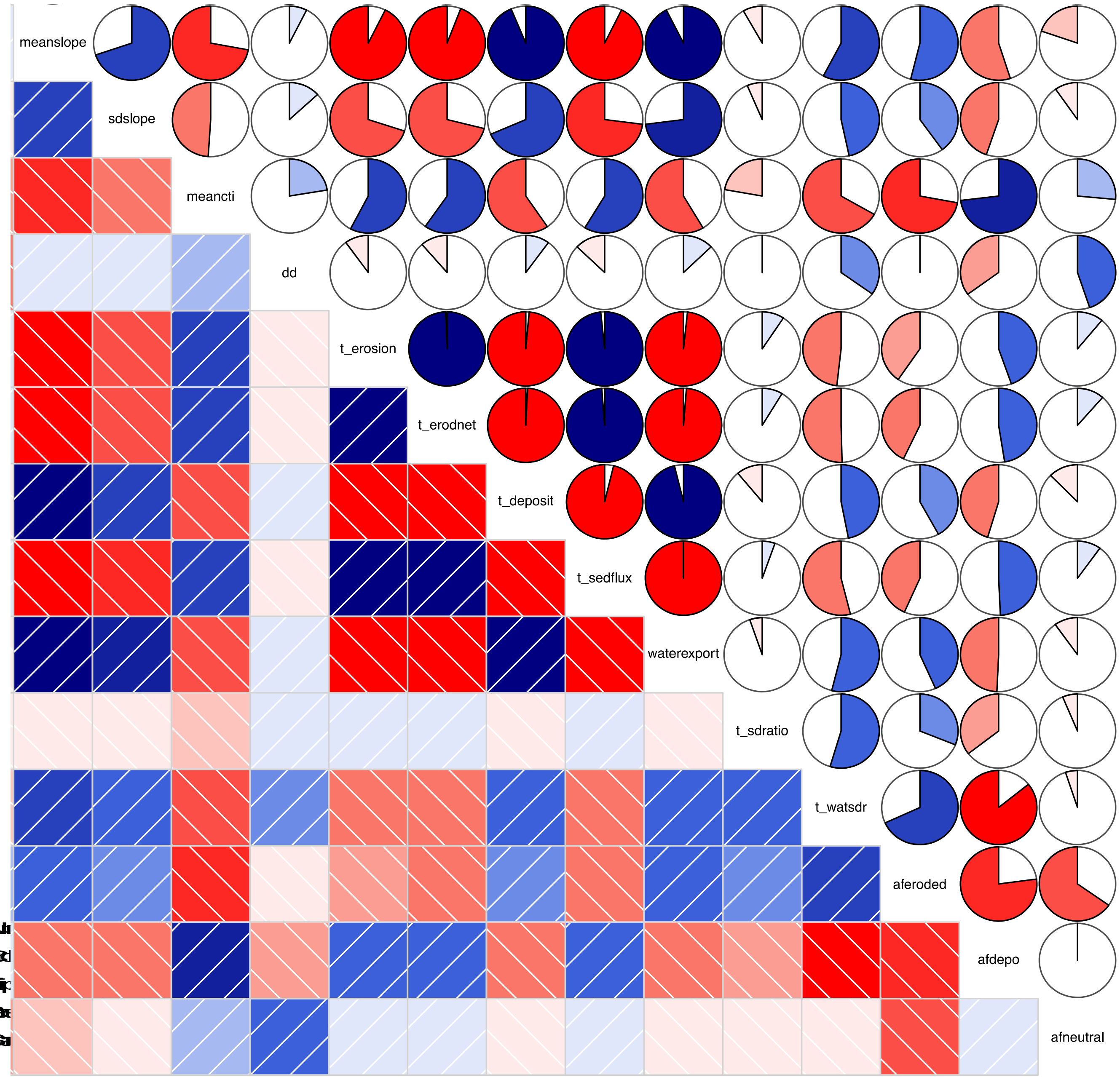
# Scaling topographical parameters

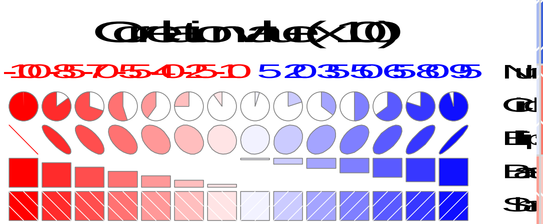
- Variables of interest:
  - Total erosion produced
  - Sediment delivery ratio (SDR)
  - Area affected by erosion/deposition

- Predictor topographic variables:
  - Mean elevation
  - Standard deviation of elevation
  - Mean slope
  - Standard deviation of slope
  - Mean Compound topographic index (CTI)
  - Standard deviation of CTI
  - Drainage density

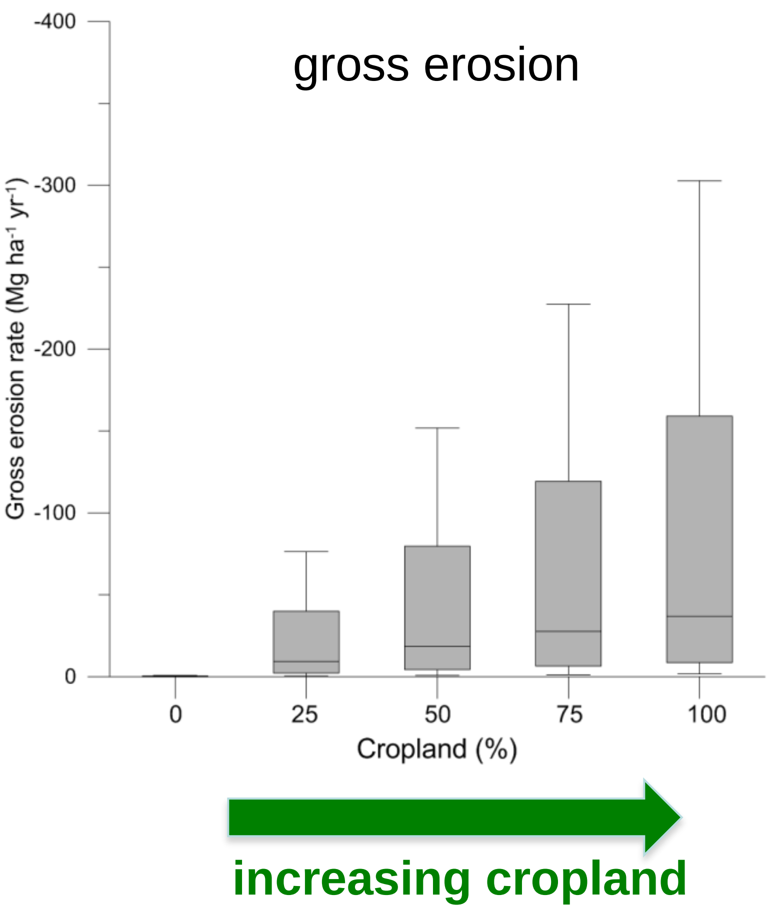
# Results: scaling overview

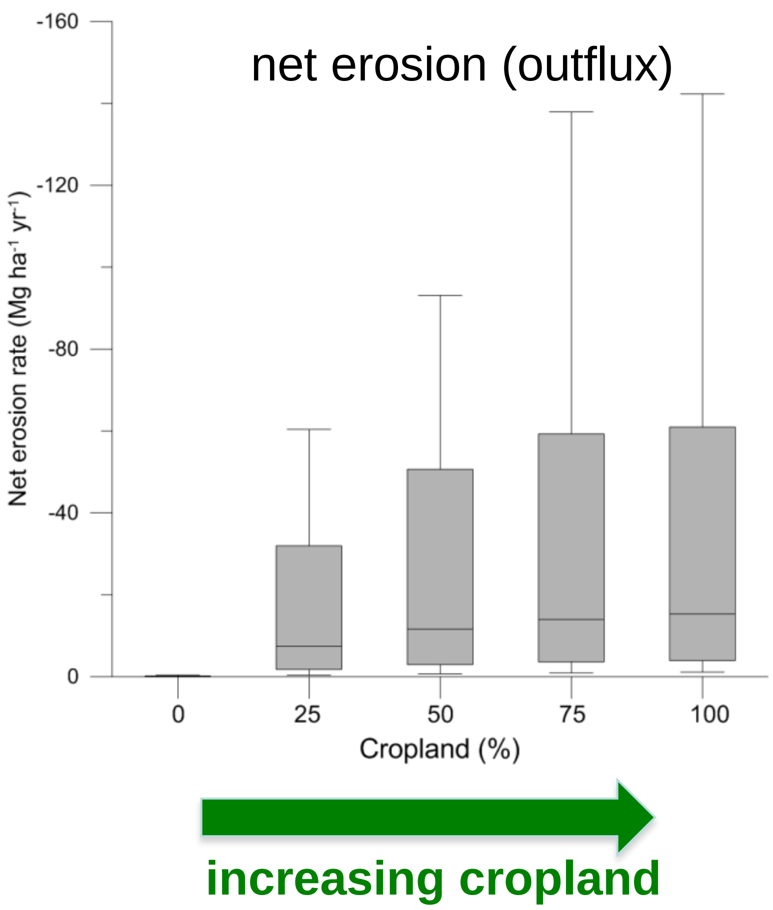
- *Correlogram*



# Results: scaling erosion rates

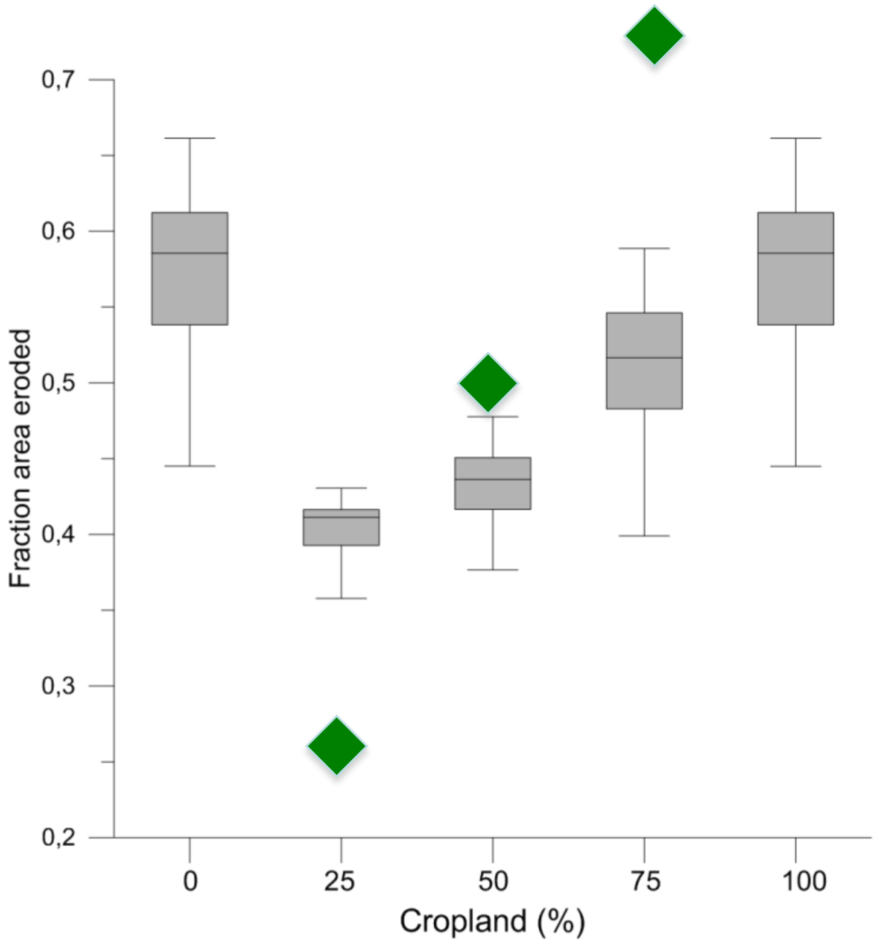


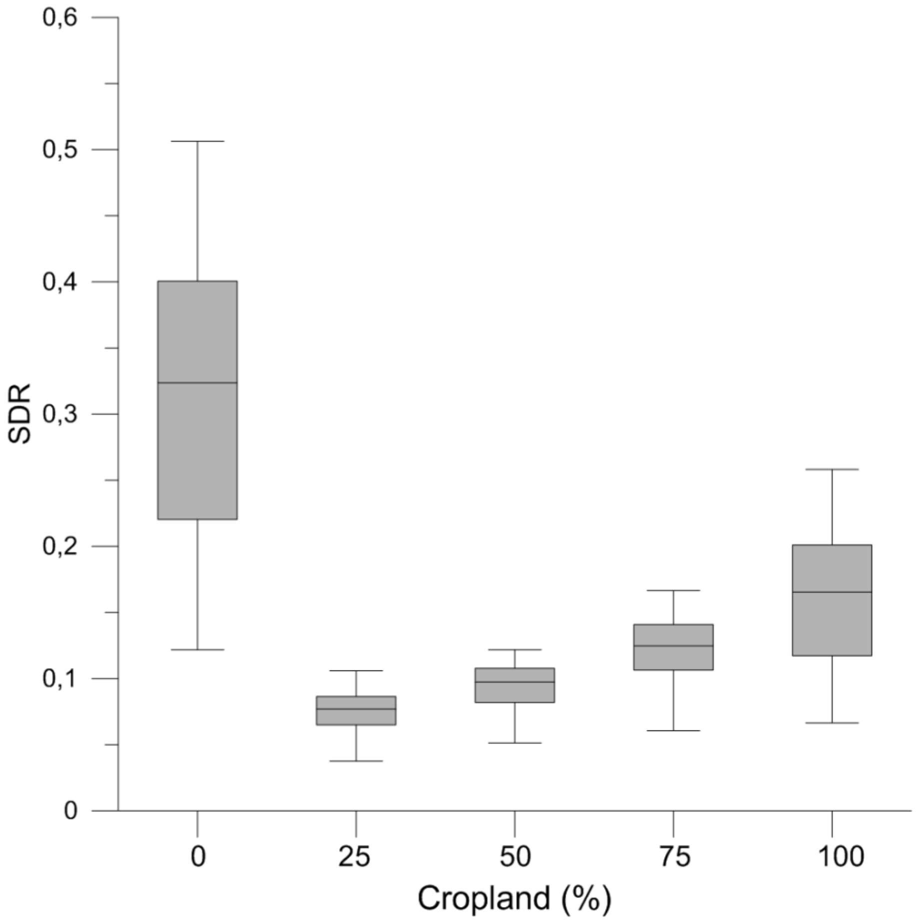

- Indication of levelling off after 75%

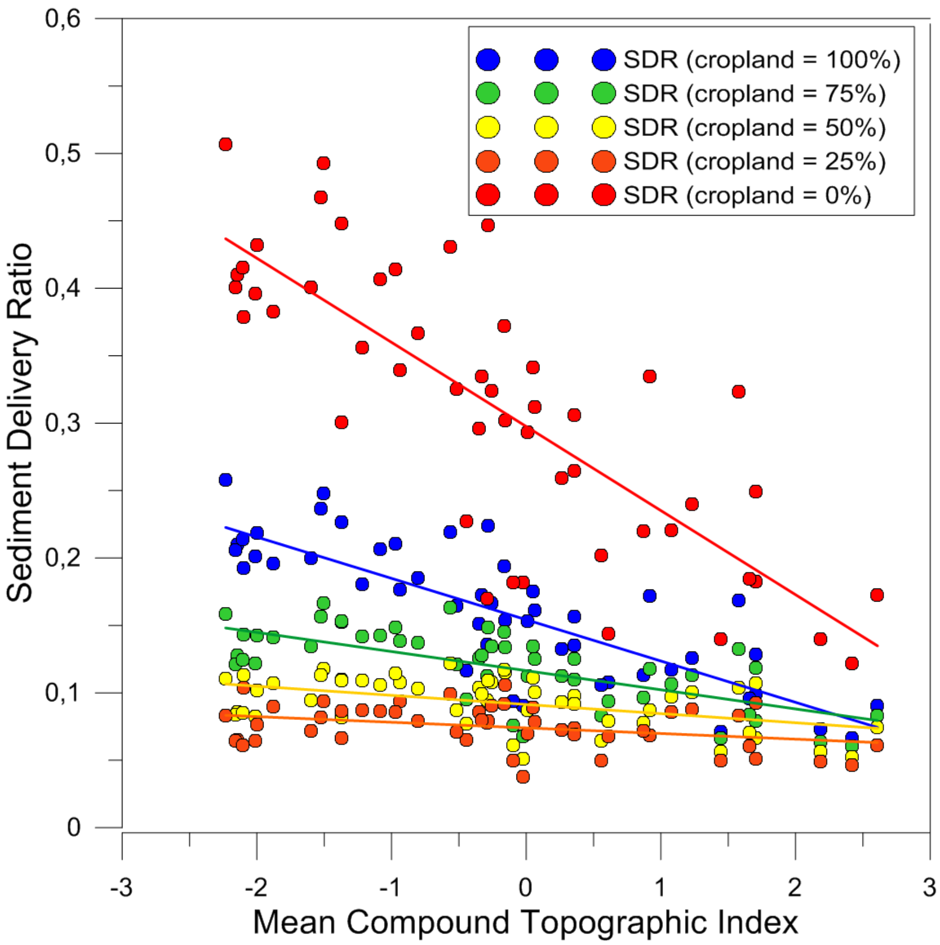
# Results: scaling area fraction eroded

- **Area fraction eroded ≠ cropland fraction**



# Results: scaling sediment delivery

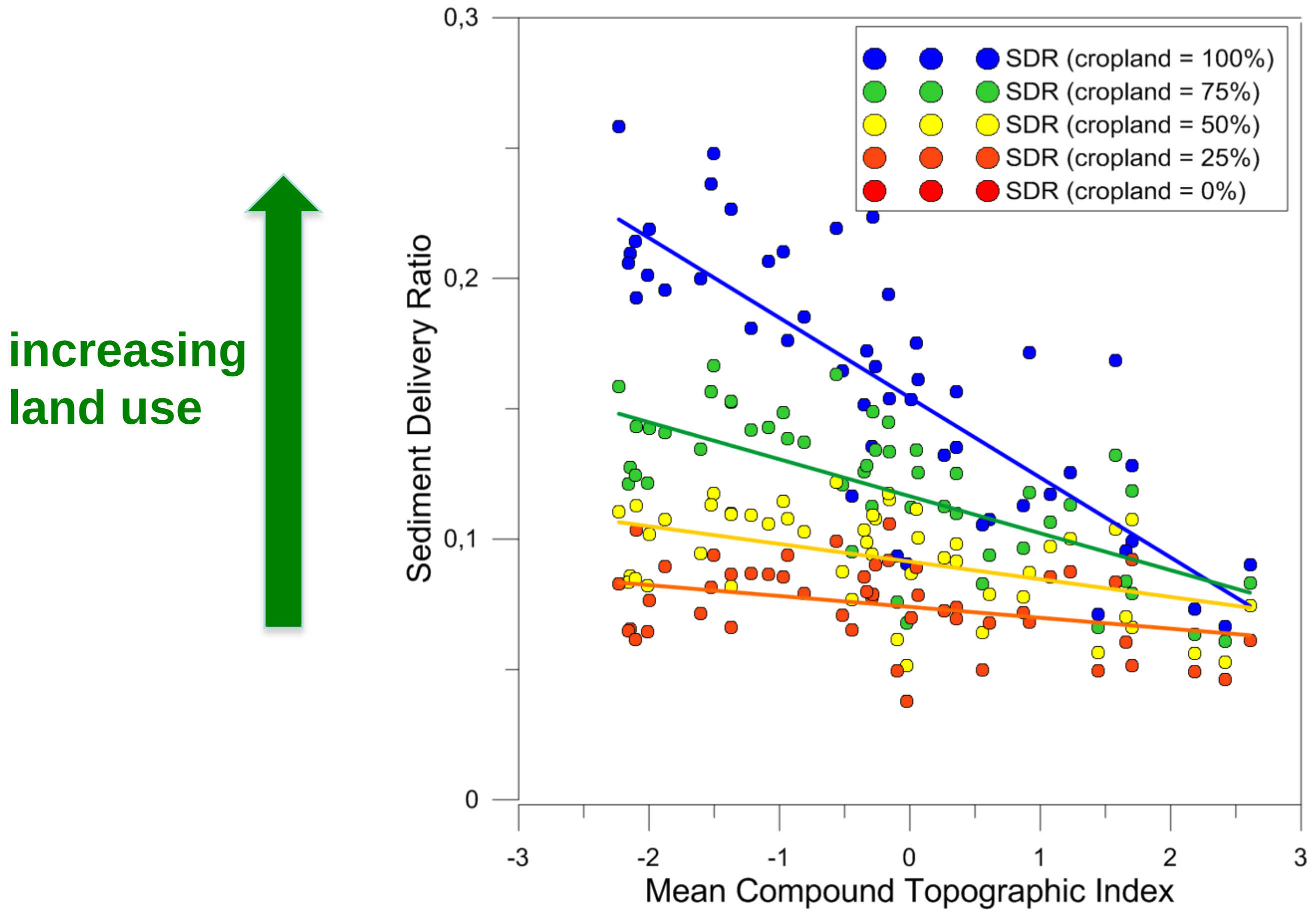


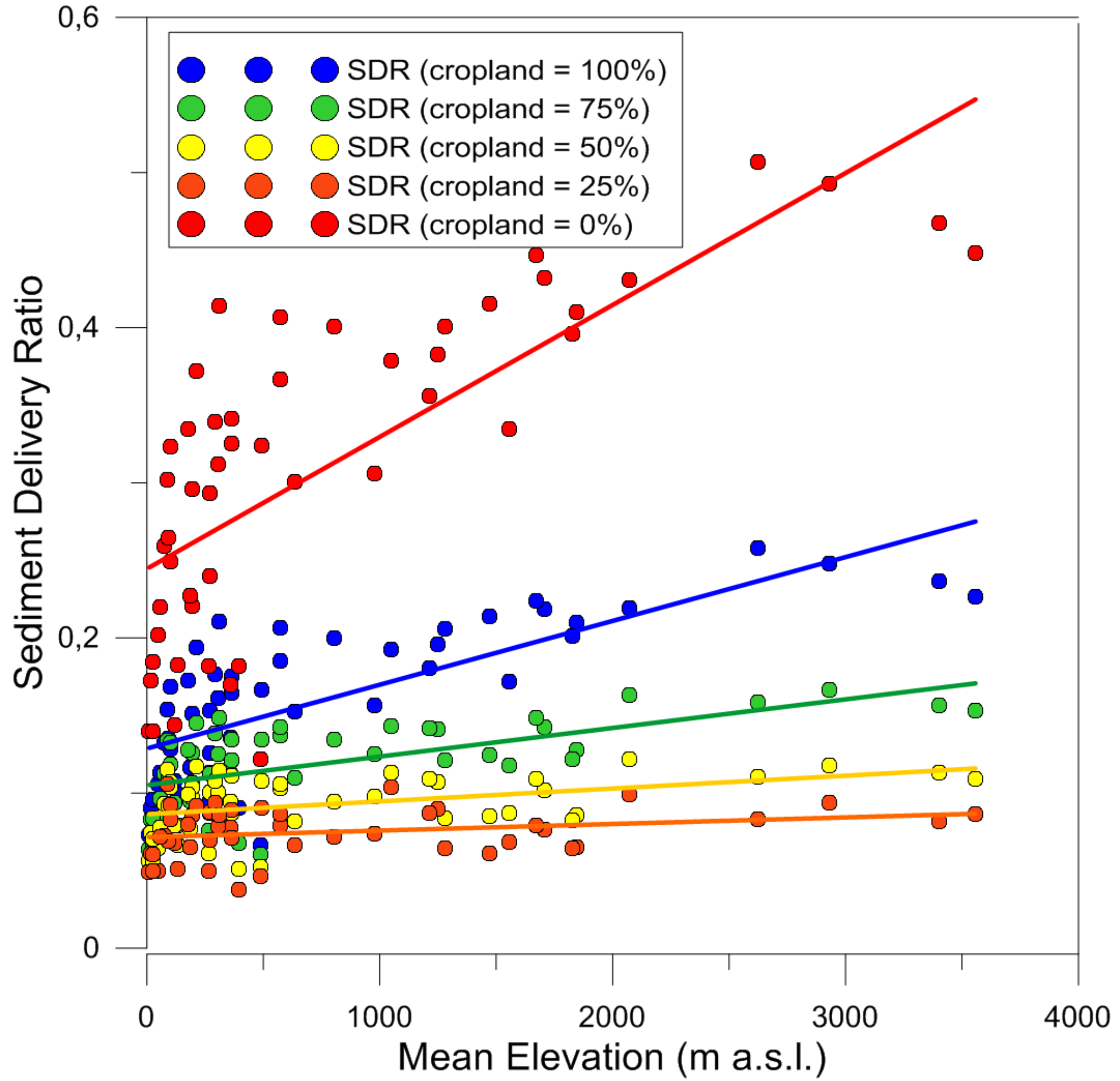

**increasing cropland**

# Results: scaling sediment delivery

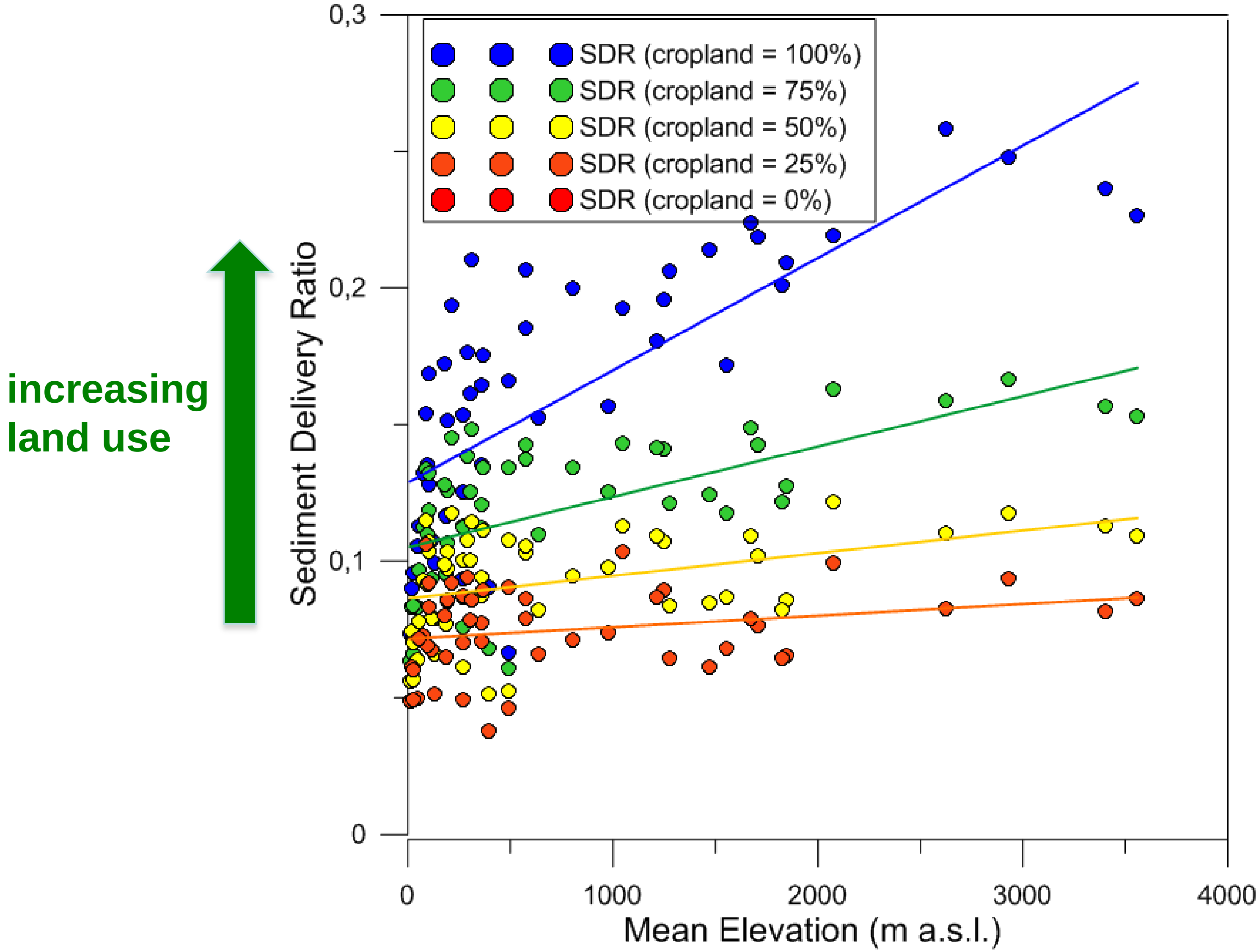
- **Excluding natural areas, where application of USLE is problematic**



# Results: scaling sediment delivery

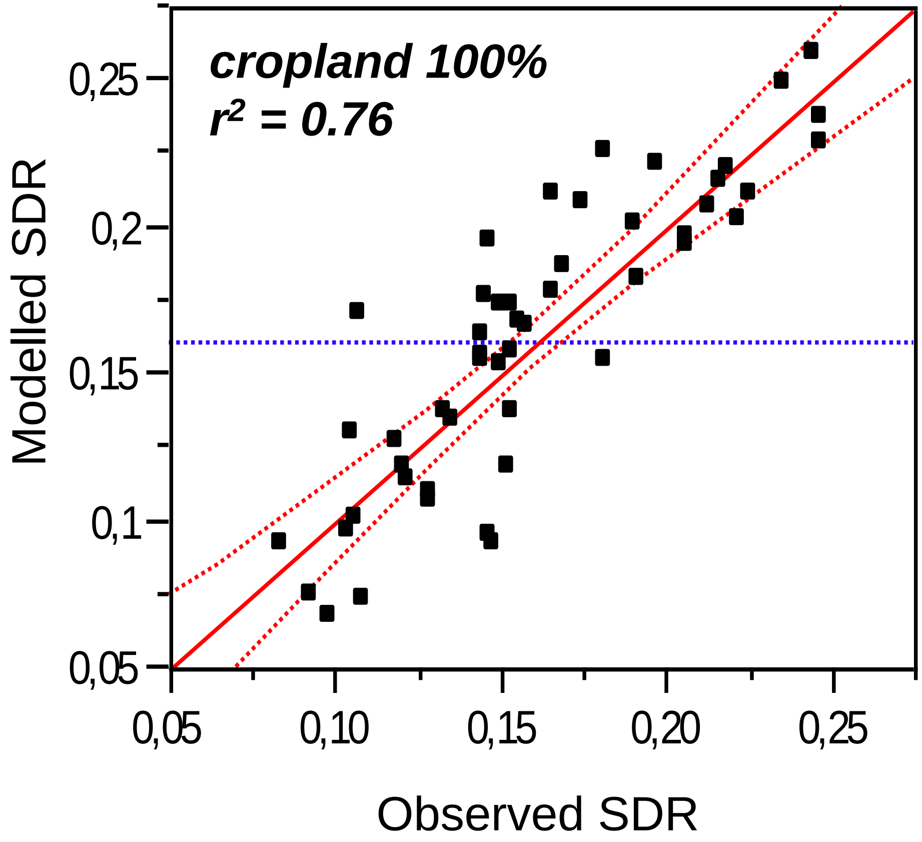


# Results: scaling sediment delivery



# Results: scaling sediment delivery

- **multiple linear regression model**
- **relations are universal, i.e. valid for all land use scenarios, although form and strength of correlation changes slightly**




| Term | Estimate | Std Error | Prob>\|t\| |
|---|---|---|---|
| Intercept | 0.14 | 0.005 | <.0001 |
| Mean Elv | 2.21E-5 | 4.96E-6 | <.0001 |
| Mean CTI | -0.02 | 0.003 | <.0001 |

# Future perspectives and conclusions

- **Erosion and deposition processes can be scaled from easily measurable topographic parameters**
- **Scaling relations appear universal**
- **Erosion and carbon cycle dynamics at the subgrid scale can be adequately represented at the coarse grid scale**
- **Most of the eroded sediment/carbon (>75 %) is redeposited before it reaches the river channels (SDR < 0.25)**
- **Include soil formation model important: feedbacks (e.g. stoniness), properties of sediment**

Guadalquivir estuary, S Spain
NASA. November 12th 2012.

**Tom Vanwalleghem**
Group for Rural Hydrology and Hydraulics
Department of Agronomy
University of Cordoba
Spain

**Jed O. Kaplan**
ARVE Group
Institute for Environmental Engineering
École Polytecnique de Lausanne
Switzerland


# Thanks to

NCAR Advanced Study Program

Ramón y Cajal Fellowship Program

Kristof Van Oost, Samuel Bochoms


**Contact: tom.vanwalleghem@uco.es**