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

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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 $\rightarrow$ 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 global scale and a Holocene timescale?

Static or dynamic soils?

Shallow marls, S Spain

Loess soil profile (INRA, France)
Relating soil profiles and erosion

- **Static versus Dynamic soil properties**

  Dynamic soil properties
  
  Eg. pH
  
  Time
  
  pH in reforested cropland (Bossuyt et al., 2002)
  
  Static soil properties
  
  Eg. Soil depth
  
  DISTURBANCE
  
  Time
Relating soil profiles and erosion

- **Static versus Dynamic soil properties**

  - Dynamic soil properties
    - Eg. pH
    - Time
    - DISTURBANCE

  - Static soil properties
    - Eg. Soil depth
    - Time
    - DISTURBANCE

  pH in reforested cropland (Bossuyt et al., 2002)

  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)

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

Vanwallegem et al. 2013. JGR-ES
Soil thickness, integrating soil formation and soil erosion

Constant moderate erosion rate, followed by 10ka high erosion rate:

Vanwalleghem et al., 2013. JGR
Erosion effect on texture

Scenario with constant moderate erosion rate:

steady-state

erosive

Vanwalleghem et al., 2013. JGR
Model for Integrating Landscape and Soil Development

- Soil organic carbon, integrating soil formation and soil erosion

Constant moderate erosion rate, followed by 10ka high erosion rate:

steady-state erosive

hillslope deposition valley-bottom deposition
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

Cerdan y col., 2010. Geomorphology

Table 5

<table>
<thead>
<tr>
<th>Land use</th>
<th>Database entries*</th>
<th>Plot-months</th>
<th>Mean (t ha⁻¹ year⁻¹)</th>
<th>Std. I</th>
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<tbody>
<tr>
<td>Bare</td>
<td>62</td>
<td>7599</td>
<td>17.12</td>
<td>30.21</td>
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<tr>
<td>Arable</td>
<td>7</td>
<td>6635</td>
<td>6.33</td>
<td>13.46</td>
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<td>Forest</td>
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<td>Grassland</td>
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<td>1.15</td>
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<td>Shrub</td>
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<tr>
<td>Vineyard</td>
<td>4</td>
<td>144</td>
<td>23.64</td>
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<tr>
<td>Orchard</td>
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<td>408</td>
<td>20.6</td>
<td>19.4</td>
</tr>
</tbody>
</table>

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

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

1. EROSION
   - C Input
     - NPP
     - Soil thickness
   - C Decomposition
     - less C available

2. TRANSPORT
   - C Decomposition
     + enhanced disturbance

3. DEPOSITION
   - C Input
     + NPP
     + Soil thickness
   - C Decomposition
     + more C available
     - anoxic – suboxic
     - Physical protection
     - Chemical protection

Adapted from Van Oost, 2007
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

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)
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Soil erosion and carbon cycle

Importance of current soil erosion for the global C cycle

Agricultural C erosion (Mg C ha\(^{-1}\) year\(^{-1}\))
Holocene soil erosion and carbon cycle

What do we know? What are key model needs?

Holocene population and atmospheric CO2

8000 BP → AD 1850

Iron Age (Eurasia)

Global population

Atmospheric CO₂

Low early land use scenario (HYDE)

High early land use scenario (KK10)

Annual C flux

Kaplan et al., 2011
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
What do we know? What are key model needs?
Carbon emission from land cover change

Holocene soil erosion and carbon cycle

8000 BP --- AD 1850

Cumulative C emissions

High early land use scenario (KK10)

Low early land use scenario (HYDE)

350 Pg C

170 Pg C

Annual C flux

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 $\rightarrow$ overestimation
$\rightarrow$ 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

Notebaert et al., 2009. Catena
Many case studies - regional scale

2 key driving processes:  
1) erosion  
2) deposition

Holocene carbon budget

Van Oost et al., 2012. PNAS
Modelling Holocene soil erosion

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

\[ \text{USLE} = R \times K \times L \times S \times C \times P \]

- Deposition: transport capacity

\[ \text{TC} = ktc \times R \times K (L \times S_{2D} - 4.1s^{0.8}) \]

- 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 5° 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 0.5° (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

- Gross erosion
- Net erosion (outflux)

**Increasing cropland**

- Indication of levelling off after 75%
Results: scaling area fraction eroded

- Area fraction eroded ≠ cropland fraction
Results: scaling sediment delivery
Excluding natural areas, where application of USLE is problematic
Results: scaling sediment delivery
Results: scaling sediment delivery

increasing land use
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

![Graph showing observed vs. modeled SDR for cropland 100%, with $r^2 = 0.76$]

| 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 |
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.
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