Spatial Distribution and Temporal Dynamics of Soil Carbon Removal Caused by Water Erosion in China

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Abstract: Using water erosion data from three national soil erosion remote-sensing surveys (the first: 1985–1986; the second: 1995–1996; the third: 2000–2001) and carbon density data from the second national soil survey (1979–1992), we computed soil carbon removal caused by water erosion, and analyzed its spatial distribution and temporal dynamics in China. Results revealed that the total removal of soil carbon caused by water erosion was about 74.61 Tg C y⁻¹, of which 51.49 Tg C y⁻¹ was organic carbon, and 23.12 Tg C y⁻¹ was inorganic carbon. The main erosion level of the whole is moderate erosion. Among the seven erosion regions, the Southwest Karst Region had the most significant removal of soil organic carbon, which was 26.48% of the total and mainly due to its moderate erosion. In contrast, about 67.62% of the soil inorganic carbon removal occurred in the Loess Plateau Region, which mainly due to its highly intense and intense erosion. As a whole, the removals of soil carbon caused by water erosion represented a decreasing trend among the three national soil erosion remote-sensing surveys. Between the first and the second survey, soil carbon removal decreased by 11.66 Tg C y⁻¹, of which 81.93% was organic carbon. Compared with that in the second survey, soil carbon removal decreased by 1.65 Tg C y⁻¹ in the third survey, of which 1.514 Tg C y⁻¹ was organic carbon, and 0.134 Tg C y⁻¹ was inorganic carbon.

Key words: China; water erosion; soil organic carbon; soil inorganic carbon; soil erosion regions

1 Introduction

Soil is the largest carbon pool in the global terrestrial ecosystems, of which slight change will result in atmosphere CO₂ increasing sharply. Batjes (1996) estimated that 2157–2296 Pg C was stored in the upper 1 meter of global soil, of which 1462–1548 Pg C was organic carbon, and 695–748 Pg C was in the form of carbonate-C. However, due to lacking of soil organic carbon (SOC) data in many regions (Yu et al. 2007), estimates of global SOC stock by different researchers were rather distinct, which ranged from 1220 Pg to 1576 Pg in the 1 m soil depth (Sombroek et al. 1993; Eswaran et al. 1993). Reserves of SOC in China were estimated to be 100.2 Pg with an average soil depth of 79 cm (Wang and Zhou 1999), 92.4±18.7 Pg with an average soil depth of 87 cm (Zhou et al. 2003), 185.7 Pg with an average soil depth of 86.2 cm (Fang et al. 1996), 82.5±19.5 Pg (Wang et al. 2004) or 89.14 Pg (Yu et al. 2005) both with an soil depth of 1 m, respectively. Stocks of soil inorganic carbon (SIC) in China were estimated to be 47.1±3.3 Pg in the upper 1 meter of soil, and 53.3±6.3 Pg in the upper 2 meter of soil (Mi et al. 2008). The above-mentioned results of soil carbon stock in China also included uncertainties owing to different data sources and methods.

Erosion is one of soil processes that can remove large quantities of stable SOC (Starr et al. 2000), and also is the main process of removing SIC. Investigations had found that the global water erosion area was about 1094×10⁶ km², of which 751×10⁶ km² was severely affected, and wind erosion area was 549×10⁶ km², of which 296×10⁶ km² was severely affected (Oldeman 1994; Lal 2003). All over the world, the removal of SOC caused by wind erosion was about 1.4 Pg y⁻¹ (Smith et al. 2001; Yan et
al. 2005); and by water erosion was about 4.0–6.0 Pg y$^{-1}$, of which 2.8–4.2 Pg C y$^{-1}$ was redistributed over the landscape, 0.4–0.6 Pg C y$^{-1}$ was transported to oceans and 0.8–1.2 Pg C y$^{-1}$ was released into atmosphere (Lal 2003). In China, areas influenced by water and wind erosions were about 209.5×10$^3$ km$^2$ and 149.4×10$^3$ km$^2$, respectively (Van Lynden and Oldeman 1997), and the sum of both represented about 22% of the world. SOC removal caused by wind erosion in northern China is between 59.76 Tg C y$^{-1}$ (Hu et al. 2004) and 75 Tg C y$^{-1}$ (Yan et al. 2005), especially, by dust storm erosion (the average of topsoil loss is 0.2–1 cm per storm event, even reach to 10 cm when very heavy storms happen) is about 53–1044 kg ha$^{-1}$ in the 1 cm top layer of soils (Lian 2002; Wang et al. 2006). However, prior researches are not yet enough, especially about the spatial distribution and temporal dynamics of soil carbon removal.

In the global carbon cycle, unbalance exists between carbon sinks and sources which partly due to the role of land use and soil erosion not being considered sufficiently. Therefore, there is a need to study the influence of soil erosion on soil carbon stock. This paper focuses on the spatial distribution and temporal dynamics of water-eroded soil carbon in China, which can further provide basic information to the regional and global carbon cycle. Our objectives are (i) to evaluate soil carbon removal caused by water erosion in seven soil erosion regions of China (MWR et al. 2010b), and (ii) to analyze the temporal dynamics of water-eroded soil carbon among the three national soil erosion remote-sensing surveys.

2 Data sources and methods

Data used in this paper include: (i) a regionalization map of soil erosion in China (provided by Professor Tang, Fig. 1) which contains seven soil erosion regions and its divided standards are these differences of nature, social economy, and soil erosion (MWR et al. 2010b); (ii) spatial data of water erosion from the second national soil erosion remote-sensing surveys in this paper, and then are zoned into the seven erosion regions for further analyze. While, the spatial distribution of that are computed based on pixel levels by using the second national soil erosion remote-sensing survey, and then are zoned into the seven erosion regions to further analyze.

2.1 Soil carbon removals caused by water erosion in seven erosion regions

Based on data (i), (ii) and (iii), removals of SOC and SIC caused by water erosion in seven erosion regions are calculated by using Arcgis 9.2 software. The formula is expressed as:

$$W = \sum_{i=1}^{n} \sum_{j=1}^{m} [S_{ij} \cdot \rho \cdot D_{ij} / (D_2 \cdot 1000)]$$

where $W$ is SOC or SIC removal caused by water erosion (kg y$^{-1}$); $S_{ij}$ is water erosion area in each pixel (m$^2$); $\rho$ is SOC or SIC density (kg m$^{-3}$); $D_{ij}$ is water eroded soil depth under different erosion levels (mm y$^{-1}$) (MWR 1997) (Table 1); $D_2$ is soil depth used for calculating soil carbon density (1 m, in this paper); $i$ and $j$ are pixel and water erosion level, respectively; 1000 is unit conversion coefficient. In this paper, water erosion depths under each erosion level are the mean of the corresponding variable range except for the most intense erosion level, which is the minimum value of its variable range (Table 1).

<table>
<thead>
<tr>
<th>Water eroded soil depth (mm y$^{-1}$)</th>
<th>Mild</th>
<th>Moderate</th>
<th>Intense</th>
<th>Highly intense</th>
<th>The most intense</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWR (1997)</td>
<td>0.15, 0.37</td>
<td>1.9–3.7</td>
<td>3.7–</td>
<td>5.9–</td>
<td>&gt;11.1</td>
</tr>
<tr>
<td></td>
<td>0.74–1.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This paper</td>
<td>1.025</td>
<td>2.8</td>
<td>4.8</td>
<td>8.5</td>
<td>11.1</td>
</tr>
</tbody>
</table>

2.2 Temporal dynamics of soil carbon removal caused by water erosion

Firstly, based on data (iii), the averages of SOC or SIC density in 31 provinces and municipalities are computed by using Arcgis 9.2 software. Then, by adding data (iv), formula 2.1 (excluding parameter $i$) is used to calculate SOC and SIC removals caused by water erosion in the three periods. Finally, we get changes of SOC and SIC removals by subtracting their values in two adjacent periods in each province or municipality.

3 Results

3.1 Spatial pattern of soil carbon density

Spatial pattern of SOC or SIC density in the top 1 m soil is obvious in China (Fig. 1). The average of SOC density is the lowest in the Sandy Grassland Region (Fig. 1A), with the value of 6.81 kg m$^{-2}$. This region locates in the arid and semiarid area, and its common ecosystems are desert and cold-desert. The average of SOC density is the highest in the Black Soil Region of Northeast China, with the value...
of 24.85 kg m\(^{-2}\). In the northernmost of this region, freeze-thaw erosion is the main erosion form. On the contrary, the SIC density has a quite different distribution (Fig. 1B). It is lower in the Red Soil Region of South China and the Karst Region of Southwest China, with the value range of 0.19–0.30 kg m\(^{-2}\). It is moderate in the Black Soil Region of Northeast China and the Rocky Mountain Region of North China, with the value range of 1.95–4.43 kg m\(^{-2}\). It is higher in the Basins of the Upper Yangtze and Other Rivers of Southwest China, the Sandy Grassland Region, and the Loess Plateau Region, with the value range of 6.67–10.15 kg m\(^{-2}\). Regard to the soil total carbon (STC) density, there is a relatively even distribution all over the China (Fig. 1C). The average of STC density is the maximum in the Black Soil Region of Northeast China, with the value of 26.82 kg m\(^{-2}\), and ranges from 11.87 to 18.81 kg m\(^{-2}\) among other regions.

### 3.2 Spatial distribution of soil carbon removal caused by water erosion

All over the country, water erosion area has a significant spatial distribution. Among the seven soil erosion regions, the ratio of water erosion area to the corresponding region area is the highest in the Loess Plateau Region, with the value of 54.10%. It is followed by 41.36% in the Karst Region of Southwest China. The Sandy Grassland Region and the Basins of the Upper Yangtze and Other Rivers of Southwest China both have the ratios less than 10%, and the former is no highly and the most intense water erosions. The Red Soil Region of South China, the Black Soil Region of Northeast China, and the Rocky Mountain Region of North China have the ratios of 12.81%, 19.79% and 21.87%, respectively, and the middle one does not have the most intense water erosion. In the national scale, 33.89% of intense erosion area, 66.81% of highly intense erosion area and 84.72% of the most intense erosion area all occur in the Loess Plateau Region, as well as 26.19% of mild erosion area and 30.91% of moderate erosion area both occur in the Karst Region of Southwest China.

#### 3.2.1 SOC removals caused by water erosion in seven soil erosion regions

The SOC removal caused by water erosion is the highest in the Karst Region of Southwest China, where the moderate erosion is the dominant erosion level (Fig. 2). It equals to 26.48% of the total SOC removal in China. The following are in the Loess Plateau Region, the Basins of the Upper Yangtze and Other Rivers of Southwest China and the Black Soil Region of Northeast China, with the ratios of 20.32%, 16.52% and 15.68%, respectively. SOC removals in the Red Soil Region of South China, the Rocky Mountain Region of North China and the Sandy Grassland Region, are all less than 10% of the national total. Among the seven erosion regions, water eroded SOC removals under different erosion levels are distinct. The maximum removals caused by highly and the most intense erosions are both in the Loess Plateau Region, caused by moderate and intense erosions are both in the Karst Region of Southwest China, and caused by mild erosion is in the Black Soil Region of Northeast China. The last region also has the maximum of erosion rates under mild, moderate and intense erosion among the different erosion regions.

#### 3.2.2 SIC removals caused by water erosion in seven soil erosion regions

Compared with those of SOC, SIC removal caused by water erosion is significantly lower. The Red Soil Region of South China, the Black Soil Region of Northeast China, and the Rocky Mountain Region of North China have the ratios of 12.81%, 19.79% and 21.87%, respectively, and the middle one does not have the most intense water erosion. In the national scale, 33.89% of intense erosion area, 66.81% of highly intense erosion area and 84.72% of the most intense erosion area all occur in the Loess Plateau Region, as well as 26.19% of mild erosion area and 30.91% of moderate erosion area both occur in the Karst Region of Southwest China.
water erosion mainly occurs in the Loess Plateau Region, where highly intense and intense erosions are the dominant erosion levels (Fig. 3). In this region, SIC removed by the most intense erosion accounts for 97.36% of that all over the country, meanwhile, removed by highly intense erosion, intense erosion and moderate erosion account for 94.31%, 79.73% and 45.57% of that in China respectively.

As a result, it occupies 67.62% of the total SIC removal in China. The following is the Sandy Grassland Region, which dominant erosion levels are moderate and mild erosions. This region has 10.85% of the total SIC removal caused by water erosion. SIC removals in other erosion regions are all less than 10%. SIC erosion rates under five erosion levels are all the maximums in the Loess Plateau Region, while the minimums in the Red Soil Region of South China.

3.2.3 Soil carbon removal caused by water erosion in China

As a whole, the water erosion area is about $169.65 \times 10^4$ km$^2$ in China (Table 2), which shows an overall tendency of decreasing with the erosion level increasing. The sum of highly and the most intense erosion areas is only 5.06% of the national total. Soil carbon removal is about 74.61 Tg C y$^{-1}$ across the whole China, including the SOC removal of 51.49 Tg C y$^{-1}$ and the SIC removal of 23.12 Tg C y$^{-1}$. Among different erosion levels, soil carbon removal under moderate erosion is the maximum, with the value of 39.24% of the total, followed by intense and mild erosion, with the value of 20.92% and 20.12% of the total, respectively, and under the most intense erosion is the minimum, only with the value of 7.00% of the total. Except highly and the most intense erosions, SOC erosion rates under the other erosion levels are higher than SIC.

3.3 Temporal dynamics of soil carbon removals caused by water erosion in different provinces and municipalities

3.3.1 Temporal dynamics of soil carbon removals between the mid-1980s and the mid-1990s

From the mid-1980s to the mid-1990s, soil carbon removal caused by water erosion in different erosion regions is shown in Fig. 2 and Fig. 3. Table 2 lists the soil carbon removal caused by water erosion under different erosion levels in China.

Table 2 Soil carbon removal caused by water erosion under different erosion levels in China.

<table>
<thead>
<tr>
<th>Water erosion level</th>
<th>Erosion area ($10^4$ km$^2$)</th>
<th>Erosion removal (Tg C y$^{-1}$)</th>
<th>Erosion rate (t C km$^{-2}$ y$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOC</td>
<td>SIC</td>
<td>STC</td>
</tr>
<tr>
<td>Mild</td>
<td>169.65</td>
<td>51.49</td>
<td>23.12</td>
</tr>
<tr>
<td>Moderate</td>
<td>80.65</td>
<td>11.64</td>
<td>3.37</td>
</tr>
<tr>
<td>Intense</td>
<td>61.24</td>
<td>22.38</td>
<td>6.89</td>
</tr>
<tr>
<td>Highly intense</td>
<td>19.17</td>
<td>10.62</td>
<td>4.99</td>
</tr>
<tr>
<td>The most intense</td>
<td>6.06</td>
<td>4.69</td>
<td>4.8</td>
</tr>
<tr>
<td>Total</td>
<td>169.65</td>
<td>51.49</td>
<td>23.12</td>
</tr>
</tbody>
</table>
removal decreases by 11.66 Tg C yr⁻¹, of which 81.93% is contributed by the decrease of organic carbon removal (Fig. 4). The decrease regions mainly locate in the middle and east of China. Specially, the regions with the decrease value more than 1 Tg C yr⁻¹ are Shaanxi, Heilongjiang, Henan, Shanxi and Sichuan provinces, and the total decrease of these five provinces is 8.33 Tg C yr⁻¹, which is about 71.45% of the national whole. On the contrary, the increase regions are Xinjiang, Xizang, Tianjin, and Gansu, Qinghai, Jiangxi and Yunnan provinces.

3.3.2 Temporal dynamics of soil carbon removals between the mid-1990s and the beginning of 21st century
From the mid-1990s to the beginning of 21st century, the regions with soil carbon removal decrease are less (Fig. 5). However, the national total removal still decreases by 1.65 Tg C yr⁻¹, of which 1.514 Tg C yr⁻¹ is SOC, and 0.134 Tg C yr⁻¹ is SIC. Remarkably, soil carbon removals in the regions of Tianjin, Yunnan, Jiangxi, and Gansu decrease, where have the increase values from the mid-1980s to the mid-1990s. The regions with the maximum decrease of SOC and SIC removals are Sichuan and Hebei provinces, respectively. The former accounts for 58.88% of the national SOC removal decrease, while the latter accounts for 80.08% of the national SIC removal decrease.

4 Discussion
According to the above analysis, we can conclude that SOC removal caused by water erosion is the maximum in the Southwest Karst Region where also has the maximum of SOC erosion rate under the most intense erosion among the seven erosion regions. As one of the most fragile ecological areas, this region is characterized by its high and steep mountains, high annual precipitation and low vegetation coverage (Zeng et al. 2011), which can direct result in severe water erosion even stony desertification. In the whole country, except for highly and the most intense erosions, the maximum of SOC erosion rates under the other erosion levels are all in the Black Soil Region of Northeast China. This region is characterized by its highly soil organic matter content, loose soil texture, and concentrated precipitation, all of these make this region subject to water erosion (Fan et al. 2004). Its excessive cultivation and special hilly topography also aggravate water erosion (Yu and Zhang 2004; Fang et al. 2006a). Moreover, long-term freeze-thaw erosion exists in the high-latitude of this region. The interaction between water and freeze-thaw erosions can further promote water erosion. It is notable that all over the country, the Loess Plateau Region has the minimum SOC erosion rates and the maximum SIC erosion rates under all five erosion levels. The one reason is that this region has been eroded seriously and its SOC content is rather low (Fu 1997). Another is that it locates in semiarid area and has high SIC content (Li et al. 2010), which is also supported by the data of SIC density in this paper (Fig. 1B).

Soil carbon removal caused by water erosion has obvious temporal dynamics in China. The regions with increased removals primarily locate in high elevation area of the western China (i.e. Xinjiang, Xizang and Qinghai) and vegetation destruction and soil degradation are the main reasons. In addition, climatic change also promotes water erosion to some extent. For example, temperature rising lead to snow and glacier melt further, which can increase surface runoff (Hao et al. 2011). In some regions, such as Yunnan, Gansu and Jiangxi provinces, soil carbon removals increased between the mid-1980s and the mid-1990s (Fig. 4), while decreased between the mid-1990s and the beginning of 21st century (Fig. 5). Some ecological recovery measures, such as afforestation, maybe contribute to this improvement (Xie et al. 2010).

Owing to the difficulties of obtaining more detailed basic data, our estimations have some uncertainties. For example, the water erosion data used for calculating soil carbon removals in seven erosion regions are derived from the second national soil erosion remote-sensing survey (1995–1996), and soil carbon densities are derived from the second national soil survey (1979–1992), which cannot represent current situation accurately. When we analyzed the temporal dynamics of soil carbon removal from the mid-1980s to the beginning of 21st century, we only obtained the water erosion areas in different provinces and municipalities, rather than more detailed spatial data. In order to match these data, the soil carbon densities have to be averaged in each district. So, the results are not exact enough. SOC and SIC densities in the upper 1 meter soil are used in this paper, while water erosion mainly occurs in the upper 20 centimeter soil. Therefore, according to the vertical distributions of that SOC density decreases with the soil depth increasing (Wang et al. 2004), while SIC density increases (Mi et al. 2008), the removal of SOC caused by water erosion tends to be underestimated and SIC tends to be overestimated. Moreover, due to soil erosion can be affected by many factors (such as climate, topography, soil characteristic and land manage etc), there is no universal method by using remote sensing images to assess soil erosion in regional or global scale (Vrieling 2006).

From the broad sense, soil erosion contains two processes of erosion and deposition, which can affect regional and global carbon cycle by direct in-situ effects and indirect off-situ effects. Firstly, soil erosion aggravates SOC mineralization and causes soil physical removal (Bajracharya et al. 2000); then, eroded soil carbon redistributes in the landscape (Jacintohe et al. 2001; Fang et al. 2006b), or be sequestrated by river, wetland, or ocean ecosystems (Stallard 1998; McCarty and Ritchie 2002; Van Oost et al. 2007). Therefore, when assessing global carbon cycle, those processes should be considered (Lal 2003).
However, the mechanisms of these complex interacted processes are very difficult to clarify without plenty of field experiments and excellent models. In the future, all of these should be further researched.

5 Conclusions

Based on the water erosion data from the second national soil erosion remote-sensing survey and carbon density from the second national soil survey, soil carbon removal caused by water erosion is about 74.61 Tg C y\(^{-1}\) in China, of which 69.01% is SOC removal. Among the five erosion levels, moderate erosion is the main erosion level, while the most intense erosion has the minimum value, both with the removal values of 29.27 Tg C y\(^{-1}\) and 5.23 Tg C y\(^{-1}\), respectively. Regard to the spatial distribution of water eroded SOC removal, the Karst Region of Southwest China has the maximum value (13.64 Tg C y\(^{-1}\)), the followed are the Loess Plateau region (10.46 Tg C y\(^{-1}\)) and the Basins of the Upper Yangtze and Other Rivers of Southwest China (8.51 Tg C y\(^{-1}\)), and the Sandy Grassland Region has the minimum value (3.01 Tg C y\(^{-1}\)). Compared with SOC, SIC has a different spatial distribution. The Loess Plateau region has 67.62% SIC removal of the total. The followed is the Sandy Grassland Region, which is just less than 1/6 of that in the Loess Plateau Region. The SIC removal in the Red Soil Region of South China is the least, only 0.12% of the national total.

Using water erosion areas from the three national soil erosion remote-sensing surveys and soil carbon densities from the second national soil survey, it is estimated that soil carbon removal decreases by 11.66 Tg C y\(^{-1}\) from the mid-1980s to the mid-1990s, of which 81.93% is SOC; and decreases by 1.65 Tg C y\(^{-1}\) from the mid-1990s to the beginning of 21\(^{st}\) century, of which 91.90% is SOC.

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References


中国区域土壤水蚀碳量空间分布及其时间动态

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摘要：本文利用三次全国土壤侵蚀遥感普查数据和第二次土壤普查土壤有机碳和无机碳密度数据，分析了我国土壤水蚀碳量的空间分布及其时间动态。研究结果表明：我国土壤水蚀碳量为74.61 Tg C y$^{-1}$，其中有机碳量51.49 Tg C y$^{-1}$，无机碳量23.12 Tg C y$^{-1}$。在七大水土流失区中，水蚀有机碳量最多的是西南岩溶区，占总水蚀有机碳量的26.48%；水蚀无机碳量最多的是黄土高原区，占总水蚀无机碳量的67.62%。前者以中度水蚀为主，后者以极强度和强度水蚀为主。80年代中期至90年代中期，我国土壤水蚀碳量共减少了11.66 Tg C y$^{-1}$，以有机碳迁移量减少为主，占总减少量的81.93%；90年代中期至21世纪初，土壤水蚀碳量依然呈下降趋势，共减少了1.65 Tg C y$^{-1}$，其中，有机碳迁移量减少了1.514 Tg C y$^{-1}$，无机碳迁移量减少了0.134 Tg C y$^{-1}$。

关键词：中国；土壤水蚀；有机碳；无机碳；水土流失区