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Erosion-induced CO_2 flux of small watersheds

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ABSTRACT

Soil erosion not only results in severe ecological damage, but also interferes with soil organic carbon formation and decomposition, influencing the global green-house effect. However, there is controversy as to whether a typical small watershed presumed as the basic unit of sediment yield acts as a CO_2 sink or source. This paper proposes a discriminant equation for the direction of CO_2 flux in small watersheds, basing on the concept of Sediment Delivery Ratio (*SDR*). Using this equation, watersheds can be classified as *Sink Watersheds*, *Source Watersheds*, or *Transition Watersheds*, noting that small watersheds can act either as a CO_2 sink or as a CO_2 source. A mathematical model for calculating the two discriminant coefficients in the equation is set up to analyze the conditions under which each type of watershed would occur. After assigning the model parameter values at three levels (low, medium, and high), and considering 486 scenarios in total, the influences are examined for turnover rate of the carbon pool, erosion rate, deposition rate, cultivation depth and period. The effect of adopting conservation measures like residue return, contour farming, terracing, and conservation tillage is also analyzed. The results show that Sink Watersheds are more likely to result in conditions of high erosion rate, long cultivation period, high deposition rate, fast carbon pool turnover rate, and small depth of cultivation; otherwise, Source Watersheds would possibly occur. The results also indicate that residue return and conservation tillage are beneficial for CO_2 sequestration.

1. Introduction

Soil plays an important part in the global carbon cycle. Soil comprises an enormous carbon pool of about 1200–2500 Gt C (see e.g. Schlesinger, 1991; Balino et al., 2001) that actively exchanges about 60 Gt C per annum with the atmosphere (Balino et al., 2001). Lal (1995, 2003) suggests that, by interfering with the process of soil carbon formation and decomposition, erosion brings about extra CO_2 fluxes that either exacerbate or alleviate the global green-house effect depending on whether the fluxes are into or out of the soil. Carbon fluxes between ground and atmosphere occur when the inorganic constituents of soil are weathered, or the soil organic carbon (SOC) is synthesized or mineralized via biological pathways. All the processes can be greatly influenced by erosion. The overland runoff absorbs CO_2 at a magnitude of 0.26–0.30 Gt C per annum by weathering certain inorganic constituents of soil (like silicate and carbonate) (Meybeck, 1982; Berner et al., 1983; Amiotte Suchet and Probst, 1995). The organic process which involves all the three stages of detachment, transport, and deposition can be more complicated. In the erosion region, with the decrease of soil fertility due to organic carbon loss in the top layer, crop residue returning into the soil carbon pool also declines (Lal et al., 2004b). Simultaneously, the decomposition of organic carbon slows down because of the decrease in fresh carbon supply (Fontaine et al., 2007). It may also be the case that newly bared mineral substances in the top layer could stabilize the SOC, and thus slow down the rate of degradation (Quinton et al., 2010). During sediment transport, the soil particles break down accelerating the decomposition of SOC (Jacinthe et al., 2002; Polyakov and Lal, 2008; Alewell et al., 2009). However, the extra CO_2 flux generated by this process may not be very significant (Van Hemelryck, et al., 2010, 2011). Terrestrial deposition of sediment enriches SOC, and consequently increases the emission of CO_2. On the other hand, the newly deposited sediment covers the original top soil in the deposition region, effectively inhibiting decomposition (Berhe et al., 2007). Moreover, deposition contributes to the aggregation of soil. In this way, SOC formation and CO_2 sequestration are promoted. Unlike terrestrial deposition, sediment deposited in reservoirs, lakes, rivers and wetlands is protected from oxidation because of the anaerobic environment (Cole et al., 2007; Aufdenkampe et al., 2011). However, Lal et al. (2004b) observe that CH_4 (another greenhouse gas) could be released as a product of anaerobic decomposition in water. Stallard (1998) points out that sediment deposited in reservoirs, lakes and

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wetlands nevertheless has the potential to grow plants, sequestering CO_2 through photosynthesis.

Although the inorganic process during erosion is becoming better understood, agreement has not yet been reached as to whether the soil organic carbon pool acts under erosion as a CO_2 source or sink. Lal (1995, 2003) calculates that the global CO_2 source induced by erosion is 0.8–1.2 Gt C per annum. However, Smith et al. (2001) suggest that the erosion-induced CO_2 sink is about 1.0 Gt C per annum. Ciais et al. (2010) estimate that cropland in Europe as a whole acts as a CO_2 source of 20 g C m^{-2} yr^{-1} in the long run. Dymond (2010) estimates that New Zealand has a CO_2 sink of 3.1 Mt per annum, mitigating its fuel burning emissions by 45%. Billings et al. (2010) conclude that whether SOC erosion acts as a sink or source depends largely on the final fate of the eroded soil. The enrichment effect of carbon in sediment resulting from the selective erosion of organic matter makes the process more complicated, and leaves the question even harder to answer (Kuhn et al., 2009). Since soil erosion is a multi-scale process which involves a series of steps (Harden et al., 2008), every single CO_2-related mechanism of each step at each scale should be studied to detect fully the total erosion-induced CO_2 flux.

As the basic unit of sediment yield, the watershed is the starting point for research into CO_2 flux during erosion. Yet, the role of watersheds in the carbon cycle is not clear. Van Oost et al. (2007) studied several small watersheds (<15 h m^2) in Europe and America. By comparing observed soil carbon inventories (C_{obv}, g m^{-2}) with simulated carbon inventories under the assumption that no vertical carbon exchanges occur (C_{sim}, g m^{-2}), Van Oost et al. discovered that the watersheds studied were sinks of erosion-induced CO_2 fluxes. By direct extrapolation, Van Oost et al. calculated the World's total CO_2 sink to be 0.12 Pg C yr^{-1}. This viewpoint is supported by Renwick et al. (2004) and Harden et al. (2008), whereas Lal et al. (2004a) and Alewell et al. (2009) insist that SOC in an erosion region decomposes at a higher rate, acting as a CO_2 source. Although Van Oost et al. (2007) designed an ingenious experiment from which they derived convincing conclusions, it should be noted that extrapolation from local regions to the global scale may not hold true, due to significant effects on erosion-induced CO_2 fluxes from spatial variations in natural and anthropogenic factors like vegetation, microbial decomposition rate, soil structures, erosion intensity and cultivation activities (Ni et al., 2008; Miao et al., 2010, 2011). Proper consideration of these variations could lead to different conclusions than obtained by Van Oost et al. The following question needs to be answered. Can it be determined whether a particular watershed in the erosion region acts as a CO_2 sink or source? Following Van Oost et al. (2007), the present paper considers the spatial variations of both natural and anthropogenic factors and sets up a discriminant equation for identifying the type of CO_2 flux that occurs in a given small watershed, based on the concept of Sediment Delivery Ratio (*SDR*). We try to provide a possible explanation aimed towards resolving the present controversy. To analyze the impacts of vegetation, microbial decomposition, soil structure, erosion intensity and human cultivation on CO_2 flux of a watershed, two parameter studies (covering a total of 486 scenarios) have been undertaken using a mathematical model of the slow carbon pool in the soil. The effects of adopting different conservation measures, such as residue return, contour farming, terracing, and conservation tillage, are evaluated. Furthermore, the enrichment effect of sediment carbon content is analyzed using both the slow carbon pool model and the *SDR* approach.

2. Discriminant equation for the type of CO_2 flux in a watershed

Van Oost et al. (2007) divide the total CO_2 flux F_A (g C yr^{-1}) of a watershed into two parts: the flux at erosion sites F_E (g C yr^{-1}), and the flux at deposition sites F_D (g C yr^{-1}):

$$F_A = F_E + F_D, \tag{1}$$

in which positive values of F_A, F_E, and F_D indicate CO_2 absorption, while negative values represent CO_2 emission. By comparing the difference between observed carbon inventories C_{obv}, (g C m^{-2}) and simulated carbon inventories under the assumption that no vertical carbon flux occurs C_{sim} (g C m^{-2}), Van Oost et al. obtained values of F_E and F_D for ten watersheds in Europe and America. They also discovered that the vertical fluxes (F_E, F_D) are linearly related to the lateral fluxes (E_C, D_C, g C yr^{-1}), with the linear coefficients being 0.11–0.55 and −0.24–0.21. The average values of the two coefficients over all the sampled watersheds are 0.26 and 0. Accordingly, Van Oost et al. calculated the total CO_2 flux of the World's small watersheds to be 0.12 Pg C per annum, and concluded that small watersheds as a whole act as a tiny CO_2 sink. However, because of the spatial variations of both natural and anthropogenic factors, the ratios between the vertical and lateral fluxes in other watersheds may be different, and the ten sampled watersheds in Europe and America cannot represent the overall situation of the World. Stallard (1998) suggests that the sequestration ratio may vary from 0 to 100% globally; Boix-Fayos et al. (2009) discovered that the sequestration ratio gradually increases to 36% in the vegetation restoration regions. Moreover, the coefficients obtained by Van Oost et al. display evident differences among the ten watersheds considered. When the coefficients change (not 0.26 or 0), the direction and intensity of erosion-induced CO_2 flux in a small watershed needs re-evaluation.

Let α and β represent ratios of the vertical carbon flux to the lateral carbon flux in the watershed:

$$\alpha = \frac{F_E}{E_c}, \tag{2}$$

and

$$\beta = \frac{F_D}{D_C}, \tag{3}$$

so that

$$F_A = \alpha E_C + \beta D_C, \tag{4}$$

given

$$D_C = E_C - T_C, \tag{5}$$

where T_C is the organic carbon exported out of the watershed (g C yr^{-1}). Thus:

$$F_A = \alpha E_C + \beta (E_C - T_C). \tag{6}$$

Dividing Eq. (6) by T_C:

$$\frac{F_A}{T_C} = \alpha \frac{E_C}{T_C} + \beta \left(\frac{E_C}{T_C} - 1 \right). \tag{7}$$

Note that the left side of Eq. (7) represents the ratio of carbon vertically exported from the watershed via CO_2 emission (F_A) to SOC laterally exported out of the region with sediment (T_C). When the ratio is positive, the watershed represents a CO_2 sink, and vice versa. The absolute value of the ratio represents the relative intensity of CO_2 emission/absorption. Thus, the ratio F_A/T_C can be regarded as an indicator of the characteristics of the erosion-induced CO_2 flux in the watershed, and we name it the Exported Carbon Ratio (*ECR*). In short,

$$ECR = \frac{F_A}{T_C}. \tag{8}$$