Erosion-induced CO2 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, using the concept of Sediment Delivery Ratio (SDR). Using this equation, a watershed can be classified as a Sink Watershed, a Source Watershed, or a Transition Watershed, noting that small watersheds can act either as a CO_2 sink or as a CO_2 source. A mathematical model is used to analyze how natural and anthropogenic factors affect the type of CO_2 flux. After assigning each factor (turnover rate of the carbon pool, erosion rate, deposition rate, cultivation depth and period) values at three levels (low, medium, and high), and combining 243 scenarios, the influence of increasing or decreasing crop residue return is also analyzed. The results show that low erosion rate, short cultivation period, low depositional rate, slow carbon pool turnover rate, and deep cultivation depth are unfavorable for the formation of the Sink Watershed; a decreased residue return by 30 % may result in transformation towards the Source Watershed; an increased residue return by 30 % may strengthen the basic CO_2 sink by a factor ranging from 2.4 to 5.4.

Dear Editor:

We would like to submit the enclosed manuscript entitled "Erosion-induced CO_2 flux of world's small watersheds", which we wish to be considered for publication in "Global and Planetary Change".

There is controversy as to whether a typical small watershed acts as a CO_2 sink or source. This paper proposed a discriminant equation for the direction of CO_2 flux in small watersheds, and found that a watershed can be classified as a *Sink Watershed*, a *Source Watershed*, or a *Transition Watershed*, noting that small watersheds can act either as a CO_2 sink or as a CO_2 source. A mathematical model is used to analyze how natural and anthropogenic factors affect the type of CO_2 flux. The present paper will possibly contribute to our understanding of CO_2 flux control.

The work described has not been submitted elsewhere for publication, and all authors have seen the manuscript and approved to submit to your journal. Thank you very much for your attention and consideration.

Sincerely yours,

Prof. Jinren Ni

Department of Environmental Engineering, Peking University, P. R. China

***Highlights**

We propose a discriminant equation for the direction of CO_2 flux in small watersheds.

The world's watersheds can be classified into source, sink, or transition watersheds.

We model how natural and anthropogenic factors affect a watershed's type of CO_2 flux.

Erosion-induced CO_2 flux of world's 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, using the concept of Sediment Delivery Ratio (*SDR*). Using this equation, a watershed can be classified as a *Sink Watershed*, a *Source Watershed*, or a *Transition Watershed*, noting that small watersheds can act either as a CO_2 sink or as a

CO_2 source. A mathematical model is used to analyze how natural and anthropogenic factors affect the type of CO_2 flux. After assigning each factor (turnover rate of the carbon pool, erosion rate, deposition rate, cultivation depth and period) values at three levels (low, medium, and high), and combining 243 scenarios, the influence of increasing or decreasing crop residue return is also analyzed. The results show that low erosion rate, short cultivation period, low depositional rate, slow carbon pool turnover rate, and deep cultivation depth are unfavorable for the formation of the Sink Watershed; a decreased residue return by 30 % may result in transformation towards the Source Watershed; an increased residue return by 30 % may strengthen the basic CO_2 sink by a factor ranging from 2.4 to 5.4.

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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 pathway. 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) (Berner et al., 1983; Meybeck, 1982; Amiotte Suchet et al., 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., 2004(b)). 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. (2004(b)) 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 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. (2011) conclude that whether SOC erosion acts as a sink or source depends largely on the final fate of the eroded soil. 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 hm^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. (2004(a)) 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. 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, a parameter study involving 243 scenarios has been undertaken using a mathematical model of the slow carbon pool in the soil. The effect of two management measures is also evaluated.

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}):

$$F_A = F_E + F_D, \quad (1)$$

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 small watershed need 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 Equation (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 Equation (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,

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

According to Equation (8), the total CO_2 flux of a watershed can be easily calculated by multiplying *ECR* by T_C obtained from the lower end of the watershed. It should be noted that

$$E_C = SOC_E \ E_S \tag{9}$$

and

$$T_C = SOC_T \ T_S, \tag{10}$$

where SOC_E and SOC_T are the organic carbon content within the eroded soil and exported sediments respectively (g kg^{-1}), E_S and T_S are the amount of soil erosion and sediment transport (kg yr^{-1}). Given that the scale of the watershed is very small, it takes a short time for the eroded soil to arrive at the lower end of the watershed. So it is reasonable to suppose that:

$$SOC_E = SOC_T. \tag{11}$$

Thus,

$$\frac{E_C}{T_C} = \frac{E_S}{T_S} = \frac{1}{SDR} \quad , \tag{12}$$

where *SDR* is the Sediment Delivery Ratio of the watershed, which can vary between 0 and 1.

Combining Equation (8) and Equation (12), the discriminant equation for CO_2 flux type is as follows:

$$ECR = \frac{\alpha + \beta}{SDR} - \beta . \qquad (13)$$

Equation (13) shows that, the indicator for CO_2 flux characteristics (i.e. direction and intensity), *ECR*, varies with α, β, and *SDR*. In practice, the equation can be used to discriminate the characteristics of the CO_2 flux for a given watershed.

3. Discrimination of CO_2 flux type in small watersheds

3.1. Classification of watershed based on characteristics of CO_2 flux

The above expression for *ECR* has the form of a hyperbola. Theoretically, *ECR* has 4 forms according to the values of α and β:

Form (1): $\alpha + \beta > 0$, $\alpha > 0$;

Form (2): $\alpha + \beta > 0$, $\alpha < 0$;

Form (3): $\alpha + \beta < 0$, $\alpha > 0$;

Form (4): $\alpha + \beta < 0$, $\alpha < 0$;

In practice, Form (2) cannot exist, because:

$$\alpha = \frac{(I_{C,E} - O_{C,E}) A_E}{E_C} \qquad (14)$$

and

$$\beta = \frac{(I_{C,D} - O_{C,D}) A_D}{D_C} , \qquad (15)$$

where I_C is the input intensity of CO_2 from the atmosphere to soil (g C yr^{-1}), O_C is the output intensity of CO_2 from the soil to atmosphere (g C yr^{-1}); A is the area in m^2; and the subscripts E and D represent erosion and deposition respectively. Within any given small watershed, the input and intensity of CO_2 through photosynthesis at both the eroding and the depositional sites can be presumed to be the same, so that

$$I_{C,E} = I_{C,D}. \quad (16)$$

The oxidation rate of SOC obeys first order dynamics. Within a single small watershed, the first order oxidation coefficient k_O (yr^{-1}) leads to equal erosion and deposition oxidation rates, such that

$$O_{C,E} = k_O C_E \quad (17)$$

and

$$O_{C,D} = k_O C_D, \quad (18)$$

where C_E and C_D are the carbon inventories at the eroding and depositional sites (g C m^{-2}). In general,

$$C_E \leq C_D, \quad (19)$$

so that

$$I_{C,E} - O_{C,E} \geq I_{C,E} - O_{C,E}. \quad (20)$$

That is, if $\alpha < 0$, then $\beta < 0$. Therefore, $\alpha + \beta$ is also smaller than 0. Form (2) does not exist.

Fig. 1 shows how *ECR* changes with *SDR* for each of the three types of watershed. A watershed represented by Form (1) is always a CO_2 sink, whatever the value of *SDR*, and we call it a *Sink Watershed*. A watershed of Form (3) transitions from a CO_2 source to a sink with *SDR* increasing from 0 to 1, and is termed a *Transition Watershed*. A watershed represented by Form (4) is always a CO_2 source no matter the value of *SDR*, and is called a *Source Watershed*. For a Sink Watershed, *ECR* decreases as *SDR* increases. When *SDR* is equal to 1, *ECR* has a minimum value of α. So α reflects the basic capability for CO_2 sequestration of a Sink Watershed. The decreasing gradient of the line from $ECR|_{SDR=1}$ to $ECR|_{SDR=0.5}$, $|2\cdot(\alpha + \beta)|$ indicates the sensitivity of CO_2 sequestration to the change in *SDR*. The *ECR* of the Transition Watershed is positively correlated with *SDR*. The critical *SDR* where $ECR = 0$ in the Transition Watershed is given by $SDR_{cr} = 1 + \alpha/\beta$. An increase in α or decrease in β makes the critical point move to the right. When $SDR < SDR_{cr}$, the watershed acts as a CO_2 source; however, when $SDR > SDR_{cr}$, the watershed acts as a CO_2 sink. In the Source Watershed, *ECR* increases as *SDR* increases. When *SDR* is equal to 1, *ECR* reaches its maximum value of α. So α reflects the basic capability for CO_2 emission of a Source Watershed. The gradient of the line from $ECR|_{SDR=1}$ to $ECR|_{SDR=0.5}$, $|2\cdot(\alpha + \beta)|$ again indicates the sensitivity of CO_2 emission to changes in *SDR*.

3.2. A possible answer to the present controversy: whether a small watershed a sink or source?

According to the Discriminant Equation for CO_2 flux type, a watershed can be either a CO_2 source (the Source Watershed or the source part of the Transition

Watershed), or a CO_2 sink (the Sink Watershed or the sink part of the Transition Watershed). Using experimental data from small watersheds published in the open literature it is possible to discriminate the CO_2 flux type for each catchment. Tables 1 and 2 list the discriminant parameters of typical Sink Watersheds and typical Source Watersheds.

4. Factors that influence the type of CO_2 flux in a watershed

4.1. Slow carbon pool model

Next a mathematical model is applied to study how natural and anthropogenic factors affect the classification of CO_2 flux in a watershed. According to the turnover time, the soil carbon pool can be classified into a *rapid carbon pool* which consists of debris and microbes (with a turnover time of less than 5 years (Potter et al., 1993; Li et al., 1994)), a *slow carbon pool* (stored in the top 20 cm, with a turnover time of decades to centuries), and a *passive carbon pool* (with a turnover time of thousands of years) (Stallard, 1998), of which the slow carbon pool is directly affected by cultivation and erosion. The change of the slow carbon pool can be described as follows (Stallard 1998; Liu et al., 2003):

In the erosion region,

$$\frac{dC_E}{dT} = I_B - (k_E + k_O)C_E + C_{sub} \quad , \qquad (21)$$

and in the deposition region,

$$\frac{dC_D}{dT} = I_B + I_D - k_O C_E - C_{sub} \quad , \qquad (22)$$

where C_E (g m^{-2}) and C_D (g m^{-2}) are the carbon inventories in the erosion and deposition regions respectively, T (yr) is the cultivation period, I_B (g m^{-2} yr^{-1}) is the carbon input intensity through photosynthesis, and I_D (g m^{-2} yr^{-1}) is the deposition intensity. Suppose that oxidation and erosion obey first order dynamics, and let k_O (yr^{-1}) represent the first order coefficient of carbon oxidation through microbial process, which also reflects the turnover rate of the slow carbon pool, k_E (yr^{-1}) is the first order coefficient of erosion, and C_{sub} (g m^{-2} yr^{-1}) is the flux from / to the lower carbon pool due to the elevation change of the top layer through erosion or deposition. C_{sub} can be calculated using the erosion (deposition) rate and the SOC distribution. Given that:

$$F_E = (I_B - k_O C_E) A_E, \qquad (23)$$

$$F_D = (I_B - k_O C_D) A_D, \qquad (24)$$

$$E_C = k_E C_E A_E, \qquad (25)$$

and

$$D_C = I_D A_D, \qquad (26)$$

where A_E and A_D (m^2) represent the erosion and deposition areas respectively. Thus,

$$\alpha = \frac{I_B - k_O C_E}{k_E C_E} , \qquad (27)$$

and

$$\beta = \frac{I_B - k_O C_D}{I_D} . \qquad (28)$$

The average α and β during the cultivation period T (yr) are:

$$\bar{\alpha} = \frac{I_B T - k_O \int_0^T C_E \,\mathrm{d}t}{k_E \int_0^T C_E \,\mathrm{d}t} \quad (29)$$

$$\bar{\beta} = \frac{I_B T - k_O \int_0^T C_D \,\mathrm{d}t}{\int_0^T I_D \,\mathrm{d}t} \quad (30)$$

where I_D can be calculated using the depositional rate and the SOC profile.

4.2 Model Validation

The model was validated using data taken from Van Oost et al. (2007). Three watersheds with uniform sampling depth (0.5 m, see Fig. 2 for the profile of each watershed) were selected, and the input parameters for the model were derived from the ^{137}Cs and SOC inventories (Table 3).

Fig. 3 compares the modeled $\bar{\alpha}$, $\bar{\beta}$ (Equation (21), (22), (29), (30)) during the cultivation period with values directly obtained from field measurements. The results are in reasonable agreement, thus validating the slow carbon pool model.

4.3. Sensitivity analysis

I_B, k_O, D_{cul}, T, v_E, and v_D are basic input parameters representing the input intensity through photosynthesis, turnover rate of the slow carbon pool, cultivation depth, cultivation period, the yearly erosion depth and deposition depth respectively. Other parameters can be derived from these basic ones (see notes below Table 3). Since erosion provides the material for deposition, v_D should be closely related to v_E.

Suppose the following linear relationship holds between v_E and v_D:

$$\frac{v_D}{v_E} = k_R \quad , \qquad (31)$$

where k_R is a deposition coefficient representing the deposition intensity. Then, v_D can be written as a function of v_E and k_R. Herein, I_B, k_O, D_{cul}, T, v_E, and k_R were assigned the average of the values obtained by Van Oost et al. (2007), and then altered by ±20 %, one at a time. The results show that α is insensitive to I_B and k_R, and is positively correlated to T, k_O, D_{cul}, and v_E. The three factors with greatest influence on α are T (±17.1 %), k_O (±11.8 %), and D_{cul} (±8.8 %). The coefficient of β is positively correlated with k_O and D_{cul}, and negatively correlated with v_E, T, and k_R. It is insensitive to I_B, but most affected by D_{cul} (±59.8 %), v_E (∓45.6 %), and T (∓36.4 %). Note that cultivation period and depth have the largest influence on for both α and β, which implies that anthropogenic factors are most important in determining the type of CO_2 flux in watersheds. It should therefore be possible to control CO_2 flux through changing human activities. The significant influence of cultivation period on α can be explained by examining the derivative of Equation (27):

$$d\alpha = -\frac{I_B}{k_E C_E^2} d C_E \quad , \qquad (32)$$

and dividing by α to obtain

$$\frac{d\alpha}{\alpha} = -\frac{I_B}{I_B - k_E C_E} \frac{d C_E}{C_E} \quad . \qquad (33)$$

In general (where erosion is not extremely severe),

$$\frac{I_B}{I_B - k_E C_E} > 1 \quad . \tag{34}$$

So, the variation becomes magnified as time passes. Inserting the values for each parameter in the sensitivity analysis, leads to

$$\frac{d\alpha}{\alpha} = 2.47 \frac{d\,C_E}{C_E} \quad . \tag{35}$$

Equation (35) demonstrates the magnification effect. The influence of cultivation period on β can be similarly explained. D_{cul} exerts influence on α and β through k_E. Since $k_E = v_E/D_{cul}$, the same variation in D_{cul} leads to a larger change in k_E compared to v_E.

4.4. Scenario Analysis

A series of scenarios has been conducted in order to study the conditions under which each of the three types of watersheds occur. Table 4 lists the range of values of k_O, D_{cul}, T, v_E, and k_R selected as key factors that determine the type of a watershed (given that α and β are both insensitive to I_B). First, the input intensity is kept constant ($I_B \equiv 75$ g C m^{-2} yr^{-1}, (Van Oost et al., 2007)), and three levels of values (high, medium and low, Table 5) are selected within the range of each factor in order to calculate the CO_2 flux type for every single combination. Then, the input intensity is varied over the cultivation period (100 yr, while keeping k_O, D_{cul}, v_E, and k_R at medium level) to simulate the impact of changing residue return on the CO_2 flux type in a watershed (reduced or increased by 30 % respectively).

(1) Steady input conditions. A total of 243 scenarios are combined according to the parameters listed in Table 5. The results are summarized in Table 6. It appears that choice of the lowest value of erosion intensity (v_E = 0.0001 m/yr) always leads to a Transition Watershed, regardless of the values assigned to the other parameters (within the range considered). Choice of the highest value of erosion intensity (v_E = 0.01 m/yr) invariably leads to a Sink Watershed. The conclusion that erosion promotes CO_2 sequestration is supported by Liu et al. (2003). This is mainly because erosion progressively exposes soil containing lower and more stable carbon, diminishing CO_2 emissions. In the region where erosion intensity is moderate (v_E = 0.001 m/yr), the period of cultivation becomes the primary impact factor. A medium or long cultivation period (50 yr, 100 yr) leads to a Sink Watershed, whereas a short cultivation period (25 yr) results in either a Transition Watershed or a Sink Watershed. Liu et al. (2003) also pointed out that CO_2 emissions decreased while CO_2 sequestration increased as time passed. When v_E and T were set to 0.001 m/yr and 25 yr respectively, it can be seen that regions with a high depositional coefficient (k_R = 1.05) are all Sink Watersheds, whereas regions with low depositional coefficient (k_R = 0.35) are all Transition Watersheds. This is due to the hiding effect of deposited sediment on the lower soil layer, which inhibits carbon decomposition, and is more effective in regions with a high depositional coefficient. In watersheds with a medium depositional coefficient (k_R = 0.7), the turnover rate (k_O) plays the determining role. For low or medium values of k_O (0.01 yr^{-1} or 0.02 yr^{-1}), a Transition Watershed occurs. However, a high turnover rate (k_O=0.04 yr^{-1}) results in

either a Sink Watershed or a Transition Watershed. Next, by setting k_R = 0.7 and k_O = 0.04 yr^{-1}, it appears that the cultivation depth begins to act as the key factor. When D_{cul} is shallow or modest (D_{cul} = 0.1 or 0.2 m), a sink Watershed results. A Transition Watershed occurs in scenarios involving a relatively large cultivation depth (D_{cul} = 0.3 m). This is because a more shallow cultivation depth corresponds to a higher erosion coefficient (k_E) when the erosion rate is the same, and thus is beneficial for CO_2 sequestration. In summary, no Source Watershed appears under the steady input scenario. Conditions of low erosion intensity, short cultivation period, low depositional coefficient, slow carbon pool turnover rate, or large cultivation depth are unfavorable for the formation of a Sink Watershed. It is important that basin management is not mono-targeted. Instead, a holistic analysis is required taking into account the effect of CO_2 flux control in terms of the economic, social, and environmental impacts (Lal, 2010). For example, erosion intensity should not be increased solely for the *ex parte* purpose of reducing CO_2 emissions.

(2) Sudden change in residue return. Fig. 4 illustrates three scenarios: (a) constant residue return; (b) an abrupt decrease of 30 % in residual return at the 51st year; and (c) an abrupt increase of 30 % in residue return at the 51st year. It is evident from Fig. 4(b) that the sudden 30 % decrease in residue return is accompanied by a sharp decrease in both α and $\alpha + \beta$ taking them from positive to negative values, associated with transformation from a CO_2 sink to a source. Although both α and $\alpha + \beta$ slowly increase afterwards, the watershed remains a source by the end of the simulation at 100 years. By continuing the simulation beyond 100 years, it was

found that the region alters to a Transition Watershed in the 110th year, and later returns to a Sink Watershed in the 175th year. Fig. 4(c) shows that the sudden 30 % increase in residue return leads to an equally abrupt increase in both α and $\alpha+\beta$. In this case, α, the capability of the watershed to sequester CO_2, increases by a factor of 5.4. Although both α and $\alpha+\beta$ slowly decline with time, they appear to saturate. It appears that the basic CO_2 sequestration still remains 2.4 times as much as the level at the 50th year immediately before the abrupt increase in residue return. In summary, a decrease in the residue return leads to a sudden transformation towards a Source Watershed, whereas a sudden increase in the ratio of residue return is beneficial for CO_2 sequestration.

5. Conclusions

There is controversy in the literature as to whether a small watershed under erosion represents a CO_2 sink or source. To help resolve this controversy, the present paper has developed a discrimination model to investigate the directional and intensity characteristics of CO_2 flux. The model can be used to categorize small watersheds into the Sink Watersheds, Source Watersheds and Transitional Watersheds, noting that a small watershed can be either a CO_2 sink or source. To evaluate the model, input data are required on the ratios of the vertical and lateral carbon fluxes at both the eroding site and the depositional site, and the Sediment Delivery Ratio of the region. By means of parameter and scenario studies, it is demonstrated that the type of a watershed is influenced by both natural and anthropogenic factors, with the latter being most important. This raises the interesting possibility of effective CO_2 flux control through changing human activities in a given small watershed. Sink Watersheds are less likely to result in conditions of low erosion intensity, short cultivation period, low depositional coefficient, slow carbon pool turnover rate, and large depth of cultivation. An abrupt decrease in the residue return may lead to a sudden transformation towards a Source Watershed. In contrast, an abrupt increase in the ratio of residue return is beneficial for CO_2 sequestration. It is hoped that the present paper will contribute to our understanding of CO_2 flux control.

References

Alewell, C., Schaub, M., Conen, F., 2009. A method to detect soil carbon degradation during soil erosion. Biogeosciences 6, 2541–2547.

Amiotte Suchet, P., Probst, J.L., 1995. A global model for present-day atmospheric/soil CO_2 consumption by chemical erosion of continental rocks (GEM- CO_2). Tellus 47B, 273-280. doi: 10.1034/j.1600-0889.47.issue1.23.x.

Aufdenkampe, A.K., Mayorga, E., Raymond, P.A., Melack, J.M., Doney, S.C., Alin, S.R., Aalto, R.E., Yoo, K., 2011. Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. Frontiers in Ecology and the Environment, 9, SI, 53-60. doi: 10.1890/100014.

Balino, B.M., Fasham, M.J.R., Bowles, M.C., 2001. Ocean biogeochemistry and global change: JGOFS Research Highlights 1988~2000. In: IGBP Science No 2., 1–32.

Berhe, A.A., Harte, J., Harden, J.W., Torn, M.S., 2007. The significance of the erosion-induced terrestrial carbon sink. Bioscience 57, 337-346. doi: 10.1641/B570408.

Berner, R.A., Lasaga, A.C., Garrels, R.M., 1983. The carbonate–silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 millions years. American Journal of Science 283, 641–683. doi: 10.2475/ajs.283.7.641.

Billings, S.A., Buddemeier, R.W., Richter, D.D., Van Oost, K., Bohling, G., 2010. A simple method for estimating the influence of eroding soil profiles on atmospheric CO_2. Global Biogeochemical Cycles 24, GB2001. doi: 10.1029/2009GB003560.

Boix-Fayos, C., de Vente, J., Albaladejo, J., Martinez-Mena, M., 2009. Soil carbon erosion and stock as affected by land use changes at the catchment scale in Mediterranean ecosystems. Agriculture Ecosystems and Environment 133, 75–85. doi: 10.1016/j.agee.2009.05.013.

Cheng, S.L., Fang, H.J., Zhu, T.H., Zheng, J.J., Yang, X.M., Zhang, X.P., Yu, G.R., 2010. Effects of soil erosion and deposition on soil organic carbon dynamics at a sloping field in Black Soil region, Northeast China. Soil Science and Plant Nutrition 56, 521-529. doi: 10.1111/j.1747-0765.2010.00492.x.

Ciais, P., Wattenbach, M., Vuichard, N., Smith, P., Piao, S.L., Don, A., Luyssaert, S., Janssens, I.A., Bondeau, A., Dechow, R., Leip, A., Smith, P.C., Beer, C., van der Werf, G.R., Gervois, S., Van Oost, K., Tomelleri, E., Freibauer, A., Schulze, E.D., 2010. The European carbon balance. Part 2: croplands. Global Change Biology 16, 1409-1428. doi: 10.1111/j.1365-2486.2009.02055.x

Cole, J.J., Prairie, Y.T., Caraco, N.F., McDowell, W.H., Tranvik, L.J., Striegl, R.G., Duarte, C.M., Kortelainen, P., Downing, J.A., Middelburg, J.J., Melack, J., 2007. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. Ecosystems 10, 171-184. doi: 10.1007/s10021-006-9013-8.

Dymond, J.R., 2010. Soil erosion in New Zealand is a net sink of CO_2. Earth Surface Processes and Landforms 35, 1763-1772. doi: 10.1002/esp.2014.

Fontaine, S., Barot, S., Barre, P., Bdioui, N., Mary, B., Rumpel, C., 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature 450, 277-280. doi:10.1038/nature06275.

Harden, J.W., Berhe, A.A., Torn, M., Harte, J., Liu, S., Stallard, R.F., 2008. Soil erosion: Data say C sink. Science 320, 178-179. doi: 10.1126/science.320.5873.178.

Jacinthe, P.A., Lal, R., 2001. A mass balance approach to assess carbon dioxide evolution during erosional events. Land Degradation Development 12, 329–339. doi: 10.1002/ldr.454.

Jacinthe, P.A., Lal, R., Kimble, J.M., 2002. Carbon dioxide evolution in runoff from simulated rainfall on long-term no-till and plowed soils in southwestern Ohio. Soil and Tillage Research 66, 23-33. doi: 10.1016/S0167-1987(02)00010-7.

Lal, R., 1995. Global soil erosion by water and carbon dynamics. In: Lal, R., Kimble, J., Levine, E., Stewart, B.A. (Eds.), Soils and Global Change. CRC/Lewis Publishers, Boca Raton, Florida, pp. 131–142.

Lal, R., 2003. Soil erosion and the global carbon budget. Environment International 29, 437–450. doi: 10.1016/S0160-4120(02)00192-7.

Lal, R., 2010. Managing Soils and Ecosystems for Mitigating Anthropogenic Carbon Emissions and Advancing Global Food Security. Bioscience 60, 708–721. doi: 10.1525/bio.2010.60.9.8.

Lal, R., Pimentel, D., 2008. Soil Erosion: A Carbon Sink or Source? Science 319, 1040–1042. doi: 10.1126/science.319.5866.1040.

Lal, R., Griffin, M., Apt, J., Lave, L., Morgan, M.G., 2004a. Managing soil carbon. Science 304, 393. doi: 10.1126/science.1093079.

Lal, R., Griffin, M., Apt, J., Lave, L., Morgan, G., 2004b. Response to comments on "Managing soil carbon". Science 305, 1567d. doi: 10.1126/science.1101271.

Li, C.S., Frolking, S., Harriss, R., 1994. Modeling carbon biogeochemistry in agricultural soils. Global Biogeochemical Cycles 8, 237-254. doi: 10.1029/94GB00767.

Liu, S., Bliss, N., Sundquist, E., Huntington, T.G., 2003. Modeling carbon dynamics in vegetation and soil under the impact of soil erosion and deposition. Global Biogeochemical Cycles 17, 1074-1097. doi: 10.1029/2002GB002010.

Meybeck, M., 1982. Carbon, nitrogen, and phosphorus transport by world rivers. America Journal of Science 282, 401-450. doi: 10.2475/ajs.282.4.401.

Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. Proceedings of the National Academy of Sciences of the United States of America 104, 13268–13272. doi:10.1073/pnas.0611508104.

Polyakov, V.O., Lal, R., 2008. Soil organic matter and CO_2 emission as affected by water erosion on field runoff plots. Goederma 143, 216-222. doi: 10.1016/j.geoderma.2007.11.005.

Potter, C.S., Randerson, J.T., Field, C.B., Matson, P.A., Vitousek, P.M., Mooney, H.A., Klooster, S.A., 1993. Terrestrial ecosystem production: A process model based on global satellite and surface data. Global Biogeochemical Cycles 7, 811-841. doi: 10.1029/93GB02725.

Quinton, J.N., Govers, G., Van Oost, K., Dardgett, R.D., 2010. The impact of agricultural soil erosion on biogeochemical cycling. Nature Geoscience 3, 311-314. doi:10.1038/ngeo838.

Renwick, W.H., Smith, S.V., Sleezer, R.O., Buddemeier, R.W., 2004. Comment on “Managing Soil Carbon” (II). Science 305, 1567c.

Schlesinger, W.H., 1991. Biochemistry: An analysis on Global Change. Academic

Press, San Diego.

Smith, S.V., Renwick, W.H., Buddenmeier, R.W., Crossland, C.J., 2001. Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. Global Biogeochemical Cycles 15, 697–707. doi: 10.1029/2000GB001341.

Stallard, R.F., 1998. Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial. Global Biogeochemical Cycles 12, 231–257. doi: 10.1029/98GB00741.

Van Hemelryck, H., Fiener, P., Van Oost, K., Govers, G., Merckx, R., 2010. The effect of soil redistribution on soil organic carbon: an experimental study. Biogeosciences 7, 3971-3986. doi: 10.5194/bg-7-3971-2010.

Van Hemelryck, H., Govers, G., Van Oost, K., Merckx, R., 2011. Evaluating the impact of soil redistribution on the in situ mineralization of soil organic carbon. Earth Surface Processes and Landforms. 36, 427-438. doi: 10.1002/esp.2055.

Van Oost, K., Quine, T.A., Govers, G., De Gryze, S., Six, J., Harden, J.W., Ritchie, J.C., McCarty, G.W., Heckrath, G., Kosmas, C., Giraldez, J.V., Marques da Silva, J.R., Merckx, R., 2007. The impact of agricultural soil erosion on the global carbon cycle. Science 318, 626-629. doi: 10.1126/science.1145724.

Table 1

Discriminant Parameters for Typical Sink Watersheds [a].

No	*LCF* [b] (g m^{-2} yr^{-1})		*VCF* [c] (g m^{-2} yr^{-1})		α [f]	β [g]
	E [d]	*D* [e]	*E* [d]	*D* [e]		
1	13.2	9.6	2.5	0	0.19	0.00
2	12.8	6.8	5.7	1.4	0.45	0.21
3	16.6	14.7	5.2	2.3	0.31	0.16
4	10.6	6.4	3.2	-1.1	0.3	-0.17
5	10.1	8.5	2.4	-0.8	0.24	-0.09
6	21	14.3	5.2	-0.7	0.25	-0.05
7	6.2	3.4	1.6	-0.8	0.26	-0.24
8	3.2	3	0.7	0.1	0.21	0.03

[a] According to Van Oost et al., 2007.

[b] Lateral Carbon Flux

[c] Vertical Carbon Flux

[d] Erosion

[e] Deposition

[f] $\alpha = VCF_E / LCF_E$

[g] $\beta = VCF_D / LCF_D$

Table 2

Discriminant Parameters for Typical Source Watersheds [a].

No	*FOC* [b] (yr^{-1})		*CF* [e] (g m^{-2} yr^{-1})		*Ct* [i] (g m^{-2})	α [j]	β [k]
	h [c]	k [d]	Cr [f]	E_C [g]			
1	0.15	0.016	698	42	6550	-0.002	-
2	0.18	0.02	230	56	2400	-0.118	-
3	0.2	0.03	358	77	3720	-0.519	-
4	0.2	0.03	238	40	2860	-0.955	-
5	0.2	0.03	67	42	2090	-1.174	-
6	0.2	0.03	201	54	1860	-0.289	-

[a] According to Jacinthe and Lal, 2001

[b] First Order Coefficient

[c] First order coefficient of humification

[d] First order coefficient of oxidation

[e] Carbon Flux

[f] The input intensity of crop residues

[g] The lateral flux of eroded carbon

[h] The local carbon inventory

[i] $\alpha = (Cr \times h - Ct \times k) / E_C$

[j] The depositional part of the watershed is not included in Jacinthe and Lal's study. However, the type of CO_2 flux in the watershed is not affected, since $\alpha < 0$ (see Fig. 1).

Table 3

Parameters used in the verification of slow carbon model.

No[a]	I_B[b]	D_z[c]	D_{cul}[d]	T[e]	C_{ref}[f]	v_E[g]	v_D[h]	C_0[i]	C_{cul}[j]	k_O[k]	k_E[l]
4	75	0.5	0.3	42	3617	3.15×10^{-3}	1.91×10^{-3}	18139	2957	0.0254	0.0105
5	75	0.5	0.22	46	3540	2.27×10^{-3}	1.91×10^{-3}	17476	2429	0.0310	0.0103
7	75	0.5	0.2	46	4633	1.22×10^{-3}	0.668×10^{-3}	21461	2876	0.0262	0.00611

[a] Original serial number in Van Oost et al's [2007] work.

[b] Rate of carbon input from crop residues (g m^{-2} yr^{-1})

[c] Sampled depth (m)

[d] Cultivation depth (m)

[e] Cultivation period (yr)

[f] Carbon inventory of the sampled layer (g m^{-2})

[g] Erosion rate (m yr^{-1}), derived from ^{137}Cs inventory at the erosion sites.

[h] Depositional rate (m yr^{-1}), derived from ^{137}Cs inventory at the depositional sites.

[i] Carbon concentration at depth 0 m (g m^{-3}), $C_0 = C_{ref} / \int_0^{Dz} Cr_z dz$. See the definition of Cr_z in Fig. 2.

[j] Carbon inventory of the cultivation layer (g m^{-2}), $C_{cul} = C_0 \cdot \int_0^{Dp} Cr_z dz$

[k] First order carbon losses through oxidation (yr^{-1}), $k_O = I_B / C_{cul}$

[l] First order carbon losses through erosion (yr^{-1}), $k_E = v_E / D_{cul}$. D_{cul} (m) is the cultivation depth. The cultivation layer would be completely mixed after plough.

Table 4

Range of each factor used in scenario analysis.

k_O (yr^{-1})	v_E (m yr^{-1})	k_R	D_{cul} (m)	T (yr)
1/30~1/120 [a]	0.0001~0.01 [b]	0.35~1.05 [c]	0.1~0.3 [d]	0~100 [e]

[a] From Potter et al., 1993

[b] Form Billings et al., 2010 and Montgomery, 2007

[c] European Average varied over ± 50 %

[d] data from experienced agricultural managers

[e] it is assumed that the carbon pool becomes steady in 100 years.

Table 5

Parameter values selected for scenario analysis.

Parameter	Level		
	Low	Medium	High
k_O (yr^{-1})	0.01	0.02	0.04
v_E (m yr^{-1})	0.0001	0.001	0.01
k_R (–)	0.35	0.7	1.05
D_{cul} (m)	0.1	0.2	0.3
T (yr)	25	50	100

Table 6

Types of watersheds for each of the 243 scenarios.

v_E	T	k_R	k_O	D_{cul}	Type of watershed
L[a]	○[e]	○	○	○	Transition
H[b]	○	○	○	○	Sink
M[c]	M	○	○	○	Sink
–[d]	H	○	○	○	Sink
–	L	H	○	○	Sink
–	–	L	○	○	Transition
–	–	M	L	○	Transition
–	–	–	M	○	Transition
–	–	–	H	L	Sink
–	–	–	–	M	Sink
–	–	–	–	H	Transition

[a] Low Level

[b] Medium Level

[c] High Level

[d] Ditto mark

[e] Indicating the three levels of value lead to the same watershed type.

Figure Captions

Fig. 1. Watershed classification based on CO_2 flux.

Fig. 2. SOC profiles employed in the verification of slow carbon pool model, where (a), (b), and (c) are the SOC profiles of the No. 4, 5, and 7 watersheds considered by Van Oost et al. (2007); z is the soil depth (m), Cr_z is the ratio of carbon concentration at z (m) C_z (g m^{-3}) to the carbon concentration in the top layer C_0 (g m^{-3}).

Fig. 3. Comparison between the simulated and averaged α and β

Fig. 4. Impact of different residue return scenarios on the CO_2 flux characteristics of a watershed: (a) steady residue return; (b) sudden decrease in residue return in the 51^{st} year; and (c) sudden increase in residue return in the 51^{st} year.

Figure 1
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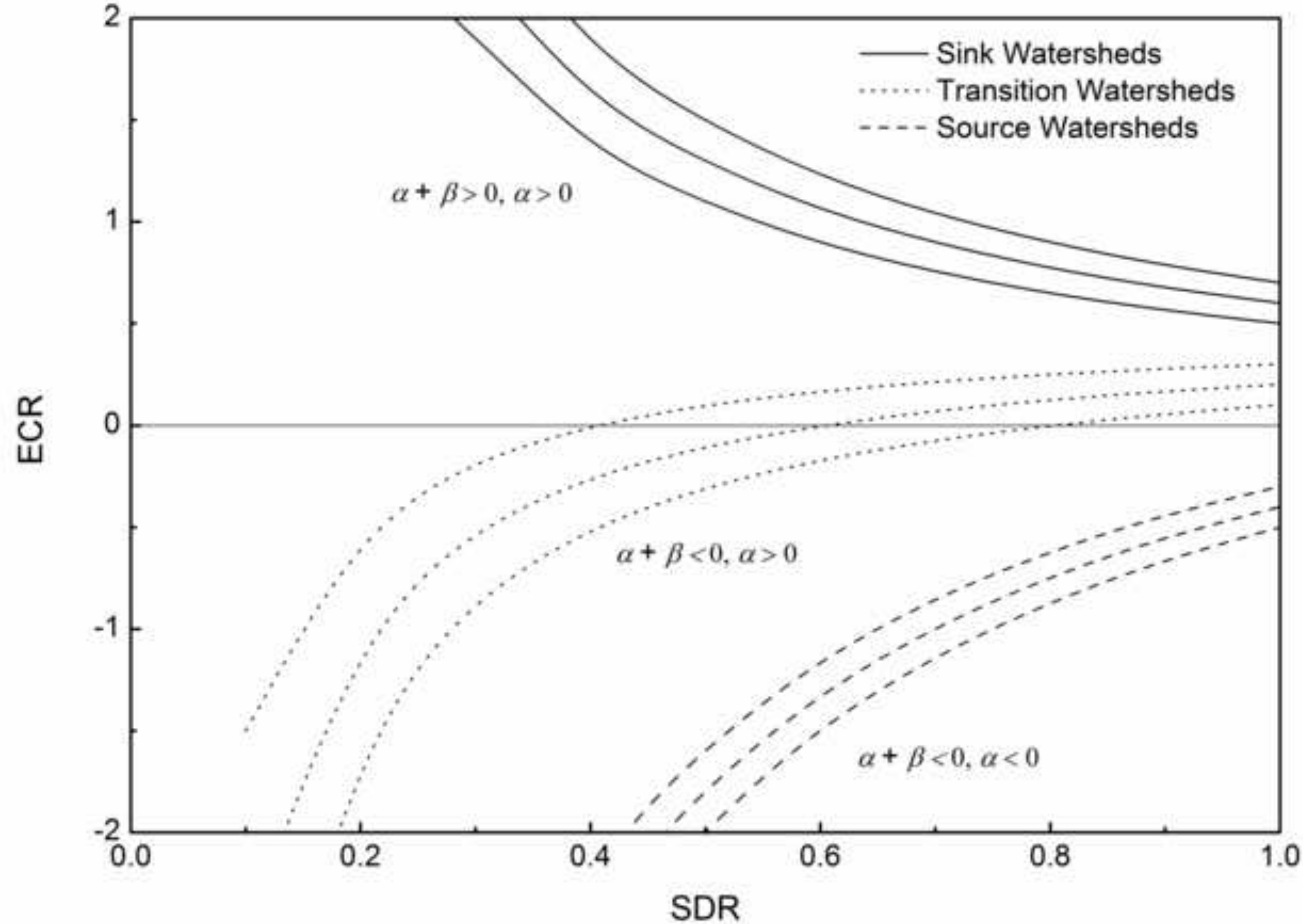

Figure 2
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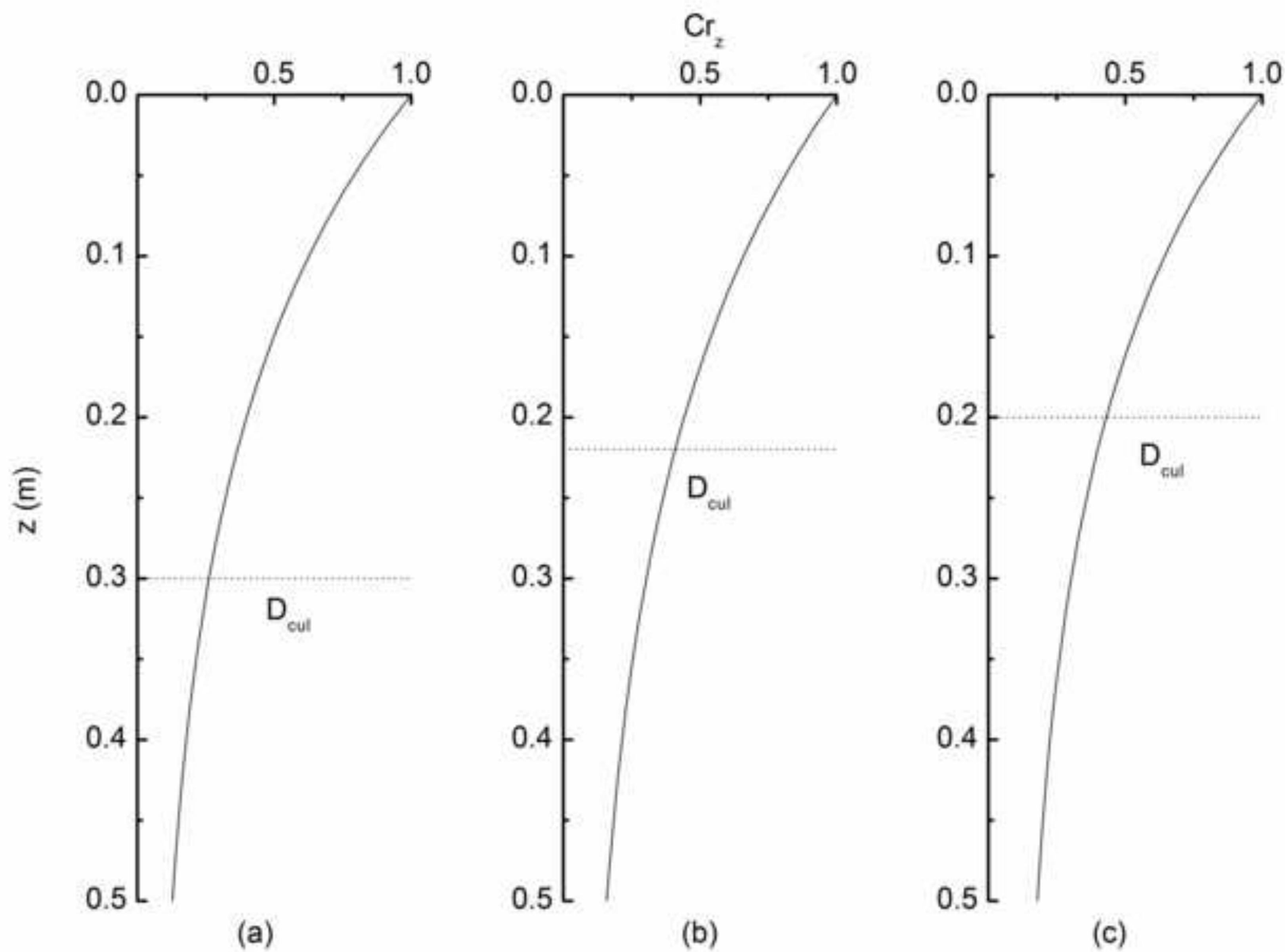

Figure 3
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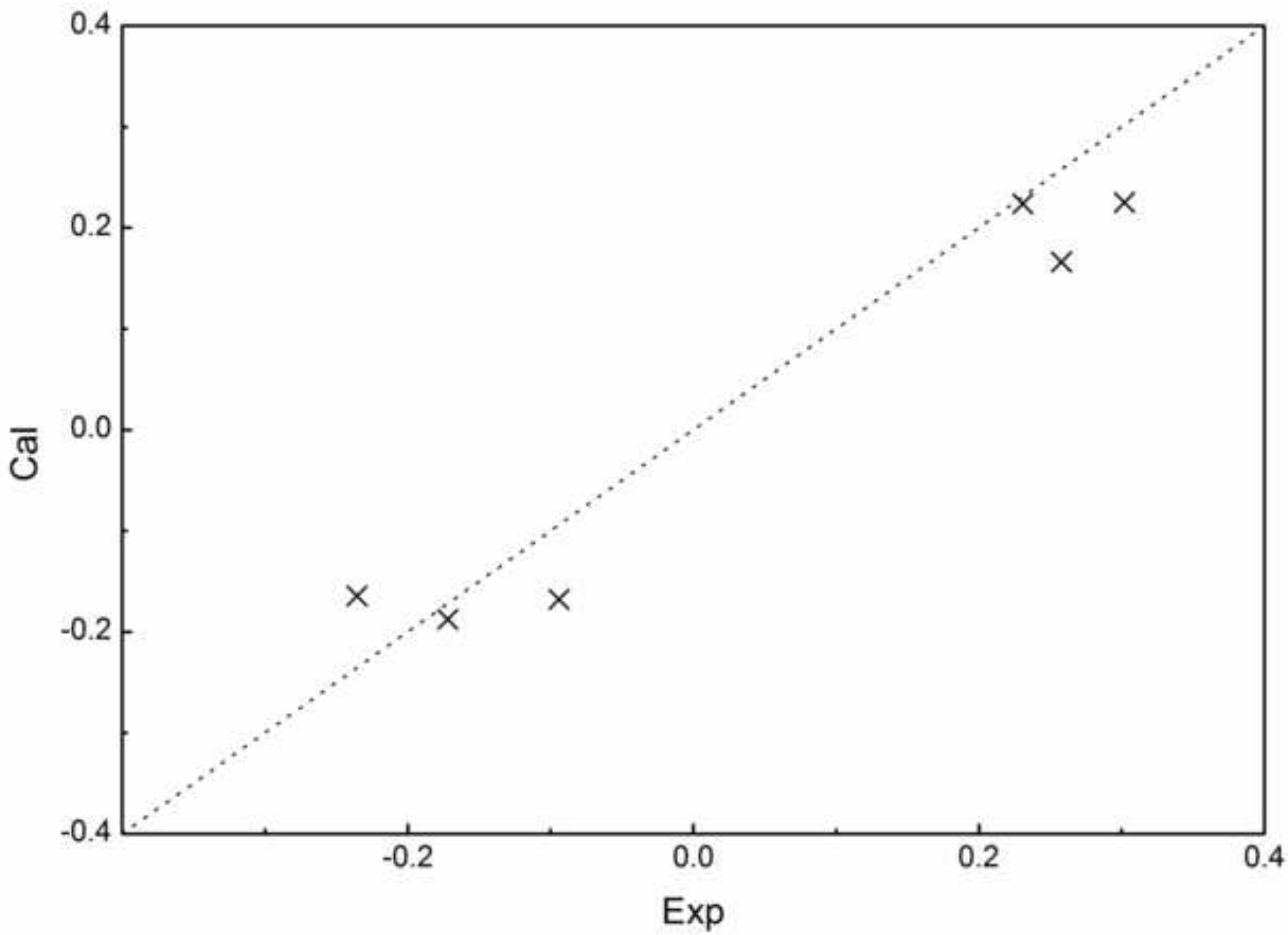

Figure 4

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