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Reconciling the paradox of soil organic carbon erosion by water

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Abstract. The acceleration of erosion, transport, and burial of soil organic carbon (OC) by water in response to agricultural expansion represents a significant perturbation of the terrestrial C cycle. Recent model advances now enable improved representation of the relationships between sedimentary processes and OC cycling, and this has led to substantially revised assessments of changes in land OC as a result of land cover and climate change. However, surprisingly a consensus on both the direction and magnitude of the erosion-induced land–atmosphere OC exchange is still lacking. Here, we show that the apparent soil OC erosion paradox, i.e., whether agricultural erosion results in an OC sink or source, can be reconciled when comprehensively considering the range of temporal and spatial scales at which erosional effects on the C cycle operate. We developed a framework that describes erosion-induced OC sink and source terms across scales. We conclude that erosion induces a source for atmospheric CO_2 when considering only small temporal and spatial scales, while both sinks and sources appear when multi-scaled approaches are used. We emphasize the need for erosion control for the benefits it brings for the delivery of ecosystem services, but cross-scale approaches are essential to accurately represent erosion effects on the global C cycle.

1 Introduction

Soil erosion has been identified as the biggest threat to global food security (Amundson et al., 2015). Reducing soil erosion to maintain or enhance soil fertility is therefore imperative to sustainably feed the growing and more demanding world population (Koch et al., 2013; Montgomery, 2007). Although there is no doubt that soil conservation practices reducing erosion result in healthier, more fertile soils, there is still a debate whether agricultural soil erosion represents a net organic carbon (OC) sink or source. Assuming that a substantial fraction of soil OC mobilized on agricultural land is lost to the atmosphere, many researchers concluded that agricultural erosion represents a source of atmospheric CO_2, with estimates of up to $1\,Pg\,OC\,yr^{-1}$ (Lal, 2004). This realization led to the notion of a win–win situation, whereby soil conservation practices that reduce soil erosion result in not only healthier soils but also an additional and large OC sink by halting the large source term associated with pre-conservation agricultural soil erosion (Koch et al., 2013; Lal, 2003, 2019; Ran et al., 2014, 2018; Worrall et al., 2016). This notion was challenged by other studies that suggested a different pathway for the eroded OC (Berhe et al., 2007; Harden et al., 1999; Van Oost et al., 2007; Smith et al., 2001; Stallard, 1998). Stallard (1998) proposed the concept of the geomorphic OC pump that transfers OC from the atmosphere to upland soils recovering from erosion to burial sites where OC is protected from decomposition in low-mineralization contexts. Along this geomorphic conveyor belt, OC originally fixed by plants is continuously displaced laterally along the earth's surface where it can be stored in sedimentary environments such as colluvial and floodplain soils, lake and reservoir sediments, and eventually the sea floor (i.e., the land–ocean aquatic continuum or LOAC) (Regnier et al., 2013). They argued that the combination of OC recovery and sedimentation on land could capture vast quantities of atmo-

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spheric C of ca. 1 Pg OC yr^{-1} and erosion therefore may represent an OC sink (Berhe et al., 2007; Smith et al., 2005; Stallard, 1998). This soil OC erosion source–sink paradox is an important knowledge gap because (i) erosion-induced OC fluxes associated with agriculture operate at rates that are relevant for the global OC budget (Aufdenkampe et al., 2011; Berhe et al., 2008; Chappell et al., 2016; Wang et al., 2017; Yue et al., 2016) and (ii) the expected future increases in food demand and climate erosivity will further exacerbate erosion and its implications for the global OC budget (Borrelli et al., 2017; Lugato et al., 2016). Here, we elucidate through a comprehensive and synthesizing literature review covering 74 studies (see Methods) how the current source–sink paradox, i.e., whether agricultural soil erosion by water represents a sink or source for atmospheric C, can be reconciled. At the very center of this paradox is the fact that water-erosion-induced processes operate across temporal and spatial scales that determine the relationship between water erosion and organic OC loss versus stabilization processes. We conceptualize the effects of the contributing water erosional (sub)processes across time and space using decay functions (see Methods). It should be noted that the available literature is biased towards humid/temperate settings where water erosion is the dominant form of erosion and drylands (where wind erosion is prevalent) are largely underrepresented.

2 Transport in runoff and rivers

At very short timescales (seconds to days) erosion events shift a portion of the soil OC from a protected state to an available state where it mineralizes to gaseous forms more rapidly. More specifically, the breakdown of aggregates, either via raindrop impact or via transport in runoff or rivers, makes previously protected mineral-associated organic matter (MAOM) and especially particulate organic matter (POM) more readily available for microbial consumption because of reduced physical occlusion (Jacinthe et al., 2002, 2004; Six et al., 2002) (Fig. 1). This facilitates the transformation of free MAOM and POM into more easily decomposable forms of OC through desorption of MAOM from mineral surfaces and comminution and dissolution of POM-derived OC (Bailey et al., 2019). Together, these processes, which can be observed during a single erosive event, result in an erosion-induced source term. Initial laboratory experiments focusing on the potential mineralization of organic OC (OC) transported by overland flow suggested that 13 % to 37 % of the transported OC could be returned to the atmosphere in a matter of several weeks, thereby representing a large and almost instantaneous source term (Guenet et al., 2014; Jacinthe et al., 2002, 2004). These high proportions of mineralizable OC were related to the preferential erosion and translocation of labile OC. Further experimental work and field observations based on in situ measurements suggested that the net erosion-induced source term, i.e., relative to non-eroded soils, was much smaller with fractional losses of only 4 ± 4.2 % (Van Hemelryck et al., 2010, 2011; Polyakov and Lal, 2008; X. Wang et al., 2014). In addition, at larger spatial scales the destabilization of eroded OC during its transport in rivers and estuaries has to be considered, and the oxidation of OC during in-river transport can be substantial (Aufdenkampe et al., 2011; Wang et al., 2017; Worrall et al., 2016). During fluvial transport, fluid turbulence mixes and aerates water, and in combination with particle abrasion, this may enhance oxidation. The oxidation of particulate organic OC mobilized by agricultural erosion during its transit time in the aquatic system is assumed to be large with estimates ranging between 0 % and 50 % (Scheingross et al., 2019; Worrall et al., 2014). Based on this literature review, we estimate the loss terms for runoff and rivers, i.e., α_{runoff} and α_{river}, at -0.04 and $-$SDRx0.5, respectively (where SDR is the fraction of the eroded OC that reaches the river network). This outgassing is usually observed to occur quickly in the time frame of several days to months. We therefore set the time constant for both processes (i.e., τ_{runoff} and τ_{river}) to 1 year. Our literature review (Fig. 2) clearly shows that studies reporting erosion as a source term typically consider mobilization and transport processes at very short timescales (0.5 ± 0.7 years). Thus, studies assuming that this short-term erosion-induced loss term is the dominant process concluded that agricultural erosion represents a large source of atmospheric CO_2.

3 Soil OC recovery after erosion

In contrast, studies considering erosion as a sink for atmospheric C typically consider longer timescales at which the geomorphic OC conveyor belt is operating; i.e., the net outcome of the geomorphic OC conveyor belt strongly depends on the OC sink mechanisms induced by erosion of upland soils (Manies et al., 2001; Van Oost et al., 2007; Stallard, 1998; Vandenbygaart et al., 2012). On eroding hillslopes, soils are truncated, and OC depleted subsoil material is brought to the surface layers. This induces two competing processes occurring simultaneously: the decomposition of old subsoil OC and the sequestration and stabilization of fresh OC inputs from newly growing plants. The exposure of deep OC by erosion of surface soil and associated changes in microclimatic conditions increase the rate of deep OC decomposition (Bailey et al., 2019). Furthermore, the mixing of formerly deep OC with labile OC provides readily available energy sources for decomposers, which speeds up the decomposition rate of older, previously stable OC, the so-called priming effect (Fontaine et al., 2007). At the same time, new OC formation from new vegetation inputs into the former subsoil may replace some or all of the eroded soil OC; i.e., erosion-induced soil truncation facilitates the new formation of more stable MAOM by the adsorption of products from POM decomposition and dissolved organic carbon

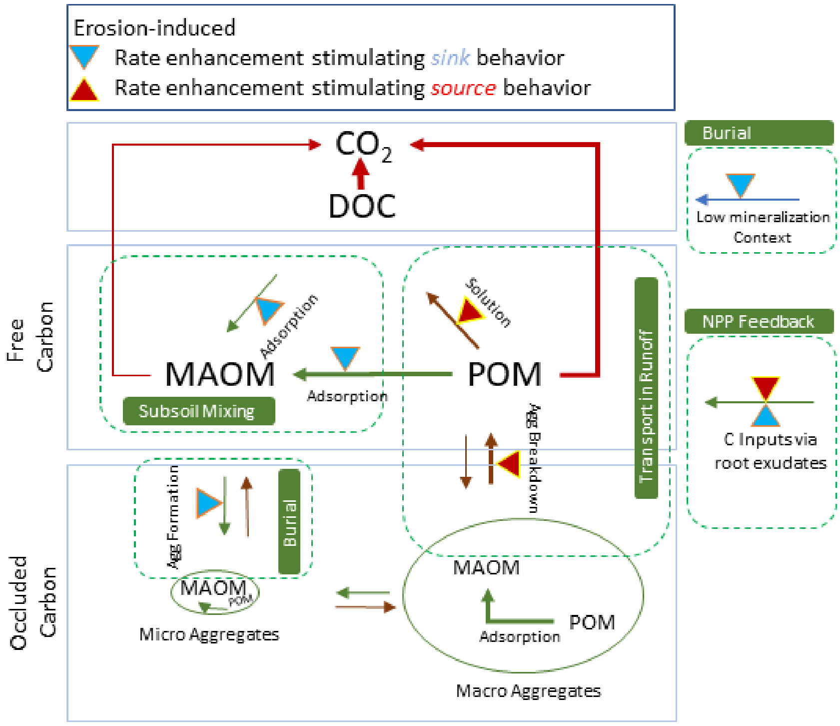

Figure 1. Schematic representation of the effect of water erosion and deposition on soil OC stabilization and loss processes. Transport in runoff: detachment and transport can shift OC from a protected state in aggregates to an available state where it mineralizes more rapidly. Burial: the deposition of eroded OC moves OC into a low-mineralization context and can also enhance protection via aggregation. Subsoil mixing: at sites of erosion new OC formation from new vegetation inputs into exposed subsoil by erosion may replace some of the eroded OC. Net primary production (NPP) feedback: erosion and deposition may affect the nutrient and soil depth status (and hence soil fertility) as well as the environmental factors that control OC input versus output.

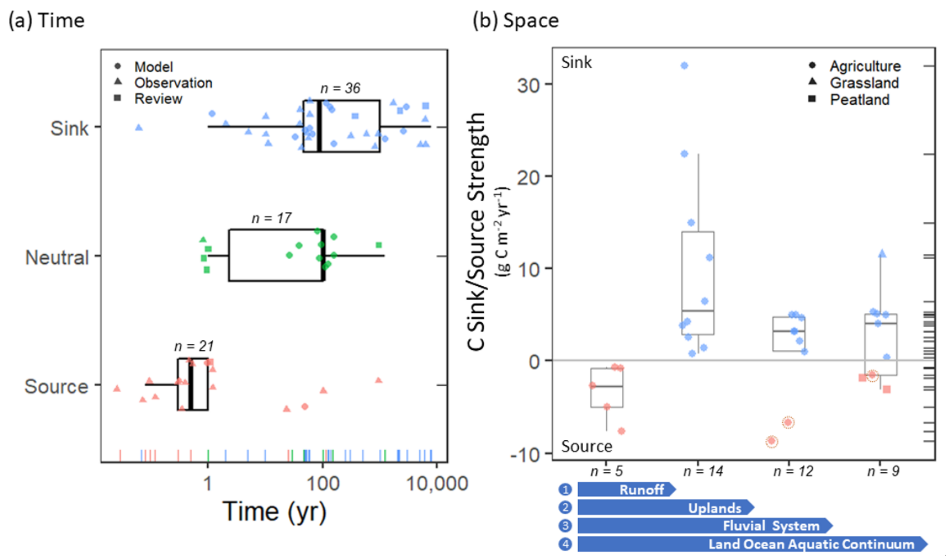

Figure 2. Effect of time and space on the erosional sink versus source term reported in the literature. Panel **(a)** shows how the reported OC source versus sink by water erosion is influenced by the timescale considered in the study (74 studies). Panel **(b)** shows how the magnitude of the reported water-erosion-induced OC source–sink strength is influenced by the spatial scale considered in the study (40 studies). We classify the studies in four spatial scales along the geomorphic cascade (see Table 1): (1) studies that only consider runoff in uplands; (2) studies that provide an assessment at the scale of eroding uplands (eroding soils and colluvium); (3) studies that consider eroding soils, colluvium, and alluvium; and (4) studies that consider the full geomorphic cascade (including the aquatic component). Estimates which do not account for OC recovery at eroding sites for scales 3 and 4 are encircled with a dotted line. Further details on the studies used are given in Table 1.

(DOC) derived from plant material onto mineral surfaces of the former subsoil (Fig. 1), thereby representing a net transfer of OC from the atmosphere to soils (Harden et al., 1999; Li et al., 2015; Liu et al., 2003; Wang et al., 2017). Observations covering a broad range of environmental conditions have shown that a substantial part of the eroded soil OC in agricultural soils can be replaced by new OC and dominates over the enhanced destabilization of deep OC (Li et al., 2015; Liu et al., 2003; Van Oost et al., 2007; Wang et al., 2017). This leads to the counterintuitive situation where a system exhibiting lateral OC loss due to erosion represents a net atmospheric sink (at the scale of eroding hillslopes). In contrast to the short-term source term described above, the underlying processes leading to an erosion-induced sink term operate at a slower rate but occur at 70 %–90 % of the affected surface, whereas the source term is spatially restricted to depositional areas (Dlugoß et al., 2012). Thus, the sink term is more difficult to isolate from the much larger background OC fluxes between soil and atmosphere, particularly at short timescales. By using OC isotopes and fallout radionuclides, in combination with space-for-time substitutions spanning several years to decades, studies have conclusively shown that a substantial part of the laterally eroded OC can be effectively replaced (50 ± 43 %) (Li et al., 2015; Quine and van Oost, 2007; Vandenbygaart et al., 2012), whereby this erosion-induced sink term was substantially larger than the source term related to erosion-induced OC destabilization (Wang et al., 2017). Our literature review clearly shows that studies reporting OC erosion recovery as a sink term typically consider these longer timescales (91 ± 1098 years) (Fig. 2).

The OC recovery potential of soils at the scale of eroding hillslopes, which is driving the OC sink term of the geomorphic pump, is however in itself also time-dependent. In the initial phases after the start of an erosional disturbance, the soil is not yet in equilibrium with the erosional disturbance and only a small fraction of the eroded OC is replaced, which leads to only a small erosion-induced sink (Fig. 3). There is, however, a transient response where the OC stocks at the eroding sites continue to decline until a new equilibrium is reached, i.e., when losses through decomposition and lateral erosion balance new OC formation. At this point, the erosion loss term is part of a steady-state flux where all the eroded OC is atmospherically replaced and the sink term potential is maximized (Li et al., 2015). For example, for European cropland subjected to a recent erosional disturbance of 2 decades associated with mechanized tillage, a sink-term representing only 26 % of the eroded OC was found (Van Oost et al., 2007). In contrast, for cropland subjected to > 100 years of continued water erosion, replacement fractions of 58 %–100 % were found (Dymond, 2010; Li et al., 2015; Naipal et al., 2020). Thus, both observation- and model-based studies support the notion that the fraction of the eroded OC that is replaced, and hence the erosion-induced sink term increases with the duration of the erosional disturbance (Fig. 3). This transient response of eroding landscapes to erosional disturbance is a key control on the erosion-induced sink strength (Li et al., 2015; Van Oost et al., 2007; Wang et al., 2017) but is often overlooked in OC budget assessments (e.g., Lugato et al., 2016, 2018; Worrall et al., 2014).

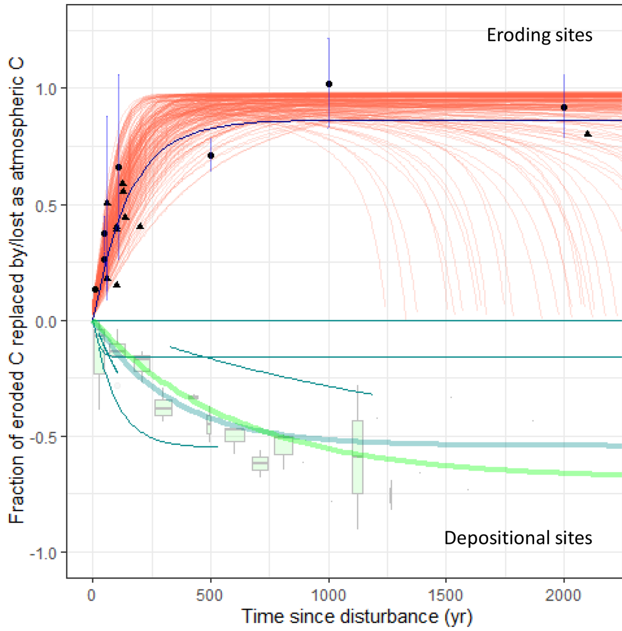

Figure 3. Fraction of eroded OC replaced by atmospheric CO_2 as a function of time since the start of agricultural erosion at eroding sites (upper part) and depositional sites (lower part). For the eroding sites, studies using mass balance (circles) and models (triangle) are considered. The error bars denote the reported uncertainty range. The bold blue line denotes a fit of a non-linear regression model through the reported soil OC recovery data points. The fine red lines represent the results of 100 model runs covering a range of typical erosion and OC turnover rates representative of global agricultural land. We use the model for cropland presented by Quinton et al. (2010). Erosion rates were allowed to vary randomly between 0.1 and 0.2 mm yr^{-1}, and soil OC residence time for the top layer varied between 200 and 1000 years. For the feedback scenario, we assumed negative feedback that ranged randomly between 3 % and 5 % yield loss for each 10 cm of cumulative erosion (Bakker et al., 2004). The green boxplots represent oxidation in colluvial settings ($n = 255$; see Table 2). The thin cyan lines represent the non-linear regression models for five alluvial studies ($n = 273$; see Table 2). The thick green and cyan lines represent the response curves for colluvial and alluvial burial using the median values for α and τ.

It is important to note, however, that at eroding sites, an erosion-induced decline in net primary production (NPP) may reduce soil OC inputs, and this may limit the sink term described above (Lal, 2019). Soil erosion reduces soil depth and modifies soil properties, which can have a detrimental effect on NPP through the decrease in the supply of water, nutrients, and rooting space (Fig. 1). Model simulations (Fig. 3) show that NPP decline reduces the efficiency of the sink term and may eventually lead to a source rather than a sink under high-erosion scenarios. Although there are documented cases where soil loss has contributed to the collapse of the soil system (e.g., Montgomery, 2007; Óskarsson et al., 2004), the available evidence from present-day agricultural land suggests that erosion-induced soil OC input decline is not the dominant mechanism (Lugato et al., 2018) but rather that OC stabilization in newly exposed subsoil results in efficient soil organic carbon (SOC) recovery and the sink term is maintained over longer timescales (Wang et al., 2017) (Fig. 3). This is most likely due to a small fraction (i.e., $< 10\,\%$) of NPP being removed by erosion (Berhe et al., 2008) and that the available observations are biased towards fertile soils in high-input systems (see Sect. 5). Based on the data available in the literature, we estimate the fractional gain at steady state for the SOC recovery term (α_{rec}) at 0.93, while the time constant (τ_{rec}) equals 167 years (Fig. 3).

4 Soil OC burial

The erosion source–sink paradox is also related to an incomplete consideration of the multiple spatial scales at which OC and erosion processes interact. After mobilization, the eroded OC is transported and a large amount of eroded sediment and OC is redeposited in alluvial and colluvial soils, while the remainder is stored in lake/reservoir deposits and ocean sediments (Aufdenkampe et al., 2011). At the global scale, colluvial and alluvial burial represent by far the largest stores of OC burial (75 %) (Wang et al., 2017). Here, the eroded OC is more efficiently protected from destabilization, relative to their origin, due to re-aggregation, the formation of MAOM, and the burial of autochthonous OC (Fig. 1). However, high rates of post-depositional OC losses in colluvial and alluvial soils have been observed with low OC burial efficiencies of only 15 %–30 % at a centennial–millennial timescale, whereas OC is preserved more efficiently in lake and ocean deposits with OC burial efficiencies of 22 %–60 % (Van Oost et al., 2012; Wang et al., 2017). This leads to the counterintuitive situation where systems receiving lateral OC inputs accumulate OC but represent a source for atmospheric C. It has been observed that OC destabilization in terrestrial burial stores is a very slow process, with half-lives of up to 300 years (Van Oost et al., 2012), and OC losses therefore lag OC burial. At decadal timescales, several studies reported no significant outgassing and hence a full protection of the buried OC (Van Oost et al., 2007; VandenBygaart et al., 2015). This lag implies that there is a commitment to the future climate as the result of both present and past agriculture and associated erosion and burial. Based on our literature review, we found a large variability in SOC burial response curves (α_{bur} and τ_{bur}, Table 1), particularly for alluvial settings. This variability is most likely driven by climatic factors that regulate the hydrologic context, by local NPP, and by differences in soil texture and geochemical parameters. Nevertheless, we found a consistent pattern across burial sites with a median α_{bur} and τ_{bur} of 0.58 and 0.0019 years, respectively.

5 Implication of soil OC erosion by water for the OC budget

Using parameter values for α and τ for the different processes constrained by published estimates as presented above and summarized in Table 2, we developed a framework where the instantaneous source terms associated with runoff and river transport are combined with the transient source–sink terms associated with oxidation during burial and SOC recovery on sites of erosion (Fig. 4). The model shows that OC stocks in stores along the LOAC are not necessarily in equilibrium with the erosional disturbance, and it is thus critical to consider the dynamic phases of both OC recovery at sites of erosion and OC destabilization in sedimentary environments. Furthermore, the time since agricultural disturbance and the residence times of OC in sedimentary environments are critical factors to consider. Considering all these processes reconciles the apparent soil OC erosion paradox by showing that both major source and sink terms for atmospheric C are simultaneously induced by water erosion. The contrasting views that water erosion represents a large sink or a source originate from a partial analysis and an incomplete consideration of the underlying processes that occur at vastly different spatial and temporal scales. When a comprehensive analysis is done by considering the complete trajectory of eroded OC (i.e., the LOAC) at the appropriate timescales, the available evidence indicates that the sink and source terms are on the same order of magnitude. This implies that the assertations of a very large effect of agricultural erosion on the global OC budget, with a net OC flux of up to 1 to 2 Pg OC yr^{-1} (Berhe et al., 2007; Lal, 2004; Smith et al., 2005), are inconsistent with integrative assessments.

Although recent work has provided full spatial integrative assessments along the LOAC, the transient response of both terrestrial and aquatic ecosystems to erosion (Van Oost et al., 2012; Wang et al., 2017) as well as the outgassing of non-CO_2 greenhouse gases (Lal, 2019; Wang et al., 2017; Worrall et al., 2016) requires more attention. Our results suggest that recently converted cropland represents a source, while a switch to a sink is observed after circa 4 decades (Fig. 4), but large uncertainties remain. In particular, the outgassing of OC in burial sites (Table 2 and Fig. 4) and the effects of selective erosion and deposition are poorly constrained (Doetterl et al., 2016). It is also important to note that the available estimates are strongly biased towards high-input agricultural systems in humid/temperate settings with deep fertile soils developed on sedimentary substrates, and thus more data on low-input systems on marginal lands and drylands are urgently needed. While we emphasize the necessity of programs to reduce soil losses because of the many benefits this brings for soil quality and delivery of ecosystems services, we urge considering both OC sink and source terms at appropriate scales when assessing the effect of erosion on the global C cycle.

Table 1. Overview of studies reporting erosion-induced OC fluxes used in our literature synthesis. Space refers to the four components of the geomorphic cascade (see Fig. 2 for key). Positive values for OC strength denote a sink, while negative values denote a source. Methods are categorized as "Data" or "Mod" (model) based. Modeling studies using scenario analysis are reported as "Mod/Scen", and a range for the sink–source strength is given. "Rec" denotes the fraction (in %) of the eroded OC that is replaced with atmospheric derived OC. Studies assuming steady state were assigned a timescale of 1 year.

Reference	Year	Method	Time (years)	Effect	Strength ($g\,OC\,m^{-2}\,yr^{-1}$)	Space	Rec (%)	Dominant land cover
Stallard (1998)	1996	Data	250	Sink	5.3	4		Agriculture
Harden et al. (1999)	1999	Mod	130	Sink	15	2	55.3	Agriculture
Smith et al. (2001)	2001	Data	10	Sink	5.1	4		Agriculture
Manies et al. (2001)	2001	Mod	137	Sink	22.4	2		Agriculture
Lal (2001)	2001	Review	1	Neutral	–	4		Agriculture
Jacinthe et al. (2002)	2002	Data	0.5	Source	−0.81	1		Agriculture
Lal (2003)	2003	Review	1	Source	−7.6	1		Agriculture
Liu et al. (2003)	2003	Mod	122	Sink	1.4	2	58.8	Agriculture
Lal (2004)	2004	Review		Source	−5.3	1		
Óskarsson et al. (2004)[c]	2004	Data	1000	Source[c]	−1.5	4		Agriculture
Jacinthe et al. (2004)	2004	Data	0.1	Source	−0.73	1		Agriculture
Page et al. (2004)	2004	Data	114	Source	–	4		Grassland
Yoo et al. (2005)	2005	Data	5000	Sink	1	2	100	Grassland
Van Oost et al. (2005)	2005	Mod	150	Sink	6.5	2	40.4	Agriculture
Smith et al. (2005)	2005	Data	10	Sink	5	4		Agriculture
Lal (2005)	2005	Review	1	Neutral	−7.6/7.6	3		Agriculture
Rosenbloom et al. (2006)	2006	Mod	3000	Sink	–	2		Grassland
Quinton et al. (2006)	2006	Mod	1	Sink	4.96	3		Agriculture
Van Oost et al. (2007)	2007	Data	47	Sink	3.8	2	26	Agriculture
Quine and van Oost (2007)	2007	Data	50	Sink	11.2	2	37.3	Agriculture
Berhe et al. (2007)	2007	Review	2150	Sink	3.98	4		
Ito (2007)	2007	Mod	1	Source	−5	1		Agriculture
Mora et al. (2007)	2007	Data	0.03	Source	–	1		Agriculture
Polyakov and Lal (2008)	2008	Data	0.3	Source	−2.74	1		Agriculture
Berhe et al. (2008)	2008	Data	6000	Sink	–	2		Grassland
Kuhn et al. (2009)	2009	Review	1200	Neutral	–	3		Agriculture
Van Oost et al. (2009)	2009	Review	300	Sink	–	2		Agriculture
Boix-Fayos et al. (2009)	2009	Data	50	Sink	–	3		Agriculture
Dymond (2010)	2010	Data	10/3000/110	Sink	2.2/4.5/11	4	66–100	Grassland/agriculture
Billings et al. (2010)	2010	Mod/Scen	150	Neutral	−21/60	2		Agriculture
Van Hemelryck et al. (2010)	2010	Data[a]	0.5	Source	–	1		Agriculture
Quinton et al. (2010)	2010	Review	1	Neutral		3		Agriculture
Wang et al. (2010)	2010	Data	2	Sink	–	2		Agriculture
Aufdenkampe et al. (2011)	2011	Data	10	Sink	–	3		
Van Hemelryck et al. (2011)	2011	Data	0.5	Source	–	1		Agriculture
Van Oost et al. (2012)	2012	Data	500	Sink	5	3	71	Agriculture
Ni et al. (2012)	2012	Mod/Scen	47	Neutral	–	2		Agriculture
Nadeu et al. (2012)	2012	Data	52	Sink	–	3		Agriculture
Vandenbygaart et al. (2012)	2012	Data	50	Sink	–	2		Agriculture
Dlugoß et al. (2012)	2012	Mod	57	Sink	0.8	2		Agriculture
Yue et al. (2012)	2012	Data	48	Sink	0.32	4		Agriculture
Hoffmann et al. (2013a)	2013	Data	7500	Sink	1.05	3		Agriculture
Hoffmann et al. (2013b)	2013	Review	8000	Sink	–	3		Agriculture
Zhang et al. (2014)	2014	Mod	29	Neutral	−20/25.3	2		Agriculture
Worrall et al. (2014)	2014	Data	1	Source	−3.1	4		Peatland[b]
Kirkels et al. (2014)	2014	Review		Neutral	–			
Ran et al. (2014)[c]	2014	Mod	50	Source[c]	−6.64	3		Agriculture
X. Wang et al. (2014)	2014	Data[a]	0.3	Source	−48	2		Agriculture
Guenet et al. (2014)	2014	Data	0.12	Source	–	1		Agriculture
Li et al. (2015)	2015	Data	1000	Sink	32	2	102	Agriculture
Nadeu et al. (2015)	2015	Mod	30	Sink	2.6	2	40	Agriculture
VandenBygaart et al. (2015)	2015	Data	50	Sink	–	2		Agriculture
Müller-Nedebock and Chaplot (2015)	2015	Data	1	Neutral	–	1		Agriculture
Fiener et al. (2015)	2015	Mod	57	Sink	4.25	2		Agriculture
Yue et al. (2016)	2016	Mod	60	Sink	4.73	3	18–50	Agriculture
Lugato et al. (2016)	2016	Mod/Scen	100	Neutral	−0.3/0.2	2		Agriculture
Zhao et al. (2016)	2016	Data	5	Sink	3.16	3		Agriculture

Table 1. Continued.

Reference	Year	Method	Time (years)	Effect	Strength ($g\,OC\,m^{-2}\,yr^{-1}$)	Space	Rec (%)	Dominant land cover
Dialynas et al. (2016a)	2016	Mod/Scen	100	Neutral	−14.5/18.2	3		Agriculture
Worrall et al. (2016)	2016	Data	1	Source	−1.8	4		Peatland[b]
Doetterl et al. (2016)	2016	Review		Neutral	–			
Olson et al. (2016)	2016	Review		Source	–	1		
Dialynas et al. (2016b)	2016	Mod/Scen	100	Neutral	−18.3/21.5	3		Forest
Novara et al. (2016)	2016	Data[a]	0.3	Source	–	1		Agriculture
Hu et al. (2016)	2016	Data	0.08	Source	–	1		Agriculture
Wang et al. (2017)	2017	Data	2000	Sink	4	4	92	Agriculture
Bouchoms et al. (2017)	2017	Mod	1000	Sink	3.19	3		Agriculture
Dialynas et al. (2017)	2017	Mod/Scen	100	Neutral	−10.3/8.4	3		Agriculture
Lugato et al. (2018)	2018	Mod/Scen	150	Neutral	−3/0.5	2	14.7	Agriculture
Remus et al. (2018)	2018	Data	0.07	Sink		2		Agriculture
Ran et al. (2018)[c]	2018	Data	25	Source[c]	−8.7	3		Agriculture
Xiao et al. (2018)	2018	Review		Neutral	–	3		Agriculture
Naipal et al. (2020)	2019	Mod	2100	Sink	2.1	3	80	Agriculture
Billings et al. (2019)	2019	Mod/Scen	100	Neutral	−41.8/55.5	2		Forest
Lal (2019)	2019	Review		Source	–	4		Agriculture

[a] Manipulation experiments. [b] Particulate organic matter sources dominated by organic soils from peatlands. [c] OC recovery on eroding soils is not considered in overall effect.

Table 2. Estimates of α and τ reported in the literature. Estimates are derived from a non-linear regression using Eq. (1).

Reference	α	τ	r^2	n	Range years
Oxidation burial (colluvial)					
Van Oost et al. (2012)	0.76 (±0.014)	0.0014 (±0.0001)	0.95	9 (309)	0–2436
Z. Wang et al. (2014)	0.82 (±0.10)	0.0016 (±0.00004)	0.82	29	0–1388
Mayer et al. (2018)[a]	0.53 (±0.035)	0.0007 (±0.0001)	0.91	5	0–5480
Zeng et al. (2020)	0.14 (±0.01)	0.26 (±0.11)	0.025	211	0–49
Oxidation burial (alluvial)					
Omengo et al. (2016)	0.54 (±0.01)	0.014 (±0.0.001)	0.42	258	0–420
Steger et al. (2019)[a]	0.84 (±6.2)	0.003 (±0.03)	0.81	3	0–105
Mayer et al. (2018)[a]	0.59 (±0.38)	0.0006 (±0.0006)	0.92	4	0–1190
Colluvial + alluvial[b]	0.54 (±0.24)	0.008 (±0.097)	0.67	586	
Oxidation runoff					
Median (see text)	0.04	1	–	–	0–1
Oxidation river					
Median (see text)	0.5	1	–	–	–
Recovery					
See text	0.86 (±0.08)	0.0060 (±0.001)	0.73	17	0–2000

[a] Two observations from Mayer et al. (2018) and one from Steger et al. (2019) with very high local NPP inputs (organic layers) were discarded; the values presented here are therefore a conservative estimate of OC burial efficiencies. [b] Considering all data from alluvial and colluvial studies.

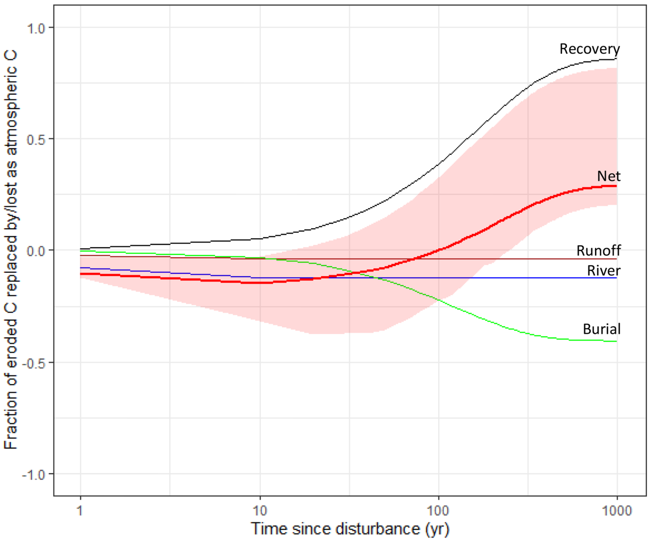

Figure 4. Framework to represent fraction gain/loss relative to mobilized soil OC for the different components of the geomorphic cascade. The example shown here (full lines) uses the best estimates of model parameters described in the text and given in Table 2 (i.e., $\alpha_{runoff} = 0.04$, $\tau_{runoff} = 1$, $\alpha_{river} = 0.5$, $\tau_{river} = 1$, $\alpha_{burial} = 0.54$, $\tau_{burial} = 0.008$, $\alpha_{recovery} = 0.86$, $\tau_{recovery} = 0.006$). The red shaded area represents the uncertainty associated with the model parameters for the net overall effect (see Methods).

6 Methods

We use the following model to describe system responses (Eq. 1):

$$R_t = \alpha \left(1 - e^{-\frac{t}{\tau}}\right), \quad (1)$$

where R_t is the erosion-induced OC loss/gain at time t of process R, expressed as a fraction of the mobilized OC; t is the time since the start of the erosional disturbance; α is the fractional OC loss/gain at steady state; and τ is the time constant that describes the pace at which the process is adjusting to the erosional disturbance. We compiled 74 studies that were available in the literature and that report on SOC erosion as a sink or source of atmospheric C. We used the search terms "soil erosion" & "OC sink"/"OC source/OC budget" in the Scopus database. This was complemented with review papers and references cited herein. From these studies we extracted whether they report water erosion as a sink, source, or neutral (if no OC flux direction is given). The data were complemented with the spatial and temporal scales considered as well as the OC flux rates (lateral and vertical fluxes). The studies considered are shown in Table 1. The statistics reported in the main text represent the median value ± interquartile range. To assess the uncertainties associated with the modeling presented in Fig. 4, we performed a Monte Carlo analysis where all parameters were allowed to vary assuming a normal distribution and the mean and standard deviation reported in Table 2 or the main text. For the SDR, we assumed a uniform distribution with a range of 0.15 and 0.35. We present the 16th and 84th percentiles of 100 simulations as an uncertainty range in Fig. 4.

Data availability. The data used in this study are presented in detail in Tables 1 and 2 and are derived from published work cited therein.

Author contributions. KVO and JS designed the study. KVO and JS acquired the research funding. KVO wrote the original draft with input from JS.

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References

Amundson, R., Berhe, A. A., Hopmans, J. W., Olson, C., Sztein, A. E., and Sparks, D. L.: Soil and human security in the 21st century, Science, 348, 1261071, https://doi.org/10.1126/science.1261071, 2015.

Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., Aalto, R. E., and Yoo, K.: Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere, Front. Ecol. Environ., 9, 53–60, https://doi.org/10.1890/100014, 2011.

Bailey, V. L., Pries, C. H., and Lajtha, K.: What do we know about soil carbon destabilization?, Environ. Res. Lett., 14, 083004, https://doi.org/10.1088/1748-9326/ab2c11, 2019.

Bakker, M. M., Govers, G., and Rounsevell, M. D. A.: The crop productivity-erosion relationship: An analysis based on experimental work, Catena, 57, 55–76, https://doi.org/10.1016/J.CATENA.2003.07.002, 2004.

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

Berhe, A. A., Harden, J. W., Torn, M. S., and Harte, J.: Linking soil organic matter dynamics and erosion-induced terrestrial carbon sequestration at different landform positions, J. Geophys. Res.-Biogeo., 113, G04039, https://doi.org/10.1029/2008JG000751, 2008.

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

Billings, S. A., Richter, D. D. B., Ziegler, S. E., Prestegaard, K., and Wade, A. M.: Distinct contributions of eroding and depositional profiles to land-atmosphere CO_2 exchange in two contrasting forests, Front. Earth Sci., 7, 36, https://doi.org/10.3389/feart.2019.00036, 2019.

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

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Montanarella, L., and Panagos, P.: An assessment of the global impact of 21st century land use change on soil erosion, Nat. Commun., 8, 2013, https://doi.org/10.1038/s41467-017-02142-7, 2017.

Bouchoms, S., Wang, Z., Vanacker, V., Doetterl, S., and Van Oost, K.: Modelling long-term soil organic carbon dynamics under the impact of land cover change and soil redistribution, Catena, 151, 63–73, https://doi.org/10.1016/j.catena.2016.12.008, 2017.

Chappell, A., Baldock, J., and Sanderman, J.: The global significance of omitting soil erosion from soil organic carbon cycling schemes, Nat. Clim. Chang., 6, 187–191, https://doi.org/10.1038/nclimate2829, 2016.

Dialynas, Y. G., Bastola, S., Bras, R. L., Marin-Spiotta, E., Silver, W. L., Arnone, E., and Noto, L. V.: Impact of hydrologically driven hillslope erosion and landslide occurrence on soil organic carbon dynamics in tropical watersheds, Water Resour. Res., 52, 8895–8919, https://doi.org/10.1002/2016WR018925, 2016a.

Dialynas, Y. G., Bastola, S., Bras, R. L., Billings, S. A., Markewitz, D., and Richter, D. D.: Topographic variability and the influence of soil erosion on the carbon cycle, Global Biogeochem. Cy., 30, 644–660, https://doi.org/10.1002/2015GB005302, 2016b.

Dialynas, Y. G., Bras, R. L., and deB. Richter, D.: Hydro-geomorphic perturbations on the soil-atmosphere CO_2 exchange: How (un)certain are our balances?, Water Resour. Res., 53, 1664–1682, https://doi.org/10.1002/2016WR019411, 2017.

Dlugoß, V., Fiener, P., Van Oost, K., and Schneider, K.: Model based analysis of lateral and vertical soil carbon fluxes induced by soil redistribution processes in a small agricultural catchment, Earth Surf. Proc. Land., 37, 193–208, https://doi.org/10.1002/esp.2246, 2012.

Doetterl, S., Berhe, A. A., Nadeu, E., Wang, Z., Sommer, M., and Fiener, P.: Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address OC cycling in dynamic landscapes, Earth-Sci. Rev., 154, 102–122, https://doi.org/10.1016/j.earscirev.2015.12.005, 2016.

Dymond, J. R.: Soil erosion in New Zealand is a net sink of CO_2, Earth Surf. Proc. Land., 35, 1763–1772, https://doi.org/10.1002/esp.2014, 2010.

Fiener, P., Dlugoß, V., and Van Oost, K.: Erosion-induced carbon redistribution, burial and mineralisation – Is the episodic nature of erosion processes important?, Catena, 133, 282–292, https://doi.org/10.1016/j.catena.2015.05.027, 2015.

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

Guenet, B., Danger, M., Harrault, L., Allard, B., Jauset-Alcala, M., Bardoux, G., Benest, D., Abbadie, L., and Lacroix, G.: Fast mineralization of land-born OC in inland waters: First experimental evidences of aquatic priming effect, Hydrobiologia, 721, 35–44, https://doi.org/10.1007/s10750-013-1635-1, 2014.

Harden, J. W., Sharpe, J. M., Parton, W. J., Ojima, D. S., Fries, T. L., Huntington, T. G., and Dabney, S. M.: Dynamic replacement and loss of soil carbon on eroding cropland, Global Biogeochem. Cy., 13, 885–901, https://doi.org/10.1029/1999GB900061, 1999.

Hoffmann, T., Schlummer, M., Notebaert, B., Verstraeten, G., and Korup, O.: Carbon burial in soil sediments from Holocene agricultural erosion, Central Europe, Global Biogeochem. Cy., 27, 828–835, https://doi.org/10.1002/gbc.20071, 2013a.

Hoffmann, T., Mudd, S. M., van Oost, K., Verstraeten, G., Erkens, G., Lang, A., Middelkoop, H., Boyle, J., Kaplan, J. O., Willenbring, J., and Aalto, R.: Short Communication: Humans and the missing C-sink: erosion and burial of soil carbon through time, Earth Surf. Dynam., 1, 45–52, https://doi.org/10.5194/esurf-1-45-2013, 2013b.

Hu, Y., Berhe, A. A., Fogel, M. L., Heckrath, G. J., and Kuhn, N. J.: Transport-distance specific SOC distribution: Does it skew erosion induced OC fluxes?, Biogeochemistry, 128, 339–351, https://doi.org/10.1007/s10533-016-0211-y, 2016.

Ito, A.: Simulated impacts of climate and land-cover change on soil erosion and implication for the carbon cycle, 1901 to 2100, Geophys. Res. Lett., 34, L09403, https://doi.org/10.1029/2007GL029342, 2007.

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

Jacinthe, P.-A., Lal, R., Owens, L. B., and Hothem, D. L.: Transport of labile carbon in runoff as affected by land use and rainfall characteristics, Soil Till. Res., 77, 111–123, https://doi.org/10.1016/j.still.2003.11.004, 2004.

Kirkels, F. M. S. A., Cammeraat, L. H., and Kuhn, N. J.: The fate of soil organic carbon upon erosion, transport and deposition in agricultural landscapes – A review of different concepts, Geomorphology, 226, 94–105, https://doi.org/10.1016/j.geomorph.2014.07.023, 2014.

Koch, A., Mcbratney, A., Adams, M., Field, D., Hill, R., Crawford, J., Minasny, B., Lal, R., Abbott, L., O'Donnell, A., Young, I., and Zimmermann, M.: Soil Security: Solving the Global Soil Crisis, Glob. Policy, 4, 434–441, https://doi.org/10.1111/1758-5899.12096, 2013.

Kuhn, N. J., Hoffmann, T., Schwanghart, W., and Dotterweich, M.: Agricultural soil erosion and global carbon cycle:

Controversy over?, Earth Surf. Proc. Land., 34, 1033–1038, https://doi.org/10.1002/esp.1796, 2009.

Lal, R.: Soil degradation by erosion, L. Degrad. Dev., 12, 519–539, https://doi.org/10.1002/ldr.472, 2001.

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

Lal, R.: Soil carbon sequestration impacts on global climate change and food security, Science, 304, 1623–1627, https://doi.org/10.1126/science.1097396, 2004.

Lal, R.: Soil erosion and carbon dynamics, Soil Till. Res., 81, 137–142, https://doi.org/10.1016/j.still.2004.09.002, 2005.

Lal, R.: Accelerated Soil erosion as a source of atmospheric CO_2, Soil Till. Res., 188, 35–40, https://doi.org/10.1016/j.still.2018.02.001, 2019.

Li, Y., Quine, T. A., Yu, H. Q., Govers, G., Six, J., Gong, D. Z., Wang, Z., Zhang, Y. Z., and Van Oost, K.: Sustained high magnitude erosional forcing generates an organic carbon sink: Test and implications in the Loess Plateau, China, Earth Planet. Sci. Lett., 411, 281–289, https://doi.org/10.1016/j.epsl.2014.11.036, 2015.

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

Lugato, E., Paustian, K., Panagos, P., Jones, A., and Borrelli, P.: Quantifying the erosion effect on current carbon budget of European agricultural soils at high spatial resolution, Glob. Chang. Biol., 22, 1976–1984, https://doi.org/10.1111/gcb.13198, 2016.

Lugato, E., Smith, P., Borrelli, P., Panagos, P., Ballabio, C., Orgiazzi, A., Fernandez-Ugalde, O., Montanarella, L., and Jones, A.: Soil erosion is unlikely to drive a future carbon sink in Europe, Sci. Adv., 4, eaau3523, https://doi.org/10.1126/sciadv.aau3523, 2018.

Manies, K. L., Harden, J. W., Kramer, L., and Parton, W. J.: Carbon dynamics within agricultural and native sites in the loess region of Western lowa, Glob. Chang. Biol., 7 545–555, https://doi.org/10.1046/j.1354-1013.2001.00427.x, 2001.

Mayer, S., Schwindt, D., Steffens, M., Völkel, J., and Kögel-Knabner, I.: Drivers of organic carbon allocation in a temperate slope-floodplain catena under agricultural use, Geoderma, 327, 63–72, https://doi.org/10.1016/J.GEODERMA.2018.04.021, 2018.

Montgomery, D. R.: Soil erosion and agricultural sustainability, P. Natl. Acad. Sci. USA, 104, 13268–13272, https://doi.org/10.1073/pnas.0611508104, 2007.

Mora, J. L., Guerra, J. A., Armas, C. M., Rodríguez-Rodríguez, A., Arbelo, C. D., and Notario, J. S.: Mineralization rate of eroded organic OC in Andosols of the Canary Islands, Sci. Total Environ., 378, 143–146, https://doi.org/10.1016/j.scitotenv.2007.01.040, 2007.

Müller-Nedebock, D. and Chaplot, V.: Soil carbon losses by sheet erosion: A potentially critical contribution to the global carbon cycle, Earth Surf. Proc. Land., 40, 1803–1813, https://doi.org/10.1002/esp.3758, 2015.

Nadeu, E., Berhe, A. A., de Vente, J., and Boix-Fayos, C.: Erosion, deposition and replacement of soil organic carbon in Mediterranean catchments: a geomorphological, isotopic and land use change approach, Biogeosciences, 9, 1099–1111, https://doi.org/10.5194/bg-9-1099-2012, 2012.

Nadeu, E., Gobin, A., Fiener, P., van Wesemael, B., and van Oost, K.: Modelling the impact of agricultural management on soil carbon stocks at the regional scale: The role of lateral fluxes, Glob. Chang. Biol., 21, 3181–3192, https://doi.org/10.1111/gcb.12889, 2015.

Naipal, V., Lauerwald, R., Ciais, P., Guenet, B., and Wang, Y.: CE-DYNAM (v1): a spatially explicit process-based carbon erosion scheme for use in Earth system models, Geosci. Model Dev., 13, 1201–1222, https://doi.org/10.5194/gmd-13-1201-2020, 2020.

Ni, J., Yue, Y., Borthwick, A. G. L., Li, T., Miao, C., and He, X.: Erosion-induced CO_2 flux of small watersheds, Glob. Planet. Change, 94–95, 101–110, https://doi.org/10.1016/j.gloplacha.2012.07.003, 2012.

Novara, A., Keesstra, S., Cerdà, A., Pereira, P., and Gristina, L.: Understanding the role of soil erosion on CO_2-OC loss using ^{13}c isotopic signatures in abandoned Mediterranean agricultural land, Sci. Total Environ., 550, 330–336, https://doi.org/10.1016/j.scitotenv.2016.01.095, 2016.

Olson, K. R., Al-Kaisi, M., Lal, R., and Cihacek, L.: Impact of soil erosion on soil organic carbon stocks, J. Soil Water Conserv., 71, 61A–67A, https://doi.org/10.2489/jswc.71.3.61A, 2016.

Omengo, F. O., Geeraert, N., Bouillon, S., and Govers, G.: Deposition and fate of organic carbon in floodplains along a tropical semiarid lowland river (Tana River, Kenya), J. Geophys. Res.-Biogeo., 121, 1131–1143, https://doi.org/10.1002/2015JG003288, 2016.

Óskarsson, H., Arnalds, Ó., Gudmundsson, J., and Gudbergsson, G.: Organic carbon in Icelandic Andosols: Geographical variation and impact of erosion, Catena, 56, 225–238, https://doi.org/10.1016/j.catena.2003.10.013, 2004.

Page, M., Trustrum, N., Brackley, H., and Baisden, T.: Erosion-related soil carbon fluxes in a pastoral steepland catchment, New Zealand, Agric. Ecosyst. Environ., 103, 561–579, https://doi.org/10.1016/j.agee.2003.11.010, 2004.

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

Quine, T. A. and van Oost, K.: Quantifying carbon sequestration as a result of soil erosion and deposition: Retrospective assessment using caesium-137 and carbon inventories, Glob. Chang. Biol., 13, 2610–2625, https://doi.org/10.1111/j.1365-2486.2007.01457.x, 2007.

Quinton, J. N., Catt, J. A., Wood, G. A., and Steer, J.: Soil carbon losses by water erosion: Experimentation and modeling at field and national scales in the UK, Agric. Ecosyst. Environ., 112, 87–102, https://doi.org/10.1016/j.agee.2005.07.005, 2006.

Quinton, J. N., Govers, G., Van Oost, K., and Bardgett, R. D.: The impact of agricultural soil erosion on biogeochemical cycling, Nat. Geosci., 3, 311–314, https://doi.org/10.1038/ngeo838, 2010.

Ran, L., Lu, X. X., and Xin, Z.: Erosion-induced massive organic carbon burial and carbon emission in the Yellow River basin, China, Biogeosciences, 11, 945–959, https://doi.org/10.5194/bg-11-945-2014, 2014.

Ran, L., Lu, X., Fang, N., and Yang, X.: Effective soil erosion control represents a significant net carbon sequestration, Sci. Rep., 8, 12018, https://doi.org/10.1038/s41598-018-30497-4, 2018.

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., Laruelle, G. G., Lauerwald, R., Luyssaert, S., Andersson, A. J., Arndt, S., Arnosti, C., Borges, A. V, Dale, A. W., Gallego-Sala, A., Goddéris, Y., Goossens, N., Hartmann, J., Heinze, C., Ilyina, T., Joos, F., Larowe, D. E., Leifeld, J., Meysman, F. J. R., Munhoven, G., Raymond, P. A., Spahni, R., Suntharalingam, P., and Thullner, M.: Anthropogenic perturbation of the carbon fluxes from land to ocean, Nat. Geosci., 6, 597–607, https://doi.org/10.1038/ngeo1830, 2013.

Remus, R., Kaiser, M., Kleber, M., Augustin, J., and Sommer, M.: Demonstration of the rapid incorporation of carbon into protective, mineral-associated organic carbon fractions in an eroded soil from the CarboZALF experimental site, Plant Soil, 430, 329–348, https://doi.org/10.1007/s11104-018-3724-4, 2018.

Rosenbloom, N. A., Harden, J. W., Neff, J. C., and Schimel, D. S.: Geomorphic control of landscape carbon accumulation, J. Geophys. Res.-Biogeo., 111, G01004, https://doi.org/10.1029/2005JG000077, 2006.

Scheingross, J. S., Hovius, N., Dellinger, M., Hilton, R. G., Repasch, M., Sachse, D., Gröcke, D. R., Vieth-Hillebrand, A., and Turowski, J. M.: Preservation of organic carbon during active fluvial transport and particle abrasion, Geology, 47, 958–962, https://doi.org/10.1130/G46442.1, 2019.

Six, J., Conant, R. T., Paul, E. A., and Paustian, K.: Stabilization mechanisms of soil organic matter: Implications for OC-saturation of soils, Plant Soil, 241, 155–176, https://doi.org/10.1023/A:1016125726789, 2002.

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

Smith, S. V., Sleezer, R. O., Renwick, W. H., and Buddemeier, R. W.: Fates of eroded soil organic carbon: Mississippi Basin case study, Ecol. Appl., 15, 1929–1940, https://doi.org/10.1890/05-0073, 2005.

Stallard, R. F.: Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial, Global Biogeochem. Cy., 12, 231–257, https://doi.org/10.1029/98GB00741, 1998.

Steger, K., Fiener, P., Marvin-DiPasquale, M., Viers, J. H., and Smart, D. R.: Human-induced and natural carbon storage in floodplains of the Central Valley of California, Sci. Total Environ., 651, 851–858, https://doi.org/10.1016/J.SCITOTENV.2018.09.205, 2019.

Vandenbygaart, A. J., Kroetsch, D., Gregorich, E. G., and Lobb, D.: Soil OC erosion and burial in cropland, Glob. Chang. Biol., 18, 1441–1452, https://doi.org/10.1111/j.1365-2486.2011.02604.x, 2012.

VandenBygaart, A. J., Gregorich, E. G., and Helgason, B. L.: Cropland OC erosion and burial: Is buried soil organic matter biodegradable?, Geoderma, 239–240, 240–249, https://doi.org/10.1016/j.geoderma.2014.10.011, 2015.

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

Van Hemelryck, H., Govers, G., Van Oost, K., and Merckx, R.: Evaluating the impact of soil redistribution on the in situ mineralization of soil organic carbon, Earth Surf. Proc. Land., 36, 427–438, https://doi.org/10.1002/esp.2055, 2011.

Van Oost, K., Govers, G., Quine, T. A., Heckrath, G., Olesen, J. E., De Gryze, S., and Merckx, R.: Landscape-scale modeling of carbon cycling under the impact of soil redistribution: The role of tillage erosion, Global Biogeochem. Cy., 19, GB4014, https://doi.org/10.1029/2005GB002471, 2005.

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

Van Oost, K., Van Hemelryck, H., and Harden, J. W.: Erosion of soil organic carbon: Implications for carbon sequestration, edited by: McPherson, B. J. and Sundquist, E. T., Wiley, 198–202, https://doi.org/10.1029/2005GM000326, 2009.

Van Oost, K., Verstraeten, G., Doetterl, S., Notebaert, B., Wiaux, F., Broothaerts, N., and Six, J.: Legacy of human-induced OC erosion and burial on soil-atmosphere OC exchange, P. Natl. Acad. Sci. USA, 109, 19492–19497, https://doi.org/10.1073/pnas.1211162109, 2012.

Wang, X., Cammeraat, E. L. H., Romeijn, P., and Kalbitz, K.: Soil organic carbon redistribution by water erosion – The role of CO_2 emissions for the carbon budget, PLoS One, 9, e96299, https://doi.org/10.1371/journal.pone.0096299, 2014.

Wang, Z., Govers, G., Steegen, A., Clymans, W., Van den Putte, A., Langhans, C., Merckx, R., and Van Oost, K.: Catchment-scale carbon redistribution and delivery by water erosion in an intensively cultivated area, Geomorphology, 124, 65–74, https://doi.org/10.1016/j.geomorph.2010.08.010, 2010.

Wang, Z., Van Oost, K., Lang, A., Quine, T., Clymans, W., Merckx, R., Notebaert, B., and Govers, G.: The fate of buried organic carbon in colluvial soils: a long-term perspective, Biogeosciences, 11, 873–883, https://doi.org/10.5194/bg-11-873-2014, 2014.

Wang, Z., Hoffmann, T., Six, J., Kaplan, J. O., Govers, G., Doetterl, S., and Van Oost, K.: Human-induced erosion has offset one-third of carbon emissions from land cover change, Nat. Clim. Chang., 7, 345–349, https://doi.org/10.1038/nclimate3263, 2017.

Worrall, F., Burt, T. P., and Howden, N. J. K.: The fluvial flux of particulate organic matter from the UK: Quantifying in-stream losses and carbon sinks, J. Hydrol., 519, 611–625, https://doi.org/10.1016/j.jhydrol.2014.07.051, 2014.

Worrall, F., Burt, T. P., and Howden, N. J. K.: The fluvial flux of particulate organic matter from the UK: The emission factor of soil erosion, Earth Surf. Proc. Land., 41, 61–71, https://doi.org/10.1002/esp.3795, 2016.

Xiao, H., Li, Z., Chang, X., Huang, B., Nie, X., Liu, C., Liu, L., Wang, D., and Jiang, J.: The mineralization and sequestration of organic carbon in relation to agricultural soil erosion, Geoderma, 329, 73–81, https://doi.org/10.1016/j.geoderma.2018.05.018, 2018.

Yoo, K., Amundson, R., Heimsath, A. M., and Dietrich, W. E.: Erosion of upland hillslope soil organic carbon: Coupling field measurements with a sediment transport model, Global Biogeochem. Cy., 19, 1–17, https://doi.org/10.1029/2004GB002271, 2005.

Yue, Y., Ni, J., Borthwick, A. G. L., and Miao, C.: Diagnosis of river basins as CO_2 sources or sinks subject to sediment movement, Earth Surf. Proc. Land., 37, 1398–1406, https://doi.org/10.1002/esp.3254, 2012.

Yue, Y., Ni, J., Ciais, P., Piao, S., Wang, T., Huang, M., Borthwick, A. G. L., Li, T., Wang, Y., Chappell, A., Chappell, A., and Van Oost, K.: Lateral transport of soil carbon and land-atmosphere CO_2 flux induced by water erosion in China, P. Natl. Acad. Sci. USA, 113, 6617–6622, https://doi.org/10.1073/pnas.1523358113, 2016.

Zeng, Y., Fang, N., and Shi, Z.: Effects of human activities on soil organic carbon redistribution at an agricultural watershed scale on the Chinese Loess Plateau, Agric. Ecosyst. Environ., 303, 107112, https://doi.org/10.1016/J.AGEE.2020.107112, 2020.

Zhang, H., Liu, S., Yuan, W., Dong, W., Ye, A., Xie, X., Chen, Y., Liu, D., Cai, W., and Mao, Y.: Inclusion of soil carbon lateral movement alters terrestrial carbon budget in China, Sci. Rep., 4, 7247, https://doi.org/10.1038/srep07247, 2014.

Zhao, J., Van Oost, K., Chen, L., and Govers, G.: Moderate topsoil erosion rates constrain the magnitude of the erosion-induced carbon sink and agricultural productivity losses on the Chinese Loess Plateau, Biogeosciences, 13, 4735–4750, https://doi.org/10.5194/bg-13-4735-2016, 2016.