Reconciling the paradox of soil organic carbon erosion by water

Kristof Van Oost[1] and Johan Six[2]

[1]Earth & Life Institute, Georges Lemaître Center for Earth & Climate Research, UCLouvain, Place Louis Pasteur 3, 1348 Louvain-la-Neuve, Belgium

5 [2]Department of Environmental Systems Science, Swiss Federal Institute of Technology, ETH Zurich, Universitätstrasse 2, 8092 Zurich, Switzerland

Correspondence to: K Van Oost (kristof.vanoost@uclouvain.be) & J Six (jsix@ethz.ch)

Abstract.

The acceleration of erosion, transport and burial of soil organic carbon (OC) by water in response to agricultural expansion

10 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 a OC sink versus source, can be reconciled when comprehensively

15 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

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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 represent a net OC sink or source. Assuming

25 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 not only result in healthier soils, but that an additional and large OC sink could be obtained 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

30 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). They 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

35 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 atmospheric C of ca. 1 Pg OC yr^{-1} and erosion therefore may represent a 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;

40 Berhe et al., 2008; Chappell et al., 2016; Wang et al., 2017; Yue et al., 2016) and (ii) the expected future increases in food

45   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

50   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

55   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

60   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.,

65   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; Wang et al., 2014a). 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

70   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,

75   (where SDR is the fraction of the eroded OC that reaches the river network). This outgassing is usually observed to occur quickly in the timeframe of several days to months. We therefore set the time constant for both processes (i.e. τ_{runoff} and τ_{river}) to 1 yr. 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 yr). 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.

80   **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. It is, 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).

90   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. It is, erosion induced soil truncation facilitates the new formation of more stable MAOM by the adsorption of products from POM decomposition and DOC derived from plant material onto mineral surfaces of the former subsoil (Fig. 1), thereby

95   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

100   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

105   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 time-scales (91 ± 1098 yr) (Fig 2).

The OC recovery potential of soils at the scale of eroding hillslopes, which is driving the OC sink term of the geomorphic

110   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

115   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 yr 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

120   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).

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

125   properties, which can have a detrimental effect on NPP through the decrease of 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, OC stabilization in newly exposed subsoil results in efficient 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 is removed by erosion (Berhe et al., 2008) and that the available observations are biased towards fertile soils in high-input systems (see discussion). Based on the data available in the literature, we estimate the fractional gain at steady state for the SOC recovery term (α_{rec}) at 135 0.93, while the time constant (τ_{rec}) equals 167 yr (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 140 (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 as well as 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 time scale; whereas OC is preserved more efficiently in lake and ocean deposits with OC burial 145 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 yr (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 150 to 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 yr, respectively.

155 **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 (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 160 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 165 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 in 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., 2019). 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 to consider both OC sink and source terms at appropriate scales when assessing the effect of erosion on the global C cycle.

Methods

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

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

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 was complemented with the space and time 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 modelling presented in Figure 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 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 Figure 4.

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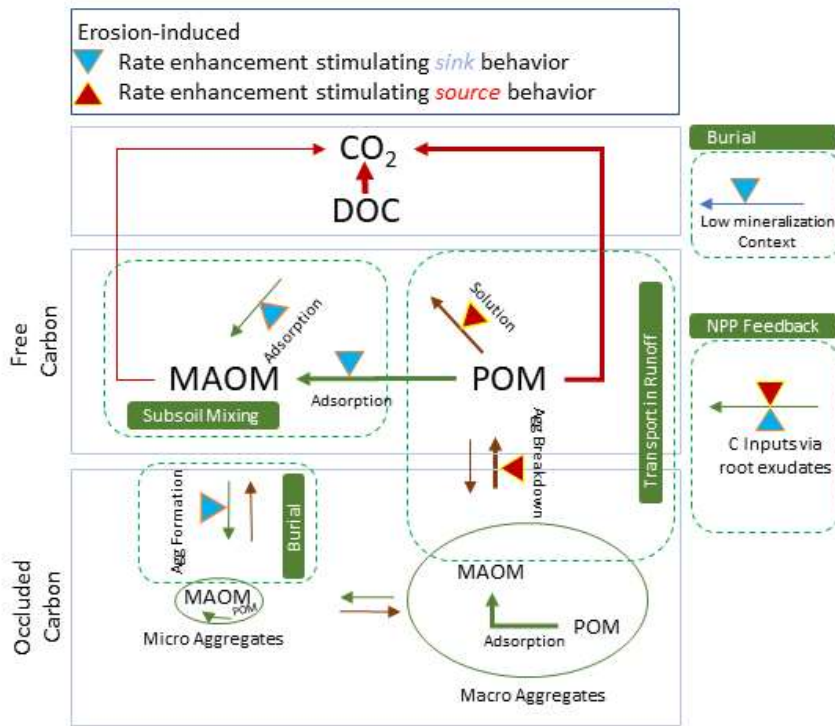
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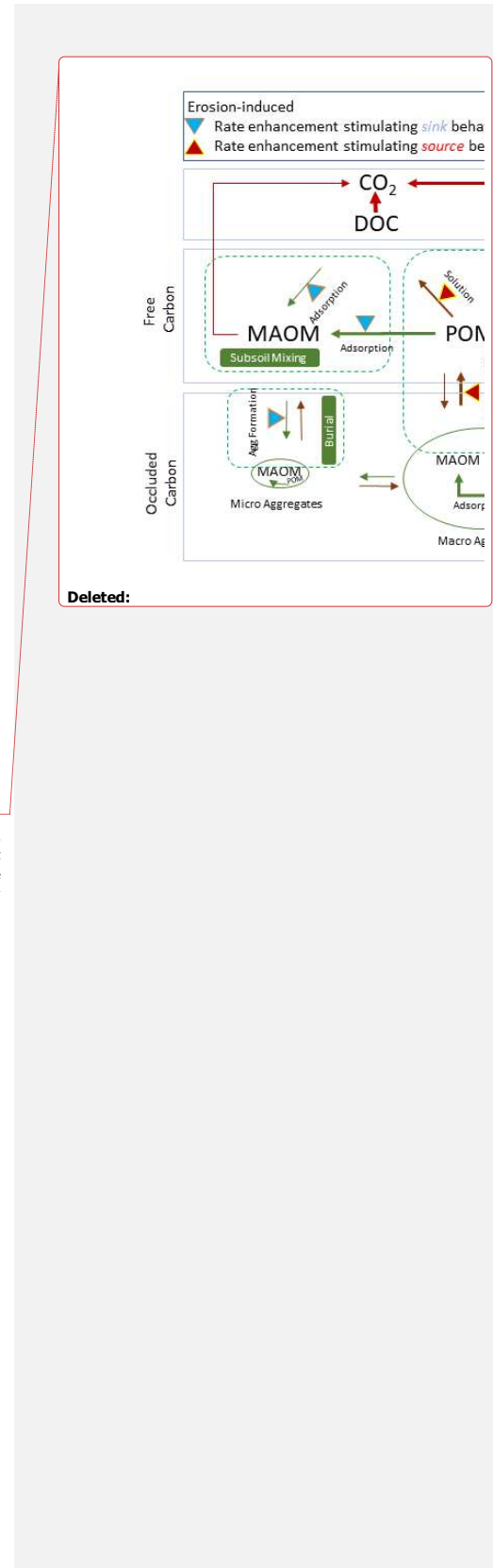
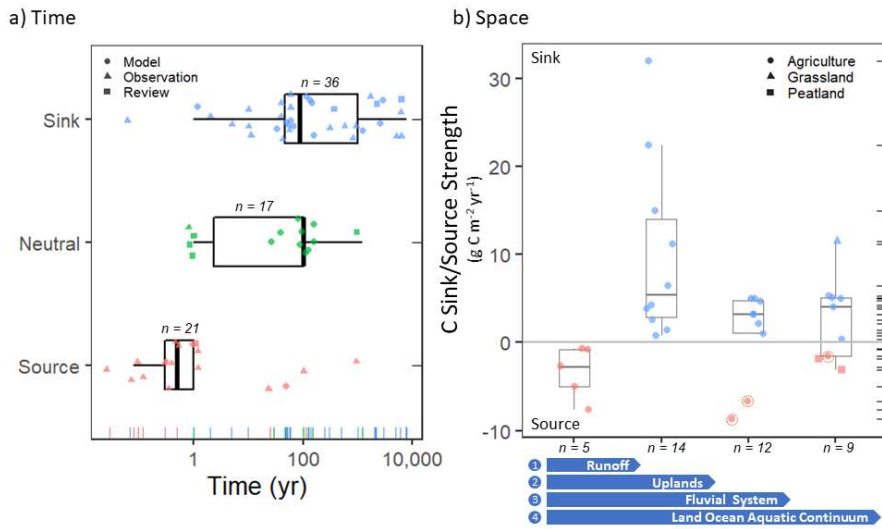
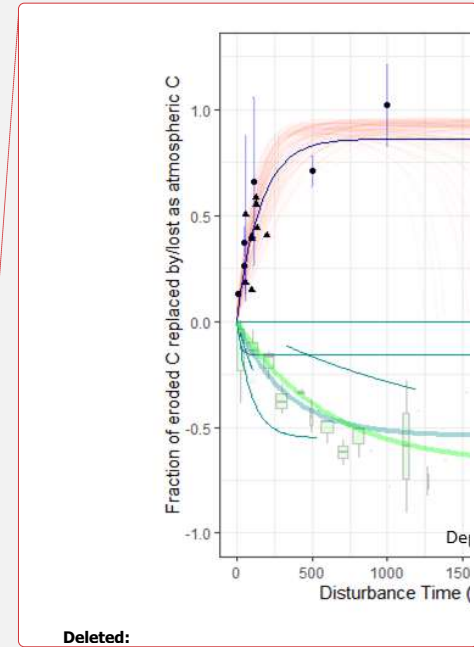
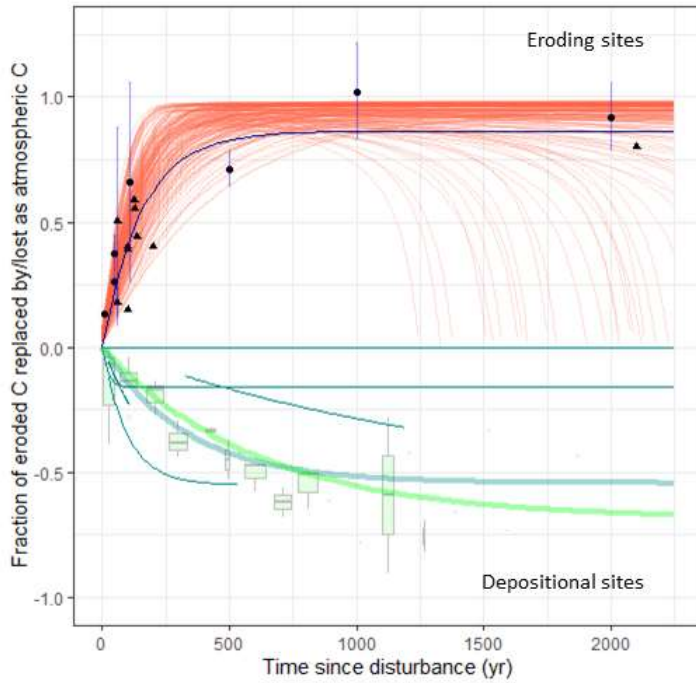
Figure 1: Schematic representation of the effect of water erosion and deposition on soil OC stabilization and loss processes. Transport in runoff: detachment and transport can shift OC from a protected state in aggregates to an available state where it mineralizes more rapidly. Burial: the deposition 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
425 **erosion may replace some of the eroded OC. 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.**

430 **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 time scale 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 fours 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**
435 **that consider eroding soils, colluvium and alluvium and (4) studies that consider the full geomorphic cascade (including 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.**

440 **Figure 3: Fraction of eroded OC replaced by atmospheric CO$_2$ as a function of time since start of agricultural erosion at eroding sites (top panel) and depositional sites (lower panel). For the eroding sites, studies using mass-balance (circles) and model (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 for global agricultural land. We use the model for cropland presented by**
445 **(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 between 200 and 1000 yr. For the feedback scenario, we assumed a negative feedback that ranged randomly between 3 to 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.**

450

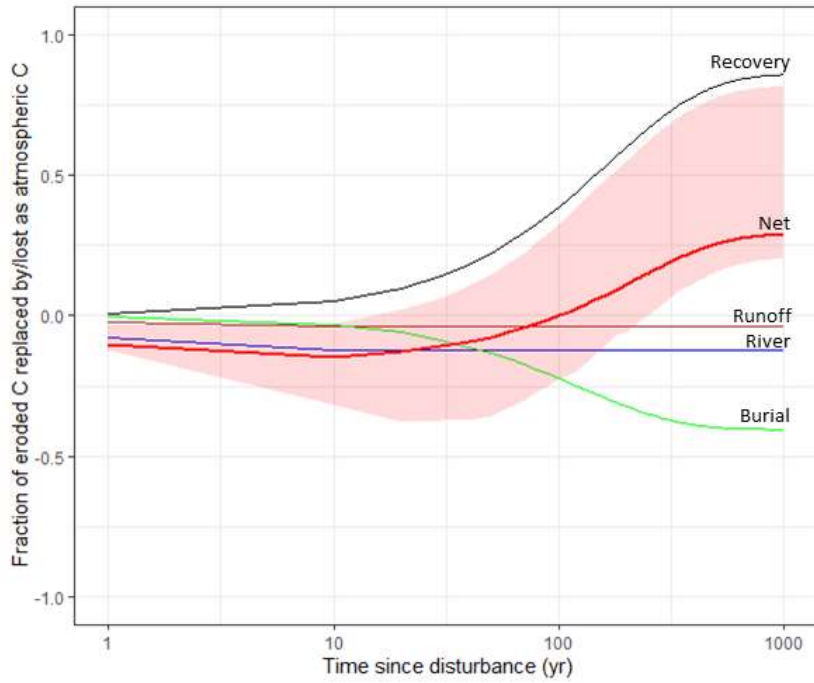



Figure 4: Framework to represent fraction gain/loss relative to mobilized soil OC for the different components of the geomorphic
455 **cascade. The example shown here (full lines) uses the best estimates of model parameters described in the text and given in Table 2 (i.e. α_{runoff}=0.04, τ_{runoff}=1, α_{river}=0.5, τ_{river}=1, α_{burial}=0.54, τ_{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)).**

Table 1: Overview of studies reporting erosion-induced OC fluxes used in our literature synthesis. Space refers to the 4 components of the geomorphic cascade (see Figure 2 for key). Positive values for OC strength denote a sink, while negative values denote a source. Methods are categorized as Data- or Model-based. Modelling 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 a steady state were assigned a time scale of 1 year.

Reference	Year	Method	Time (yr)	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)‡	2004	Data	1000	Source‡	-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	110	Sink	10/3000/ 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*	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°
(Kirkels et al., 2014)	2014	Review		Neutral	/			
(Ran et al., 2014)‡	2014	Mod	50	Source‡	-6,64	3		Agriculture
(Wang et al., 2014a)	2014	Data*	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

Reference	Year	Type						
(Zhao et al., 2016)	2016	Data	5	Sink	3,16	3		Agriculture
(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⁺
(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*	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)⁺	2018	Data	25	Source⁺	-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

⁺Manipulation experiments, ⁺Particulate organic matter sources dominated by organic soils from peatlands, ⁺OC recovery on

465 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	r²	n	range yrs
Oxidation Burial (Colluvial)					
(Van Oost et al., 2012)	0.76 (±0.014)	0.0014 (±0.0001)	0.95	9 (309)	0-2436
(Wang et al., 2014b)	0.82 (±0.10)	0.0016 (±0.00004)	0.82	29	0-1388
(Mayer et al., 2018)[*]	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)[*]	0.84 (±6.2)	0.003 (±0.03)	0.81	3	0-105
(Mayer et al., 2018)[*]	0.59 (±0.38)	0.0006 (±0.0006)	0.92	4	0-1190
Colluvial + Alluvial[§]	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

* 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 conservative estimate of OC burial efficiencies. *§Considering all data from alluvial and colluvial studies.*