Discusion Letter Van Oost & Six, BG

Reviewer 1:

The authors assess the effect of soil erosion on soil Carbon fluxes at different spatial and time scales, based on a literature review and relatively simple modelling. The work is highly relevant, original, and of interest to the readers of Biogeosciences. Moreover, the work has large societal relevance in light of sustainable development goals with regard to land degradation neutrality and climate change.

// Thank you very much for this positive assessment.

My main reservation with regard to the work is that the literature reveals large uncertainties in the parameters that govern the C fluxes in (parts of) the total system at different timescales. Yet, in the Table 2 (summarizing parameters) and in the modelling that is reported in Fig. 4 the authors only report and use the estimates derived from a non-linear regression, without uncertainties. Hence the uncertainty is not shown in the final modelling result, which is a pity and a shortcoming of the work. I would encourage the authors to include uncertainties in the table and model, and represent these uncertainties in shading in the resulting figure 4. Such a representation would provide a much better image of the state of knowledge on this subject, including which parts of the system are least well understood.

// We fully agree. We have added the errors associated with the parameter estimates in Table 2. This illustrates which parts of the system are least well understood. The oxidation in burial settings is the least constraint and this is now discussed in the implications section (lines 171-173). Furthermore, we added an uncertainty analysis (Monte Carlo) for our model application. The uncertainty range for our predictions (as informed by the observations) is now represented in Figure 4. We have added the following description in the Methods section "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 25th and 75th percentiles of 100 simulations as an uncertainty range in Figure 4."

In addition, I suggest that some additional effort is needed to improve layout and clarity of the figures, including legends and captions. Specific recommendations with regard to figures and text are added to the annotated PDF of the manuscript.

// Thank you very much for the suggestions, we have implemented the minor modifications you suggested in the pdf. We responded to these detailed comments in the pdf (attached to revision files). The main modification is the improved explanation of figure 1. Regarding the second comment on line 67 (presumably this 0.5 reflects the 50% mentioned above. Why is this upper value used, while for runoff the mean value of 4% is adopted?) : In the literature values close to 50% are reported (eg Worrall et al.) but a full in depth review is outside the scope of this paper. Furthermore, using the upper limit also provides a conservative estimate of the overall net erosion induced sink term. We therefore use 50% for our best estimate. However, in the

uncertainty analysis, we consider that this value can vary between 0 and 50% and this is reflected in the uncertainty assessment.

Finally, I would encourage the authors to relate their findings to the present challenges with regard to land degradation neutrality and climate change. Their figure 4 shows that soil erosion is a net Carbon source at decadal timescales. This is exactly the timescale at which reducing atmospheric CO2 is most needed to reach Paris climate agreement targets. Thus, while (pre-)historic soil erosion may be a C sink in coming decades, present-day erosion will provide a C source in that same time period. This implies that preventing soil erosion contributes not only to food security, but also to climate change mitigation in coming decades.

// Fig 4 refers to the time since agricultural conversion. Based on our literature review and meta-analysis, we suggest that recently converted land may provide a net source. However, most agricultural land has been converted for more than several decades and only recently converted land represents a source. As a result, the suggestion that present-day erosion represents a source is not consistent with our findings. Our simulations show that only newly converted cropland most likely represents a source. The dynamic phases of both sink and source terms are exactly a key message of our paper. We have added a sentence in the discussion to clarify this: . Our results suggest that recently converted cropland represents a source while a switch to a sink is observed after c. 4 decades (Fig 4) (Line 172).

Reviewer 2

General comments

The article attempts to do exactly as the title describes, to reconcile potentially competing perspectives on soil carbon erosion. The reconciliation is undertaken within the framework of scale which is used by the authors to demonstrate how these competing perspectives can exist at the same time and hence explain the paradox. I think this work contrasts markedly from the vast majority on this topic and many others in environmental science. The characteristics of that majority is typically atomised, perhaps even siloed, with a single perspective which is much easier to write, much easier for reviewers to understand and therefore readily published. Consequently, I congratulate the authors on this sophisticated integrated approach which is difficult to undertake and explain. The benefits of such a sophisticated approach are evident in the work, we have a proposal for understanding difference in perspective which enables the potential for the soil erosion community to re-gather momentum around the idea. I think the work is valid, straight-forward and effective which from my perspective equates to the work being incisive. On these bases I think the work should be published to act as a catalyst for further discussion on the topic. I have included below in the next section some specific comments which could form the basis for that discussion, would need clarification in the manuscript, but which I feel do not preclude the publication of this work.

// We thank the reviewer for these very positive comments and are grateful for his view on the topic that is in line with ours. We agree that a single perspective is most often chosen because it is easier, while an integrated approach, like we present, is needed.

Specific comments

There is an implicit assumption by many researchers working on soil erosion that the processes are dominated by water erosion. This is of course not the case in the vast nearly 50% of the Earth's land surface dominated by drylands where magnitude and frequency of wind erosion and dust emission very likely outweigh the influence of water erosion. Consequently, I would like to see improved clarification of the specific processes that are being considered throughout this manuscript. For example, starting with the title, should it read something like: "Reconciling the paradox of soil carbon erosion by water". The first sentence of the abstract perhaps should more precisely be "The acceleration of erosion, transport and burial of soil organic carbon (C) by water in response to….".

// we have modified the title and abstract accordingly

Clarifications of this type throughout the manuscript, I think will serve to remind readers that much of the current thinking about SOC erosion is dominated by humid / temperate experience and measurements. Whilst the processes may be universal (notwithstanding a difference in fluid viscosity) the outcomes may be very different in relatively dryland regions. The authors might even like to include in their manuscript a statement that the paradox is only understood to occur in humid-temperate regions because there is far less work / understanding on this topic in dryland regions. The point I raise is perhaps best exemplified at Line 77 “On eroding hillslopes, soils are truncated, and C depleted subsoil material is brought to the surface layers.” In drylands, I think soils may not be truncated and the subsoil may not be C depleted. The implication of this difference is that in drylands, soil erosion may be a limiting factor in the balance between SOC decomposition and SOC redistribution. This thinking is already included in the Section on C recovery and evident in the text around Lines 100-110. However, it is not clear how or indeed whether drylands are included in the universal nature of the description, whether wind erosion and dust emission are a special case, or are not included. I have no problem with the authors simply clarifying the scope of the manuscript and not extending in to these larger issues, unless of course they are already included and just not explicit. In which case, I think there is a need to clarify on that basis.

// The reviewer raises a very valid point. We have clarified the scope of our study (I.e. focus on water erosion with insights derived mainly from humid/temperate settings) in the title and throughout the manuscript in the revised version (e.g. Title and lines 49-51). The reviewer also brings up an interesting hypothesis about soil erosion being a limiting factor in the balance between SOC decomposition and redistribution in drylands. However, addressing this in our manuscript would be out of scope because of our focus on water erosion in humid/temperate settings. We have however added a sentence in the introduction to highlight the bias: 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.”

The points above about soil carbon erosion in drylands raise the need to consider an additional clarification. There is only one mention (in the abstract) of the word organic linked to the words carbon erosion. I think the focus on soil organic carbon (SOC) erosion should be made clear (like the point above about water erosion), in the title and throughout the manuscript as appropriate. I think this is important so that the focus on SOC erosion is distinguished from soil inorganic carbon (SIC) erosion. The SIC cycling and erosion processes are prevalent in dryland regions but not widely recognised / connected in the literature on soil erosion. Consequently, it is not clear from the manuscript whether / how SIC processes should be considered in the paradox.

// We fully agree and have more clearly highlighted that we focus on organic carbon erosion and not on SIC erosion We added ‘organic’ in the title and in the beginning of the manuscript when talking about carbon(introduction).

The geography of SOC erosion demonstrates the overlap particularly in semi-arid regions of wind and water erosion processes. The significance of that interplay between wind and water erosion is its redistribution and difference in the sink of SOC. Wind erosion and particularly dust emission releases SOC in to the atmosphere and may transport SOC large distances from source, potentially influencing ocean carbon cycling. The main focus in the manuscript and the paradox, is the redistribution of SOC by water which is for a given erosion event relatively localised. Furthermore, there appears to be an implicit assumption that water erosion is dominant even in regions well-known to be influenced by wind erosion and dust emission. The question remains in my mind whether these differences influence the source-sink paradox. I recognise that this issue is beyond the scope of this manuscript. As in the previous paragraphs, I think there is a need in this manuscript to clarify the scope of the SOC erosion paradox described and perhaps even include a statement that defines clearly the focus. The impact of these clarifications will I think be the broader recognition that the geomorphic conveyor is beyond water and consequently there may then be much broader recognition of the source-sink across domains. I note that some clarity already exists e.g., Section 2 is entitled Transport in runoff and rivers. However, the preceding section is written in a way which gives me the impression that the commentary is universally applicable. However, I think we are a little way from that knowledge and understanding from across wind and water erosion and from drylands being combined.

// We fully accept this criticism but feel that including wind and dust emissions into our manuscript will make it less focused. We think that a clear definition of the scope (i.e. water erosion in humid/temperate settings) in the revised manuscript as described above address this comment.

The next point I have to make is a little tricky since it is not directly evident in the literature. Nevertheless, it is relatively easy to appreciate even if one does not accept it. Some of the C recovery section in the manuscript is based on the relation between net primary productivity (NPP) and SOC erosion. Whilst NPP is an important concept, it is grounded / implemented by the use of leaf area index underpinned by reflectance-based vegetation indices. The vegetation indices describe greenness which is due but cannot readily be assigned to dual signals of plant health and / or plant coverage. Consequently, if e.g., plant coverage changes as is partially evident in satellite measurements of global 'greening', then it is very difficult to distinguish plant coverage from plant productivity. Incorrect attribution of greening to one or the other will introduce Type I and II errors incrreasing uncertainty about the relation between NPP and C erosion. Although the duality of information contained in NDVI is well known, it has not generally been troubling because of the endemic assumption of stationarity and in modelling which is intrinsically steady state. However, a changing climate or other underlying changes, now confound the ability to understand plant productivity. So the relevance to this manuscript is that over long time periods underlying change may cause a difference in the response between SOC erosion and plant productivity, where that productivity is assumed stationary by using a contemporary vegetation index framework.

// Detecting the relation between SOC erosion and plant productivity based on remote sensing methods is indeed difficult. However, most of the studies used in our literature review are small-scale case-studies based on process measurements or space for time substitutions and do not rely on remote sensing. The issue highlighted by the reviewer is therefore a methodological issue that is relevant when upscaling or performing global scale monitoring of SOC erosion. Our work provides a perspective that should fuel further discussion on the topic and we feel adding this issue would dilute the concepts and main message of our study.

I'm not a great fan of merging a Discussion and a Conclusion. I wonder if what is provided in the labelling of that section of the manuscript is strictly neither of those, but is something more akin to 'The implications of….'. I think many of the clarifications and issues raised here could usefully be included in that section to encourage workers to consider the implications from various perspectives.

// We agree and have modified the title of this section 'Implications of SOC erosion for the C budget".

Again, congratulations on putting together such a sophisticated and well-considered commentary. I believe and hope that it will act as an important catalyst for broad considerations of the C erosion paradox.

// Thank you! We really appreciate the constructive and thoughtful review provided by you!

Best wishes,

Adrian Chappell

Reply

Reviewer 3

The manuscript submitted by Kristopf van Oost attempts to be a review of the state of the research on the role of soil erosion for the global Carbon cycle. Depending on the study, erosion is seen as either a source or a sink of organic Carbon. Kristof van Oost and Johan Six argue, as in most of their previous work in the past 20 years, that soil erosion moves Carbon from the atmosphere into long-term geologic sinks.

I have reviewed a manuscript by the two authors with the same title for another journal approximately a year ago. Apparently, the manuscript has been rejected by that journal. Comparing the two manuscripts reveals no major changes in both argument and literature.

// We strongly disagree with this statement. This study was indeed submitted to another journal, but the decision was a major revision, not a rejection. The editor of that journal also suggested to rework our paper as an original research paper. As also identified by reviewer 1 and 2, we see our work as a perspective that reconciles the opposing views and should serve as a starting point for future discussions on this topic. Hence, in the end, we felt that the BG Letters format was a much better outlet for our perspective than the original research paper format requested by the editor of the other journal. We also like to highlight that the paper has been substantially revised (based on the reviews received from the previous journal) for BG letters with much more observational data (colluvial and alluvial) and a conceptual framework that links the different space and time scales. We are of the opinion that these major changes have substantially improved the manuscript and are in that sense grateful for the reviewers comments received from the original journal.

The key conclusion of this manuscript, as in the other publications by the authors on the topic is that the uptake, or dynamic replacement, of atmospheric Carbon at sites of erosion compensates for a part of the Carbon loss caused by erosion. In additon, eroded Carbon is deposited in long-term permanent sinks, leaving a negative net balance for atmospheric Carbon caused by erosion. Since many field scale studies show a major negatie impact of erosion on soil Carbon, the sink caused by dynamic and deposition in long-term sinks has been questioned. Kristof van Oost and Johan Six argue that the negative impact observed in field-scale and process studies does is balanced when taking a large-scale, long-term perspectve. There are three key problems with this argument.

First, soil erosion rates are poorly constrained on a global scale. In their contribution to Nature Communications, Borelli et al. (2017, DOI: 10.1038/s41467-017-02142-7) showed that an increase of the resolution in their global scale erosion model by reducing raster cell sizes to 250 m reduced the estimated global erosion rate approximately by half. This would imply that also only half of the soil Carbon is eroded than previous models suggested, which in turn significantly reduces the potential for Carbon uptake at the sites of erosion. The number of studies currently published on improving the representation of topography in erosion (e.g. Panagos et al. 2015 10.3390/geosciences5020117, Schmidt et al. 2019 doi.org/10.1016/j.mex.2019.01.004) supports the position that the quality of Carbon flux modelling for regional to global scales currently is still poor.

// The suggestion that initial estimates of global soil erosion are most likely overestimates has been around for more than a decade now (eg Quinton et al NGS 2010). Our paper focusses on processes and the reconciliation of the opposing views in the context of space-time scales. As such, the absolute magnitude of agricultural soil erosion is not the topic of our paper. When accepting the revised global estimates (of c. 20-40 Pg of soil), organic carbon fluxes associated with soil erosion are still very high and of relevance for the global C budget. Furthermore, the papers cited by the reviewer only consider interrill and to some extent rill erosion because they are based on the RUSLE model. This implies that other erosion processes such as gullying, tillage erosion, harvest erosion etc are not considered yet and thus most likely underestimate erosion rates.

A second problem arises from the lack of a geographically comprehensive data set on the actual impact of erosion on soil Carbon. The lack of reliable data on soil Carbon, especially from rangelands, has been acknowledged in many studies, including a 2014 paper in Nature that was co-authored by Johan Six (Pittelcow et al. doi.org/10.1038/nature13809) where the authors admit that the data on soil Carbon and from large parts of the planet are poor, mostly concentrated on European and American cropland, and thus the assessment of impacts of farming practices on soil organic matter are highly uncertain for most of Earth's agricultural land. The final major uncertainty in the argument for an erosion-iduced C sink is the lack of data on the past soil and sediment organic matter content. Kristof van Oost and Johan Six argue that over long periods of time and large spatial scales, the sink effect dominates. To my knowledge, there is no source-to-sink study on a higher order catchment scale that traces eroded soil organic from slope to ocean, nor has this been attempted for the past. Individual sink reconstructions exist, but they lack information on original soil C source which has been eroded or at non-eroding sites, been modified by land use. This leaves the balance Kristof van Oost and Johan Six want to solve with more than one unknown.

// We are caught between a rock and a hard place. Our paper is the first study to collate and synthesize all available data. In our discussion, we also identify that there is a bias with an underrepresentation of tropical and dryland regions. We strongly believe that our assessment and concepts, although it may not be fully representative due to the lack of data, is informative and should be a stimulus for future discussions. Furthermore, we have included, based on the comment of reviewer 1, an uncertainty analysis in our revised manuscript. In the end, this is the main objective of our work. Secondly, there are source-to-sink studies that also include higher order catchments and these are included in our study (eg. Stallard 1998, Dymond 2010, Worrall 2016, Wang 2017 …).

In the light of these uncertainties in the data on Carbon erosion and depostion in space and time, the conclusions drawn by Kristof van Oost and Johan Six appear biased towards the Carbon sink argument. It is also not new, Sandermann and Berhe already made a similar argument in 2017 in their paper on The soil carbon erosion paradox in Nature Geoscience (10.1038/nclimate3281), also referring to Wang et al. (2017) and Chapell et al. (2016). This leaves the key statements of the manuscript presented by Kristof van Oost neither novel nor substantiated by new or more reliable data.

// The main point of our work is that the source vs sink behavior can be reconciled, and not that erosion represents a sink or a source. We feel that reconciliation, rather than reiterating the paradox as done in other studies, is novel. The latter is also emphasized by reviewer 1 and especially reviewer 2). We hope that the reviewer can agree with this now.

Furthermore, the small size of the potential C-sink induced by soil erosion has been accepted in the scientific literature for about 15 years (e.g. Berhe et al. 2007 doi.org/10.1641/B570408) and the IPCC has followed this argument in its reports on climate change. This leaves the discussion on the impact of erosion on the global Carbon cycle with a small effect, but a large uncertainty. A review should therefore in my mind point out the uncertainties and identify the research needs, rather than developing a conclusion.

// We agree, and have revised our conclusion by avoiding to specify erosion as a source or sink and focus on the implications of our reconciliation framework.

I therefore cannot help but think that this review, in particular the submission of a previously rejected manuscript to a different journal, is an attempt to preserve the legacy of the previous research of the authors rather than being open to the arguments made by reviewers. I therefore suggest to reject the paper.

// As indicated above, this assessment is ungrounded: Firstly, the manuscript was not rejected. Secondly, we have revised our manuscript based on the constructive comments of reviewer input (new data and a conceptual approach that provides a framework to align past research across spatial and temporal scales). Again, we strongly feel that the BG letter format is much more appropriate for a perspective paper as opposed to an original research paper format that was suggested by the editor of that previous journal.

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The soil carbon erosion paradox reconciled

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Abstract.

The acceleration of erosion, transport and burial of soil organic carbon (C) 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 C cycling and this has led to substantially revised assessments of changes in land C 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 C exchange is still lacking. Here, we show that the apparent soil C erosion paradox, i.e., whether agricultural erosion results in a C 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 C sink and source terms across scales. We conclude that erosion is 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 represent a net C sink or source. Assuming that a substantial fraction of soil C 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 C 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 C 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 notion was challenged by other studies that suggested a different pathway for the eroded C (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 C pump that transfers C from the atmosphere to upland soils recovering from erosion to burial sites where C is protected from decomposition in low-mineralization contexts. Along this geomorphic conveyor belt, C 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 C recovery and sedimentation on land could capture vast quantities of atmospheric C of ca. 1 Pg C yr^{-1} and erosion therefore may represent a C sink (Berhe et al., 2007; Smith et al., 2005; Stallard, 1998). This soil C erosion source-sink paradox is an important knowledge gap because (i) erosion-induced C fluxes associated with agriculture operate at rates that are relevant for the global C 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 C 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 represents a sink or source for atmospheric C, can be reconciled. At the very center of this paradox is the fact that erosion-induced processes operate across temporal and spatial scales that determine the relationship between erosion and C loss versus stabilization processes. We conceptualize the effects of the contributing erosional (sub-)processes across time and space using decay functions (see methods).

2 Transport in runoff and rivers

At very short timescales (seconds to days) erosion events shift a portion of the soil C from a protected state to an available state where it faster mineralizes to gaseous forms. 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 C through desorption of MAOM from mineral surfaces and comminution and dissolution of POM-derived C (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 C transported by overland flow suggested that 13 to 37% of the transported C 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 C were related to the preferential erosion and translocation of labile C. 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 C during its transport in rivers and estuaries has to be considered and the oxidation of C 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 carbon 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 C 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.

3 SOC recovery after erosion

In contrast, studies considering erosion as a sink for atmospheric C typically consider longer timescales at which the geomorphic C conveyor belt is operating. It is, the net outcome of the geomorphic C conveyor belt strongly depends on the C 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 C depleted subsoil material is brought to the surface layers. This induces two competing processes occurring simultaneously: the decomposition of old subsoil C and the sequestration and stabilization of fresh C inputs from newly growing plants. It is, exposure of deep C by erosion of surface soil and associated changes in microclimatic conditions increase the rate of deep C decomposition (Bailey et al., 2019). Furthermore, the mixing of formerly deep C with labile C provides readily available energy sources for decomposers, which speeds up the decomposition rate of older, previously stable C, the so called priming effect (Fontaine et al., 2007). At the same time, new C formation from new vegetation inputs into the former subsoil may replace some or all of the eroded SOC. 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 representing a net transfer of C 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 SOC in agricultural soils can be replaced by new C and dominates over the enhanced destabilization of deep C (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 C loss due to erosion represents a net atmospheric sink. 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 (Dlugoß et al., 2012). Thus, the sink-term is more difficult to isolate from the much larger background C fluxes between soil and atmosphere, particularly at short timescales. By using C 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 C 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 C destabilization (Wang et al., 2017). Our literature review clearly shows that studies reporting C erosion recovery as a sink term typically consider these longer time-scales (91 ± 1098 yr) (Fig 2).

The C recovery potential of soils at the scale of eroding hillslopes, which is driving the C 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 C is replaced, which leads to only a small erosion-induced sink (Fig. 3). There is, however, a transient response where the C 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 C formation. At this point, the erosion loss term is part of a steady state flux where all the eroded C 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 c. 2 decades associated with mechanized tillage, a sink-term representing only 26 % of the eroded C was found (Van Oost et al., 2007). In contrast, for cropland subjected to >100 yr of continued water erosion, replacement rates 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 C 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 C budget assessments (e.g. Lugato et al., 2016, 2018; Worrall et al., 2014).

It is important to ~~not~~, however, that at eroding sites, an erosion-induced decline in net primary production (NPP) may reduce soil C 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 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 C input decline is not the dominant mechanism (Lugato et al., 2018), but rather, C 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). Based on the data available in 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 yr (Fig. 3).

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4 SOC burial

The erosion source-sink paradox is also related to an incomplete consideration of the multiple spatial scales at which C and erosion processes interact. After mobilization, the eroded C is transported and a large amount of eroded sediment and C 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 C burial (75 %) (Wang et al., 2017). Here, the eroded C 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 C (Fig. 1). However, high rates of post-depositional C losses in colluvial and alluvial soils have been observed with low C burial efficiencies of only 15-30 % at a centennial/millennial time scale; whereas C is preserved more efficiently in lake and ocean deposits with C burial efficiencies of 22-60 % (Van Oost et al., 2012; Wang et al., 2017). This leads to the counterintuitive situation where systems receiving lateral C inputs accumulate C but represent a source for atmospheric C. It has been observed that C destabilization in terrestrial burial stores is a very slow process, with half-lives of up to 300 yr (Van Oost et al., 2012), and C losses therefore lag C burial. At decadal timescales, several studies reported no significant outgassing and hence a full protection of the buried C (Van Oost et al., 2007; VandenBygaart et al., 2015). This lag implies that there is a commitment 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.

5 Discussion and conclusion

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 C 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 C recovery at sites of erosion and C destabilization in sedimentary environments. Furthermore, the time since agricultural disturbance and the residence times of C in sedimentary environments are critical factors to consider. Considering all these processes This reconciles the apparent soil C erosion paradox by showing that both major source and sink terms for atmospheric C are simultaneously induced by erosion. The contrasting views that 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 C (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 C budget, with a net C flux of up to 1 to 2 Pg C yr^{-1} (Berhe et al., 2007; Lal, 2004; Smith et al., 2005) are inconsistent with integrative assessments. Nevertheless, when considering the studies focusing on agricultural systems and accounting for all components of the geomorphic cascade, the available data suggests that the sink terms dominate and agricultural erosion represents a small sink in the order of 5 g C m^{-2} yr^{-1}, but a sink nonetheless (Fig. 2 and Table 1).

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 other GHG (Lal, 2019; Wang et al., 2017; Worrall et al., 2016) requires more attention. It is also important to note that the available estimates are strongly biased towards high-input agricultural systems with deep fertile soils developed on sedimentary substrates and thus more data on low-input systems on marginal lands 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 C 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 Rt is the erosion-induced C loss/gain at time t of process R, expressed as a fraction of the mobilized C, t is the time since the start of the erosional disturbance, α is the fractional C 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 CO_2. We used the search terms “soil erosion” & “C sink”|”C source|C budget” in the Scopus database. This was complemented with review papers and references cited herein. From these studies we extracted whether they report erosion as a sink, source or neutral (if no C flux direction is given). The data was complemented with the space and time scales considered as well as the C 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.

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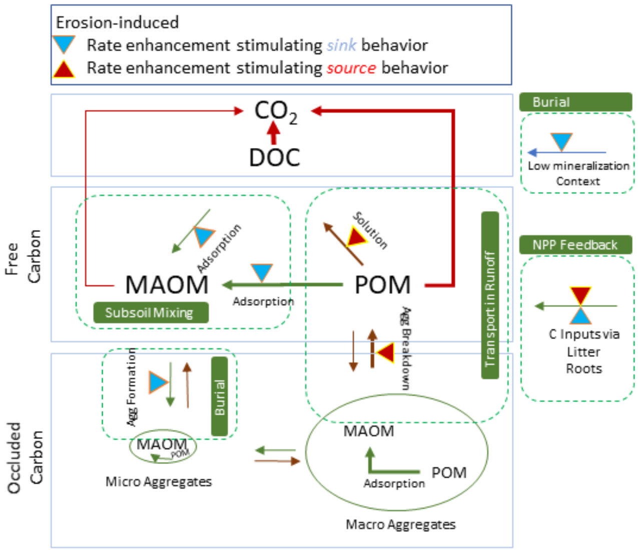

Figure 1: Schematic representation of the effect erosion on soil C stabilization and loss processes. The red triangles represent erosion-induced C loss enhancement processes, while blue triangles represent processes leading to increased stabilization.

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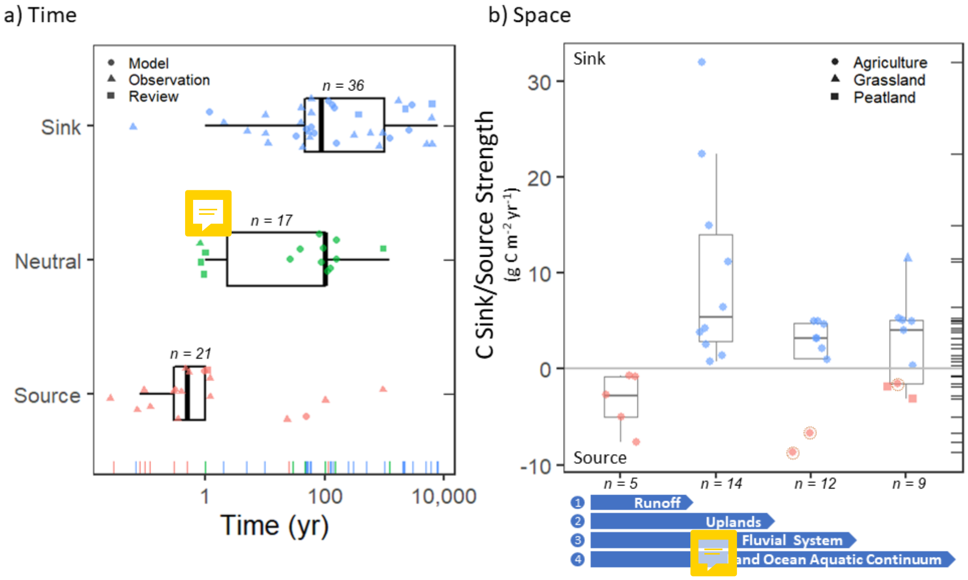
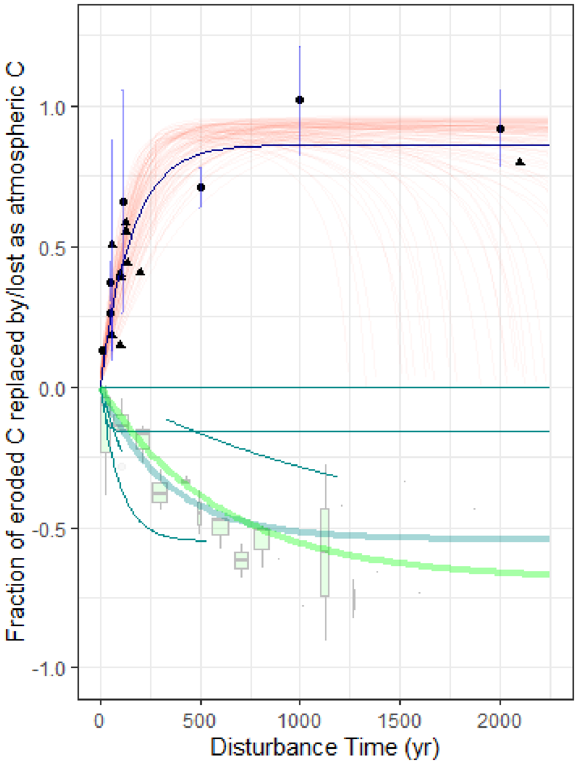


Figure 2: Effect of time and space on the erosional sink versus source term reported in the literature. Panel a) shows how the reported
405 **C source versus sink by erosion is influenced by the time scale considered in the study (74 studies). Panel b) shows how the magnitude of the reported erosion-induced C source/sink strength is influenced by the spatial scale considered in the study (40 studies). Estimates which do not account for C 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.**



Fig[illegible]: Fraction of eroded C replaced by atmospheric CO_2 (rec) as a function of time since start of agricultural erosion based on studies using mass-balance (circles) and model (triangle) approaches. The error bars denote the reported uncertainty range. The bold blue line denotes a fit of a non-linear regression model through the reported SOC recovery data points. The fine red lines represent the results of 100 model runs covering a range of typical erosion and C turnover rates representative for 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 [illegible] mm yr-1 and soil C 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 (bur, 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.

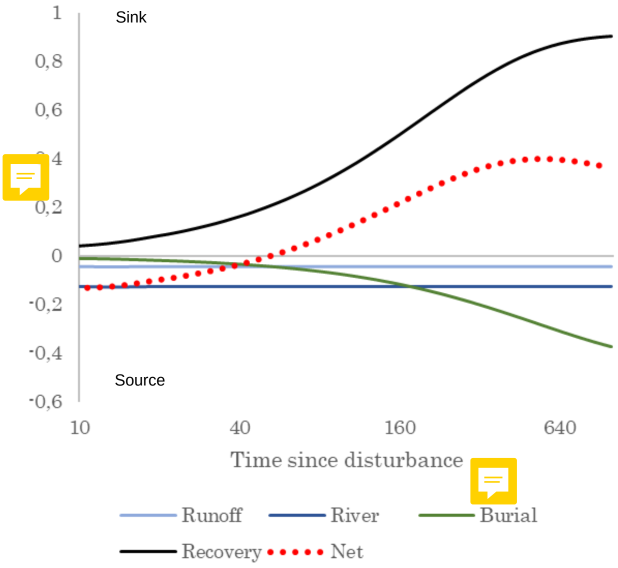


Figure 4: Framework to represent fraction gain/loss relative to mobilized SOC. The example shown here uses α_{runoff}=0.04, τ_{runoff}=1, α_{river}=0.5, τ_{river}=1, ~~α [illegible] ff=0.04, τ_{run} [illegible] 1,~~ α_{burial}=0.584, τ_{burial}=0.0019, $\alpha_{recovery}$=0.91, $\tau_{recovery}$=0.005.

Table 1: Overview of studies reporting erosion-induced C fluxes used in our literature synthesis. Space refers to the 4 components of the geomorphic cascade (see Figure 2 for key). Positive values for C 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 C that is replaced with atmospheric derived C.

Reference	Year	Method	Time (yr)	Effect	Strenght (g C 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	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*	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
(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)[ǂ]	2018	Data	25	Source[ǂ]	-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, [ǂ] C 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 yrs
Oxidation Burial (Colluvial)					
(Van Oost et al., 2012)	0.79	0.0019	0.95	309	0-2436
(Wang et al., 2014b)	0.87	0.0014	0.89	29	0-1388
(Mayer et al., 2018)*	0.584	0.0005	0.66	5	0-5480
(Zeng et al., 2020)	0.14	0.26	0.025	211	0-49
median	*0.69*	*0.0017*			
Oxidation Burial (Alluvial)					
(Omengo et al., 2016)	0.54	0.011	0.42	258	0-420
(Steger et al., 2019)*	0.84	0.003	0.81	3	0-105
(Mayer et al., 2018)*	0.59	0.00067	0.92	4	0-1190
(Hoffmann et al., 2013a)	0	0	/	1126	0-5000
(Van Oost et al., 2012)	0.16	0	/	133	0-2436
median	*0.54*	*0.00067*			
median (col+all)	0.58	0.0014			
Oxidation Runoff					
Median (see text)	0.04	1	/	/	0-1
Oxidation River					
Median (see text)	0.5	1	/	/	-
Recovery					
See text	0.93	0.0060	0.71	19	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 C burial efficiencies.