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de Nijs, E.A.; Cammeraat, L.H.

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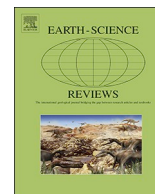
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# The stability and fate of Soil Organic Carbon during the transport phase of soil erosion

Evy A. de Nijs\*, Erik L.H. Cammeraat

*Institute for Biodiversity and Ecosystem Dynamics, Ecosystem and Landscape Dynamics Group, University of Amsterdam, Science Park 904, PO Box 94240, 1090 GE Amsterdam, the Netherlands*



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## ABSTRACT

Soil organic carbon (SOC) is the largest pool of non-sedimentary terrestrial carbon (C) and small changes in vertical SOC fluxes in the erosion-transport-deposition system could have a significant effect on atmospheric C levels. The ongoing sink/source discussion related to SOC seems to depend on which mechanisms are dominant during each of the three stages of soil erosion: detachment, transportation and deposition. Understanding C dynamics during each phase of soil erosion is essential to accurately assess the net effect of erosion. Currently, there is a knowledge gap when it comes to the movement of mobilized SOC from the site of detachment to the depositional site. This review provides an overview on the current understanding of the fate of eroded SOC during the transport phase of soil erosion. The stability of SOC appears to be a logistic interplay between SOC accessibility, presence of decomposers and suitable abiotic conditions. The main protection mechanisms of SOC are physical and/or chemical protection, which both make SOC inaccessible to decomposers and hence prevent mineralization. Transport subjects the SOC to disturbances and changing environmental conditions which interfere with the effectiveness of the protection mechanisms. The vulnerability of these mechanisms to erosive transport are not yet known. Increased physical impact is associated with disaggregation which releases previously protected SOC. Changes in geochemical composition of soil potentially changes the extent of organo-mineral bindings and hence either strengthen or weaken chemical protection. Complex chemical structures might result in more resistant C called biochemical stable SOC and is vulnerable to destabilization during transport due to changes in (a)biotic conditions along the trajectory. A complete understanding of the fate of mobilized SOC during transportation is essential to assess the net effect of soil erosion under different conditions. Standardization of both methodology and terminology in the field of soil erosion will further contribute to resolving the controversy on the net effect of erosion. The focus for future research should be on documenting the different interacting processes active during erosive transport and their effect on SOC fluxes.

## 1. Introduction

Soil organic carbon (SOC) is the largest pool of non-sedimentary terrestrial carbon (C), storing more C than the aboveground vegetation and atmosphere combined (Houghton, 2007). Since the SOC pool is relatively large, even small changes in the SOC stock could have significant effects on the levels of atmospheric C concentration, which, under the current conditions could further increase atmospheric C levels (Stockmann et al., 2013). Increased C mineralization can occur during soil erosion resulting in an increased vertical C flux towards the atmosphere. Globally, soil erosion is the most important form of soil degradation, with estimates of more than 1600 million hectare worldwide to be affected by either severe water or wind erosion (Lal, 2003). This review will inventorise and synthesize the existing knowledge

regarding the stability and fate of SOC during the transport phase of soil erosion.

The effect of soil erosion on C dynamics is an ongoing scientific debate referred to as the C sink/source discussion (Van Oost et al., 2007; Lal and Pimentel, 2008). Soil erosion consists of 3 distinct phases: detachment, transport and deposition (Fig. 1, Doetterl et al., 2016). Most research is focused on either the detachment or the deposition phase, however SOC is affected during each phase of soil erosion (Kirkels et al., 2014). Thus, there is a knowledge gap when it comes to the sensitivity of C to mineralization during specifically the transportation phase of soil erosion. This knowledge gap has been indicated by several reviews as future challenges, however no indepth review regarding the C dynamics during erosive transport has yet been presented (Table 1). Understanding which mechanisms are influencing the C

\* Corresponding author.

E-mail address: [evydenijs@gmail.com](mailto:evydenijs@gmail.com) (E.A. de Nijs).

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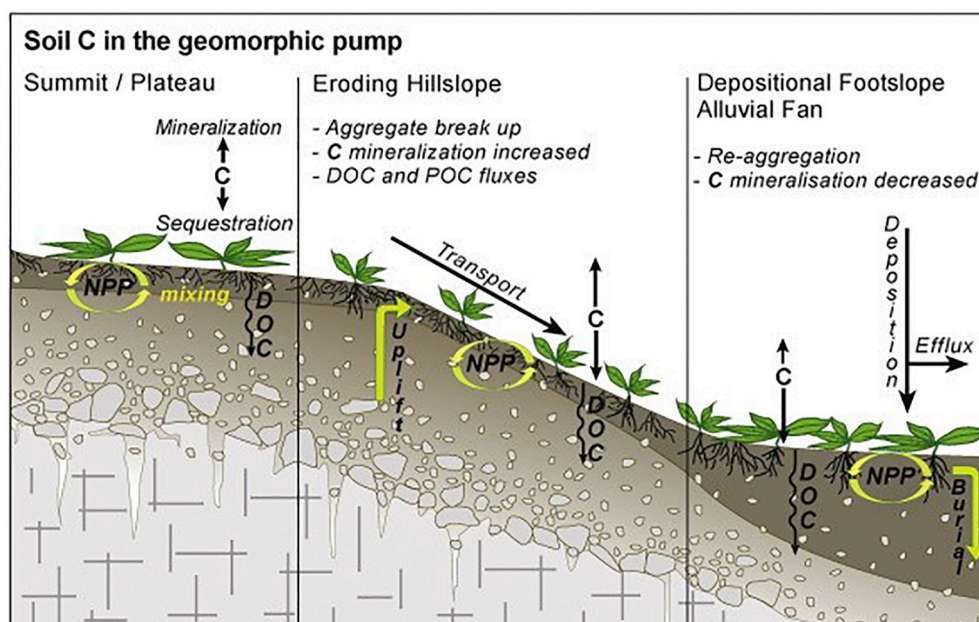


Fig. 1. The C dynamics along a hillslope profile, showing the three phases of soil erosion; detachment, transportation and deposition (from Doetterl et al., 2016).

Table 1

Overview of the main review papers on SOC stability during erosive transport.

Reference	Main topic	Future challenges
Doetterl et al., 2016	Soil C erosion and deposition	'Close the gap between small scale process understanding and large-scale representation of lateral C fluxes in global models'
Berhe et al., 2018	Role of soil erosion in biogeochemical cycling	Improving understanding of key processes associated with soil erosion and their implications for biogeochemical cycling
Kirkels et al., 2014	Role of soil erosion in C dynamics on agricultural soils	To gain insight into the fate of SOC in agricultural landscapes during erosion and depositional processes
Xiao et al., 2018a	C dynamics in relation to agricultural soil erosion	Improve quantification and understanding of SOC dynamics during transport, priming effects, stability of buried SOC and interaction of SOC dynamics with microbial properties
Lal, 2019	Effects of soil erosion on C stocks	Quantitative research regarding the fate of SOC at all different erosional stages
Kuhn et al., 2009	Effect of agricultural (inter)rill erosion on C	Three key issues: Erosive transport studied from an eco-geomorphological perspective, changes in C erosion over time, fate of C in surface sinks

stability during transport will help in closing the knowledge gap and improve the predictive understanding of global C cycling. This will help scientists to better assess the potential consequences of climate change by improving the soil C component of global climate models. Furthermore, it will contribute to the sustainable management of vulnerable areas.

The aim of this review is to investigate the vulnerability of the different mechanisms influencing SOC stability during the transport phase of soil erosion within the discussion on the effects of soil erosion. This will be discussed by addressing, (1) the characteristics of stable organic C and which factors influence the stability of SOC; (2) how the stability of SOC is influenced during the transport phase of soil erosion; and lastly (3) how these findings on the stability of SOC during transport fit within the discussion on soil erosion and its contribution to the global C cycle. Since the process of erosion covers a broad range of spatial scales an integrative approach of soil science, biogeochemistry and geomorphology was applied.

## 2. SOC stability: definition and mechanisms

### 2.1. Stable soil organic carbon

SOC is a substantial part of soil organic matter (SOM) and is seen as a continuum ranging from; the labile fraction (i.e. active) to the stable fraction (i.e. passive) (Dungait et al., 2012; Lehmann and Kleber, 2015). The latter fraction can be encapsulated in aggregates or form

associations with soil minerals, both mechanisms protect the C from mineralization and are therefore defined as stable. The labile fraction does not profit from either of these mechanisms and thus experiences rapid turnover times. Within the field of biogeochemistry, SOC is considered stable when both the amount of C and/or composition of SOC remain constant following the definition of Doetterl et al. (2012) and Berhe and Kleber (2013). However, this can change rapidly in response to disturbances (Morgan, 2005). Decomposition is the breakdown of substances via physical, chemical or biological processes. Mineralization is a form of decomposition where, in this case, SOC is completely converted into the inorganic compounds  $\text{CO}_2$ ,  $\text{H}_2\text{O}$  and nutrients.

### 2.2. Mechanisms influencing SOC stability

The mechanisms influencing SOC stability have been a subject of discussion since new analytic methods did not support the standing paradigm (Schmidt et al., 2011; Lehmann and Kleber, 2015). Previously, the presence of stable SOC was assigned to the recalcitrance of the molecular structure and/or large molecule size (Schmidt et al., 2011; Doetterl et al., 2016). The emerging understanding is that stable SOC is not merely the result of its intrinsic characteristics but rather influenced by accessibility for decomposers governed by an interaction between a set of physical, chemical and biological drivers. Decomposition rates decline when one of the conditions required for optimal decomposition is not met, which might result in the presence of undecomposed, but decomposable C in soils (Dungait et al., 2012).

The stability associated with a complex chemical composition of C components can both be a property inherent to the origin or be attained during the decomposition trajectory through condensation and complexation processes (Six et al., 2002). Complex chemical composition can both slow down the decomposition process and influence the chemical stabilization mechanism, where certain compounds are unable to profit from organo-mineral bonds (Lutzow et al., 2006; Wang et al., 2014a). Overall, the concept of recalcitrance appears to be relevant for C stability in soils when discussing persistence in terms of years rather than long-term stability (Dungait et al., 2012).

Long-term SOC stability is currently considered to be governed mainly via the chemical and physical protection mechanisms. Prevention of decomposition leads to stable SOC under these specific circumstances. Chemical protection is driven by the association of C with mineral surfaces, in different forms such as adsorption, complexation or precipitation (Berhe and Kleber, 2013). The affinity of the associations of C with mineral surfaces exceeds that of an enzyme, which makes the C unavailable as a resource for decomposers and hence the bonded C is called stable. The presence of sorptive mineral surfaces is essential for organo-mineral bonding, the extent of protection is thought to be dependent on soil characteristics such as mineralogy, texture and surface area (Six et al., 2002; Dungait et al., 2012; Doetterl et al., 2016). Weathered soils are an example where mineral surfaces are well represented through accumulation of reactive metal oxides, resulting in an environment promoting SOC stabilization (Doetterl et al., 2016). A high clay content might indicate the presence of suitable sorptive surfaces, however this is strongly dependent on the mineralogy of the clay-fraction. Organo-mineral associations are for example more dominant with swelling clay minerals compared to non-swelling clay minerals (Regelink et al., 2015). Physical protection is driven by the spatial separation from decomposers, such as encapsulation of C within soil aggregates or burial in deep soil (Schmidt et al., 2011). Furthermore, it limits the diffusion of enzymes, oxygen and moisture, which are in varying importance all needed for decomposition. Physical and chemical protection strongly interact in several ways, the complexed fraction of SOC is for instance protected via strong associations with organo-minerals and can further be physically isolated through its feature of enhancing aggregation (Dungait et al., 2012).

### 2.3. Interactions and the emerging view on C stability

Stabilization mechanisms are interactive and strongly dependent on site-specific conditions. Organo-mineral bindings, for example, enhance the formation of aggregates, and complex molecules can get incorporated within aggregates thus further enhancing protection of C from decomposition (Berhe et al., 2012; Dungait et al., 2012; Doetterl et al., 2016). Chemical protection is dependent on the availability of mineral surfaces and physical protection on the formation and stability of aggregates. Furthermore, the abiotic conditions influence the efficiency of decomposers and hence their effectiveness.

The extent and efficiency of the main C stabilization mechanisms is dictated by the geochemical composition of the soil and environmental conditions. The mineralogy of a soil is often not uniform along a hill-slope and hence influences the sorption effectiveness caused by the changing saturation levels of chemically associated SOC (Six et al., 2002; Doetterl et al., 2016).

Soil structure is one of the factors involved in C stabilization and refers to the organization of primary soil particles which, when assembled, are called aggregates (Morgan, 2005). Soil aggregates isolate SOC from decomposers and realise unsuitable conditions within the aggregate for decomposition (Six et al., 2004; Doetterl et al., 2016). The stability of aggregates accounts for the stability of the encapsulated C and is influenced by various factors which all show spatial variability. Due to the inverted relation with energy needed for breakdown, macro-aggregates are usually more easily disrupted compared to micro-

aggregates (Kuhn et al., 2009; Dungait et al., 2012). The hierarchical aggregate concept of Oades (1984) states that micro-aggregates are necessary for the formation of macro-aggregates but that at the same time micro-aggregates develop within macro-aggregates, hence inception alongside the sequential formation of macro-aggregates. Micro-aggregates are found to experience enhanced stability due to encrustation with inorganic materials, so a combination of physical and chemical protection (Oades and Waters, 1991). With the formation of stable soil aggregates different mechanisms of binding are at play at different hierarchical levels, thus soil aggregate stability cannot be described as a sliding scale (Regelink et al., 2015).

The stability of aggregates is influenced by several factors which illustrate the complex interplay. The pH of a soil influences aggregate stability, a more alkaline soil has, under most circumstances, a higher mineral surface concentration and thus enhances formation of organo-mineral associations. Furthermore, a decreased pH increases the strength of these bindings and their tendency to coagulate and thus form aggregates (Regelink et al., 2015). However, soils with high levels of calcium carbonate often have low association potency. This is once again the outcome of an interactive process where these soils often occur in arid areas with low biomass production and OM addition to the soil is a prerequisite for aggregate stability (Fernández-Ugalde et al., 2009). SOC levels declined drastically in a study where soils were deprived of OM input for an extended period of time due to a decrease in aggregate stability (Hirsch et al., 2009; Regelink et al., 2015). The current concept of the formation of stable aggregates is the hierarchical order of aggregation with SOM as main binding agent (Six et al., 2004). Currently it is widely accepted that the stable micro-aggregates are responsible for the long-term protection of SOC (Oades and Waters, 1991; Six et al., 2004).

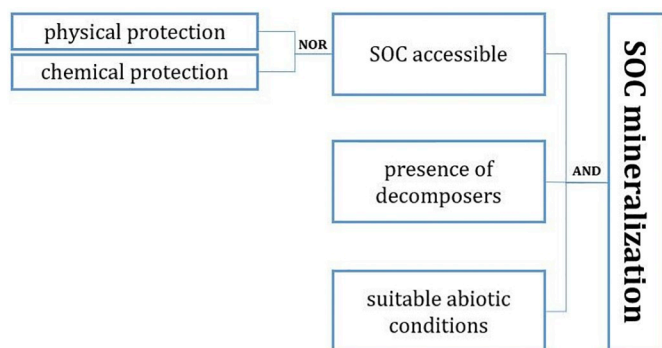
The effectiveness of decomposers is influenced by the abiotic circumstances such as the relative levels of moisture, oxygen availability and temperature which are subjected to change during transport (Doetterl et al., 2016). Unsuitable abiotic conditions are achieved with the encapsulation in aggregates and burial in subsoils (Schmidt et al., 2011). The importance of oxygen availability does not appear to be crucial. Wang et al. (2013) found that oxygen (O) levels were not driving C mineralization in the Belgian Loess Belt. Their study showed that oxygen levels do play an important role in topsoil decomposition but can be excluded as ruling control on subsoil decomposition. Decomposition of complex stable SOC is often sensitive to rising temperatures since their higher resistance is associated with an increased activation energy (Dungait et al., 2012; Stockmann et al., 2013). Finally, the biological process of priming or co-metabolism affects the decomposition rates of SOC. When readily available ('labile') C sources become available they speed up the decomposition of more complex ('stable') C components (Stockmann et al., 2013). This easily accessible energy stimulates the growth of previously depleted microbial communities which in turn leads to increased C mineralization rates (Doetterl et al., 2016). Physical and biological factors change during erosive transport influencing the effectiveness of decomposers and hence the extent of mineralization.

Within this emerging view on C stability, mineralization of SOC could be described as a logistic interplay where water, oxygen, SOC and decomposers have to be available at the same spatial and temporal point (Six et al., 2002; Dungait et al., 2012). When one of the conditions is not met, C is not decomposed and hence considered stable (Fig. 2).

## 3. SOC stability during erosive transport

### 3.1. Forms of erosion

Erosional processes, either physical, biological or chemical weaken a soil and thereby increase the susceptibility of a soil for detachment and transportation (Morgan, 2005; Dungait et al., 2012). There are several ways in which subsequent erosive transport can occur. Different



**Fig. 2.** Schematic overview of the process of SOC mineralization seen as a logistic interplay of factors which all three need to be positive (AND gate) at the same spatial and temporal moment for mineralization to occur. A NOR gate only gives a positive output when both inputs (physical and chemical protection) are negative. If one of these requirements is not met, SOC mineralization will not take place.

types of erosion cause slightly diverse disturbances and hence interact with SOC stability mechanisms in relatable, but still diverging ways. All mechanisms governing potential mineralization are affected by the disturbances associated with transport processes and the interactions between these mechanisms (Kirkels et al., 2014). To make an educated guess about the vulnerability of SOC protection mechanisms during the transport phase, an overview of erosion types is required.

Water and wind are the most common erosive agents causing detachment of soil particles and provide energy to transport the soil particles. Transporting agents subject sediments to physical perturbations and transfer the sediments along sites with different biological and chemical characteristics which all might lead to changing decomposition rates. Limited studies are available on the effect of wind erosion on the SOC pool. Yan et al. (2005) found losses of SOC on catchment scale due to wind erosion, however more quantitative research is needed before accurate conclusions can be drawn.

Water driven erosive transport can be divided in three main groups; interrill erosion, rill & gully erosion and splash erosion. These occur respectively in the form of sheet erosion, channel formation or via the impact of raindrops (Morgan, 2005). Each erosion process is associated with different transport velocities, resulting in either selective or non-selective mobilization of SOC. Interrill erosion is selective and often has low flow velocities resulting in the preferential mobilization of SOC to mineral soil, resulting in SOC enriched sediments (Kuhn et al., 2009). Rill and gully erosion are non-selective and with the channeled water flow results in higher flow velocities. The deposited sediment is in theory identical to the soil from the detachment site (Morgan, 2005; Kuhn et al., 2009). Splash erosion is caused by the impact from raindrops on soil particles where the momentum of a raindrop is transferred to a soil particle. The transfer of energy to the soil particles results in the detachment of particles and delivers a disruptive force which potentially causes disaggregation (Morgan, 2005). Tillage erosion is induced by the anthropogenic activity of redistributing soil through plowing and mainly operating at the detachment site (Beniston et al., 2015).

The type of erosion process and associated flow velocity results in shifting SOC concentrations along a hillslope. This is supported by a study which showed that the relative abundance of the fine size aggregate fraction and SOC enrichment increased in the sediments further down the slope (Wei et al., 2017). Finally, as mentioned earlier, the geomorphological aspects of the landscape strongly influence the impact of the disturbances. Both longer slopes and increased slope steepness lead to an increase in the effect of gravity (Morgan, 2005). This results in higher transport velocities and thereby detachment of more soil particles and potentially increase the power of perturbations such as physical impact resulting in aggregate destruction.

### 3.2. SOC movement through landscapes

The stability of SOC is often discussed within a stable state situation, where the different mechanisms act and interact at a specific spatial location (Doetterl et al., 2016). However, in the case of erosion, spatial displacement plays an important role during the transport phase which is likely to influence stabilization mechanisms of SOC. Very little is known about the sensitivity of SOC to the processes associated with sediment displacement.

Three mechanisms are identified which are thought to be the main drivers behind the net SOC flux during an erosion process at catchment scale. The *first* mechanism is the replacement of SOC at the eroding sites, decreasing the amount of available SOC for rapid decomposition (Berhe et al., 2008). The *second* mechanism concerns the deep burial of SOC leading to decreased decomposition and *lastly*, enhanced mineralization of SOC due to both physical and chemical disturbances during detachment and transport (Van Oost et al., 2007). The specific catchment conditions determine the dominance and interaction of these mechanism, and hence the resulting C flux. Researchers who argue that soil erosion is a net source of SOC put emphasize on the importance of the breakdown of aggregates during detachment and transport and tone down the effects of SOC replacement at the eroding sites (Lal and Pimentel, 2008). The lack of consensus is reflected in the problems with quantifying the effects of these interacting mechanisms on a global scale.

Kuhn et al. (2009) contradict the theory of increased SOC mineralization during erosive transport, they looked at the effects of isolated erosion types on fine scales to increase the understanding of SOC movement through landscapes. Their study showed that both selective and non-selective erosion influences the SOC concentrations of the mobilized sediment whether or not preferentially mobilized. The preferentially mobilized SOC through interrill erosion is usually deposited relatively nearby in the form of depositional crusts. Depositional crusts are formed by the deposition of soil particles in puddles (Morgan, 2005). This C-rich crust can be vulnerable to mineralization due to the exposed location at the earth's surface where physical protection is limited. Normal rill erosion is non-selective but the movement of sediment through landscapes does result in the separation of sediments based on texture and aggregate size. The combination of earlier deposition of larger particles and the variation of SOC content of sediment with particle size results in an enrichment of SOC content further along the hillslope.

There are other studies which identified fine scale erosion processes altering the behavior of SOC in ways which are not in line with the conventional mineralization perspective (Schiettecatte et al., 2008; Kuhn et al., 2009; Nadeu et al., 2011; Wei et al., 2017). Whether these processes contribute strongly to the net C flux depends on the location, environmental conditions and spatial extent at which the measurements are conducted. Nadeu et al. (2011) found for instance C content impoverishment in the sediments on catchment scale for all researched forms of erosion (i.e. gully, interrill, bank and tillage erosion) in SE Spain, hence suggesting that SOC mineralization during erosion is enhanced. However, in this specific situation the environmental circumstances (e.g. high erosive activity and lack of stable depositional sites) could have facilitated mineralization and led to results representing a more extreme situation. But Wan and El-Swaify (1997), Wang et al. (2010), Wei et al. (2017) on the other hand found that erosion led to SOC enrichment in the delivered sediment indicating high selectivity of erosion processes with regard to the preferred size of aggregates transported. Stacy et al. (2019) found that the amount of precipitation played an important role in the type of SOC being mobilized, high annual precipitation resulted in relatively more mineral associated SOC to be mobilized. This was supported by Jacinthe et al. (2004) who found that labile C was preferentially detached during low-intensity storms. However, overall erosive impact is strongly influenced by high-energy storms resulting in increased soil loss (Jacinthe et al., 2004). These

controversial results once again emphasize the importance of an integrated eco-geomorphological approach when researching the effects of erosion (Kuhn et al., 2009).

### 3.3. Potential SOC mineralization during transportation

During transport, stable SOC is subjected to physical, chemical and biological processes which influence the different protection mechanisms. The interplay between water, gravity and site-specific conditions is complex and often have interactions, where combined action might lead to increased C mineralization. If we recall the emerging view on SOC stability, we can describe SOC stability as an interplay of accessible SOC, decomposers, water and oxygen. The protection mechanisms set a priori limits to decomposition by limiting substrate availability and hence mineralization potential. Transport subjects the SOC to disturbances which might interfere with the effectiveness of the protection mechanisms and thus enhance decomposition.

#### 3.3.1. Physical perturbations

Physical perturbation can lead to disaggregation making previously occluded SOC susceptible to decomposers (Yue et al., 2016; Wei et al., 2017). The expected changes in pH, SOM turnover rates and rainfall impact during transport also influence aggregate stability. The extent to which aggregate destruction contributes to C mineralization is controversially discussed with estimates from ranging from minor to 20% or even complete mineralization (Table 1 in Kirkels et al., 2014). These values are strongly influenced by the local conditions, i.e. hillslope length, steepness, soil type, rainfall intensity and type of transporting agent (Berhe and Kleber, 2013; Xiao et al., 2018a). These site-specific factors and the different approaches to the inclusiveness of catchments are often not included when comparing studies, resulting in a skewed view on the processes involved. Furthermore, the methods currently used for soil erosion research and upscaling are associated with inconsistencies in methodology and unreasonable assumptions (Xiao et al., 2018a).

#### 3.3.2. Biological processes

Environmental conditions change during transport which results in transitions of (a)biotic conditions such as decomposer abundance, SOM availability, pH, temperature and soil mineralogy. Changes in biological processes might affect SOC which is stable due to its chemical composition. Soil conditions can become more favourable, such as a higher temperature resulting in higher energy levels and might thereby cross the threshold for decomposition of the more complex molecules (Dungait et al., 2012). Furthermore, the provision of labile SOC can have a significant influence. The accessible C can set decomposition in motion through the process of priming or co-metabolism (Schmidt et al., 2011; Dungait et al., 2012). An interactive situation could be disaggregation releasing complex C molecules in a changed environment where labile SOC is present, potentially leading to enhanced decomposition. Besides, the growth of previously depleted microbial communities can hereby be stimulated and might further increase mineralization rates (Doetterl et al., 2012).

#### 3.3.3. Chemical and physicochemical processes

The chemical protection mechanisms can either be strengthened or weakened by variation in the geochemical composition of a soil along the slope. If changes occur in the direction of increased presence of clay minerals, the freshly exposed SOC could benefit from this resulting in enhanced SOC sequestration. On the other hand, chemically protected SOC could also suffer from the breakdown of aggregates caused by the physical impact as a result of the transportation. With water as the erosive agent a balance between chemical reactions and organo-mineral associations is likely to establish. A combination of translocation and physical disturbance in a water driven environment could expose the organo-mineral associations to chemical weathering resulting in

leaching of the formerly protected C. The mobilized C could leach from the soil into groundwater or be transported further downhill and potentially be buried in sediments at the depositional site (Kindler et al., 2011). Specific research conducted on the susceptibility of the breakdown of the chemical protection mechanism during erosive transport has not yet been carried out. Research has shown that C leaching differs strongly between different land-use systems, with the sorption capacity for the SOC as one of the important controlling factors for the magnitude of C leaching (Kindler et al., 2011). Erosive transport is likely to partially break down the aggregates and hence expose SOC, but the SOC which is also chemically associated is still protected and hence not immediately accessible to the decomposers. Another physicochemical process interaction that may give access to occluded SOC is the process of soil aggregate disintegration upon wetting in situ by rainfall and wetting during transport. Clay dispersion might occur because of wetting by rainwater with a low electrolyte content (Blume et al., 2016; Koorevaar et al., 1983), and especially at the onset of overland (sheet and rill) flow, may induce swelling and dispersion and hence contribute to aggregate disruption. This is however also related to the type of clay minerals involved in the soil assemblage. An overview of processes involved in the physical and physicochemical disintegration of soil aggregates is given in i.a. Le Bissonnais (1996) and Xiao et al. (2018b).

The location in the landscape is another important factor to consider when assessing potential SOC mineralization. Soil erosion on a catchment scale is a process of alternation between detachment and deposition, resulting the temporal storage of C along the transport line (Van Hemelryck et al., 2010). This implies that the three phases of soil erosion cannot be treated in isolation. For example, since both erosive detachment and deposition takes place mid-slope, the lowest levels of SOC are often found here (Ritchie et al., 2007). This could expose subsoil SOC and depending on the erosive intensity result in immediate mineralization, mobilization or enhanced SOC sequestration due to the relatively low SOC concentrations (Kirkels et al., 2014).

The extent to which physical, biological and (physico)chemical processes influence protection mechanisms of SOC during transportation are unknown, while both quantitative and qualitative knowledge on this matter is necessary to quantify the extent of potential SOC mineralization.

## 4. Discussing the fate of mobilized SOC

The fate of mobilized SOC during erosive transport is largely unknown and causes uncertainties within the controversial discussion on the C related effects of soil erosion. Specifically, the effects of interactive processes influencing the stability of eroded SOC during transport need to be considered within the field of soil erosion and its contribution to the global C cycle. The lack of knowledge and data in regard to the different aspects of SOC transportation were identified and suggestions for future research are provided.

So far, this review provided an overview on the different mechanisms stabilizing SOC and how these can be affected by the different interacting processes during erosive transport. The protection of SOC is under pressure during transport, potentially leading to enhanced mineralization rates. Physical perturbation could lead to disaggregation and changing environmental conditions might lead to enhanced microbial activity, but the effects of changes in geochemical composition and physicochemical disaggregation are far less understood. The obstacle with assessing the role of mobilized C to the vertical C flux is linked to the limited availability of studies focussing on specifically the transport phase of soil erosion. Different physical, biological & (physico)chemical processes take place and interact during erosive transport but the knowledge regarding these mechanisms is limited (Table 2).

The effect of erosive transport was studied by Wang et al. (2014b) who looked at C mineralization from a loess soil upon discharge in surface water. Their results indicated that only a small portion of eroded SOC mineralized during transport. This was supported by a

**Table 2**  
Overview of interaction processes during the transport of SOC.

	Process interaction during transport	Identified knowledge gap	Reference
Physical	Disaggregation	Extent to which disaggregation contributes to mineralization	Kirkels et al., 2014; Berhe and Kleber, 2013; Xiao et al., 2018a
Biological	Particle size selectivity	Particle size relation with SOC stability	Wang et al., 2019; Nie et al., 2018
	Changing (a)biotic circumstances	The interaction between 'complex' stable SOC & labile SOC input & microbial activity	Dungait et al., 2012; Doetterl et al., 2012; Schmidt et al., 2011
(Physico)Chemical	Variation in geochemical soil composition	Vulnerability of organo-mineral associations to transport & potential increase in bonding	Kindler et al., 2011
	Aggregate slaking / clay dispersion in (rain) water	Extent to which this process gives access to occluded SOC	Xiao et al., 2018b

study from Van Hemelryck and Govers (2011) who measured the extent of increased mineralization on an agricultural field on the loess belt of Belgium, after an erosion event. During a 112-day period the CO<sub>2</sub>-efflux was measured in situ and the results indicated an additional emission of CO<sub>2</sub> of less than 10% of the total deposited SOC caused by the process of soil redistribution. However, a meta-analysis on studies focussing on the effect of erosive transport resulted in the broad range of observed mineralization levels, estimates of mineralization fell between 0 and 43% of the eroded SOC (Xiao et al., 2018a). This wide range was partly caused by dissimilarities in site-specific conditions and methodology and stress the need for further research.

The importance of location within a catchment is essential to consider since detachment and deposition alternate with transportation along the transport line. Aggregate stability during detachment and deposition was investigated in the Belgium loess belt by Wang et al. (2014a) who found that erosion-induced aggregate disruption resulted in increased SOC sequestration via both protective mechanisms at the depositional site. They hypothesised that the encapsulation of SOC in aggregates serves as way for eroded SOC to be chemically stabilized later on. This is supported by studies which showed that increased abundance of mineral surfaces at the depositional site resulted in more chemically protected SOC (Doetterl et al., 2012; Wang et al., 2014a). This chemically protected SOC in turn enhances the formation and stabilization of aggregates (Berhe et al., 2012; Dungait et al., 2012; Doetterl et al., 2016). Changing water availability could also result in disaggregation via the interactive process of aggregate slaking and clay dispersion. Overall, physical and physicochemical processes are expected to result in increased aggregate disruption, but it is likely that the availability of charged mineral surfaces and suitable soil water content determines the net C flux (Hu and Kuhn, 2014; Wang et al., 2014a; Lal, 2019).

Another uncertainty comes from the lack of knowledge regarding the susceptibility of organo-mineral associations to dissociation caused by the conditions characteristic for transportation. Laboratory experiments could give insight into the behaviour of C-binding organo-mineral associations to the different perturbations sediments are subjected to during erosive transport. One experiment to analyse this could be mixing sediment rich in organo-mineral associations with rainwater, subjecting the suspension to a physical disturbance via for instance shaking and subsequently remeasuring the equilibrium between the associated C and dissolved C. These types of laboratory-controlled experiments could clarify the fate of chemically protected SOC in eroded sediment.

The sink/ source debate of soil erosion seems to be driven by a combination of shortage of experimental data and differential use of concepts related to soil erosion processes. To enable comparative analyses it is important to put the focus on standardizing both the terminology and methodology (Berhe and Kleber, 2013; Lal, 2019; Xiao et al., 2018a). The scarcity and incomparability of studies resulted in the debate on whether soil erosion is a C sink (Van Oost et al., 2007; Berhe et al., 2018) or source (Lal, 2003; Lal and Pimentel, 2008; Olson et al., 2016). Jacinthe and Lal (2001) demonstrated that the net

modelled effect of soil erosion could change from a C source to a C sink by changing the parametrization of the mineralization magnitude. The dominating processes vary strongly per landscape unit, biogeochemical soil composition and their interaction, which makes the development of accurate predictive models for the global C cycle even more complicated. A better understanding of the effect of soil erosion will help in assessing the potential effects of climate change, since the predicted increase in intensive rainfall events is associated with elevated erosive activity (Dai, 2013; IPCC, 2013; Morgan, 2005).

The research challenges regarding the fate of SOC during erosive transport lie within increasing our understanding of the interacting processes during erosive transport as well as gathering quantitative data on the extent of the potential mineralization effect. The identified knowledge gaps represented in Table 2 provide a starting point for future research directions. The experiments should be set up in a way it could be replicated under different conditions and ecosystems by other research groups.

The stability of eroded SOC during the transport phase of soil erosion is underexplored in the literature and mostly overlooked in the discussion on the contribution of soil erosion to the global C cycle. To accurately assess the net effect of C exchange between the mobilized sediment and atmosphere, all processes taking place during each stages of soil erosion should be understood and quantified.

## 5. Conclusion

The aim of this review is to assess the effects of transport on the stability of mobilized SOC during the transport phase of soil erosion and its contribution to the global C cycle. Whether soil erosion leads to SOC mineralization or sequestration is widely discussed and so far no consensus has been reached. This controversy is driven by the effect of the relative stability of SOC during each of the three stages of soil erosion, and hence it is striking to see that the fate of SOC during the transportation phase is underexplored in research. SOC stability is mainly driven via an interplay of SOC accessibility, presence of decomposers and suitable abiotic circumstances, mineralization will not take place when one of these conditions is not met. Physical and chemical protection mechanisms prevent mineralization by making SOC inaccessible to the decomposers. The physical disturbance caused by translocation results in disaggregation and hence deterioration of the physical protection mechanism. Geochemical soil composition changes along the trajectory and could potentially change the extent of organo-mineral bindings and hence either strengthen or weaken chemical protection. Studies on the net effect of erosive transport and the interaction between the process mechanisms are scarce, and hence no accurate predictions can be made. Relatively simple laboratory experiments on the effect of erosive perturbation on the stability of organo-mineral associations could give insight into potential effects of soil erosion on the chemical protection mechanism. This review indicated severe knowledge gaps in the process of erosive transport, this knowledge is essential to assess the net effect of soil erosion at different landscape units and under different circumstances. The opposing views on whether soil

erosion is a net C sink or source is caused by contradictive outcomes on the magnitude of the mineralization of mobilized SOC. There is a lot to gain from increasing our understanding of the sensitivity of SOC protection mechanisms to erosive transport and the consequences for C fluxes which is shown to be driven by site-specific conditions. Standardizing both methodology and terminology in the field of soil erosion will further contribute to resolving the controversy on the net effects of soil erosion. Future research should focus on the processes involved in erosive transport and their interacting effects on SOC in mobilized sediment. The challenge for the coming years will be to translate insights obtained from small-scale laboratory experiments on the fate of mobilized SOC to field circumstances in order to improve global C flux predictions.

### Declaration of Competing Interest

The authors of this review entitled 'The stability and fate of Soil Organic Carbon during the transport phase of soil erosion' declare no conflict of interest.

### References

- Beniston, J.W., Shipitalo, M.J., Lal, R., Dayton, E.A., Hopkins, D.W., Jones, F., ... Dungait, J.A.J., 2015. Carbon and macronutrient losses during accelerated erosion under different tillage and residue management. *European Journal of Soil Science* 66 (1), 218–225.
- Berhe, A.A., Kleber, M., 2013. Erosion, deposition, and the persistence of soil organic matter: mechanistic considerations and problems with terminology. *Earth Surf. Process. Landf.* 38 (8), 908–912.
- Berhe, A.A., Harden, J.W., Torn, M.S., Harte, J., 2008. Linking soil organic matter dynamics and erosion-induced terrestrial carbon sequestration at different landform positions. *J. Geophys. Res. Biogeosci.* 113 (G4).
- Berhe, A.A., Harden, J.W., Torn, M.S., Kleber, M., Burton, S.D., Harte, J., 2012. Persistence of soil organic matter in eroding versus depositional landform positions. *J. Geophys. Res. Biogeosci.* 117 (G2) (n/a-n/a).
- Berhe, A.A., Barnes, R.T., Six, J., Marín-Spiotta, E., 2018. Role of Soil Erosion in Biogeochemical Cycling of Essential elements: Carbon, Nitrogen, and Phosphorus. *Annu. Rev. Earth Planet. Sci.* 46, 521–569.
- Blume, H.P., Bruemmer, G.W., Fleige, H., Horn, R., Kandeler, E., Koegel-Knapner, I., Kretschmar, R., Stahr, K., Wilke, B.M., 2016. Scheffer/Schachtschabel Soil Science. Springer, Berlin Heidelberg.
- Dai, A., 2013. Increasing drought under global warming in observations and models. *Nat. Clim. Chang.* 3 (1), 52–58.
- Doetterl, S., Six, J., Van Wesemael, B., Van Oost, K., 2012. Carbon cycling in eroding landscapes: geomorphic controls on soil organic C pool composition and C stabilization. *Glob. Chang. Biol.* 18 (7), 2218–2232.
- Doetterl, S., Asefaw Berhe, A., Nadeu, E., Wang, Z., Sommer, M., Fiener, P., 2016. Erosion, deposition and soil carbon: a review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth-Sci. Rev.* 154, 102–122.
- Dungait, J.A.J., Hopkins, D.W., Gregory, A.S., Whitmore, A.P., 2012. Soil organic matter turnover is governed by accessibility not recalcitrance. *Glob. Chang. Biol.* 18, 1781–1796.
- Fernández-Ugalde, O., Virto, I., Bescansa, P., Imaz, M.J., Enrique, A., Karlen, D.L., 2009. No-tillage improvement of soil physical quality in calcareous, degradation-prone, semiarid soils. *Soil Tillage Res.* 106 (1), 29–35.
- Hirsch, P.R., Gilliam, L.M., Sohi, S.P., Williams, J.K., Clark, I.M., Murray, P.J., Murray, P.J., 2009. Starving the soil of plant inputs for 50 years reduces abundance but not diversity of soil bacterial communities. *Soil Biol. Biochem.* 41, 2021–2024.
- Houghton, R.A., 2007. Balancing the Global Carbon Budget. *Annu. Rev. Earth Planet. Sci.* 35 (1), 313–347.
- Hu, Y., Kuhn, N.J., 2014. Aggregates reduce transport distance of soil organic carbon: are our balances correct? *Biogeosciences* 11, 6209–6219.
- IPCC, 2013. Climate Change 2013 - the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (Stocker, Thomas F. Qin, Dahe Plattner, Gian-Kasper Tignor, Melinda M.B. Allen, Simon K. Boschung, Judith Nauels, Alexander Xia, Yu Bex, Vincen).
- Jacinthe, P.A., Lal, R., 2001. A mass balance approach to assess carbon dioxide evolution during erosional events. *Land Degrad. Dev.* 12 (4), 329–339.
- Jacinthe, P.A., Lal, R., Owens, L.B., Hothem, D.L., 2004. Transport of labile carbon in runoff as affected by land use and rainfall characteristics. *Soil Tillage Res.* 77 (2), 111–123.
- Kindler, R., Siemens, J., Kaiser, K., Walmsley, D.C., Bernhofer, C., Buchmann, N., ... Kaupenjohann, M., 2011. Dissolved carbon leaching from soil is a crucial component of the net ecosystem carbon balance. *Glob. Chang. Biol.* 17 (2), 1167–1185.
- Kirkels, F.M.S.A., Cammeraat, L.H., Kuhn, N.J., 2014. The fate of soil organic carbon upon erosion, transport and deposition in agricultural landscapes — a review of different concepts. *Geomorphology* 226, 94–105.
- Koorevaar, P., Menelik, G., Dirksen, C., 1983. Elements of soil physics. In: *Developments in Soil Science* 13. Elsevier, Amsterdam.
- Kuhn, N.J., Hoffmann, T., Schwanghart, W., Dotterweich, M., 2009. Agricultural soil erosion and global carbon cycle: controversy over? *Earth Surf. Process. Landf.* 34, 1033–1038.
- Lal, R., 2003. Soil erosion and the global carbon budget. *Environ. Int.* 29 (437–150).
- Lal, R., 2019. Accelerated soil erosion as a source of atmospheric CO<sub>2</sub>. *Soil Tillage Res.* 188, 35–40.
- Lal, R., Pimentel, D., 2008. Soil erosion: a carbon sink or source? *Science* 319, 1040–1042.
- Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *Eur. J. Soil Sci.* 47, 425–437.
- Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. *Nature* 528 (7580), 60.
- Lutzow, M., Kogel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - a review. *Eur. J. Soil Sci.* 57 (4), 426–445.
- Morgan, R.P.C., 2005. *Soil Erosion & Conservation*.
- Nadeu, E., De Vente, J., Martínez-Mena, M., Boix-Fayos, C., 2011. Exploring particle size distribution and organic carbon pools mobilized by different erosion processes at the catchment scale. *J. Soils Sediments* 11, 667–678.
- Nie, X., Li, Z., Huang, J., Liu, L., Xiao, H., Liu, C., Zeng, G., 2018. Thermal stability of organic carbon in soil aggregates as affected by soil erosion and deposition. *Soil Tillage Res.* 175, 82–90.
- Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management. *Plant Soil* 76 (1–3), 319–337.
- Oades, J., Waters, A., 1991. Aggregate hierarchy in soils. *Aust. J. Soil Res.* 29 (6), 815.
- Olson, K.R., Al-Kaisi, M., Lal, R., Cihacek, L., 2016. Impact of soil erosion on soil organic carbon stocks. *J. Soil Water Conserv.* 71 (3), 61A–67A.
- Regelink, I.C., Stoof, C.R., Rousseva, S., Weng, L., Lair, G.J., Kram, P., Comans, R.N.J., 2015. Linkages between aggregate formation, porosity and soil chemical properties. *Geoderma* 247–248, 24–37.
- Ritchie, J.C., McCarty, G.W., Venteris, E.R., Kaspar, T.C., 2007. Soil and soil organic carbon redistribution on the landscape. *Geomorphology* 89 (1–2), 163–171.
- Schiettecatte, W., Gabriels, D., Cornelis, W.M., Hofman, G., 2008. Enrichment of Organic Carbon in Sediment Transport by Interrill and Rill Erosion Processes. *Soil Sci. Soc. Am. J.* 72 (1), 50–55.
- Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., ... Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478 (7367), 49–56.
- Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* 241 (2), 155–176.
- Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* 79, 7–31.
- Stacy, E.M., Berhe, A.A., Hunsaker, C.T., Johnson, D.W., Meding, S.M., Hart, S.C., 2019. Stabilization mechanisms and decomposition potential of eroded soil organic matter pools in temperate forests of the Sierra Nevada, California. *J. Geophys. Res. Biogeosci.* 124 (1), 2–17.
- Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., ... Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems and Environment* 164, 80–99.
- Van Hemelryck, H., Govers, G., Van Oost, K., Merckx, R., 2011. Evaluating the impact of soil redistribution on the in situ mineralization of soil organic carbon. *Earth Surf. Process. Landf.* 36 (4), 427–438.
- Van Hemelryck, H., Fiener, P., Van Oost, K., Govers, G., Merckx, R., 2010. The effect of soil redistribution on soil organic carbon: an experimental study. *Biogeosciences* 7, 3971–3986.
- Van Oost, K., Quine, T.A., Govers, G., De Gryze, S., Six, J., Harden, J.W., et al., 2007. The impact of agricultural soil erosion on the global carbon cycle. *Science* 318, 626–629.
- Wan, Y., El-Swaify, S.A., 1997. Flow-induced transport and enrichment of erosional sediment from a well-aggregated and uniformly-textured Oxisol. *Geoderma* 75 (3–4), 251–265.
- Wang, Z., Govers, G., Steegen, A., Clymans, W., Van den Putte, A., Langhans, C., ... Van Oost, K., 2010. Catchment-scale carbon redistribution and delivery by water erosion in an intensively cultivated area. *Geomorphology* 124 (1–2), 65–74.
- Wang, X., Cammeraat, L.H., Wang, Z., Zhou, J., Govers, G., Kalbitz, K., 2013. Stability of organic matter in soils of the Belgian Loess Belt upon erosion and deposition. *Eur. J. Soil Sci.* 64 (2), 219–228.
- Wang, X., Cammeraat, E.L.H., Cerli, C., Kalbitz, K., 2014a. Soil aggregation and the stabilization of organic carbon as affected by erosion and deposition. *Soil Biol. Biochem.* 72, 55–65.
- Wang, X., Cammeraat, E.L.H., López, C.D., Kalbitz, K., 2014b. Mineralization of Eroded Organic Carbon Transported from a Loess Soil into Water. *Soil Sci. Soc. Am. J.* 78 (4), 1362.
- Wang, L., Huang, X., Fang, N.F., Niu, Y.H., Wang, T.W., Shi, Z.H., 2019. Selective transport of soil organic and inorganic carbon in eroded sediment in response to raindrop sizes and inflow rates in rainstorms. *J. Hydrol.* 575, 42–53.
- Wei, S., Zhang, X., McLaughlin, N.B., Chen, X., Jia, S., Liang, A., 2017. Impact of soil water erosion processes on catchment export of soil aggregates and associated SOC. *Geoderma* 294, 63–69.
- Xiao, H., Li, Z., Chang, X., Huang, B., Nie, X., Liu, C., ... Jiang, J., 2018a. The mineralization and sequestration of organic carbon in relation to agricultural soil erosion. *Geoderma* 329, 73–81.
- Xiao, H., Liu, G., Zhang, Q., Fenli, Z., Zhang, X., Liu, P., Zhang, J., Hu, F., Elbasit, M.A.A., 2018b. Quantifying contributions of slaking and mechanical breakdown of soil aggregates to splash erosion for different soils from the Loess plateau of China. *Soil Tillage Res.* 178, 150–158.
- Yan, H., Wang, S., Wang, C., Zhang, G., Patel, N., 2005. Losses of soil organic carbon under wind erosion in China. *Glob. Chang. Biol.* 11 (5), 828–840.
- Yue, Y., Ni, J., Ciais, P., Piao, S., Wang, T., Huang, M., ... Van Oost, K., 2016. Lateral transport of soil carbon and land-atmosphere CO<sub>2</sub> flux induced by water erosion in China. *Proceedings of the National Academy of Sciences* 113, 6617–6622.