

COMMENTARY

The significance of carbon-enriched dust for global carbon accounting

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Abstract

Soil carbon stores amount to 54% of the terrestrial carbon pool and twice the atmospheric carbon pool, but soil organic carbon (SOC) can be transient. There is an ongoing debate about whether soils are a net source or sink of carbon, and understanding the role of aeolian processes in SOC erosion, transport and deposition is rudimentary. The impacts of SOC erosion by wind on the global carbon budget, and its importance for carbon accounting remain largely unknown. Current understanding of SOC losses to wind erosion is based on the assumption that the SOC content of eroded material is the same as that of the parent soils. However, measured enrichment factors for the SOC content of Australian dusts relative to parent soils show that the SOC content of dusts can be up to seven times (by weight) larger than that of source-area soils, with enrichment factors ranging from 1.67 to 7.09. Assuming dust emissions from the continent of ~110 Mt yr⁻¹, SOC dust emissions would be 0.13–4.65 Mt SOC yr⁻¹ without enrichment but 0.94–7.77 Mt SOC yr⁻¹ with enrichment; which represents an uncertainty of around 60%. Representing SOC enrichment within dust emission models will reduce uncertainty in estimates of the impact of wind erosion on SOC flux and provide an approach for the inclusion of wind erosion processes in carbon accounting systems.

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Soil erosion and the global carbon cycle

Soils play an important role in the global carbon cycle, through the capacity to act as a source and sink for carbon-dioxide (CO₂) emissions. Soil organic carbon (SOC) stores contain an estimated 1550 Pg (Pg = petagram = 1 billion metric ton) carbon, amounting to 54% of the terrestrial carbon pool, and twice the atmospheric carbon pool of 760 Pg (Lal, 2003). Soil redistribution processes (erosion, transport and deposition) are important mechanisms for the movement of carbon between these pools, and influence SOC flux in natural and human-impacted landscapes (Fig. 1). Soil erosion therefore impacts the global carbon budget by affecting rates of carbon sequestration and storage in soils, lateral fluxes of carbon between soils and to water bodies, vertical fluxes of carbon to the atmosphere, and the release of greenhouse gases (e.g. CO₂) that influence global warming (Van Oost *et al.*, 2007). However, there is ongoing debate about whether soils act as a net source or sink for carbon emissions, and there is an outstanding need to determine the impacts of geomorphic pro-

cesses on SOC redistribution (Doetterl *et al.*, 2012). It is yet to be resolved how soil erosion influences soil carbon stocks relative to losses from mineralization, replacement at eroded sites through biological activity, and land-use and land-cover change (Van Oost *et al.*, 2007). Without identifying all the relevant pathways, and balancing the different fluxes, in which soil redistribution processes interact with the carbon cycle, it is difficult to quantify the impacts of soil erosion on the carbon budget and determine the importance of soil redistribution for carbon accounting (Lal, 2003). Action is required to address this significant source of uncertainty for the long-term management of SOC stocks, and to develop comprehensive carbon accounting systems that include the impacts of soil redistribution (Victoria *et al.*, 2012).

An estimated 900–3300 Mt yr⁻¹ of soil is eroded globally by wind from the land surface (Shao *et al.*, 2011). Wind-driven (aeolian) erosion of soil occurs naturally in dryland environments where protection of the soil surface by vegetation is sparse, but has been accelerated by vegetation clearing for agriculture and human disturbance of rangelands. Whereas water erosion, sediment transport and deposition processes are constrained by catchment boundaries and slope, ae-

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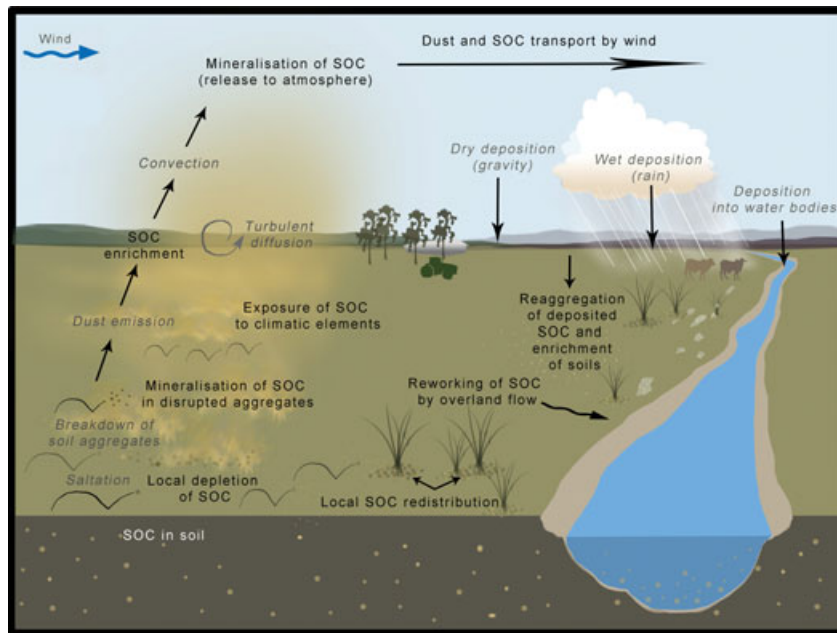


Fig. 1 Illustration showing the impact of wind erosion on soil organic carbon (SOC) flux. At eroding sites, wind erosion can result in the mobilization and breakdown of soil aggregates containing SOC, the entrainment and enrichment of SOC in dust and local SOC redistribution among vegetation patches. SOC may be transported by wind at local to regional scales, and on deposition be reaggregated within soils or incorporated into aquatic and marine systems. Wind-eroded SOC may also be carried off-shore along global dust transport pathways, and deposited over oceans or adjacent continents.

lian sediment transport and deposition are limited mainly by the transport capacity of winds (Shao *et al.*, 2011). The impacts of the movement of SOC by wind erosion on the carbon cycle may therefore be far reaching and globally important.

While recent studies of the impact of soil erosion on the global carbon cycle have acknowledged the general contribution of wind erosion to the movement of carbon between sources and sinks (Quinton *et al.*, 2010), they are yet to consider its impact. Research is yet to formalize the potential significance of wind erosion for SOC flux and the global carbon budget.

The impact of wind erosion on soil organic carbon flux

Wind erosion selectively removes silt and clay-size particles ($<20 \mu\text{m}$) from soils, and SOC is often assumed to be selectively removed with this soil fine fraction (Lal, 2003) (Fig. 1). However, SOC does not have the same properties as the mineral fraction of soils, and different types of SOC are affected differently by erosion processes as a consequence of variations in their size, shape and density (Lal, 2003). SOC losses to wind erosion have been quantified by Yan *et al.* (2005) using erosion estimates based on caesium-137 (^{137}Cs)-derived soil redistribution data and assuming that the SOC content of eroded material is the same as that of the parent

soils. As this approach does not account for the selective removal and enrichment of SOC in wind-eroded sediment, it underestimates the impact of wind erosion on SOC flux.

At the soil surface, wind erosion directly impacts the 'active' or 'labile' soil carbon pool (of fresh plant residue), and for prolonged or intense erosion events with highly erosive winds may deplete the 'slow' soil carbon pool comprised of humus and clay-sorbed carbon forms (Doetterl *et al.*, 2012). As the turnover rates for carbon in these pools ranges from <10 to 100 years, redistribution and reduction in SOC by wind erosion may affect the build-up of carbon in the 'resistant' or 'passive' pool (Parton *et al.*, 1987). Wind erosion may therefore result in the localized depletion of SOC due to its preferential removal, the acidification of exposed calcareous layers and accelerated mineralization of SOC due to the breakdown of soil aggregates during saltation and exposure of SOC to climatic elements (Lal, 2003) (Fig. 1). These processes release SOC from the terrestrial carbon pool at source to the atmosphere and downwind carbon sinks, but there are few data to quantify them.

Soil organic carbon eroded by wind may be carried in the atmosphere, and deposited along dust transport pathways that track global atmospheric circulation systems. Rates of mineralization of SOC transported in dust (e.g., by photochemical oxidation) are currently unknown, and understanding of the release of carbon

to the atmosphere by these processes remains rudimentary. The magnitude of SOC release by wind erosion from the terrestrial to atmospheric carbon pool is therefore a significant source of uncertainty for the global carbon budget. At depositional sites close to source (short-duration transport) SOC may be sequestered by reaggregation and incorporation into soils (Doetterl *et al.*, 2012). Deposition zones can therefore act as SOC sinks, and may balance SOC losses from eroding source areas. However, the fine fraction of sediment and SOC may be transported long distances, where dry or wet (precipitation-induced) deposition can result in SOC enrichment of down-wind soils or incorporation into aquatic and marine systems (Fig. 1). The deposition of SOC into marine systems can be considered a loss of carbon from the terrestrial to oceanic carbon pool, but without knowledge of rates of SOC mineralization during transport, or SOC deposition rates, it is difficult to estimate the net impact of wind erosion on carbon sequestration in these systems. While SOC losses from mineralization may be small for short-duration transport and less significant for the global carbon budget (Quinton *et al.*, 2010), the capacity for long-range (and off-shore) aeolian transport of SOC makes wind erosion a particularly important component of carbon accounting systems. Quantifying SOC contained in wind-eroded sediment, and the process of SOC enrichment in dust, is a necessary requisite in explaining its importance.

SOC enrichment factors to quantify aeolian SOC flux

The potential for agricultural and rangeland soils to erode and produce dust (their erodibility) varies significantly over space and time with soil texture (particle size), moisture, salt, carbonate (CaCO_3) and organic matter (OM) contents (Shao *et al.*, 2011). The comparatively large SOC content of agricultural soils typically reduces their erodibility relative to soils in rangelands, but when agricultural soils do erode their SOC emissions are large. Conversely, the small SOC content of rangeland soils increases their erodibility, but their SOC emissions are small. However, the proportional losses of SOC from rangeland environments may be substantially greater than from agricultural settings due to their broad geographic extent (Victoria *et al.*, 2012). Spatial and temporal variations in SOC emissions from agricultural and rangeland soils are therefore likely to be important for the redistribution of SOC between sources and sinks. Accounting for differences in the contributions of soils to aeolian SOC redistribution will therefore be central to the assessment of the global carbon budget and carbon accounting.

Few studies have quantified the SOC content of dust emissions or have sought to evaluate the mechanisms of SOC enrichment in dust. Boon *et al.* (1998) determined that the OM content of dusts sampled across eastern Australia comprised 16–38% of eroded material in dust transport events, for example dust storms, and up to 90% of background suspended dusts. These values appear large in a global context, with a range of smaller OM contents recorded in North Africa (4–27%), the Argentinean Pampas (6–8%) and southern United States (10%) (Goudie & Middleton, 2006).

Field measurements within dust source areas are valuable because they illustrate the variability in SOC enrichment by wind erosion in space and time. However, such measurements are rare because they are time consuming and relatively expensive to acquire. Recent fieldwork by the first author provided Australian enrichment factors for the SOC content of aeolian sediment samples relative to parent soils (Table 1). They show that the SOC content and enrichment of SOC in dust are highly spatially variable. The SOC content of dusts may be up to seven times (by weight) larger than that of source-area soils, with enrichment factors ranging from 1.67 to 7.09. Source soils with relatively large SOC content do not necessarily produce dusts with large SOC enrichment. Across the five sites (Table 1), the dusts with the largest enrichment (7.09 times source SOC by weight) were derived from sandy soils with the smallest SOC content (0.12% by weight). The SOC content and enrichment factors also vary considerably over time, apparently independently of the source SOC content.

With few other measurements available for Australia, we assumed that the range of SOC enrichment ratios in Table 1 is representative of Australian dust source areas, and estimated SOC losses for the continent's dust emissions ($\sim 110 \text{ Mt yr}^{-1}$; Shao *et al.*, 2011). SOC emissions were estimated at $0.13\text{--}4.65 \text{ Mt SOC yr}^{-1}$ without enrichment; assuming the SOC content of dusts is equal to that of the soils in Australian dust source areas (Table 1). Accounting for the enrichment of SOC in dust increased the estimate to $0.94\text{--}7.77 \text{ Mt SOC yr}^{-1}$. The difference between the estimates represents an uncertainty of around 60% on the impact of wind erosion on SOC flux, with implications for the global carbon budget and carbon accounting.

Linking wind erosion and the carbon cycle to improve carbon accounting

Soil organic carbon loss by wind erosion is an important component of the global carbon cycle, and amounts to a significant omission from carbon accounting systems (Victoria *et al.*, 2012). However, the current

Table 1 Summary of the percentage soil organic carbon content (%SOC) of dust source-area soils at five locations across western Queensland, Australia, and average SOC content and enrichment ratios of SOC in wind-blown sediment samples (2 m above surface) relative to the soils. Wind-blown sediment was collected using Big Spring Number Eight wind-vane samplers on a monthly basis over 2½ years (June 2006–December 2007), and along with samples of the local source-area soils were measured for organic matter (OM) content using loss-on-ignition, whereby soils were combusted at 375 °C for 4 h following Boon *et al.* (1998). The SOC content was then calculated from OM using the conversion $SOC = 0.58 \times OM$, following Yan *et al.* (2005). Values of %SOC (\pm standard deviation) for the source-area soils are based on 10 subsamples analysed for each site. Site locations are in the Mitchell grasslands (S23°30'53", E143°14'28"), Mulga woodlands (S26°28'37", E146°08'46"), a Mulga sandplain (S28°04'39", E144°11'06"), the Simpson Desert dunefield (S23°51'20", E138°27'04") and within a fire scar (burnt in 2001) in the Simpson Desert (S23°49'22", E138°24'06")

Location	Parent soil %SOC (\pm SD)	Dust %SOC (range)	SOC enrichment ratio (range)
Mitchell grass downs	4.23 (0.14)	7.06 (4.65–12.94)	1.67 (1.1–3.06)
Mulga woodland	0.93 (0.02)	4.47 (1.69–9.59)	4.81 (1.82–10.32)
Mulga sandplain	0.54 (0.02)	1.96 (1.93–2.59)	3.63 (3.58–4.79)
Simpson desert dunefield	0.12 (0.05)	0.85 (0.66–2.12)	7.09 (5.53–17.64)
Simpson desert fire scar	0.32 (0.02)	0.97 (0.66–1.18)	3.02 (2.07–3.68)

approach to estimating SOC emissions without enrichment (e.g. Yan *et al.*, 2005), will likely lead to a significant underestimate of SOC losses to wind erosion and of the magnitude of SOC movement between sources and sinks. The evidence in the literature and the data presented here demonstrate that there is considerable spatial and temporal variation in SOC enrichment across soils and land uses globally. These data indicate that enrichment processes have a substantial influence on the magnitude of the wind erosion impact on SOC releases and sequestration and the global carbon budget. Including information on the enrichment of SOC across soil and land use types will therefore likely improve evaluations of the impact of wind erosion on SOC flux. This information will reduce uncertainty in quantifying SOC movement between carbon pools, and provide more robust data to support the inclusion of soil redistribution in carbon accounting.

Future research directions

Very little is known about either the types or fate of wind-eroded carbon. Quantifications of these are required, along with estimates of SOC flux, to evaluate the effects of the movement of SOC by wind erosion on the carbon cycle and the net impact of soil redistribution on the global carbon budget.

Research is required to explore the various impacts of aeolian erosion, transport and deposition on SOC pools at source, mineralization rates, the loss of SOC to the atmosphere and the enrichment of SOC at deposition sites through reaggregation within soils, and losses within aquatic and marine systems.

Measuring and scaling-up these processes to evaluate their significance at the national and global scales is a key challenge, and will benefit greatly from a capacity to

represent the linkages between soil redistribution processes and the carbon cycle in process-based models.

Representing SOC enrichment within wind erosion models will enable more advanced assessments to be made of the impact of wind erosion, transport and deposition on SOC flux, and will provide an approach for the inclusion of wind erosion processes in carbon accounting systems.

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