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Soil organic carbon enrichment of dust emissions: magnitude, mechanisms and its implications for the carbon cycle

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Earth Surface Processes and Landforms

ABSTRACT: Soil erosion is an important component of the global carbon cycle. However, little attention has been given to the role of aeolian processes in influencing soil organic carbon (SOC) flux and the release of greenhouse gasses, such as carbon dioxide (CO_2), to the atmosphere. Understanding the magnitude and mechanisms of SOC enrichment in dust emissions is necessary to evaluate the impact of wind erosion on the carbon cycle. This research examines the SOC content and enrichment of dust emissions measured using Big Spring Number Eight (BSNE) wind-vane samplers across five land types in the rangelands of western Queensland, Australia. Our results show that sandy soils and finer particulate quartz-rich soils are more efficient at SOC emission and have larger SOC dust enrichment than clay-rich aggregated soils. The SOC enrichment ratios of dusts originating from sites with sand-rich soil ranged from 2·1–41·9, while the mean enrichment ratio for dusts originating from the clay soil was 2·1. We hypothesize that stronger inter-particle bonds and the low grain density of the aggregated clay soil explain its reduced capacity to release SOC during saltation, relative to the particulate sandy soils. We also show that size-selective sorting of SOC during transport may lead to further enrichment of SOC dust emissions. Two dust samples from regional transport events were found to contain 15–20% SOC. These preliminary results provide impetus for additional research into dust SOC enrichment processes to elucidate the impact of wind erosion on SOC flux and reduce uncertainty about the role of soil erosion in the global carbon cycle. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: wind erosion; aeolian dust; carbon cycle; soil nutrients; rangelands

Introduction

Soil erosion perturbs the carbon cycle by influencing the distribution of soil organic carbon (SOC) across landscapes and soil carbon emissions (van Oost *et al.*, 2007). The dust cycle represents the processes of aeolian erosion, transport and deposition, and interacts with many physical, chemical and bio-geological processes that influence the carbon cycle (Shao *et al.*, 2011). These processes drive SOC emissions, transport and deposition at the plant inter-space and patch scales, across landscapes, and globally through long-range dust transport and deposition (Li *et al.*, 2008; Field *et al.*, 2010). Few measurements of the impacts of wind erosion on SOC flux exist and discussion of the significance of aeolian processes for the carbon cycle is frequently omitted from the current debate (Evans *et al.*, 2012). Aeolian SOC flux has received little attention, and our understanding of the impacts of wind erosion on the global carbon budget remains rudimentary. Quantitative data on the magnitude of the SOC content and enrichment within dust emissions are required to elucidate the significance of wind erosion for the carbon cycle and national carbon accounting (Webb *et al.*, 2012).

Globally, an estimated 900–3300 Mt of soil is eroded by wind from the land surface each year (Shao *et al.*, 2011), removing preferentially the fine, nutrient- and carbon-rich fraction of soil (Li *et al.*, 2008). With organic carbon contents ~5% by weight of the eroded material (Franzen *et al.*, 1994; Sterk *et al.*, 1996; Boon *et al.*, 1998; Ramsperger *et al.*, 1998; Gill *et al.*, 2000), losses of SOC due to wind erosion would be equivalent to 45–165 Mt yr^{-1}. These losses have significant implications for agricultural productivity, soil nutrient redistribution, land degradation, and carbon emissions (Lal, 2007; Li *et al.*, 2008; Quinton *et al.*, 2010; Doetterl *et al.*, 2012a). However, much remains unresolved about the contribution of soil erosion in general, and wind erosion in particular, to carbon dynamics and the release of greenhouse gas (i.e. carbon dioxide, CO_2) emissions (e.g. Kuhn *et al.*, 2009; Dymond, 2010; Chappell *et al.*, in review). This includes rates of SOC erosion and deposition, the types of carbon eroded by wind, and the fate of eroded SOC and its conversion to CO_2 through mineralization processes. Quantitative data on the enrichment of SOC in wind-eroded sediment is required as a first step to evaluate the impact of the dust cycle on SOC flux, and to determine

the net contribution of soil erosion to the global carbon cycle (Lal, 2003; Doetterl *et al.*, 2012b).

Field measurements (Daniel and Langham, 1936; Li *et al.*, 2009), remote sensing (Harper *et al.*, 2010) and cesium-137 (^{137}Cs)-derived net soil redistribution mapping (Yan *et al.*, 2005; Chappell *et al.*, 2012) have been applied to derive estimates of wind-driven SOC redistribution and losses in both agricultural lands and rangelands. However, few studies have considered the magnitude of SOC enrichment in dust emissions, or controls on spatial and temporal variations in SOC enrichment (Goossens, 2004; Van Pelt and Zobeck, 2007, Li *et al.*, 2009; Kavouras *et al.*, 2012). Without accounting for the selective removal of SOC from soils and its enrichment in wind-eroded sediment, estimates of the impacts of wind erosion on SOC flux likely underestimate the significance of aeolian SOC redistribution (Webb *et al.*, 2012). There is a dearth of measured enrichment data necessary to quantify the impact of the dust cycle on SOC flux, and estimate the magnitude and types of SOC transported in dust to determine its wider bio-geochemical interactions (Ravi *et al.*, 2011). This paper reports on research to quantify SOC enrichment of dusts sampled across different land types in the arid and semi-arid rangelands of western Queensland, Australia. The objective of the research is to: (i) capture broad spatial variations in the SOC content of dusts emitted from the north-eastern portion of Australia's major dust source area (the Lake Eyre Basin); (ii) use these data to identify the nature and potential mechanisms of variations in SOC dust enrichment between land types. Measuring the enrichment of SOC in dust emissions is intended to enable more accurate estimates of the dust cycle impact on SOC flux, and to facilitate more robust evaluations of the extent to which wind erosion and dust emission contribute to CO_2 emissions.

Materials and Methods

Site description

Five field sites were established across the arid and semi-arid rangelands of Queensland, Australia (Figure 1). The area receives on average 200–500 mm yr^{-1} rainfall and maximum air temperatures range from > 40 °C in summer (December to February) to the high teens and mid-twenties in winter (June to August). The study area is ~672 000 km^2 and can be divided into four bio-geographical regions (DSEWPC, 2011) based on dominant vegetation communities and the Australian Soils Classification (Isbell, 2002). These include: (1) Channel Country, forbfields and grassland downs with intervening anabranching river systems and woodlands, and small areas of sand plains and dunes in the floodplain sediments; (2) Mitchell Grass Downs, undulating downs (grasslands) and low woodlands on grey and brown cracking clay soils; (3) Mulga Lands, shrublands and low woodlands on undulating plains and low hills on red earths and lithosols; (4) Simpson-Strzelecki Dune fields, arid dune fields and sand plains with sparse shrublands and hummock grasslands. The dominant land-use across the study area is livestock (beef and wool) production.

The five study sites were selected to sample dusts originating from some of the major dust source areas within the bioregions. These land types experience a high level of variability in their susceptibility to wind erosion due to regional climate variability and livestock grazing (Webb *et al.*, 2009). The 'Spoilbank' site is representative at the landscape scale of open grassy plains dominated by *Astrebla* spp. on grey and brown cracking clay Vertosols (Figure 2). The 'Croxdale' and 'Lake Bindegolly' sites

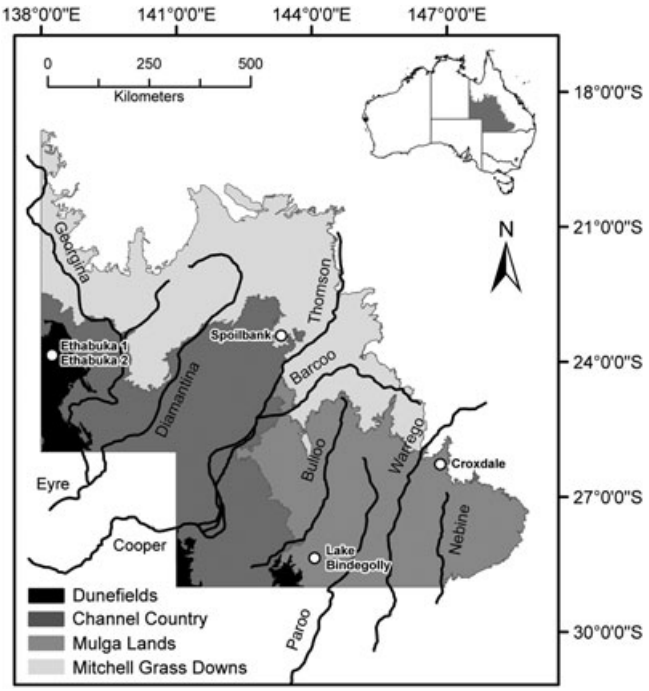

Figure 1. Study area map showing the study area location within Australia, the location of the five field sites in relation to the major bioregions, and significant landforms including the internally draining river systems and longitudinal dune fields.

are located in the Mulga (*Acacia aneura*) woodlands on deep read earths (Croxdale) and a sand plain (Lake Bindegolly). The 'Ethabuka' sites are located on a vegetated (predominantly *Triodia basedowii* and *Zygochloa paradoxa*) sand dune crest, denoted 'Ethabuka dune crest', and within a denuded fire scar (burnt in 2001) in a dune swale ('Ethabuka dune swale') on the eastern fringe of the Simpson Desert.

Sample collection

Fieldwork was conducted between July 2005 and October 2007. Soil samples were collected at each field site for analyses of their soil characteristics. At each site, 18 soil samples were taken as cores from the top 5 cm (7·5 cm internal diameter) and stored in air-tight bags for later analysis. Soil samples were collected at locations around the 'Big Spring Number Eight' (BSNE) wind-vane samplers. A portion of the sampled soil was bulked to represent source area soil particle size distributions (PSDs) and SOC content.

Aeolian sediment flux was measured at a monthly frequency at each site using BSNE wind-vane samplers (Fryrear, 1986) modified with a rain hood (Shao *et al.*, 1993). Samplers were positioned on masts at heights of 0·09 m, 0·5 m and 2·0 m to provide vertical profiles of sediment moving in saltation and suspension (photographs of the samplers in Figure 2). The BSNE samplers are ~90% efficient for sampling saltation material (> 100 μm), and ~40% efficient for sampling dust (< 10 μm) (Shao *et al.*, 1993; Goossens and Offer, 2000). As SOC is typically associated with the fine and lighter-weight fraction of eroded sediment (Goossens, 2004), these sampling inefficiencies are likely to result in an underestimation of SOC loads in the wind-eroded material and of SOC enrichment relative to the dust source area soils. However, BSNE samplers are preferred because their sampling efficiency is consistent at a range of wind velocities (Goossens and Offer, 2000). They were also easily serviced by non-expert volunteers at the remote field locations, and have been used extensively for

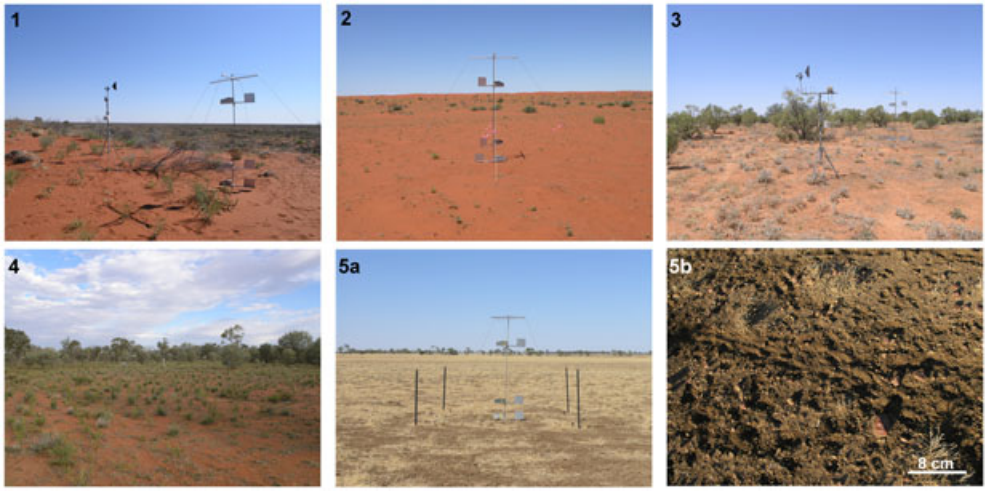

Figure 2. Images of the five study sites, including: (1) Ethabuka Site 1, located on the crest of a vegetated longitudinal dune in the northeast Simpson Desert; (2) Ethabuka Site 2, located in a dune swale within an extensive fire scar approximately 2 km northwest of Site 1; (3) Lake Bindegolly, located in arid Mulga (*Acacia aneura*) woodland on a sand plain east of the Bulloo River; (4) Croxdale, located in the semi-arid Mulga shrublands to the far east of the study area; (5a) Spoilbank, located on the open plains of the Mitchell grass downs; (5b) close-up of the Spoilbank vertosol, with crusted surface broken into sand-size aggregates after trampling by sheep. Ground cover is low in the photograph set, which was taken during the dry season (August) of 2006 and following a sequence of four years with below-average rainfall. Soils are classified according to the Australian Soils Classification (Isbell, 2002). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

sampling horizontal aeolian sediment flux in rangelands, including studies of nutrient and carbon dynamics (Li *et al.*, 2007; Van Pelt and Zobeck, 2007). Despite its likelihood to underestimate SOC enrichment, the benefit of the sampling approach is its wide spatial distribution and reasonable temporal coverage which enables comparison of dust and SOC emissions from the different land types. Each month the trapped sediments were brushed from the BSNE samplers into plastic vials, which were used for storage until laboratory analysis.

Laboratory analysis

Fine-resolution particle size analyses (PSA) of the parent soils were conducted using a Coulter Multisizer3. Sub-samples (40 g) of the bulked site parent soils were analysed in minimally and fully-dispersed conditions. The minimally-dispersed condition approximates the natural, aeolian transport-stable condition of the soil, but entails a small level of dispersion as the method requires samples to be analysed in a fluid medium. Soils analysed in a fully-dispersed condition were in particulate form, with aggregates reduced to their component particles. It was determined through the PSA that the Spoilbank soil was highly aggregated; breaking down to reveal large silt and clay content under the fully-dispersed treatment (described in the Results section). Therefore, to evaluate the PSD of the soil in a wind-eroded state we applied an intermediate dispersion treatment, approximating the condition of the soil exposed to abrasion from saltating particles that impact the surface (Butler *et al.*, 2010).

Samples analysed in a minimally dispersed condition were added to an electrolyte [3% tri-sodium orthophosphate ($Na_3PO_4{\cdot}12H_2O$) and glycerol ($C_3H_8O_3$) at 50% m_i V^{-1}] and gently stirred to create a homogeneous mixture prior to analysis. In the intermediate dispersal analysis of the Spoilbank soil, to represent aggregate break-down under saltation, dry soil samples were abraded using a reciprocating shaker (SHR-2D DAIHAN Scientific) at 200 rpm for 10 minutes before being added to the electrolyte and stirred. A combination of these chemical and physical dispersion techniques were used to break down aggregates for the fully-dispersed PSA. Samples were placed in 10 ml of 10% $Na_3PO_4{\cdot}12H_2O$ and 10 ml of 1M sodium hydroxide (NaOH). The samples were then subject to 3 × 3 second ultrasonic pulses, followed by 10 minutes on a reciprocal shaker and 12 hours on an end-over-end shaker, before being added to the electrolyte and gently stirred. The PSA was conducted using 2000, 1000, 560, 280, 140 and 50 µm tubes with an analytical range of 1·0 to 1000 µm.

A dry-sieving technique was used to determine which size fraction of the parent soils their SOC was associated with in a field condition, without dispersion. Five sub-samples of each of the parent soils were shaken for 15 minutes using a Ro-Tap shaker (CE Tyler, Ontario). Endecott sieves at quarter-phi size classes were used. Each fraction was weighed and prepared for determination of organic matter (OM) content by loss on ignition (LOI), following the methods of Boon *et al.* (1998). The samples were placed in crucibles, re-weighed and then combusted at 375 °C for four hours to ensure that mineral carbon (e.g. calcium carbonate, $CaCO_3$) in the samples was not combusted. The OM content in each sieve fraction was then expressed as a percentage of the initial soil sample mass. The standard deviation of the OM content in the sub-samples was calculated to express the variation in the LOI measurements.

The monthly sediment mass from the BSNE samplers for each site was measured by weighing the sediment collected in each sampler at the three sampling heights. A total of 24 complete sediment profiles were obtained for analysis with sufficient size (> 0·01 g) for combustion and detection of OM content. Samples were visually inspected for large vegetation and insect fragments, which we considered to be separate to the SOC content of the soil-derived aeolian sediments and removed. The OM content of the aeolian sediment at each height was determined using the same LOI technique applied to the parent soils. The SOC content was calculated for soil and aeolian sediment samples following Yan *et al.* (2005), using the relation SOC = 0·58 × OM. This calculation assumes a constant relationship between the OM and SOC contents of soil types and within dust emissions (Nelson and Sommers, 1996; Schumacher, 2002).

Data analysis

The streamwise sediment flux $q(z)$ provides a measure of the mass of sediment moving horizontally (downwind) at height z

through a given area over a period of time. To calculate $q(z)$, the mass of sediment collected in each BNSE sampler was divided by the area of the sampler inlet (2 cm × 5 cm) and the sampling period (one month) then expressed in weeks (g m^{-2} wk^{-1}). The streamwise SOC flux was calculated from the mass of SOC in each sample. Following McTainsh *et al.* (1999), power functions describing the distribution of sediment with height were fitted using least squares regression to the monthly sediment flux profiles for each site:

$$q(z) = \alpha(z)^{-\beta}, \quad (1)$$

where α and β are coefficients of the fitted power function and z is the height above the surface (in metres). The fit provided an average r^2 value of 0·93 across all of the profiles for the sites. The power function was chosen over the conventionally used exponential function (Ellis *et al.*, 2009), which provided a poor fit to the data (average $r^2 = 0{\cdot}6$, $p > 0{\cdot}4$) with a significant reduction in sediment and SOC mass over the 2·0 m profiles. The large reduction in sediment mass is likely due in part to the low efficiency of the BSNE samplers in collecting fine (< 10 μm) sediment (Goossens and Offer, 2000). However, we had insufficient data to correct for the sampler inefficiency (Goossens and Buck, 2012). Total (integrated) streamwise sediment fluxes (Q) and SOC fluxes were calculated for each sediment profile by integrating the power functions between the surface and 2·0 m height (z), and dividing by the duration of the sampling period:

$$Q = \int_0^2 q(z)dz, \quad (2)$$

where Q has the units of mass per unit length per time (g m^{-1} wk^{-1}).

Enrichment ratios for the SOC content in the wind-blown samples were calculated for each site by dividing the SOC content of dust at 2·0 m by the SOC content of the parent soils. To standardize for the effect of variations in saltation flux that results in dust emission, we also calculated the SOC enrichment in dust relative to the SOC content in the saltation layer, at 0·09 m (after Chappell *et al.*, 2008). This approach differs to that of Goossens (2004), Li *et al.* (2007) and Van Pelt and Zobeck (2007), whose field sampling campaigns enabled reliable calculation of SOC enrichment relative to dust source area soils. Because our topsoil SOC samples were not collected at the same interval as the dust samples we believe that the parent soil samples do not capture the variability in topsoil SOC at the field sites, the soil SOC content during each wind erosion event, or the location of the dust source areas. Critically, the standardized SOC enrichment values enabled between-site differences in the SOC enrichment of dust emissions to be determined, without the confounding influence of differences in saltation flux between sites and between sampling intervals. Thus, differences in wind erosivity between sampling months should not affect the comparison of SOC enrichment or interpretation of enrichment mechanisms from the data.

Results

Streamwise sediment flux profiles

Examples of streamwise sediment flux profiles for the five study sites are presented in Figure 3. The profiles show a typical decline in sediment mass with height, as the bulk of material is transported in saltation, from the surface to about 0·5 m height. For the full set of 24 profiles there is considerable variation in the streamwise sediment flux both within and between sites (Table I). Between-site flux variations reflect differences in land type erodibility. Sites with sandy soils (Ethabuka dune crest) had much larger integrated sediment mass fluxes (mean 55·79 g m^{-1} wk^{-1}) than the finer Ethabuka dune swale and Lake Bindegolly sites (mean 13·05–21·33 g m^{-1} wk^{-1}). The Mulga woodland site at Croxdale had the lowest horizontal fluxes (mean 0·37 g m^{-1} wk^{-1}). The within site temporal differences in sediment flux reflect differences in wind erosivity between months.

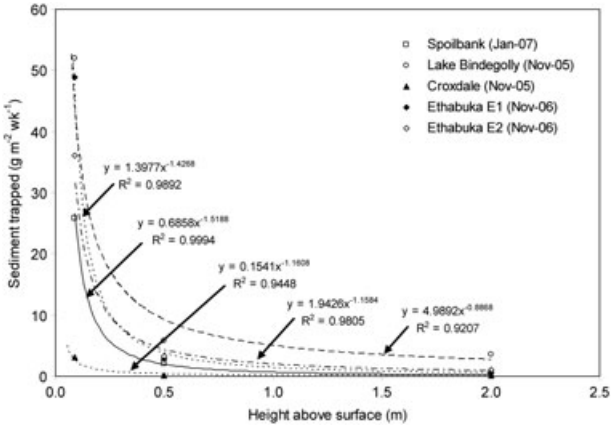

Figure 3. Streamwise sediment flux profiles for selected months at the five field sites. The measurements are fitted with power functions that describe the decline in sediment mass with height above surface.

SOC content of wind-blown sediments

The SOC content of the parent soils at each field site and the wind-blown samples from the 24 vertical profiles are presented in Table I. The SOC content of saltation sediments (0·09 m) was generally similar to the soils at the four more-sandy field sites, but it is reduced at the clay-rich Spoilbank site. The similarity between the saltation sediment SOC content and that of the sandy parent soils suggests that: (1) the soils in the vicinity of the BSNE samplers at these field sites were contributing wind-blown sediment to the samplers; (2) the sediment collected near ground level (0·09 m) reflects the *en masse* removal of the soils, generally without enrichment. The reduced SOC content of the saltation sediment at Spoilbank indicates that some of the SOC-rich aggregates are not entrained by the wind, while more of the low SOC quartz sands are entrained.

All sites show increases in the SOC content of sediments with height (to 2·0 m). The most dramatic increase was recorded at the Croxdale site; reaching 29% SOC at 2·0 m in April 2006. The total (integrated) SOC flux at Croxdale in April 2006 is, however, equal to the average for the three recorded profiles at the site (0·01 g m^{-1} wk^{-1}). The largest integrated SOC flux was recorded at the Ethabuka dune crest site (0·64 g m^{-1} wk^{-1}) in November 2006.

SOC enrichment ratios

We divided the SOC content of samples at each height in the vertical profiles by the SOC content in saltation to standardize SOC enrichment for the effects of variations in the saltation load. Table I shows the enrichment ratios for the sediment sampled at 2·0 m above the surface. On average, Spoilbank recorded the smallest enrichment of SOC in sediment at 2·0 m. Enrichment ratios at the other sites are two to three times that of Spoilbank, but may also be considerably larger. The Ethabuka dune swale site recorded a dust event with the largest

Table I. Summary of the soil organic carbon (SOC) content of the dust source area (parent) soils at the five field sites and of the wind-blown samples, integrated streamwise sediment and SOC fluxes, the SOC enrichment ratio for dust (2·0 m) relative to the soil, and the standardized SOC enrichment ratio for dust (2·0 m) relative to saltation (0·09 m)

Location	Parent soil %SOC (±SD)	Sampling month	$\%SOC_{0\cdot09\ m}$	$\%SOC_{0\cdot5\ m}$	$\%SOC_{2\cdot0\ m}$	$Q_{0–2\ m}$ (g m^{-1} wk^{-1})	SOC $flux_{0–2\ m}$ (g m^{-1} wk^{-1})	Enrichment ratio ($\%SOC_{2\cdot0}$:$\%SOC_{soil}$)	Enrichment ratio ($\%SOC_{2\cdot0}$:$\%SOC_{0\cdot09}$)
Spoilbank	4·23 (±0·14)*	January-06	2·04	3·53	2·73	1·76	0·04	0·65	1·33
		March-06	3·60	3·99	6·08	0·63	0·02	1·44	1·88
		April-06	3·57	3·58	4·02	1·89	0·07	0·95	1·13
		May-06	2·37	3·46	3·74	0·25	0·01	0·88	1·58
		December-06	2·78	2·72	3·06	3·56	0·10	0·72	1·10
		January-07	2·34	2·15	12·99	2·42	0·11	3·07	5·55
		October-07	2·86	3·48	5·14	3·75	0·13	1·22	1·79
Mean			2·79	3·27	5·39	2·04	0·07	1·28	2·05
Croxdale	0·93 (±0·02)	September-05	1·17	2·97	5·52	0·34	0·01	5·94	4·71
		November-05	1·18	3·83	5·52	0·53	0·02	5·94	4·68
		April-06	0·89	4·72	29·00	0·24	0·01	31·18	32·58
Mean			1·08	3·84	13·35	0·37	0·01	14·35	13·99
Lake Bindegolly	0·54 (±0·02)	November-05	0·77	2·08	2·76	13·63	0·25	5·11	3·58
		February-06	0·46	1·39	1·38	16·48	0·17	0·31	3·00
		January-07	0·47	1·02	2·05	33·88	0·38	3·79	4·36
Mean			0·57	1·50	2·06	21·33	0·27	3·07	3·65
Ethabuka dune crest	0·12 (±0·05)	May-06	0·17	0·65	1·67	56·92	0·34	13·92	9·74
		November-06a	0·17	0·46	0·93	6·48	0·05	7·75	5·47
		November-06b	0·25	0·81	2·18	155·08	0·64	18·17	8·72
		August-07	0·21	0·24	3·68	4·69	0·01	30·67	17·52
Mean			0·20	0·54	2·12	55·79	0·26	17·63	10·36
Ethabuka dune swale	0·32 (±0·02)	May-06	0·44	0·55	1·18	2·48	0·02	3·69	2·68
		November-06a	0·51	0·63	1·06	13·49	0·09	3·31	2·08
		December-06	0·23	0·32	0·67	51·13	0·19	2·09	2·91
		April-07	0·17	0·44	0·64	16·39	0·06	2·00	3·76
		May-07	0·23	0·37	0·76	5·76	0·02	2·38	3·30
		August-07	0·28	1·20	0·96	0·63	0·01	3·00	3·43
		September-07	0·37	4·43	15·50	1·44	0·02	48·44	41·89
Mean			0·32	1·13	2·97	13·05	0·08	9·27	8·58

Error ranges represent the standard deviation (SD) of five re-measured sub-samples from the bulked surface soil samples.
Note in November 2006 the Ethabuka sites were sampled twice, on: (a) 15th of the month; (b) 30th of the month.

enrichment of SOC in suspension, with 41·9 times the SOC measured in saltation (at 0·09 m) in September 2007. While the integrated sediment flux at Croxdale in April 2006 is relatively small (0·24 g m^{-1} wk^{-1}), the sample at 2·0 m has an enrichment ratio of 32·6 over the soil OC content of the saltation sediment trapped in that month (Table I). Conversely, for the same month Spoilbank recorded the second smallest enrichment ratio (1·13), despite having a larger integrated SOC flux (0·04 g m^{-1} wk^{-1}) than at other sites.

Site separation based on SOC enrichment

The relationship between the SOC content in the saltation layer (0·09 m) and the enrichment of SOC with height for the different sampling months is shown in Figure 4. There is separation of these data, suggesting that the field sites have different capacities for enrichment of SOC in dust emissions. Along the *x*-axis, sites are separated on the basis of the SOC content of sediment trapped in saltation, which at the sites with more sandy soils represent the SOC content of local source area soils (Table I). Along the *y*-axis, sites are separated on the basis of the efficiency at which SOC is released from the soil surface and enriched in the wind-eroded sediment. The site separation along the *y*-axis does not follow the pattern of SOC content of the parent soils (largest at Spoilbank and smallest at the Ethabuka sites) (Table I). Spoilbank has the largest SOC content in the parent soil, and the largest amount and greatest variability of SOC in the sediments trapped in saltation (0·09 m), but produces the smallest enrichment of SOC with height. While the horizontal sediment fluxes at Spoilbank are consistently smaller than the Lake Bindegolly and Ethabuka sites, the Spoilbank SOC fluxes are a similar order of magnitude. Sediments trapped in saltation at the Ethabuka dune crest and dune swale sites have the smallest SOC content (Table I) and the sites have the smallest parent soil SOC content, but consistently produce the largest enrichment of SOC. The samples containing the largest enrichment occur at the Croxdale and Ethabuka dune swale sites in April 2006 (32·6) and September 2007 (41·9), respectively (Table I). The enrichment ratios for these sampling periods are considerably greater than those measured in other months and at other sites, and the SOC profiles (Table I) show anomalously large SOC content at 2 m relative to the remaining profiles and relative to that measured at 0·5 m, 0·09 m and in the local soils. In both cases, regional dust events associated with a series of troughs and cold fronts passed over the study area, contributing significant sediment to BSNE samplers from outside the immediate local dust source areas associated with the sites (O'Loingsigh *et al.*, in review). Figure 5 shows maps of mean sea level pressure (MSLP) and meteorological stations recording atmospheric dust for the two regional dust events, sourced from the Australian Bureau of Meteorology (http://www.bom.gov.au/australia/charts/).

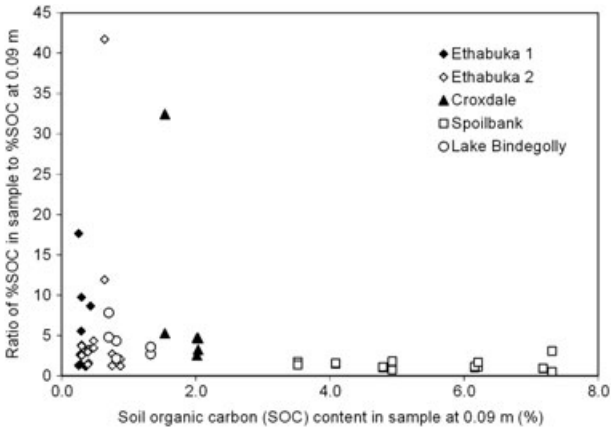

Figure 4. Scatterplot of the ratio of percentage soil organic carbon (%SOC) in samples at 0·5 m and 2·0 m to the %SOC of the sediment trapped in saltation at 0·09 m above surface.

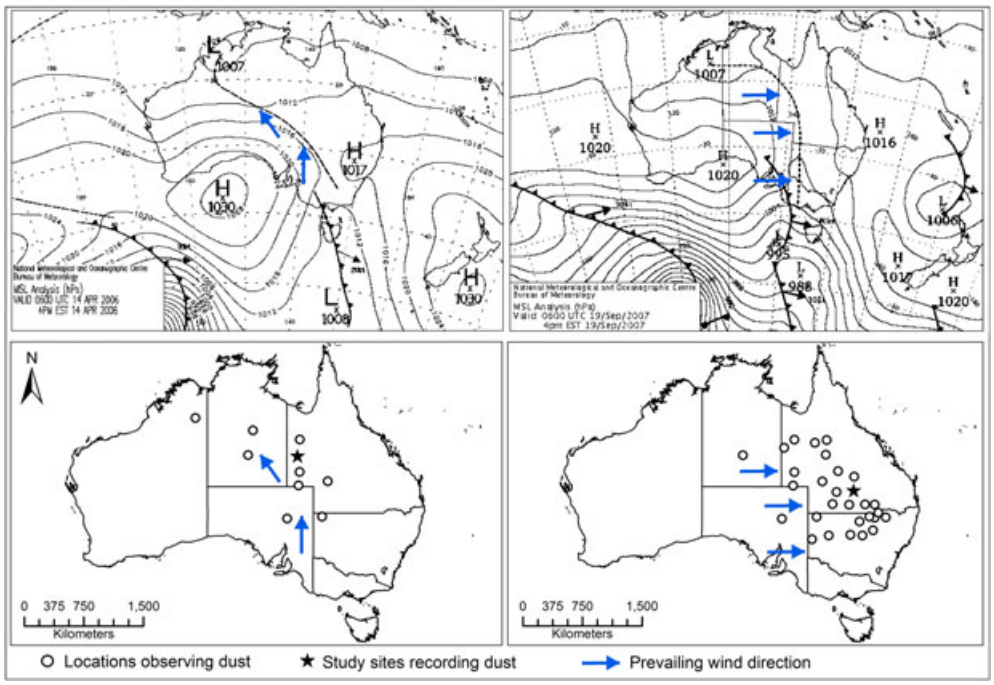

Figure 5. Maps showing mean sea level pressure (MSLP) (500 hPa) and Bureau of Meteorology stations recording atmospheric dust for two regional dust events that led to large SOC enrichment of measured dust samples for 14 April 2006 and 19 September 2007. The regional dust events were associated with the trough lines and west-to-east passage of cold fronts that produced strong south-easterly and westerly flow. Arrows indicate the direction of dust-transporting winds during the events. MSLP maps were obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/australia/charts/). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

SOC in size-fractionated soils

The PSDs, determined by dry sieving the surface soils at the five field sites, are presented in Figure 6a. Note that the coarse fractions of the soils are shown in half-phi increments, which fall within the range of fine to medium sand (125–500 μm). All sites have a mode in the range 125–250 μm, while the Ethabuka dune crest soil has a uni-modal PSD and the Spoilbank soil has a multi-modal PSD. The remaining sites have secondary modes around 75 μm (Ethabuka dune swale), 63 μm (Lake Bindegolly) and 53–63 μm (Croxdale).

Figure 6b shows the distribution of SOC within the soils across the particle-size fractions. At the Spoilbank site, the SOC is clearly associated with the coarser fraction (100–500 μm), with a secondary mode in the 53 μm fraction. At Croxdale, a coarse component (> 500 μm) of the SOC was identified as being residual plant material. There is a secondary mode in SOC associated with the coarse silt (65 μm range) and an increase in the < 45 μm fraction. There appears to be no significant association of SOC with a particular soil particle-size fraction at the Lake Bindegolly, Ethabuka dune crest or dune swale sites. The representativeness of this size fractionation of SOC within each site cannot be tested without more extensive soil sampling and analysis, which were beyond the resources available for this study.

The high-resolution PSDs (Figure 7) reveal that the soil at the Ethabuka dune crest site is comprised of particulate sand, with a distinct mode around 250 μm in both minimally and fully-dispersed conditions. The soil at the Ethabuka dune swale site typifies an alluvial deposition environment within the Simpson Desert dune system, having accumulated a significant amount of fine sediment (60–150 μm), which increased slightly following dispersion. The Croxdale and Lake Bindegolly sites also show only slight signs of aggregation when fully dispersed (Figure 7). However, the Spoilbank soil is highly aggregated, having a mode in the range of very fine sand (~170 μm) in minimally and intermediately dispersed conditions. Under the fully dispersed treatment these aggregates were broken down, revealing a substantial component of fines (< 60 μm).

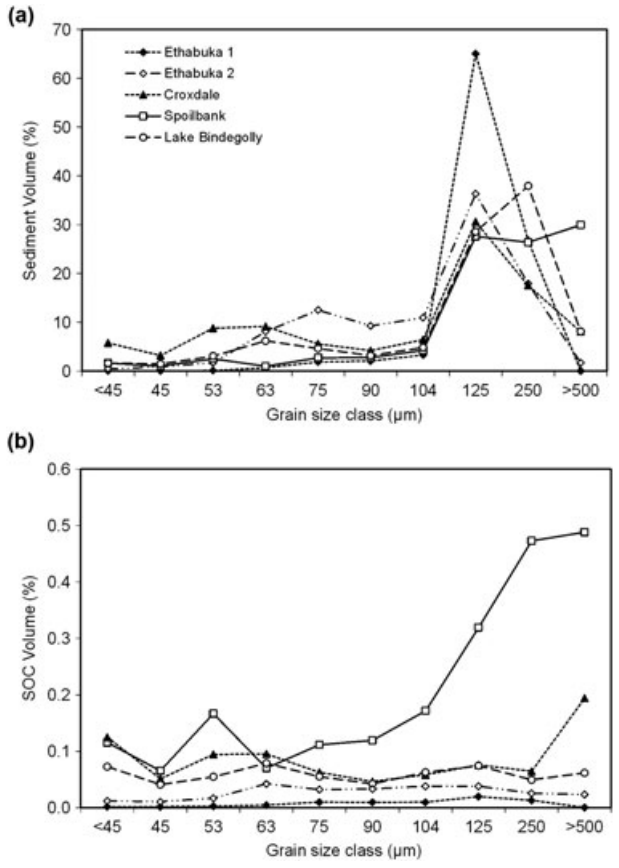

Figure 6. Graphs showing (a) the particle-size distribution (PSD) of the dust source area (parent) soils at the five field sites, as determined by dry sieving in a field condition and (b) the soil organic carbon (SOC) associated with each size fraction of the soils, expressed as a percentage of the volume of total sediment.

Discussion

Field measurements of SOC and enrichment ratios

The SOC content of wind-eroded sediment from our study sites varied from 0·24 to 4·72% for sediment trapped at 0·5 m, and from 0·64 to 29·0% in suspended dusts at 2·0 m. Few measurements of the OM or SOC content of dust emissions are available with which we can compare our results. In Australia, Boon *et al.* (1998) measured dust OM contents in the range 16–38% for regional dust storm events, and up to 90% of background suspended dusts (e.g. dust hazes). A range of smaller OM contents have been recorded in North Africa (4–27%; Franzen *et al.*, 1994) and the Argentine Pampas (6–8%; Ramsperger *et al.*, 1998). By the conversion SOC = 0·58 × OM (Yan *et al.*, 2005), these values appear similar to our measurements from western Queensland.

The SOC enrichment ratios for our dust samples (2·0 m height) are of a similar magnitude to those measured in the croplands of southwest Niger (Sterk *et al.*, 1996) and in the Chihuahuan Desert (Li *et al.*, 2007, 2009) and southern cropping lands of the United States (Van Pelt and Zobeck, 2007). In common with these studies, our results show that variability in the SOC enrichment of dust occurs between land types, and between dust events. This variability may be influenced by seasonal variations in vegetation cover and the breakdown of plant litter, and differences in the propensity of plants to abrade during wind erosion and release fragments to the airstream. However, it appears that the enrichment of SOC in dust in general is due to: (1) physical characteristics of the soil surface during the process of dust emission; (2) physical sorting of suspended mineral and SOC dust during transport. The mechanisms of enrichment in both processes are dependent on the erosive force of the wind (erosivity), its transport capacity, and the physical, chemical and mineralogical characteristics of the dust and hence the nature of soils (their erodibility) from which it originates (Gillette, 1999).

Soil particle-size influences on SOC enrichment

The enrichment of SOC in dust is determined first by the mechanisms of dust entrainment at eroding source areas. Our five field sites are quite different in terms of their SOC enrichment ratios (Figure 4). We interpret this separation using soil particle-size characteristics of the study sites, and the SOC contents. Our results indicate that larger SOC enrichment values are related to larger sand content of the eroding source area soils. This result is confirmed in the positive at the sandy Ethabuka dune crest sites and in the negative at the clay-rich aggregated Spoilbank site. On the fine particulate soils at Lake Bindegolly, Croxdale and Ethabuka dune swale sites, SOC enrichment ratios were smaller than on the Ethabuka dune crest, except for two months (April 2006 at Croxdale and September 2007 at the Ethabuka dune swale) when large regional events occurred. The increased erosivity of these

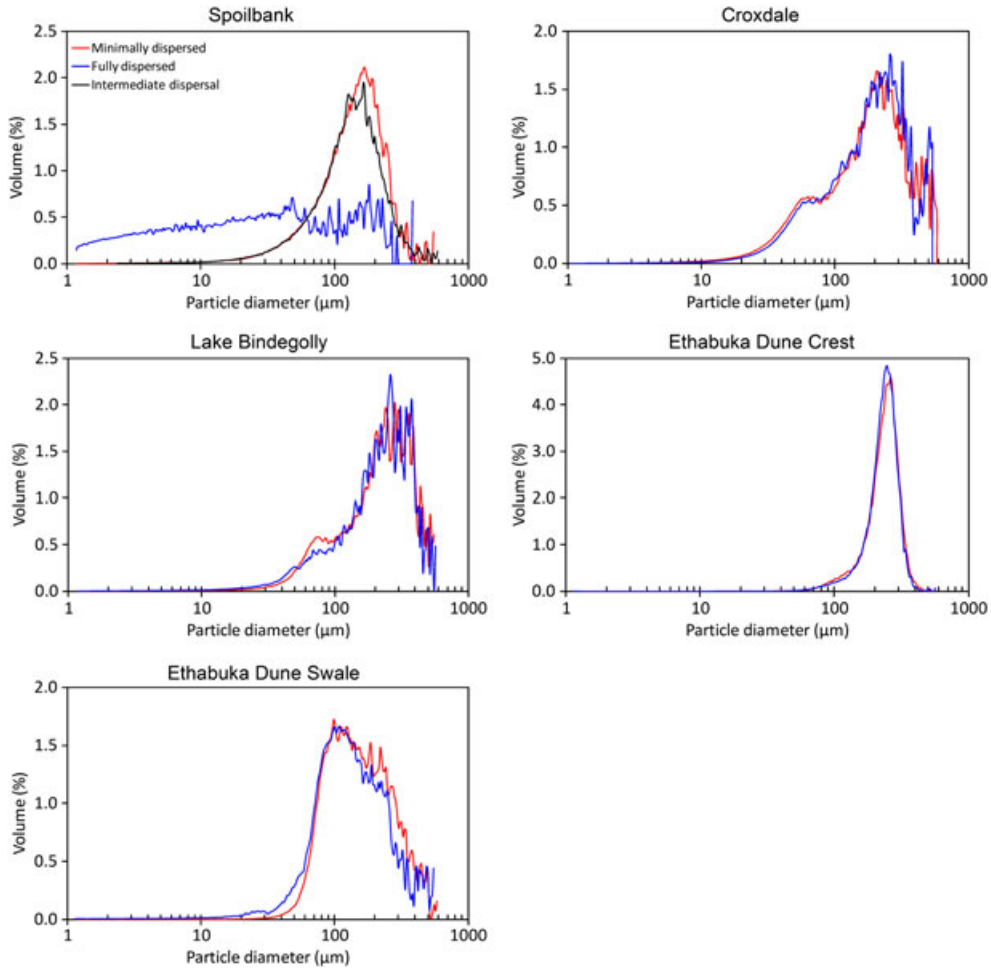

Figure 7. Particle size distributions (PSDs) of the dust source area (parent) soils at the five field sites, determined using a Coulter Multisizer3. Soils were analysed in minimally and fully dispersed conditions, while an intermediate dispersal treatment was applied to the highly aggregated Spoilbank soil to represent the effects of abrasion under saltation bombardment (see Methods for details). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

events and the presence of regional dusts with larger SOC content may explain the increased enrichment ratios at these sites. The increase in SOC enrichment of dust also appears to be associated with the low SOC content of source area soils (Table I). This suggests that soils that are sandy (Ethabuka dune crest site), or if finer have limited aggregation (Lake Bindegolly, Croxdale and Ethabuka dune swale sites), are more efficient at releasing SOC and result in larger SOC enrichment in their dust emissions. This finding is consistent with that of Goossens (2004), who found that soils with larger sand content produced greater dust OM enrichment values than soils with loamy to clay textures. Our findings are also consistent with evidence for the effects of soil texture, crusting and aggregation on the efficiency of soils at releasing dust under aeolian abrasion. The positive relationship between soil sand content and dust emission (Mirzamostafa *et al.*, 1998), and negative relationship between crust and aggregate stability and dust emission are well established (Zobeck, 1991; Fryrear *et al.*, 1994). We hypothesize that these controls extend to the emission of SOC.

Significance of mineralogy for the enrichment process

Three processes are responsible for the emission of fine mineral particles from the soil surface during wind erosion and, we contend, also control SOC emissions. These are: (1) the deflation of fines under erosive winds (aerodynamic lift); (2) particle emission due to ballistic impacts that abrade soil grains; (3) disaggregation during saltation (Pye, 1987). Chappell *et al.* (2008) found that differences in grain density (due primarily to mineralogy) were also responsible for spatial variations in dust emission in the Bodélé Depression, northern Chad. Our results suggest that grain density effects extend to the emission and enrichment of SOC in dust. Logically, the smaller weight of SOC relative to mineral grains should also facilitate its capacity to be lofted above the soil surface and transported by wind.

Soils that are sandy, or if finer are particulate, and are quartz dominated (i.e. have large particle densities) tend to be more efficient at emitting dust-size particles through aerodynamic lift, splash and abrasion. Soils such as those at the Croxdale, Lake Bindegolly and the Ethabuka sites have a greater availability of loose fine sediments respectively, and their saltating mineral grains may have larger impact energies than the clay aggregates found at the Spoilbank site. The density of quartz grains like those found at these sandy sites is 2·55–2·67 g cm^{-3}, whereas the density of clay aggregates of the same diameter (180 µm) found at Spoilbank is 2·11–2–17 g cm^{-3}, determined by volumetric displacement (after McIntyre and Stirk, 1953). The Spoilbank soil has a similar PSD to the sandy sites in an aggregated condition. However, the smaller density of the clay aggregates would reduce their impact energies relative to the quartz sand grains found in much greater proportions at Croxdale, Lake Bindegolly and the two Ethabuka sites. The stability of the clay aggregates, which is influenced by their SOC contents, and the greater binding energies of SOC to clay minerals than to quartz grains, will affect their efficiency at releasing SOC under the impact of saltating grains and by aeolian abrasion (Fryrear *et al.*, 1994; Van Pelt and Zobeck, 2001).

Notably, these results are evident after normalization of SOC in dust relative to saltation (Figure 4). The finding supports the argument that for the same amount of sediment moving in saltation, more SOC (and mineral dust) will be emitted from sandy quartz soils and finer particulate soils than aggregated clay soils (Table I).

The enrichment of SOC in suspended dust is related to the PSD of suspended mineral and SOC material, the transport capacity of winds, and the distance from source at which the SOC content of dust is measured. The large SOC enrichment of dust recorded at the Croxdale (April 2006) and Ethabuka dune swale (September 2007) sites (Table I) suggests that material collected in the BSNE samplers during these periods contained dust from a distant source area. This is supported by meteorological observations (Figure 5). Boon *et al.* (1998) show that the OM content of background (regional) dusts is larger and exhibits less variation than in dusts associated with local entrainment events. We propose, therefore, that the larger enrichment ratios of these dust samples is due to sorting of mineral sediment and SOC during transport. The transport capacity of wind affects the degree of gravitational sorting of dust and SOC during transport, and the small mass of SOC increases its potential to be transported larger distances (Pye, 1987). Therefore, the enrichment of SOC in dust is likely to increase with distance from source. Analyses of the SOC content and physical characteristics in dusts sampled from deposition traps at distance from source areas would provide further evidence of SOC enrichment during transport.

Conclusions

Quantitative data on the magnitude of SOC enrichment within dust emissions is required to determine the impact of wind erosion on SOC flux and better understand the significance of aeolian processes for the global carbon cycle. Our results provide data on SOC enrichment from dust emissions across the rangelands of western Queensland, Australia, and demonstrate the variability in SOC enrichment between land types. They show that the enrichment of SOC in dust emissions varies between land types, and suggest that soil textural properties and mineralogy influence the efficiency of SOC emission and enrichment in dust. Standardized for the quantity of sediment moving in saltation, it appears that sandy soils and to a lesser extent finer particulate soils more readily release SOC than soils that are aggregated and have large silt, clay and SOC contents. These findings suggest that soil textural properties and the mineralogy of eroding soils may be used to develop a first-approximation of SOC enrichment in process-based dust emission models.

Our interpretation of the mechanisms of SOC enrichment in dust is based on knowledge of the processes of mineral dust emission and transport, and the assumption that SOC follows similar pathways. Our findings are somewhat speculative because they are based on few measurements, but are supported by Goossens (2004) who provides the only other analysis of carbon dust enrichment mechanisms known to the authors. Assuming that the average dust SOC content measured across the five land types (4·9%) is representative of the variability in SOC dust loading, we estimate SOC losses in Australian dust emissions at 5·39 Mt yr^{-1} (~100 Mt yr^{-1} mineral dust emission; Shao *et al.*, 2011), and 147 Mt yr^{-1} globally (~3000 Mt yr^{-1} mineral dust emission; Shao *et al.*, 2011). These values appear small in the context of the global soil carbon pool (estimated at 1550 Pg; Lal, 2003) but are likely to be significant at the regional scale through impacts on soil fertility, nutrient redistribution and agricultural production. Managing SOC losses to wind erosion will have important implications under a changing climate, and particularly for mitigation and adaptation efforts that seek to maintain agricultural productivity while reducing carbon emissions. Variability in the magnitude of SOC loads in dust emissions lends weight to the need to consider further the regional impacts of dust on Earth-system processes (Bullard, 2013), and represents a significant source of uncertainty while not considered in carbon cycle modelling and accounting (Doetterl *et al.*, 2012b). The results provide a compelling basis for investigating in detail, and with adequate resources, the mechanisms of SOC emission and its enrichment in dust.

Our results suggest that SOC lost to wind erosion is important for regional carbon cycling, and may amount to a significant omission from carbon accounting systems. There is considerable spatial and temporal variation in the SOC content of measured dust emissions, indicating that there exists considerable variability in SOC enrichment across soils and land uses globally. Enrichment processes appear to have a substantial and underestimated influence on SOC dust emissions and the impact of wind erosion on SOC flux. Understanding the selective removal and enrichment of SOC in dust source areas is necessary for estimating SOC losses due to wind erosion at eroding sites. Conversely, understanding the magnitude and processes of SOC enrichment of dust during transport and between local and regional dust events is required for quantifying SOC deposition rates, and the potential for deposition zones to be carbon sinks. Both components are required to understand the role of aeolian processes in net SOC redistribution, and in its contribution to the net source/sink of CO_2 emissions.

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References

Boon KF, Kiefert L, McTainsh GH. 1998. Organic matter content of rural dusts in Australia. *Atmospheric Environment* **32**: 2817–2823.

Bullard JE. 2013. Contemporary glacigenic inputs to the dust cycle. *Earth Surface Processes and Landforms* **38**: 71–89.

Butler HJ, Leys JF, Shao Y, Strong CL, McTainsh GH. 2010. Caring for our Country – Wind Erosion Extent and Severity Maps for Australia (WEESMap), Schedule Under LCWPA/HEAD00088/00001 Project progress report – 3 November 2010.

Chappell A, Warren A, O'Donoghue A, Robinson A, Thomas A, Bristow C. 2008. The implications fir dust emission modeling of spatial and vertical variations in horizontal dust flux and particle size in the Bodélé Depression, Northern Chad. *Journal of Geophysical Research* **113**: D04214. DOI: 10.1029/2007JD009032

Chappell A, Sanderman J, Thomas M, Read A, Leslie C. 2012. The dynamics of soil redistribution and the implications for soil organic carbon accounting in agricultural south-eastern Australia. *Global Change Biology* **18**: 2081–2088.

Chappell A, Webb NP, Viscarra Rossel R. In review. Australian net (1950s–1990) soil organic carbon erosion is a CO_2 source. *Global Change Biology.*

Daniel HA, Langham WH. 1936. The effect of wind erosion and cultivation on the total nitrogen and organic matter content of soils in the southern High Plains. *Journal of the American Society of Agronomy* **28**: 587–596.

Department of Sustainability, Environment, Water, Population and Communities (DSEWPC). 2011. Australia's Bio-geographical Regions. http://www.environment.gov.au/parks/nrs/science/bioregion-framework/ibra/maps.html [20 November 2011].

Doetterl S, Six J, Van Wesemael B, Van Oost K. 2012a. Carbon cycling in eroding landscapes: geomorphic controls on soil organic C pool composition and C stabilization. *Global Change Biology* **18**: 2218–2232.

Doetterl S, Van Oost K, Six J. 2012b. Towards constraining the magnitude of global agricultural sediment and soil organic carbon fluxes. *Earth Surface Processes and Landforms* **37**: 642–655.

Dymond JR. 2010. Soil erosion in New Zealand is a net sink of CO_2. *Earth Surface Processes and Landforms* **35**: 1763–1772.

Ellis JT, Li B, Farrell EJ, Sherman DJ. 2009. Protocols for characterizing aeolian mass-flux profiles. *Aeolian Research* **1**: 19–26.

Evans M, Quine T, Kuhn N. 2012. Geomorphology and terrestrial carbon cycling. *Earth Surface Processes and Landforms*. DOI: 10.1002/esp.3337

Field JP, Belnap J, Breshears DD, Neff JC, Okin GS, Whicker JJ, Painter TH, Ravi S, Reheis MC, Reynolds RL. 2010. The ecology of dust. *Frontiers in Ecology and the Environment* **8**: 423–430.

Franzen LG, Hjelmroos M, Kallberg P, Brorstrom-Lunden E, Jutto S, Savolainen AL. 1994. The 'yellow snow' episode of northern Fennoscandia, March 1991 – a case study of long-distance transport of soil, pollen and stable organic compounds. *Atmospheric Environment* **28**: 3587–3604.

Fryrear DW. 1986. A field dust sampler. *Journal of Soil and Water Conservation* **41**: 117–120.

Fryrear DW, Krammes CA, Williamson DL, Zobeck TM. 1994. Computing the wind erodible fraction of soils. *Journal of Soil and Water Conservation* **49**: 183–188.

Gill TE, Reynolds RL, Zobeck TM. 2000. Measurements of Current and Historic Settled Dusts in West Texas. Air Waste Management Publication VIP 97, 0715. Air & Waste Management Association: Pittsburgh, PA; 15 pp.

Gillette DA. 1999. A qualitative geophysical explanation for 'Hot Spot' dust emitting source regions. *Contributions to Atmospheric Physics* **72**: 67–77.

Goossens D. 2004. Net loss and transport of organic matter during wind erosion on loamy sandy soil. In Wind Erosion and Dust Dynamics: Observations, Simulations, Modelling, Goossens D, Riksen M (eds). ESW Publications: Wageningen; 81–102.

Goossens D, Buck BJ. 2012. Can BSNE (Big Spring Number Eight) samplers be used to measure PM10, respirable dust, PM2.5 and PM1.0? *Aeolian Research* **5**: 43–49.

Goossens D, Offer ZY. 2000. Wind tunnel and field calibration of six aeolian dust samplers. *Atmospheric Environment* **34**: 1043–1057.

Harper RJ, Gilkes RJ, Hill MJ, Carter DJ. 2010. Wind erosion and soil carbon dynamics in south-western Australia. *Aeolian Research* **1**: 129–141.

Isbell RF. 2002. The Australian Soil Classification, revised edition. CSIRO Publishing: Collingwood, Victoria.

Kavouras IG, Nikolich G, Etymezian V, DuBois DW, King J, Shafer D. 2012. In situ observations of soil minerals and organic matter in the early phases of prescribed fires. *Journal of Geophysical Research* **117**: D12313. DOI: 10.1029/2011JD017420

Kuhn NJ, Hoffmann T, Schwanghart W, Dotterweich M. 2009. Agricultural soil erosion and global carbon cycle: controversy over? *Earth Surface Processes and Landforms* **34**: 1033–1038.

Lal R. 2003. Soil erosion and the global carbon budget. *Environment International* **29**: 437–450.

Lal R. 2007. Carbon management in agricultural soils. *Mitigation and Adaptation Strategies for Global Change* **12**: 303–322.

Li J, Okin GS, Alvarez L, Epstein H. 2007. Quantitative effects of vegetation cover on wind erosion and soil nutrient loss in a desert grassland of southern New Mexico, USA. *Biogeochemistry* **85**: 317–332.

Li J, Okin GS, Alvarez L, Epstein H. 2008. Effects of wind erosion on the spatial heterogeneity of soil nutrients in two desert grassland communities. *Biogeochemistry* **88**: 73–88.

Li J, Okin GS, Epstein HE. 2009. Effects of enhanced wind erosion on surface soil texture and characteristics of windblown sediments. *Journal of Geophysical Research* **114**: G02003. DOI: 10.1029/2008JG000903

McIntyre DS, Stirk GB. 1953. A method for determination of apparent density of soil aggregates. *Crop & Pasture Science* **5**: 291–296.

McTainsh GH, Leys JF, Nickling WG. 1999. Wind erodibility of arid lands in the Channel Country of western Queensland, Australia. *Zeitschrift für Geomorphologie N.F* **116**: 113–130.

Mirzamostafa N, Hagen LJ, Stone LR, Skidmore EL. 1998. Soil aggregate and texture effects on suspension components from wind erosion. *Soil Science Society of America Journal* **62**: 1351–1361.

Nelson DW, Sommers LE. 1996. Total carbon, organic carbon, and organic matter. In Methods of Soil Analysis, Part 2, 2nd edn, Page AL (ed). American Society of Agronomy: Madison, WI; 961–1010.

O'Loingsigh T, Tews EK, McTainsh GH, Strong CL, Leys JF, Shinkfield P. In review. The Dust Storm Index (DSI): a method for monitoring broad scale wind erosion using meteorological records. *Journal of Soil and Water Conservation*.

Pye K. 1987. Aeolian Dust and Dust Deposits. Academic Press: London.

Quinton JN, Govers G, Van Oost K, Bardgett RD. 2010. The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience* **3**: 311–314.

Ramsperger B, Peinemann N, Stahr K. 1998. Deposition rates and characteristics of aeolian dust in the semi-arid and sub-humid regions of the Argentinean Pampa. *Journal of Arid Environments* **39**: 467–476.

Ravi S, D'Odorico P, Breshears DD, Field JP, Goudie AS, Huxman TE, Li J, Okin GS, Swap RJ, Thomas AD, Van Pelt S, Whicker JJ, Zobeck TM. 2011. Aeolian processes and the biosphere. *Reviews of Geophysics* **49**: RG3001.

Schumacher BA. 2002. Methods for the Determination of Total Organic Carbon (TOC) in Soils and Sediments. United States Environmental Protection Agency: Las Vegas, NV.

Shao Y, McTainsh GH, Leys JF, Raupach MR. 1993. Efficiencies of sediment samplers for wind erosion measurement. *Australian Journal of Soil Research* **31**: 519–532.

Shao Y, Wyrwoll K-H, Chappell A, Huang J, Lin Z, McTainsh GH, Mikami M, Tanaka TY, Wang X, Yoon S. 2011. Dust cycle: an emerging core theme in Earth system science. *Aeolian Research* **2**: 181–204.

Sterk G, Herrmann L, Bationo A. 1996. Wind-blown nutrient transport and productivity changes in southwest Niger. *Land Degradation and Development* **7**: 325–335.

Van Oost K, Quine TA, Govers G, De Gryze S, Six J, Harden JW, Ritchie JC, McCarty GW, Heckrath G, Kosmas C, Giraldez JV, Marques de Silva JR, Merckx R. 2007. The impact of agricultural soil erosion on the global carbon cycle. *Science* **318**: 626.

Van Pelt RS, Zobeck TM. 2001. Carbonaceous materials in soil-derived dusts. In Soil Carbon Sequestration and the Greenhouse Effect, Lal R, Follett RF (ed). Soil Science Society of America Special Publication no. 57. Soil Science Society of America: Madison, WI; 183–205.

Van Pelt RS, Zobeck TM. 2007. Chemical constituents of fugitive dust. *Environmental Monitoring and Assessment* **13**: 3–16.

Webb NP, McGowan HA, Phinn SR, McTainsh GH, Leys JF. 2009. Simulation of the spatiotemporal aspects of land erodibility in the northeast Lake Eyre Basin, Australia, 1980–2006. *Journal of Geophysical Research* **114**: F01013. DOI: 10.1029/2008JF001097

Webb NP, Chappell A, Strong CL, Marx SK, McTainsh GH. 2012. The significance of carbon-enriched dust for global carbon accounting. *Global Change Biology* **18**: 3275–3278.

Yan H, Wang S, Wang C, Zhang G, Patel N. 2005. Losses of soil organic carbon under wind erosion in China. *Global Change Biology* **11**: 828–840.

Zobeck TM. 1991. Abrasion of crusted soils: influence of abrader flux and soil properties. *Soil Science Society of America Journal* **55**: 1091–1097.