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TECHNICAL ADVANCE

Soil organic carbon dust emission: an omitted global source of atmospheric CO_2

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Abstract

Soil erosion redistributes soil organic carbon (SOC) within terrestrial ecosystems, to the atmosphere and oceans. Dust export is an essential component of the carbon (C) and carbon dioxide (CO_2) budget because wind erosion contributes to the C cycle by removing selectively SOC from vast areas and transporting C dust quickly offshore; augmenting the net loss of C from terrestrial systems. However, the contribution of wind erosion to rates of C release and sequestration is poorly understood. Here, we describe how SOC dust emission is omitted from national C accounting, is an underestimated source of CO_2 and may accelerate SOC decomposition. Similarly, long dust residence times in the unshielded atmospheric environment may considerably increase CO_2 emission. We developed a first approximation to SOC enrichment for a well-established dust emission model and quantified SOC dust emission for Australia (5.83 Tg CO_2-e yr^{-1}) and Australian agricultural soils (0.4 Tg CO_2-e yr^{-1}). These amount to underestimates for CO_2 emissions of ≈10% from combined C pools in Australia (year = 2000), ≈5% from Australian Rangelands and ≈3% of Australian Agricultural Soils by Kyoto Accounting. Northern hemisphere countries with greater dust emission than Australia are also likely to have much larger SOC dust emission. Therefore, omission of SOC dust emission likely represents a considerable underestimate from those nations' C accounts. We suggest that the omission of SOC dust emission from C cycling and C accounting is a significant global source of uncertainty. Tracing the fate of wind-eroded SOC in the dust cycle is therefore essential to quantify the release of CO_2 from SOC dust to the atmosphere and the contribution of SOC deposition to downwind C sinks.

Keywords: Australia, carbon accounting, carbon budgets, carbon dioxide, dust emission, soil organic carbon

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Introduction

Uncertainty about the fate of eroded soil organic carbon (SOC) has led to debate about the impact of soil erosion on the global C budget, and in particular whether erosion is a net source or sink of CO_2 emissions (Stallard, 1998; Lal, 2003; Berhe *et al.*, 2007; Van Oost *et al.*, 2007; Lal & Pimentel, 2008; Quinton *et al.*, 2010). Much of this debate originates from research into C fluxes by water erosion (e.g., Doetterl *et al.*, 2012). Regnier *et al.* (2013) place this debate into the context of anthropogenic perturbation of the carbon budget along the 'aquatic continuum'. The magnitude of C fluxes due to wind erosion is largely unknown. Of the few studies conducted to date (e.g., Yan *et al.*, 2005), none have accounted for the enrichment of SOC in dust emissions. The significance of SOC emission by wind erosion is also unknown relative to other terrestrial emissions sources, such as land-use and land-cover change. Process-based assessments of the magnitude of SOC erosion and transport in dust emissions are required to determine the significance of wind erosion for the C cycle and CO_2 emissions.

The significance of wind erosion for C cycling and C accounting systems is that it selectively removes the finest silt- and clay-sized mineral particles from soils, including the SOC fraction (Gregorich *et al.*, 1998). Thus, dust containing SOC are highly enriched (henceforth SOC dust). The removal of SOC by wind erosion can immediately deplete the 'active' or 'labile' SOC pool and break down protective soil aggregates and microenvironments at the surface via aeolian abrasion, which may accelerate the mineralization and release of CO_2 to the atmosphere (Fig. 1).

In large magnitude events and extended periods of erosion the 'slow' SOC pool can also be reduced by

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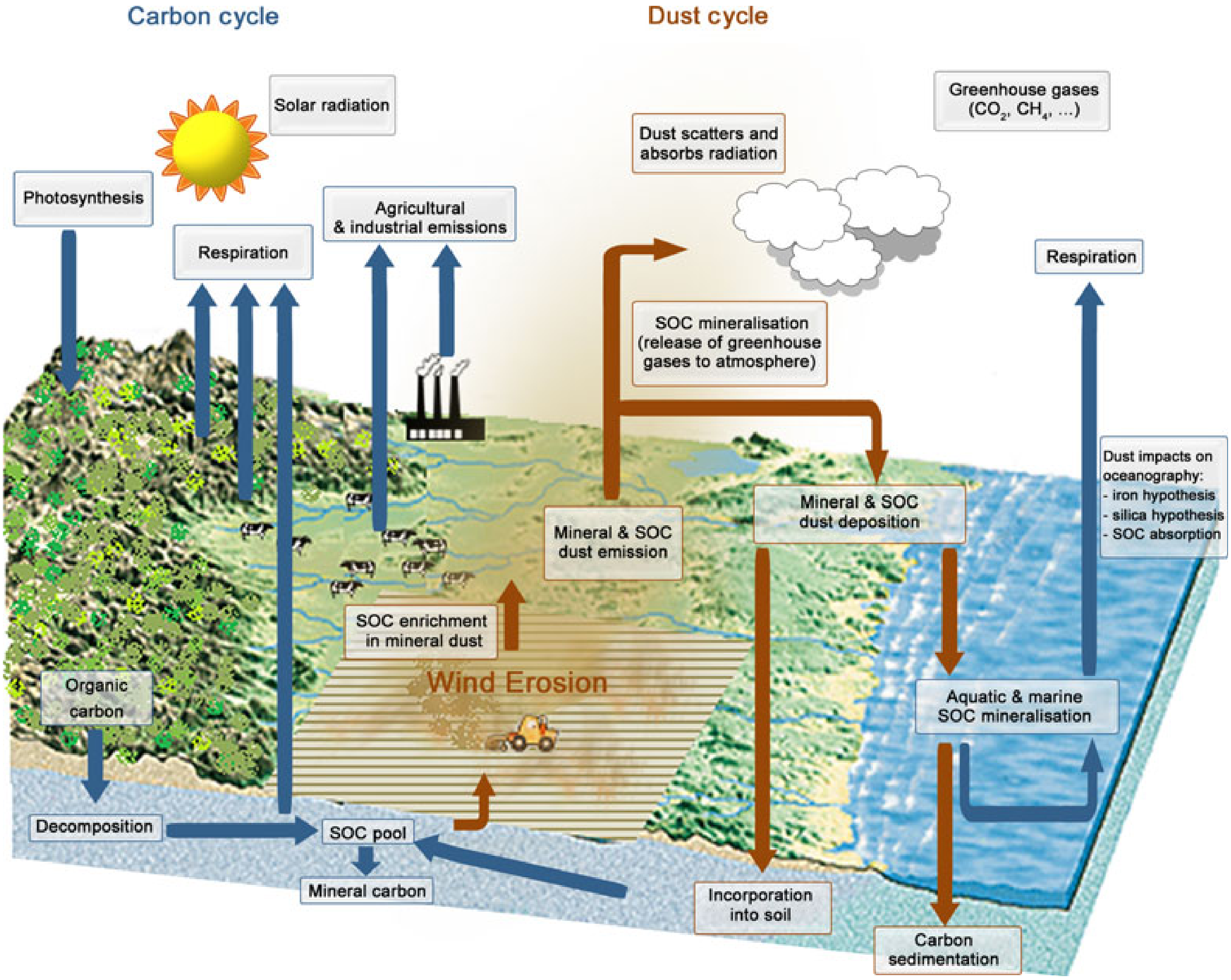

Fig. 1 The main processes of the dust cycle, its impact on soil organic carbon (SOC) and interactions with the carbon cycle.

removal and exposure of fresh substrate to acidification and mineralization processes (Lal, 2003). Once in the airstream, considerable amounts of the largest dust size will be redeposited locally, but because of their low specific density most SOC dust is likely carried long distances via dust-transport pathways that follow global atmospheric circulation systems (Goudie & Middleton, 2006). The relatively long residence time of dust in the atmosphere may facilitate SOC mineralization and accelerate the release of CO_2. Ultimately, SOC dust may be deposited by rain-out over oceans (Goudie & Middleton, 2006). The deposition of micronutrients (e.g., Fe) has potential to stimulate phytoplankton blooms particularly in the Fe-limited waters of the Southern Ocean, enhancing CO_2 sequestration (Jickells *et al.*, 2005) and leading to typically lower glacial atmospheric CO_2 concentration ('iron hypothesis'; Calvo *et al.*, 2004). The complementary 'silica hypothesis' suggests that diatom productivity may have been favoured due to an increased availability of Fe and Si and draw down atmospheric CO_2 levels to glacial values via an increase in ocean alkalinity and pH (Calvo *et al.*, 2004). The quantification of SOC fluxes during wind erosion, transport and deposition is, therefore, central to understanding the linkages between the dust cycle and the C cycle (Fig. 1; Shao *et al.*, 2010) and evaluating their significance for the C budget and national C accounting (Smith *et al.*, 2001; Haverd *et al.*, 2012).

The focus of this study is upon the first stage of the dust cycle; the entrainment and emission of SOC dust, using Australia as a case study. Modelling studies show that Australia is the largest dust source in the southern hemisphere (SH; Tanaka & Chiba, 2006); accounting for 59% of total SH emissions, sourcing 34% of the dust inputs to the Southern Ocean (Li *et al.*, 2008) and having a significant influence on SH atmospheric dust loading (Luo *et al.*, 2003). Australian SOC dust has considerable variation in SOC content ($\bar{x}$ = 37%, SD = 22%; Boon et al., 1998). Measurements elsewhere on Earth suggest that SOC dust may be many times larger than that of source area soils. Yan et al. (2005) report aeolian SOC erosion rates for the Earth (1.4 Pg SOC yr^{-1}), United States (34 Tg SOC yr^{-1}) and China (75 Tg SOC yr^{-1}). However, in not accounting for the selective removal and enrichment of SOC, these estimates may have uncertainties of up to 60% in the magnitude of SOC eroded by wind (Webb et al., 2012). Representing spatial and temporal variability in SOC dust is critical to improving estimates of SOC flux due to wind erosion and their inclusion in C cycle models and C accounts. Here, we modify a dust emission model to account for SOC dust emission. We estimate the spatial and temporal variation in total monthly dust and SOC emissions for 2000–2011 in Australia and consider the implications for national and international C cycling and C accounting.

Materials and methods

We quantify the spatial and temporal variation in SOC load in Australian dust emissions using numerical simulations of the Computational Environmental Management System (CEMSYS v5) wind erosion model (Shao, 2000). A physically-based approximation of SOC enrichment is used to estimate SOC emissions. We estimate SOC dust emission in the <22 μm fraction which has the greatest potential for long-range transport off the Australian continent (McGowan et al., 2000). The methodology assumes that the SOC enrichment in dust is proportional to the enrichment of soil fines (<22 μm; Goossens, 2004; Webb et al., 2013). We use this approach to estimate the spatio-temporal variation of SOC dust emission due to variations in the amount of surface SOC and the location and intensity of wind erosion. We ran CEMSYS to simulate SOC dust emissions at a 50 km spatial resolution across Australia, using SOC content data derived from several national sources (Viscarra Rossel & Webster, 2011) and an Atmosphere and Land Surface Interaction Scheme (ALSIS) coupled to a limited area atmospheric model. The simulations produced total monthly dust and SOC emissions for 2000–2011. Australian land-use data were used to determine sectoral contributions to national SOC dust emissions, and their relative contributions to existing components of the national C accounting system.

We assume, following Boon et al. (1998), that SOC dust emission (E; g SOC m^{-2} yr^{-1}) can be calculated as the product:

$$E = F \times P \times SOC_{surf} \times 0.315; \tag{1}$$

where F is the <22 μm dust flux rate (μg m^{-2} s^{-1}), P is the SOC enrichment ratio and SOC_{surf} is the proportion of SOC at the soil surface (%SOC 0–0.1 m). We converted monthly flux data (μg m^{-2} s^{-1}) into g m^{-2} s^{-1} by multiplying by 10^{-6} and into g m^{-2} yr^{-1} by multiplying by 3.15×10^7. The F is provided by CEMSYS (See Supplementary Section S2; Shao, 2000). Enrichment of SOC by wind erosion and dust emission P is largely unknown because it requires spatial information on the amount of SOC in the dust and the amount of SOC in the soil and how those proportions change over time. The CEMSYS provides a physical basis for the enrichment of dust size fractions relative to the surface particle size distribution and aggregate size distribution. In the absence of P for SOC, we assume that dust enrichment is similarly applicable to the enrichment of SOC:

$$P = \text{SOC in dust/SOC in soil (dimensionless)}. \tag{2}$$

We have spatial information on SOC but little information on SOC in dust (D). So, we approximate P using P' as:

$$P' = D_f/S_f, \tag{3}$$

where D_f is the dust mass <22 μm divided by the dust mass ≤52 μm and S_f is the soil surface fines <22 μm/soil surface fines <52 μm. The ratio P' estimates the proportion of 'fine' dust in transport. Replacing this approximation in the original expression (Eqn 1) provides:

$$E = F \times (D_f/S_f) \times SOC_{surf}. \tag{4}$$

We use these fractions (D_f and S_f) to standardize for the constraint (<52 μm) imposed by our use in this instance of the CEMSYS model. In other situations, where, for example, we might know the entire size distribution of dust in transport, we could select a fraction that contains more of the SOC. Equation (4) was used in our calculations. Only the minimally dispersed (i.e., transport stable) surface soil size distribution is used in the calculation of S_f. The distributions were reconstructed and then attributed to a range of soils across Australia (see Supplementary Section S3).

We recognize that different types of SOC will likely travel in different fractions due to variation in their density, size and shape. However, information is not available on the size fractions of SOC transported by dust, and the types of SOC transported in dust are poorly understood (Webb et al., 2012). Nevertheless, the calculations here provide a valuable first approximation.

The Australian soil visible near-infrared spectroscopic database (Viscarra Rossel & Webster, 2011) was used to predict the SOC and bulk density (Bd; g cm^{-3}) of 4000 surface soil samples (0–10 cm) that were used to derive the SOC density (SOC_{den}) map. The soil samples originated from CSIRO's National Soil Archive, the National Geochemical Survey of Australia and other State Departments, regional and field scale surveys. Thus, SOC_{den} (t ha^{-1}) was calculated by:

$$SOC_{den} = SOC \times Bd \times d, \tag{5}$$

where d is the depth (cm) from where the samples were taken. The SOC_{den} values were mapped by ordinary kriging on an approximate 50 km grid to coincide with the other data layers used here. From this SOC stock map the total SOC stock for Australia was calculated and used to determine the proportion of SOC removed by SOC dust emission.

We accumulated the dust flux of Australia for each month (between February 2000 and June 2011) and then calculated the average of the available months to provide the annual dust flux (g m^{-2} yr^{-1}). To calculate the total annual dust flux, we multiplied the converted flux data (g m^{-2} yr^{-1}) for each month by the eroded area for each land-use class. The eroded area was calculated as the number of pixels associated with each of the eight land-use classes multiplied by the pixel area (equal area projection: 49.7 km × 58 km = 2884 km^2) and then multiplied by 10^6 to convert into m^2.

The source of land-use information for Australia is provided in Supplementary Section S4 and also describes its use to summarize SOC dust emission across Australia, its rangelands and agricultural regions. Additional information on SOC accounting is provided in Supplementary Section S5.

Results and discussion

We find that total SOC dust emission (<22 μm) for Australia is 1.59 Tg SOC yr^{-1} (Table 1). Assuming that the fine (<22 μm) dust fraction is transported off the continent (McGowan *et al.*, 2000), the total Australian SOC dust emission amounts to a loss of 5.83 Tg CO_2 equivalents yr^{-1} from the terrestrial system.

We acknowledge that this assumption neglects the fate of SOC dust in the atmosphere or oceans, or its direct effect on radiative forcing. Biochemical reactions of SOC dust in the atmosphere and oceans may counter the effects of SOC mineralization that result in CO_2 production. More work is required to elucidate the types and significance of these processes to determine the fate and impact of SOC dust. However, on this basis, the emission is similar in magnitude to Kyoto Accounting categories of Industrial Processes and Agriculture including Prescribed Burning of Savannas (≈8.6 Tg CO_2 equivalents yr^{-1}; (DCCEE) Department of Climate Change & Energy Efficiency, 2010). The Australian SOC dust emission amounts to ≈10% of Australian CO_2 emissions due to combined C pools (above- and belowground biomass, soil C and litter; (AGO) Australian Greenhouse Office, 2005). Although the SOC dust emission represents a relatively small contribution of the national CO_2 emissions (2%; 1990–2003), it is a significant ≈5% source of uncertainty relative to the net CO_2 emissions from the Australian rangelands (≈104 Tg CO_2 equivalents yr^{-1}; AGO, 2005). The National Greenhouse Gas Inventory estimate is 13.2 Tg CO_2 equivalents yr^{-1} from agricultural soils (AGO, 2005). Our estimate of SOC dust emission from agricultural soils is 0.11 Tg SOC yr^{-1} which is 0.40 Tg CO_2 equivalents yr^{-1}. This value is an underestimate of ≈3% to this category of Australian Kyoto Protocol accounting. The SOC fraction >22 μm, representing a greater proportion of the total SOC dust emission by mass, is less likely to be transported offshore except during large dust storm events with highly erosive winds (McGowan *et al.*, 2000). This large SOC dust fraction is more commonly redistributed among local SOC sources and sinks, influencing biogeochemical processes that affect patterns of plant growth and crop productivity (Li *et al.*, 2008). Significant SOC dust emissions originate from agricultural regions that are under pressure from demands for increased productivity. Future land management strategies could have a substantial impact on SOC dust emissions.

The total mineral dust emission for Australia is 148 Tg yr^{-1}, which is at the larger end of previous dust emission simulations for Australia (Shao *et al.*, 2011). However, unlike previous studies our estimates included the two largest recorded dust storms in Australia, in 2002 and 2009. Rangelands produce on average, larger mineral dust emissions (35.96 g m^{-2} yr^{-1}) than agricultural lands (19.10 g m^{-2} yr^{-1}). Although

Table 1 Soil organic carbon dust (<22 μm) emission by land-use classes for 2000–2011

Description	Mean dust flux (g m^{-2} yr^{-1})	Mean enrichment ratio	Mean soil organic carbon (% SOC)	Mean SOC dust emission (g SOC m^{-2} yr^{-1})	Mean eroding area ($m^2 \times 10^{12}$)*	Total SOC dust emission (g SOC $yr^{-1} \times 10^{12}$)
Conservation and natural environments	16.54	2.39	0.74	0.28	1.00	0.28
Production from relatively natural environments	47.34	2.54	0.66	0.57	1.92	1.10
Production from dryland agriculture and plantations	19.29	1.93	1.50	0.50	0.21	0.11
Production from irrigated agriculture and plantations	16.77	1.54	1.73	0.58	0.01	0.00
Intensive uses	4.70	1.46	1.91	0.10	0.00	0.00
Rangeland	35.96	2.48	0.70	0.46	2.92	1.34
Agriculture	19.10	1.92	1.51	0.50	0.22	0.11
Australia	35.20	2.44	0.82	0.48	3.35	1.59

*Using an equal area projection the area of a pixel is 49.7 km × 58 km = 2884 km^2.

the SOC enrichment ratios for agricultural lands are smaller than for rangelands, mean SOC dust emissions for agricultural land uses (0.50 g SOC m^{-2} yr^{-1}) are greater than for rangelands (0.46 g SOC m^{-2} yr^{-1}) because of their larger topsoil SOC content and greater soil disturbance. On a per unit area basis, agricultural lands used for crop production produce larger SOC dust emissions than rangelands. Therefore, agricultural lands are an important source of Australian SOC dust emissions. However, accounting for the size of the eroding dust source areas reveals that the extensive Australian rangelands contribute 84% of the continent's SOC dust emissions.

Spatial patterns of Australian SOC dust emission are a product of the patterns of mineral dust emission, the topsoil SOC content and patterns of SOC enrichment (Fig. 2). There is significant interannual variability arising from such influencing factors as wind erosivity, rainfall and land use. Consistent with global dust emission models (Ginoux *et al.*, 2012), dust emissions are concentrated in three major known dust source areas (Fig. 2a): (i) the Lake Eyre Basin which extends from South Australia (SA) to western New South Wales (NSW) and into southwestern Queensland (QLD); (ii) the semiarid Murray–Darling Basin (MDB) in western New South Wales (NSW); and (iii) the Pilbara and the

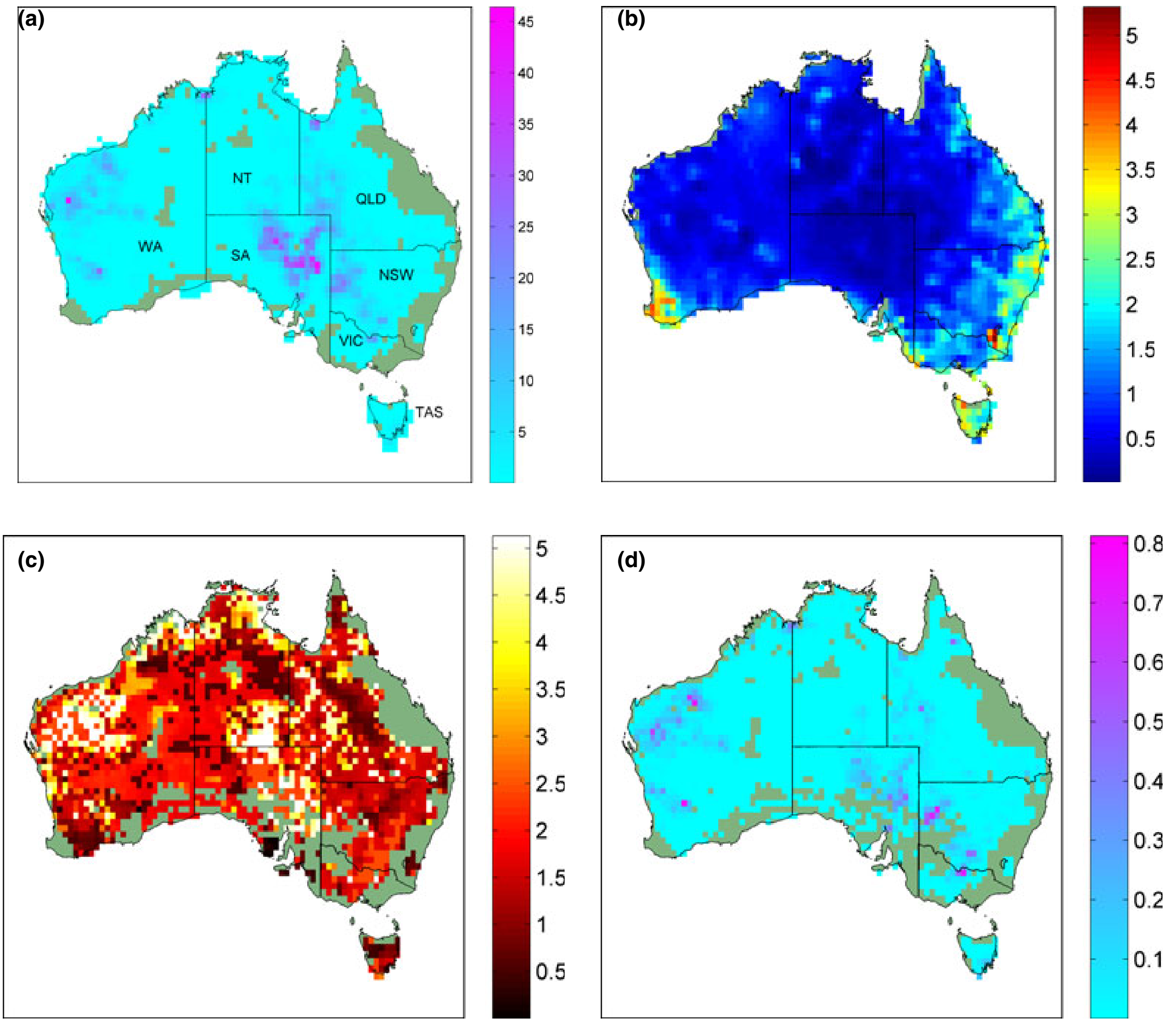

Fig. 2 Mean annual (2000–2011) (a) dust emission (g m^{-2} yr^{-1}), (b) soil organic carbon (%; 0–0.1 m), (c) soil organic carbon enrichment in dust and (d) soil organic carbon dust emission (g SOC m^{-2} yr^{-1}) in the major dust sources in Western Australia (WA), South Australia (SA), New South Wales (NSW) and Queensland (QLD).

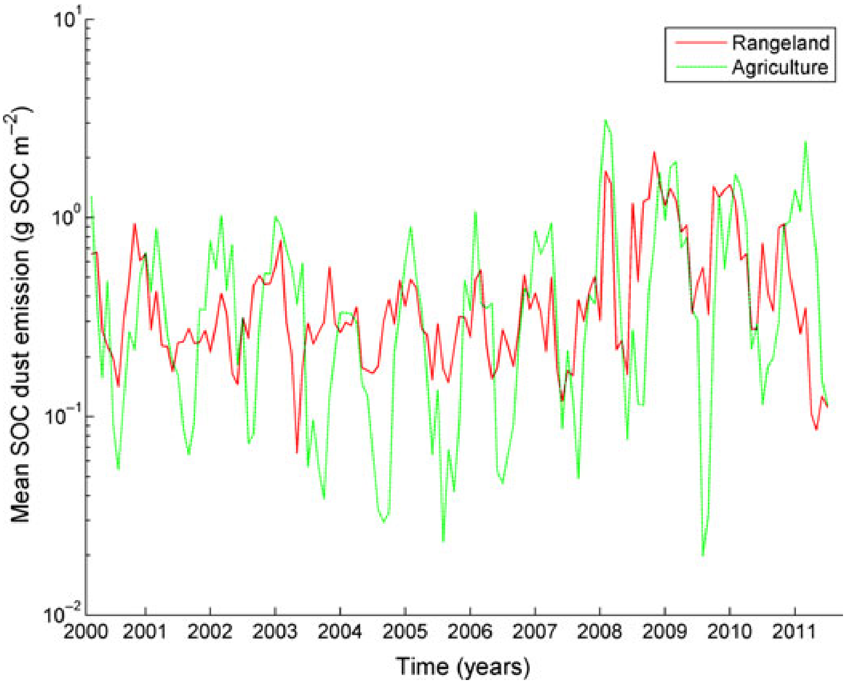

Fig. 3 Temporal variation in the mean soil organic carbon dust emission (g SOC m^{-2}) for Australia (Note log scale for *y*-axis).

Gascoyne regions in northwestern Western Australia (WA). While dust emissions occur naturally in the source regions, the southeastern and southwestern source areas are more prone to the impacts of agriculture than the arid interior and far western source areas.

The temporal variation in the mean monthly SOC dust emission (g SOC m^{-2}) illustrates the seasonal variation in the rangeland and agricultural regions. The rangeland region has smaller interannual variation than the agricultural region which represents the extremes in ground cover and therefore susceptibility to wind erosion and dust emission (Fig. 3). The increased amount of SOC dust emission from 2008 indicate the drier conditions in Australia due to prolonged El Nino-related drought. Notably, these amounts have reduced considerably in recent years and may have returned to their approximately 'pre-drought' values (Fig. 3). The SOC content of soils in the dust source areas is small (<1%) relative to humid coastal regions, but increases (up to 2.5%) in the MDB of NSW and in southwest WA (Fig. 2b).

The SOC enrichment factors reflect spatial patterns in the particle size of eroding soils (Fig. 2c) and spatio-temporal patterns in the transport capacity of erosive winds that influence the particle size distribution of emitted dust. At locations where the SOC enrichment is less than or equal to one there is less fine SOC in dust than in parent topsoils. Locations with large enrichment factors (>1) are efficient at releasing resident fines and SOC. In previous studies that quantified SOC dust emission, the absence or inaccuracy of enrichment information is a significant source of uncertainty in estimating SOC erosion. The largest SOC dust emissions originate from source areas in semiarid regions with larger topsoil SOC content, but which are subject to disturbance due to more intensive land uses (Fig. 2d). We are able to make these assertions based on our physically-based enrichment process. It assumes that SOC is transported along the same pathway as mineral fines because SOC bonds to the finest soil clay fraction. However, our recent field measurements (Webb *et al.*, 2013) suggest that this does not occur everywhere/all the time. Our approximation is based on the distribution of the SOC for which there is also a dearth of information. Further work on these topics will considerably improve the larger basis for estimating SOC redistribution. Furthermore, a largely unknown source of uncertainty and SOC dust emission arises from plume-driven wildfires. Bormann *et al.* (2008) found that approximately 60% of C in mineral soil horizons was removed largely as a consequence of soil erosion on steep slopes once the protective vegetation cover was removed by fire.

Our estimates of SOC dust emission are based on a well-established wind erosion model and an approximation developed here to account for the enrichment/depletion of SOC (relative to the parent material) during erosion. They show that SOC dust emission is greatest in agricultural areas where topsoil C content is medium and soils are regularly disturbed. However, the removal of small SOC content from vast rangeland soils produces the single largest source of SOC dust, from an area that is highly sensitive to SOC change (Tanaka & Chiba, 2006). Wind erosion and dust emission also have the potential to accelerate decomposition rates of SOC pools due to the breakdown of soil aggregates, increased oxidation and mineralization. Similarly, long dust residence times in this unshielded atmospheric environment may considerably increase CO_2 emission. We suggest that the omission of SOC dust emission from C cycling and C accounting is a significant source of uncertainty. Tracing the fate of wind-eroded SOC in the dust cycle is therefore essential to quantifying the release of CO_2 from SOC dust to the atmosphere and the contribution of SOC deposition to downwind C sinks.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Section S1. Spatial variation in monthly soil organic carbon dust emission.
Section S2. The Computational Environmental Management System (CEMSYS v5).
Section S3. Particle size distribution reconstruction.
Section S4. Australian Land use.
Section S5. Carbon accounting calculations.