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The global significance of omitting soil erosion from soil organic carbon cycling schemes

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Soil organic carbon (SOC) cycling schemes used in land surface models (LSMs) typically account only for the effects of net primary production and heterotrophic respiration[1]. To demonstrate the significance of omitting soil redistribution in SOC accounting, sequestration and emissions, we modified the SOC cycling scheme RothC (ref. 2) to include soil erosion. Net SOC fluxes with and without soil erosion for Australian long-term trial sites were established and estimates made across Australia and other global regions based on a validated relation with catchment-scale soil erosion. Assuming that soil erosion is omitted from previous estimates of net C flux, we found that SOC erosion is incorrectly attributed to respiration. On this basis, the Australian National Greenhouse Gas inventory overestimated the net C flux from cropland by up to 40% and the potential (100 year) C sink is overestimated by up to 17%. We estimated global terrestrial SOC erosion to be 0.3–1.0 Pg C yr^{-1} indicating an uncertainty of −18 to −27% globally and +35 to −82% regionally relative to the long-term (2000–2010) terrestrial C flux of several LSMs. Including soil erosion in LSMs should reduce uncertainty in SOC flux estimates[3,4] with implications for CO$_2$ emissions, mitigation and adaptation strategies and interpretations of trends and variability in global ecosystems[5].

Soils are estimated to store up to 80% of the organic carbon in the terrestrial biosphere (2,376–2,450 Pg C to a depth of 2 m) and contain more than three times the organic carbon in the atmosphere[6]. The amount of carbon dioxide (CO$_2$) captured and converted to SOC annually through terrestrial net primary production or released as CO$_2$ by soil microbial respiration is about an order of magnitude greater than the annual increase in atmospheric CO$_2$ (ref. 7). Soil therefore represents a substantial component within the global carbon cycle and small changes in the SOC stock may result in large changes of atmospheric CO$_2$ particularly over tens to hundreds of years[8]. Similarly, global climate change could influence fixation and respiration with implications for terrestrial ecosystems and feedbacks to global biogeochemistry and radiative forcing[9].

Soil erosion is a global issue[10] that occurs more intensively on cultivated land than on rangeland[11]. Since agricultural expansion, many global regions have subsequently introduced conservation agriculture to reduce soil erosion and consequently there is considerable spatial and temporal variation of soil erosion associated with the history of land use and management (for example, conservation agriculture in Australia[12–14]). Soil erosion has removed considerable quantities of topsoil[10], which may continue and perhaps be exacerbated by projected extremes, for example, Australian climate change[15]. There is renewed awareness of the global significance of soil erosion probably due in part to the debate about whether soil erosion is a sink or source[16] of CO$_2$ and its impact on soil nutrient redistribution and global biogeochemistry[17].

Carbon cycling schemes, for example, RothC (ref. 2), Century[18] and crop models such as APSIM (ref. 19) are used to predict C change for different environmental and management conditions. These types of model underpin regional assessments of the terrestrial carbon budget that consider the processes of net primary production and respiration. One of the most widely used SOC turnover models is RothC. For example, SOC cycling in RothC underpins the Australian Government's spatial modelling framework Full Carbon Accounting Model (FullCAM) and the modified Carnegie–Ames–Stanford approach (CASA) within the LSM CABLE[20].

Here we demonstrate that SOC flux should also include losses (and gains) due to soil erosion (and deposition). We modified the C cycling scheme RothC (version 26.3) to include an erosion component (RothCE; Supplementary Section 1.1). For several long-term experimental plots in Australia (Supplementary Section 1.3) we measured ^{137}Cs and estimated net (1973–1993) soil erosion using three approaches (Table 1 and Supplementary Sections 1.4 and 1.5). These results demonstrated that plots had been exposed to soil erosion involving the loss of SOC (SOC erosion). The different estimates of soil erosion were used with RothCE, established decomposition rates for Australia[21] and the measured SOC fractions, to estimate SOC loss with and without erosion (Fig. 1). Depending on the magnitude of erosion there may be a considerable difference between the model predictions with and without erosion. The net C flux of optimized RothCE was compared with that of the model without erosion and showed a consistent under-estimate of net C flux in the presence of soil erosion that we interpreted as SOC erosion (Table 1 and Fig. 1).

We adopted the RothCE optimized approach (Supplementary Section 1.4) for estimating soil erosion at each of the other 98 long-term plots across Australia where no ^{137}Cs measurements were available (Supplementary Section 2 and Supplementary Table 1). The RothCE model was fitted to SOC fraction data with and without soil erosion to estimate net SOC flux with and without erosion. Approximately half of the model optimizations implicated erosion (mean $= -5.55$ and s.d. $= 9.69$ t soil ha^{-1} yr^{-1}) and the remainder estimated soil erosion at 0. We summarized the results (Fig. 2) by plotting soil erosion (<0) against the net C flux difference with and without erosion (SOC erosion). The predicted magnitude of SOC erosion was strongly dependent on the intensity of soil erosion. A power function fitted best the scatter of these data ($R^2 = 0.84$, p value < 0.01) and the relation demonstrated that as soil erosion increased so too did SOC erosion but at a much reduced rate. We validated the plot scale relation by plotting (Fig. 2; red symbols) global soil erosion and SOC erosion estimates from the catchment scale[22]. That relation seemed robust to the issue of scale because those regional

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Table 1 | Estimates of soil erosion for selected long-term Waite rotation trials.

Soil erosion estimates	WF	WOF	2W4Pa	WW	Pa
Australian empirical model (t soil ha^{-1} yr^{-1})	−1.17	−1.77	−1.54	−1.27	−2.80
Mass-balance model (t soil ha^{-1} yr^{-1})	−8.90	−11.40	−12.50	−8.10	−16.80
RothC optimization (t soil ha^{-1} yr^{-1})	−3.58	−7.18	−4.54	0	−3.46
Net C flux without erosion (t C ha^{-1} yr^{-1})	0.88	1.16	1.99	0.92	3.26
Net C flux with erosion (t C ha^{-1} yr^{-1})	0.98	1.42	2.17	0.92	3.44
Net C flux difference with and without erosion (t C ha^{-1} yr^{-1})	0.10	0.26	0.18	0.00	0.18

Selected rotations: WF, wheat-fallow; WOF, wheat-oat-fallow; 2W4Pa, 2 years wheat, 4 years pasture; WW, wheat; Pa, pasture.

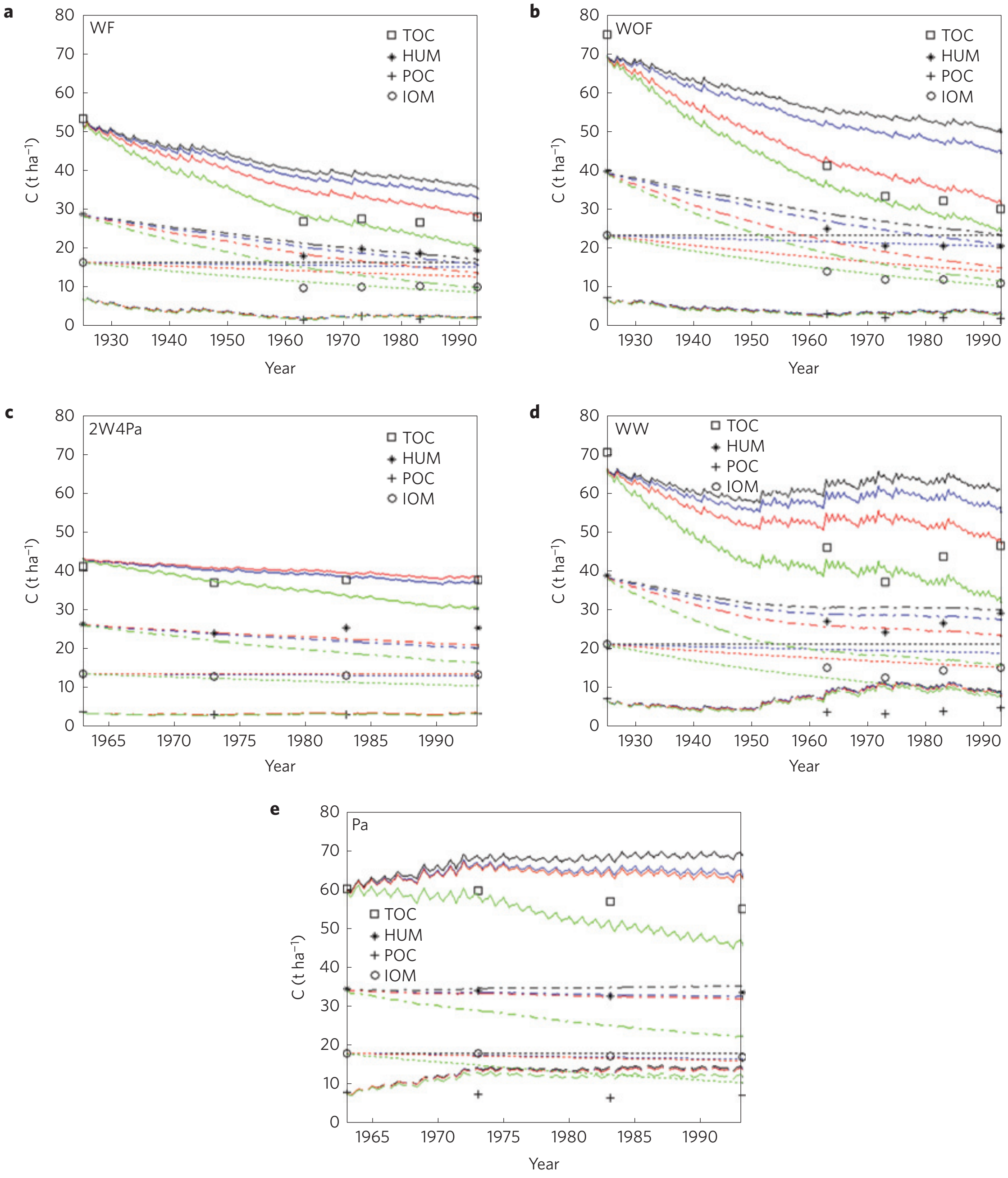

Figure 1 | Temporal variation in measured (symbols) and modelled (lines) soil organic carbon for the Waite rotation trial plots. a–e, RothCE model predictions used established decomposition rates for Australia (RPM = 0.15 yr^{-1}) without soil erosion (black line), with soil erosion estimated using the Australian empirical model (blue line) and the mass-balance model (green line) and optimized erosion estimates using the RothC model (red line). TOC, total organic carbon; HUM, humic pool; POC, particulate organic carbon; IOM, inert organic matter; RPM, resistant plant material. The rotation acronym (as defined in Table 1) is indicated in the top left corner of each plot.

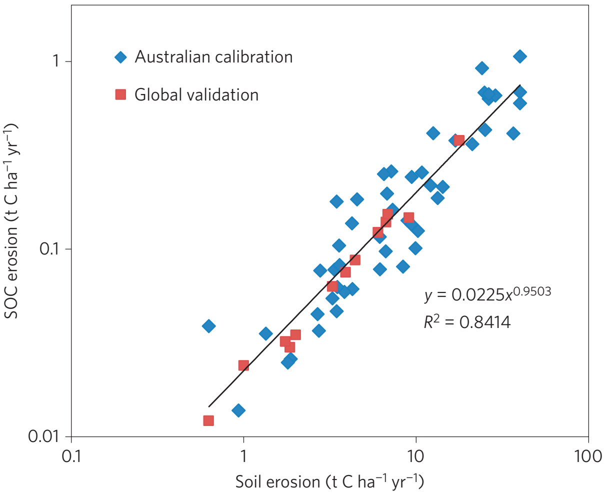

Figure 2 | Relation between soil erosion and the difference in net C flux. The model RothC was calibrated with and without soil erosion using Australian experimental (plot scale) trial data (blue diamonds). Validation data (not used to produce the model; red squares) at the catchment scale was provided from global data[22]. Both axes are in log scale.

estimates provided a relation with SOC erosion that was very similar to the relation established for the Australian plot-based estimates. We assumed that soil erosion was omitted in the models for SOC accounting, SOC sequestration and LSMs (Supplementary Section 3.1). These findings and other considerations (Supplementary Section 3.2) give confidence that the relation can be used to make estimates across Australia and other global regions.

We estimated the total SOC erosion for agricultural and rangeland Australia and found that the combined estimate omitted from the Australian terrestrial SOC budget was similar in magnitude to other included components (Supplementary Section 3.3). The Australian National Greenhouse Gas Inventory[23] estimated 4.2 Tg C yr^{-1} for cropland using FullCAM based on RothC. That C cycling model omits soil erosion and has been calibrated against data used in this study for which we have estimated approximately half of the trial plots have eroded. At those sites the national account is overestimating the SOC loss as CO_2 due to soil respiration. If we adopt the catchment-scale median net (1950s–1990) erosion for agricultural Australia (−1.5 t ha^{-1} yr^{-1}; ref. 12) and assume it was applicable to Australian cropland (approx. 26.2 × 10^6 ha) and estimated (using Fig. 2) SOC erosion at 0.033 t C ha^{-1} yr^{-1}, it provides an estimated 0.87 Tg C yr^{-1}. We reduced the estimate by assuming that 20% of the eroded SOC is mineralized and reached the atmosphere (Supplementary Section 1.5). Consequently, we estimate 0.70 Tg C yr^{-1} for total SOC erosion that has been incorrectly attributed to respiration in the Australian national account. Using estimates of catchment-scale ^{137}Cs-derived net (1950s–1990) erosion for cropland up to −4 t ha^{-1} yr^{-1} (25th percentile) suggested that estimates of total SOC erosion for Australian cropland may be up to 2.2 Tg C yr^{-1} (1.7 Tg C yr^{-1} after 20% mineralization). On this basis the Australian national inventory has overestimated the net C flux to the atmosphere as CO_2 by up to 40%.

The omission of SOC erosion in crop production models has implications for potential SOC sequestration in Australia and elsewhere. For example, simulations with APSIM (ref. 24) and extrapolations based on C measurements[25] have suggested that Australian cropland could potentially increase C stocks (0–30 cm) by about 1 Pg C (over 100 years) and would be a net sink of atmospheric carbon dioxide under conservation agricultural practices. Assuming our first approximations to the total catchment-scale C erosion for Australian cropland (up to 1.7 Tg C yr^{-1}) are applicable, over the 100 year time period up to 0.17 Pg C would be removed by soil erosion and therefore up to 17% of the potential C sink is overestimated.

We estimated the SOC erosion (Fig. 2) for all lands within the main global regions and compared the SOC erosion with estimates of terrestrial C flux made by LSMs. We assumed that the LSMs had used a SOC cycling model that had been calibrated against long-term sites that had been exposed to soil erosion. We partitioned the estimates between water erosion (Table 2) and wind erosion/dust emission (Supplementary Section 3.3 and Supplementary Table 2). The range of SOC erosion was then compared with the range of LSM estimates of terrestrial C flux (2000–2010) taken from the Global Carbon Atlas (Supplementary Section 4). The difference (%; Table 2) was calculated to provide a range of the impact of SOC erosion between the minimum SOC erosion (adjusted for mineralization; Supplementary Section 1.5) and the minimum model estimate of the terrestrial C flux and also the maximum SOC erosion (adjusted for mineralization) and the maximum model estimate of the terrestrial C flux. The differences in Table 2 were interpreted as uncertainty in net C flux.

We interpreted the global regions' net SOC loss due to water erosion and mineralization as uncertainty in the terrestrial C flux by 14–403 Tg C yr^{-1}. These regional estimates are between +35 and −82% of the long-term (2000–2010) model terrestrial C flux for these regions. The global uncertainty due to the omission of SOC erosion is 0.3–1.0 Pg C yr^{-1}, which is between −18 and −27% of the global long-term terrestrial C flux (Table 2). Up to around one-quarter of the uncertainty in global C flux could be attributed to the omission of SOC erosion with implications for recent interpretations that excluded SOC erosion about model uncertainty[3,4] and trends and variability in global ecosystems[5]. For the conterminous USA about 11 ± 1 Tg C yr^{-1} are lost through rivers to the coastal ocean[26]. It is the same order of magnitude as our estimates for North America. Our minima estimates used regional

Table 2 | Soil organic carbon (SOC) erosion and model estimates of terrestrial SOC flux for major regions of the Earth.

	Min-max* water erosion (t ha^{-1} yr^{-1})	SOC erosion (t C ha^{-1} yr^{-1})	Water eroded area (ha × 10^6)†	Total SOC erosion (Tg C yr^{-1})	SOC erosion with 20% oxidation (Tg C yr^{-1})	Terrestrial C flux (Pg C yr^{-1})‡	Difference (%)
Africa	3.7–12.9	0.08–0.26	1,000	78.0–255.6	62–204	−0.1, −1.9	62.4–10.8
Asia	4.3–16.6	0.09–0.32	1,550	138.2–503.5	111–403	−0.21, −0.49	52.6–82.2
S. America	5.7–22.1	0.12–0.43	510	59.9–217.4	48–174	−0.18, −1.82	26.6–9.6
N. America	4.4–12.3	0.09–0.24	430	39.7–105.0	32–84	−0.22, −0.85	14.4–9.9
Europe	6.7–13.4	0.14–0.27	300	41.0–79.5	33–64	−0.05, −0.45	65.5–14.1
Oceania	1.7–9.5	0.04–0.19	460	17.5–87.9	14–70	+0.04, −0.46	+35.0–15.3
Global	4.1–15.2	0.09–0.30	4,250	369.0–1,269.6	295–1,016	−1.67, −3.82	17.7–26.6

*Minima and maxima water erosion estimates for these regions[22] and sediment yield estimates[6]. †Estimates of land area affected by water and tillage erosion[22]. ‡The terrestrial flux (negative away from land) provided is the range of long-term mean (2000–2010) of the land surface models (LSMs) estimates available from the Global Carbon Atlas. The difference is the mineralized proportion of the eroded SOC relative to the minimum and maximum model estimate of the terrestrial C flux expressed as a percentage of the LSMs estimates.

soil erosion and affected land area[22]. With the exception of the region of South America our estimates of net SOC flux match closely those of previous estimates[22] including our estimate of global SOC erosion by water at 369 Tg C yr^{-1}. Consequently, we believe our estimates of the SOC erosion are reasonable and our approach robust for making estimates in global regions.

The estimates of wind erosion/dust emission are an order of magnitude smaller than those for water erosion despite C erosion being similar per hectare (Supplementary Section 3.3 and Supplementary Table 2). Between the regions soil erosion by wind is slightly smaller than that of water erosion, but land area affected by water and tillage erosion is here quantified as much larger than that affected by wind erosion. Consequently, even small SOC erosion by water produces substantial totals that amount to large proportions of the current C flux.

The inclusion of soil erosion in LSMs could create a realistic feedback between soil erosion and dynamic soil characteristics (for example, clay content, soil depth) but which are held static at present. Soil erosion removes preferentially the fine, C- and nutrient-rich fractions[27], which may change over time the soil albedo, soil temperature, soil moisture holding capacity and soil hydraulic properties. Surface lowering will most likely change the soil micro-environment, the decomposition rate and rooting depth. For example, the flux of soil could be made equivalent to a depth of soil removed. Catchment-scale global soil erosion (from Table 2; for example, $10\ t\ ha^{-1}\ yr^{-1} = 0.1\ g\ cm^{-2}\ yr^{-1}$) over the past 100 years would amount to 7 cm surface lowering (soil bulk density of $1.3\ g\ cm^{-3}$). This surface lowering would then require the LSMs to replace the soil surface (0–5 cm) characteristics with those from deeper soil layers with implications for changed hydrologic and energy budgets. To our knowledge, there are no water erosion schemes coupled to LSMs and dust emission schemes are coupled only for atmospheric radiative purposes. Implementing a realistic and dynamic feedback between soil redistribution (erosion and deposition), C cycling and dynamic soil characteristics would improve the fidelity of LSMs and global climate models with little cost to parsimony. Until soil erosion schemes are properly (dynamically) coupled to the LSMs, they could include ^{137}Cs-derived net (1950s–1990) soil redistribution maps that account for the fate of eroded soil[28]. Much work remains necessary to understand the fate of the eroded C and the role of dynamic replacement[29,30]. In the absence of global maps of net soil redistribution, those of gross soil erosion[22] could be used as a first approximation and an external variable in the LSMs. This boundary condition soil erosion layer, perhaps initially static over time, would be the only additional information necessary to drive the revised C cycle (for example, RothCE) in the LSM. Subsequently, the boundary condition soil erosion data could be considered dynamic as influenced by land use change and global soil conservation (conservation agriculture)[11,13]. Ultimately, soil erosion would be estimated intrinsically using a physical basis from available data in much the same way as wind erosion and dust emission are estimated and partially coupled to LSMs. Notably, including soil erosion in the LSMs would enable wind erosion and dust emission to be coupled fully and provide the realistic land surface feedback that would, for example, lower soil surfaces and regulate the provision of erodible sources and avoid static prescriptions. In any case, there is sufficient evidence of the global significance of SOC erosion and data sets available to encourage the development of LSMs to include SOC erosion.

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Author contributions

A.C. conceived of the project in consultation with J.B. and J.S. J.S. organized the soil samples and measurement of ^{137}Cs and A.C. calculated the estimates of soil redistribution. A.C. wrote the code in Matlab to analyse the data, performed the analyses and interpreted the results in consultation with J.B. and J.S. A.C. led the manuscript writing with contributions from J.B. and J.S.

Additional information

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Competing financial interests

The authors declare no competing financial interests.