

FATES OF ERODED SOIL ORGANIC CARBON: MISSISSIPPI BASIN CASE STUDY

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Abstract. We have developed a mass balance analysis of organic carbon (OC) across the five major river subsystems of the Mississippi (MS) Basin (an area of 3.2×10^6 km²). This largely agricultural landscape undergoes a bulk soil erosion rate of ~ 480 t·km⁻²·yr⁻¹ ($\sim 1500 \times 10^6$ t/yr, across the MS Basin), and a soil organic carbon (SOC) erosion rate of ~ 7 t·km⁻²·yr⁻¹ ($\sim 22 \times 10^6$ t/yr). Erosion translocates upland SOC to alluvial deposits, water impoundments, and the ocean. Soil erosion is generally considered to be a net source of CO₂ release to the atmosphere in global budgets. However, our results indicate that SOC erosion and relocation of soil apparently can reduce the net SOC oxidation rate of the original upland SOC while promoting net replacement of eroded SOC in upland soils that were eroded. Soil erosion at the MS Basin scale is, therefore, a net CO₂ sink rather than a source.

Key words: CO₂; erosion; Mississippi Basin; regional budget; soil fertility; soil organic carbon.

INTRODUCTION

We analyze the role of soil and soil erosion in the carbon cycle by quantitatively assessing soil erosion, translocation, redeposition, oxidation, and CO₂ sequestration across the five major river subsystems in the Mississippi Basin (Fig. 1). These were analyzed by aggregating soil composition and erosion data at the level of USGS HUC8 cataloging units (a total of 833 such units, with an average area of about 4000 km²; see Appendix). While there are environmental, agricultural, and socioeconomic reasons to study soil erosion and to minimize anthropogenic enhancement of erosion, we focus here on erosion in the context of organic carbon (OC) mass balance.

Fig. 1a shows a budgetary framework for tracking eroded soil and associated soil organic carbon (SOC) from upland soils, through various transport pathways and depositional compartments within a subsystem of the Mississippi Basin, to the eventual removal from that subsystem of some fraction of the eroded SOC via river transport. Solid arrows represent lateral relocation of soil and SOC after they are mobilized during erosion. Dotted arrows illustrate possible sites of OC oxidation (“Ox?”) and CO₂ sequestration into OC (“Seq?”). Of particular interest is the role of soil erosion in the balance between Ox and Seq as SOC moves through the system.

Quantifying global SOC and anthropogenically induced changes in SOC are conceptually simple but op-

erationally difficult. Current estimates for the mass of SOC in the upper 100 cm of soil are 1500 to 1600 Gt (metric ton = t = 1 Mg) (e.g., Bohn 1982, Eswaren et al. 1993, Jobbagy and Jackson 2000), but there are serious uncertainties in these estimates: (1) spatial variability in SOC within landscapes and mapping units (Jobbagy and Jackson 2000); (2) uncertainties about the temporal effects of land-use practices (tillage methods, cropping practices, fertilizer application rates, etc.) on in situ balances between SOC oxidation, CO₂ sequestration into SOC, erosion, and the fates of eroded and relocated SOC (Rosenzweig and Hillel 2000, Amundson 2001, Post et al. 2001, Swift 2001, Lal 2003, Liu et al. 2003, Lal et al. 2004); and (3) the inadequacy of remote sensing to meet the needs for increased accuracy.

Lal (1995, 2003, 2004) indicates that a significant portion of eroded SOC is exposed to greater oxidation rates during and after erosion. He attributes this increased oxidation largely to the breakdown of aggregates, exposing more SOC to the atmosphere and thus reducing OC of eroded soil by $\geq 20\%$. This assumption has been widely used in models of the carbon cycle, but regionally integrated evidence for erosion-associated oxidation consists primarily of the observation that little eroded C is exported to the ocean (e.g., Schlesinger 1995).

Fluvial geomorphologists recognize that there can be a long (millennial) delay between upland erosion of bulk materials and discharge of those materials from large river basins to the ocean (e.g., Meade et al. 1990, Dearing and Jones 2003). Even at scales of smaller

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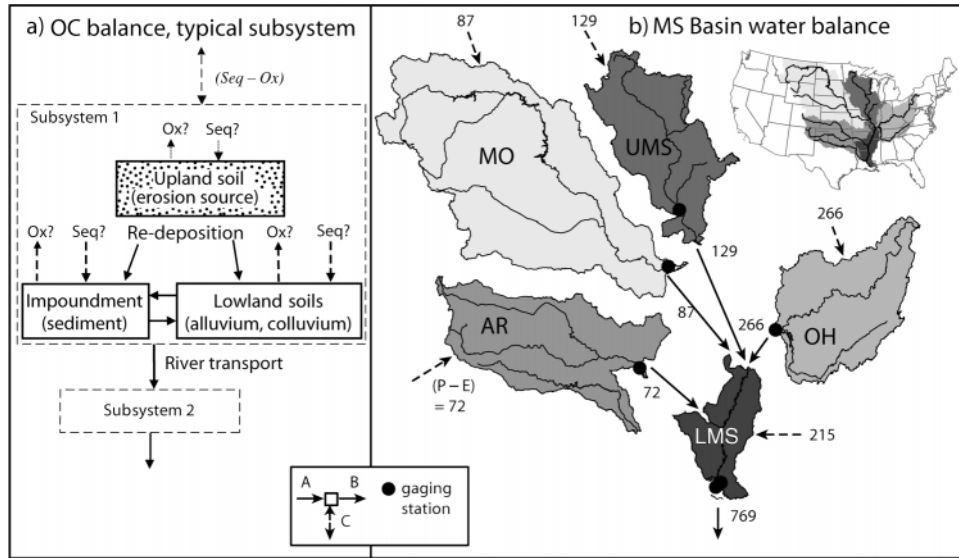


FIG. 1. (a) Conceptual diagram illustrating upland soils as erosional sources delivering materials to alluvial soils, water body sediments, and river transport. Oxidation (Ox?) and CO₂ sequestration (Seq?) can accompany each step in the erosion, transportation, and deposition sequence. (b) Location map showing the five major subsystems of the Mississippi Basin, and an “exploded map” that illustrates fluxes within and between the subsystems. Arrows and associated numbers show the water budget from lines A1, B1, and C1 of Fig. 1c; the LMS influx is the sum of the efflux from the other subbasins. River gaging stations (Appendix Table A1) are shown as black circles on the exploded map. (c) Budgets of water, bulk sediment, and organic carbon (OC) fluxes within and between the subsystems. Direct estimates of inputs, outputs, and mobilization or retention within the subsystems are based on independently available estimates. Inferred values are fluxes that are required to close the budgets: for water, river fluxes between the subsystems must be balanced by (P - E); for sediments, the difference between sediment erosion and river flux is assumed to be retained (re-deposited) within the subsystem. The OC contents of eroded soil, deposited sediment, and river fluxes are all known, so the net of (Seq - Ox) is required to balance the organic carbon budget within each subsystem. Water fluxes are in 10⁹ m³/yr; sediment and OC fluxes are in 10⁶ t/yr. Entries in part C of the table are italicized to emphasize that they are inferred to balance the budget, rather than being directly estimated.

individual catchments, this delay can be considerable (e.g., Trimble 1983, Church and Slaymaker 1989, Phillips 1991). The OC fraction of bulk erosion products would experience a similar delay. Raymond and Bauer (2001) estimated that OC transported in American rivers varies in age between about 700 and 5000 years.

It should be noted, however, that the OC age range reflects the combination of the age of OC reaching the rivers and the time for that OC to be transported through the river systems.

The extent to which increased SOC oxidation occurs as a direct result of erosion has not been reliably quan-

TABLE 1. Characteristics of the MS Basin and its subsystems.

Subsystem	Area (10 ⁶ km ²)	Mean elevation (m)	(Maximum – minimum) elevation (m)	Mean annual temperature (°C)	Mean annual precipitation (cm)	Cropland (%)
AR	0.642	706	4246	13.7	81	38
MO	1.350†	999	4158	7.6	53	41
UMS	0.492	298	536	8.2	86	65
OH	0.528	345	1890	11.9	119	38
LMS	0.210	81	751	16.7	140	47
MS Basin	3.222	664	4282	10.2	81	44

Notes: Abbreviations used are AR, Arkansas–Red; MO, Missouri; UMS, upper Mississippi; OH, Ohio–Tennessee; LMS, lower Mississippi; MS, Mississippi.

† Includes ~30 000 km² in Canada.

tified. A study of CO₂ fluxes from soils in Ohio showed the highest SOC contents in depositional-phase soils, and no statistically significant differences in CO₂ fluxes between soils in depositional phases and those characterized as in severe, moderate, or slight erosion phases (Bajracharya et al. 2000). Pedologists and soil geomorphologists have recognized that soils in depositional slope positions (toe slopes, floodplains, etc.) generally have higher SOC contents than soils in erosional slope positions (sloping summit, shoulder, backslope, etc.) (Kleiss 1970, Martel and Paul 1974, Aguilar and Heil 1988), although variations have been noted (Yonker et al. 1988, Brubaker et al. 1993). The spatial pattern of higher SOC contents in depositional slope positions is probably some function of the deposition of organic-rich topsoil, with higher moisture contents supporting more lush vegetation (i.e., greater biomass inputs), and the fact that soils above some optimum moisture content have diminished oxidation rates (Liu et al. 2003).

SOC can accumulate photosynthetically back into the soil profile after erosion. Modeling studies by Stallard (1998), Harden et al. (1999), and Liu et al. (2003) have pointed out the potential importance of “dynamic replacement” of SOC in eroded soil profiles. Van Oost et al. (2004) observed that erosion and subsequent dynamic replacement can lead to net CO₂ sequestration rates of the same magnitude as no-till agriculture, an increasingly used conservation practice in the United States and elsewhere (e.g., Uri 2001).

This paper is an examination, at a regional scale, of the fates of SOC from upland soil erosion through re-deposition or river export. Erosion moves bulk soil and SOC from one location to another. We account for the translocated bulk materials in order to determine how much the OC content of the bulk soil changes as it is relocated. This permits estimation of, or inference about, organic matter (OM) oxidation and production rates and how they are likely to affect C cycling at regional and global scales.

STUDY REGION

We have extended our original sediment and OC budgets for the conterminous United States (Smith et al.

2001) to a more detailed mass balance analysis for five major river subsystems that together comprise the 3.2 × 10⁶ km² Mississippi (MS) Basin (Fig. 1b). The subsystems are approximately equal to USGS Water Resources Hydrological (HUC2) Units 05–06 (Ohio, Tennessee: OH), 07 (Upper MS: UMS), 10 (Missouri: MO), 11 (Arkansas, Red: AR), and 08 (lower MS: LMS) (see Appendix).

The MS Basin constitutes ~40% of the conterminous United States and spans a wide range of physiographic and climatic conditions. Regional catchment relief (maximum–minimum elevation) and area are considered to be primary variables controlling river sediment yield (Milliman and Syvitski 1992, Syvitski and Moorehead 1999). Jenny (1941) and subsequent authors (summary in Amundson 2001) have recognized the importance of mean annual temperature and precipitation as regional factors influencing the spatial distribution of SOC. Because of their potential importance in bulk soil erosion, sediment yield, and SOC distribution, these physiographic and climatic variables are summarized in Table 1 (see details in Appendix).

Soils within the MS Basin provide a reasonable cross section of soil orders found within temperate latitudes. Mollisols and Alfisols are the dominant soil orders, especially within the Great Plains and Midwest; however, significant areas of Ultisols, Entisols, Inceptisols, Histosols, Vertisols, Aridisols, and Spodosols are present within the MS Basin (Soil Survey Staff 1999).

The MS Basin accounts for 70% of U.S. cropland. About 60% of the cattle and 90% of the hogs in the United States are found in the basin. The combination of agricultural, physiographic, and climatic variables are ideal for examining the OC budget of this large agricultural region, and its size and diversity make it likely that conclusions about the MS Basin are applicable elsewhere.

The hydrology of the MS Basin is conveniently considered in terms of a simple “plumbing diagram” that treats the subsystems as storage compartments (Fig. 1b). Landscape processes occur within each compartment (Fig. 1a), and river flow is the common drain that transfers materials from the subsystems and eventually to the ocean. The Missouri (MO) converges with the

upper MS (UMS) near St. Louis, Missouri. The Ohio–Tennessee (OH) and the UMS converge about 200 km southeast of St. Louis; below that point the MS is identified as the lower MS (LMS). The Arkansas and the Red River systems flow separately into the western side of the LMS subsystem about 400 and 700 km south, respectively, of the OH inflow. Because data are scanty for the Red River system (the smaller of these two), these have been aggregated into a single subsystem (AR).

MATERIALS AND METHODS

This section summarizes the materials and methods used in our analyses. More detailed descriptions are given in the Appendix.

River-borne fluxes

River fluxes of water, total suspended sediment (TSS), and dissolved and particulate OC (DOC, POC) at the gaging stations shown on Fig. 1b were calculated and scaled to the total subsystem areas.

Erosion

The methodology for erosion estimation is discussed in Smith et al. (2001) and in the Appendix. Data are aggregated at the scale of the USGS 8-digit hydrologic mapping units. There are 833 HUC8 units across the MS Basin (after removal of ones that are water or local drainages near the mouth of the MS River). The average size of the remaining HUC8s is ~ 4000 km².

In the present mass balance analysis, water, bulk sediment, and OC budgets are linked. River flow through the system establishes the excess of precipitation over evaporation ($P - E$). Independent estimates of ($P - E$) are used to validate the water budget. Bulk soil is detached and transported by slope erosion processes. Some of this detached soil reaches channels through which it is transported as suspended sediment into larger perennial streams. We assume that the remainder is redeposited somewhere within the subsystem of origin. In Smith et al. (2001) we established that depositional sites within the system (large and small water impoundments, alluvial sediments, etc.) readily have the capacity to receive the estimated amount of eroded soil, without the need to constrain the budget with a very uncertain (statistically noisy) direct estimate of redeposition from impoundment sedimentation rates. We follow that same approach here.

OC from eroded soil also moves through the stream network. OC that does not exit each subsystem via rivers either locally accumulates in depositional sites or might be oxidized. The percent OC relative to bulk materials in the eroding soils, in alluvial and impoundment depositional sites, and in river transport is estimated, so that OC fluxes can be scaled to bulk sediment fluxes. Scaling the OC mass to bulk sediment mass leaves a residual amount of OC required to balance the OC budget. This residual is attributed to the difference

between oxidation and sequestration processes linking SOC to atmospheric CO₂ (Fig. 1a).

Organic carbon

We assess OC fluxes within the storage compartments on the basis of information available in the scientific literature. Conservation of mass established in the budget analysis allows us to evaluate how soil erosion and translocation (lateral transfers) have apparently affected the net vertical flux of C between OC and the atmosphere. We analyzed SOC using the State Soil Geographic Database (STATSGO; U.S. Department of Agriculture 1994). Average organic carbon (OCA) is the average SOC percentage in surface soil horizons, calculated from ranges of organic matter (OM) within each of $\sim 33\,000$ STATSGO map units (see Appendix).

In order to compare SOC in erosional and depositional soils and estimate the geographic extent of these areas, we identified those soil units in the STATSGO database that could be considered “floodplain” soils, as representative of alluvium. STATSGO does not contain an attribute that directly differentiates between upland and floodplain soils, so we used inundation frequency for this purpose (see Appendix). We assume that upland soils are the sources and that a combination of the floodplain and low terrace soils and water impoundments are depositional areas for eroded SOC. This is an oversimplification, because there will be local depositional areas within the upland soils and erosional areas within the soils designated as floodplains. However, at the regional scale, we feel it is reasonable to think of upland soils as source areas and floodplain and low terrace soils as dominantly depositional. For subsequent comparisons, the data for upland and floodplain SOC were aggregated back to HUC8, and then to subsystem average values.

RESULTS

Soils across the Mississippi Basin

Fig. 2 shows the spatial distribution of STATSGO map units that we classified as upland and floodplain soils (including low terraces that flood) across the MS Basin, and illustrates the OCA of these soils. STATSGO data are designed for regional analysis, so the map underestimates the area of alluvial deposits in smaller stream systems. Nevertheless, the analysis is useful for comparison between upland soils and larger floodplain features, and underestimation of area should be small in comparison to the area of large floodplain deposits.

At this scale and resolution, floodplain soils represent $\sim 8\%$ of the total basin area, but both soils and organic carbon are heterogeneously distributed. Floodplain soils occupy $>50\%$ of the LMS area, $<1\%$ of the AR, and $\sim 5\%$ of the other subsystems. Both the northern reaches of the UMS and the lower portion of the MS delta have soils with OCA $>4\%$. No other region-

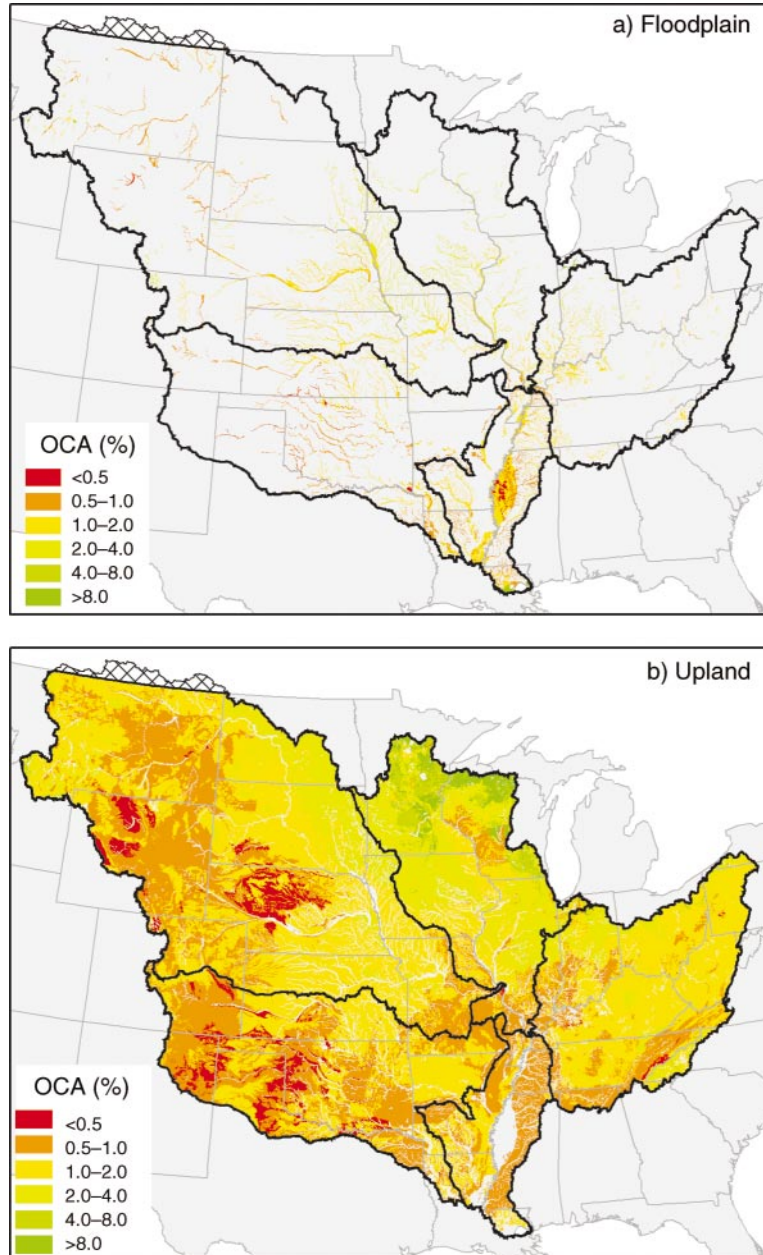


FIG. 2. Average soil organic carbon (OCA) for (a) upland and (b) floodplain soils across the Mississippi Basin, as derived from STATSGO.

ally significant area exceeds 4%, even though individual map units throughout the area show OCA >4% when viewed in detail. Widespread areas have OCA <1%, and the average for the entire Basin is 1.5%.

Because STATSGO is based on modern soil surveys (generally conducted since 1960), properties in its database reflect anthropogenically induced changes in the erosional and depositional phases of map units delineated during this time period. The data used to assign values for properties such as OM have also been affected by land use. That is, the properties in the STATSGO

database are primarily a function of long-term regional factors (climate, organisms, relief, time), with an overprint of recent (~150 yr) influences by land use.

Floodplain soils would have OCA similar to upland soils from which they were derived if erosion were conservative with respect to SOC. A negative or positive difference between floodplain and upland OCA would indicate the difference between oxidation and sequestration. Floodplain and upland OCA, respectively, at the HUC8 aggregation are 1.52 ± 0.06 and

$1.53 \pm 0.04\%$ (mean \pm SE; see details in Appendix; floodplain OCA/upland OCA = 0.99 ± 0.07). These percentages do not differ significantly at the 95% CL (t test). We conclude that upland and associated floodplain soils are indistinguishable with respect to OCA, at the scale of the HUC8s and as an average across the basin.

Erosion of bulk soil and carbon

In our earlier publication on the fates of eroded materials in the conterminous United States (Smith et al. 2001), we included both wind and water erosion. In the present analysis we exclude wind erosion. Much of the wind-eroded material is apparently redeposited relatively close to its source, and only a small proportion of it appears to leave the continent. Because this redeposition represents dispersal across the landscape, rather than accumulation into localized deposits, it becomes a part of the soil surface. Its subsequent erosion by water would be accounted for in the Universal Soil Loss Equation (USLE) estimates for sheet and rill erosion. Water erosion rates for bulk soil and SOC across the MS Basin are summarized by HUC8 in Fig. 3, and the average ratio of SOC erosion to bulk erosion by subsystem is in Table 2.

Fates of eroded material

We next discuss lateral translocations of erosion products in terms of river efflux from the subsystems and within-system deposition in impoundments and alluvium.

River efflux.—Table 3 summarizes river efflux and composition for the five subsystems. Effluxes from the upper subsystems represent erosional influxes entering the rivers within those subsystems, while effluxes from the LMS include both influxes from upstream and erosional influxes originating within the LMS. Flow-weighted average concentrations for the gaging stations are listed in Table 3. Although the MO is by far the largest subsystem by area, all subsystems other than the AR have higher river discharges. Even the AR has a higher discharge per unit area. The MO has by far the highest total suspended solids (TSS) concentration, has a higher fraction of its total organic carbon (TOC) as particulate organic carbon (POC) than as dissolved organic carbon (DOC), and has the lowest TOC/TSS ratio. A comparison of Tables 2 and 3 demonstrates that the MO has a TOC/TSS export ratio fairly close to the SOC erosion/total erosion ratio, while the other subsystems have TOC/TSS export ratios substantially exceeding the erosion ratios.

Deposition in water impoundments.—As previously discussed (Smith et al. 2001, 2002; Renwick et al. 2005, *in press*), water impoundments cover only $\sim 2\%$ of the landscape area, yet their deposition accounts for $\geq 50\%$ of bulk erosion products. A surprising conclusion is that small artificial water bodies (primarily farm ponds) occupying only one-fifth of total impoundment

area may account for 25–50% of total impoundment deposition. Even though small impoundments cover a much smaller area, they have much higher deposition rates than the larger water bodies (see also Renwick 1996, 2005). Ritchie (1989) showed that sediments in 58 impoundments across the United States have about the same OC content as the upland soils from which they were derived (impoundment OC/SOC = 0.92 ± 0.22).

Alluvial deposition.—We estimated that floodplain soils cover $\sim 8\%$ of the area of the MS Basin, and that these soils have essentially the same OCA as their upland counterparts. We have no way to evaluate typical alluvial deposition rate in any regionally comprehensive manner, but we assume that alluvial deposition per unit area is substantially higher than in situ soil formation rates (e.g., Schlesinger 1990).

Depositional sites, represented here by impoundments ($\sim 2\%$ of the land surface area) and alluvial systems (approximated as floodplain soils; 8% of the area) thus represent $\sim 10\%$ of the land surface area and have essentially the same OCA values as the remainder of the area—the erosional sites.

DISCUSSION

Water budget

Total river discharge from the basin is estimated to be 769×10^9 m³/yr (Fig. 1c). Discharges for each subsystem represent precipitation minus evapotranspiration ($P - E$) that occurs within the region in order to balance the river discharges. Thus $P - E$ is shown on the budget sheet as an inferred flux (Fig. 1c). The total discharge from the basin is equivalent to an area-normalized discharge of 23.8 cm/yr. This is close to the long-term discharge (22.2 cm/yr) estimated by Ropelewski and Yarosh (1998) for the “Central United States” (a region roughly equivalent, although not identical, to the MS Basin).

Bulk sediment budget

Eroded materials move laterally until they are redeposited. The redeposition can occur within the boundaries of the subsystem or beyond those boundaries. The major medium for material transport is water, so the river gaging station near the downstream boundary of each subsystem is the monitoring point for transport beyond the boundaries of that subsystem. Fig. 1c incorporates erosion data (from Fig. 3a) and river flux of suspended material (from Table 3) into a bulk sediment budget, with inferred fluxes for the redeposition of erosion products that occur within each subsystem balancing erosion and river efflux. Our estimate for sediment discharge from the MS Basin (161×10^6 t/yr) is within 4% of the estimate of 167×10^6 t/yr by Turner and Rabalais (2004).

Erosion across the entire basin totals 1523×10^6 t/yr, while sediment discharge is only 161×10^6 t/yr.

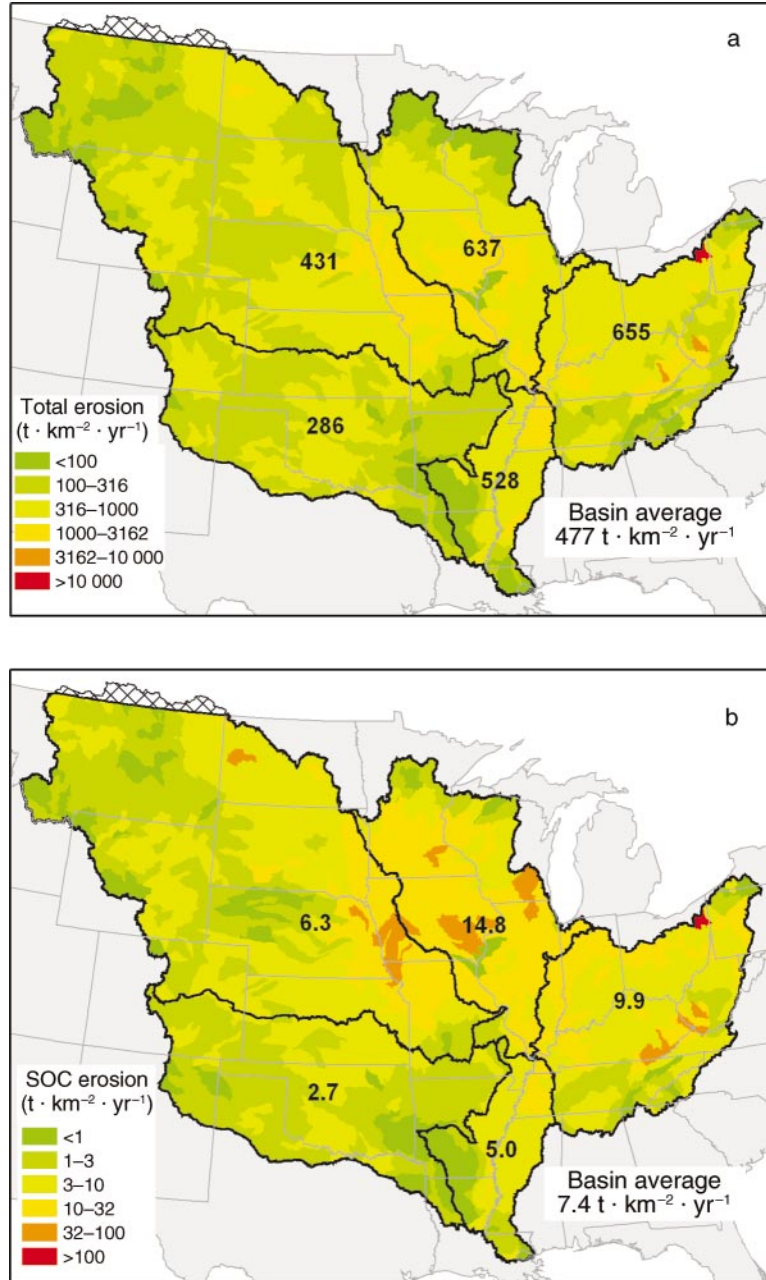


FIG. 3. Water erosion of (a) bulk soil and (b) soil organic carbon across the Mississippi Basin, by HUC8.

TABLE 2. Ratio of soil organic carbon (SOC) erosion by water to total erosion by water, for each subsystem, as averaged from the HUC8s for that subsystem.

Subsystem	SOC erosion/total erosion
AR	0.0093
MO	0.0147
UMS	0.0233
OH	0.0150
LMS	0.0095
MS Basin	0.0155

Notes: Abbreviations used are as in Table 1.

Thus ~90% of the erosion products must be redeposited within the basin, rather than exported. The retention within the various subsystems lies between 86 and 96%, consistent with the observations that water impoundments and local alluvial deposits are efficient in trapping erosion products in the short term, substantially slowing their downstream translocation on longer time scales (Meade et al. 1990). Processes such as gullying and stream bank erosion contribute significantly to total erosion locally and to an unknown amount at a regional scale. Therefore the discrepancy between

TABLE 3. Subsystem river water efflux and flow-averaged concentrations, based on data from the gaging stations listed in Appendix Table A1 and illustrated in Fig. 1b.

Subsystem	Water ($10^9 \text{ m}^3/\text{yr}$)	Total suspended solids, TSS (g/m^3)	Dissolved organic carbon, DOC (g/m^3)	Particulate organic carbon, POC (g/m^3)	Total organic carbon, TOC (g/m^3)	POC/TOC	TOC/TSS
AR	72	111	4.5	1.2	5.7	0.21	0.051
MO	87	905	4.8	5.6	10.4	0.54	0.012
UMS	129	199	6.0	3.0	9.0	0.33	0.045
OH	266	127	4.3	2.1	6.4	0.33	0.050
LMS	769	210	4.0	2.0	6.0	0.33	0.029

Notes: Flux values are adjusted from the gaged area to total system areas. Data for the two LMS stations were combined. Abbreviations used are as in Table 1.

erosion and discharge, and consequently the redeposition within the subsystems, is larger than we have estimated. The observation that most bulk erosion products remain within their subsystem of origin is important to our analysis.

Organic carbon budget

SOC is also detached and relocated by erosion. Some fraction of the eroded SOC redeposits with the bulk sediment. SOC can also be modified by two additional processes: oxidation of old OC or sequestration of CO_2 into new OC. The terms "Ox?" and "Seq?" on Fig. 1a illustrate where these processes might occur.

Fig. 1c summarizes the OC budget. The erosion and river flux data constrain mobilization of SOC and OC export from the subsystems. The sediment budget itself provides an additional part of the OC budget. We have estimated the bulk sediment deposition within each subsystem, and we have demonstrated that the various depositional sites all have about the same proportion of OC as their respective upland soils. Therefore, within each subsystem, we use the SOC/total erosion ratio (Table 2) and the bulk sediment redeposition (Fig. 1c) to estimate OC redeposition. These are direct calculations, rather than values inferred to close the budget.

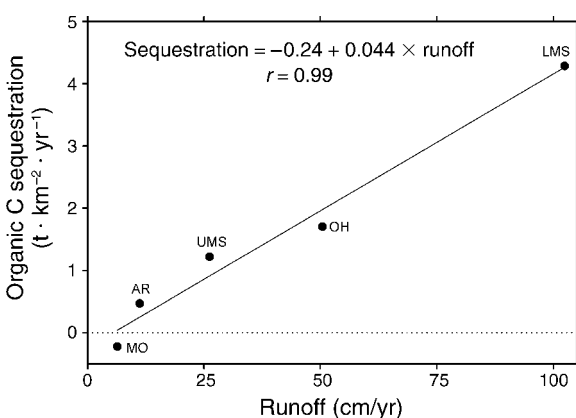


FIG. 4. Model II regression between precipitation minus evaporation (scaled to subsystem area) vs. a similar scaling of net C sequestration, from Fig. 1c, for the different subsystems.

SOC erosion totals $\sim 23.7 \times 10^6 \text{ t/yr}$ ($\sim 1.5\%$ of bulk soil erosion). About 90% of the eroded SOC is redeposited within the basin (subsystem range = 86–100%). However, export of OC from the entire basin is equivalent to $\sim 20\%$ of SOC erosion, in contrast to 10% for total sediment export as a fraction of bulk soil erosion. Turner and Rabalais (2004) report OC export from the MS Basin to be $4.5 \times 10^6 \text{ t/yr}$, 7% lower than our estimate of $4.8 \times 10^6 \text{ t/yr}$. It is important to note that, as observed for bulk sediment, relatively little of the eroded SOC is exported in the rivers. However, the OC fraction, relative to erosion, exported by rivers is larger than the exported bulk soil fraction.

The OC budget, like the water and bulk sediment budgets, has an inferred balancing term for each subsystem (Fig. 1c). This balancing term is the net of OC sequestration minus oxidation (Seq – Ox), exchanging with the subsystem boundary on Fig. 1a. Except for the MO, all of these fluxes are positive with respect to the subsystems, implying that the subsystems internally gain OC in order to balance the budget (total net sequestration = $2.4 \times 10^6 \text{ t/yr}$).

As stated earlier, there is no significant difference in the OC content of upland soils and depositional sites within the subsystems, and the river export of OC in proportion to total sediments is higher than the erosion ratio (contrast Tables 2 and 3). Because of the export imbalance, net sequestration is required in order to maintain the observed equivalence of OC in erosional source areas and depositional sites within the subsystems. This calculation does not identify where, within each subsystem, the net sequestration occurs.

When this estimated sequestration rate is scaled to area and plotted against runoff (Fig. 4), there is a strong correlation between these variables ($r = 0.99$). The observation that runoff is an apparent indicator of C sequestration in the soils (e.g., Liu 2003) is a direct consequence of the budgets; beyond closing the budgets as we have done, there is no assumption that forced this result. We interpret the net sequestration as a regional budgetary estimate of dynamic replacement (see Stallard 1998, Harden et al. 1999, Liu et al. 2003), with subsystem means between -0.2 and $4.3 \text{ t} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$ and a basin mean for C of $0.7 \text{ t} \cdot \text{km}^{-2} \cdot \text{yr}^{-1}$. These regional-

scale replacement rates are low in comparison with modeled field-scale rates for C (tens of $\text{t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$; e.g., Liu et al. 2003); this will vary based on erosion rates, climatic variability, and land use. Precipitation and soil moisture have a strong impact on SOC formation (e.g., Jenny 1941), so sequestration is likely to be limited by precipitation. The large, dry MO subsystem, with a sequestration rate <0 , dominates the regional value. The wet OH and LMS subsystems have sequestration rates of ~ 2 and $4 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$, respectively.

Uncertainties in the bulk sediment and organic carbon budgets

The largest obstacle to providing a formal uncertainty analysis of the MS Basin sediment and OC budgets is an uncertain absolute value for erosion. Erosion estimates are based on a large database, so the precision standard error of the estimates can be assumed to be near 0 (Smith et al. 2001). However, the rates are model-based estimates with inherent biases and do not include erosional processes such as gully and river-bank erosion. Thus the uncertainty in accuracy cannot be formally evaluated regionally. By scaling OC erosion and deposition to bulk soil erosion and deposition, the accuracy uncertainties in bulk erosion and deposition are used to normalize the same uncertainties for OC. From Fig. 1c, redeposition accounts for $\sim 90\%$ of bulk sediment erosion, and river export accounts for 10%, closely in line with estimates and expectations discussed by Meade et al. (1990).

Estimated OC:bulk sediment ratios for eroded soil, redeposited sediments, and river efflux are 0.015, 0.015, and 0.030, respectively, based on the OC composition of eroded soil, and on compositional comparisons between upland soils and reservoir sediments, upland and floodplain soil composition, and river fluxes. We estimate that the errors on these composition ratios are $<10\%$, regardless of uncertainties on the fluxes. Most eroded soil redeposited within the basin has an OC content close to the OCA of the upland soil from which it was derived, while the OC:sediment export ratio is about twice the OCA of the eroded soil. This is based on the assumption that floodplain soils and impoundment sediments are derived from eroded upland soils within the same HUC8 or impoundment catchment.

Rates of oxidation in flooded or alluvial environments

The budget as constructed does not address the question of whether the translocated soil, once redeposited, reacts differently than it did in its original state as uneroded upland soil. For this evaluation we turn to the scientific literature.

Primary production occurs in lakes and other freshwater bodies, and various authors have considered the role of this production as a possible sink for atmospheric CO_2 (Mulholland and Elwood 1982, Ritchie

1989, Dean and Gorham 1998, Stallard 1998). However, any net sink or source would be represented by the difference between primary production and respiration, not by primary production alone. Recent considerations have addressed the possibility that the net characteristic of freshwater bodies might be CO_2 release rather than uptake (Cole et al. 1994, St. Louis et al. 2000). St. Louis et al. (2000) stated that the net C release rate from temperate water impoundments is about $140 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$. Their “temperate sites” are largely in Wisconsin and British Columbia. These authors reported higher fluxes for tropical sites ($\sim 350 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$). We suspect that many of the MS Basin impoundments experience a release rate that is higher than the higher latitude sites of that study, so we use an intermediate value of $250 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ for net CO_2 emissions from water bodies in the MS Basin.

Richey et al. (2002) estimated CO_2 emission rates for the rivers and wetlands of the Amazon basin to be about $120 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$, and Cole and Caraco (2001) estimated emissions from the Hudson river system as $\sim 200 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$. These are the closest we have found to estimates for emission from alluvial areas and rivers. These rates for one large tropical river system (including wetlands and river) and one moderately large temperate river system are in the lower part of the range of estimated emission rates for impoundments. Because these data are both limited and within the scatter of impoundment rates, we assign a nominal net CO_2 emission rate of $<250 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ to all depositional sites (alluvial soils and impoundments).

Water bodies and alluvial soils are clearly CO_2 sources, but these sources must be compared to the locations from which the decomposing OC came. In the absence of SOC erosion, primary production minus respiration in impoundments should equal or exceed 0, so the material driving net OC decomposition must come from a terrestrial source, ultimately erosion. The question relevant to this study is neither “Are the depositional sites CO_2 sources or not?” nor “Is there oxidation of soil organic carbon deposited in sediment in water bodies and alluvial deposits?” but rather “How does the CO_2 flux of depositional sites compare with the flux for the same material before it was displaced from upland soils into the depositional sites?”

Global soil respiration totals $\sim 60\text{--}70 \times 10^9 \text{ t/yr}$ (Raich and Schlesinger 1992, Schimel 1995). This respiration is in approximate balance with terrestrial primary production. If this respiration primarily occurs over an area of about $100 \times 10^6 \text{ km}^2$ (that is, about two-thirds of the global land area, leaving out polar regions and extreme deserts), it is equivalent to an average respiration of $\sim 650 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$. Using the equations of Raich and Schlesinger (1992), the estimated flux derived for the average conditions in the subsystems of the MS Basin (Table 1) is $\sim 500 \pm 40 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$, a value within $\sim 25\%$ of the global average and twice the estimated emission rate per unit area for

depositional sites. Both the upland soil respiration rate and net respiration in depositional sites can be considered background rates that have been perturbed by some unknown extent by accelerated erosion. Because SOC erosion ($\sim 7 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ across the MS Basin) is equivalent to $<4\%$ /yr of upland soil respiration, we assume that this perturbation of background respiration is also small.

Alluvial soils and freshwater impoundments across the MS Basin cover $\sim 10\%$ of the terrestrial area, so net oxidation of OC derived from upland soil erosion and delivered to these depositional sites is estimated to account for $10\% \times (<250/500)$, or $<5\%$ of the oxidation rate that this same material would have undergone as upland soils. This regionally integrated rate of oxidation in depositional sites is dominated by the differences in total area between upland soils and depositional sites, with probable differences in emission rates per unit area being of secondary importance. Assigning the small loss of upland SOC to export and redeposition vs. elevated in situ oxidation would be difficult to isolate experimentally. Our interpretation of export to depositional sites and consequent diminution of oxidation is consistent, however, with process-based arguments and models based on the effects of water content on SOC oxidation (Rice 2002, Liu et al. 2003, Hanson et al. 2004).

From Fig. 1c, it can be seen that an amount of OC equivalent to $\sim 90\%$ of the SOC eroded across the MS Basin is subsequently redeposited within the basin ($\sim 21 \times 10^6 \text{ t/yr}$, out of a total erosion of $\sim 24 \times 10^6 \text{ t/yr}$). The deposition sites include alluvium and freshwater bodies; colluvial deposition is of unknown importance but assumed to behave similarly to these other depositional modes. The eroded organic matter was part of the SOC, which was respiring at an average rate of about $500 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$. The combined effect of moving the material from the landscape as a whole to much smaller depositional areas in which respiration per unit area is somewhat diminished results in a substantially decreased total decomposition rate. This is also consistent with the discussion by Liu et al. (2003), of widespread vs. concentrated deposition scenarios. Our analysis suggests that, integrated across the landscape, eroded material is respiring at a rate $<5\%$ of the oxidation rate that this same material would have experienced as upland soil, so this erosion and redeposition causes an effective net sink of $\sim 21 \times 10^6 \text{ t/yr}$ ($7 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$). This “passive” depositional sink for $\text{CO}_2\text{-C}$ is in addition to the active net CO_2 sequestration sink (or dynamic replacement) of $2 \times 10^6 \text{ t/yr}$ ($0.6 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$) inferred to balance OC erosion and translocation (net sequestration, or dynamic replacement; Figs. 1c, 4).

CONCLUSIONS

Agriculturally induced soil erosion in the MS Basin accelerates soil degradation by removal of OM from

upland soils (occupying 90% of the landscape) and relocation to depositional sites (10%), rather than by net loss of OM to oxidation. The “spatial appearance” of relocating SOC from the landscape as a whole to a dramatically smaller area is a lower value for area-averaged SOC. The total mass of OC across the landscape remains approximately constant; the redistributed OC has a lower spatially integrated oxidation rate; and the areas with erosionally diminished SOC are sites of OC regrowth. The OC erosion and relocation are significant agricultural issues because they lower the area and fertility of arable lands, but diminished fertility of arable lands does not, per se, constitute a net loss of SOC from the global soil bank to atmospheric CO_2 . In addition, of course, there is a net OC river export in excess of bulk sediment export.

The conventional view of the C-cycle consequences of soil erosion is that at least 20% of the eroded SOC is oxidized (Lal 2003). This widely used but poorly supported assumption would predict that the MS Basin soil erosion (with a basin average SOC erosion rate of $7.4 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ across the $3.6 \times 10^6 \text{ km}^2$ of the MS Basin) results in a loss of at least $1.5 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ of OC to atmospheric CO_2 . Instead, our budgetary calculations show that four of the five subsystems apparently exhibit a net sequestration of CO_2 into OC, with an overall total of about $7 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$. This amounts to a net difference of $>8 \text{ t}\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$, with respect to CO_2 release vs. sequestration between the “ $>20\%$ oxidation” conceptual model for OC loss and the budgetary evidence for both slowed oxidation and uptake of CO_2 into SOC. In short, for the region studied, soil erosion results in or contributes to a net sink for atmospheric CO_2 , not a net source.

If this conclusion holds for other regions, it has major implications for balancing the global C budget. We have previously suggested (Smith et al. 2001, Renwick et al. 2004) that eroded SOC undergoes little oxidation, and that the apparently incorrect assumption that it does oxidize represents a fallacious source that could account for up to about 1 Gt/yr of the “missing sink” for atmospheric CO_2 globally. The present results not only confirm this earlier estimate but also increase the estimated size of the sink by finding evidence for net uptake rather than simply reduced emission. Data from other environments are needed to scale up this study of the MS Basin quantitatively, but based on the original estimates of Smith et al. (2001), we now suggest that our initially estimated sink strength is likely to be low.

We believe this is a realistic regional appraisal of a temperate climate region that has been the site of intense agricultural activity for more than 100 years. Over most of this period, the land use has represented “modern agricultural practices” for the time. This analysis, like others (e.g., Stallard 1998, Liu et al. 2003), suggests the need for reconsideration of the role of soil OC erosion and redeposition in global carbon

budgets. The budgetary approach used here can be used both in other regions of the globe and in more detailed (local) analysis within regions to provide an objective assessment of the fates of eroded SOC.

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APPENDIX

Details of materials and methods used are available in ESA's Electronic Data Archive: *Ecological Archives* A015-057-A1.