GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 15, NO. 3, PAGES 697-707, SEPTEMBER 2001

Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States

S. V. Smith[1], W. H. Renwick[2], R. W. Buddemeier[3], and C. J. Crossland[4]

Abstract. The fate of soil organic matter during erosion and sedimentation has been difficult to assess because of the large size and complex turnover characteristics of the soil carbon reservoir. It has been assumed that most of the carbon released during erosion is lost to oxidation. Budgets of bulk soil and soil organic carbon erosion and deposition suggest that the primary fates of eroded soil carbon across the conterminous United States are trapping in impoundments and other redeposition. The total amount of soil carbon eroded and redeposited across the United States is ~0.04 Gt yr^{-1}. Applying this revision to the U. S. carbon budget by *Houghton et al.* [1999] raises their net sequestration estimate by 20–47 %. If comparable rates of erosion and redeposition occur globally, net carbon sequestration would be ~1 Gt yr^{-1}.

1. Introduction

One of the most persistent questions in global carbon cycle research concerns the so-called "missing sink" for carbon dioxide. Global carbon budget models and inventories suggest that between ~0.5 and 2 Gt carbon yr^{-1}, not otherwise counted in increasingly more comprehensive inventories, is being sequestered somewhere in the Earth system, probably on land [e.g., *Tans et al.*, 1990]. The sequestration is thought to occur primarily in northern temperate latitudes [*Melillo et al.*, 1996], and attention has focused on forest biomass [*Schimel*, 1995; *Houghton et al.*, 1999]. However, the actual sequestration reservoir remains unidentified and controversial [*Schindler*, 1999; *Field and Fung*, 1999].

This "missing sink" may represent a single unknown or improperly quantified reservoir; it may represent the summation of several smaller, unknown reservoirs; or it may represent summed errors (biased in one direction) in the "standard reservoirs." Accepting that the terrestrial biosphere in general apparently contains the missing sink, this paper seeks to assess the likely sink or sinks more specifically.

Reservoirs related to soil carbon appear to be particularly appropriate targets to consider for this sink. Soil carbon fluxes are not counted effectively in present assessments, largely because of the difficulty in evaluating small changes in a large reservoir. Soil organic carbon (a global stock of at least 1500 Gt) is the largest "active" organic carbon pool (i.e., excluding fossil organic carbon); this pool is substantial relative to the other large active pool (oceanic dissolved inorganic carbon; ~40,000 Gt) [*Schlesinger*, 1990; *Hedges and Keil*, 1995; *Schimel*, 1995].

Further, the pool has complex, heterogeneous turnover characteristics ranging from annual or shorter turnover times of fresh detritus to millennia for soil carbon deep in the soil horizon [*Harrison and Broecker*, 1993; *Matthews*, 1997; *Schlesinger*, 1990, 1997]. The average turnover time appears to be ~30 years [*Raich and Schlesinger*, 1992]. *Schlesinger* [1990] concluded that soil organic matter has a low potential as a CO_2 sink because of the very slow long-term rates of carbon accumulation in this reservoir. *Schlesinger* [1995] further argued that organic carbon lost during erosion is largely oxidized, rather than being transported in eroded soils.

A particular alternative reservoir related to soil carbon mobilized during erosion has repeatedly been given some attention: burial of soil carbon in water catchment impoundments, lakes, bogs, and other terrestrial deposits. We use the term "impoundments," rather than the commonly used term "reservoirs," in order to avoid confusion between these water bodies and global stocks of carbon (reservoirs) that are the primary topic of this paper. Generally flux to this pool has been postulated to be <0.5 Gt yr^{-1} [e.g., *Mulholland and Elwood*, 1982; *Ritchie*, 1989; *Dean and Gorham*, 1998], but *Stallard* [1998] postulated that the flux might be as large as 0.6–1.5 Gt yr^{-1}.

The various estimates of the size of this carbon storage in impoundments have depended heavily on limited estimates of sediment accumulation in large water catchment impoundments. This paper approaches the terrestrial sediment storage of carbon from a somewhat different perspective. Bulk particulate materials are budgeted as they erode and move from soil into the sediment transport and deposition regime at an approximately continental scale. Organic carbon fluxes in the eroded and sedimented materials are then normalized against the bulk sediment fluxes.

The major processes accounting for carbon flux in the terrestrial biosphere (primary production and respiration) cycle carbon between organic matter and CO_2 at rates of ~60 Gt yr^{-1} globally [*Schimel*, 1995]. It is difficult to assess a background net rate

[1]Department of Oceanography, University of Hawaii, Honolulu, Hawaii.

[2]Department of Geography, Miami University, Oxford, Ohio.

[3]Kansas Geological Survey, University of Kansas, Lawrence, Kansas.

[4] LOICZ International Project Office, Netherlands Institute for Sea Research, Den Burg, Texel, Netherlands.

Paper number 2000GB001341.
0886-6236/01/2000GB001341$12.00

operating near 1 Gt yr^{-1} as the difference between these much faster rates of carbon turnover. The approach used here avoids direct consideration of this large turnover cycle and allows assessment of the net fate of organic carbon as soil is eroded and deposited. These sedimentary fluxes are operating at rates near the magnitude of the sink we are attempting to isolate.

As we will demonstrate, an inherent advantage of our estimate of erosion and redeposition over earlier estimates is that we take the difference between two rates which differ greatly from one another–erosion and river transport—in order to derive sediment accumulation on land. A seminal summary paper dealing with soil erosion and sediment fates across the United States is that by *Meade et al.* [1990]. A key point to that paper is that soil erosion and sediment deposition are far from being in balance across the United States. While we provide some more up-to-date and comprehensive estimates of sediment erosion and deposition, these alone are not conceptual advances from that paper. The advance offered by the present paper is an analysis of organic carbon sources and fates in proportion to bulk soil erosion and sedimentation.

Data required for this budgeting are more readily available for the United States than for the remainder of the globe. Erosion, river transport, and sedimentation in inventoried water catchment impoundments for the conterminous United States can be relatively robustly assessed. Other less well-quantified sedimentation fluxes are then inferred. We estimate both bulk sediment and sedimentary organic carbon budgets for the conterminous United States.

The sedimentary organic carbon fluxes for the United States can then be examined in the context of both atmospherically based estimates [*Fan et al.*, 1998] and inventories of changing land use [*Houghton et al.*, 1999] that have been offered to constrain the North American terrestrial carbon sink. With a relatively firm description of the United States budget, we then offer rough extrapolations to the remainder of the globe, in order to evaluate the likely magnitude of this storage in a global context.

2. Methods

2.1. Data Sources and Analysis

In addition to conventional literature citations, the analyses presented here are dependent upon available databases. Several of these are on the World Wide Web and are so-cited. The information presented is keyed to the U. S. Geological Survey hydrological unit classification (HUC) (*Seaber et al.* [1987]; http://water.usgs.gov/nawqa/sparrow/wrr97/geograp). We aggregated information in terms of the coarse "HUC-2" designators that denote 18 separate hydrological regions across the conterminous United States; we then aggregated the data from these HUC-2 regions into nine "continental drainage provinces" that are the basic unit of analysis in this paper (Plate 1, Table 1).

We use *National Resources Conservation Service* [1995] (http://nhq.nrcs.usda.gov), for estimates of erosion rates across the United States. This National Resources Inventory (NRI) database is available on CD-ROM, allowing mapping of the data with geographic information system software (ArcView). This data set uses measured soil properties, land use, and weather to calculate erosion at ~10^6 sites across the United States every 5 years since 1982. The data used were averaged for 1982, 1987, and 1992. The data were averaged for each of the ~2000 8-digit hydrologic accounting units, aggregated to the 18 HUC-2 regions, and then to the nine drainage provinces used here.

Water erosion is estimated according to the Universal Soil Loss Equation (USLE) [*Wischmeier and Smith*, 1978], and wind erosion is estimated from the Wind Erosion Equation (WEE) [*Skidmore and Woodruff*, 1968]. Both sets of estimates must be regarded with caution, especially the WEE [*Board of Agriculture*, 1986; *Gillette*, 1986; *Trimble*, 1999; *Trimble and Crosson*, 2000]. Nevertheless, they provide objective, regional-scale assessments of erosion across the United States.

The NRI erosion database excludes erosion on federal lands (~20% of the 7.8 x 10^6 km^2 of the conterminous United States),

Table 1. Area, Erosion, and Sedimentation in the Discharge Provinces of the Conterminous United States

Discharge Province	HUC-2 Regions	Area, 10^3 km^2	Water Erosion, Gt yr^{-1}	Wind Erosion, Gt yr^{-1}	Total Erosion, Gt yr^{-1}	River Suspended Discharge, Gt yr^{-1}	Impoundment Sedimentation, Gt yr^{-1}	Other Sedimentation[a], Gt yr^{-1}
NE Atlantic	01, 02	437	0.08	0.00	0.08	0.03	0.07	-0.01
SE Atlantic	03	711	0.14	0.00	0.14	0.02	0.48	-0.36
Great Lakes	04, 09	456	0.07	0.14	0.21	0.00	0.12	0.09
Mississippi Basin	05-08, 10, 11	3255	1.51	1.22	2.73	0.21	2.24	0.28
NW Gulf of Mexico	12, 13	814	0.19	0.88	1.07	0.04	0.26	0.76
Colorado Basin	14, 15	663	0.13	1.57	1.70	0.00	0.04	1.65
Central Basin	16	355	0.09	0.70	0.79	0.00	0.10	0.69
NW Pacific	17	714	0.19	0.15	0.34	0.01	0.01	0.31
SW Pacific	18	420	0.11	0.20	0.31	0.10	0.10	0.11
TOTAL		7825	2.50	4.86	7.36	0.41	3.43	3.52

[a]Note that 0.2 Gt yr^{-1} of the "other sedimentation" is attributed to river bed load + dissolved transport.

forest lands (~20%), and urban areas (~5%); water covers ~3% of the area. Erosion rates on forested lands and urban areas are assumed to be 0. On federal lands, we assumed erosion rates to equal the average rates for the remainder of the area within each of the drainage units. The potential for error in the assumed erosion rates for Federal lands becomes a particular problem in much of the western portion of the United States, where over half of the land area is federal.

The State Soil Geographic Data Base (STATSGO) [*U. S. Department of Agriculture*, 1994] was used to estimate soil organic matter. The variables "omh" (maximum organic matter in the soil profile for each soil type) and "oml" (minimum organic matter) are reported; we use "omh" and the average of "omh" and "oml" as representing the likely range in organic matter eroding at the soil surface. It seems likely that "oml" is partly or largely below the erosion depths in most profiles, so it is an unreasonable estimate of the lower range of organic matter in eroded materials. The organic matter estimates were converted to organic carbon by dividing by 1.72 (guidelines in the National Soil Survey Handbook, http://www.statlab.iastate.edu/soils/nssh/). The STATSGO database is available in various formats; we used the data available at http://water.usgs.gov/lookup/getspatial?ussoils; these data are organized according to the HUC-2 regions. Wind and water erosion rates averaged across each of the HUC-8 cataloging units were multiplied by the aerially averaged soil organic C content for that cataloging unit. These C erosion data for the HUC-8 units were aggregated across the United States to derive an erosion-weighted average of soil C erosion. These results will be reported in more detail elsewhere by S. V. Smith et al. (manuscript in preparation, 2001).

Another database used is a summary by *Dendy and Champion* [1978] of pre-1976 information on sediment accumulation rates in approximately 1600 water catchment impoundments across the conterminous United States. The rates are expressed as annual volume of sediment deposition per unit area of the impoundment catchments. Accumulation rate scaled to catchment area is denoted "sediment yield," in contrast to "sedimentation rates" per unit area of the impoundments themselves. Because sedimentation rates must vary widely as a function of the ratio of impoundment area to catchment area, sediment yield is the more useful variable to understand the landscape processes of interest here. Data are converted from volumetric rates to mass rates using an average sediment bulk density of 1 g cm^{-3}, by inspection of tabulated bulk densities in *Dendy and Champion* [1978].

We used the National Inventory of Dams (NID) (http://crunch.tec.army.mil/nid/webpages/nid.cfm), as a source of information on the distribution of water impoundments across the United States. This survey enumerates dams that meet one or more of three criteria: The impoundments are considered flood hazards; the dams are > ~2 m (6 feet) high; the impoundments contain more than ~30,000 m^3 (25 acre feet) of water. Obviously this database excludes many smaller impoundments (ponds) that are local sediment traps across the continent.

As discussed by *Stallard* [1998], the NID database includes locations, drainage areas, sizes, and selected other impoundment characteristics for ~70,000 impoundments. After exclusion of sites for a variety of reasons (incomplete data on drainage area or impoundment size, multiple dams on the same impoundment, dams that are apparently not on streams, etc.), we were left with a database for ~43,000 individual impoundments that account for about half of the water area listed in the NRI database.

Milliman et al. [1995] provide a summary of suspended load transport from rivers to the ocean. This database, called GLORI (Global River Inventory), includes estimates derived from U. S. Geological Survey gauging stations for suspended load transport by 57 rivers or river systems draining 82% of the area of the conterminous United States.

2.2. Conceptual Model

Consider the following simple transport model for production, transport, and sedimentation of bulk sediments:

$$E_S = Q_S + I_S + O_S. \qquad (1)$$

E, Q, I, and O represent erosion, river transport, impoundment sedimentation, and other sedimentation processes, respectively; the subscript S represents bulk sediment. E_S, Q_S, and I_S are directly estimated from available data, while O_S is determined by difference and includes analytical errors in the budget. Q_S is delivered to the ocean, so we can view the above equation as the balance between erosion (i.e., sediment production) and the sum of the sedimentation terms. The equation states that bulk sediments are conserved during erosion and sedimentation.

A similar equation can be written for erosion and sedimentation of organic carbon, where the subscript "C" represents organic carbon. There is an additional flux for carbon in this equation. That flux is oxidation to CO_2 gas, represented by G; such a flux pathway can be considered insignificant for bulk sediment. Thus, for carbon:

$$E_C = Q_C + I_C + O_C + G_C. \qquad (2)$$

Equation (1) provides an account of bulk sediment production, transportation, and deposition; and (2) extends (1) to organic carbon. Because G_C is a term not reflected in the bulk sediment cycle, it can be said that carbon may not be conserved relative to bulk sediments during erosion and sedimentation.

Q_C is considered to be adequately known. E_C and I_C are not directly known but can be approximated as being proportional to the bulk sediment:carbon ratio in soil erosion products and impoundment sediments, respectively; we represent these ratios by "transfer coefficients" (α):

$$\left[\alpha_E = \left\{\frac{C}{S}\right\}_E\right]; \left[\alpha_I = \left\{\frac{C}{S}\right\}_I\right].$$

The carbon:sediment ratio for O is not known but is assumed to have some unknown value α_O. Q_C can also be represented by a transfer coefficient based on river flux,

$$\left[\alpha_Q = \left\{\frac{C}{S}\right\}_Q\right],$$

although Q_C is actually known directly. G_C is not described via such a transfer coefficient because it is assumed that bulk soil loss via the gas phase is insignificant. The value for G_C is not well known. Equations (1) and (2) can be rearranged and solved for G_C as a function of the known quantities and the unknown coefficient α_O:

$$G_C = E_S\alpha_E - Q_S\alpha_Q - I_C\alpha_I - O_S\alpha_O. \qquad (3)$$

Section 3 evaluates the terms in (1) and (3).

Plate 1. Map showing the nine continental drainage provinces for the conterminous United States as derived from the two-digit USGS HUC regions.

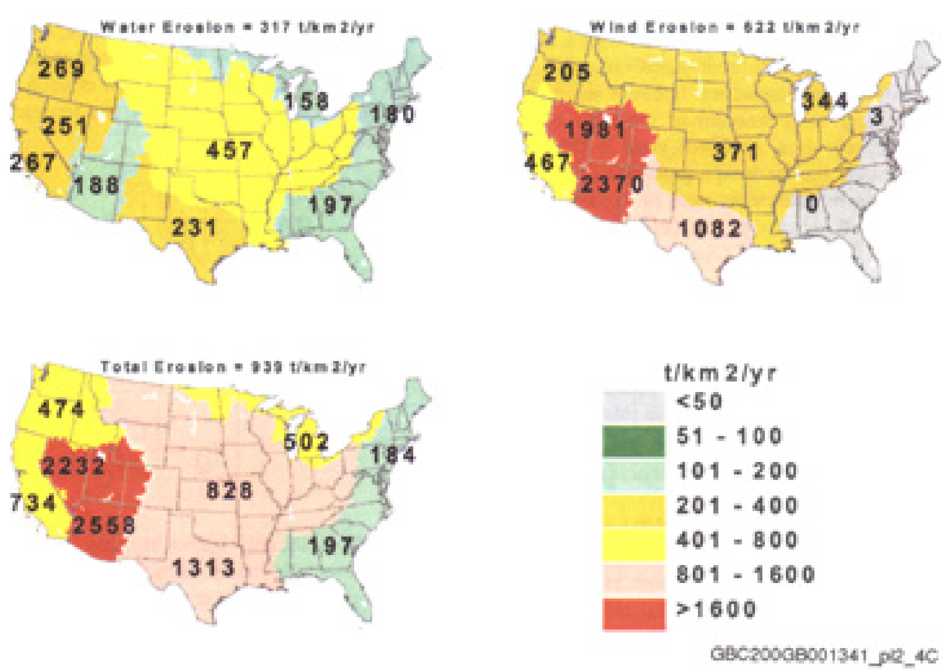

Plate 2. Estimated water, wind, and total erosion rates for each of the continental drainage provinces.

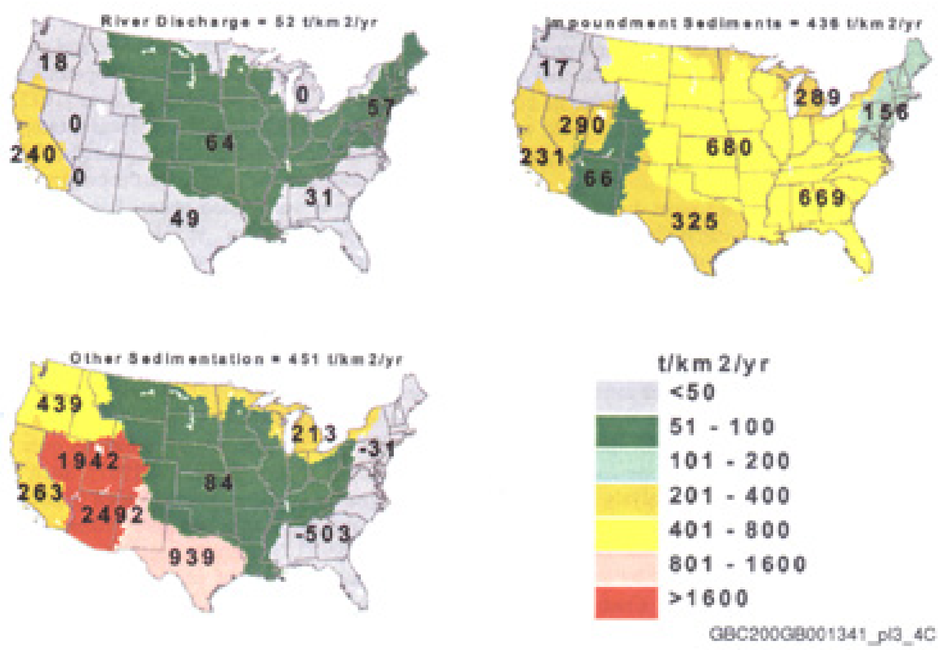

Plate 3. Estimated river transport of sediments, sediment accumulation in water catchment impoundments, and other sedimentation not accounted for by these two.

3. Results

3.1. Bulk Sediment Budget

3.1.1. Erosion. Plate 2 and Table 1 summarize average water and wind erosion rates of soil within each of the nine continental drainage provinces aggregated across the conterminous United States, averaged for the years 1982, 1987, and 1992. Several broad patterns can be seen.

Water erosion averaged ~320 t km^{-2} yr^{-1} across the conterminous United States over this period. The rate was highest in the midwestern portion of the country; it fell off sharply to the east and somewhat less sharply to the west. The Mississippi Basin was a region of high water erosion (~460 t km^{-2} yr^{-1}); most of this region is subjected to intensive cultivation and has relatively high runoff.

Wind erosion averaged across the United States was almost twice water erosion, (~620 t km^{-2} yr^{-1}). Rates were highest in the arid, southwestern portion of the United States, averaging about 2000 t km^{-2} yr^{-1}. This region also has a high proportion of federal lands (>50%), so the estimated rates are the most questionable.

Total wind plus water erosion across the conterminous United States averaged ~940 t km^{-2} yr^{-1} for the years in question. Erosion throughout most of the United States exceeded 800 t km^{-2} yr^{-1}, and only the eastern portion of the country was characterized by rates <200 t km^{-2} yr^{-1}. Although the highest total erosion yields (rates per area) were in the arid southwestern United States, the agricultural region of the midwestern United States was the dominant region of continental-scale erosion (Table 1). Total erosion across the conterminous United States was ~7.4 Gt yr^{-1}.

3.1.2. River transport. Suspended sediment transport to the ocean is relatively well characterized. River suspended load discharge to the ocean was estimated from GLORI for 57 rivers. For each of the continental drainage provinces, sediment discharges from monitored portions of the catchments were extrapolated to the entire area. The time period characterized by the river transport cannot be precisely stated because the data are for differing periods. It will be seen that this is not a major problem in the budgeting.

As illustrated in Plate 3, only the SW Pacific drainage had river transport in excess of 100 t km^{-2} yr^{-1}. This region is characterized by high-yield, small, mountainous rivers, as discussed by *Milliman and Syvitski* [1992]. The region is also the most poorly represented in the GLORI database, so it has the largest potential for error. Although the sediment yield from this region is high, its contribution to the entire budget is relatively small (25%; Table 1). The countrywide average was ~50 t km^{-2} yr^{-1} (0.4 Gt yr^{-1}), only ~5% of the total erosion rate.

Rivers also carry materials as both bed load and dissolved load. From *Meade et al.* [1990] and *Garrels and Mackenzie* [1971], it can be estimated that the sum of these transports is no more than 0.2 Gt yr^{-1}. We therefore estimate the total river transport to be 0.6 Gt yr^{-1}. It is clear that rivers are not transporting most contemporaneous sediment erosion products from the conterminous United States to the ocean. This large discrepancy between erosion and river transport is a well-documented phenomenon [e.g., *Meade et al.*, 1990; *Trimble and Crosson*, 2000]. Even if river flux to the oceans has increased dramatically in response to human activities [*Meade*, 1982], this flux constitutes a small portion of elevated erosion products.

3.1.3. Sedimentation in inventoried water catchment impoundments. Various authors have used sedimentation rates from a relatively small number (<100) of impoundments, have calculated average sedimentation rates, and have then extrapolated to estimate water impoundment area as an estimate of impoundment trapping. There are problems with this approach, as illustrated by *Renwick* [1996].

Impoundment sediment accumulation is extremely variable, at least in part dependent upon land use. Further, sediment yield decreases as a function of catchment area, although the trend is extremely noisy. The noise in the relationship is interpreted as representing variable erosion rates as well as uncertainty in both the erosion and yield estimates. The decreasing trend with area is interpreted to represent progressive retention of erosion products within progressively larger catchments. We have adopted the following strategy to deal with at least part of the issue of high variability and with the issue of decreasing sediment yield as a function of catchment area (W. H. Renwick, manuscript in preparation, 2001).

The impoundment sediment yield data were divided into the HUC-2 regions, and regressions were calculated for each unit. The NID data were used to estimate the distribution of catchment areas within each HUC-2 region, and the sediment accumulation in the NID reservoirs was calculated and expressed as sedimentation rate within each of these provinces. These sedimentation rates are then scaled to total sediment accumulation by multiplying sedimentation rate by total water area as summarized in the NRI database. These calculations within the HUC-2 regions were then aggregated into the nine continental discharge provinces (Table 1).

There are at least two problems with this analysis. One problem with this approach is a time mismatch between the impoundment deposition estimates (pre-1976) and the erosion estimates (1982-1992). Erosion rates have declined by an unknown amount during the 20th Century [*Trimble and Crosson*, 2000]. Second the catchment areas of the small impoundments are not well characterized. Both the NID impoundment database and the *Dendy and Champion* [1978] sedimentation database are biased towards larger impoundments and ones with larger catchments. The extrapolation of the sediment yield curves toward small impoundments and small catchment areas may therefore not be entirely reliable.

Within the constraints of these limitations, the impoundment sediment accumulation is given in Plate 3. Sediment accumulation within impoundments was highest in the Mississippi Basin and SE Atlantic. The Mississippi Basin was the region with highest water erosion, while erosion rates in the southeast were lower than impoundment sedimentation. Much of the southwestern United States showed moderate rates of impoundment accumulation, although the Colorado Basin was noteworthy by its low accumulation. The average across the conterminous United States was ~440 t km^{-2} yr^{-1} (3.4 Gt yr^{-1}), accounting for about half of the estimated erosion. Thus, a substantial amount of the erosion products, but not all of them, can be found in impoundments.

3.1.4. Other sedimentation. The difference between total erosion (7.4 Gt yr^{-1}) and river transport + impoundment sedimentation (4.0 Gt yr^{-1}) provides a measure of that sediment not being counted in this inventory (Plate 3). This amount is 3.4 Gt yr^{-1}, an average of ~450 t km^{-2} yr^{-1}, or almost half of the total erosion. This result emphasizes the point by *Trimble and Crosson* [2000] that much of the eroded soil "...remains close by, and thus is not lost..." Having some understanding of this large and undefined sedimentation is of importance to the budgets.

Let us consider potential sites and processes of sedimentation not accounted for, including the anomalous negative "other" sedimentation in the SE Atlantic discharge province. Wind transport to the global ocean is not well defined, but apparently lies between ~0.4 and 0.9 Gt yr^{-1} [*Garrels and Mackenzie*, 1971; *Prospero*, 1996]. The combination of atmospheric transport trajectories and accumulation basins [*Péwé*, 1981] makes it unlikely that as much as 10% of this transport originates from the conterminous United States. We therefore conclude that <0.1 Gt yr^{-1} of the total United States soil erosion is reaching the ocean via atmospheric transport. Despite the qualitative importance of wind transport of sediment to the ocean basins, this does not seem likely to be quantitatively significant to the United States sediment budget.

It is our interpretation that much of the "other" sedimentation of Plate 3 represents alluvial, colluvial, and perhaps wetland storage not well approximated by the impoundment sedimentation across much of the United States. *Costa* [1975], *Phillips* [1991], and *Trimble* [1999] all provide local examples that sediment storage within the landscape can greatly delay the discharge of erosion products to the ocean. At the continental scale, it appears that ~3.3 Gt yr^{-1} of eroded material is being redeposited across the landscape (~400 t km^{-2} yr^{-1}) [also see *Meade et al.*, 1990].

The distribution pattern of a large amount of the "other" sediment in the arid southwest makes it likely that the primary transport pathway for some of this material is wind. The estimate is uncertain because of the high proportion of federal lands, for which erosion is not estimated; nevertheless, there clearly is high "other" sedimentation in this region. This material may be largely deposited as dunes or other dry sediments in those areas; much of it may also be moved elsewhere over the continent (especially to the southeast) [Péwé, 1981]. Such a transport pattern might at least partially explain the high impoundment sedimentation rates and apparently negative "other" sedimentation in that region (Table 1). Apparent negative sedimentation likely also reflects remobilization of sediment previously stored in floodplains and subsequently moved into impoundments by channel processes [*Trimble*, 1974; *Knox*, 1987; *Phillips*, 1987].

3.1.5. Summation of bulk sediment budget terms. Perhaps the single greatest problem with the NRI erosion rate estimates concerns the meaning of these measurements. Eroded sediment is not equivalent to "...removed from land," a point made by *Trimble and Crosson* [2000] and explicitly obvious in Plate 3 and Figure 1. Erosion and river transport of eroded materials to the ocean are clearly not in balance. Sedimentation in impoundments is the largest single term that can be identified to approach a balance between erosion and sedimentation but still leaves a substantial fraction of the sedimentation uncounted. It seems likely most of the eroded sediment not either accumulating in impoundments or being transported to the ocean by rivers is redeposited across the landscape, probably largely near its erosion sites. We refer to this category as "local redeposition," where "local" refers to an internal transfer within the landscape.

One major source of error is not well addressed by this budget, decreasing erosion rates over time. This decrease is documented both in some individual sites [e.g., *Beach*, 1992; *Trimble and Lund*, 1982] and in the NRI database (see, for example the recently released summary of 1997 data [*Natural Resources Conservation Service*, 1999]. We can at least qualitatively address the effect of such an erosion decrease on the budget.

The pre-1976 period of the impoundment sediment accumulation rate surveys used here would have corresponded to a period of higher erosion. Therefore the discrepancy between the dominating, well-defined terms of soil erosion and impoundment deposition would have been larger than we have estimated. There is no reason to believe that either river discharge or dust flux would emerge as being quantitatively significant. Therefore the other large term, local redeposition, would have been larger than we have estimated, so the proportional importance of impoundment deposition would be lower than we have estimated. The overall pattern we have derived with respect to the relative importance of land, coastal ocean, open ocean, and atmospheric sinks would not change greatly.

3.2. Sediment Organic Carbon Budget

While it would be desirable to undertake the budget for the erosion and sedimentation of organic carbon in the same geographic detail that has been offered for bulk sediments (Plates 2

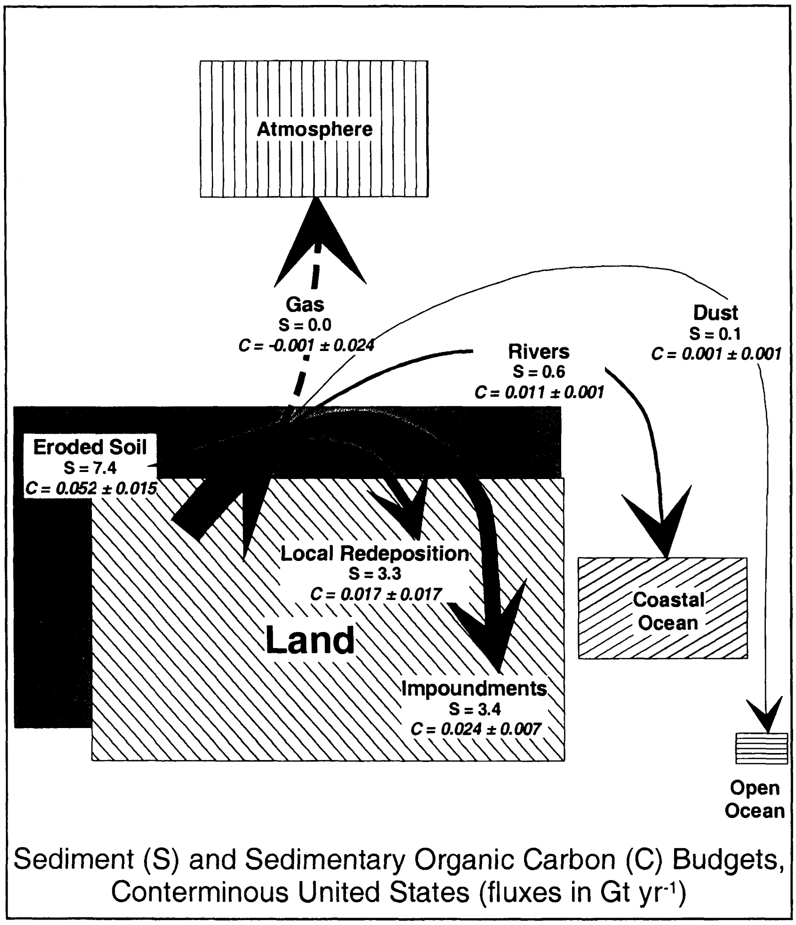

Figure 1. Sediment and sedimentary organic carbon budgets for the conterminous United States. "S" represents bulk sediment fluxes, while "C" represents organic carbon fluxes. The line widths of the arrows are approximately proportional to the average carbon fluxes. The boxes for land, atmosphere, coastal zone, and ocean are approximately proportional to the net carbon fluxes to those boxes.

and 3), such an assessment is not presently feasible. For the present purpose, we therefore use (3) together with organic carbon transfer coefficients (α values, as defined above) at the scale of the entire conterminous United States (Figure 1). The soil carbon fluxes are shown on the same diagram as the bulk sediment fluxes, to emphasize the linkages between these two budgets.

Soil organic C varies widely, as a function of soil type, local soil environment, and depth in the soil horizon [e.g., *Brady*, 1990]. We have used the STATSGO soil properties [*U. S. Department of Agriculture*, 1994] to estimate that the aerially averaged soil C content across the United States lies between 0.9 and 1.3%. When the soil C is mapped to the soil erosion rates at the scale of the eight-digit HUC cataloging units, the estimated C percentage of eroded materials lies between 0.5 and 0.9%. By comparison, *Ludwig et al.* [1996] report a global average of 12 kg C m^{-3} for soil organic C. This value is essentially the same as the aerially averaged figure for the United States, but well above the erosion-averaged figure. We assign α_E a value of 0.007 ± 0.002. Using the bulk sediment erosion rate of 7.4 Gt yr^{-1} across the United States, we calculate that the erosion of soil carbon is 0.052 ± 0.015 Gt yr^{-1}.

Direct estimates of river transport of organic carbon from the conterminous United States can be estimated from data in *Leenheer* [1982] to be ~0.01 Gt yr^{-1}. Of this transport, ~80% is dissolved organic carbon. This poses an interesting contrast with global river transport of organic carbon, which is approximately equally divided between dissolved and particulate organic matter [e.g., *Meybeck*, 1982; *Ludwig et al.*, 1996]. We use the ratio of organic transport to bulk sediment transport by rivers to calculate that α_Q is ~0.017. A global coefficient of 0.021 can be derived from the flux estimates of *Ludwig et al.* [1996]. We use an average α_Q of 0.019 ± 0.002. From these estimates, we estimate the river transport of organic C from the conterminous United States to be 0.011 ± 0.001 Gt yr^{-1}.

Ritchie [1989] compared the soil organic C percentage in each of ~60 watersheds across the United States with the percent organic C accumulating in the water catchment impoundments of those watersheds. The percentages were statistically indistinguishable (2% for his data). On the assumption that this 1:1 proportionality (rather than either the aerially averaged or the erosion averaged C content) is generally applicable across the United States and based on our estimate of α_E, α_I would be 0.007 ± 0.002. This coefficient is constrained to have the same range as that for eroded soil (above). The estimated organic carbon accumulation in inventoried impoundments is calculated to be impoundment sediment accumulation (3.4 Gt yr^{-1}) multiplied by this transfer coefficient or 0.024 ± 0.007 Gt yr^{-1}. An important point to reiterate is that α_I and α_E are the same in this analysis. If we have misestimated α_E, we have compensated for that misestimate with a similar error in α_I. This seems to be a conservative estimate of C sedimentation in impoundments.

The "other" sedimentation terms remain to be analyzed. The transfer coefficient for wind transport to the ocean is unimportant because the bulk transport is small. We estimate that this transfer might be 0.001 ± 0.001Gt yr^{-1} (equivalent to a transfer coefficient of 0.01 ± 0.01). Even if the upper limit of the transfer coefficient were doubled to allow for soil deflation (and disproportional transport of light organic matter relative to inorganic matter) [*Mainguet*, 1994; *Péwé*, 1981; *Péwé et al.*, 1981], this flux would still be small.

The final sedimentation term is local redeposition. The transfer coefficient for the local redeposition is not known but is estimated to range between 0.000 (i.e., none of the locally redeposited sediment has C; unlikely, we believe) and 0.009 (the upper limit used for average C in eroded soils). That is, the average transfer coefficient is 0.005 ± 0.005. With this range, local redeposition of eroded soil C is 0.020 ± 0.020 Gt yr^{-1}.

Solution of (3) allows us to estimate transfer of soil organic carbon to gaseous C (assumed to be primarily CO_2 but also CH_4). The errors on the individual transfer coefficients are treated as being statistically independent (not entirely true, of course) in propagating an error for the C loss to gas flux. This analysis leads to the conclusion that an insignificant net gas flux (-0.001 ± 0.024 Gt yr^{-1}) accompanies soil erosion. At the upper limit of the likely error on the gas flux estimate, it accounts for less than half of the C mobilization by erosion. It can be concluded that carbon flux during erosion and sedimentation is close to conservative with respect to bulk sediment flux. In a recent estimate of gas flux from water catchment impoundments, *St. Louis et al.* [2000] estimated that impoundments worldwide release ~300 t km^{-2} yr^{-1} of CO_2 + CH_4. On the basis of an estimated impoundment surface area of ~60,000 km^2 for the United States, this would be equivalent to <0.02 Gt yr^{-1}; this is within the uncertainty of our estimate of gas flux to close the sediment C budget.

The net transfer of carbon from the soil to other depositional sites apparently accounts for most organic C mobilized during soil erosion, with most (~80%) of this deposition occurring on land rather than in the ocean. River flux of sediments to the ocean represents the balance between elevated flux due to increased erosion and decreased flux due to increased trapping on land. We conclude that the United States land sequestration of 0.05 Gt yr^{-1} (~6.5 t km^{-2} yr^{-1}) is the primary organic C sink associated with elevated erosion rates. Any elevation in the present river flux of 0.01 Gt yr^{-1} above a lower preanthropogenic flux would be a small contribution to the budget.

It is useful to consider the effect of the time mismatch between bulk soil erosion estimates and impoundment deposition estimates on the carbon budget. Impoundment carbon deposition would be unaffected, but local redeposition of carbon would be elevated (along with the error on this term). As a result, both the absolute value and the uncertainty in the gas-phase carbon loss would be elevated. Sedimentation, not oxidation, would still dominate the carbon budget.

4. Discussion

We recognize that there are potential errors in the estimates of both water and wind erosion, particularly the latter [*Board of Agriculture*, 1986; *Gillette*, 1986]. We assume that there are not strong biases in the analysis, and we only apply the analyses across large spatial scales. We further assume that, with an assessment based on ~10^6 samples per sampling time and three sampling times (1982, 1987, 1992), errors in the continental-scale erosion estimates are relatively small. We further note that the difference between bulk sediment erosion and river discharge of sediment makes it clear that most bulk erosion products are redeposited across the continent. There is, of course, uncertainty associated with the partitioning of the sedimentation between impoundments and other sediments. With this background in mind, we assume that most of the error in the budget calculations is associated with the carbon transfer coefficients.

We have attempted to include reasonable estimates of error in the transfer coefficients leading from the sediment budget to the carbon budget presented here. Within the limits of those errors, deposition somewhere, rather than decomposition and carbon escape to the gas phase, appears to be the major fate for eroded soil organic carbon.

One important aspect of the error analysis has emerged as we have refined (and lowered) the estimated C content of the eroded material from an initial estimate of 1.5% [from *Brady*, 1990]. The overall "importance" of the sedimentary C sink of course decreases with decreasing soil C. However, within the rules used to assign the transfer coefficients, lowering the C content of the eroded materials decreases the importance of the gas flux. If the eroded materials did average 1.5% C, sediment sink would double, and the gas flux term would account for ~20% of the eroded C.

Schlesinger [1995] concluded that most eroded soil organic carbon oxidizes during erosion, rather than being transported to the ocean by rivers. It is well and repeatedly documented that soils lose 20–40% of their organic carbon content during cultivation [e.g., *Davidson and Ackerman*, 1993]. However, the most persuasive argument for oxidation of that lost soil organic carbon seems to be that soil erosion of organic carbon greatly exceeds river transport of organic carbon to the ocean. There are, however, additional possible fates for the carbon.

In principle, it would seem desirable to close the soil carbon budget by quantifying any regional change of soil respiration due to erosion. This would be difficult. *Raich and Schlesinger* [1992] document that soils typical of much of the United States have respiration rates between 200 and 700 t C km^{-2} yr^{-1}. This compares with carbon erosion of an estimated 6.5 t km^{-2} yr^{-1}. The quantification would require measuring a small increase against a large background. Measuring regional changes in soil organic carbon oxidation by 1–3% (i.e., 6.5 divided by 200–700) would be required to demonstrate that all of the loss is due to oxidation.

If all of the C associated with soil erosion were to respire in impoundments covering ~60,000 km^2 across the United States, the expected average respiration would be ~900 t km^{-2} yr^{-1}. This seems high compared to the estimated global CO_2 evasion rate from impoundments (averaging 300 t km^{-2} yr^{-1}) [*St. Louis et al.*, 2000]. Elevated soil respiration on a regional scale to balance soil C erosion would be difficult to prove, and elevated respiration in impoundments would appear too high to be reasonable. Process-based models provide one approach to constraining the importance of soil erosion, deposition, and oxidation [e.g., *Stallard*, 1998; *Harden et al.*, 1999]. Well-constrained budgets provide another approach to this problem.

The calculations presented in the present analysis provide a relatively robust, if still imprecise, estimate of the fates of eroded soil organic carbon without measuring changes in soil or reservoir respiration. Apparently most eroded soil carbon is redeposited, rather than being oxidized, and most of that sedimentation occurs on land, rather than in the ocean.

We emphasize that the sediment and carbon budgets record a net effect. Organic matter may, indeed, oxidize and then subsequently be replaced by photosynthesis; or the organic matter may move between erosion and deposition sites without loss. While the resolution of this question is of interest in understanding uptake and release processes and pathways, it is immaterial to the carbon mass balance.

If two conditions are met, eroded carbon qualifies as a sink for anthropogenically generated CO_2; we believe both of these conditions are met. First, the erosion must represent an increase above rates which prevailed before human influence on the cycle. If these processes are simply a reflection of long-term, "natural" (largely nonanthropogenic) patterns of soil redistribution, then the carbon erosion and burial would represent an unquantified, but implicit, part of the natural terrestrial carbon cycle. It seems clear that human activities have elevated erosion rates by at least an order of magnitude above natural rates [e.g., *Pimentel et al.*, 1995; *Harden et al.*, 1999). This first condition is therefore met.

Second, if the eroded carbon were moved between two reservoirs with the same characteristic turnover times, this transfer would be a relocation, but would not comprise a sink. Past thinking has supposed that erosion was moving the carbon from a "slow-turnover" pool to an environment with rapid carbon oxidation: a CO_2 source. The sediment and carbon budgets do not support this conclusion. Instead, the soil carbon appears to be moved from one reservoir in which it has a characteristic turnover time into another reservoir with a much longer characteristic turnover time; this constitutes a net carbon dioxide sink. Carbon is moved from the upper portion of the soil horizon, where turnover times are short (decades, or shorter), into either of two classes of environments with longer turnover times.

Much of the material is transferred to water-saturated environments (impoundments, lakes, wetlands, etc.) that occupy only ~3% of the United States landscape, and typical sediment respiration rates per unit area are suppressed by 50% or more relative to soil respiration [e.g., *Gunnison et al.*, 1983]. Much of the remainder of the sediment may not be moved to water-saturated environments but will be focussed into relatively smaller depositional areas than that material originally occupied as soil. Deeper burial will also suppress oxidation. As a first approximation, the soil carbon moves from reactive to nonreactive reservoirs; contribution of that carbon oxidation to atmospheric CO_2 effectively stops.

Regrowth of organic carbon into the soils is known to occur and indeed is being enhanced by modern agricultural management practices [e.g., *Harden et al.*, 1999; *Bruce et al.*, 1999]. *Houghton et al.* [1999] used various literature estimates to conclude that the regrowth of soil carbon in managed soils is a sink of 0.14 Gt yr^{-1} across the United States. We emphasize that this is not the sink being assessed in this paper.

According to the calculations we have presented, erosion and redeposition of soil organic carbon sequesters ~0.05 Gt yr^{-1} across the conterminous United States. *Houghton et al.* [1999] estimated that the net terrestrial sequestration lies between 0.15 and 0.35 Gt yr^{-1}, the difference reflecting uncertainty in forest and woodland regrowth . Their net estimate includes a soil C loss of ~0.02 Gt yr^{-1} to the atmosphere owing to cultivation and soil erosion. Our modification of their budget eliminates the soil erosion loss source term and adds a sediment sink. This represents a net erosion-associated shift in the budget from –0.02 to +0.05 Gt yr^{-1}, for a total change in the budget of 0.07 Gt yr^{-1}. Net sequestration for the United States, based solely on these modifications of the Houghton et al. budget, would be 0.22–0.42 Gt yr^{-1} (a 20–47 % upward shift in their estimated net storage).

Despite this addition to the *Houghton et al.* [1999] estimate of the North American terrestrial carbon sink, these estimates still fall well short of the 1.7 ± 0.5 Gt yr^{-1} North American sink estimated by *Tans et al.* [1990]. Either that estimate is in error or there still remains a substantial North American sink not yet accounted for.

We can make three assumptions based on the United States budget to extrapolate globally (Table 2). (1) The α_E is the same as estimated for the United States, ~0.007. (2) The global ratio of erosion:river yield of bulk sediment is ~10:1, and α_Q is ~0.019. (3) An insignificant amount of the eroded soil C is lost to the atmosphere.

On the basis of a global river yield of ~20 Gt yr^{-1} for bulk sediment [*Walling and Webb*, 1996], the river flux would of organic C would be ~0.4 Gt yr^{-1} (close to values of 0.3–0.4, estimated by *Ludwig et al.* [1996] and other authors). These figures would be equivalent to a global bulk erosion rate of about 200 Gt yr^{-1} (~1300 t km^{-2} yr^{-1} across the land area) and 1.4 Gt yr^{-1} of organic carbon. The sink associated with the deposition of ero-

Table 2. Extrapolation From Budgets for Conterminous United States, to Global

Process	United States, Gt yr^{-1}	Global, Gt yr^{-1}	Comments on Global Extrapolation
		Bulk Materials	
Erosion	7.4	200	From United States, ≈ 10 times river flux; gives global rate of 1300 t km^{-2} yr^{-1}.
River + wind flux to ocean	0.7	20	Consensus (Walling and Webb, 1996).
Land deposition	6.7	180	Balances the budget.
		Organic Carbon	
Erosion	0.05	1.4	Assume $\alpha_E = 0.007$.
River + wind flux to ocean	0.01	0.4	Assume $\alpha_Q = 0.019$; Ludwig et al. (1996) and other authors estimate 0.3- 0.4 Gt yr^{-1}.
Gas loss	0.00	0.0	From United States, near 0.
Land deposition	0.04	1.0	Balances the budget.

sion products on land would be ~1 Gt yr^{-1}. Because of the latitudinal distribution of land, runoff, sediment transport, and inferred erosion this sink would mostly lie in the northern hemisphere. Such extrapolation is not rigorous and certainly requires more detailed assessment.

5. Conclusions

The net result we obtain, that terrestrial sedimentary processes constitute a net CO_2 sink of ~1 Gt yr^{-1}, is very similar to the model reported by *Stallard* [1998]; the inherent difference is the simplicity and robustness of the assumptions underlying the budgetary analysis. Three key points emerge.

One point to the analysis presented here is that normalizing soil organic carbon to bulk erosion products and to the transfer of those products through the landscape provides a robust assessment of the net fate of that eroded soil carbon. A sediment budget, which is very unbalanced between erosion and river transport across the United States, can then be used to construct a carbon budget.

A second point is that assessment of vertical exchanges of carbon between the soil and the atmosphere requires consideration of both carbon transfers within the land box and, laterally, between land and ocean. These internal transfers and lateral transfers are critical to characterizing the rate of carbon oxidation. Once these transfers are considered, it appears likely that relatively little of the eroded soil carbon is oxidized.

A third point is that slowing a gross source term in any complex, nonsteady state budget is as much a net sink in that budget as accelerating a gross sink term.

Acknowledgments. We thank Fred Mackenzie, Rich Sleezer, Dennis Swaney, Larry Mayer, Leal Mertes, Will Steffen, and James Syvitski for helpful discussions, Jeremy Bartley for assistance with GIS analysis, and Eric Hochberg for assistance in processing the NRI data. John Milliman and two anonymous reviewers provided further assistance with the manuscript. This research was undertaken as part of the LOICZ (Land-Ocean Interactions in the Coastal Zone) core project element of the IGBP (International Geosphere-Biosphere Programme). SOEST Contribution no. 5458.

Notation List

E_S, Q_S, I_S, O_S fluxes of bulk sediment due to erosion, river transport, impoundment trapping, and other sedimentation processes.

E_C, Q_C, I_C, O_C, G_C fluxes of organic carbon due to erosion, river transport, impoundment trapping, other sedimentation processes, and gas flux.

$\alpha_E, \alpha_Q, \alpha_I, \alpha_O$ organic carbon to bulk material flux ratios for erosion products, river transport, impoundment trapping, and other sedimentation processes.

References

Beach, T., Estimating soil loss from medium-size drainage basins, *Phys. Geogr., 13,* 206-224, 1992.

Board of Agriculture, *Soil Conservation: Assessing the National Resources Inventory,* vol. 1, 114 pp., Natl. Acad. Press, Washington, D. C., 1986.

Brady, N. C. *The Nature and Properties of Soils,* 10th ed., 621 pp., Macmillan, Old Tappan, New Jersey, 1990.

Bruce, J. P., M. Frome, E. Haites, H. Janzen, R. Lal, and K. Paustian, Carbon sequestration in soils, *J. Soil Water Conserv., 54,* 382-389, 1999.

Costa, J. E., Effects of agriculture on erosion and sedimentation in the Piedmont Province, Maryland, *Geol. Soc. Am. Bull., 86,* 121-1286, 1975.

Davidson, E. A., and I. L. Ackerman, Changes in soil carbon inventories following cultivation of previously untilled soils, *Biogeochem., 20,* 161-193, 1993.

Dean, W. E., and E. Gorham, Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands, *Geology, 26,* 535-538, 1998.

Dendy, F. E., and W. A. Champion, Sediment Deposition in US Reservoirs: Summary of Data Reported Through 1975, *Misc. Pub. 1362,* 82 pp., U. S. Dep. of Agric., Washington, D. C., 1978.

Fan, S., M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi, and P. Tans, A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models, *Science, 282,* 442-446, 1998.

Field, C. B., and I. Y. Fung, The not-so-big U. S. carbon sink, *Science 285,* 544-545, 1999.

Garrels, R. M., and F. T. Mackenzie, *Evolution of Sedimentary Rocks,* 397 pp., Norton, New York, 1971.

Gillette, D. A., Wind erosion, in *Soil Conservation: Assessing the National Resources Inventory,* vol. 2, pp. 129-158, Natl. Acad. Press, Washington, D. C., 1986.

Gunnison, D., R. L. Chen, and J. M. Brannon, Relationship of materials in flooded soils and reservoir sediments to the water quality of reservoirs, I, Oxygen consumption rates, *Water Res., 17,* 1609-1617, 1983.

Harden, J. W., J. M. Sharpe, W. J. Parton, D. S. Ojima, T. L. Fries, T. G. Huntington, and S. M. Dabney, Dynamic replacement and loss of soil carbon on eroding cropland, *Global Biogeochem. Cycles, 13,* 885-901, 1999.

Harrison, K., and W. Broecker, A strategy for estimating the impact of CO_2 fertilization on soil carbon storage, *Global Biogeochem. Cycles, 7,* 69-80, 1993.

Hedges, J. I., and R. G. Keil, Sedimentary organic matter preservation: an assessment and speculative synthesis, *Mar. Chem. 49,* 81-115, 1995.

Houghton, R. A., J. L. Hackler, and K. T. Lawrence, The U. S. carbon budget: Contributions from land-use change, *Science, 285,* 574-578, 1999.

Knox, J. C., Historical valley floor sedimentation in the upper Mississippi Valley, *Ann. Assoc. Am. Geogr., 77,* 224-244, 1987.

Leenheer, J., United States Geological Survey data information service, in *Transport of Carbon and Minerals in Major World Rivers,* vol. 1, edited by E. T. Degens, pp. 355-356, Mitt. Geol-Paläont. Inst., Univ. Hamburg, Hamburg, 1982.

Ludwig, W., J.-L. Probst, and S. Kempe, Predicting the oceanic input of organic carbon by continental erosion, *Global Biogeochem. Cycles, 10,* 23-41, 1996.

Mainguet, M., *Desertification: Natural Background and Human Mismanagement,* 2nd ed., 314 pp., Springer-Verlag, New York, 1994.

Matthews, E., Global litter production, pools, and turnover times: Estimates from measurement data and regression models, *J. Geophys. Res., 102,* 18,771-18,800, 1997.

Meade, R. H., Sources, sinks and storage of river sediment in the Atlantic drainage of the United States, *J. Geol., 90,* 235-252, 1982.

Meade, R. H., T. R. Yuzyk, and T. J. Day, Movement and storage of sediment in rivers of the United States and Canada, in *Surface Water Hydrology, Geol. of North America., O-1,* edited by M. G. Wolman and H. C. Riggs, pp. 255-280, Geol. Soc. Am., Boulder, Colo., 1990.

Melillo, J. M., I. C. Prentice, G. D. Farquhar, E.-D. Schulze, and O. E. Sala, Terrestrial biotic responses to environmental change and feedbacks to climate, in *Climate Change 1995: The Science of Climate Change,* edited by J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, pp. 443-481, Cambridge Univ. Press, New York, 1996.

Meybeck, M., Carbon, nitrogen, and phosphorus transport by world rivers, *Am. J. Sci., 282,* 401-450, 1982.

Milliman, J. D., and J. P. M. Syvitski, Geomorphic/tectonic control of sediment discharge to the ocean: importance of small mountainous rivers, *J. Geol., 100,* 525-544, 1992.

Milliman, J. D., C. Rutkowski, and M. Meybeck, *River Discharge to the Sea: A Global River Index (GLORI)*, Rep. and Stud., 125 pp., Land-Ocean Interactions in the Coastal Zone, Texel, Netherlands, 1995.

Mulholland, P. J., and J. W. Elwood, The role of lake and reservoir sediments as sinks in the perturbed global carbon cycle, *Tellus, 34,* 490-499, 1982.

Natural Resources Conservation Service, *Summary Report: 1992 National Resources Inventory*, 54 pp., U. S. Dep. of Agric. Nat. Resour. Conserv. Serv., Iowa State Univ. Stat. Lab., Ames, Iowa, 1995.

Natural Resources Conservation Service, *Summary Report: 1997 National Resources Inventory*, 84 pp., U. S. Dep. of Agric. Nat. Resour. Conserv. Serv., Iowa State Univ. Stat. Lab., Ames, Iowas, 1999.

Péwé, T. L., Desert dust: An overview, in *Desert Dust: Origin, Characteristics, and Effect on Man*, edited by T. L. Péwé, *Spec. Pap. Geol. Soc. Am., 186,* 1-10, 1981.

Péwé, T., L., E. A. Péwé, R. H. Péwé, A. Journaux, and R. M. Slatt, Desert dust: Characteristics and rates of deposition in central Arizona, in *Desert Dust: Origin, Characteristics, and Effect on Man*, edited by T. L. Péwé, *Spec. Pap. Geol. Soc. Am., 186,* 169-190, 1981.

Phillips, J. D., Sediment budget stability in the Tar River Basin, North Carolina, *Am. J. Sci., 287,* 780-794, 1987.

Phillips, J. D., Fluvial sediment delivery to a coastal plain estuary in the Atlantic drainage of the United States, *Mar. Geol., 98,* 121-134, 1991.

Pimentel, D., et al., Environmental and economic costs of soil erosion and conservation benefits, *Science, 267,* 1117-1123, 1995.

Prospero, J. M., The atmospheric transport of particles to the ocean, in *Particle Flux in the Ocean,* edited by V. Ittekkot, et al., pp. 18-52, John Wiley, New York, 1996.

Raich, J. W., and W. H. Schlesinger, The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate, *Tellus Ser. B., 44,* 81-99, 1992.

Renwick, W. H., Continental-scale reservoir sedimentation patterns in the United States, in *Erosion and Sediment Yield: Global and Regional Perspectives,* edited by D. E. Walling and B. W. Webb, *IAHS Publ., 236,* 513-522, 1996.

Ritchie, J. C., Carbon content of sediments of small reservoirs, *Water Resour. Bull., 25,* 301-308, 1989.

Schimel, D. S., Terrestrial ecosystems and the carbon cycle, *Global Change Biol., 1,* 77-91, 1995.

Schindler, D.W., Carbon cycling: The mysterious missing sink, *Nature, 398,* 106-106, 1999.

Schlesinger, W. H., Evidence from chronsosequence studies for a low carbon-storage potential of soils, *Nature, 348,* 232-234, 1990.

Schlesinger, W. H., Soil respiration and changes in soil carbon stocks, in *Biotic Feedback in the Global Climatic System: Will the Warming Feed the Warming?,* edited by G. M. Woodwell and F. T. Mackenzie, pp. 159-168, Oxford Univ. Press, New York, 1995.

Schlesinger, W. H., *Biogeochemistry: An Analysis of Global Change,* 2nd ed., 588 pp., Academic, San Diego, Calif., 1997.

Seaber, P.R., F. P. Kapinos, and G. L. Knapp, Hydrologic Unit Maps, *U.S. Geol. Surv. Water Supply Pap., 2294, 1-63,* 1987.

Skidmore, E. L., and N. P. Woodruff, Wind erosion forces in the United States and their use in predicting soil loss, *Agr. Handbook 346,* 42 pp., U. S. Dep. of Agric., Washington, D. C, 1968.

Stallard, R. F., Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial, *Global Biogeochem. Cycles, 12,* 231-257, 1998.

St. Louis, V. L., C. A. Kelly, E. Duchemin, J. W. M. Rudd, and D. W. Rosenberg, Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate, *BioScience, 50,* 766-775, 2000.

Tans, P. P., I. Y. Fung, and T. Takahashi, Observational constraints on the global atmospheric CO_2 budget, *Science, 247,* 1431-1438, 1990.

Trimble, S. W., *Man-Induced Soil Erosion on the Southern Piedmont, 1700-1970,* 180 pp., Soil Conservation Soc. of Am., Ankeny, Iowa, 1974.

Trimble, S. W., Decreased rates of alluvial sediment storage in the Coon Creek Basin, Wisconsin, 1975-93, *Science, 285,* 1244-1246, 1999.

Trimble, S. W., and P. Crosson, U. S. soil erosion rates—Myth and reality, *Science, 289,* 248-250, 2000.

Trimble, S. W., and S. W. Lund, Soil conservation and the reduction of erosion and sedimentation in the Coon Creek Basin, Wisconsin, *U. S. Geol. Surv. Prof. Pap., 1234*, 1-35, 1982.

U. S. Department of Agriculture, *State Soil Geographic (STATSGO) Data Base, Misc. Publ. 1492,* 35 pp., 1994.

Walling, D. E., and B. W. Webb, Erosion and sediment yield: a global perspective, in *Erosion and Sediment Yield: Global and Regional Perspectives,* edited by D. E. Walling and B. W. Webb, *IAHS Publ., 236,* 3-19, 1996.

Wischmeier, W. H., and D. D. Smith, Predicting rainfall erosion losses: A guide to conservation planning, *Handbook 537,* 58 pp., *U.S. Dep. Agric.*, Washington D.C., 1978.

R. W. Buddemeier, Kansas Geological Survey, University of Kansas, Lawrence, KA 66047. (buddrw@kgs.ukans.edu)

C. J. Crossland, LOICZ International Project Office, Netherlands Institute of Sea Research, Den Burg, Texel, Netherlands. (ccross@nioz.nl)

W. H. Renwick, Department of Geography, Miami University, Oxford, OH 45056. (renwicwh@muohio.edu)

S. V. Smith, Department of Oceanography, University of Hawaii, Honolulu, HI 96822. (svsmith@soest.hawaii.edu)

(Received August 29, 2000; revised February 8, 2001; accepted March 1, 2001.)