The impact of humans on continental erosion and sedimentation

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ABSTRACT

Rock uplift and erosional denudation of orogenic belts have long been the most important geologic processes that serve to shape continental surfaces, but the rate of geomorphic change resulting from these natural phenomena has now been outstripped by human activities associated with agriculture, construction, and mining. Although humans are now the most important geomorphic agent on the planet's surface, natural and anthropogenic processes serve to modify quite different parts of Earth's landscape. In order to better understand the impact of humans on continental erosion, we have examined both long-term and short-term data on rates of sediment transfer in response to glacio-fluvial and anthropogenic processes.

Phanerozoic rates of subaerial denudation inferred from preserved volumes of sedimentary rock require a mean continental erosion rate on the order of 16 m per million years (m/m.y.), resulting in the accumulation of ~5 gigatons of sediment per year (Gt/yr). Erosion irregularly increased over the ~542 m.y. span of Phanerozoic time to a Pliocene value of 53 m/m.y. (16 Gt/yr). Current estimates of large river sediment loads are similar to this late Neogene value, and require net denudation of ice-free land surfaces at a rate of ~62 m/m.y. (~21 Gt/yr). Consideration of the variation in large river sediment loads and the geomorphology of respective river basin catchments suggests that natural erosion is primarily confined to drainage headwaters; ~83% of the global river sediment flux is derived from the highest 10% of Earth's surface.

Subaerial erosion as a result of human activity, primarily through agricultural practices, has resulted in a sharp increase in net rates of continental denudation; although less well constrained than estimates based on surviving rock volumes or current river loads, available data suggest that present farmland denudation is proceeding at a rate of ~600 m/m.y. (~75 Gt/yr), and is largely confined to the lower elevations of Earth's land surface, primarily along passive continental margins; ~83% of cropland erosion occurs over the lower 65% of Earth's surface.

The conspicuous disparity between natural sediment fluxes suggested by data on rock volumes and river loads (~21 Gt/yr) and anthropogenic fluxes inferred from measured and modeled cropland soil losses (75 Gt/yr) is readily resolved by data on thicknesses and ages of alluvial sediment that has been deposited immediately downslope from eroding croplands over the history of human agriculture. Accumulation of postsettlement alluvium on higher-order tributary channels and floodplains (mean rate ~12,600 m/m.y.) is the most important geomorphic process in terms of the erosion and deposition of sediment that is currently shaping the landscape of Earth. It far exceeds even the impact of Pleistocene continental glaciers or the current impact of alpine erosion by glacial and/or fluvial processes. Conversely, available data suggest that since 1961, global cropland area has increased by ~11%, while the global population has approximately doubled. The net effect of both changes is that per capita cropland area has decreased by ~44% over this same time interval; ~1% per year. This is ~25 times the rate of soil area loss anticipated from human denudation of cropland surfaces. In a context of per capita food production, soil loss through cropland erosion is largely insignificant when compared to the impact of population growth.

Keywords: erosion, denudation, humans, soils, rivers, alluvium.

INTRODUCTION

The importance of natural and anthropogenic processes in modifying Earth's subaerial surface is generally apparent in terms of amounts of sediment released and transported during the chemical and physical breakdown of exposed rocks and minerals. Determining characteristic rates for each of these general sets of processes primarily involves determining fluxes of dissolved and particulate sedimentary material at quite different temporal and spatial ranges. At a geologic time scale, rates of continental denudation are approximately balanced by rates of sediment accumulation, and epoch-interval rates of erosion can therefore be estimated from surviving volumes of Phanerozoic sediment when corrected for erosional and subductional destruction. At a millennial scale, fluvial sediment fluxes to global oceans resulting from the combined influence of both geologic and human-induced changes over individual drainage basins is largely reflected in the current sizes of bed loads, suspended loads, and solute loads of major river systems. At a centennial to decadal scale, the impact of humans on continental erosion has been estimated from measured and modeled amounts of soil that are typically lost in response to various agricultural, constructional, and mining practices.

Although the general magnitudes of erosion rate at any of these three scales of consideration are now reasonably well constrained, fluxes to sedimentary reservoirs, fluxes from river drainages, and fluxes from monitored agricultural plots are typically reported in very different units of length or mass per unit area per unit time. As a result, the importance of these different erosional processes, typically measured over quite dissimilar land areas and time spans, is perhaps not fully appreciated by individuals working in different but closely related fields of research. In addition, those areas of Earth's surface that are primarily influenced by glacial and/or fluvial processes are largely exclusive

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of those regions undergoing extensive human modification through predominantly agricultural activity. As a result, the net human impact on continental erosion is perhaps not fully appreciated, particularly by members of the geomorphic or sedimentologic communities who tend to work at decidedly longer temporal and somewhat broader spatial scales of resolution.

Over Earth's orogens, at spatial dimensions of exposed continents and chronological dimensions of geologic time, it is generally recognized that rates of tectonism and uplift are largely balanced by rates of erosion. As a result, different orogenic belts may exhibit similar geomorphologies that are mostly independent of tectonic and/or climatic setting (e.g., Montgomery and Brandon, 2002). Over lower-elevation portions of Earth's surface, at a similar spatial scale of Earth's ice-free continents but at the temporal scale of human civilization (e.g., Ruddiman et al., 2005), cultivation has been the primary process of anthropogenic soil loss, and has chiefly affected those arable portions of tectonically stable cratons and passive continental margins. Across Earth's landscape, natural and agricultural erosion have impacted areas that are almost mutually exclusive.

In addition, despite the fact that rivers have probably served as the most important of all geomorphic processes in shaping the surface of Earth over most of geologic time, this state of dominance was exceeded some thousand years ago in response to the rock- and soil-moving activities of humans (e.g., Hooke, 2000). An appreciation of rates of tectonic uplift, rates of subsequent rock and mineral breakdown by weathering, and rates of transport of weathering products across the planet's surface to global oceans is of considerable relevance to understanding and anticipating the ongoing impact of human activities on continental geomorphology.

Here, our purpose is to present a global view of the current state of continental denudation, particularly with respect to identifying those portions of Earth's surface that are primarily impacted by natural glacial and fluvial processes, compared to those areas more recently impacted by human agricultural activities. We begin by summarizing deep-time constraints on rates of continental denudation imposed by surviving volumes of sedimentary rock. We then discuss relations between river basin geography and sediment yield, and apply these relations to a global digital elevation model to determine and map regions of maximum sediment flux. We take a similar approach to determine and map regions of maximum cropland soil loss, and then compare the significant difference in sediment fluxes that result from fluvial and agricultural erosion. We conclude with a short discussion of the significant disequilibrium that is being imposed on global fluvial systems through the impact of humans on continental erosion.

Continental Erosion from Sedimentary Rock Volumes

Tabulations of epoch-interval data on rock composition and volume by Ronov (1983) indicate that sediment on Phanerozoic continental and oceanic crust equals ~630 × 10^6 km^3, an amount sufficient to blanket all continental surfaces to a depth of ~3 km, and all ocean basins to a depth of ~300 m, respectively. Moreover, surviving rock volume in both continental and oceanic settings decreases with increasing age, a relation that reflects the progressive destruction of sedimentary (and other) rocks with the passage of geologic time (e.g., Garrels and Mackenzie, 1971). As noted by Veizer and Jansen (1979), data on decrease in rock volume with increasing age are typically exponential in form, a relation arising from the fact that the first-order cycling rate is largely dependent on rock reservoir size. Differences in rate of destruction among terrigenous clastic and carbonate sediments in continental (by erosion) and deep-marine (by subduction) settings reflect both long-term transfer of carbonate accumulation from deep- to shallow-marine settings (e.g., Berry and Wilkinson, 1994; Walker et al., 2002), as well as differences in rates of sediment cycling, primarily by subaerial erosion of epicontinental deposits and by subduction of deeper oceanic oozes.

From data on Phanerozoic change in volumes of surviving sediment, Wilkinson (2005) estimated characteristic reservoir sizes, fluxes, and cycling rates for terrigenous and carbonate sediments deposited on continental and oceanic crust. Differences between measured sedimentary rock volumes and those expected from characteristic reservoir fluxes and cycling rates reflect greater or lesser amounts of continental denudation, allowing for the calculation of Phanerozoic rates of sediment supply to the global sedimentary reservoir (Fig. 1). Phanerozoic fluxes have ranged over an order of magnitude, from ~0.6 × 10^6 km^3/m.y. during the Mississippian to ~7.7 × 10^6 km^3/m.y. during the Pliocene. The significance of this Pliocene flux, which is ~4 times that of the Phanerozoic average (2.0 × 10^6 km^3/m.y.) and ~3 times that of the preceding Miocene Epoch (~3.1 × 10^6 km^3/m.y.) has been noted by Hay et al. (1988), and discussed at some length by Peizhen et al. (2001) and Molnar (2004), who suggested that accelerated erosion over the latter part of the Neogene may relate to changes in sea level, to changes in climate, and/or increased glaciation in response to large oscillations in global climate. Regardless of the causes of this recent increase, values through much of the earlier Phanerozoic are less variable; even including the Pliocene value, the 25 epoch-interval sediment fluxes exhibit a standard deviation (1.6 × 10^6 km^3/m.y.), only 80% of the average flux (2.0 × 10^6 km^3/m.y.).

In addition to these epoch-interval estimates of Phanerozoic sediment volumes, which were principally derived from subaerial weathering of continental crust, Scotese and Golonka (1992) integrated plate tectonic, paleomagnetic, and paleogeographic data in order to estimate the areal distribution of subaerial mountain ranges and lowlands that were undergoing erosion during these same time intervals. Because regions of erosion and deposition are constantly changing over the duration of any single geologic time interval, these area-of-denudation estimates are somewhat dependent on the lengths of the epochs under consideration (e.g., Wise, 1974). In spite of this bias, areas of submergence and emergence covary with inferred intervals of continental flooding and exposure, ranging from a minimum exposed area of 72.1 × 10^6 km^2 attained during the Late Cambrian Sauk transgression, to a maximum exposure of 144.9 × 10^6 km^2 reached during the Late Permian Gondwanan emergence (Fig. 1).

More importantly, estimates of volumetric fluxes of sediment to the global sedimentary reservoir from data in Ronov (1983) and independent estimates of areas of subaerial continental crust undergoing erosion from Scotese and Golonka (1992) allow for calculation of mean rates of continental denudation over the past ~542 million years of Earth history. These range from ~4 m per million years (m/m.y.) during the Middle Triassic to ~53 m/m.y. during the Pliocene, with a mean of 16 (SD = 11) m/m.y. Regardless of reasons for epoch-to-epoch differences in sediment flux, this Phanerozoic mean reflects the net result of tectonic uplift and subaerial erosion over approximately the last half-billion years of Earth history. It serves as a base-line rate of mean deep-time continental denudation against which shorter-term anthropogenic modifications can be evaluated.

Continental Erosion from River Sediment Loads

In order to understand and appreciate the vertical and lateral scales of human-induced erosion, it is necessary to ascertain comparable parameters for fluvial systems that, along with any headwater regions influenced by glaciation, are the primary mechanisms of natural denudation of continental surfaces. As a step in this direction, we first briefly examine relations between topography and river sediment loads,

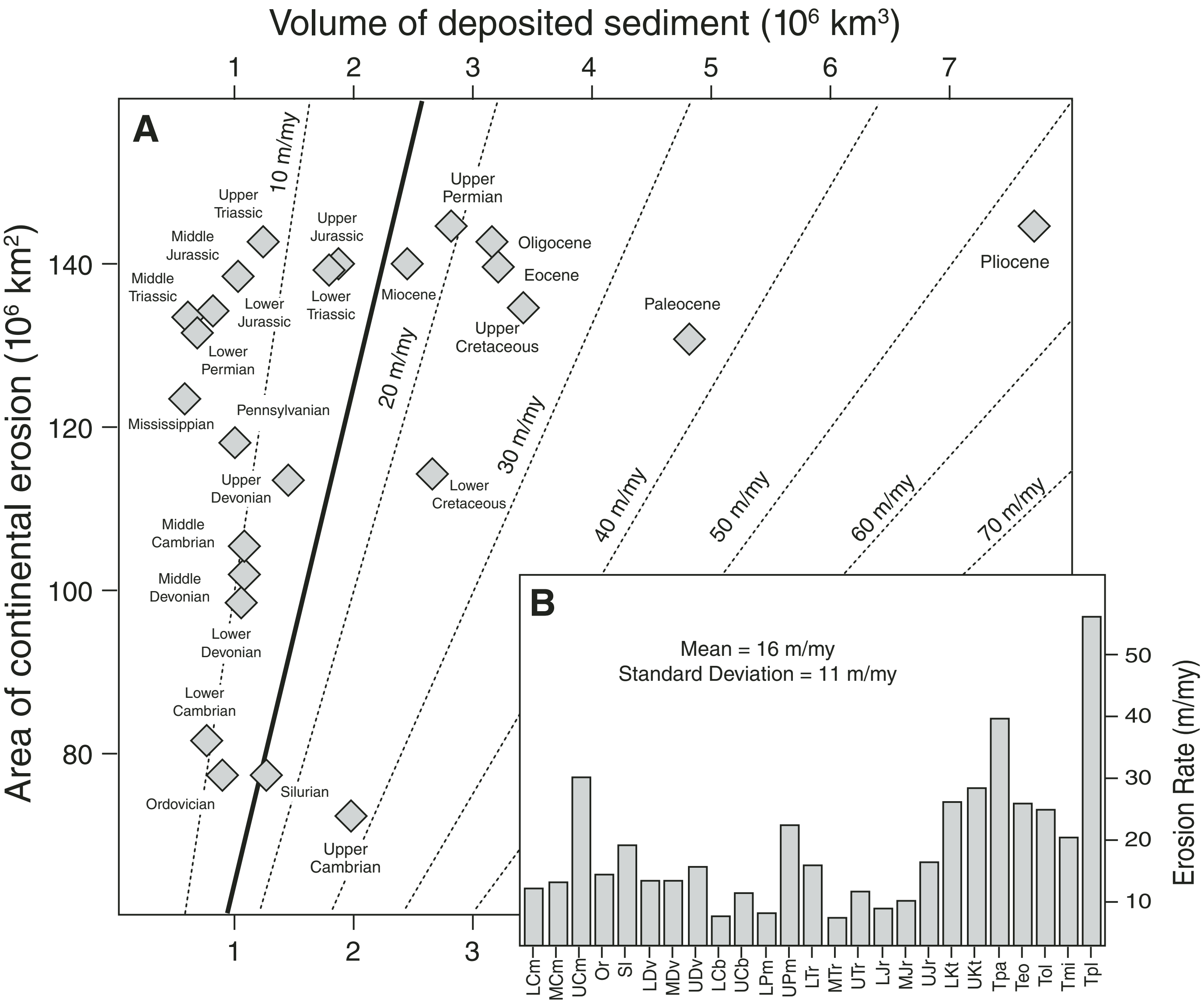

Figure 1. Geologic history of continental denudation from volumes and ages of Phanerozoic sediment. (A) Epoch-interval fluxes of Phanerozoic sediment (horizontal axis; from Ronov, 1983) and areas of continents exposed to subaerial erosion (vertical axis; from Scotese and Golonka, 1992). Dashed diagonals are lines of equal denudation rate; Phanerozoic mean = 16 m/m.y. (heavy solid line). (B) Temporal distribution of denudation rates.

and then relate these fluxes to spatial variation in topography across Earth's surface.

Fluvial Denudation

A significant body of literature now exists on relations between river sediment fluxes and different geographic and geomorphic characteristics that either directly or indirectly influence rates of continental erosion. From these investigations, the general magnitude of riverine bed load, suspended load, and solution load to global oceans has been reasonably well known for several decades, with estimates of suspended load ranging from 13.5 to 20.0 Gt/yr (e.g., Milliman and Meade, 1983; Berner and Berner, 1987; Walling, 1987; Milliman and Syvitski, 1992; Harrison, 1994; Summerfield and Hulton; 1994). Recently, Syvitski et al. (2005) suggested that the current annual global riverine suspended sediment flux to global oceans is on the order of 12.6 Gt, and that ~3.6 Gt is retained behind dams in reservoirs. Syvitski et al. (2005) also suggested that bed load makes up 1.6 Gt, and data in Summerfield and Hulton (1994) require that the solution load comprises an additional 2.9 Gt. On the basis of these values, the annual net riverine flux of all weathering products to global oceans is on the order of ~21 Gt.

Spatial Variation

Because topographic slope, relief, climate, vegetation, and rock type have been related to rates of continental denudation, many investigations have also attempted to quantify the relative importance of these parameters in controlling net rates of fluvial erosion. While denudation rates among individual river drainage basins can vary by orders of magnitude, many studies have concluded that rates of chemical weathering are primarily dependent on climate and rock type (e.g., Berner and Berner, 1987), while higher rates of mechanical erosion primarily reflect the combined influences of elevation and/or relief, with a lesser effect imposed by some measure of the amount of water available for erosion (e.g., Summerfield and Hulton, 1994) and the mean and annual range of ambient temperature (e.g., Harrison, 2000).

The overriding influence of topography and climate on continental erosion is readily apparent in the global distribution of sediment delivered to the oceans (Fig. 2). Ludwig et al. (1996) reported estimates of suspended load delivered to global oceans at a grid resolution of 2° × 2.5° that encompasses most of Earth's ice-free land surface. Assuming a mean suspended load/bed load ratio of ~10 (Syvitski et al., 2005) and a particulate/solution load ratio of ~6 (Summerfield and Hulton, 1994), as noted already, these data represent a net weathering flux of ~21 Gt/yr, and reflect a mean denudation rate of ~71 m/m.y. over the globe's entire exposed land surface. The spatial distribution of these coastal sediment fluxes indicates that the highest rates of erosion (per unit area of exposed continental crust) indeed do reflect the influence of both climate and tectonics. Coastal fluxes with erosion rates in excess of 100 m/m.y. generally occur in regions of high precipitation in low latitudes and in regions of more intense tectonism along active continental margins, such as those of the Pacific Rim and the Mediterranean Sea.

In addition to these rather qualitative conclusions about the effect of topography on continental denudation, we can take a more quantitative approach by combining data on river basin slope/elevation relations and rates of erosion with an appropriate digital elevation model in order to delimit those continental areas in which erosion yields the maximum amount of sediment. As noted already, many studies have established significant relations between river sediment loads and some index of basin topography, and these have variably described linear, exponential, and power law relations between erosion rate and mean elevation (e.g., Garrels and Mackenzie, 1971; Hay and Southam, 1977; Holland, 1978; Berner and Berner, 1987; Harrison, 1994, 2000; Pinet and Souriau, 1988; Pazzaglia and Brandon, 1996), local relief (Ahnert, 1970), and catchment slope (Aalto et al., 2006). As noted by Montgomery and Brandon (2002), the specific nature of linear, exponential, and/or power law relations between rate of erosion and each of the various topographic indices is related to regional differences in local uplift rate, climate, vegetation, and rock type.

Moreover, at broad scales of consideration, the magnitudes of elevation and various attributes of topography are intimately interrelated. For example, data on major world drainage basins from Summerfield and Hulton (1994)

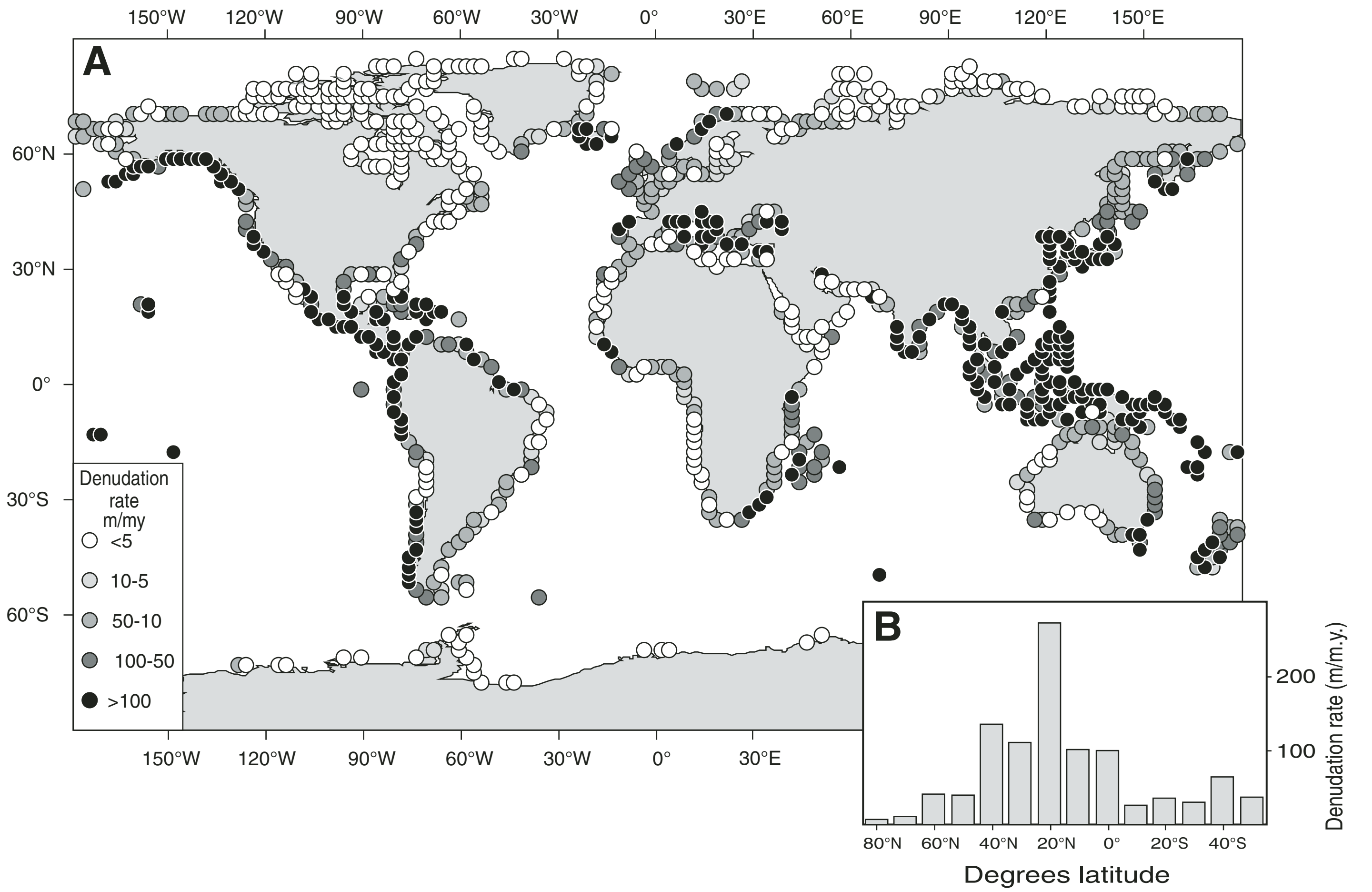

Figure 2. Spatial distribution of continental denudation rates (m/m.y.) needed for total sediment delivery to global oceans. (A) Flux values were derived from suspended sediment fluxes of Ludwig et al. (1996; http://islscp2.sesda.com), assuming a suspended load/bed load ratio of 10 and a particulate load/solution load ratio of 6. These data represent a net weathering flux of ~21Gt/yr derived from most ice-free continental land surfaces (~118 × 10⁶ km²), and require a mean denudation rate of ~62 m/m.y. Note that the highest sediment yields occur across coastal regions at low latitudes and adjacent to regions of rapid uplift (e.g., the Pacific Rim). (B) Distribution of net denudation rates as a function of latitude.

indicate that denudation rate correlates equally well with mean modal elevation ($r^2 = 0.44$), with basin relief ($r^2 = 0.49$), and with basin gradient ($r^2 = 0.44$). Here we use data on 33 basin sediment loads and mean modal elevations (means of modal elevations within 10 min grid cells weighted in proportion to their area variation by latitude) from Summerfield and Hulton (1994) in order to determine the elevations of maximum sediment yield (Fig. 3). Denudation rates range from 4 m/m.y. within the Kolyma River drainage (northeastern Siberia) at 0.56 km elevation, to 688 m/m.y. across the Brahmaputra River at 2.7 km elevation, and suggest that erosion rates increase by ~0.15% per meter increase in elevation.

River Sediment Fluxes

Given this relation between basin elevation and denudation rate, and the fact that ever-greater rates of erosion (with increasing elevation) occur over ever-smaller areas of land, we might then ask: which portions (elevations) of subaerial continents are yielding the largest *volumes* of river-borne sediment? The most current data on Earth surface elevations are made available by the Eros Data Center of the U.S. Geological Survey, and information pertaining to data sources and accuracy accompany the online data. Here we use the GTOPO30 data (http://edcdaac.usgs.gov/gtopo30/gtopo30.html), which represent average elevations contained within individual areas with 30 arc second length sides. The grid structure is composed of data at equiangular distances with a total of ~270 million elevations for all of the subaerial crust. To compute the distribution of continental elevations, the area of Earth's surface represented by each grid cell was calculated on the basis of its bounding latitudes (Snyder, 1987). Total areas were then tabulated for 1 m elevation increments, the maximum precision given in GTOPO30 (1996). Because here we are primarily interested in relating Earth surface areas to anticipated rates of fluvial erosion, only elevations of ice-free land surfaces (exclusive of Antarctica and Greenland) were tabulated.

An interesting contrast with respect to determining which portion of Earth's exposed surface

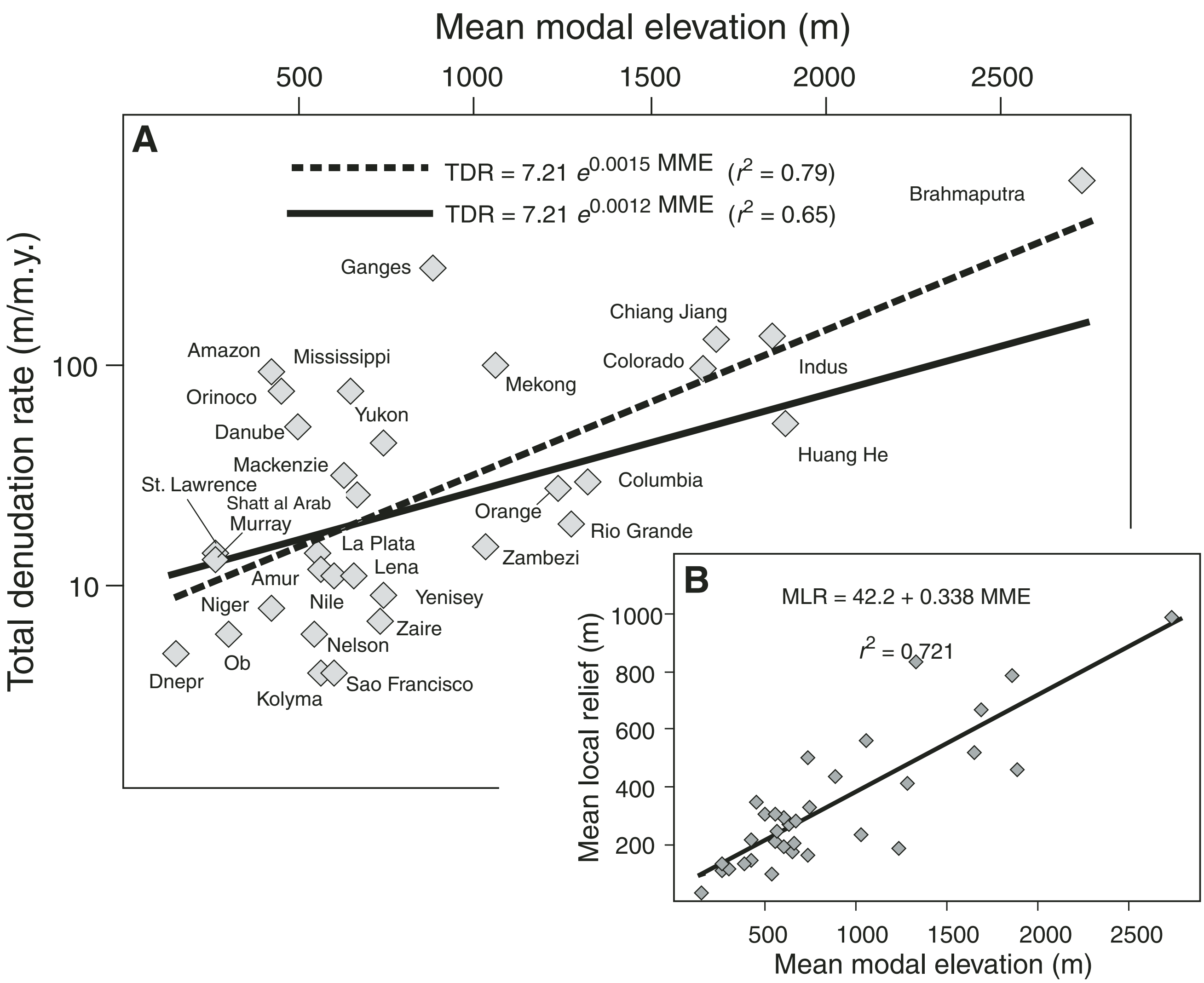

Figure 3. River basin denudation rate and topographic data from Summerfield and Hulton (1994). (A) Relation between mean modal elevation (MME) and total (chemical and mechanical) denudation rate (TDR) for 33 large river basins that drain ~39% (52×10^6 km^2) of Earth's ice-free land surface. Heavy dashed line is the best-fit exponential through the data (denudation decreases ~0.15% with each meter decrease in elevation); heavy solid line is the relation in best agreement with current estimates of river loads, and yields a global sediment flux of ~21 Gt/yr. (B) Linear relation between mean modal elevation and mean local relief (MLR).

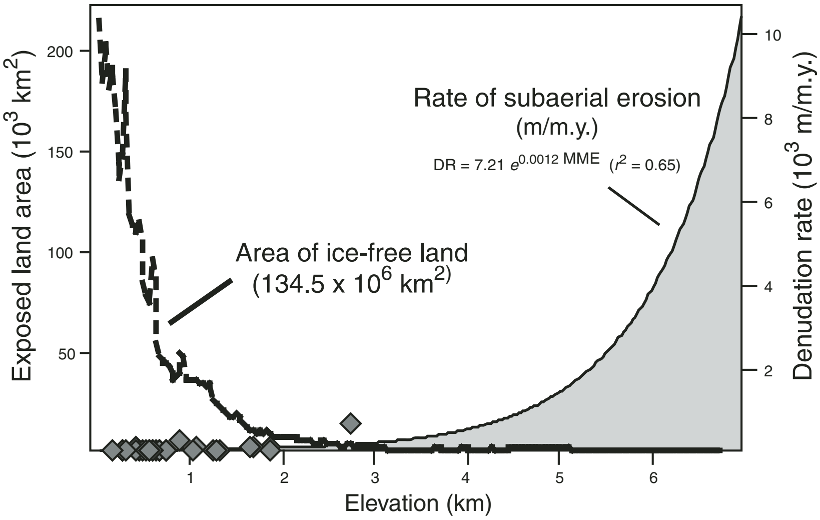

Figure 4. Areas of ice-free continental surfaces from GTOPO30 (dashed line; left axis), and anticipated rates of subaerial erosion (solid line; right axis) as a function of elevation (horizontal axis), and relation between mean modal elevation (MME) and denudation rate (DR). Diamonds are denudation rates from river basin areas (Summerfield and Hulton, 1994; diamonds in Fig. 3). Solid line is an extrapolation of these data constrained by total global river sediment loads (Syvitski et al., 2005; solid line in Fig. 3).

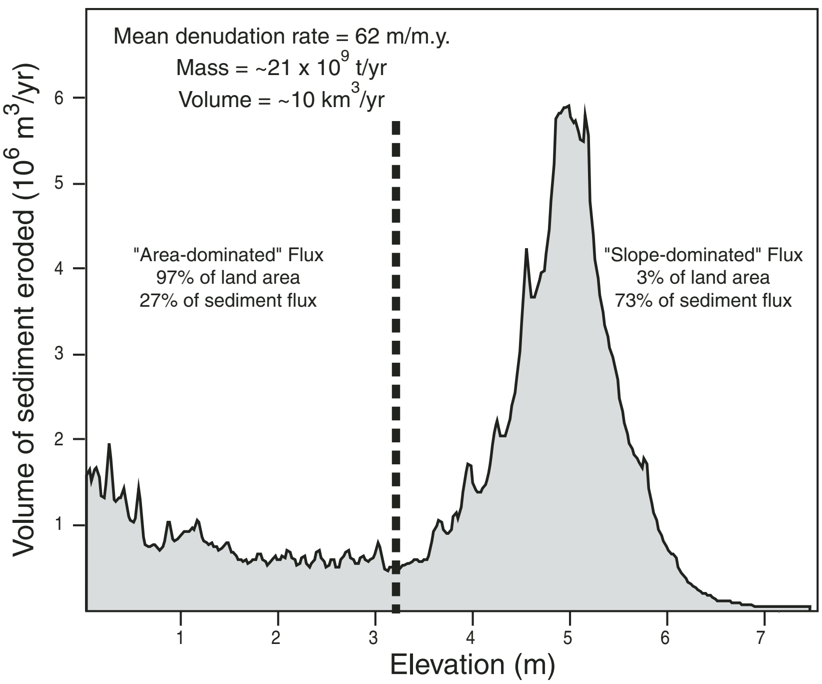

Figure 5. Volumes of material displaced by fluvial-glacial processes calculated from the product of Earth-surface areas (GTOPO30) and a denudation rate increasing by ~0.12% per meter of elevation (e.g., Summerfield and Hulton, 1994).

yields the greatest quantity of river sediment is that, with increasing elevation, rates of erosion exhibit a nonlinear increase (Fig. 3), while land area exhibits a concomitant nonlinear decrease (McElroy and Wilkinson, 2005). Taking the Summerfield and Hulton (1994) relation between land surface elevation and denudation rate at face value, the lowest rates of erosion (7.21 m/m.y.) occur over surfaces near sea level, where relief and slopes are presumably at a minimum; above this elevation, erosion rate increases by ~0.15% for every meter increase in elevation (Fig. 4).

Concatenation of vertical erosion rates from this relation with areas of exposed land from GTOPO30 yields a net volume estimate of material derived by fluvial erosion over Earth's subaerial surface as a function of elevation. However, combining the Summerfield and Hulton (1994) relation:

$$\text{denudation rate (m/m.y.)} = 7.21 \times e^{0.0015 \times \text{elevation (m)}} \tag{1}$$

(from Fig. 3) with areas of exposed land (GTOPO30) results in a net material flux of ~87 Gt/yr and a net denudation rate of ~257 m/m.y. These values are about four times those currently accepted from studies of river loads (21 Gt/yr; 62 m/m.y.). When applied to Earth's land surface, denudation rates derived from the major river basins (Eq. 1) are clearly too high, and most probably represent an imprecise extrapolation of generally low-elevation river data (the Brahmaputra River basin is the highest of the 33 basins at 2.7 km average elevation) to elevations in excess of 8.0 km. Because we know that the net global river load is on the order of ~21 Gt per year, it is therefore necessary to use a somewhat lower rate of increase in erosion rate with elevation in order to arrive at a global sediment flux in agreement with river data. Appraisal of different exponents shows that application of a value of ~0.12% per meter (versus 0.15%) to the GTOPO30 data yields a net annual material mass of ~21 Gt per year and a net annual global denudation rate of ~62 m/m.y., which are in good agreement with generally accepted global fluxes and erosion rates (e.g., Garrels and Mackenzie, 1971; Holland, 1978; Berner and Berner, 1987; Syvitski et al., 2005).

Data on areas and elevations of exposed land from GTOPO30, and the relation between rates of erosion versus elevation (with a coefficient of ~0.0012) from Summerfield and Hulton (1994), allow us to calculate volumes of glacio-fluvial erosion as a function of land elevation. These calculations suggest that the maximum volumetric flux of sediment from subaerial erosion occurs at an elevation of ~5 km (Fig. 5). Above this elevation, the weathering flux decreases because of less land area; below this level, the weathering flux decreases to an elevation of ~3.25 km because of lower rates of erosion; below ~3.25 km, flux increases somewhat because of ever-greater land area at ever-lower elevations. Above 3.25 km, riverine sediment flux is primarily determined by drainage slope, below 3.25 km, by drainage area. This pattern suggests that more than 73% of sediment delivered to the world's oceans originates from the erosion of mountainous areas with elevations greater than 3.25 km, which represent ~3% of ice-free continents. Fluvial erosion is mainly confined to drainage headwaters.

This rather extreme high-elevation focus of glacial-fluvial processes is perhaps best illustrated by considering the distribution of estimated rates of denudation over the conterminous United States. When the erosion versus elevation relations from Summerfield and Hulton (1994) are combined with U.S. GTOPO30 elevations, it becomes apparent that most extreme rates of denudation (>135 m/m.y.) are (perhaps not surprisingly) confined to those Cordilleran regions greater than ~2.5 km in elevation; the mean U.S. erosion rate is ~21 m/m.y. (Fig. 6).

Continental Erosion from Soil-Loss Data

Although mean rates of continental denudation derived from large global river loads (~62 m/m.y.) are not greatly different from Pliocene rates derived from global sediment volumes (53 m/m.y.), these values pale in comparison to the amounts of sediment routinely moved through human activities, primarily manifested as soil loss through agriculture. Following an approach similar to that taken with respect to river erosion, we first briefly summarize data on farmland soil losses, examine relations between agriculture and land elevation, and then attempt to relate sediment fluxes from soil erosion to Earth topography.

Farmland Denudation

Although the movement of rock and soil during road construction, building excavation, and other construction activities accounts for ~30% of all humanly transported material (Hooke, 2000), and although volumes of material displaced during mining activities can regionally exceed even this amount by many times (e.g., Douglas and Lawson, 2000), agricultural practices are far and away the dominant process of global anthropogenic erosion (Pimentel et al., 1995). Data on rates of agricultural soil losses are dispersed throughout the scientific literature, largely because the topic is studied widely by geomorphologists, agricultural engineers, soil scientists, hydrologists, and others, and is of considerable interest to policy-makers, farmers, environmentalists, and many others. Despite this, there is no clear consensus about current rates of cropland erosion in the United States or across other, less studied, parts of the world.

In the United States, research on cropland soil erosion started in the 1930s and, over subsequent decades, the U.S. Department of Agriculture (USDA) and other organizations have developed quantitative procedures for estimating soil loss in response to agricultural practices, primarily across the stable North American craton.

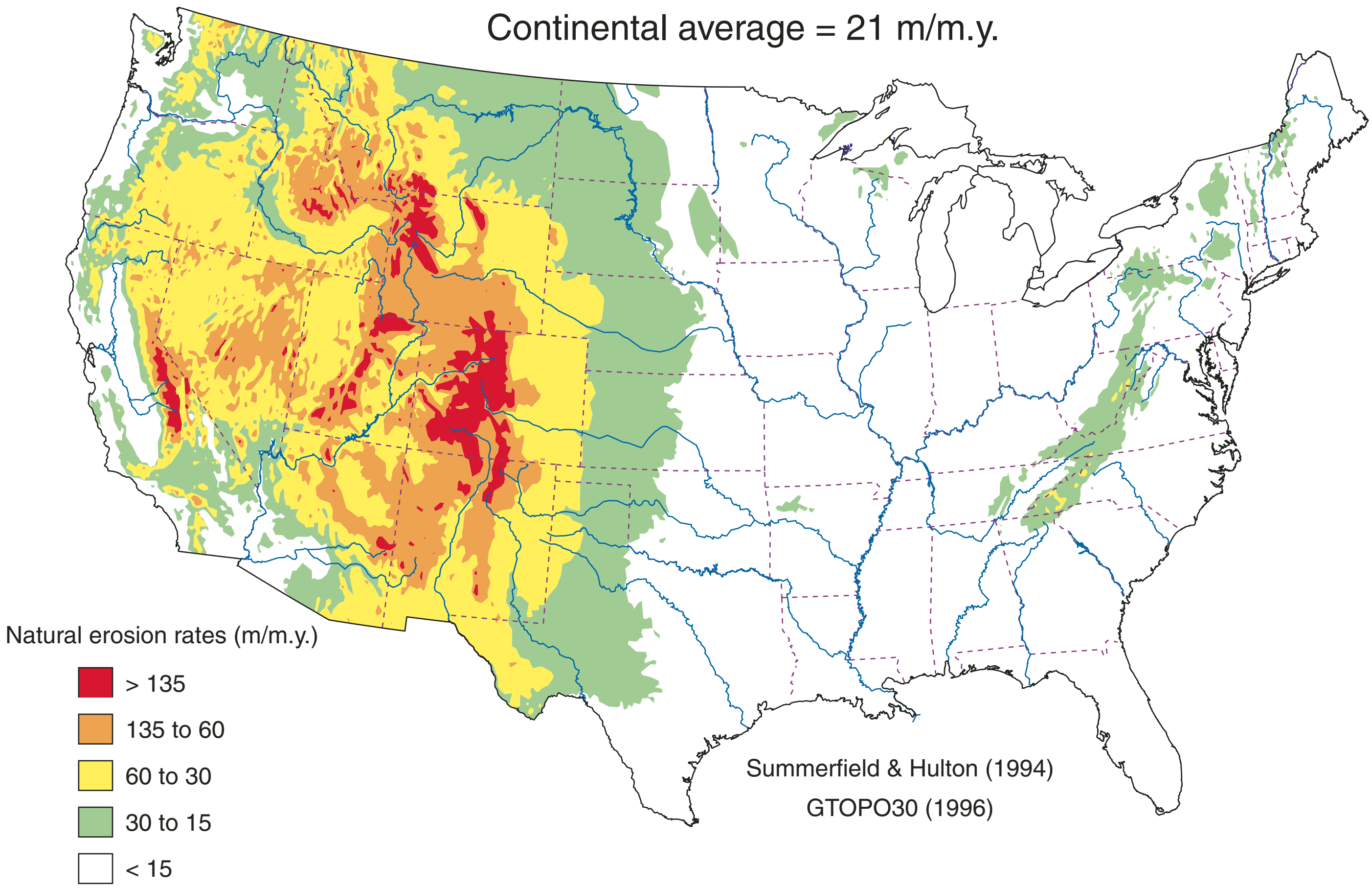

Figure 6. Estimates of average natural erosion (denudation) rates inferred from GTOPO30 area-elevation data and global fluvial erosion-elevations relations from Summerfield and Hulton (1994). Mean rate of denudation for the entire area of the contiguous United States is ~21 m/m.y.

The Agricultural Research Service (ARS) established the National Runoff and Soil Loss Data Center at Purdue University in 1954 to locate, assemble, and consolidate available data from throughout the United States. Since then, many tens of thousands of plot-years of runoff and soil-loss data have been collected from a wide range of U.S. locations.

Based on these and related data, a number of studies have attempted to constrain estimates of U.S. cropland soil losses; these have resulted in order-of-magnitude differences, ranging from ~200 m/m.y. to ~450 m/m.y. (USDA, 1980) to ~900 m/m.y. (Beasley et al., 1984) to ~1000 m/m.y. (Barlowe, 1979) to ~1500 m/m.y. (Harlin and Barardi, 1987). This array of values has given rise to a similar array of opinions concerning the importance of soil erosion and its potential societal impact ranging from "90% of U.S. cropland is losing soil above the sustainable rate" (Pimentel et al., 1995) to "estimates of soil erosion are fallacious" (Parsons et al., 2004). In light of this range of interpretations of soil-loss data, it is difficult to arrive at an unequivocal value for cropland soil losses.

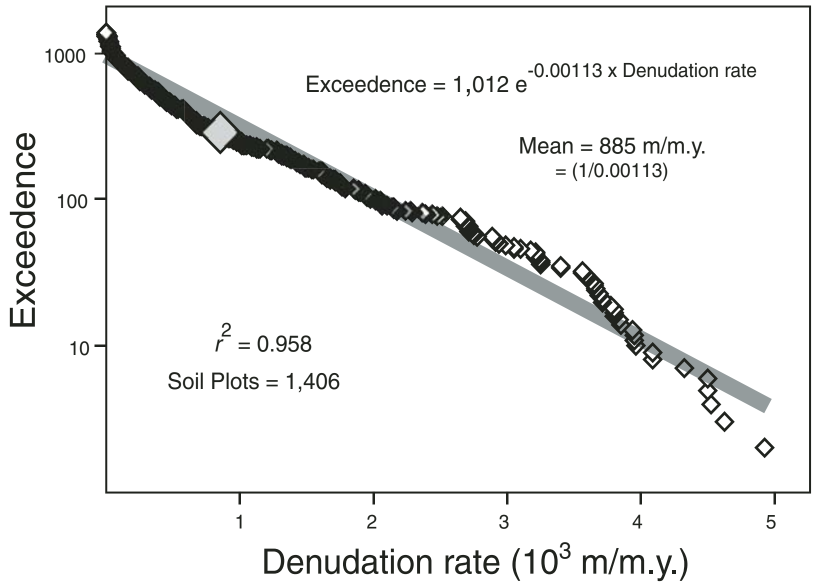

Figure 7. Exceedence plot of annual erosion plot soil losses (*x* axis) relative to number of loss rates larger than some *x*-axis value (*y* axis). Note that these define an exponential distribution of loss magnitudes; the reciprocal of the slope yields a mean soil-loss rate of 885 m/m.y. (gray diamond).

Perhaps the best summary of U.S. soil-loss measurements is that by Nearing et al. (1999), who examined data on variability in soil erosion collected between 1939 and 1989 from replicate plot pairs, and presented over 700 annual erosion measurements from 13 sites across the conterminous United States (Fig. 7). These data exhibit an exponential distribution; erosion plot exceedence (number of plot soil-loss measurements exceeding some soil-loss value) versus loss rate defines a trend in which exceedence decreases by 0.113% for each unit increase in erosion rate. The underlying reason for this distribution is probably complex in detail, but must generally relate to the fact that diverse natural processes exhibit similar Poisson distributions of process magnitude; amounts of rainfall during one precipitation event are the particular example probably most closely related to the equivalent distribution of annual soil losses. Regardless of origin, an exponential distribution of soil-loss magnitudes allows for the straightforward determination of mean loss rates in that the reciprocal of the slope of exponentially distributed data is the population mean. In the case of these USDA-ARS data, mean soil losses are therefore equal to 885 m/m.y. in the areas under cultivation. This value falls somewhere in the middle of the range of U.S. loss values noted above, and is in general agreement with fairly recent estimates of 680 m/m.y. (Pimentel et al., 1995), 520 m/m.y. (USDA, 1994), and 480 m/m.y. (Uri and Lewis, 1999).

In addition to these cropland soil losses, which occur over ~11% of the global land surface (Food and Agriculture Organization, 2004), a somewhat lower rate of pastureland erosion (240 m/m.y.; USDA, 1989) occurs over an additional 26% of Earth's land area. While these estimates are derived from U.S. erosion data, soil losses are even higher in many other countries. Pimentel et al. (1995) estimated that cropland erosion rates are highest (~1300 m/m.y.) in the ~62% of Earth's surface encompassed by Asia, Africa, and South America. Based on these considerations, it seems that a conservative estimate of global mean soil loss from all agricultural activities should be on the order of ~600 m/m.y. in the areas under cultivation, and this is the value we employ here in assessing the net impact of humans on continental erosion. This value does not include any rock and soil moved during mining and construction; if these activities were also included, the value would be significantly higher. Even this relatively conservative value for human denudation is ~30 times that of deep-time rates inferred from sedimentary rock volumes (16 m/m.y.), and ~7 times that indicated by modern river sediment loads (62 m/m.y.).

Spatial Variation

If we accept the premise that 600 m/m.y. is a reasonable estimate for the impact of humans on agricultural land surfaces, we might then ask: What is the spatial distribution of croplands across Earth's landscape that experience these sorts of erosion rates, and how does this distribution compare with that for fluvial processes (e.g., Fig. 6)? In order to address this first question, it is necessary to resolve how cropland erosion is distributed with respect to continental geomorphology. Although we are unaware of any data on the distribution of global farmlands with respect to elevation, the USDA Natural Resources Conservation Service does provided an estimate of the distribution of erosion across U.S. croplands (http://www.nrcs.usda.gov/technical). For this map, soil losses were calculated from the Universal Soil Loss Equation, which estimates average annual soil loss from sheet and rill erosion based on rainfall characteristics, soil erodibility, slope length and steepness, land cover, and agricultural practices (Fig. 8). Although the mean rate of cropland denudation determined using this approach (250 m/m.y.) is somewhat lower than other estimates of U.S. soil loss based on direct measurement (885 m/m.y., Nearing et al., 1999; 680 m/m.y., USDA, 1989), it does serve to demonstrate that arable areas of the United States largely occur in the Mississippi River drainage basin, which is largely located on the stable craton. These regions are almost entirely at elevations of less than 1 km.

To the degree that this distribution of cropland across other land surfaces relative to elevation is similar to that inferred for the United States, we can conclude that most of the ~37% of global land area used as farmland also occurs at elevations less than 1 km in elevation, a supposition

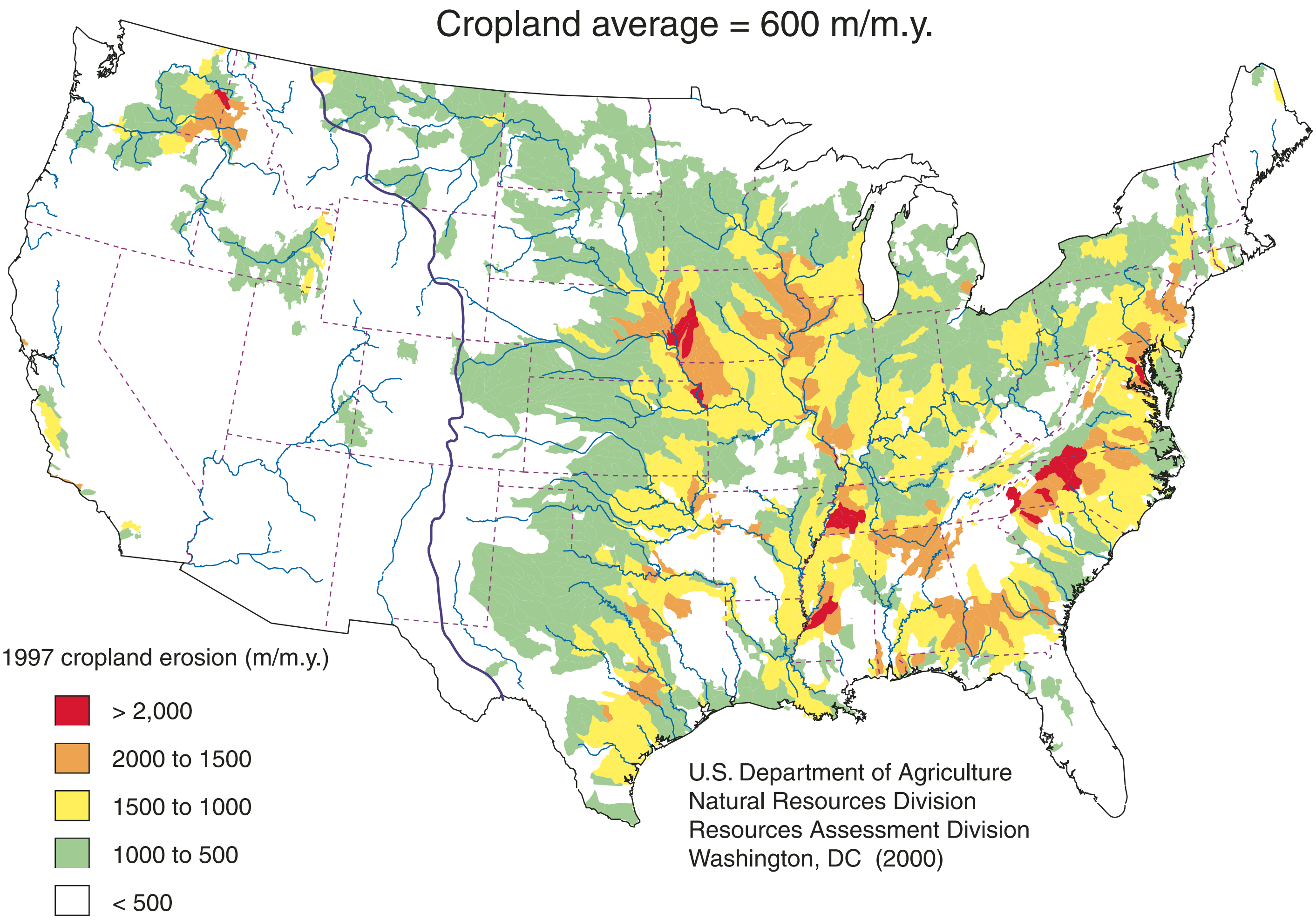

Figure 8. Rates of cropland erosion derived from estimates by the Natural Resources Conservation Service using the Universal Soil Loss Equation, and scaled to a farmland average of 600 m/m.y. The solid blue line is the western edge of the North American craton, here defined as the margin of the Great Plains physiographic province. Areas of arable land are largely confined to cratonic regions under 1 km in elevation.

enforced by the fact that a significant portion of Earth's population lives within 100 km from some coast.

Farmland Sediment Fluxes

Assuming a global farmland soil-loss rate on the order of ~600 m/m.y., and this qualitative relation between elevation and farmland cover (e.g., Fig. 9), we can now ask: What portions of subaerial continents yield the largest volumes of agriculturally derived sediment? In order to quantify relations between elevation and intensity of agriculture (and in the absence of more specific data), we assume that the proportion of land utilized for agriculture (cropland and pasture; Pct_{ag}) as a function of elevation (m) is adequately described by the empirical relation:

$$Pct_{ag} = 0.6\, e^{-0.001\ \text{elevation}}. \quad (2)$$

In other words, ~60% of the land surface near sea level is farmland, and this amount decreases by ~0.1% for each meter increase in elevation. Equation 2 and the GTOPO30 elevation data allow us to calculate areas of farmland as a function of elevation (Fig. 9). This intercept and slope were chosen because they yield the actual net farmland area now on modern Earth (~50 × 10^6 km^2; ~37% of ice-free subaerial continents), and constrain ~93% of farmland areas to elevations of less than 1 km. Assuming a mean farmland soil-loss rate of 600 m/m.y. and this inferred relation between elevation and cropland soil loss (Eq. 2), we can then proceed to calculate volumes of soil loss through agricultural practices as a function of land elevation (Fig. 10). These figures indicate that more than 65% of the sediment derived from global farmlands originates from the erosion of lowlands at elevations of less than 350 m, ~50% of ice-free continental surfaces. Agricultural erosion is primarily confined to low-elevation passive margin regions.

POTENTIAL SOURCES OF ERROR

On the basis of data on volumes of Phanerozoic sedimentary rocks, on loads of modern rivers, and on annual amounts of soil lost from agricultural farmlands, it seems apparent that while current rates of sediment delivery to global oceans are within the range of variation expected from long-term rates of continental denudation, volumes of soil loss from farmland surfaces are several times that amount. When converted to mass (~2.5 g/cm^3), epoch-interval sedimentary rock volumes indicate continental denudation rates of ~4.9 ± 4.0 Gt/yr (Fig. 11). The inferred Pliocene rate (19 Gt/yr) is similar to that estimated from current river loads (21 Gt/yr), but both of these are ~1/3 the mass

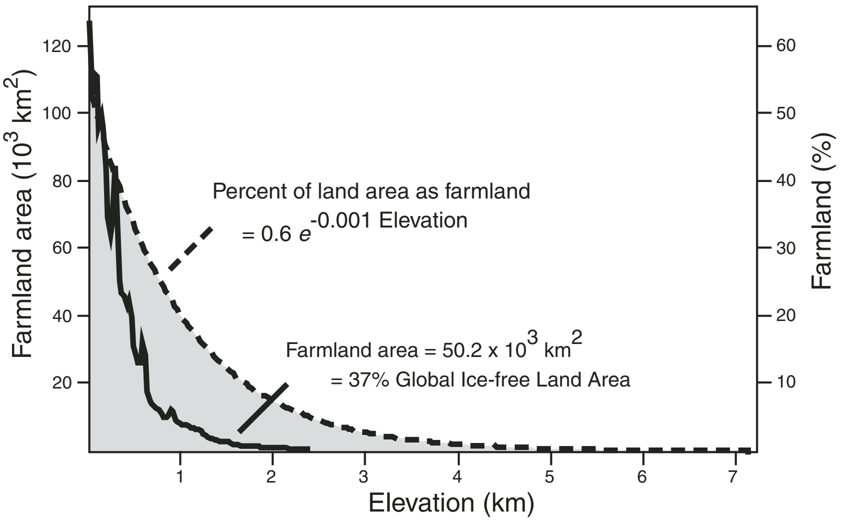

Figure 9. Inferred distribution of amount of farmland area relative to total land area versus elevation (right axis; dashed curve) and modeled areas of farmland (left axis; solid curve) derived from GTOPO30 area/elevation data.

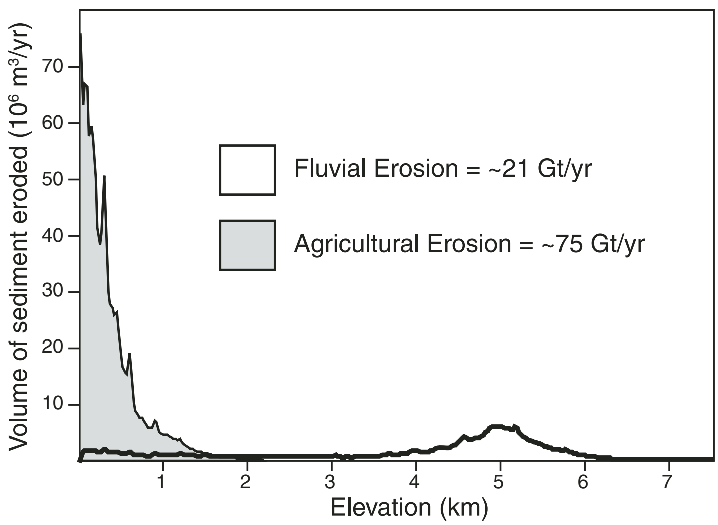

Figure 10. Volumes of sediment sourced by fluvial (open, solid line) and agricultural (gray shading) processes as a function of elevation. Fluvial fluxes are the same as those plotted on Figure 5.

of sediment displaced by agriculture (63 Gt/yr; Fig. 11).

This difference suggests that: (1) sediment delivery by major rivers is not demonstrably different from that which has occurred over the past several million years of Earth history; the activity of humans in displacing soil from agricultural areas has had a relatively small impact on large river sediment fluxes to global oceans; and (2) amounts of sediment removed from farmland regions of generally low elevation are ~3 times higher than that of current river sediment loads. This difference represents a significant imbalance in the Earth-surface sediment budget, and must either represent a noteworthy misunderstanding in current rates of farmland denudation, or indicate significant storage of eroded sediment somewhere between cropland surfaces and the edges of global oceans.

Are the significant rates of cropland denudation simply in error? Several aspects of compiling soil-erosion plot data and/or comparing these with rates those derived from other metrics of continental erosion might give rise to significant but spurious differences. First, it should be recognized that a significant amount of data utilized to infer rates of U.S. farmland erosion is in part or entirely derived from the repository of the USDA-ARS National Soil Erosion Research Laboratory at West Lafayette, Indiana. Although these soil losses are routinely expressed as annual values, the individual values that comprise these data are themselves derived from measurements taken over significantly shorter durations of time, typically spanning individual storm events, and largely represent the amount of erosion that occurs over fairly small cropland plots that are normally 2–8 m in width and 22 m in length (e.g., Risse et al., 1993). Several models of cropland soil loss intended to augment these field data have now been widely employed to estimate soil losses over broader regions (e.g., Wischmeier, and Smith, 1978; Skidmore and Woodruff, 1968). These models yield results that are broadly consistent with rates of cropland erosion determined by direct measurement.

However, the spatially and temporally limited nature of soil-loss measurements, and the broad application of numerical models of cropland denudation, such as the Universal Soil Loss Equation (USLE), the Wind Erosion Equation (WEE), and their derivatives, have led several authors to question the widely held notion of extreme soil losses. Trimble and Crosson (2000), for example, pointed out that rates of soil loss are poorly constrained by field data, that the commonly used numerical models of soil erosion only predict the amount of sediment moved *on* a field but not necessarily removed *from* a field, and that significantly more data, such as cropland and watershed sediment mass budgets, are needed in order to arrive at a truly informed estimate of magnitudes of soil erosion. Parsons et al. (2004) took an even harder line, arguing that long-term amounts of basin lowering required by general hypotheses of ruinous soil losses are incompatible with observations, that no simple relation exists between area of cropland erosion and net sediment flux, and that perceptions of soil erosion rates on the order of hundreds of meters per million years are grossly exaggerated.

If perceptions of the magnitudes of soil loss are indeed overstated, this inaccuracy may relate to: (1) the significant differences in the temporal scale at which large river basin and cropland erosion rates are determined, (2) the effect of sediment storage behind dams, or (3) biases in continental erosion stemming from a reliance on data from large river basins to characterize all continental surfaces. If none of these factors is sufficient to account for the seemingly enormous impact of humans on continental erosion, then it is necessary to attempt a general sediment budget, at the scale of continental surfaces, that largely accommodates the apparent mismatch between farmland sediment yields and river sediment loads.

Temporal and Spatial Scales of Erosion

While it seems evident that farming practices are the most important processes of erosion acting on the surface of modern Earth, the significance of this conclusion might be challenged on the basis of the fact that rock volumes, river loads, and agricultural erosion rates are characteristically determined over quite dissimilar time intervals. This difference in duration of observation is of potential importance for two reasons. First, processes that proceed with a high degree of irregularity, such as geomorphic and tectonic processes (Gardner et al., 1987), sediment deposition (Sadler, 1981), and biologic evolution (Gingerich, 1993), exhibit negative power law relations between net rate and the duration of time over which the rate is established. Second, because annual cropland soil losses are primarily determined by the summation of soil losses over relatively short storm events, and because studies assessing the impact of agriculture will tend to focus on those times when some measurable amount of erosion is actually occurring, soil-loss rates might be expected to be significantly higher than those derived from volumes of sedimentary rock.

However, differences in duration of observation between the accumulation of sedimentary rock over geologic epochs, annual sediment yields by large rivers, and the removal of cropland soil during storm-related precipitation events are probably not a significant explanation for the disparity in cropland and riverine sediment fluxes. The reason for discounting this potential bias is that, as noted already, large river fluxes are not demonstrably different than those suggested by Pliocene rock volumes. Even though most large-river sediment loads are typically reported as annual fluxes, several have been evaluated with monthly resolution (Syvitski et al. 2005). These subannual (as well as annual) time scales of large river load observation are largely the same as those employed in arriving at (significantly larger) cropland fluxes, but are still in general agreement with rates derived from sedimentary rock volumes, even though the latter span six to seven orders of magnitude more time.

Sediment Storage behind Dams

Could differences between large-river sediment delivery to global oceans and that anticipated from cropland soil losses be resolved by virtue of the fact that a significant volume of cropland-derived sediment is stored in reservoirs behind dams and other impoundments? Although dams currently affect over half of large river systems (Nilsson et al., 2005), the amount of stored sediment does not explain this discrepancy. Syvitski et al. (2005), for example, estimated that ~20% of modern particulate riverine sediment is trapped in large reservoirs; Vörösmarty et al. (2003) suggested that an additional 23% is trapped behind smaller impoundments. Although the storage of river-borne sediment in reservoirs has been sufficient to reduce the net coastal flux by ~10% (Syvitski et al., 2005), the net retention of sediment by dams is small (~4 Gt/yr) when compared to the size of the farmland flux (~63 Gt/yr). In spite of rather dramatic increases in land erosion that have resulted from human activities, the net impact of various anthropogenic processes on the fluvial delivery of sediment to global oceans has been modest. It should also be noted, however, that Vörösmarty et al. (2003) also reported a 6-fold increase in the amount of riverine particulate sediment retained in large reservoirs between 1950 and 1985. Given the significant difference between farmland fluxes and current river delivery to coasts, this proportion may significantly increase over the coming decades.

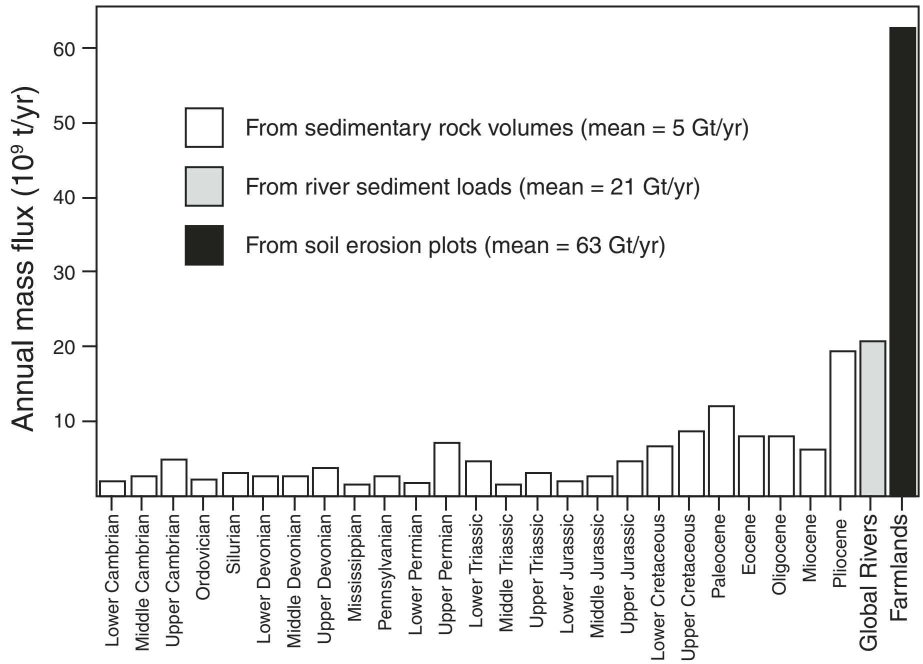

Figure 11. Annual rates of global erosion and resultant sediment delivery from data on sedimentary rock volumes (open bars), river loads (shaded bar), and farmland soil losses (black bar). Note that the erosion rate inferred from soil losses is ~3 times that suggested by global river loads and younger Neogene sediment volumes.

Effect of River Basin Size

The vast majority of meteoric precipitation that falls on Earth's landscape is ultimately delivered to some continental coast where the junction between a river basin and the coast is essentially a point with no lateral dimensions. As a result, outlines of river catchments are crudely rectilinear in shape, with one corner of the rectangle serving as the point of coastal discharge. Because lesser basins serve to drain regions between larger areas of coastal discharge, smaller catchments are typically nearer the coast and have lower mean elevations (e.g., Fig. 12). Because agriculture is most widespread across regions of lower elevation, could the significant imbalance between cropland soil losses and river sediment loads merely reflect the fact that a significant fraction of cropland-derived sediment is being carried to global oceans by unmonitored smaller rivers?

Catchments across South America, for example, decrease in area toward both the Pacific and the Atlantic coasts, even though it has roughly equal portions of active and passive continental margins. Moreover, of the thousands of river basins that could be defined as the area drained by any coastal channel and its tributaries, only five (Amazon, Orinoco, Paraná, Sao Francisco, and Tocantins) are of sufficient size to be included in tabulations of river sediment loads such as that by Summerfield and Hulton (1994), and these largely drain more stable cratonic crust (Guyanan and Brazilian Shields).

When considering metrics of river basin shape across all continents, it can also be shown that a power law distribution fits many size-frequency relations, such as areas of drainage above randomly determined points along stream channels (such as oceanic points of entry) and above stream confluences (e.g., Hack, 1957; Horton, 1945). Such power law distributions imply that one could also define an infinitely large number of drainages along global coasts. Because of limitations imposed by typical continental hypsometries, the greater number of basins along coastal regions also implies that each encompasses a lower mean elevation. Also, because cropland erosion is preferentially distributed among regions of low elevation, it follows that unit-area sediment yields biased toward larger river drainages may be significantly lower than loads carried by smaller, more intensively farmed basins along coastal margins.

Data on river sediment loads are typically derived from measurement of larger river basins that, by necessity, also drain regions of higher mean elevation. It is therefore at least plausible that selective measurement of large river sediment fluxes serves to grossly underestimate net sediment delivery to global oceans. Because most current estimates of sediment delivery by smaller basins are primarily model-based (e.g., Ludwig and Probst, 1998; Syvitski et al., 2005), it is difficult to unequivocally evaluate the plausibility of this. However, several aspects of these data suggest that this potential bias cannot account for differences between cropland soil losses and river sediment loads. Available data (e.g., Summerfield and Hulton, 1994) show no relation between basin area and area-normalized sediment yield. The Brahmaputra (640 × 10^3 km^2) and Dnepr (540 × 10^3 km^2) Rivers, for example, are among the smallest of the "large" river basins, yet differ drastically in net denudation rate (688 m/m.y. versus 5 m/m.y., respectively), while erosion across the largest (Amazon, 6000 × 10^3 km^2) is intermediate (93 m/m.y.).

In addition, differences between "big" river sediment loads and inferred cropland losses appear to be, at least qualitatively, too large to even be accommodated by hypothesized excess soil losses across drainages of "small" coastal drainages. Current areas of U.S. farmland are on the order 3.8 × 10^6 km^2, ~40% of total area. From the spatial distribution of cropland erosion rates (Fig. 8), it seems apparent that most of this acreage occurs along the Mississippi River and its tributaries. Denudation across the

Figure 12. South American drainage basins derived from a sinusoidal projection of GTOPO30 digital elevation model data as described by Jenson and Dominingue (1988). Note that basin area decreases with proximity to the coast.

Mississippi River basin has been variably estimated from suspended sediment load to range from ~26 m/m.y. (Meade and Parker, 1985; Hovius, 1988; Milliman and Syvitski, 1992; Harrison, 2000) to ~65 m/m.y. (Darwin, 1881; Ludwig et al., 1996) to ~70 m/m.y. (Pinet and Souriau, 1988; Summerfield and Hulton, 1994), and has varied annually between ~10 m/m.y. and 80 m/m.y. between 1950 and 1980 (Walling and Fang, 2003). When corrected for reasonable additions of dissolved and bed load, all of these rates fall within the norm for major river fluxes estimated globally to be ~60 m/m.y. (Ludwig et al., 1996; Summerfield and Hulton, 1994). Because these Mississippi River basin rates, by definition, do not include any contribution from smaller coastal drainages, it therefore seems apparent that differences between these rates and those anticipated from studies of soil erosion are in fact real; a significant volume of agriculturally derived sediment is currently being stored in global river systems some distance downslope from sites of cropland disturbance, and some distance upslope from coastal points of river discharge.

Sediment Storage as Postsettlement Alluvium

The literature is replete with studies showing that measured river sediment yields do not accurately portray actual rates of farmland denudation. The ratio of sediment yield to net denudation has been termed the *sediment delivery*

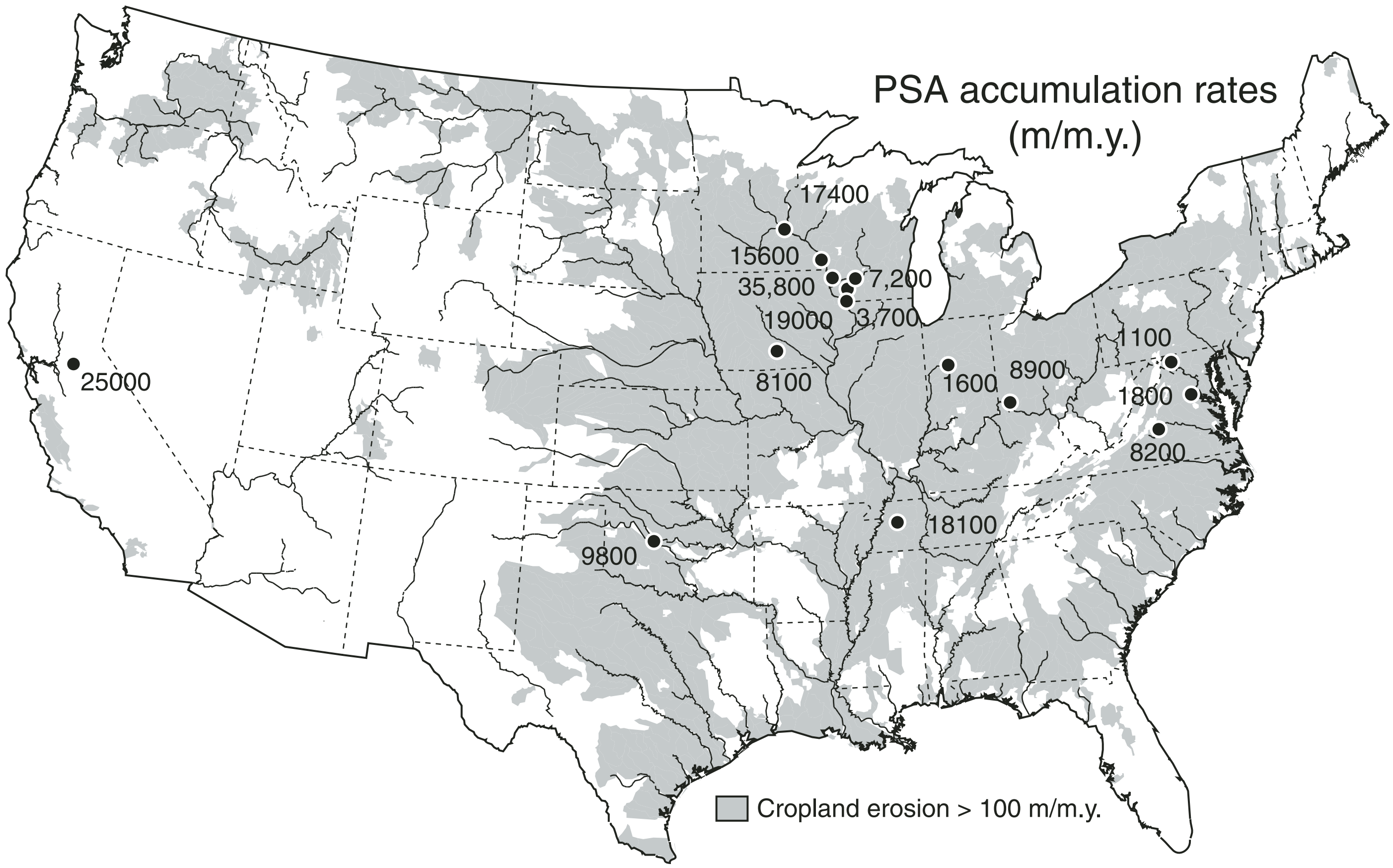

Figure 13. Vertical accumulation rates for 15 reported (see text) deposits of postsettlement alluvium (PSA). These primarily occur along the valleys of 3rd-to 6th-order drainages immediately downslope from cropland areas of accelerated agricultural erosion. Shaded area is that portion of the United States where cropland soil losses exceed 500 m/m.y. (Fig. 8).

ratio (Roehl, 1962), and merely reflects the fact that cropland sediment yields are typically only a fraction of cropland soil losses. It has also been widely acknowledged that a significant portion of eroded material may be deposited immediately adjacent to agricultural acreage on alluvial fans, on colluvial slopes, within 3rd- to 6th-order stream channels, and/or on their floodplains (Fig. 13). Such deposits are commonly referred to as postsettlement alluvium, and the composition, stratigraphy, and depositional history of postsettlement alluvium have now been reported from many areas, primarily throughout the Midwestern states (e.g., Knox, 1972, 1977; Costa, 1975; Johnson et al., 1980; Magilligan, 1985; Jacobson and Coleman, 1986; Norton, 1986; Wolfe and Diehl, 1993; Beach, 1994; Lecce, 1997; Trimble, 1999; Bettis and Mandel, 2002; Florsheim and Mount, 2003).

Tabulation of thickness and age from these sources indicates that, like soil-plot erosion data (Fig. 7), postsettlement alluvium accumulation rates exhibit an exponential distribution in which exceedence (number of rate measurements exceeding some value) decreases by 0.0079% for each meter per million year increase in accumulation rate (Fig. 14). As noted already with respect to measurement of plot soil losses, the reciprocal of the exponent slope is the mean of that population, and yields an average postsettlement alluvium accumulation rate of ~12,600 m/m.y. This rate is, of course, many times larger than the inferred mean rate of cropland soil loss (600 m/m.y.), and suggests that a significant amount of material derived from cropland erosion is indeed accumulating as alluvial material adjacent to cropland acreage.

Although several investigations (e.g., Beach, 1994; Trimble, 1999) have derived rather detailed regional sediment budgets of soil erosion and alluvium deposition for parts of Minnesota and Wisconsin, it is difficult to rely on sparse regional studies alone to clearly establish the net amount of sediment currently stored as postsettlement alluvium, and to unequivocally determine whether this mass suffices to make up the difference between inferred global farmland losses and river sediment loads. Insufficient data on amounts of postsettlement alluvium exist with which to compute such a global budget.

However, an approximation can be attempted by beginning with the assumption that most sediment derived from past agricultural practices has accumulated as alluvium across tributary channels and floodplains. If mass is so conserved, it follows that the ratio of net area of farmland erosion to net area of postsettlement alluvium deposition must equal the ratio of rate of postsettlement alluvium (PSA) accumulation to rate of soil erosion as:

$$\frac{\text{Rate of PSA accumulation}}{\text{Rate of farmland erosion}} = \frac{\text{Area of farmland erosion}}{\text{Area of PSA accumulation}} \quad (3)$$

Because significantly more data exist on *vertical* rates of soil loss and postsettlement alluvium accumulation than on *areal* extents of soil erosion and associated alluviation, ratios of mean

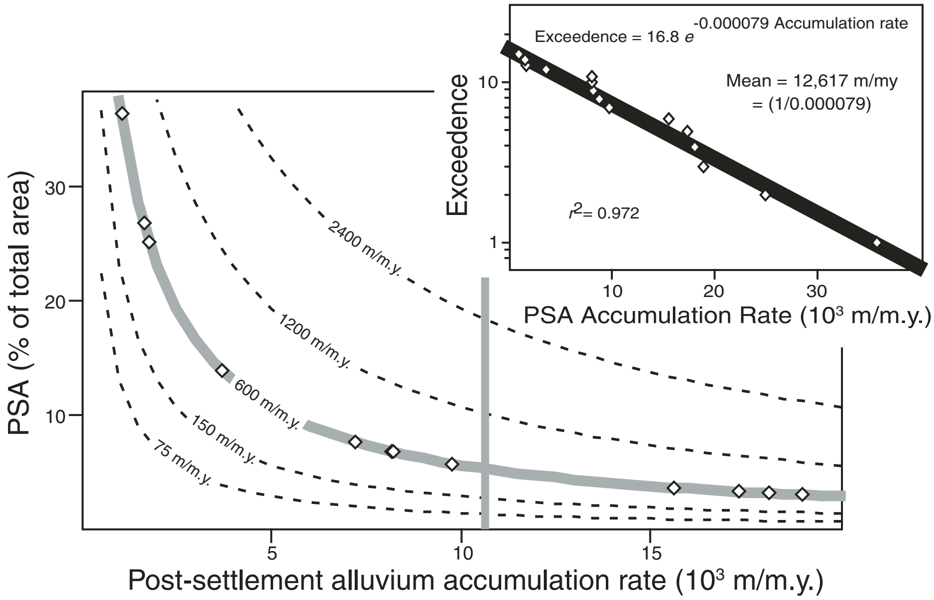

Figure 14. Relation between rate of farmland denudation (curved lines), rate of eroded soil alluviation (*x* axis), and the requisite proportion of land area undergoing alluviation assuming a closed system with respect to sediment transfer. Curved gray line is an inferred average agricultural denudation value of 600 m/m.y.; open diamonds are 15 PSA accumulation rates from the literature (Fig. 13) plotted here to show requisite PSA percent of total area at this rate of soil loss; vertical gray line is the mean of these values (~12,600 m/m.y.). Intersection of the two gray lines indicates that the ratio of areas of erosion to areas of alluvium accumulation is ~18.3. Inset is postsettlement alluvium (PSA) accumulation rate versus value exceedence.

vertical changes allow for determination of the relative proportion of land area over which post-settlement alluvium would need to accumulate in order to balance cropland soil losses. Assuming that 12,600 m/m.y. (reciprocal of 0.000079; Fig. 14) is an acceptable representation of mean postsettlement alluvium accumulation, and that mean agricultural soil loss is ~600 m/m.y., the ratio of postsettlement alluvium accumulation to farmland erosion suggests that the ratio of farmland area to alluviation area is ~21. In other words, if the entire amount of material from agricultural soil losses were stored as postsettlement alluvium, the area of aggrading alluvial surfaces would only have to be ~5% that of degrading farmland surfaces in order to arrive at a balanced soil sediment budget. Postsettlement alluvium need only occupy a very small fraction of rural landscapes in order to account for differences between cropland erosion and net sediment yield. Moreover, because worldwide, ~37% of land area is currently used for agriculture (Food and Agriculture Organization, 2004), only ~2% of Earth's land area need serve as sites of postsettlement alluvium accumulation in order to adequately store all of the sediment eroded from the remaining 35% serving as farmland.

DISCUSSION

The significant differences between vertical rates of cropland denudation and postsettlement alluvium accumulation require that deposition of eroded soil particles must occur over a small fraction of cultivated regions in order to completely balance the effects of human impact on continental erosion and sedimentation. This analysis further implies that: (1) per unit area, the deposition of postsettlement alluvium far exceeds rates of cropland soil loss, (2) postsettlement alluvium accumulation is probably the most important geomorphic process taking place on the surface of our planet, and (3) the storage of this sedimentary material represents a significant and perhaps a transient change in the equilibrium state of global river systems. Several ramifications of this human-induced perturbation seem apparent.

Sediment Budgets and Change in Rates of Soil Erosion

From a pragmatic point of view, a general consideration of a longer-term global sediment budget provides a context in which to evaluate the effects of shorter-term, human-induced changes to that system. This aspect of sediment transfer is particularly relevant to current discussions about rates of cropland denudation over the past half century. As noted already, Beach (1994) and Trimble (1999) have shown that, across four rather typical Midwest drainages, only a small fraction of displaced agricultural sediment is exported from the basins in question; the vast majority of eroded soil material is stored close to sites of erosion. Trimble (1999) noted that the net amount of sediment exported from the Wisconsin Coon Creek basin remained fairly constant (~37 t/yr) over the period from 1853 through 1993, while the amount of eroded sediment supplied to and stored within basin tributaries actually decreased from 1853 to 1938 (~405 t/yr) through 1938–1975 (~204 t/yr) and 1975–1993 (~80 t/yr). Other studies (Magilligan, 1985; Jacobson and Coleman, 1986; Wolfe and Diehl, 1993; Florsheim and Mount, 2003) have noted similar decreases in rates of stream valley and floodplain alluviation since the late 1930s, leading to the suggestion that some combination of farm abandonment and soil conservation has perhaps significantly reduced rates of farmland erosion over the past half century. While this view of significantly decreased soil loss is not uniformly embraced (e.g., Nearing et al., 2000), it does emphasize the point recently made by Trimble and Crosson (2000) that understanding erosion in upland areas plainly requires equal understanding of sediment accumulation in downslope streams and wetlands. If the 80% reduction in sediment flux to the Coon Creek drainage between 1853 and 1975 is even distantly analogous to global trends in cropland erosion, then the more recent cropland flux estimated at 75 Gt/yr might in fact be too high. In spite of the obvious importance of understanding current rates of farmland denudation, particularly in the face of a growing human population that now utilizes almost all available land area for farming, at this point in time, we just do not know if this is the case.

The Impact of Humans on Continental Erosion

The storage of significant masses of farmland-derived sediment in channels and floodplains of 3rd- to 6th-order tributaries represents the imposition of a significant disequilibrium on the world's rivers. The history of human modification of Earth's surface spans thousands of years (Ruddiman, 2003). Even if, as noted herein, farmland soil losses are now declining, human activity has still imposed a substantial increase in the amount of sediment delivered to tributary channels of global rivers. A general approximation of this mass of material can be derived from data in Hooke (2000), who estimated the per capita mass of soil displaced through agricultural and construction practices over the course of human civilization. These values, in conjunction with tabulations of population growth (U.S. Census Bureau, 2005) suggest that, through agricultural activity alone, humans have displaced something on the order of 20,000 Gt of soil through cropland erosion over the history of civilization. This transfer of material represents ~250 times the current rate of soil that would be translocated if cropland denudation actually does proceed at 600 m/m.y., and ~1000 times the current load (~21 Gt/yr) of global rivers. Moreover, because current fluxes of riverine sediment (e.g., Figs. 5 and 6) are largely exclusive of regions of agricultural erosion (Figs. 8 and 10), most of this material is presumably still stored in tributary channels and floodplains. Vörösmarty et al. (2003) reported a tripling (from 5% to 15%) in the storage of sediment behind dams in large reservoirs between 1950 and 1968, and another doubling (to 30%) by 1985. Just possibly, this enormous volume of farmland sediment stored as postsettlement alluvium is becoming noticeable as load in larger fluvial systems.

About how much material is 20,000 Gt of sediment? It represents a volume of ~8000 km^3, an amount sufficient to cover the state of Rhode Island to a depth of almost 3 km, or the entire Earth landscape to a depth of ~6 cm. Perhaps more importantly, it represents huge amounts of continental erosion and associated alluviation over extremely short durations of geologic time. A somewhat analogous interval of Earth history may be the Pleistocene Epoch, when higher-order stream tributaries were also loaded with significant volumes of regionally derived glacial drift that was deposited immediately adjacent to, and downslope from, continental and alpine glaciers. These deposits currently are composed of significant accumulations of till, outwash, loess, and other glacially related sediments, many of which were deposited substantial distances inland from continental coasts, and at significantly higher elevations. Like postsettlement alluvium, these deposits represent the relatively rapid accumulation of large volumes of sediment somewhat downslope from areas of erosion, and often along channels of those same river systems that now serve as the principal surface conduits for the transport of sediment to global oceans.

Compared to the ~75 Gt of anthropogenic sedimentary material that is annually produced by wind and water erosion, it is informative to at least roughly estimate comparable metrics for rates of accumulation of glacial till and outwash emplaced during the Pleistocene. If we assume that ~30% of Earth's surface was glaciated during the Pleistocene, that half of this area was then blanketed with till and outwash during glacial retreat, and that mean drift thickness was on the order of 50 m, then the net mass of Pleistocene continental deposits is on the order of 3×10^6 Gt. Although one might take exception to one or all of these values, it seems a largely inescapable conclusion that, over the duration of the Pleistocene Epoch, the flux of sedimentary materials into continental glacial drift proceeded at a rate of several gigatons per year. Even though rates of erosion and sediment evacuation by glaciers are among the highest reported for any natural process of denudation (Hallet et al., 1996), the net effect of Pleistocene glaciers is quite small when compared to that resulting from human activity. If erosion and deposition in response to Pleistocene glaciations are at the "high" end of the sedimentological spectrum, then soil erosion through human activities is not only the most important geomorphic process acting on the modern Earth's surface, we might also conclude that it has never been exceeded during the course of the Phanerozoic.

The Impact of Humans on the Global Soil Reservoir

One remaining aspect of discussing the importance of humans as geologic agents is an attempt at an assessment of these activities on the global soil reservoir, particularly with respect to evaluating the potential importance of cropland erosion on areas of arable land requisite to the nourishment of a growing human population. More specifically, if rates of cropland soil losses are indeed on the order of hundreds of meters per million years, it seems logical to ask if this alone (independent of other deleterious processes, such as desertification and salinization) is sufficient to impact areas of global cropland.

As an initial step in addressing this question, we first need to know: what is the spatial distribution of soil thicknesses across Earth's surface? The most complete data on soil profile thickness are that derived by Webb et al. (1991, 1993) from the Food and Agriculture Organization of the United Nations–United Nations Educational, Scientific, and Cultural Organization (FAO/UNESCO) *Soil Map of the World*. These data suggest that the population of global soil thicknesses exhibits a crude log-normal distribution, with a mean of ~130 cm (Fig. 15A). To the degree that frequency of occurrence reflects areal dominance of different soil profile depths, it is a relatively straightforward exercise to determine the anticipated changes in the areal extent of the global soil reservoir under different scenarios of cropland erosion (Fig. 15B).

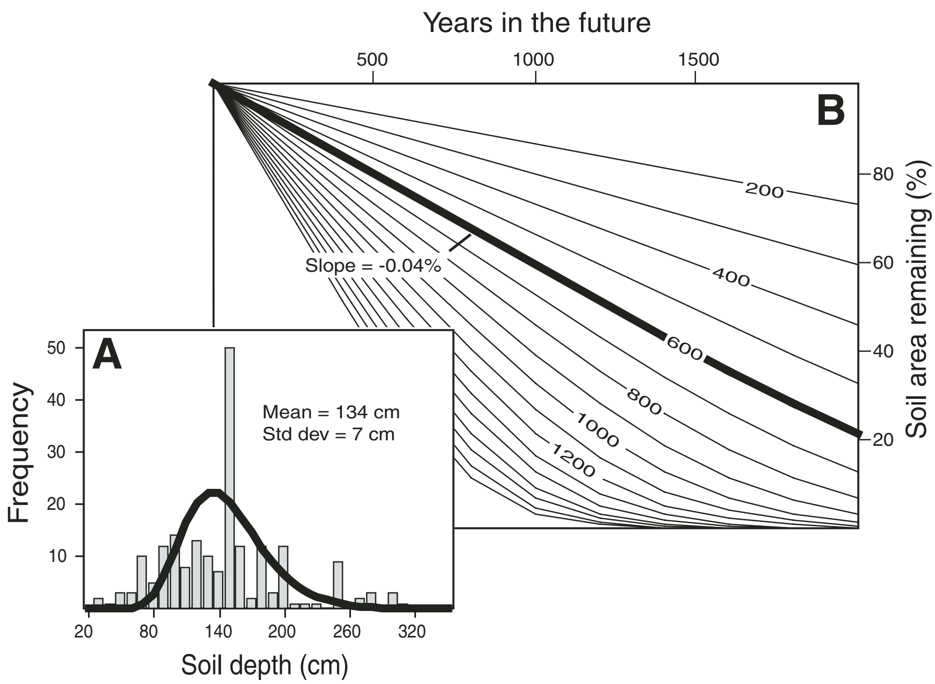

Figure 15. Impact of cropland erosion on areal extent of the global soil reservoir. (A) Frequency distribution of soil profile depths from Webb et al. (1991, 1993). (B) Rates of change in the global soil reservoir anticipated from the population of soil thicknesses in A and different mean rates of cropland erosion. Note that a cropland soil loss of 600 m/m.y. (heavy line) results in a decrease in arable land area of ~0.04% per year.

Although these calculations are little more than rather crude approximations, they do suggest that a mean cropland soil loss on the order of 600 m/m.y. should reduce net cropland soil area only by ~0.04% per year.

As context for this number, data available from the Food and Agricultural Organization of the United Nations (FAO, 2004; http://apps.fao.org/default.jsp) suggest that since 1961, global cropland area has increased by ~11%, while the global population has approximately doubled. The net effect of both changes is that per capita cropland area has decreased by ~44% over this same time interval; ~1% per year. This is ~25 times the rate of soil area loss anticipated from human denudation of cropland surfaces. In a context of per capita food production, soil loss through cropland erosion is largely insignificant when compared to the impact of population growth.

CONCLUSIONS

In the preceding presentation, we have attempted to summarize current knowledge about rates of natural and anthropogenic sediment transfer across Earth's surface. Rates of continental denudation inferred from existing Phanerozoic rock volumes suggest a mean denudation rate on the order of 16 m/m.y. (~5 Gt/yr), increasing to a Pliocene value of 53 m/m.y. (~16 Gt/yr). Current estimates of river sediment loads are little different than this value for the late Neogene, and require denudation of ice-free surfaces at a rate of 62 m/m.y. (~21 Gt/yr). Consideration of river sediment loads and geomorphology of respective river basins suggests that ~83% of the current global river sediment flux is derived from the highest 10% of Earth's surface.

Continental erosion as a result of human activity, primarily through agricultural practices, has resulted in a sharp increase in rates of erosion. Although less well constrained than estimates based on rock volumes or river loads, available studies suggest that current farmland denudation is proceeding at a mean global rate of ~600 m/m.y. (~75 Gt/yr), and is primarily confined to lower elevation portions of Earth's land surface, primarily across stable cratons and passive continental margins. The striking difference between sediment fluxes suggested by data on rock volumes and river loads, and those inferred from measured and modeled cropland soil losses, cannot be easily resolved as being an artifact of biases in data collection or sediment trapping in reservoirs. Admittedly sparse data on the alluvial deposits immediately downslope from eroding croplands suggest mean accumulation rates on the order of 1200 m/m.y., and imply that areas of alluvial sediment storage need be only a small fraction of areas of agricultural erosion in order to balance the global sediment budget.

The importance of these observations primarily resides in the rapidity at which human beings have modified the global landscape. Geologists tend to hold a somewhat broader perspective of environmental change, perhaps because of a wider appreciation of the history of past changes that have served to sculpt Earth's landscape. As noted herein, the net impact of humans as geologic agents has been to lower Earth's landscape by ~6 cm. In a context of a mean continental elevation of ~840 m, this seems to be a fairly modest change. However, in a context of past geologic rates of sediment transfer across global continents, in a context of the relatively modest soil thicknesses that presently exist across the planet's land surface, and in a context of the necessity to sustain a growing human population by way of agricultural regions that are already highly developed, the impact is significant.

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