# Soil erosion and agricultural sustainability

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**Data drawn from a global compilation of studies quantitatively confirm the long-articulated contention that erosion rates from conventionally plowed agricultural fields average 1–2 orders of magnitude greater than rates of soil production, erosion under native vegetation, and long-term geological erosion. The general equivalence of the latter indicates that, considered globally, hillslope soil production and erosion evolve to balance geologic and climate forcing, whereas conventional plow-based agriculture increases erosion rates enough to prove unsustainable. In contrast to how net soil erosion rates in conventionally plowed fields (≈1 mm/yr) can erode through a typical hillslope soil profile over time scales comparable to the longevity of major civilizations, no-till agriculture produces erosion rates much closer to soil production rates and therefore could provide a foundation for sustainable agriculture.**

agriculture | civilization

Recognition of the detrimental influence of accelerated soil erosion on agricultural societies dates back to Plato and Aristotle, and several now-classic studies have attributed the bare rocky slopes of the classical world to ancient soil erosion (1–3). In recent decades, archaeological studies confirmed pronounced episodes of soil erosion associated with the rise and subsequent decline of civilizations in the Middle East, Greece, Rome, and Mesoamerica, as well as other regions around the globe (4–8). Most commentators, however, generally attribute such erosional episodes to the effects of deforestation (9–12) and neglect the role of agriculture in maintaining accelerated erosion in upland environments.

Soil erosion is a complex process that depends on soil properties, ground slope, vegetation, and rainfall amount and intensity (13). Changes in land use are widely recognized as capable of greatly accelerating soil erosion (14–16), and it has long been recognized that erosion in excess of soil production would eventually result in decreased agricultural potential (2, 3, 17–19). Although soil fertility generally declines with accelerated erosion, soil fertility is itself a function of agricultural methods and site conditions such as soil type, nutrient, and organic matter content. Consequently, in the following analysis, I more narrowly focus on the issue of soil erosion, as the maintenance of soil fertility over the long run still requires maintenance of the soil itself. Until recently, however, few quantitative data have been available on natural rates of soil production or long-term geological erosion rates against which to compare erosion rates from agricultural fields.

Instead, estimates of anthropogenic increases in soil erosion typically rely on the universal soil loss equation, developed as a planning tool to provide a common empirical framework within which to evaluate local controls on soil erosion rates (20). Although based on >10,000 plot years of runoff and soil erosion data from small experimental plots across the U.S., the model has been shown to predict erosion well in some cases (21) but to significantly over- or underpredict soil erosion in others (22, 23). In addition, using erosion rates determined from small plot studies has been criticized as inappropriate for extrapolation across large spatial scales (24).

The other common method for estimating soil erosion based on sediment yield studies (25, 26) is complicated by deposition in floodplains, which produces a typical decrease in per-unit area sediment yields with increasing drainage area. Recently, Syvitski *et al.* (27) estimated that human activity has reduced sediment delivery to the oceans by half because of dam construction, despite substantially increased hillslope erosion in upland source areas. Consequently, sediment yield-based estimates of the magnitude of anthropogenic acceleration of upland erosion remain questionable. Even though much of the soil eroded from hillslopes can be redeposited in colluvial or floodplain environments (24, 28), the transfer of sediment to colluvial foot slopes and alluvial valley bottoms can eventually take agricultural uplands out of production, entombing once-productive soils in smaller cultivatable areas, such as occurred on the South Pacific island of Mangaia, where violent conflict over access to arable soils sequestered in localized depositional areas erupted after ancient upland Polynesian agriculture stripped the soil off most of the island (29).

Recognizing the potential for accelerated erosion under modern industrial agriculture, the U.S. Department of Agriculture (USDA) established in the 1950s soil-loss tolerance values, or *T* values, against which to evaluate "acceptable" rates of soil erosion. Generally, soil conservation programs consider *T* values to be ≈5–12 tons/hectare per year (30), equivalent to ≈0.4–1 mm/yr of erosion (assuming a soil bulk density of 1,200 kg/m$^3$). Although studies reporting that only highly erodible land was eroding faster than *T* values (31) have been interpreted by some as indicating that soil erosion poses little risk to agricultural production (32, 33), other researchers have expressed concern that *T* values themselves are set substantially higher than soil production rates, because of political and economic considerations (34). To date, the veracity of either claim has been compromised by a dearth of data on both soil production and geological erosion rates and uncertainty over how to interpret differences between modern and geological erosion rates because of their intrinsically different time scales. Referring to the basis for setting *T* values, Keeney and Cruse (35) recently went so far as to maintain that "seldom has such an important policy been based on such a dearth of defendable data." Although soil conservation measures and incentives under the Food Security Act of 1985 helped reduce the total erosion from U.S. cropland from 3.4 billion tons in 1982 to 2.0 billion tons in 1997 (36), it remains unclear how far soil erosion rates remain above background rates.

In evaluating the long-term effects of agricultural soil erosion, there is a fundamental difference between floodplain agriculture, where annual flooding refreshes mineral soils, and upland agriculture, where soils gradually thin and lose productivity as soil erosion outpaces soil production. Over time, hillslope soils tend to evolve toward a balance between erosion and soil

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Abbreviation: USDA, U.S. Department of Agriculture.

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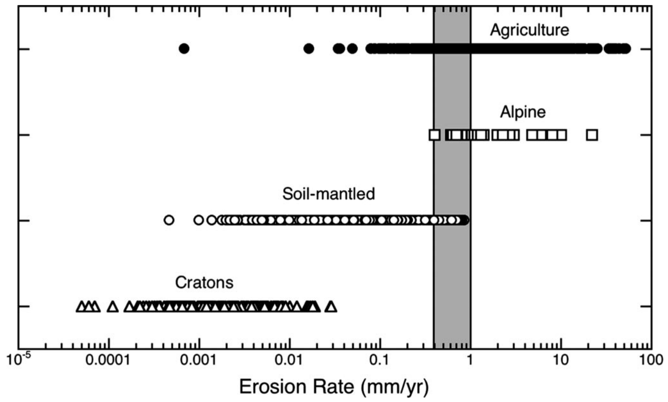

**Fig. 1.** Comparison of rates of soil erosion from agricultural fields under conventional agriculture ($n$ = 448) and geologic erosion rates from low-gradient continental cratons ($n$ = 218), soil-mantled landscapes ($n$ = 663), and alpine terrain ($n$ = 44) (sources are listed in SI). Soil erosion rates reported in various units were converted to equivalent lowering rates assuming a soil bulk density of 1,200 kg/m$^3$. Shaded area represents range of the USDA. $T$ values (0.4–1.0 mm/yr) were used to define tolerable soil loss.

production, promoting development of a characteristic soil thickness for a particular climate and geologic setting. In this view, soils, landscapes, and plant communities evolve together through a mutual interdependence on the balance between soil erosion and soil production. Under such a scenario, soil production and erosion would be expected to balance each other over time scales required to produce the equilibrium soil thickness. In this context, the appropriate metric against which to evaluate sustainable rates of soil erosion is what Bennett and Lowdermilk (37) termed the geological erosion rate, the rate at which soil in a particular environment would erode under native vegetation, which they maintained would match the rate of soil production. Here I adopt and update their approach to compare direct measurements of rates from a variety of methods from studies around the world to evaluate potentially sustainable erosion rates.

## Results

Geological erosion rates generally increase from the gently sloping lowland landscapes of ancient continental cratons ($<10^{-4}$ to 0.01 mm/yr), to moderate gradient hillslopes of soil-mantled terrain (0.001 to 1 mm/yr) and steep tectonically active alpine topography (0.1 to $>$10 mm/yr) (Fig. 1). Cultivated fields from all of these different regions generally erode at rates typical of alpine terrain. Moreover, the similarity in the aggregate probability distributions for ranges of soil production rates and both contemporary erosion under native vegetation and longer-term geological erosion rates in different settings supports the hypothesis that landscapes evolve to maintain a natural balance between soil production and erosion, despite the wide range in time scales encompassed by such measurements (Fig. 2). Although these rates are substantially lower than the $T$ values endorsed by the USDA, they provide strong support for the general concept of an equilibrium soil thickness under natural conditions.

In contrast to the general agreement between soil production rates, contemporary erosion rates under native vegetation, and the pace of erosion over geologic time, rates of soil erosion under conventional agricultural practices almost uniformly exceed 0.1 mm/yr, with the compiled data exhibiting median and mean values $>$1 mm/yr (Table 1). Hence, the composite probability distribution of erosion rates under conventional agriculture represents a 10- to 100-fold increase over any of the possible bases for estimating background rates. This discrepancy implies an average net loss of soil under conventional agriculture on the order of 1 mm/yr, a figure close to $T$ values meant to achieve no net soil loss (i.e., to balance soil production). In contrast, the distribution of erosion rates under soil conservation practices such as conservation tillage, no-till methods, and terracing is close to the distribution of geological erosion rates.

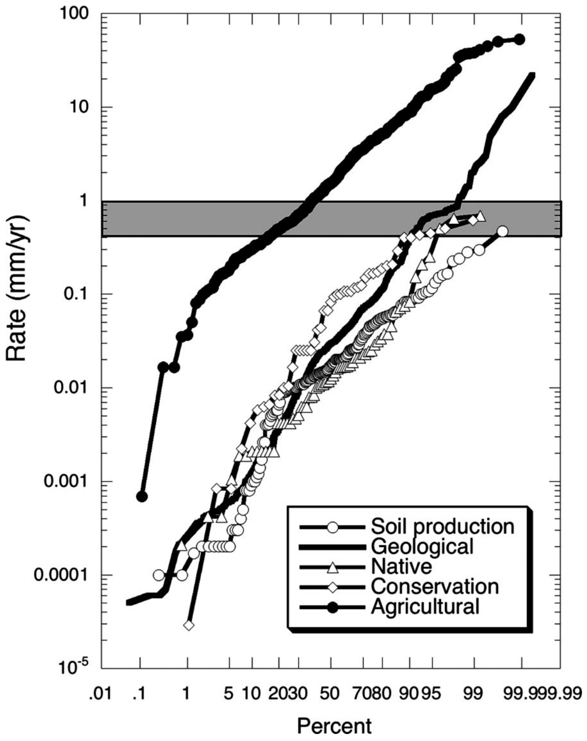

**Fig. 2.** Probability plots of rates of soil erosion from agricultural fields under conventional (e.g., tillage) and conservation agriculture (e.g., terracing and no-till methods), with erosion rates from areas and plots under native vegetation, rates of soil production, and geologic rates of erosion (a composite distribution of the data for cratons, soil-mantled landscapes, and alpine areas in Fig. 1). Data sources for agricultural and geologic rates are the same as for Fig. 1. Shaded area represents range of USDA. $T$ values (0.4–1.0 mm/yr) were used to define tolerable soil loss.

Erosion and soil production rates around the world vary over $>$4 orders of magnitude, depending on local site characteristics, particularly climate, geology, soils, topography, and vegetation. So how representative are the distributions and range of environments covered by the compiled data? The favorable comparison of the median geological erosion rate reported here with previous independent estimates of average global erosion rates (Table 2) supports the view that the data are spatially representative, and that the brute force data compilation approach used here represents a reasonable global range of conditions. Moreover, given geologists' predilection for working in scenic alpine terrain, it is likely that high-relief terrain is overrepresented in the compilation of geological erosion rates, which would imply that the mean geological erosion rate represents a maximum constraint. In addition, the soil production distribution averages are also close to independently estimated global average soil production rates, further indicating that the values compiled here are reasonably representative.

Another constraint on the global geologic erosion rate is given by Ahnert's general relation between erosion rate ($E$) and mean local relief ($R$) (38). Reanalysis of a broader global data set by Montgomery and Brandon (39) reported that a relation of the form $E = 0.2\,R$, where $E$ is in millimeters per year, and $R$ is in kilometers, characterized the relation between geological ero-

**Table 1. Characteristics of erosion rate distributions for the compiled data presented in Figs. 1 and 2**

| Measurement type | Sample size, *n* | Median, mm/yr | Mean, mm/yr | Standard error, mm/yr |
|---|---|---|---|---|
| Conventional agriculture | 448 | 1.537 | 3.939 | 0.321 |
| Conservation agriculture | 47 | 0.082 | 0.124 | 0.022 |
| Native vegetation | 65 | 0.013 | 0.053 | 0.016 |
| Soil production | 188 | 0.017 | 0.036 | 0.004 |
| Geological | 925 | 0.029 | 0.173 | 0.029 |

Data sources are listed in SI.

sion rate and mean local relief. In that study, they reported data for which a median value of 86 m characterized the mean local relief defined over a 10-km-diameter circle for all of North America, Europe, South America, and Asia. Introduced into the foregoing relation, this value corresponds to an erosion rate of 0.017 mm/yr, close to global geological erosion rate estimates reported previously and identical to the median soil production value for the data compilation reported here. The observation that erosion rates increase nonlinearly with increasing mean local relief above $R = 1$ km (39) implies that mean geological erosion rates should substantially exceed median rates, as found in the data compilation. However, <5% of Earth's land mass has $R > 1{,}000$ m, and therefore the mean geological erosion rate of six times the median rate found in the present compilation likely reflects both a propensity for geologists to study alpine terrain and disproportionately high erosion rates in such environments.

Given the tremendous range of erosion rates in different environments, the ideal comparison to assess the effects of agriculture on soil erosion involves direct before/after studies for the same or comparable land under native vegetation and under agricultural production. Although far fewer such direct comparisons are available, the range of ratios for the 46 examples located in the present study confirms the general acceleration implied by the data compiled in Fig. 1. Specifically, individual studies involving direct comparison of rates of erosion under native vegetation and conventional agriculture report 1.3- to >1,000-fold increases (Fig. 3), with median and mean ratios of 18- and 124-fold, respectively, for the studies compiled.

In the mid-20th century, recognition that conventional agriculture dramatically accelerated soil erosion led to experimentation with conservation tillage and no-till agriculture (40, 41). Over the past several decades, no-till agriculture has been increasingly adopted as a cost-effective alternative to conventional tillage practices. Whereas in the 1970s few farmers used no-till techniques, in 2000, 16% of the cultivated area on U.S. farms used no-till methods (42). Although no-till practices have been increasingly adopted in North and South America, only 5% of global cropland is managed by using no-till methods (43). No-till agriculture involves leaving crop stubble on the ground surface instead of plowing it under, with seeds inserted directly into the soil by a specialized drill. The layer of organic matter left on the ground surface acts as mulch that promotes infiltration, thereby reducing both runoff and erosion by the runoff that does occur.

**Table 2. Average global geologic erosion rates and global soil production rates reported in previous studies**

| Source | Rate, mm/yr |
|---|---|
| Global geologic erosion | |
| Montgomery and Brandon (39) | 0.017 |
| Wilkinson (49) | 0.024 |
| Wilkinson and McElroy (50) | 0.016 |
| Global soil production | |
| Wakatsuki and Rasyidin (51) | 0.058 |
| Troeh *et al*. (52) | 0.083 |

Given the wide range of site-specific conditions that affect agricultural soil erosion, direct comparisons of methods on the same fields or comparable ground provide the best way to evaluate and compare the erosional effects of no-till and conventional agriculture. In the late 1970s, one of the first field trials of no-till methods reported a >75% reduction in soil erosion from Indiana cornfields (44). Another study in Ohio reported a >10-fold decrease in soil loss for no-till vs. plowed watersheds (40). More recently, agricultural researchers found no-till farming reduced soil erosion by >90% over conventional tobacco cultivation (45). Comparison of soil loss from cotton fields in northern Alabama found that no-till plots averaged two to nine times less soil loss than tilled plots (46). One study in Kentucky reported that no-till methods decreased soil erosion by an astounding 98% (47). Although the effect on erosion rates depends on a number of local factors, such as the type of soil and the crop, the 39 examples involving direct comparisons of soil erosion under conventional and no-till methods compiled here represent a wide variety of settings with very different erosion rates and show that no-till practices reduce soil erosion 2.5 to >1,000 times, with median and mean values of 20 and 488 times, respectively (Fig. 4), enough to bring agricultural erosion rates into line with rates of soil production.

The similar differences between rates of soil erosion from conventionally cultivated and both no-till fields and geological erosion rates indicate that these differences cannot arise simply from the different time scales under consideration (48). The observation that no-till practices reduce erosion by amounts

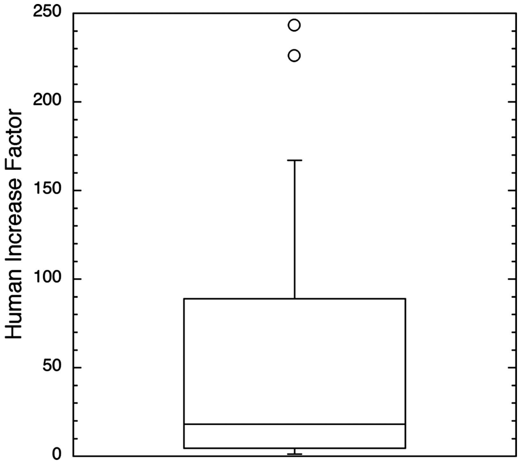

**Fig. 3.** Box-and-whiskers plot showing the range of reported increases in erosion rate for studies reporting direct comparisons of erosion under conventional agriculture vs. native vegetation for comparable settings ($n = 46$, median = 18, mean = 124, minimum = 1.3, maximum = 1,878). Data include studies that reported both rates individually and those that simply reported a ratio between erosion rates under native vegetation and conventional cultivation.

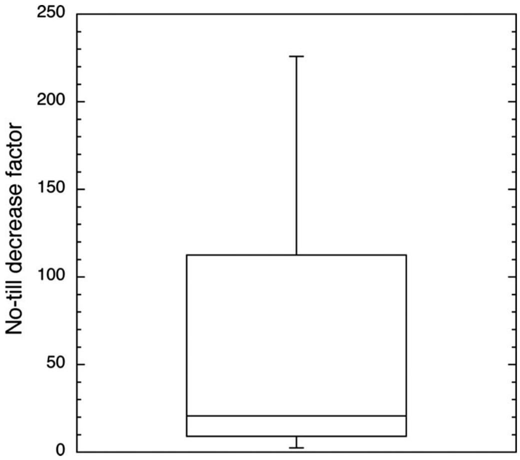

**Fig. 4.** Box-and-whiskers plot showing the range of reported decreases in erosion rate for studies reporting direct comparisons of conventional tillage and no-till practices for comparable settings ($n$ = 39, median = 20, mean = 488, minimum = 2.5, maximum = 7,620). Data include studies that reported both rates individually and those that simply reported a ratio between erosion rates under conventional or no-till cultivation.

comparable to the increase in erosion under conventional agriculture provides strong inverse confirmation of the generality of a 1–2 order of magnitude increase in erosion rates under conventional agriculture.

## Discussion

The mean and median soil production rates from the compilation reported here are somewhat lower, and the mean agricultural erosion rates are somewhat higher, than those reported previously for global and U.S. estimates (Table 3). Previous estimates of the mean soil loss from U.S. and global croplands range from 0.2 to 1.5 mm/yr, with a mean of 0.95 mm/yr for the reported values for U.S. croplands summarized in Table 3. Estimates of global average erosion rates for the past 500 million years range from 0.016 to 0.024 mm/yr based on sediment volumes preserved in the geologic record (49, 50) and thus overlap with the median value of geologic erosion rates found here but are several times lower than the mean values. Previous estimates of average global soil production range from 0.058 to 0.083 mm/yr (51, 52), several times higher than the mean for the data compiled here. In any case, however, there is >1 order of magnitude discrepancy between contemporary rates of erosion under conventional agriculture and long-term rates of erosion and soil production.

**Table 3. Average global and U.S. cropland erosion rates reported in previous studies**

| Source | Mean erosion rate, mm/yr |
|---|---|
| Global cropland | |
| Wilkinson (49) | 0.64 |
| U.S. cropland | |
| Barlowe (56) | 1.00 |
| USDA (57) | 0.20–0.45 |
| Beasley *et al*. (58) | 0.90 |
| Harlin and Barardi (59) | 1.50 |
| USDA (60) | 0.52 |
| Pimentel *et al*. (61) | 0.68 |
| Uri and Lewis (36), 1982 | 1.67 |
| Uri and Lewis (36), 1997 | 1.08 |
| Wilkinson and McElroy (50) | 0.89 |

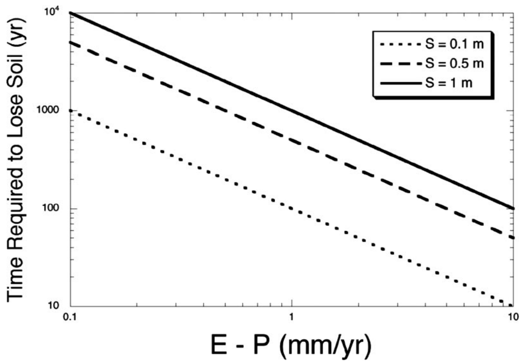

**Fig. 5.** Critical time ($T_c$) required to erode a soil profile of differing initial thickness ($S$) for different net soil erosion rates set by the difference between rates of soil erosion ($E$) and production ($P$), defined by $T_c = S/(E-P)$.

Given that plowed fields erode substantially faster than rates of soil production and natural soil erosion, a limiting lifespan of an agricultural civilization can be estimated by the time needed for conventional agriculture to erode through the native stock of topsoil. The critical time, $T_c$, it takes to erode through a soil profile may be expressed as

$$T_c = S/(E - P), \quad [1]$$

where $S$ is the initial thickness, $E$ is the soil erosion rate, and $P$ is the soil production rate (53). With average soil production and geological erosion rates of <0.2 mm/yr and average soil erosion rates under conventional agricultural practices of >1 mm/yr, the time required to erode through the soil is on the order of a few hundred to a few thousand years for an initially decimeter- to meter-thick soil profile typical of undisturbed areas of temperate and tropical latitudes (Fig. 5). This simple constraint on the lifespan of agricultural soils predicts reasonably well the historical pattern of a 500- to several-thousand-year lifespan for major civilizations around the world, supporting the argument that it was not the axe that cleared forests but the plow that followed that undermined many ancient societies (54).

The data compiled here demonstrate this problem is not just ancient history. A direct implication of the imbalance between agricultural soil loss and erosion under both native vegetation and geologic time is that, given time, continued soil loss will become a critical problem for global agricultural production under conventional upland farming practices. With little new land that could be brought under sustained cultivation (55) and a projected increase in global population to >10 billion later this century, the issue of long-term agricultural sustainability will become increasingly pressing, although maintaining soil health and agricultural productivity additionally requires preventing nutrient depletion. Yet if agricultural erosion rates remain far beyond rates of soil production, global society will eventually be compelled to either adopt agricultural methods that sustain the soil or face increasing competition over a shrinking agricultural land base.

## Materials and Methods

Data were compiled from a growing body of studies on rates of soil production, long-term geological erosion, erosion under native vegetation, and agricultural fields. In compiling such data, I have avoided including data from sediment-yield studies for drainage basins where sediment storage issues complicate assessing upland erosion rates (such as from large river systems) or floodplain environments where soil production does not proceed directly from rock weathering but instead occurs from redeposition of former upland soils.

The compiled data encompass 1,673 measurements drawn from 201 studies from a wide range of environments and geological settings [see supporting information (SI)]. Geological erosion rates include stratigraphic constraints, lake sedimentation, estimated depths of dated pluton emplacement, and studies based on cosmogenic $^{10}$Be and $^{26}$Al from both single rocks and river sand to estimate whole-catchment erosion rates. Soil production rates are also based on $^{10}$Be studies, as well as studies of weathering rates and river geochemistry. Contemporary rates of erosion under native vegetation are based on studies of measured soil loss from both experimental plots and catchment-scale investigations. Rates of erosion from conventional agriculture and no-till and conservation tillage are based on studies using $^{137}$Cs and soil-loss data from both experimental plots and field-scale investigations, as well as longer-term studies based on deposition in closed basins, soil profile truncation, and elevated cemetery plots.

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