

# 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 ( $\approx 1$  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  $\approx 5$ – $12$  tons/hectare per year (30), equivalent to  $\approx 0.4$ – $1$  mm/yr of erosion (assuming a soil bulk density of  $1,200$  kg/m<sup>3</sup>). 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 defensible 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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**Table 1. Characteristics of erosion rate distributions for the compiled data presented in Figs. 1 and 2**

Measurement type	Sample size, <i>n</i>	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,

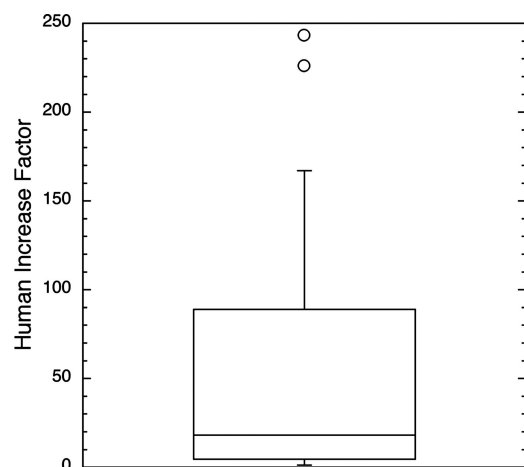
thereby reducing both runoff and erosion by the runoff that does occur.

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

**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



**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.





