Insights into the future of soil erosion

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Integrating a long-established soil erosion model with Intergovernmental Panel on Climate Change (IPCC) scenarios, Borrelli et al. (1) set out to meet the needs of policymakers and earth-system modelers to better understand the future of soil erosion this century. Policymakers need this insight because of the constraints erosion places on achievement of multiple sustainable development goals including zero hunger, clean water and sanitation, no poverty, and life on land (2). The record of humankind does not induce confidence, evidencing our effect on soil distribution and quality and the consequences for past civilizations (3). The impact that soil erosion and deposition has on biogeochemical cycles (4–6) is leading to a recognition that earth-system models (ESMs) must look beyond vertical exchanges between soil and atmosphere and address carbon cycle perturbation cause by lateral transport of soil from land to ocean (7). The study by Borrelli et al. (1) is, therefore, timely.

Research, dating back as far as the 1930s and the stimulus of the Dust Bowl, has provided valuable insights into the causes and consequences of soil erosion. However, global synthesis of erosion rates measured using a wide range of methodologies, has proven to be extremely challenging (8). By applying an empirical soil erosion model employing consistent and high spatial resolution global datasets, Borrelli et al. (1) address this challenge and offer simulations that can be coupled in a consistent manner to land use, soil conservation, and climate change scenarios. Comparing modeled soil erosion for 2015 and 2070, Borrelli et al. (1) identify potential for ~10% reduction in global rates under a sustainability-focused scenario (SSP1-RCP2.6), ~10% increase in global rates for a fossil-fuel intensive scenario (SSP5-RCP8.5), and relatively little change (+2%) for an intermediate scenario (SSP2-RCP4.5). These results suggest cobenefits for erosion reduction in attempts to pursue a path to sustainability and increased risk to the environment and human populations if little proactive intervention is made to control climate change. This risk of increased water erosion consequent on inaction is emphasized in the climate projections that indicate a more vigorous hydrological cycle with greater risk of the extreme events that cause droughts and floods.

Borrelli et al. (1) advance empirical modeling by using high-resolution global datasets and an analytical approach that benefits from progress in data science and increase in computing power. Indeed, it is possible that they have reached the end point or summit for such empirical approaches. To explore this, it is necessary to understand some background to the empirical model that underpins the work presented, namely the Revised Universal Soil Loss Equation (RUSLE) and the Universal Soil Loss Equation (USLE) from which it is derived. The USLE was developed by US Department of Agriculture scientists led by Wischmeier and Smith (9). It is an empirical equation describing the relationship between soil loss rate due to flowing water per unit area and the following controlling factors: the erosivity of the agent (rainfall and runoff); the erodibility of the soil; the topography including slope length (which influences the amount of runoff) and slope angle (influencing velocity); the vegetation cover; and management practice. This is a comprehensive set of factors controlling soil erosion by water on slopes; however, the strength of USLE and its enduring use lie in the enormity of the dataset that underpins and informs the equation. This was an early application of "big data" employing a database that included several thousand plot years of measurements of soil erosion under varied conditions on the soils of the United States. The offspring of USLE, including RUSLE, benefit from this unrivalled empirical database, and these models have been used extensively across the globe in soil erosion prediction (10). Naturally, widespread adoption and use is not the same as verification, and as an empirical regression model, there are risks in applying the model outside the parameter-space of the underlying database. These risks have been discussed in several studies (11). Nevertheless, it is important to note that while the underpinning database continues to be extended, it is

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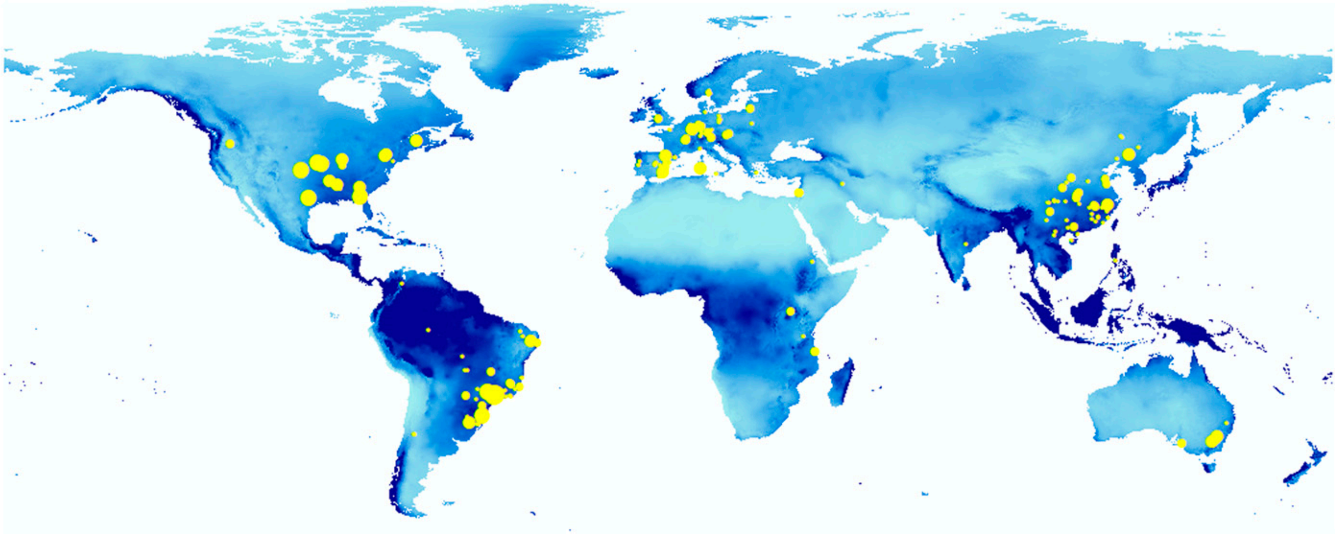

Fig. 1. Global distribution of soil erosion plot experiments (12) representing 11,439 plot years, superimposed on variation in annual rainfall (13). The size of the dots is proportional to the number of observed plot years. The dark colors represent high annual rainfall amounts, while the light colors represent low amounts.

still dominated by coverage of the following: cropland, plots of slope length 22 m (original experimental design), and the continental United States. The geographic and climatic limits of the database are illustrated in Fig. 1 (12, 13). It has been suggested that the geographic limits are of limited importance because the soils of the United States are not unique. While this is true, it is also the case that they are not an unbiased sample of soils and soil management practices of the world and there are conditions in Asia, Africa, and Australasia that are not well represented in the RUSLE database. This is particularly relevant when considering the identification by Borrelli et al. (1) of the global tropics, a region largely underrepresented in the database, as an erosion hot spot under climate change.

RUSLE may be expected to perform well in the context for which it was developed, farm-level advice and guidance; it may be expected to provide reliable estimates of erosion due to flowing water in headwater environments where the soil, land use, and climate conditions fall within the parameter space of the underlying database. It is less likely to perform well where soils or climate lie outside the database. Particularly significantly, it has been demonstrated to perform poorly in natural lands (forest, grassland, and shrubland) (12) and where slope lengths are longer than most in the database and flowing water converges to cause rill and gully erosion, which have been identified as the quantitatively dominant mechanism of soil erosion by water (14). Furthermore, actual water erosion taking place on agricultural land, as opposed to the mean response on experimental plots, is controlled by the interactions between climatic events such as extreme rainfall events, landscape structure (e.g., field layout and terracing), and human decisions such as the type and timing of crop. While no model employed at large scale could capture all of these, it is particularly unlikely that highly episodic drivers and human adjustments to changing climate can be captured by the linear RUSLE model structure. While the modeling platform can predict erosion at high resolution (250 m), policymakers using this would be well advised to treat the spatially explicit data with caution because the analysis demonstrates agreement with observed erosion data only at continental and large climate–ecosystem level. In the context of these limitations, it is less surprising that the erosion model implementation used by Borrelli et al. (1), which is grounded in the RUSLE, produces such a poor fit with observed erosion rates from experimental plots under natural rainfall conditions. One limitation in the solution offered for policymakers is, therefore, the reliability of the water erosion assessment made using RUSLE. It is important to note that this is not a product of the implementation by Borrelli et al. (1) but a fundamental limitation of RUSLE-based approaches. A further limitation of RUSLE-based approaches, which Borrelli et al. (1) acknowledge, is the exclusion from the simulation of important soil erosion processes of significance in land use decisions to enhance sustainability and prevent land degradation. In a significant proportion of agro-environments, the impact of wind erosion may exceed that of water erosion, both as a cause of soil thinning and in off-site impacts on adjacent populations including dust storms. When considering the impact of eroded soil on water quality, it is, again, necessary to look beyond the processes that can be reliably modeled using RUSLE and include rill and gully erosion, mass movements, such as landslides, and channel migration. Finally, when considering causes of soil thinning, it is essential to account for tillage erosion (15).

Borrelli et al. (1) have taken an important step forward in integrating an established erosion model into a global platform and exploring the implications of IPCC scenarios on model outputs. Meeting earth-system modelers in use of common data structures and scenarios is a fundamental requirement for further integration. Nevertheless, of necessity, the erosion modeling was undertaken offline, independently of the climate and land use modeling. This introduces important constraints on the capacity to represent erosional response to the changing erosivity of the climate and to capture soil change in response to erosion, including its erodibility.

First, the data required to estimate future rainfall erosivity are currently not provided by scenarios or by ESMs, and therefore, the authors had to rely on the important simplification of assuming that future changes in erosivity can be estimated from the empirical relation between past rainfall erosivity and aggregated climatic metrics. Under the circumstances, the simplification is necessary; however, it is important to note that the relations used are unlikely to remain stationary in the future given the importance of rainfall intensity patterns, drop size distribution, and alignment with plant growth cycles in determining the erosivity of a rainfall event.

Second, there is a conundrum in the use of static soil erodibility properties as inputs when exploring how soil properties may be impacted by erosion to the extent that crop production is threatened. There is now increasing awareness that humankind, and especially agriculture, represents a major soil forming factor (16, 17). Accelerated erosion may lead to a rapid evolution of basic soil characteristics such as soil thickness, albedo, horizon development, and hydrological properties. The evolution and significance of erosion-induced changes in soil properties are currently not represented in ESMs. Furthermore, soil erosion and deposition contribute to evolution of soil variability at larger spatial scales because erosion is a multistage process and mobilization represents the initial part of the erosion pathway. Most soil particles mobilized by erosion do not reach the global ocean, but are, at least temporarily, stored in terrestrial deposits such as hillslope colluvium, lakes, reservoirs, and fluvial deposits, including important agricultural soil landscapes throughout the world. Eroded soil is also a vector for redistribution of nutrients, carbon, pathogens, and pollutants, and their residence times and exchanges with other compartments of the earth system (hydrosphere, biosphere, and atmosphere) are key to understanding the overall impact of erosion on the earth system.

These dynamic interactions and feedbacks between soil properties, land use, climate change, soil erosion, and land degradation cannot be captured in offline simulations such as that by Borrelli et al. (1). Their study is not unique in this regard because the case for allocation, within ESMs, of the resource needed for such dynamic simulations is only just beginning to gain traction (18). The next steps for predicting future erosion must build on the important foundations of the past, benefit from expanding global databases, and enable dynamic simulation of our evolving relationship with one of our most critical living resources, the planet's soil.

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