Geomorphology 239 (2015) 160–173

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Invited review

A meta-analysis of soil erosion rates across the world

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ARTICLE INFO

Article history:
Received 10 July 2014
Received in revised form 6 March 2015
Accepted 7 March 2015
Available online 17 March 2015

Keywords:
Erosion rates
Sediment yield
Geomorphological methods
Experimental plots
Experimental catchments
Scale-dependency

ABSTRACT

Over the last century extraordinary efforts have been devoted to determining soil erosion rates (in units of mass per area and time) under a large range of climatic conditions and land uses, and involving various measurement methods. We undertook a meta-analysis of published data from more than 4000 sites worldwide. The results show that there is extraordinarily high variability in erosion rates, with almost any rate apparently possible irrespective of slope, climate, scale, land use/land cover and other environmental characteristics. However, detailed analysis revealed a number of general features including positive relationships of erosion rate with slope and annual precipitation, and a significant effect of land use, with agricultural lands yielding the highest erosion rates, and forest and shrublands yielding the lowest. Despite these general trends, there is much variability that is not explained by this combination of factors, but is related, at least partially, to the experimental conditions. Our analysis revealed a negative relationship between erosion rate and the size of the study area involved; significant differences associated with differing measurement methods, with direct sediment measurement yielding the lowest erosion rates, and bathymetric, radioisotope and modeling methods yielding the highest rates; and a very important effect of the duration of the experiment. Our results highlight that, when interpreting erosion rates, the experimental conditions involved must be taken into account. Even so, the data suggest that only order of magnitude approximations of erosion rates are possible, and these retain a very large degree of uncertainty. Consequently, for practical purposes such as calculation of global sediment budgets, empirical equations are not a substitute for direct measurements. Our results also show that a large proportion of the experiments have been short-term (less than 3 years), which reduces dramatically the reliability of the estimated erosion rates, given the highly non-normal behavior of soil erosion (time-dependency). Despite the efforts already made, more long-term measurement experiments need to be performed, especially in regions of the world that are under-represented in global datasets. In addition, protocols need to be established for standardizing the measurement methods and reporting the results, to enable data to be compared among diverse sites.

Contents

http://dx.doi.org/10.1016/j.geomorph.2015.03.008
0169-555X/

1. Introduction

Together with water and air, soil is a major natural resource for life on Earth. It provides a large variety of goods and services (Verheijen et al., 2009), particularly in relation to biodiversity, soil biota, plant composition, runoff control, water-holding capacity, carbon sequestration and ecosystem productivity (Van Oost et al., 2000). Consequently, soil degradation is one of the most important threats to soil productivity and human welfare (Pimentel et al., 1976). Soil erosion is a major cause of soil degradation because it involves removal of the most fertile topsoil, where organic matter and nutrients are concentrated (Li et al., 2009). Given that in most cases the rate of erosion occurring in agricultural areas is higher than the rate of soil formation (Verheijen et al., 2009), several reports (e.g. Boardman, 2006) have highlighted a decrease in soil quality in many areas worldwide. This in part explains increases in production costs, declining crop yields, and in the worst cases, farmland abandonment (Montgomery, 2007). In certain developing regions the combined effects of increasing population, insufficient nutrition and poverty have resulted in the cultivation of marginal lands and significant soil erosion (Tato and Hurni, 1992), following a similar process that occurred in developed countries more than a century ago. As a consequence, the agricultural land area per head of population is continuing to shrink globally with increasing population growth (Pimentel et al., 1995). This is making soil erosion a critical problem (Montgomery, 2007) that requires holistic solutions involving physical and socioeconomic approaches.

The measurement of soil erosion has been a major target of scientific research and government programs since the beginning of the 20th century, and for a variety of reasons remains one of the highest research priorities. For instance, de Vente et al. (2013) stated the need for measurement "of soil erosion rates and sediment yield (SY) at regional scales under present and future climate and land use scenarios". According to Toy et al. (2002), erosion should be measured to assess the environmental impacts of erosion and conservation practices, the development of erosion prediction technologies, and the implementation of conservation policies. Vanmaercke et al. (2011a) noted that the specific sediment yield rate (the quantity of sediment reaching the catchment outlet per unit time and per unit area) is central to many environmental processes, including river delta formation and maintenance, sedimentation in harbors, reservoir and lake silting, floodplain aggradation and instability, and riparian vegetation dynamics. Perhaps the major reason justifying investment in studies of soil erosion is its enormous indirect costs (Pimentel et al., 1995). This can be particularly significant in the case of reservoir silting; reservoirs behave as large sediment traps, and siltation can cause a rapid decline in capacity, reducing the life span of the reservoir and threatening the sustainability of inland water storage. Knowledge of current soil erosion rates enables comparison with tolerable soil erosion rates (Verheijen et al., 2009; Bilotta et al., 2012), although this is difficult to assess.

The importance of soil erosion rates explains the large investments in time, effort and funds to determine soil loss at scales ranging from very small plots (<1 m^2) to large basins (>1000 km^2). Nevertheless, in analyzing the adequacy of erosion measurements, Stroosnijder (2005) warned of a scientific and technical crisis because "there are insufficient empirical data of adequate quality, a lack of funds to improve that situation, a lack of development of new technologies and equipment, and a lack of skilled personnel". This commonly leads to the use of erroneous erosion prediction models, usually calibrated using data collected at inappropriate scales (Poesen et al., 1996, 2003). Boardman (2006) concluded that "for most areas in the World the erosion data is woefully inadequate". These reports have highlighted that little real progress has been achieved despite decades of effort, and soil formation rates are even less well understood, making assessment of sustainability extremely uncertain.

Some studies have reported limitations in the recent evolution of soil erosion research (e.g. Boardman, 2006; Parsons et al., 2006; de Vente et al., 2007; Parsons, 2011; Fryirs, 2013). Kirkby (2010) noted that "much progress has already been made towards an improved understanding of soil erosion mechanisms, but a number of gaps can still be identified", including the evolution of threads into rills during an erosion event, and the differentiation of transport and supply-limited removal of coarse and fine material, respectively. Boardman (2006) was even more explicit in stating that "in soil erosion science we seem to have avoided the ambitious questions in favor of more limited, easy-to-answer ones". With some notable exceptions, this explains the absence of "seminal papers", despite much effort still being invested in determining soil erosion rates.

One of the problems in attempts to compare among published erosion rates is the uncertainty created by the use of different erosion measurement methods. A clear distinction must be made between erosion rate and sediment yield. Formally, an erosion rate is the long-term balance between all processes that detach soil material and remove it from a site, and those processes that deliver new material and deposit it at the site. Thus, erosion rates can be negative (net mass loss) or positive (net mass gain). In contrast, sediment yield refers to the mass that is exported from a given landscape unit, and is always a positive quantity. While some methods (e.g. radioisotope surveys) measure true erosion rates, others (e.g. plot or stream sediment monitoring) measure sediment yields. However, it is easy to confuse the two measurements because they are expressed in the same units (mass per unit time, or mass per unit surface and time). Here we use the term 'erosion rate' in a general way to include both erosion rates and sediment yields, enabling comparison of each measurement type, although we distinguish between them where necessary.

In this review paper we analyzed: (i) the variability among published erosion rates, and assessed the difficulties in finding useful relationships between the published rates and environmental factors; (ii) the differences in erosion rates arising from non-environmental factors, including the time and space conditions of the experiments, as well as the measurement methods used; and (iii) the limitations in interpretation of the results. This study seeks to reflect on the methods used in the estimation of erosion rates and their validity for improving the theory and practice on soil erosion studies. To achieve these objectives we constructed a meta-database based on erosion rates published worldwide for studies undertaken at various spatial and temporal scales, involving differing land uses and land covers, and using different methods. Statistical analysis was used to identify the main strengths and drawbacks of the available information.