A META-ANALYSIS OF SOIL EROSION RATES ACROSS THE WORLD

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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.

Key words: Erosion rates, Sediment yield, Geomorphological methods, Experimental plots, Experimental catchments, Scale-dependency

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 socio-economic 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 ($< 1 \text{ m}^2$) to large basins ($> 1000 \text{ km}^2$). 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. Parsons, 2011; Boardman, 2006; Parsons et al., 2006; de Vente et al., 2007; 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.

2. Methods

2.1. Data collection

A dataset of erosion rate measurements was collected from scientific articles published in international journals since 1981. We used two widely used bibliographic databases (Scopus and ISI Web of Knowledge) to identify articles matching the keywords: *soil erosion* and *sediment yield*. For each entry in the database, the following information was collected (if available): (i) spatial location (country, name of the study area, and coordinates); (ii) erosion rate ($\text{Mg km}^{-2} \text{ yr}^{-1}$); (iii) study surface area (m^2); (iv) slope gradient (m m^{-1}); (v) measurement period (years); (vi) measurement method, including direct measurement in runoff plots and gauging stations in catchments, bathymetric surveys in reservoirs, modeling, radioisotope survey, or rainfall simulation; (vii) land use/land cover type; and (viii) mean annual precipitation. This process identified a total of 276 articles from which 1639 records from 62 countries were obtained.

This dataset was merged with three additional sources: (i) the USLE dataset provided by the United States Department of Agriculture and the National Soil Erosion Research Laboratory (USDA-NSERL, 2014), which provided data from 635 erosion plots; (ii) the suspended sediment database of the United States Geological Service (USGS, 2014), which provided data from 1582 catchments; and (iii) the hydrometric database of the Canadian Hydrological Service (HYDAT, 2014), which provided data from 480 catchments. These data were derived from sites throughout North America, spanning a large range of vegetation types, soils and land use conditions, together with large variations in mid-latitude climate conditions (for more details see González-Hidalgo et al., 2009, 2010, 2012, 2013).

The land uses/land covers were coded according to the following classes: (i) agriculture (herbaceous plants, including cereals, sunflower, sugar cane, corn and potato); (ii) agriculture (trees and shrubs), including olive orchards, and particularly vineyards; (iii) forest (including forest crops such as eucalypts); (iv) shrubs and

rangeland; (v) mixed landscapes with crops, forest, shrubs and/or pastureland; (vi) pastureland (natural herbs and some herbaceous crops such as lucerne); (vii) bare soil; (viii) forest tracks, roads and urban areas; (ix) bench terraced fields; (x) areas affected by wildfires; (xi) abandoned fields; (xii) fallow land; and (xiii) badlands. Only for categories (i)–(vi) and (ix) were the sample sizes adequate for inclusion in the statistical analysis.

The final dataset comprised 4377 data entries, although not every entry included data for every variable. The full dataset is included as online supplementary material in the digital version of this article.

2.2. Statistical analysis

Scatterplots were used to provide a visual relationship between erosion rates and other continuous covariates including slope, annual precipitation, and catchment size. To prevent excessive clustering of points because of large sample sizes, hexagonal binning was used to represent the density of observations in the x–y space. A loess (local polynomial regression) fitting was added as a piece-wise estimation of the mean of the erosion rate conditioned to the covariates. A color ribbon was plotted around the loess line, representing the 95% confidence interval of the mean. This confidence interval is a model of the mean of the data, and not a model of the data itself; thus, it tells nothing about where future observations of erosion rates are likely to fall, given a particular covariate.

Probability density plots were used to compare the distribution of erosion rates for different levels of factor covariates associated with different measurement methods and land uses. The use of densities (summed to a value of 1) instead of frequencies (number of observations) enabled comparisons among sets of different size.

Linear regression was used to determine the significance and effect of single covariates on erosion rates. Multivariate regression was used to test the ability of a combination of environmental factors (precipitation, slope and land use) to predict the (logarithmic) erosion rates. Two alternative model configurations were tested: one using the variables noted above, and another that also included the measurement method, the catchment size and the experiment duration. These models were compared to assess whether non-environmental factors related to the characteristics of the data collection method had a significant influence on the reported erosion rates. A likelihood ratio test based on the Akaike Information Criterion (*AIC*) was used for comparing the model

configurations. A sample of $n = 274$ observations was available for fitting the complete model, as many data entries lacked data for at least one of the variables.

3. Results

Fig. 1 shows the spatial distribution of the sites included in the database. North America and Europe comprised the largest number of study sites; other areas represented in the dataset included Chile, China and some African countries. Little information was available for large areas of South America, western Africa and the Middle East. The map does not precisely reflect the regional importance of erosion processes, but rather the presence of research groups in universities and research institutions, and the availability of financial resources to carry out monitoring at experimental stations and in catchments. However, in the case of Europe a large proportion of the studies concerned the Mediterranean region (García-Ruiz et al., 2013), because the variety of dramatic eroded landscapes in the region have attracted the interest of local geomorphologists, and others from Germany, the United Kingdom, Belgium and the Netherlands in particular.

The most outstanding feature of the data is the extraordinary variability in erosion rates and environmental conditions, but also in relation to the measurement techniques used. For instance, the size of the experimental sites varied by more than ten orders of magnitude, and the duration of the studies ranged from minutes to several decades. Similarly, experiments involving distinct land use/land covers involved a large variety of slope gradients, and the methods used to determine erosion rates included various levels of complexity and cost. In addition, there was variability among studies in the quality of the reporting of information concerning the experimental area, making comparison of the results and general conclusions difficult. Many authors did not provide information on land cover, slope gradient, climate characteristics, or even the size of the study area or its location (geographic coordinates). Particularly problematic was the absence in some cases of data on the duration of the experiments, and only in a few cases did the erosion rates reported include a standard deviation or variance statistic in addition to the mean value. In studies spanning several years, only in a few cases was information given about the interannual variability of erosion rates. In most cases the rainfall characteristics during the study period were not compared with the longest temporal context. Ideally, the climate characteristics during a study period should be

compared with the general climate of the region, based typically on data from at least 30 years.

Below we report the patterns of erosion rate in relation to independent environmental variables including precipitation, slope gradient and land use/land cover, and non-environmental variables including the measurement method, size of the study area, and duration of the experiment. In the last section we present the results of a multivariate analysis that included all factors.

3.1. Precipitation

Fig. 2 relates the erosion rate ($\text{Mg ha}^{-1} \text{ yr}^{-1}$) to the mean annual precipitation (mm yr^{-1}), based on data from 3431 records. Most of the studies were carried out in areas having precipitation $> 1500 \text{ mm yr}^{-1}$, but the dataset also included areas with semi-arid climates (precipitation $< 500 \text{ mm yr}^{-1}$). No studies involved regions with $< 100 \text{ mm yr}^{-1}$ (arid climates), probably because of the relative absence of water erosion processes under conditions of very low mean annual precipitation. Nevertheless, very high erosion rates (up to $10,000 \text{ Mg ha}^{-1} \text{ yr}^{-1}$) have been recorded in semi-arid areas ($200\text{--}500 \text{ mm yr}^{-1}$) despite apparently very low levels of runoff. Few studies have been performed in areas with rainfall $> 2000 \text{ mm yr}^{-1}$.

Large variability in erosion rates is evident in Fig. 2, which shows that almost any erosion rate is possible under almost any climatic condition. The loess smoother line indicates an increase in the mean erosion rate with increasing precipitation, at least until approximately 1400 mm yr^{-1} . The sudden increase in the slope of this relationship between 1000 and 1400 mm yr^{-1} seems to be influenced by a cluster of records of very high erosion rates coinciding with this level of precipitation. The relationship between erosion rate and precipitation is less clear for precipitation levels $> 1400 \text{ mm yr}^{-1}$, probably because of the small sample size.

The linear regression analysis indicated a significant effect ($\alpha = 0.05$) of precipitation on the erosion rate, although the effect size was very small ($R^2 = 0.013$).

3.2. Slope gradient

The relationship between erosion rate and the slope gradient (m m^{-1}) is represented in Fig. 3, based on data from 624 records. Slope gradient has consistently been considered a critical factor explaining the variability of erosion rates under all environmental conditions. However, as Fig. 3 shows, there was very high variability in

erosion rates associated with both gentle and steep slopes. The loess smoother line suggests an increase in the mean erosion rate for gradients of 0–0.2 m m⁻¹ (an angle of approximately 11°). Most of the studies involved slopes in this range, because of the predominance of experimental plots in agricultural land, which is typically in that slope gradient range. The confidence band of the loess smoother line became very wide for slope gradients > 0.2, and consequently was unreliable.

The linear regression analysis indicated a significant effect ($\alpha = 0.05$) of slope gradient on the erosion rate, although the effect size was again very small ($R^2 = 0.024$).

3.3. *Land use/land cover*

Fig. 4 shows the erosion rates in relation to land use/land cover, from a total of 860 records. The sample size for each land cover type is given in parenthesis in the figure legend. Although there is a relatively chaotic distribution of erosion rates, four features are noteworthy: (i) among the highest erosion rates, studies involving agricultural activities produced the highest values, although moderate erosion rates were also evident; (ii) forest fires were associated with relatively low erosion rates, although this interpretation is questionable because in many cases the occurrence of rainfall immediately following the fires was not reported. This information is critical because of the effect of rapid plant colonization and declining erosion following fire. In addition, only ten studies were included in this analysis, which is too few for the results to be representative of the diversity of forest fire sites; (iii) areas with shrubs tend to be associated with low and moderate erosion rates, although high erosion rates are also possible; and (iv) pasture areas tend to be associated with intermediate erosion rates. No significant association was found for the other land use/land covers, particularly in the case of forest environments. The linear regression analysis that included land use/land cover types as a factor (equivalent to an ANOVA analysis, but also indicating the sign of the difference in factor levels) yielded significant results ($\alpha = 0.05$), although the effect size was very small ($R^2 = 0.052$).

3.4. *Measurement method*

Fig. 5 relates the erosion rates to the measurement method used, from a total of 4165 records. The sample size for each factor level is given in parenthesis in the figure. Erosion models, radioisotope and (to a lesser extent) bathymetric methods tended to

show a higher proportion of high erosion rates. Direct measurement of sediment yield in the field (using experimental plots or monitored streams) was associated with comparatively low erosion rates, although very high rates also occurred. Marked differences were also found between plot and catchment studies, with a large proportion of plots having the highest erosion rates (Fig. 6).

The linear regression analysis indicated significant differences ($\alpha = 0.05$) among measurement methods, but the effect size was small ($R^2 = 0.077$). The variance explained increased for the distinction between plot and catchment studies, but not to high levels ($R^2 = 0.106$).

3.5. Size of the study area

The relationship between erosion rate and the size of the study area (m^2) is shown in Fig. 7, based on 3236 records. A large density of data points is evident around 60 m^2 , coinciding approximately with the area of the USLE plots, and around 1000 km^2 , coinciding with the typical size of many monitored catchments.

The most outstanding result is that a broad range of erosion rates is possible at any spatial scale. However, the loess smoother line suggests an almost linear relationship between erosion rate and study area size, in the double logarithmic scale of the plot. This relationship was particularly evident for study area sizes of $>10 \text{ m}^2$, as the line remains approximately flat for smaller sizes.

Fig. 8 shows the previous figure combined with information on the measurement method used, based on 3207 records. A negative linear relationship between erosion rate and area was more apparent for direct measurements. Only at the largest scales ($>10,000 \text{ m}^2$) did modeling and bathymetric studies yield average erosion rates that were higher than those from direct measurements. On the other hand, rainfall simulation and radioisotope studies mainly occur in the smallest scales (less than 10^8 m^2). The linear regression analysis confirmed a significant relationship between erosion rate and study area size, with the effect of size increasing when the measurement method was also included (from $R^2 = 0.158$ to $R^2 = 0.208$, respectively).

3.6. Duration of the study

The duration of the study (the time period over which the measurements were made) was primarily analyzed because of the importance of extreme events on erosion rates. It was assumed that during short-term field experiments the probability of an

extreme event was less than during longer field experiments, so in the latter case erosion rates more closely approximate the long term average. In addition, the occurrence of an extreme event during a short-term field experiment greatly increases the estimated erosion rate, confounding comparison between experiments of differing duration.

The probability distribution of the duration of the study (Fig. 9) shows a clear bimodal distribution, both for plot and catchment studies. A large proportion of studies spanned only one year, which appears to be too short to obtain reliable estimates of long-term erosion rates. The second peak occurred at approximately 10 years for plots, and 2–10 years for catchments. Experiments longer than 10 years are in general rare, and very few studies have exceeded 25 years in length.

The relationship between erosion rate and the duration of the study was based on 3053 records and is shown in Fig. 10, which indicates extremely high variability among erosion rates. The loess smoothed line suggests increasing erosion rate with increasing study duration; this relationship was significant, but the effect size was small ($R^2 = 0.027$).

It is noteworthy that the standard error of the mean erosion rate (based on 2697 records) decreased markedly with the duration of the study (Fig. 11). This statistic reflects the uncertainty related to estimation of mean erosion rates based on annual data. The uncertainty was high for studies spanning < 10 years, and remained at relatively high levels (0.25) up to 20 years. This demonstrates that in short-term experiments the high interannual variability typical of erosion rates at any spatial scale can lead to unreliable estimates of the erosion rate. This relationship was significant, with an effect size of $R^2 = 0.1777$.

The importance of the duration of the experiment can also be assessed for those catchments for which interannual data were available (a total of 2697 records), by considering the ratio between the maximum and mean annual erosion rates. This ratio is an indicator of the weight of extreme events within the study period (Fig. 12). The ratio increases progressively as the number of years of the study increases, up to approximately 20 years, when the loess smoothed line flattened. Thus, a period of at least 20 years of measurements seems to be optimal for obtaining reliable erosion rates. The relationship was significant, with an effect size of $R^2 = 0.254$.

3.7. Multivariate analysis

Regression analysis showed a significant effect of the three environmental factors considered (precipitation, slope and land use/land cover) on the log-transformed erosion rates. A positive relationship was found for precipitation and slope. For land use/land cover, agriculture was the reference land use with which all the other land uses were compared; only the pasture, shrub and forest sites differed significantly from the agricultural sites, having a negative effect on erosion rate. The model was significant (F-statistic: 10.62 on 8 and 265 degrees of freedom for a p value < 0.001 ; $R^2 = 0.243$, $AIC = 659.879$), with a residual standard error of 0.791.

A second model including all the above variables plus the non-environmental factors related to the particular experimental setup (measurement method, size of the study area, and duration of the study) significantly improved the prediction of erosion rates (F-statistic: 21.05 on 13 and 260 degrees of freedom for a p value < 0.001 ; $R^2 = 0.5128$, $AIC = 549.024$), with a residual standard error of 0.640. A negative effect was found for the study area, while the experiment duration had a positive effect. Among the methods, direct measurement was used as the reference measurement, with bathymetric, model and radioisotope methods having a positive association with erosion rates. The coefficients of the analysis are shown in Table 1.

Table 1. Multivariate regression analysis results for log-transformed erosion rates. Note that the variables were scaled and centered before the analysis, to enable interpretation of the coefficients (this transformation does not affect the significance tests or the overall results of the analysis).

Coefficients	Estimate	Std. Error	t value	$\Pr(> t)$
Intercept	2.544	0.055	45.891	<0.001
Environmental factors:				
Precipitation	0.137	0.045	3.018	0.003
Slope	0.202	0.049	4.163	<0.001
Landuse: forest	-0.635	0.152	-4.171	<0.001
Landuse: shrubland	-0.542	0.142	-3.805	<0.001
Landuse: pastureland	-0.370	0.183	-2.026	0.044
Landuse: orchard	-0.216	0.256	-0.841	0.401
Landuse: others	-0.122	0.200	-0.608	0.544
Landuse: mixed	-0.058	0.169	-0.344	0.731
Experimental factors:				
log(area)	-0.211	0.052	-4.092	<0.001
Period	0.264	0.047	5.649	<0.001

Method: model	1.767	0.477	3.702	<0.001
Method: bathymetry	0.578	0.200	2.892	0.004
Method: radio isotope	0.549	0.135	4.069	<0.001

This confirms the importance of controlling for the measurement method and the experiment duration in analysis of erosion rate data from different sources.

However, the predictive power of the model is limited, as shown in Fig. 13. The scatterplot of predicted against observed erosion rates shows a good average relationship, but the prediction interval (range that comprises 95% of the observations) spans almost two orders of magnitude, while the entire range of the variable spans in excess of four orders of magnitude.

4. Discussion: facing new challenges in estimating erosion rates

4.1. General trends: the role of environmental factors

The database used in this study was compiled from information published in hundreds of studies from diverse countries worldwide, and included data for a number of plots and experimental catchments from the USDA, the USGS and the Canadian Hydrological Service. It was compiled from various data sources including reservoir and lake bathymetries, radioisotope surveys, simulations and models. We believe it is one of the most complete and up-to-date compilations for studying the occurrence of erosion patterns at a worldwide scale, and for identifying the drivers that explain erosion processes and rates.

Our analysis confirms that no general rule, normalized approach, or universal criteria have been applied to the study of erosion processes and to determining erosion rates. With the exception of the USLE experimental plots, field experiments have been carried out under an extremely large variety of conditions, using diverse methods and at various spatial scales. This variability in experimental conditions is a barrier to the interpretation of the environmental factors influencing erosion rates.

Our results demonstrate that differing experimental conditions can be successfully accounted for in a regression model as random factors (non-environmental influences), thus allowing a better assessment of the environmental factors that are really of interest. However, of great concern is that very few studies provide complete information about the study area and/or the experiment characteristics, with relevant data including the bedrock, climate characteristics, weather conditions during the study

period, topography, duration of the study, and plant cover and land use being very often not reported. This severely restricts the potential for meta-analysis of data from different experiments, and reduces the value of the efforts made in the field and laboratory. It also reduces the potential to use most of the data in parameterization and validation of models.

Analysis of the database identified some general trends in soil erosion rates:

(i) Erosion rates tend to increase with increasing slope in experiments below 0.2 m m⁻¹, and no trend has been found over that threshold. This could be related to the high variability of erosion rates reported in studies of low and moderate slopes. Band (1985), Parsons and Abrahams (1986) and Abrahams et al. (1988), among others suggested that the relationships among slope, runoff and erosion are complex.

(ii) Erosion rates tend to increase with increasing mean annual precipitation. The erosion rates seem to be greater for mean annual precipitation between 1000 and 1400 mm yr⁻¹, but this may be the effect of a specific cluster of records in our dataset. The small sample size prevented this relationship from being extended beyond 1500 mm yr⁻¹, although our data suggest that it becomes flat. This pattern is not the same as that described by Langbein and Schumm (1958), probably because it is conditioned by human activity and the associated disturbance to plant cover, which enhances soil erosion with increasing precipitation. It is more consistent with the patterns suggested by Walling and Kleo (1979), who identified three climatic zones where erosion rates can be particularly high (Mediterranean, monsoonal and semiarid areas). Furthermore, the extreme dependence of soil erosion on few annual events (e.g. Edwards and Owens, 1991; González-Hidalgo et al., 2009, 2010) shows that most precipitation does not generate soil erosion, that the mean precipitation value is not a good predictor of soil erosion, and that “caution should be taken when rainfall is considered in soil erosion prediction by means of different rain erosivity indices” (González-Hidalgo et al., 2009).

(iii) In general, land use/land cover have a determining role in soil erosion rates (Montgomery, 2007; Cerdan et al., 2010; García-Ruiz, 2010; Cerdà et al., 2012; Dotterweich, 2013; Nadal-Romero et al., 2013), and there has been general agreement about the protective effect of natural plant cover. Seminal papers on this topic by Elwell and Stocking (1976) and Thornes (1987) have provided hypotheses about the effect of plant cover and its vertical structure on erosion. In our compiled data the variability was extremely high because of the diversity of land management systems and their complex interactions with climate and slope; this causes thresholds and non-linearity (Thornes,

1987; García-Ruiz et al., 2013). Our results confirm that agricultural activity tended to be associated with the highest erosion rates, although there was enormous variability. The same occurred for the forest and shrubland areas, which showed moderate erosive behavior, but high and very low erosion rates were possible. As suggested by Armstrong and Mitchell (1988) and González-Hidalgo et al. (1997), splash, runoff and soil erosion under shrub cover are strongly controlled by rainfall partitioning processes (stemflow and throughfall), which in turn depend on shrub characteristics. Pastures also showed a moderate relationship, whereas the areas affected by wildfires showed an unexpected response, with a high concentration around relatively moderate erosion rates, contradicting the idea that high erosion rates occur after fire. This is a consequence of the lack of agreement concerning the study period following fires.

An important issue is why there is such high variability, and why the results are so unclear despite the large investments of time, effort and funds. Boardman (1986, 1996, 2006) has analyzed periodically the problems affecting soil erosion studies. In some cases it seems that there is an excess of improvisation, particularly in the case of short-term field experiments, and that field monitoring is adjusted to financial constraints and the need to rapidly obtain quantitative information enabling publication, rather than addressing the most important erosion questions (Boardman, 2006). Quantification of erosion rates is necessary, but it is critical to understand how to use this information, what the data really represent, and what are the data limitations. Our results confirm that, in addition to the environmental factors, there are factors related to the experimental conditions that need to be accounted for when comparing erosion rates among different studies. These non-environmental factors are described below.

4.2. Scale-dependency of soil erosion processes and rates

Cantón et al. (2011) noted that “the arbitrary choice of spatial and temporal measurement scale significantly affects results”. This is because different erosion processes are active at different spatial scales. For instance, sheet wash erosion and in some cases rill erosion are the prevailing erosion processes studied in erosion plots, whereas gullies and landslides can yield very large quantities of sediment in the case of small- and medium-size catchments. Large basins are more related to long-term erosion and storage processes (Kirkby et al., 2002; Lesschen et al., 2009).

In general, there is consensus on the scale-dependency of erosion processes (Osterkamp and Toy, 1997; Poesen and Hooke, 1997; Cammeraat, 2002, 2004; de

Vente and Poesen, 2005; Stroosnijder, 2005; Parsons et al., 2006; de Vente et al., 2007; Vanmaercke et al., 2011b), although the results obtained have been quite confusing. Vanmaercke et al. (2011a) reported that the relationship between catchment area and erosion rate throughout Europe is very weak “and subject to a lot of scatter”, with statistically significant correlations only associated with temperate and relatively flat regions. Vanmaercke et al. (2011b) found a negative relationship between catchment area and erosion rate, because of the greater probability of occurrence of gentler slopes in larger catchments, and the presence of areas of predominantly sediment deposition (Walling, 1983). To explain these negative relationships, Vanmaercke et al. (2012) argued that “the majority of sediments eroded from hillslopes are deposited at parcel boundaries, footslopes and floodplains”. Boix-Fayos et al. (2006) pointed out that erosion and sedimentation processes “change markedly downstream as watershed area increases”. In the case of experimental plots, the sediment-contributing area becomes proportionally smaller as the size of the plot enlarges (Rejman et al., 1999; de Luis et al., 2003). Cantón et al. (2011) also found a decrease in erosion rate with increasing catchment area, based on data for sedimentation in reservoirs. In Mediterranean badland areas, Nadal-Romero et al. (2011, 2014) demonstrated that for areas of less than 10 ha, erosion rates are very high because of the absence of sediment storage in badland areas, whereas for catchment areas larger than 10 ha the erosion rate decreases non-linearly as the area increases because sediment is trapped in the valley bottoms and in the footslopes. Church et al. (1999) also found a negative relationship between these parameters in basins of Canada, which was attributed to channel aggradation. Conversely, de Vente et al. (2007) cited a study in a humid tropical basin of Costa Rica, where erosion rates showed a positive relationship with the area. This was related to land use, as dense forest covered the headwater and intensive agriculture dominated on the alluvial fans.

The occurrence of thresholds in certain erosion and transport processes (gully erosion, landslides, and bank erosion) can increase erosion rates as catchment area enlarges until a new threshold, caused by the predominance of gentle slopes, leads to transport-limited conditions. de Vente and Poesen (2005) presented a conceptual model of the area–erosion relationship for Mediterranean environments. They argued that erosion at small scales is caused mostly by splash, sheet wash erosion and rilling, which lead to low erosion rates. With an increase in area, other more active processes (gullying) are involved, and together with an increase in sediment connectivity they

result in high erosion rates. In drainage areas larger than 10 km² a progressive decline in erosion rates occurs because of the presence of large sediment sinks (footslopes and alluvial plain). It is clear that a change in scale that incorporates gullies represents a threshold in sediment yield, as gullies are the most effective link in the transfer of sediment from the hillslopes to channels (Poesen et al., 2003; Bathurst et al., 2005; Valentin et al., 2005; Tamene et al., 2006). Thus, the vast literature dealing with the relationships between area and erosion confirms the importance of scale, and the difficulties of comparing results from studies of experimental areas of differing size, and extrapolating from one scale to another.

4.3. Influence of measurement methods

Erosion studies include a variety of methods leading to quantification of the material that is removed from the hillslopes, transferred to the channel and transported to other channels, lakes and oceans. The selection of method depends on the characteristics of the research group (number of members and training capacity), financial support, objectives, and size of the study area. However, the results obtained have not been independent of the method used (de Vente et al., 2007), because each method tends to be related to a spatial scale or a range of spatial scales, and consequently each method is selected to measure particular erosion processes. The methods used include experimental plots of distinct sizes, rainfall simulations, small ponds, check dams and reservoirs to estimate the accumulated sediment, erosion pins and profilometers, radioisotope surveys, experimental catchments, and models. Nevertheless, most methods have been subject to substantial criticism.

Thus, for several decades experimental plots were a major source of information on erosion under various land uses/land covers, but their use has recently been criticized as a means of deriving erosion rates. Boix-Fayos et al. (2006) questioned the validity of information obtained from experimental (closed) plots because of disturbance to part of the hillslope caused by artificial drainage boundaries, the inadequate representation of natural conditions, the exhaustion of sediment in the mid-term, and the problem of extrapolating the erosion rates obtained to larger areas (Govers, 1991; Cammeraat, 2002, 2004; Leser et al., 2002; Parsons et al., 2006). Le Bissonnais et al. (1998) concluded that even small differences in the size of the experimental plots cause large differences in runoff and erosion, as a consequence of reduced flow velocities and lower probabilities of infiltration in the smaller plots. In addition, most plot-based studies have

assumed that runoff and erosion are derived from the entire area enclosed in the plot, but there is mounting evidence that the source area of water and sediment is relatively small, and is usually located close to the plot outlet (Parsons, 2011). Furthermore, soil exhaustion related to increasing stoniness has been described (Ollesch and Vacca, 2002), and results in changes in soil erosion processes from transport-limited to detachment-limited. Consequently, it appears that little credence can be given to erosion rates obtained from closed plots of several square meters, particularly when the area actually producing the water and sediment is uncertain, and that results subsequently extrapolated to large areas ($\text{Mg km}^2 \text{yr}^{-1}$) are probably unreliable. Also of importance is that large differences in erosion rates and runoff have been detected among replicate experimental plots (Rüttiman et al., 1995; Nearing et al., 1999; de Luis et al., 2003). Although experimental plots have contributed substantially to knowledge of infiltration, runoff generation processes, rainfall–runoff–erosion relationships, and the relative erosion rates from various land uses/land covers, it is not possible to extrapolate their results to any other scale (Boardman, 2006; Boix-Fayos et al., 2006; Vanmaercke et al., 2011b).

Rainfall simulation plots face greater criticism than experimental plots because of their small area (commonly $< 0.5 \text{ m}^2$) and the particular characteristics of rainfall. This does not invalidate rainfall simulation as a useful method for the study of a certain erosion-related process such as infiltration, the evolution of the hydrological and sedimentological response, and penetration of the wetting front (González-Hidalgo et al., 2004). However, the values obtained for erosion (from the suspended sediment concentration in runoff) are only of interest in relative comparisons of the response of distinct soil types or plant covers. Besides, even in the latter case the spatial distribution of plants within the rainfall simulation plot can condition the results (de Luis et al., 2003). For these reasons, rainfall simulations can only be considered to be a complementary method in soil erosion studies, although in some of them it was the main research method used.

Other methods have been also questioned. Thus, erosion pins and profilometers, commonly used in badland areas, have been shown to overestimate the erosion rates for the entire area (Nadal-Romero et al., 2011). More complex infrastructure, such as collecting tanks, is commonly destroyed during extreme events, and consequently data on the most interesting rainstorm and sediment yield events are lost. Bathymetric studies in reservoirs can provide information on sediment accumulation (and therefore

erosion rates) over long periods of time extending to decades, or centuries in the case of ancient reservoirs (Molina-Navarro et al., 2014). For this reason it is arguably the best way to determine erosion rates. Nevertheless, information from reservoir studies are subject to five types of problems: (i) in some cases the trapping effectiveness of reservoirs is unknown or of uncertain reliability, and this typically leads to underestimates of erosion; Verstraeten and Poesen (2002) pointed out that estimates of erosion rates from small ponds are subject to error, estimated to be between 40% and 50% for 21 catchments in central Belgium; (ii) establishing the temporal variability of sedimentation and erosion rates is impossible unless a detailed analysis of sediment cores is carried out; (iii) erosion rates determined from sedimentation in reservoirs provides a value for a large catchment, although it is very difficult to know the location of sediment sources; some attempts have been made to study this based on the sediment composition in water from the main tributaries of the basin (Valero-Garcés et al., 1998); (iv) the sediment management approaches vary among reservoirs, mainly depending on the size of the reservoir in relation to annual discharge, and the characteristics of floods; and (v) the organic fraction of sediment is often combusted or digested prior to measurement of sediment, omitting an important fraction of the eroded soil that has a biological impact in freshwater ecosystems (Bilotta and Brazier, 2008).

The use of radioisotope methods is a newly developing tool in soil erosion studies (Navas et al., 2005). While most other methods can only measure the sediment yield from a given closed area, radioisotope surveys can provide true erosion rates, including intermediate deposition areas. At the field scale, radioisotope measurements provide point estimates of soil erosion, as the sampling area is typically very small (in the order of several square centimeters). Thus, spatial surveys must be very carefully designed and executed to obtain a good representation of the erosion rates at the landscape scale. The point estimates must then be transferred to the landscape scale using one of several techniques, including spatial averaging or interpolation, statistical analysis, or mechanistic models. Boardman (2006) noted that it is a time-consuming method, and the assumptions on which it is based are debatable. Parsons (2011) and Parsons and Foster (2011), argued that the loss of ^{137}Cs is not necessarily proportional to the loss of soil. Furthermore, it is quite difficult to establish a site where no erosion or accumulation has occurred in the last 60 years, to provide a reference for values of ^{137}Cs determined for eroded soils. ^{137}Cs is preferentially adsorbed to clay particles and organic matter, which are easily eroded (Stroosnijder, 2005), and this introduces bias

into soil erosion estimates. Parsons and Foster (2011) concluded that ^{137}Cs “cannot be used to provide information about rates of erosion”. However, recent studies have reaffirmed the usefulness and accuracy of radioisotope methods for soil erosion studies (e.g. Mabit et al., 2013; Navas et al., 2013).

Simulation models have been widely used to predict soil erosion rates. However, it is noteworthy that models are simply representations of reality (Kirkby et al., 1993); they are not substitutes for field measurements, and their validation requires high quality field data (Brazier, 2004). Several studies have criticized the perfunctory use of simulation models (Trimble and Crosson, 2000; Kinnel, 2003, 2005). In general, models have been used to estimate soil erosion under present and future land cover or climate scenarios, or to predict erosion in areas for which little quantitative data are available. For instance, Boix-Fayos et al. (2008) applied the WATEM-SEDEM model to a semi-arid catchment in southeast Spain under six land use scenarios with and without check dams. This simulation demonstrated the efficiency of check dams in sediment control projects, and the consequences of increasing land cover density. Similarly, Alatorre et al. (2010, 2012) forecasted sediment yields and developed corresponding sediment delivery maps for the Arnás catchment, central Spanish Pyrenees, under three temporal scenarios: past (with the entire catchment cultivated), present (with the catchment covered by shrubs and some forest patches) and future (with the catchment covered mainly by forest). These studies reflect that models are crucial to forecasting reservoir siltation, alluvial plain sedimentation, future water resources, and the hydrological and erosive response of catchments to extreme events. Nevertheless, major improvements need to be made to model performance, to overcome issues of data quality/availability and the inadequate representation of erosion and sediment transport processes (de Vente et al., 2011). de Vente and Poesen (2005) argued that large variations in catchment characteristics and the occurrence of non-linear relationships between sediment yield and environmental variables reduces the quality of the results. In evaluating the application of 14 models involving 700 catchments, de Vente et al. (2013) concluded that “it is easier to predict sediment yield than to know where the sediment originates from and what the dominant erosion and sediment transporting processes are”, and that “predictions for large catchments are generally more accurate than for smaller catchments”. Boardman (2006) qualified models as “a good thing”, although several problems reduce their applicability, including complexity, data availability, and up-scaling from small to larger scales. This

author stressed that most erosion data are collected at inadequate scales for use in models; thus, information from experimental plots has limited application in the development of models for the landscape scale. Alatorre et al. (2012) stressed the need for spatially-distributed soil erosion data in addition to catchment outlet sediment yields, to enable calibration of soil erosion models.

4.4. Complex hydrological and geomorphological response and interactions of hillslopes and catchments

In the last few decades much effort has been devoted to analyzing hydrological and geomorphological processes at the catchment scale. Most of the conceptual problems related to soil erosion need to be solved at this scale, because it integrates hillslopes and channels, and encompasses sediment sources and sinks. Some years ago the literature contained definitions of erosion, but it is now less clear what this term means. Trimble (1975) defined soil erosion as “the total amount of soil material dislocated and removed some distance by erosion within an area”. This seems sound, but as pointed out by Parsons et al. (2006) it does not contain information about the distance a soil particle must be moved to be considered “eroded”. For this reason, geomorphologists and agronomists tend to use the term “erosion” in a general context, and use the concept of “sediment yield” to refer to the material removed from a hillslope or a catchment, which includes the erosion processes associated with the hillslopes and channels, sedimentation at some sites, and delivery to the catchment outlet (Walling, 1983; Parsons et al., 2006; de Vente et al., 2008).

The catchment scale integrates the geomorphic processes in a landscape perspective, and provides information on “natural”, undisturbed situations. The sediment carried by a stream to the catchment outlet provides information on the seasonal variability of sediment yield; the relationships among rainfall events, discharge, erosion and sediment transport; and the relationships between the height of the water table and the hydromorphological response. However, the sediment yield value, expressed as $\text{Mg km}^{-2} \text{ yr}^{-1}$, is like a black-box model that provides little information on the internal processes, or on sediment sources and sinks within the catchment. Consequently, few conclusions can be drawn from the sediment yield value alone, and comparisons with other catchments lead to crucial geomorphological errors. Some of the main sources of error are described below.

(i) Sediment yield data are not always representative of the intensity of erosion processes on hillslopes, because of the occurrence of sediment sinks (e.g. footslopes, alluvial plains, concavities, and small flat areas at mid slope) where the eroded material accumulates. For instance, many hillslopes have unconfined debris flows for which the runout distance is too short to connect with the stream, and consequently their contribution to sediment yield is very limited (Bathurst et al., 2007). For this reason the connectivity between eroded areas on hillslopes and the fluvial channel is a key aspect of the problem. In fact, only a small proportion of the material removed from a hillslope becomes sediment yield (Fryirs, 2013). Conversely, the protection conferred on a catchment by a dense cover of forest or a shrub community does not ensure a low sediment yield, as the presence of even a small number of gullies or landslides close to the stream favors rapid connectivity and a relatively high sediment concentration.

(ii) Vanmaercke et al. (2011b) noted that sediment yield usually reflects “the integrated effects of various processes over longer time periods”. Therefore, sediment yield values cannot be considered to represent the current land use/land cover characteristics (Trimble, 1999; Prosser et al., 2001). This issue was first identified by Schumm (1977), who noted that sediment yield is not necessarily a consequence of current erosion processes on hillslopes, but may be the effect of past erosion (see also Richards, 2002; Phillips, 2003; Verstraeten et al., 2009). This incorporates the important concept of inertia (similar to the concept of relaxation time, as suggested by Thornes and Brunnsden, 1977) in geomorphological research. Owens et al. (2010) referred to the reaction time following a change in plant cover, and highlighted the occurrence of a time lag between a disturbance and the corresponding reaction, with the latter being “a function of the topography and size of the river basin”.

(iii) In many cases the estimates of sediment yield have not taken into account the extremely influential effect of channels as sediment sinks and sources. For instance, it has frequently been demonstrated that a natural or artificial increase in land cover in a catchment following centuries of human activity does not result in a decline in sediment yield because other areas (mainly the channel) become the principal sediment sources. For instance, Trimble (1999) noted that “alluvial sediment storage has been greatly reduced in the Coon Creek basin (Wisconsin, USA), but sediment yield from the basin has remained constant”. In that catchment the introduction of conservation practices reduced soil erosion, although sediment yield did not decline because of erosion of sediment previously stored in the lower parts (Trimble, 2009). Trimble (1999) argued

that this demonstrated “the limited short-term diagnostic utility of sediment yields”. In a small catchment affected by farmland abandonment and natural revegetation, Lana-Renault and Regüés (2009) showed that the main sediment source areas were close to the channel or in the channel itself. In a more recent report, Sanjuán et al. (2014) confirmed that the channel and the riverbanks are now the main sediment source in the Ijuez catchment in the Spanish Pyrenees, following rapid reforestation and the consequent reduction of erosion on hillslopes. This resulted in a 3 m incision during the last 50 years and an increase in sediment size in the channel (Gómez-Villar et al., 2004). In a review of the hydrological and geomorphological consequences of farmland abandonment in Europe, García-Ruiz and Lana-Renault (2011) cited many reports of incision and riverbank erosion processes in Mediterranean and Alpine catchments, associated with a decline of sediment supply from hillslopes (e.g., Liébault and Piégay, 2002; Piégay et al., 2004; Keesstra et al., 2009; Sanchis-Ibor and Segura-Beltrán, 2014). Stroosnijder (2005) suggested that the “large sediment load in a stream may primarily be due to bank erosion”. These results confirm “how poorly sediment yield can relate to sediment fluxes within a basin and thus how reliance on sediment yield monitoring can lead to erroneous conclusions about erosional processes within a basin” (Trimble, 1999).

Another source of uncertainty is that because of difficulties in measurement and quantification, many catchment studies have not considered bedload in the estimation of sediment budgets and yield (Parsons, 2011). This is a problem, because bedload is a good indicator of the geomorphological behavior of hillslopes and channels, and can represent a relatively high proportion of the total sediment yield. An associated issue is that analysis of solutes is arbitrarily included in sediment yield studies, depending on the availability of appropriate instruments in study catchments. The fact that some suspended sediment or bedload is dissolved during transport introduces another variable in estimating sediment yield.

4.5. Importance of long-term field experiments to increase the representativeness of estimated soil erosion rates

Debate about the minimum time needed to achieve representative values of soil erosion is not recent. A time span of 15–22 years was suggested by Rise et al. (1993), and Lane and Kidwell (2003). A shorter period (3 years) was suggested by Ollesch and Vacca (2002), while González-Hidalgo et al. (2009, 2012) suggested measurement of a

minimum number of daily erosive events instead of analysis over a number of years, for both plots and catchments. Short-term studies produce varying results depending on the study period selected (Hjelmfelt et al., 1986), and simple extrapolation is likely to produce large errors (Kirkby, 1984). A consequence is that soil conservation management practices based on average conditions can be adequate for erosion control in most years, but not for conditions involving severe storms.

Our analysis of a large number of studies shows that a high proportion involved periods of less than 5 years, with many of approximately 2 years. Studies of more than 10 years are exceptional, and only those undertaken by large institutional organizations (e.g. USDA and USGS) have records for 20 years or more. This is a very important problem that relates the continuity of records to the continuance of research groups and the availability of research funds. We found a trend of increase in estimated erosion rates with increasing duration of the record, and there was an associated reduction in the standard error of the mean erosion rate (i.e. uncertainty in the estimated erosion rate decreased). This is a consequence of the effect of rare or extreme events on erosion and sediment yield, because the probability of their occurrence increases as the period of the study increases. For this reason, the ratio between the maximum and the mean erosion rate increases with time, whereas the standard error of the mean rapidly decreases. It is noteworthy that in some studies the biggest erosion-producing events can account for > 60% of the total erosion (Edwards and Owens, 1991), and > 70% (Nadal-Romero et al., 2012) over a long study period. This phenomenon, referred to by some as “time compression”, is particularly high under Mediterranean climate conditions, where rainstorms exceeding 200 mm in 24 h are relatively common, and the three largest events each year are usually responsible for > 50% of the annual and interannual sediment yield (González-Hidalgo et al., 2007). Based on information from 1800 catchments in the USA and Canada, González-Hidalgo et al. (2013) found that the 25 largest daily events yielded 46–63% of the total sediment load.. González-Hidalgo et al. (2010) reported that 10% of daily events yielded 50% of the total soil eroded in USLE plots. Boardman and Favis-Mortlock (1999) suggested that in a 10-year database having information on erosion events, it is unlikely to record the large events that usually occur over a longer period of records. The importance of extreme events is related to the highly skewed nature of precipitation, but also to the occurrence of thresholds in erosion and sediment transport processes, which are only triggered when a certain level of precipitation is exceeded. Examples of such processes are incision in first and second

order channels, widening of alluvial plains, and landslides (García-Ruiz et al., 2013); examples of these dramatic landscape changes have been provided by White et al. (1997), Le Lay and Saulnier (2007), Ortega and Garzón Heydt (2009), and Serrano-Muela et al. (2013).

These findings highlight the problems of comparing results among catchments based on short-term studies. Stroosnijder (2005) and Vanmaercke et al. (2012) also noted large interannual variability of erosion rates, related to precipitation variability and the variable state of the soil (Schnabel and Gómez-Gutiérrez, 2013).

5. Conclusions

Our study provided the following nine conclusions:

(i) The construction of a large database of data from experimental stations and catchments, rainfall simulation experiments, erosion rates from bathymetric and radioisotope studies, and simulation models, enabled identification of a major problem in soil erosion studies: variability in the procedures for data acquisition, particularly in field studies, where the results have been based on different scales and methods. The database is far from complete because of the lack of fundamental information provided in many studies. This limits the application of some statistical analyses, reducing the usefulness of many field experiments and the funds invested. The development of models is particularly affected by the variability in the data.

(ii) The data includes extremely high variability in values for soil erosion rates, with high variability possible for any slope, scale or land use/land cover.

(iii) In spite of this variability, some general trends were found including an increase in erosion rates with increasing slope and annual precipitation, the association of agricultural practices with the highest erosion rates, and a correlation between shrub coverage and the lowest erosion rates.

(iv) A multivariate model including several basic environmental factors enabled almost 50% of the variance in erosion rates to be explained. To achieve this, however, it was necessary to account for non-environmental factors related to the experimental conditions that produced those erosion rates, including the measurement method, the size of the study area and the duration of the study. Although the results of such analyses are significant, a large proportion of the variance remains unexplained, highlighting the need for continuous, long-term erosion measurement studies.

(iv) Most studies are short-term, with most in the order of 2 years and few extending beyond 10 years. The results suggest that the optimum study period is 20–25 years, with this period necessary to reduce the variability in erosion rates and to incorporate the occurrence of extreme events that are responsible for the highest sediment yields. Such studies highlight the problem that experimental plots tend to show signs of exhaustion after 10–15 years of experimentation, and have to be abandoned prior to the optimum study period being reached.

(v) A clear bias in the dataset was evident because of the use of various scales and methods. Each measurement method is appropriate to address a particular scientific question. Thus, rainfall simulations can provide information on infiltration rates and the evolution of the wetting front. Studies using experimental plots are useful for the identification of erosion and sediment transfer processes, establishing relationships between precipitation, runoff, erosion and sediment outputs, identifying trends in runoff and sediment yield under distinct land use changes, and assessing the variable response of discharge and erosion to distinct rainstorm events. The resulting erosion rates can be used to compare various land uses, providing the control area is of similar size. Scientists need to be conscious of the limitations of experimental plots, as the results cannot be extrapolated to other scales. Studies at the experimental catchment scale are needed to identify runoff and sediment contributing areas and how they vary with the characteristics of rainstorm events, the location of temporal sediment storage areas, the hydrological and geomorphological consequences of different land covers, the temporal variability of the various types of sediment, and the role of fluvial channels and riverbanks in storing and delivering sediment.

(vi) The catchment is the optimum scale for obtaining information on erosion processes and the relationships between hillslopes and channels. It is also the optimum scale for studying the effects of landslides and gullies, and for analyzing the effects of land use/land cover changes on erosion and sediment transport. However, sediment yield results must be carefully interpreted in view of the complex response of catchments, which are partially affected by past geomorphological processes. In many cases, sediment yield values cannot be considered to represent the current land use/land cover characteristics. Furthermore, sediment yield from catchments depends on a large variety of factors, including the catchment size, location of the sediment sources, connectivity, topography, spatial distribution of plant cover, and channel and riverbank dynamics.

(vii) Bathymetry is probably the best approach for determining sediment yields from evaluation of sediment accumulated in reservoirs, because of the long period passed since the dam was constructed. This technique integrates all erosion and sediment transport processes, although the internal functioning of the system is unknown. In general, the area drained by a reservoir is very large, making interpretation of the sediment yield difficult.

(viii) Models are a critical tool for forecasting the consequences of erosion and sediment yield on sediment siltation, alluvial-plain sedimentation, evaluation of future water resources, evolution of discharge and erosion according to land use/land cover changes, and the effects of extreme events. Nevertheless, modelers need to be aware of the limitations of the information available from plots and catchments. Plots can provide data on infiltration, water storage and field capacity, although data on runoff and erosion are of limited value for uses other than those for which the experiment was planned. In the case of data from experimental catchments, modelers need substantial geomorphological knowledge in interpreting the extremely high complexity of catchments, their sediment sources and sinks, and the inertia of past erosion processes.

(ix) Determining long-term erosion rates characteristic of a variety of landscapes and land uses/land covers is very relevant to soil erosion studies, since they allow understanding the geomorphological and sediment transport dynamics at regional scales. Nevertheless, their significance and representativeness of published erosion rates must be carefully assessed on a case-by-case basis. Geomorphologists should be more interested in processes, causes, internal relationships, and the role of stream channels than in obtaining erosion rates, the interpretation of which can lead to numerous errors.

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FIGURE CAPTIONS

Fig. 1. Spatial distribution of the sites included in the database.

Fig. 2. Relationship between erosion rate and precipitation.

Fig. 3. Relationship between erosion rate and slope gradient.

Fig. 4. Erosion rate frequencies in relation to land use/land cover: agricultural uses, bare soil, burnt areas, forest, mixed, orchards, others, pastures, and shrubs.

Fig. 5. Erosion rate frequencies in relation to the methods used.

Fig. 6. Erosion rate frequencies in relation to the type of experiment (plots and catchments).

Fig. 7. Relationship between erosion rate and the size of the study area.

Fig. 8. Relationship between erosion rate and the size of the study area, according to the study method used.

Fig. 9. Study period frequencies for field experiments (plots and catchments).

Fig. 10. Relationship between erosion rate and the duration of the study.

Fig. 11. Relationship between the standard error of the mean erosion rate and the duration of the study.

Fig. 12. Relationship between the annual maximum/mean erosion rate and the duration of the study.

Fig. 13. Scatterplot of predicted vs. observed erosion rates. The regression line and $\alpha = 0.95$ prediction interval are shown.