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A comparison of measured catchment sediment yields with measured and predicted hillslope erosion rates in Europe

Matthias Vanmaercke · Willem Maetens · Jean Poesen · Benediktas Jankauskas · Genovaite Jankauskiene · Gert Verstraeten · Joris de Vente

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Abstract
Purpose This study aims to understand better the relationship between measured soil loss rates due to sheet and rill erosion (SL), predicted SL rates and measured catchment sediment yields (SY) in Europe.
Materials and methods Analyses were based on a recently established database of measured annual SY for 1794 catchments, a database of 777 annual SL rates measured on runoff plots and two recent maps of predicted sheet and rill erosion rates in Europe (i.e. one based on empirical extrapolations of measured SL data and one based on the PESERA model). To identify regional trends, all data were grouped into eight climatic zones.
Results and discussion Measured SL rates are generally a factor of five to ten times larger than predicted SL rates and are strongly biased towards erosion-prone situations in terms of land use. Also measured SY are generally higher than predicted SL rates, especially in the Mediterranean and Alpine regions where SY is generally ten times higher than predicted SL rates. This illustrates the importance of other erosion processes contributing to SY. Regional differences in the importance of these processes and their implications are discussed.
Conclusions This study confirms previous findings indicating the relatively low sheet and rill erosion rates compared to SY in the Mediterranean region and illustrates the importance of other erosion processes contributing to SY in most regions of Europe. This indicates that hillslope erosion rates cannot be used directly to estimate SY, and consequently soil conservation programmes should focus more on the dominant erosion processes in each catchment.

Keywords Plot soil loss · Scale dependency · Sediment sources · Sheet and rill erosion · Soil erosion model

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M. Vanmaercke · W. Maetens · J. Poesen · G. Verstraeten
Division of Geography, KU Leuven,
Celestijnenlaan 200E,
3001 Heverlee, Belgium

M. Vanmaercke (✉)
Research Foundation Flanders (FWO),
Egmontstraat 51000,
Brussels, Belgium
e-mail: matthias.vanmaercke@ees.kuleuven.be

B. Jankauskas · G. Jankauskiene
Kaltinenai Research Station,
Lithuanian Research Centre of Agriculture and Forestry,
Silale District,
Kaltinenai, Lithuania

J. de Vente
Soil Erosion and Conservation Research Group,
Centro de Edafología y Biologia Aplicada
del Segura CEBAS-CSIC,
Murcia, Spain

1 Introduction

It is widely reported that land use changes may have a tremendous effect on soil loss rates (SL, tonne per square kilometer per year) due to sheet and rill erosion at the hillslope scale. Compilations of SL measurements at the plot scale indicate that humans are currently one of the dominant geomorphic agents, with SL rates under conventional agriculture strongly exceeding geological erosion rates (e.g. Montgomery 2007; Wilkinson and McElroy 2007). Although there are several studies that show an important impact of land use changes on catchment sediment yield (SY, tonne per square kilometer per year) (e.g. Beguería et al. 2003; Renwick and Andereck 2006; Bakker et al. 2008; Boix-Fayos et al. 2008), the human impact on sediment fluxes is generally expected to decrease as spatial scale increases from hillslopes to catchments (e.g. Trimble 1999; Dearing and Jones 2003; Syvitski et al. 2005). This may be partly explained by the fact that river basins are rarely entirely occupied by agriculture, but also by the fact that various processes other than sheet and rill erosion affect catchment SY. SY is the integrated result of all erosion, sediment transport and deposition processes operating in a catchment. As catchment area (A, square kilometer) increases, mean travel distance of sediments increase, while the mean slope generally decreases. As a result, the mean SL rate decreases while sediment deposition opportunities increase with increasing A (e.g. Walling 1983). It has been frequently observed that a majority of sediments eroded from hillslopes are deposited at parcel boundaries, footslopes and floodplains (e.g. Trimble 1999; Notebaert et al. 2009), explaining why catchment sediment yields per unit area are often smaller than hillslope SL rates in agricultural catchments, and why SY generally decreases with A (Boyce 1975; Walling 1983; Wilkinson and McElroy 2007). On the other hand, erosion processes that do not operate at the plot or hillslope scale may contribute to catchment SY (e.g. gully erosion, mass movements, channel erosion). As a result, the relative contribution of SL to catchment SY strongly varies, depending on the magnitude of all processes affecting SY and the size of the catchment.

A good understanding of this relative contribution is relevant for the prediction of SY at the catchment scale (e.g. Osterkamp and Toy 1997; Merritt et al. 2003; de Vente et al. 2008) and for the development of strategies to mitigate high catchment sediment yields and their harmful effects (e.g. Osterkamp and Toy 1997; Vanmaercke et al. 2011a). The most straightforward strategy to estimate the relative contribution of SL to SY is by establishing a detailed sediment budget which quantifies all soil erosion and sediment deposition processes in a catchment (e.g. Trimble 1999; Notebaert et al. 2009). Nevertheless, sediment budgets are catchment-specific and may change over time. Furthermore, their establishment is generally time-consuming and expensive. As a result, they are rarely used at a regional scale, and simplified budgets identifying the most important processes are often a more appropriate tool for catchment management purposes (Slaymaker 2003).

As an alternative approach, several studies have compared measured SL rates at the hillslope scale with the SY of catchments of different sizes for specific regions. For example, Osterkamp and Toy (1997) illustrated for the semi-arid San Pedro basin (Arizona) and the forested Susquehanna basin (Pennsylvania) that SY for catchments between 0.1 and 100 km² increased with A and are about an order of magnitude higher than estimated sheet and rill erosion rates. These differences are explained by the relatively greater contribution of gully and channel erosion, while sheet and rill erosion is only a minor sediment source for catchment SY. Only for larger catchments (>100 km²) did SY decline with increasing A, due to the relatively greater importance of sediment deposition processes. In a global comparison, Koppes and Montgomery (2002) indicated that catchment sediment yields from small (1–10,000 km²) river systems in tectonically active regions or river systems with temperate glaciers are generally higher than erosion rates under conventional agriculture, while the sediment output of larger rivers is generally lower.

For Mediterranean Europe, various studies have also indicated that SL rates, measured at the plot scale under natural rainfall conditions, are generally lower than SY due to the importance of erosion processes that are not active at the plot scale, such as gully erosion, landslides and riverbank erosion (e.g. Poesen and Hooke 1997; Cammeraat 2004; Boix-Fayos et al. 2005; de Vente and Poesen 2005; Vanmaercke et al. 2011a). For other regions in Europe, however, studies that compare measured SL with measured SY data are rare.

Furthermore, measured SL rates are not necessarily representative of the actual hillslope conditions. Recent reviews indicated, for example, that a majority of SL measurements in Europe have been conducted on arable land and often on relatively steep slopes (Cerdan et al. 2006; Maetens et al. 2009; Cerdan et al. 2010). This bias on the available measured SL data impedes a clear interpretation of the observed differences between SL rates and catchment SY.

Over the last few decades, however, our understanding about the spatial variability and controlling factors of SL rates throughout Europe has increased significantly, by means of extensive databases of measured SL rates (Cerdan et al. 2006; Maetens et al. 2009), extrapolations of such databases to actual slope conditions (Cerdan et al. 2010), and models (e.g. the PESERA-model: Kirkby et al. 2004, 2008). Also catchment sediment yields have been extensively measured in Europe. In a recent literature review, Vanmaercke et al. (2011b) compiled SY measurements for 1794 catchments in Europe. Analyses of this database indicated important regional differences in the magnitude and scale-dependency of SY, although the factors controlling these differences are currently not fully understood (Vanmaercke et al. 2011b). The availability of numerous measured SY data, measured SL data and maps with predicted erosion rates in Europe allows an extensive comparison between hillslope erosion rates and catchment sediment yields throughout Europe. Such broad scale comparison may indicate regional differences in the relative importance of sheet and rill erosion rates, compared to other processes that affect SY.

Therefore, the overall objective of this study is to understand better the relationship between average annual catchment sediment yields and hillslope erosion rates in Europe. The specific objectives are i) to provide a regional comparison between measured SY data and measured SL data; ii) to provide a regional comparison between measured SY data and hillslope erosion rates as indicated on recently published maps of predicted sheet and rill erosion rates in Europe and iii) to discuss observed differences in terms of representativeness of the measured SL data and the potential importance of the various processes controlling catchment SY. The hypothesis behind these objectives is that the contribution of different erosion processes to catchment SY varies with catchment scale and between different regions in Europe.

2 Data description and analyses

2.1 Catchment sediment yield data

Catchment SY data for this study were collected by an extensive literature review of reported sediment yields. A full description of the procedures used and data collected is given by Vanmaercke et al. (2011b). Only data measured at gauging stations or derived from reservoir siltation rates over a period of at least 1 year were considered. In total, SY data from 1794 catchments throughout Europe were collected, representing at least 29,203 catchment-years of observations. Measuring periods of the SY observations at a gauging station or reservoir vary between 1 and 235 years, with a mean of 16 years. Each of the catchments included has a known outlet location and a catchment area (A, square kilometer) ranging between 0.01 km² and 1,360,000 km² (median 164 km², mean 10,090 km²). Although relatively few data are available for some regions (e.g. France, Ireland, Ukraine and Western Russia), the available data cover a wide range of environmental conditions in Europe (Fig. 1).

2.2 Data on measured plot soil erosion rates

Data on measured plot SL rates were also collected through an extensive literature review and communication with various researchers. A detailed description of the plot data selection procedure and the database is given by Maetens et al. (2009). Only SL measured under natural rainfall and for conventional land uses (i.e. without the application of soil and water conservation practices) for a period of at least 1 year were considered. The dataset used in this study comprises 777 average annual plot SL rates, measured at 187 different study sites which are relatively well spread across Europe (see Fig. 1). Measurements were conducted on slope gradients varying between 2% and 73% (mean 15.5%, median 12%). The length of the plots varied between 1 and 200 m (mean 33.4 m, median 22 m). Of these SL rates, 723 were measured on bounded runoff plots draining to collector tanks that trap the eroded sediment (for a description of this procedure, see Renard et al. 1997). On average, SL measurements on plots were conducted for a period of 8.4 years, resulting in a total of 6,065 plot-years of measurements. The other 54 plot SL rates were determined by accurately measuring the volume of sediments that were eroded over a known period (i.e. rill volume measurements; Govers and Poesen 1988). On average these volumetric measurements span a period of 14 years, representing another 760 plot-years of observations. Although more SL measurement data may exist, the database used in this study is considered to be representative of SL measurements in Europe.

2.3 The sheet and rill erosion map of Europe (SEM)

Cerdan et al. (2010) produced a map of predicted long-term average annual sheet and rill erosion rates (SEM) that is expected to give an unbiased estimate of sheet and rill erosion rates on European hillslopes, as it considers the effects of land use, topography and soil characteristics. Based on statistical analyses of a dataset of 259 annual plot soil loss rates measured at 81 different locations (representing 2,741 plot-years of observations), the relationships between SL and land use, topography (slope and slope length) and soil type were investigated. These empirical relationships, in combination with reported relationships, were used to estimate annual sheet and rill erosion rates throughout Europe, based on available spatial data describing land use, topography and soil characteristics. A detailed description of the procedure is given by Cerdan et al. (2010). The resulting map has a resolution of 100 m×100 m. As the required spatial data were not always available, the SEM does not cover the entire considered study area (see Fig. 1). The area covered by the SEM is indicated in Fig. 2.

2.4 The PESERA soil loss map

An alternative map indicating predicted long-term average annual sheet and rill erosion rates (in tonne per hectare per year) in Europe was provided by application of the Pan European Soil Erosion Risk Assessment model (PESERA; Kirkby et al. 2004, 2008). PESERA is a process-based model that is designed to estimate mean annual soil loss rates by sheet and rill erosion. Obtained erosion rates are considered to be the total amount of sediment delivered to the base of the hillslopes within each pixel. Processes such as landslides, gully erosion, channel erosion, channel delivery processes and channel routing are not explicitly considered. PESERA is built around a partition of precipitation into components for overland flow, evapotranspiration and changes in soil moisture storage. Transpiration is used to drive a generic plant growth model, while the amount of overland flow is used in combination with other factors (such as the slope gradient, soil texture and soil organic matter content) to predict the SL rate.

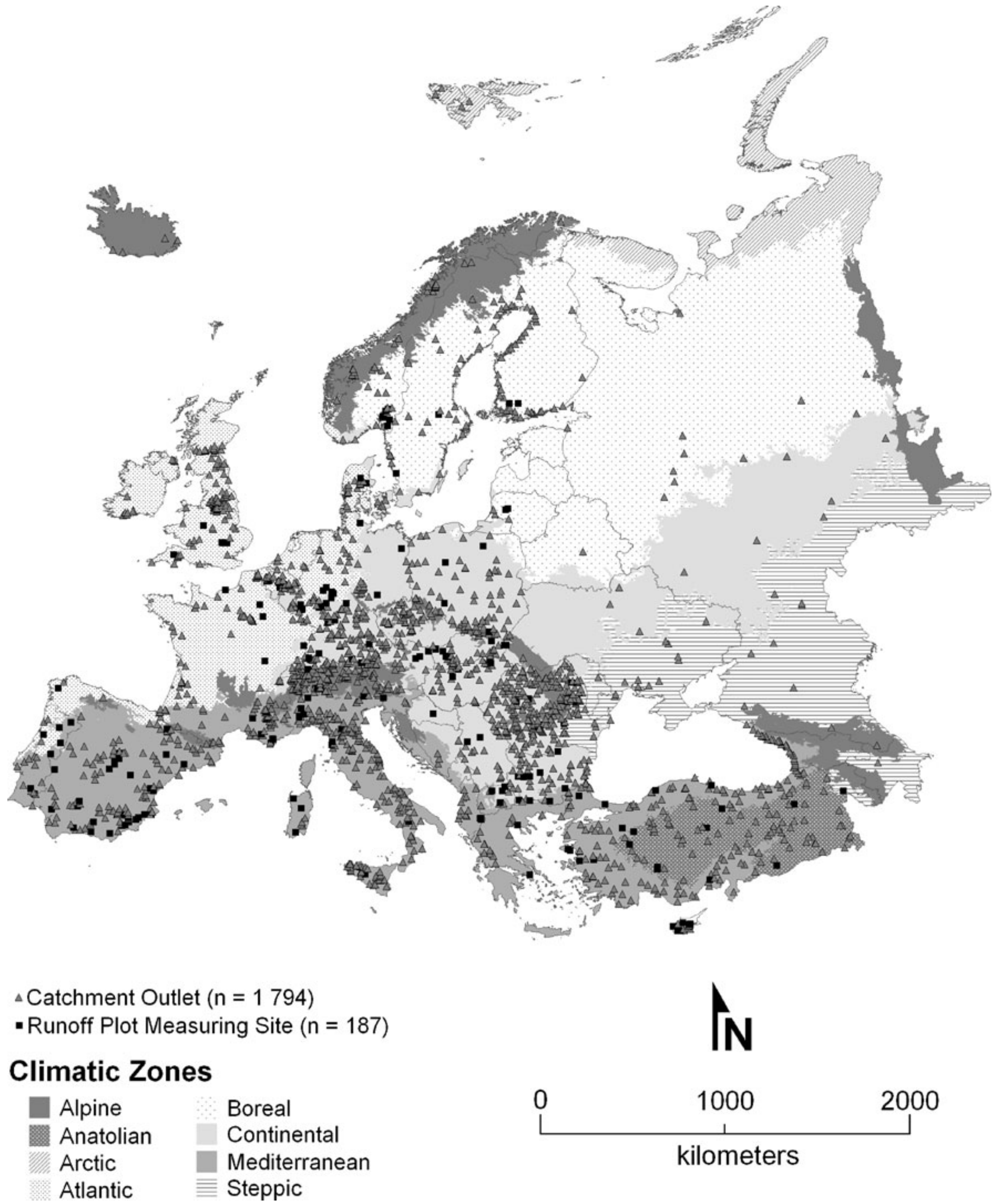


Fig. 1 Location of catchment outlets for which measured catchment sediment yield data are available and runoff plot sites for which measured soil loss rates are available. Climatic zones were derived from the LANMAP2 classification (Metzger et al. 2005; Mücher et al. 2010)

A detailed description of the model is given by Kirkby et al. (2008).

The PESERA map used in this study was obtained by applying the PESERA model using available datasets for Europe and depicts sheet and rill erosion rates at a 1-km² resolution. A detailed explanation on the creation of the map can be found in Kirkby et al. (2004). Figure 2 indicates which regions are covered by the PESERA map.

2.5 Classification and analyses of the data

To allow regional comparison, all catchment SY and SL rates were assigned to a climatic region, based on the LANMAP2 climatic classification (Metzger et al. 2005; Mücher et al. 2010). This classification is based on a principal component analysis of 20 relevant variables (e.g. monthly air temperature, monthly precipitation, hours of sunshine and altitude a.s.l.)

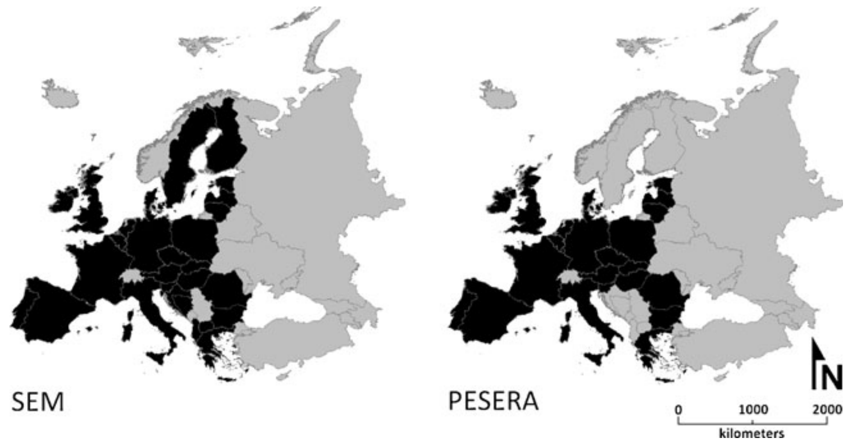


Fig. 2 Areal coverage of the predicted sheet and rill soil loss rates by the Soil Erosion Map (SEM; Cerdan et al. 2010) and the PESERA map (Kirkby et al. 2004). Countries for which predicted soil loss rates are available are indicated in *black*

and distinguishes eight climatic regions in Europe (see Fig. 1). It was chosen as it covers the entire Pan-European area considered in this study and was developed using well-evaluated statistical procedures (Metzger et al. 2005). Although this classification is mainly based on climatic variables, the resulting regions provide a meaningful physical geographical subdivision of Europe. Furthermore, it has been shown that this classification agrees well with other European classifications (Metzger et al. 2005). Although more detailed regional subdivisions of Europe exist, this subdivision into only eight zones was chosen as a trade-off between a sufficient level of detail and a sufficient number of data in each zone.

Measured SL rates were assigned to their climatic region, based on the location of the measuring site. Likewise, the SL values from the pixels on the PESERA and SEM maps were assigned to the climatic zone in which the pixel is located. Both maps include pixels for which the soil loss rate is indicated as zero. For the SEM map, the areal extent of these pixels is limited (7% of the area covered by the map) and mainly coincides with large water bodies and built-up areas. For the PESERA map, the fraction of zero-SL values is much larger (32% of the covered area). The reasoning behind these zero-values could not be found in the original documentation, but it was observed that they mainly occur in mountainous regions. To avoid interpretation difficulties, all analyses in this study regarding the SEM and PESERA maps were based only on pixels with SL rates >0 $t km^{-2}$ per year. All non-zero pixels from the PESERA map were considered for the analyses. However, for practical purposes, a stratified sample was used for the analyses of the SEM map. This stratified sample was created by placing a grid over the original map with a grid size of 5×5 pixels and only considering the central pixel in each grid cell. Analyses for a 16,000-km² test region indicated that the statistical properties of this subset (containing 4% of the original data) are identical to the statistical properties of the original map.

Catchment SY values were assigned to a climatic zone, based on the location of the catchment outlet. As some catchments are located in more than one climatic region, their assignment to the climatic region of the outlet may be disputable. However, this holds mainly for larger catchments. It was estimated that a maximum 30% of the catchments cover more than one climatic region. For catchments smaller than 1,000 km², this is less than 5%, while 80% of the catchments larger than 10,000 km² are potentially situated in more than one climatic region (Vanmaercke et al. 2011b). Since the catchments considered in this study cover a wide range of drainage areas, and SY is generally expected to be influenced by catchment area (e.g. Walling 1983; de Vente et al. 2007), the SY observations were also further subdivided into catchment area classes. The borders of these classes (i.e. <10; 10–100; 100–1,000; 1,000–10,000; 10,000–100,000; and >100,000 km²) were chosen arbitrarily, based on a trade-off between a sufficient level of detail and a sufficient number of data in each A-class.

Differences between the SL, SY, SEM and PESERA values for the different climatic zones were studied by analyzing their frequency distributions. Lilliefors tests (Lilliefors 1967) indicated that most of these distributions were not normally distributed, but positively skewed. Similar frequency distributions were also observed in other studies compiling measured SY and SL data (e.g. Koppes and Montgomery 2009). Therefore, non-parametric Wilcoxon tests were used to detect for significant differences between the various distributions (at a significance level of 5%). Also, differences between SY values of different A-classes were evaluated based on non-parametric Wilcoxon tests. Results were visualized using cumulative distribution plots and boxplots.

3 Results

3.1 Comparison between measured soil loss rates and catchment sediment yields

Figure 3 displays the cumulative frequency distribution of all measured SL rates and all measured catchment sediment yields. Although SL rates show a larger variability than the

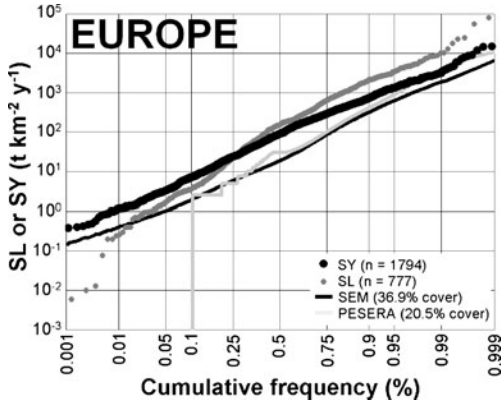


Fig. 3 Cumulative frequency distribution of all measured catchment sediment yields (SY), measured plot soil loss rates (SL) and predicted soil loss rates by the Soil Erosion Map (SEM: Cerdan et al. 2010) and by the PESERA map (PESERA: Kirkby et al. 2004). Cover indicates areal fraction of Europe (see Fig. 1) for which predicted soil loss rates >0 t km^{-2} per year are available

catchment SY, the cumulative distributions are fairly similar, with SL rates slightly higher than catchment SYs. The non-parametric Wilcoxon test indicates that both distributions differ significantly. Subdivision of the SY values according to their catchment area (Fig. 4) indicates that SY from small catchments (A < 10 km²) is comparable with measured SL rates and SY tends to decrease for larger catchments.

Cumulative frequency distributions of all measured SL rates and catchment SY, subdivided per climatic zone, are given in Fig. 5. Wilcoxon tests indicated that measured SL rates in the Atlantic, Boreal and Continental zones are significantly larger than measured SY in these zones. For the Mediterranean region, however, measured SL rates were found to be significantly lower than measured SY. For the Anatolian zone, no significant difference was found between measured SL and SY. Since very few or no measured SL data were available for the Alpine, Steppic and Arctic zones, no meaningful observations on the difference between measured SL and SY could be made for these regions.

Figure 6 displays boxplots of the measured SL rates and SY for each climatic zone, with SY values subdivided according to their catchment area. Similar to Fig. 4, it can be noted that most groups of SL and SY observations are positively skewed, with a mean that is generally higher than the median. Furthermore, different trends between the SY values and A classes can be observed between the climatic zones. For the Atlantic and Continental zones, median and mean SY consistently decrease as A increases. With some exceptions, this trend can also be observed for the Boreal and Steppic zones. Catchment area classes deviating from these trends (i.e. A >10^5 km² in the Boreal zone and 10 < A < 100 km² in the Steppic zone) have a very low number of observations. For the Alpine, Anatolian and Mediterranean zones, no clear decrease of SY with increasing A can be observed. Too few observations are available to detect a pattern for the Arctic zone.

3.2 Comparison between erosion maps, measured soil losses and catchment sediment yields

Figure 3 also displays the cumulative frequency distributions of the predicted SL rates for Europe, as shown on the SEM and PESERA maps. Figure 5 displays the cumulative frequency distributions per climatic zone. SEM and PESERA SL rates are significantly smaller than both measured SL rates and SY values (see Fig. 3). The SEM SL rates (median 18.7 t km^{-2} per year) are generally one order of magnitude smaller than measured SL rates. SL rates of the PESERA map show a slightly different frequency distribution and have a higher median

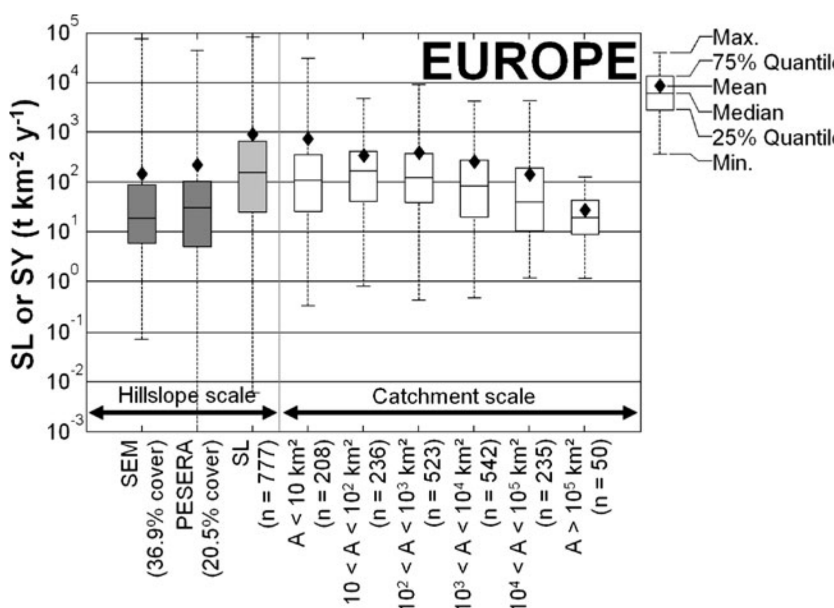


Fig. 4 Boxplots of the predicted soil loss rates (SL) by the Soil Erosion Map (SEM; Cerdan et al. 2010) and by the PESERA map (PESERA; Kirkby et al. 2004), the measured plot soil loss rates (SL) and the measured catchment sediment yield (SY) data for different catchment area (A) classes. Cover indicates areal fraction of the study area (see Fig. 1) for which predicted soil loss rates >0 t km^{-2} per year are available

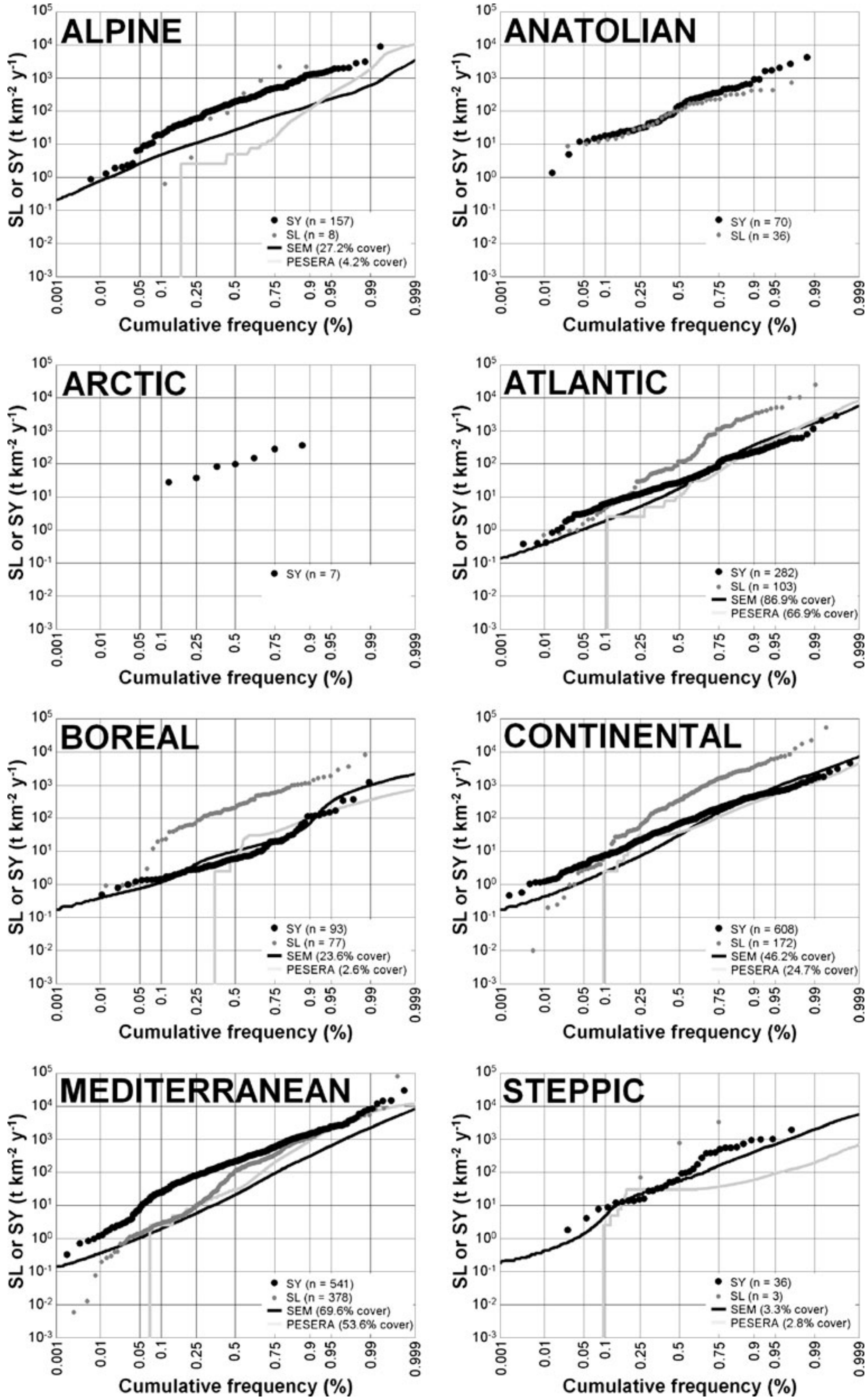
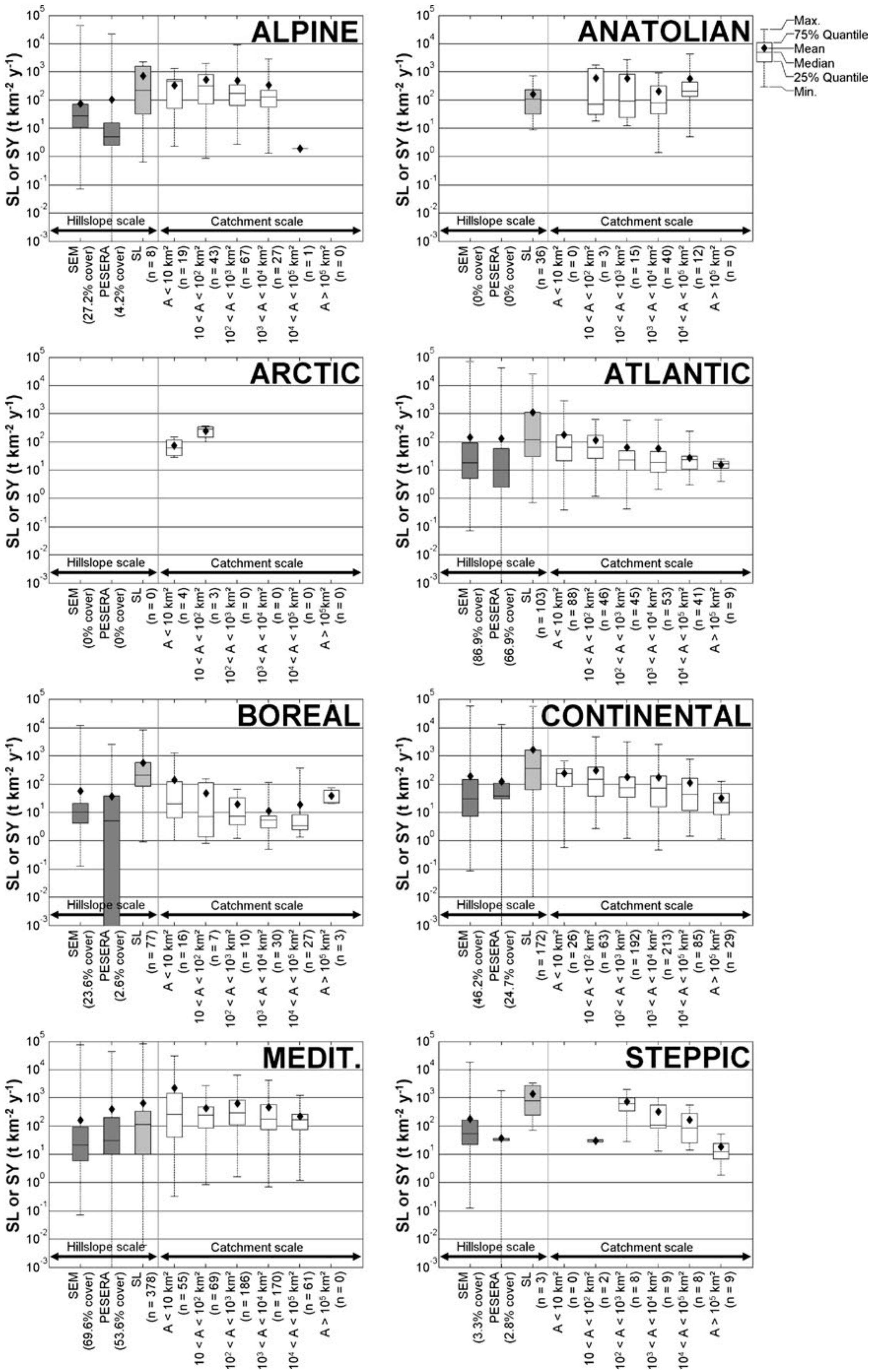


Fig. 5 Cumulative frequency distribution of all measured catchment sediment yields (SY), measured plot soil loss rates (SL) and predicted soil loss rates by the Soil Erosion Map (SEM; Cerdan et al. 2010) and by the PESERA map (PESERA; Kirkby et al. 2004) per climatic zone (see Fig. 1). Cover indicates the areal fraction of the climatic zone for which predicted soil loss rates >0 t km^{-2} per year are available

value (30 t km^{-2} per year), but are still significantly below the measured SL rates. Also, the SEM and PESERA SL rates differ significantly from each other. Figure 4 indicates that, although the SEM and PESERA SL rates have higher maxima, SY for catchments <10,000 km² are generally larger than the SL rates predicted by these maps. Similar to the measured SL rates and SY values, the distributions of SEM and PESERA SL rates are positively skewed, having mean values (144 and


ALPINE
ANATOLIAN
ARCTIC
ATLANTIC
BOREAL
CONTINENTAL
MEDIT.
STEPPIC
Max.
75% Quantile
Mean
Median
25% Quantile
Min.
SL or SY (t km-2 y-1)
Hillslope scale
Catchment scale
SEM (27.2% cover)
PESERA (4.2% cover)
SL (n = 8)
A < 10 km² (n = 19)
10 < A < 10² km² (n = 43)
10² < A < 10³ km² (n = 67)
10³ < A < 10⁴ km² (n = 27)
10⁴ < A < 10⁵ km² (n = 1)
A > 10⁵ km² (n = 0)
SEM (0% cover)
PESERA (0% cover)
SL (n = 36)
A < 10 km² (n = 0)
10 < A < 10² km² (n = 3)
10² < A < 10³ km² (n = 15)
10³ < A < 10⁴ km² (n = 40)
10⁴ < A < 10⁵ km² (n = 12)
A > 10⁵ km² (n = 0)
SEM (0% cover)
PESERA (0% cover)
SL (n = 0)
A < 10 km² (n = 4)
10 < A < 10² km² (n = 3)
10² < A < 10³ km² (n = 0)
10³ < A < 10⁴ km² (n = 0)
10⁴ < A < 10⁵ km² (n = 0)
A > 10⁵km² (n = 0)
SEM (86.9% cover)
PESERA (66.9% cover)
SL (n = 103)
A < 10 km² (n = 88)
10 < A < 10² km² (n = 46)
10² < A < 10³ km² (n = 45)
10³ < A < 10⁴ km² (n = 53)
10⁴ < A < 10⁵ km² (n = 41)
A > 10⁵ km² (n = 9)
SEM (23.6% cover)
PESERA (2.6% cover)
SL (n = 77)
A < 10 km² (n = 16)
10 < A < 10² km² (n = 7)
10² < A < 10³ km² (n = 10)
10³ < A < 10⁴ km² (n = 30)
10⁴ < A < 10⁵ km² (n = 27)
A > 10⁵ km² (n = 3)
SEM (46.2% cover)
PESERA (24.7% cover)
SL (n = 172)
A < 10 km² (n = 26)
10 < A < 10² km² (n = 63)
10² < A < 10³ km² (n = 192)
10³ < A < 10⁴ km² (n = 213)
10⁴ < A < 10⁵ km² (n = 85)
A > 10⁵ km² (n = 29)
SEM (69.6% cover)
PESERA (53.6% cover)
SL (n = 378)
A < 10 km² (n = 55)
10 < A < 10² km² (n = 69)
10² < A < 10³ km² (n = 186)
10³ < A < 10⁴ km² (n = 170)
10⁴ < A < 10⁵ km² (n = 61)
A > 10⁵ km² (n = 0)
SEM (3.3% cover)
PESERA (2.8% cover)
SL (n = 3)
A < 10 km² (n = 0)
10 < A < 10² km² (n = 2)
10² < A < 10³ km² (n = 8)
10³ < A < 10⁴ km² (n = 9)
10⁴ < A < 10⁵ km² (n = 8)
A > 10⁵ km² (n = 9)

◀ **Fig. 6** Boxplots per climatic zone of the predicted soil loss (SL) rates by the Soil Erosion Map (SEM; Cerdan et al. 2010), predicted soil loss rates by the PESERA map (PESERA; Kirkby et al. 2004), measured plot soil loss rates (SL) and measured catchment sediment yield (SY) data for different catchment area (A). Cover indicates areal fraction of the climatic zone (see Fig. 1) for which soil loss estimates >0 tkm^{-2} per year are available

204 tkm^{-2} per year, respectively) that are about one order of magnitude larger than the median values.

Figure 5 displays the cumulative distributions of the PESERA and SEM SL rates per climatic zone. These figures clearly indicate that for each zone with sufficient data (i.e. the Atlantic, Boreal, Continental and Mediterranean zones) measured SL values are generally larger than the predicted SEM and PESERA SL rates. For the Alpine and Mediterranean zones, predicted PESERA and SEM SL rates are considerably lower than the measured SY values. For the other climatic zones, the difference between catchment SY and the SEM and PESERA SL rates is less clear, but still apparent. Wilcoxon tests indicate that for the Atlantic and Continental zones, median SY is also significantly larger than the median PESERA and SEM SL rates. For the Boreal zone, no significant difference was found. For the Steppic zone, median SY differs significantly from the median PESERA SL rate, but not from the SEM SL rate. It should be noted, however, that for this zone, both the number of SY observations and the areal cover by the SEM and PESERA maps are very low.

Figure 6 indicates that, especially for catchments smaller than 1,000 km², SY values are generally significantly higher than SEM or PESERA SL rates. Furthermore, a different trend is observed for the median and mean values. Whereas the median SEM and PESERA SL rates are generally smaller than the median SY values, the mean values show relatively little difference. This is especially the case for the Atlantic, Continental and Mediterranean zones.

Figures 5 and 6 further indicate differences between the SEM and PESERA SL rates. For all European regions, these differences were found to be significant (Wilcoxon tests at a significance level of 5%). In particular for the Mediterranean zone, PESERA SL rates tend to be systematically higher than the SEM SL rates.

4 Discussion

4.1 How reliable are the measured and predicted soil loss rates?

4.1.1 Measured soil loss rates

As Figs 3, 4, 5 and 6 indicate, the measured SL rates display a very large variability. This can be explained by the large variability in plot conditions that are known to have a strong influence on sheet and rill erosion rates, such as slope length and gradient (e.g. Renard et al. 1997), land use (Cerdan et al. 2010) and soil characteristics (Poesen et al. 1994; Torri et al. 1997). Furthermore, the results indicate important differences between measured SL rates and SL rates predicted by the SEM and PESERA maps (see Figs 3, 4, 5 and 6). However, SL measurements are not necessarily representative of mean hillslope conditions in Europe, since SL measurements are mostly conducted as controlled experiments with the purpose to fulfil specific research needs. Although SL rates are controlled by a range of factors, analyses of a large set of SL measurements in Europe indicated that SL is mainly controlled by land cover, with the largest measured SL rates observed for bare conditions, arable land and permanent crops and much lower values observed under forest and pasture (Cerdan et al. 2006, 2010).

The database of measured SL rates is strongly biased towards these erosion-prone land use conditions. This is illustrated in Fig. 7, where the relative fractions of the land uses for which the SL measurements were conducted are compared with the actual areal fractions of these land uses in Europe. Figure 8 shows a similar comparison for each climatic zone. Land use data for Europe were derived from the LANMAP2 land cover layer, which was obtained by the integration of various global and European land cover databases (Mücher et al. 2010). On a European scale (see Fig. 7), the fractions of SL measurements conducted on arable land, shrubs and herbaceous vegetation and artificial vegetation correspond relatively well with their areal cover. However, SL plots under forests are strongly underrepresented, while the fraction of SL measurements under permanent crops and especially 'bare'

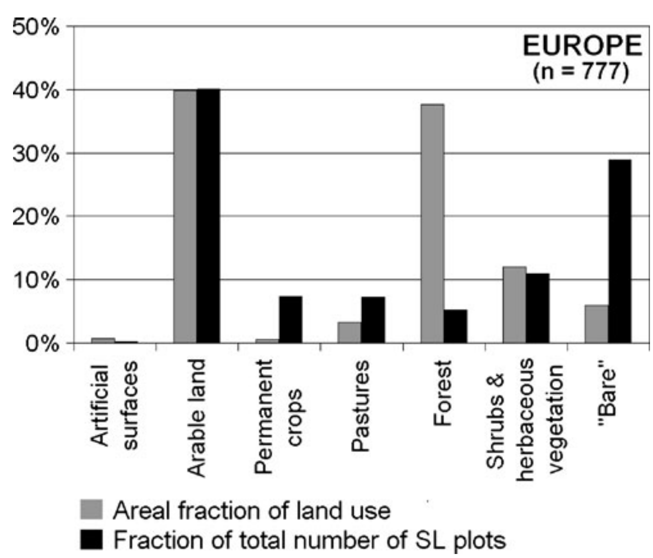


Fig. 7 Comparison between the fraction of the total number of plots (n=777) with a specific land use and the areal fraction of that land use in Europe, as derived from the LANMAP2 classification (Mücher et al. 2010)

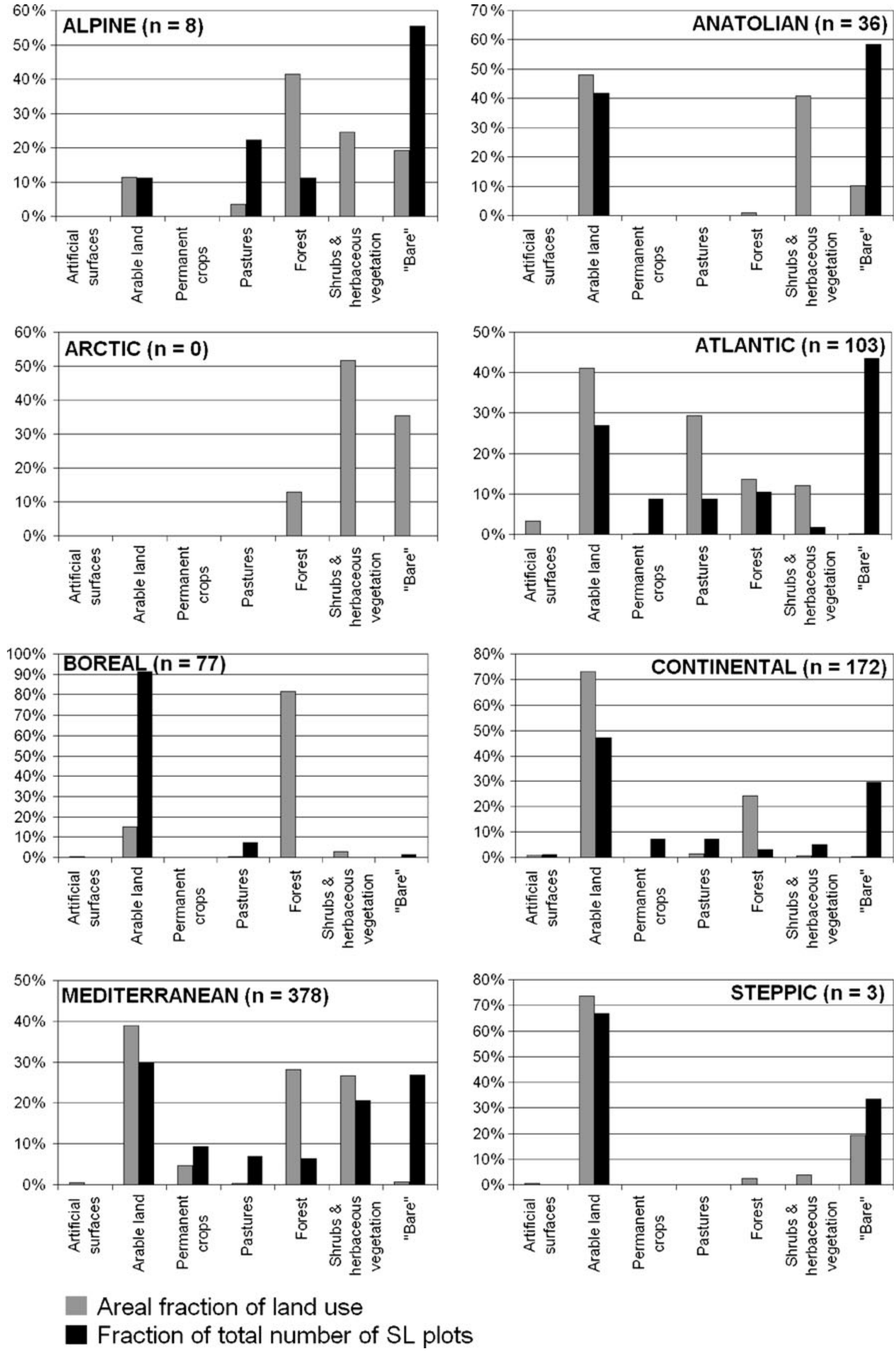

ALPINE (n = 8)
ANATOLIAN (n = 36)
ARCTIC (n = 0)
ATLANTIC (n = 103)
BOREAL (n = 77)
CONTINENTAL (n = 172)
MEDITERRANEAN (n = 378)
STEPPIC (n = 3)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Artificial surfaces
Arable land
Permanent crops
Pastures
Forest
Shrubs & herbaceous vegetation
"Bare"
Areal fraction of land use
Fraction of total number of SL plots

Fig. 8 Comparison between the fraction of the total number of plots (n=777) with a specific land use and the areal fraction of that land use for different climatic zones, as derived from the LANMAP2 classification (Mücher et al. 2010)

conditions are significantly higher than their actual areal fractions. Furthermore, bare conditions for SL measurements generally refer to clean-tilled fallow hillslope conditions with tillage performed upslope and downslope (e.g. Renard et al. 1997), while 'bare' in the European land cover databases mainly refers to open spaces with little to no vegetation (e.g. beaches, bare rocks and sparsely vegetated areas; Mücher et al. 2010). Also, for the different climatic zones (see Fig. 8), the fraction of SL plots for erosion-prone conditions is generally overrepresented, while SL plots for land uses that are less susceptible to erosion are mostly underrepresented. As a result, the frequency distributions of the compiled measured SL rates will be generally larger than the frequency distribution of the actual sheet and rill erosion rates in Europe. Several previous studies have identified a strong bias of SL measurement towards erosion-prone conditions (Auerswald et al. 2009; Cerdan et al. 2010). Although this is sometimes neglected, extrapolation of measured SL rates without correcting for the actual hillslope conditions may strongly overestimate the actual erosion rates (Boardman 1998; Cerdan et al. 2010; Quinton et al. 2010).

4.1.2 Predicted soil loss rates

The frequency distributions of the predicted SL rates as derived from the SEM and PESERA maps are significantly smaller than the frequency distribution of measured SL rates. Since both erosion maps explicitly consider the effect of land use on the estimated SL rates (as well as the effect of topography and soil characteristics), the SL frequency distributions derived from these maps are probably more representative of actual sheet and rill erosion rates on European hillslopes than the frequency distribution of SL rates from the plot database. Nevertheless, these SEM and PESERA erosion rates are subject to important uncertainties. Modelling soil erosion (as well as catchment sediment yield) always involves assumptions and process descriptions that do not necessarily correspond with field conditions. As a result, different soil erosion models can lead to significantly different results, even if the considered input data are identical (e.g. Favis-Mortlock 1998; Jetten et al. 1999).

Also, the SL frequency distributions as derived from the SEM and PESERA maps show clear differences (Fig. 5). Although these differences may be partly attributed to the different areal cover of both maps (especially for the Alpine, Boreal and Steppic zones), these differences are also related to the different model concepts of both maps. Thorough validation of the model results (preferably with measured field data) is therefore crucial. However, direct validation of these European sheet and rill erosion maps (i.e. SEM and PESERA) is very difficult, since this would require detailed data on measured erosion rates for large areas within Europe. Currently, no validation of SEM exists. Furthermore, the PESERA model has never been fully validated for the entire area of Europe. However, available case studies suggest that the SL rates predicted by the PESERA model can deviate strongly from measured SL rates at the plot or hillslope scale (Tsara et al. 2005; Licciardello et al. 2009; Maetens et al. 2011). These deviations can be attributed to several factors, including uncertainties in the measured SL data, but clearly illustrate that predicted sheet and rill erosion rates should be interpreted with great caution.

4.2 Factors and processes controlling sediment yield at the catchment scale

In contrast with SL measurements, catchment SY measurements are generally not conducted as controlled experiments, but are meant to monitor the state of a river system. Furthermore, the catchments considered in this study are relatively large and relatively well spread over the study area (see Fig. 1). As a result, it can be expected that the catchments considered in this study are representative of the actual physical characteristics of Europe and that the areal fractions shown in Figs. 7 and 8 on average correspond with the land uses of these catchments.

Eroded sediment may be (partly) deposited at parcel boundaries, footslopes or in floodplains, lakes and reservoirs (e.g. Trimble 1999; Wilkinson and McElroy 2007). Therefore, it may be expected that catchment SY values are lower than gross erosion rates on hillslopes, especially in larger catchments, since the probability of sediment deposition increases with the mean travel distance and hence with catchment area (e.g. Boyce 1975; Walling 1983; Van Rompaey et al. 2001; de Vente et al. 2007). Nevertheless, it can be noted that SY values in Europe are generally larger or at least comparable to the predicted SEM and PESERA SL rates (see Figs. 3 and 4). This may be partly the result of the positively skewed distribution of SL rates. For example, in the Atlantic zone (see Fig. 6) median SEM and PESERA SL rates are generally lower than the median SY, but the mean SL rates are comparable to the mean SY of catchments smaller than 100 km² and even higher than the mean SY for larger catchments. This possibly indicates the importance of 'erosion hotspots', i.e. areas with a limited spatial extent which are responsible for a disproportionally large fraction of the sediment exported from the catchments. Although this pattern is less clear for the other zones, the importance of such erosion hotspots has also been described in other regions (e.g. Bogen 2004; Nadal-Romero et al. 2011).

However, the comparisons between SL rates and SY mainly illustrate that erosion processes other than sheet and rill erosion strongly contribute to catchment SY. Several studies (e.g.

Poesen and Hooke 1997; Cammeraat 2004; Boix-Fayos et al. 2005; de Vente and Poesen 2005) indicated that sheet and rill erosion contributes relatively little to the SY of Mediterranean catchments. For the other zones (and especially the Alpine zone), our results indicate that SY may be strongly controlled by erosion processes other than sheet and rill erosion. Therefore, we briefly discuss the various processes that may contribute to SY, regional differences in their potential importance and their relation with spatial scale and land use.

4.2.1 Sheet and rill erosion

Relatively large differences in measured and predicted SL rates can be observed between the climatic zones (Fig. 5). Although these differences are partly explained by differences in land use (see Fig. 8), regional variation in sheet and rill erosion is also controlled by other factors, such as soil erodibility. Analyses of a large datasets of measured soil erodibility factors indicated erodibility is generally higher for temperate and cool climates than for Mediterranean and warm climates (Salvador Sanchis et al. 2008). This difference is further increased by differences in soil thickness and soil stoniness. Whereas soils of the temperate regions are generally thick, soils in the Mediterranean region are often shallow and stony (Poesen and Lavee 1994; Seeger and Ries 2008). Various studies indicate that these stony soils are at least partly a result of their often long and intense history of deforestation and cultivation, during which erosion rates were larger than the long-term soil formation rate (Yaalon 1997; Clapp et al. 2000; Lasanta et al. 2006; Seeger and Ries 2008; García-Ruiz et al. 2010). Although stony soils do not necessarily generate less runoff, they are considerably less susceptible to water erosion (Poesen et al. 1994). This was also reported by various studies (e.g. Poesen and Lavee 1994; Poesen and Hooke 1997; Cerdan et al. 2006; Govers et al. 2006; Vanmaercke et al. 2011a), which showed generally lower measured SL rates for the Mediterranean region compared to other regions. For mountainous regions, it may be expected that soils are relatively less susceptible to sheet and rill erosion, due to their higher rock fragment content.

The overall higher stoniness of Mediterranean soils potentially also contributes to the observed difference between the erosion rates of the SEM and the PESERA maps for this region (see Fig. 5). Whereas stoniness was explicitly considered by the SEM map (Cerdan et al. 2010), it was unclear if this was also the case for the PESERA map.

4.2.2 Gully erosion

Gullies generally result from concentrated flow and only occur when a specific slope and drainage area threshold is exceeded (Vandekerckhove et al. 2000). This threshold depends on various factors such as climate, soil properties and especially vegetation cover (e.g. Poesen et al. 2003; Van Walleghem et al. 2005a). Especially in semi-arid environments, gullies are often a very important sediment source, contributing up to 80% of the catchment SY (Poesen et al. 2003). Furthermore, gullies not only function as a sediment source but can also increase landscape connectivity (Poesen et al. 2003). Gullies therefore help explain why SY is generally higher than the estimated and measured SL rates in the Mediterranean region (see Figs. 5 and 6). However, their contribution can also be considerable in other regions. A study of an agricultural catchment in the Belgian Loess belt, for example, indicated that ephemeral gully erosion is responsible for 41% of the total soil loss (Vandaele and Poesen 1995). Deep gully systems generally have a higher slope-area formation threshold compared to ephemeral gullies, and often contribute even more sediment to catchment SY (Van Walleghem et al. 2005b).

The contribution of gully erosion to SY is, however, often very episodic. For example, gully heads on the Moldavian plateau were found to retreat at a rate between 0 and 19 m per year (mean 5 m per year) during the 16 years of observation (Ionita 2006). In addition, gully systems in the Mediterranean region often show a very large temporal variability in headcut retreat rates (e.g. Vandekerckhove et al. 2003; Marzolff et al. 2011). Furthermore, not all sediments that are produced by these headcut retreats contribute to the catchment SY. Detailed resurveying of gully systems shows that significant volumes of eroded sediments may be stored at the bottom of the gully (Marzolff and Poesen 2009). This large temporal variability and complex sediment dynamics make it difficult to quantify the contribution of gully erosion to average catchment sediment yields.

4.2.3 Mass movements

Although few quantitative data are available, mass movements can contribute significantly to SY (e.g. Korup et al. 2004; Bathurst et al. 2005). Mass movements are discrete events which can be triggered by various factors, such as extreme rainfall (e.g. Caine 1980), seismic activity (e.g. Keefer 1995) and land use changes (e.g. Glade 2003). Forest clearing, for example, may dramatically accelerate shallow landsliding in steep terrain (e. g. Montgomery et al. 2000; Lorente et al. 2002; Bathurst et al. 2007). In general, however, susceptibility to mass movements is mainly controlled by the local lithology and (especially) topography (e.g. Van Den Eeckhaut et al. 2010).

Landslides that are not connected to the drainage network do not necessarily affect catchment SY (Bathurst et al. 2007). However, when they occur, for example at deeply incised river sections, they can overwhelm the river system with large volumes of sediment (e.g. Korup et al. 2004; de Vente et al. 2006; Ouimet et al. 2007). After such landslide events, catchment SY is often controlled by the transport capacity of the river system (e.g. Hovius et al. 2000; Ouimet et al. 2007). This is also suggested by the fact that generally no significant negative trend between A and SY has been found for catchments that are strongly influenced by landslides (de Vente et al. 2006).

Landslides mainly occur in hilly and mountainous regions (Van Den Eeckhaut et al. 2010). Especially in tectonically active mountain regions, mass movements are considered to be a dominant geomorphic process (e.g. Montgomery and Brandon 2002; Lee and Tu Dan 2005). Landslides therefore probably strongly influence the SY of catchments in the Alpine zone, which is indicated by the large difference between estimated SL rates and catchment SY, as well as by the lack of a significant decrease of SY with increasing A (see Fig. 6). However, in other regions, SY can also be strongly influenced by landslides (e.g. de Vente et al. 2006; Delmas et al. 2009).

4.2.4 Channel erosion

Another erosion process that may contribute significantly to SY is river or channel erosion. The volume of sediment detached by a river strongly depends on its stream power, which generally increases with increasing A. Since the detached sediment are also readily available for transport by the river, both the relative and absolute contribution of bank erosion to catchment SY can be expected to increase with increasing catchment area (e.g. Church and Slaymaker 1989; Birkinshaw and Bathurst 2006).

Channel erosion is often expected to be a dominant sediment source in previously glaciated, densely vegetated regions with little human disturbance (Church and Slaymaker 1989; Dedkov and Moszherin 1992; Dedkov 2004; de Vente et al. 2007), such as many catchments in the Boreal zone (Fig. 6). However, in other regions this process may also be important (e.g. Walling and Collins 2005). Especially in previously disturbed catchments (e.g. by deforestation or agriculture), a recovery in vegetation cover or the implementation of soil conservation measures may lead to a remobilization of previously stored alluvial sediments (e.g. Vandenberghe 1995; Trimble 1999). Numerous studies throughout Europe report river incision after reforestation or as a response to hydrological control works (e.g. Lach and Wyzga 2002; Liébault and Piégay 2002; Boix-Fayos et al. 2007; Castillo et al. 2007; García-Ruiz et al. 2010).

4.2.5 Glacial erosion

The SY of some of the catchments in the Alpine and Arctic zones may also be strongly affected by the presence of glaciers. Reported SY values due to glacial erosion generally range between 100 and 200,000 $t km^{-2}$ per year, with the magnitude of glacial erosion depending on various factors such as the underlying lithology and the temperature regime (Hallet et al. 1996; Riihimaki et al. 2005; Koppes and Montgomery 2002). Furthermore, the erosive power of a glacier is strongly controlled by its size (e.g. Montgomery 2002). As a result, catchment SY in glaciated basins has been reported to increase with increasing A (Hallet et al. 1996).

4.2.6 Differences in sediment sinks

Regional variation in SY and its scale dependency are also partly attributable to regional differences in sediment sinks. Whereas significant fractions of eroded sediment are often deposited as colluvium or as alluvium in lowland catchments (e.g. Notebaert et al. 2009), sediment deposition may be expected to be smaller in many steep mountainous catchments. For example, a quantification of postglacial sediment storage in the Alps indicated that 90% of the areas where sediment is stored are located in the lowest 25% of the mountain belt (Straumann and Korup 2009). Nevertheless, the occurrence of lakes and glacially overdeepened valleys are often very important sediment traps in mountainous environments (e.g. Korup and Tweed 2007).

In the Mediterranean basin, sediment deposition is often constrained by the generally steep topography. Whereas a majority of the Mediterranean drainage basin is higher than 500 m a.s.l., most regions in the European part of this basin are located less than 200 km from the present coastline (Woodward 1995). On the other hand, the ephemeral nature of many Mediterranean river systems often contributes to the temporary storage of sediment (e.g. Cammeraat 2004).

Furthermore, a significant volume of sediment is trapped by natural lakes and anthropogenic reservoirs and hence does not reach the sea or ocean (e.g. Vörösmarty et al. 2003). Although lakes and reservoirs occur in all climatic zones, the large majority of natural lakes of Europe are located in the Boreal zone. Three quarters of the more than 500,000 natural lakes larger than 0.01 km^2 in Europe are located in Norway, Sweden, Finland and the Karelo-Kola part of Russia (Stanners and Bourdeau 1995). This large number of sediment-trapping natural lakes partly explains the generally lower SY values for this region.

4.3 Implications for sediment yield prediction and catchment management

Based on the various erosion processes discussed in "Sections 4.2.1–4.2.5", we conclude that catchments that are little or not susceptible to sheet and rill erosion (e.g. due to stony soils or a dense vegetation cover) do not necessarily have a low sediment yield. As this short review indicates, most of these erosion processes only become significant when the area is large enough, for example:

- gully erosion only occurs when a slope-area threshold is exceeded;

- due to their discrete and stochastic nature, the effect of mass movements on sediment yield only becomes apparent when a sufficiently large area is considered;
- the potential importance of channel erosion depends on the river discharge and availability of alluvial sediments, which both generally increase with catchment area; and
- the erosive power of a glacier also depends on its size.

This scale-dependent and generally episodic nature of erosion processes poses important challenges to process-based models aiming to predict catchment sediment yield, as most of these models only consider sheet and rill erosion as a sediment source. For example, the WATEM-SEDEM model (Van Oost et al. 2000; Van Rompaey et al. 2001) estimates SY by calculating a spatial pattern of mean sheet and rill erosion rates in the catchment and by routing the eroded sediment to the river channel network. The model was found to predict SY well in the Loess belt of central Belgium (Van Rompaey et al. 2001; Verstraeten et al. 2002) and the hilly areas of the Czech Republic (Van Rompaey et al. 2003). However, for various Italian (Van Rompaey et al. 2005) and Spanish (de Vente et al. 2008) catchments, the model performed significantly worse, due to the larger importance of other erosion processes. This finding corresponds well with our results: SY in the Mediterranean and Alpine zones (which include the Italian and Spanish catchments) are generally much higher than the measured and predicted erosion rates, while this difference is less apparent in the Atlantic and Continental zones (which include Belgium and the Czech Republic). The WATEM-SEDEM model is no exception to this issue. Most process-based models aiming to predict SY at the catchment scale only consider sheet and rill erosion as a sediment source, while other erosion processes are generally not accounted for (for a review, see Merritt et al. 2003). Although such an approach works reasonably well in catchments where sheet and rill erosion is indeed the dominant sediment source, these models are of relatively little value in regions where other erosion processes are more important.

Considering the full range of erosion processes is not only necessary for the accurate prediction of SY but also for assessing how human impacts may affect SY and how high sediment loads can be mitigated. Whereas the effect of land use on sheet and rill erosion rates at the hillslope scale is relatively well understood (e.g. Kirkby et al. 2008; Cerdan et al. 2010), the effect of land use changes on SY is more difficult to predict. With increasing spatial scale, the number of processes involved also increases. As discussed in "Section 4.2", these other processes are also sensitive to human impacts. Furthermore, these different processes may interact with each other, making their effect on catchment SY very difficult to predict. Incorporating these other erosion processes and their relation with spatial scale in future models will therefore be crucial for our further understanding of the factors controlling SY. However, over the last few years, important progress has been made in this field (e.g. Dietrich et al. 2003; Birkinshaw and Bathurst 2006; Bathurst et al. 2007).

The different erosion and sediment transport processes that were discussed in "Section 4.2" not only lead to spatial, but also to temporal, scale effects. Whereas hillslope erosion rates generally react quickly to land use changes, catchment sediment yield may show a much slower response (e.g. Church and Slaymaker 1989; Trimble 1999). SY is therefore not solely controlled by the current conditions of the catchment, but may also reflect previous disturbances. The measured and predicted SL rates considered in this study are based on static land use conditions: no land use changes occurred during the time of SL measurements, while both the SEM and PESERA maps consider land use to be constant. However, this is not the case for the considered SY measurements. It is very likely that for several catchments in the SY database, important land use changes occurred before or during the period that SY was measured and that these changes had a significant impact on the SY. Unfortunately, no data are available to assess to what extent the SY data were influenced by previous catchment disturbances.

5 Conclusions

Recently established databases and maps allowed a first comparison between measured SL rates due to sheet and rill erosion, modelled sheet and rill SL rates, and measured catchment SY values for Europe. This study confirmed that currently available measured plot SL rates are not representative of mean hillslope conditions in Europe, as they mainly focus on erosion-prone conditions. Extrapolated or modelled SL rates at a regional scale are clearly smaller as they incorporate the effects of land use, topography and soil characteristics. Despite their uncertainties, these modelled or extrapolated erosion rates give a more realistic picture of the actual sheet and rill erosion rates occurring in Europe.

Despite the fact that large proportions of eroded sediment may be deposited before reaching the catchment outlet, SYs at the catchment scale were found to be significantly higher than extrapolated and modelled hillslope erosion rates for most European regions. This was especially the case for the Mediterranean and Alpine zones, but was also observed for small catchments (i.e. < 100 km²) in other regions. This clearly illustrates the importance of erosion processes other than sheet and rill erosion contributing to SY at the catchment scale (i.e. gully erosion, mass movements, channel erosion and glacial erosion). The relative importance of these soil erosion and sediment-deposition processes strongly depends on the region considered, catchment scale and land use history.

As a result, the impact of catchment disturbances (or restoration measures) on catchment SYs not only depends on the rate of change in hillslope erosion, but also on the importance of other erosion and transport processes and their feedbacks. Gully erosion, channel erosion and landslides are all known to be sensitive to land use changes and are often coupled with other processes. Identification and quantification of the dominant sediment sources is therefore crucial for our understanding about human impacts on catchment SY and for the development of management strategies to reduce SY at the catchment scale.

Most current models aimed at predicting sediment yield at the catchment scale mainly consider sheet and rill erosion processes. Although these models may perform relatively well in areas where sheet and rill erosion represent the dominant sediment source, they can certainly not be used to predict SY of catchments where other erosion processes are dominant. Future models should therefore aim to also include these additional erosion processes, as well as interactions between them. However, the generally episodic nature of many of these erosion processes, as well as their complex response to environmental (e.g. land use) changes, provides us with important challenges.

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