Article

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Effects of land use on annual runoff and soil loss in Europe and the Mediterranean: A meta-analysis of plot data

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Abstract

The largest currently compiled database of plot runoff and soil loss data in Europe and the Mediterranean was analysed to investigate effects of land use on annual soil loss (SL), annual runoff (R) and annual runoff coefficient (RC). This database comprises 227 plot-measuring sites in Europe and the Mediterranean, with SL for 1056 plots (PL) representing 7024 plot-years (PY) and R for 804 PL representing 5327 PY. Despite large data variability, continental-wide trends are observed. Construction sites have the highest mean annual RC (57%) and SL (325 $Mg.ha^{-1}.yr^{-1}$). Bare soil, vineyards and tree crops have high mean annual RC (5–10%) and SL (10–20 $Mg.ha^{-1}.yr^{-1}$). Cropland and fallow show similar mean annual RC (8.0 and 7.3%), but lower SL (6.5 and 5.8 $Mg.ha^{-1}.yr^{-1}$). Plots with (semi-)natural vegetation cover show lowest mean annual RC (<5%) and SL (<1 $Mg.ha^{-1}.yr^{-1}$). Plot length and slope gradient correlations with R and SL depend on land-use type and are not concurrent for R and SL. Most land-use types show positive correlations between annual R and SL. Plots in cold climates have higher annual RC than plots in temperate and pan-Mediterranean climates. Annual SL in the pan-Mediterranean is less than in temperate zones, due to stony or clayey soils having a low erodibility. Annual RC in the pan-Mediterranean was higher than in temperate zones. Annual R increases strongly with increasing annual precipitation (P) above 500 $mm.yr^{-1}$, while annual SL was found to stabilize at P > 500 $mm.yr^{-1}$. For shrubland, annual SL was found to decrease for P > 250–500 $mm.yr^{-1}$, which is attributed to

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an accompanying increase in vegetation cover. However, no such trend was found for R. The results allow a rapid assessment of the impact of land-use changes on annual R, RC and SL, based on field-measured plot data.

Keywords

annual precipitation, climatic zone, interrill and rill erosion, land use, runoff plot, runoff-soil loss relation

I Introduction

Runoff and soil loss due to interrill and rill erosion are important processes of soil degradation that cause significant on-site and off-site problems (e.g. Boardman and Poesen, 2006; Montgomery, 2007; Poesen and Hooke, 1997). An integrated approach to these problems at subcontinental scale requires runoff and soil loss to be assessed for a wide range of representative environmental conditions. An extensive assessment and mapping approach for large areas (e.g. Evans, 2002; Le Gouée et al., 2010; Oldeman et al., 1991) may provide an overview of the scale of the problem and locate erosion hotspots, but to gain insight into these processes and to develop strategies to mitigate their impacts, more detailed field-measured experimental data that accurately quantify soil loss are needed. Recently, such quantitative assessment of annual soil loss (SL, $Mg.ha^{-1}.yr^{-1}$) rates at a pan-continental scale for Europe has seen several applications like risk assessment mapping through modelling (Kirkby et al., 2004), exploration of spatial variability and controlling factors of annual SL rates (Cerdan et al., 2006, 2010), assessment of scale effects on sediment production (Vanmaercke et al., 2012) and the development of indicator systems to identify and monitor problem areas (e.g. Gobin et al., 2004). All these continental-wide applications either directly make use of available field-measured soil loss data or conclude they would benefit from a validation with such data.

While aforementioned studies place strong emphasis on the assessment of annual SL rates, runoff plays an important role as a causal factor of annual SL and the relations between annual runoff (R, $mm.yr^{-1}$), annual runoff coefficients (RC, %) and annual SL are not yet fully understood quantitatively. Nevertheless, several process-based erosion models use runoff in order to estimate annual SL rates (Merritt et al., 2003) and good knowledge on these relations is an important part of soil loss modelling (e.g. Jetten and Favis-Mortlock, 2006; Kinnell and Risse, 1998). Furthermore, annual R and RC also directly relate to on-site problems like agricultural productivity (Rockström et al., 2010) and off-site problems like export of nutrients and pesticides (Rossi Pisa et al., 1999), flash floods (e.g. García-Ruiz et al., 2010; Poesen and Hooke, 1997) and the potential activation of other sediment sources (such as river banks and gullies) further downstream (Vanmaercke et al., 2011a). Hence, it is important to assess both annual R and SL rates in conjunction, as well as the effect of key controlling factors on annual R and SL rates.

Over the last 60 years, numerous quantitative experimental studies on annual R and SL have been conducted throughout Europe and the Mediterranean region, using different experimental methods (e.g. runoff plots, rainfall simulations, rill volume measurements, tracer methods). From these, bounded runoff plot studies under natural rainfall conditions can be considered as the most used and standardized experimental method (e.g. Boix-Fayos et al., 2006; Cammeraat, 1993; Cerdan et al., 2006; Evans, 1995; Hudson, 1993). Studies on runoff and soil loss plots have been extensively used in large-scale coordinated research projects in the United States, leading to the development of the (R)USLE(2) equation (Renard et al.,

Table 1. Overview of studies reporting measured runoff and soil loss plot data without soil and water conservation techniques, collected at country, regional or subcontinental scale for Europe and the Mediterranean. Key: – = not reported in study, + = reported in study, NA = not available, R = annual runoff, SL = annual soil loss, #PY = number of plot-years. Ba = bare, Cr = cropland, Fa = fallow, Fo = forest, Gr = grassland, Pf = post-fire, Sh = shrubland, Tc = tree crops, Vi = vineyard.

Region/country	R	SL	Land-use types	#PY	Source
Mediterranean					
MEDALUS project field sites; Spain, France, Italy, Greece	+	+	Cr, Vi, Tc, Sh, Eucalyptus	NA	Kosmas et al., 1997
Portugal, Spain, France, Italy, Greece, Israel	–	+	Cr, Vi, Tc, Sh	c. 150	Wainwright and Thornes, 2004
Spain, Portugal, Greece, Syria	+	+	olive orchards	54	Fleskens and Stroosnijder, 2007
Spain, France, Italy, Morocco	–	+	Cr, Sh	59	Gónzalez-Hidalgo et al., 2007
Italy, Spain	–	+	Sh, Pf, Fo, Cr, Ba, Fa, Gr	74	de Vente et al., 2007
Portugal, Spain, France, Italy, Greece, Israel, Croatia	–	+	Pf, Cr, Vi, Sh, Eucalyptus	NA	Shakesby, 2011
Germany	–	+	Cr, Fa, Gr, Vi, Fo	1,078	Auerswald et al., 2009
Europe	–	+	Ba, Ba, Fo, Gr, Sh, Vi, Tc	2,741	Cerdan et al., 2006, 2010
Europe	–	+	Ba, Cr, Fa, Fo, Gr, Pf, Sh, Tc, Vi	NA	Boardman and Poesen, 2006

1997; Wischmeier and Smith, 1960, 1978). However, projects of such an extent have not taken place in Europe where many individual runoff and soil loss plot studies have been reported. As a result, the findings of runoff plot studies in Europe and the Mediterranean region are dispersed over numerous scientific papers, reports and theses. They are mostly designed to analyse effects of erosion controlling factors on annual R and SL in a particular area. These individual studies have provided better insights into runoff and soil loss processes at local scales, but the diversity and natural variability of runoff and soil loss plot studies limit the potential to extrapolate these findings to other environmental conditions. Boardman (1998) showed that published soil erosion rates for large areas, based on a small number of observed data, should be interpreted with care or may not be relevant at all. Furthermore, an overall assessment of runoff and soil loss rates is also hampered by a high temporal variability (e.g. Bagarello et al., 2011; Martínez-Casasnovas et al., 2002; Ollesch and Vacca, 2002).

From this lack of an overview and difficulties in extrapolating local R and SL data to larger areas arises the need for a pan-European compilation of all available R and SL data. As a response to this need, national-scale data sets on soil erosion have recently been assembled for most countries in Europe, although the methodology used and the erosion processes considered differ (Baade and Rekolainen, 2006; Boardman and Poesen, 2006). With respect to annual R and SL, several recent studies have compiled field-measured plot runoff and/or soil loss data at the regional, national or subcontinental scale (Boardman and Poesen, 2006; Table 1).

From these compilations, a better insight into some key factors determining rates and variability of annual R and SL at (sub)continental and regional scales has been gained. The dominant control of land-use type on annual SL was illustrated by Cerdan et al. (2006, 2010), where also soil type, plot length and slope gradient were used to account for further variability. Kosmas et al. (1997) found that the relation between annual precipitation (P, $mm.yr^{-1}$) and annual R and SL at plot scale at eight different sites in the northern Mediterranean is mainly influenced by land use and hence temporal and spatial patterns of vegetation cover. For shrubland, these authors also observed a vegetation feedback mechanism whereby with increasing annual P (up to $P = 200–300\ mm.yr^{-1}$) SL first increases, then decreases with increasing annual P. This effect is similar to the one described by Langbein and Schumm (1958), who demonstrated for catchments in the United States that the relation between annual P and catchment sediment yield does not only reflect the increasing erosion potential of higher annual P but also includes feedback effects from a larger vegetation biomass with increasing annual precipitation, effectively reducing sediment yield above an annual P threshold of about 254 to 381 $mm.yr^{-1}$ (10–15 $inch.yr^{-1}$). For the other land uses studied by Kosmas et al. (1997), annual R and SL were all positively related to annual P.

However, several key elements to obtain a comprehensive understanding of annual R, RC and SL rates and controls in Europe and the Mediterranean region are not fully considered in these studies. First and foremost, the existing overviews mainly consider annual SL, while annual R and RC are studied to a lesser extent (Table 1). While Europe-wide assessments of plot-scale annual SL exist (Cerdan et al., 2010; Vanmaercke et al., 2012), this is not the case for annual R. In addition, most of these studies assess the effects of one or more controlling factors on annual R and SL, but recognize that they lack information on other important controlling factors. As such, Cerdan et al. (2006, 2010) acknowledge the importance of annual precipitation but did not include this in their analysis. Similarly, Kosmas et al. (1997) do not assess the effect of plot length or slope gradient but nevertheless cite its importance. Which controlling factors are included in the analysis, and how they are assessed, may have a significant impact on the discussion of annual R and SL rates. For instance, Fleskens and Stroosnijder (2007) argued that average annual SL rates in olive groves are unlikely to exceed 10 $Mg.ha^{-1}.yr^{-1}$, which was contested by Gómez et al. (2008) on the basis that several scale and environmental factors like plot length were not sufficiently taken into account.

Hence, there are still unresolved questions with respect to the relationships between precipitation, runoff (coefficients) and soil loss, and the effect of different land uses on these relations. While several local-scale studies address part of these questions, it is not known whether the findings of these studies also apply to other regions. At a continental-wide scale, there are no studies that comprehensively and quantitatively explore all of these relations. Nevertheless, such analysis is of great use to support model assumptions and contribute to an integrated approach towards soil degradation. Therefore, this study aims (1) to provide an overview of both R and SL rates by interrill and rill erosion, measured at the plot scale for Europe and the Mediterranean region; (2) to assess the variability in both R and SL rates for different land uses and different climatic regions in the study area; and (3) to analyse the relationship between observed R and SL rates, and their relationship to annual precipitation (P, $mm.yr^{-1}$).

For a list of abbrevations and symbols used in this paper, see the Appendix.

II Materials and methods

1 Runoff plot selection criteria and database compilation

A database was constructed with annual R and SL data, measured on bounded runoff plots under natural rainfall conditions in Europe and the Mediterranean region (Figure 1). Data were collected

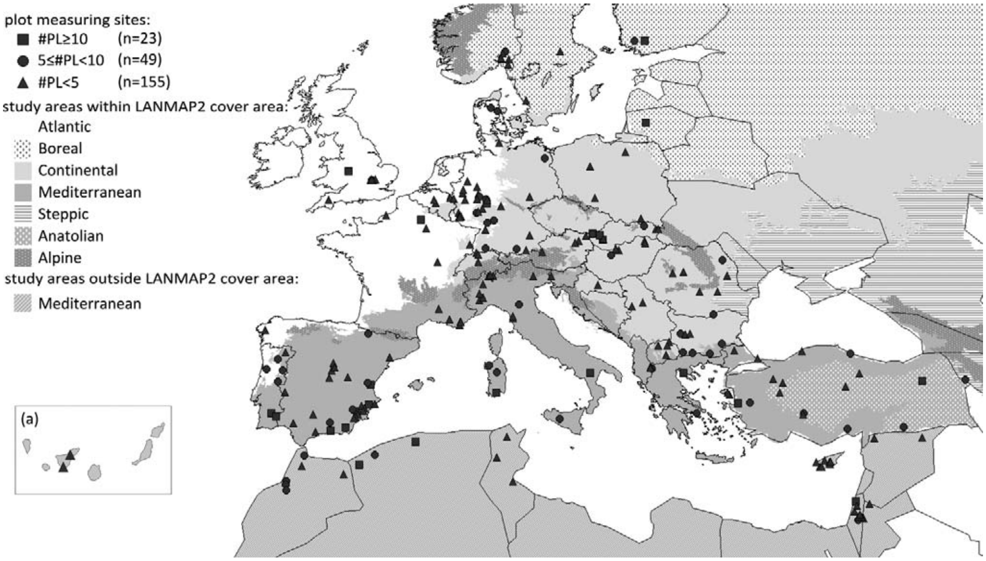

Figure 1. Geographical distribution of plot runoff and soil loss measuring sites over Europe and the Mediterranean with indication of the climatic zones derived from the LANMAP2 classification (Metzger et al., 2005; Mücher et al., 2010). Inset (a): Canary Islands. #PL = number of plots, n = number of plot-measuring sites.

from scientific papers, books (Boardman and Poesen, 2006), project reports and PhD theses, and through personal communication with various researchers. Only runoff and/or soil loss measurements conducted on bounded runoff plots under natural rainfall conditions with a known land use, a minimum plot length of 5 m, and for a measuring period (MP) that is representative (see section II(2) below for more details) for at least one year were considered. Results from runoff plots that were treated with soil and water conservation techniques were not included in this analysis since they do not represent prevailing field conditions. A list of the excluded soil and water conservation techniques is given in Table 2a. While plots without any soil cover throughout the year, i.e. bare plots (Table 2b), are not a common land use practice, they are often used in soil erosion studies as reference plots, representing maximum potential SL for the study conditions. However, traditional agricultural practices on cropland often leave the soil bare after tillage during part of the year. Hence, plots with bare soil were included in the database for reference purposes.

While most plots use collection tanks or flow samplers to determine the total runoff and soil loss by interrill and rill erosion, in a small number of studies, soil loss is determined by measuring the rill volume (Govers and Poesen, 1988; Jankauskas and Fullen, 2002; Jankauskas and Jankauskiene, 2003a; Jankauskas et al., 2004). Based on a literature survey by Govers and Poesen (1988), total soil loss for these studies was calculated by adding 25% to the measured rill soil loss to account for interrill soil loss.

Each runoff and soil loss plot (PL) in the database represents measurements of annual runoff and/or soil loss at a particular measuring site for a specific combination of land use, soil type, plot length and slope gradient. For each of these PL, the corresponding number of plot-years (PY) was also recorded, which indicates the number of years represented by the data for that PL. PY = 1 corresponds to a measuring period of one year on a single runoff plot. When measurements were conducted on several

Table 2a. List of soil and water conservation techniques (SWCT) tested on runoff plots and thus excluded from the plot database used for the analysis of the effects of land use on annual runoff and annual soil loss in Europe and the Mediterranean. Ba = bare, Cr = cropland, Fa = fallow, Fo = forest, Sh = shrubland, Ra = rangeland, Pf = post-fire, Gr = grassland, Vi = vineyards, Tc = tree crops, Cs = construction sites.

SWCT	Land-use types	Description of SWCT
Tillage techniques:		
no-tillage	Ba, Cr, Fa, Tc, Vi	no tillage operations when the local practice is conventional tillage (e.g. Turtola et al., 2007)
conservation tillage	Ba, Cr, Fa, Tc, Vi	different forms of reduced tillage resulting in a smaller disturbance of the plough layer than conventional tillage (e.g. Kwaad et al., 1998)
contour tillage	Ba, Cr, Fa, Tc, Vi	tillage operations parallel the contour (e.g. Quinton and Catt, 2004)
deep tillage	Cr	deep non-inversion tillage to improve percolation (e.g. Chomaničová, 1988; Suchanic, 1987)
Soil cover:		
cover crops	Ba, Cr, Tc, Vi	cover crop grown during the intercropping season, drilled after harvest (e.g. Laloy and Bielders, 2010)
mulching	Cr, Gr, Pf, Ra, Sh, Vi	application of organic mulch (crop residue or straw)
geotextile	Ba, Cs, Tc, Vi	application of geotextile mats (Bhattacharyya et al., 2008, 2009; Jankauskas et al., 2008; Mitchell et al., 2003)
Sediment traps:		
buffer strips	Ba, Cr, Fa, Tc, Vi	Strips of perennial vegetation (usually grasses) used to increase infiltration, slow down runoff and increase sediment deposition (e.g. Uusi-Kämppä, 2005)
contour bunds	Vi	stone or earthen bunds constructed parallel to the contour (e.g. Pinczés, 1982)
strip cropping	Cr	drilling or planting in strips of alternating crop types (e.g. Köse and Taysun, 2002; Köse et al., 1996)
contour cropping	Cr	crop planting or drilling parallel to the contour (e.g. Jung and Brechtel, 1980)
terraces	Ba, Cr, Fo, Gr, Pf, Sh, Tc, Vi	construction of earthen or stone terraces parallel the contour (e.g. Koulouri and Giourga, 2007)
Other:		
drainage	Cr, Gr	application of subsurface drainage pipes (e.g. Øygarden, 1996; Øygarden et al., 1997)
soil amendment	Ba, Cr, Fa, Gr, Ra, Sh, Cs	application of soil conditioners to improve soil soil structural stability – e.g. phosphogypsum (Agassi and Benhur, 1991; Agassi et al., 1990) or polyacrylamide (Lopez-Bermudez et al., 1991; Romero-Díaz et al., 1999)

replicate plots with identical experimental setup and results were reported individually for the different replicates, they were included as different PL in the database. If the average annual R and SL value for the replicate plots was reported (e.g. Bagarello and Ferro, 2010; Bagarello et al., 2010a, 2010b; Lopes et al., 2002; Mohammad and Adam, 2010) the average values for all replicates were counted as one PL in the database, while the number of PY was considered to be the sum of all PY of the replicates.

Table 2b. Land-use types considered in the plot database for Europe and the Mediterranean

Land-use type	Abbreviation	Crop	Description
bare	Ba		continuously bare soil without crops or natural vegetation, sometimes tilled annually
fallow	Fa		plot with natural regrowth of grass and herbaceous species, or sowing of those species in a rotation scheme
cropland	Cr	cereals	cereal (wheat, barley, oats, rye) cultivation
		maize	silage or grain maize cultivation
		sunflower	sunflower cultivation
		sugar beet	sugar beet cultivation
		potato	potato cultivation
		leguminous	leguminous (beans, peas, vetch, lentil, alfalfa, clover, yellow lupine) cultivation
		other	cultivation of other annual crops
tree crops	Tc		olive, almond or fruit (apple, citrus) cultivation
vineyards	Vi		vineyards, rows may have different orientation with respect to the contour
grassland	Gr		permanent grassland
rangeland	Ra		grass- or shrubland browsed by cattle
forest	Fo		natural vegetation or plantation with predominance of tree species
shrubland/matorral	Sh		natural vegetation or plantation with predominance of shrub species
post-fire	Pf		forested land or shrubland, burnt in the recent past (0–30 years)
construction sites	Cs		areas where urban-industrial activity (roadcut sites, mine areas) is the primary source of disturbance

Based on the description given by the authors, all PL were assigned to a land-use type (Table 2b). When different land-use types were present on a single runoff plot (e.g. cropland-fallow rotation or cropland-grassland rotation), the years having the same land use were grouped together as one PL. Hence, data from a runoff plot with a rotation of cropland and fallow is entered in the database as 2 PL, one for cropland and one for fallow. This approach does not take into account possible effects of crop cultivation and soil treatment prior to the measuring period, which may persist during the two following years (Wischmeier and Smith, 1978) and hence may explain part of the observed variability in R and SL rates. Furthermore, the location of each of the plot-measuring sites was determined, either from coordinates given by the authors or from maps and descriptions in the publications. Some studies report data for plots that were installed at different sites close to each other (e.g. different slope aspects or gradients in the same valley). Whenever it was possible to accurately distinguish between these different sites, they were incorporated as separate plot-measuring sites in the database but if this was impossible, the location of the study area where plots were located was included as one plot-measuring site. Subsequently, the climatic zone (CZ) of each of the plot-measuring sites was determined according to the LANMAP2 classification (Metzger et al., 2005; Mücher et al., 2010). Plot-measuring sites in the Near East and northern Africa that fall outside the LANMAP2 cover area were classified as Mediterranean (Figure 1). While soil properties like texture, rock fragment cover, soil organic matter content and soil erodibility are recognized as important determinants of runoff and soil loss (e.g. Cerdan, 2006, 2010; Poesen and Lavee, 1994; Poesen et al., 1994; Sanchis et al., 2008; Torri et al., 1997), quantitative data on these properties were not systematically reported in the literature from which plot data were extracted for the database. Hence, a quantitative analysis of the effect of these soil properties on annual R and SL could not be made.

2 Annual data and data extrapolation procedures

All data used in this analysis are annual data. More than 84% of #PL (corresponding to >90% of #PY) reported annual R and SL that were obtained during a measuring period of one or more years and are reported as annual values by the author. In some studies, however, measurements were not carried out for full years, but the authors indicated that the data were representative for full years because no or negligible runoff and soil loss occurred during the period that the runoff plots were not in operation. This was the case for some studies during the dry season in the Mediterranean region (e.g. Mohammad and Adam, 2010; Roxo et al., 1996) or during permanent snow cover and frozen soil in colder climates (e.g. Fulajtár and Janský, 2001). In these cases, the measuring period was considered to be full years when calculating the corresponding PY for that PL. Other studies where the MP is shorter than 1 year were only included in the plot database when the authors explicitly report data as annual (extrapolation by the authors), or a reasonable extrapolation could be made. This was only done if measurements were conducted for a period during which at least two-thirds of the annual rainfall depth was recorded and rainfall is distributed uniformly throughout the year. In these cases annual R and SL were estimated by linear extrapolation according to the corresponding annual P. If no annual P data were available, data were extrapolated linearly to annual values according to the corresponding number of days if measurements continued for a period of at least 80% of the year and rainfall is distributed uniformly throughout the year. Uniformity of rainfall was checked visually using the long-term average rainfall distribution for the plot-measuring site, as given by the New_LocClim program (FAO, 2006).

3 Database analyses

Plot length, slope gradient and soil characteristics need to be taken into account to explain variability in annual R, RC and SL. Previous studies indicated that the relationship between plot length or slope gradient and annual SL or R is non-linear (Cerdan et al., 2010; Nearing, 1997; Poesen and Bryan, 1989; Wischmeier, 1966; Wischmeier and Smith, 1978).

The effect of plot length and slope gradient on annual R and SL was assessed by calculating the non-parametric Spearman's rank correlation coefficients (r_s). For annual SL, also the correlations with the RUSLE length factor (L_{PL}, equation 1; Renard et al., 1997), a slope factor (S_{PL}, equation 2; Nearing, 1997) and the product of the L_{PL} and S_{PL} (LS-factor, equation 3) were calculated. For all PL with a land-use type for which annual SL was significantly correlated to the LS-factor, the annual unit plot soil loss (SL_u) was calculated using equation 4 (Bagarello et al., 2010b).

$$L_{PL} = \left(\frac{\lambda}{22.13}\right)^{0.5} \qquad (1; \text{Renard et al., } 1997)$$

$$S_{PL} = -1.5 + \frac{17}{1 + \exp(2.3 - 6.1 \times \sin\theta)} \qquad (2; \text{Nearing, } 1997)$$

$$LS_{PL} = L_{PL} \times S_{PL} \qquad (3)$$

$$SL_u = \frac{measured\ plot\ SL}{LS_{PL}}$$

(4; Bagarello et al., 2010b)

where L_{PL}= plot length factor, λ = plot length (m), S_{PL} = plot slope gradient factor, Θ = plot slope angle (°), LS_{PL}= plot LS-factor, SL_u = annual unit plot soil loss ($Mg.ha^{-1}.yr^{-1}$).

As no standard procedure for the correction of annual R and RC values to a unit plot exists, no correction factor could be calculated for annual R and RC. Regardless of other factors, it can be expected that the reliability of average annual R and SL measurements increases with increasing PY, as they capture more of the occurring natural variability. According to the central limit theorem, the standard error of a sample is inversely related to the square root of the number of observations (Tijms, 2004). Therefore, average annual R, RC and SL values were calculated by weighting the reported mean value of each PL with the square root of the number of plot-years. While this is a very basic approach and does not take into account the complex temporal variation in annual SL and often non-normal distributions of annual SL time series (Maetens et al., 2011), it can be expected that this weighting results in more reliable estimates of average annual R, RC and SL rates (Cerdan et al., 2010; Vanmaercke et al., 2011b). A k-sample Kolmogorov-Smirnov test (KS-test) was used to test for significant differences in the distribution of annual R, RC, SL and SL_u data between each combination of two land-use types, whereby the significance level of the test was adapted using Bonferroni's Inequality to account for familywise error in multiple corrections (Brittain, 1987). The same procedure was applied to test for significant differences between CZ for each land-use type. To further explore the runoff-soil loss relationship, regression equations of the form:

$$Y = aX^b \tag{5}$$

were calculated, where the dependent variable Y was either annual SL or SL_u, the independent variable X was either annual R or RC and a and b are empirical constants. Both unweighted and regressions weighted according to the square root of the number of plot-years of each plot were calculated.

Precipitation has been studied intensively as the causal factor of runoff and soil loss. The rainfall erosivity index (EI30) has been proposed as a good measure for relating precipitation to (potential) annual SL (Wischmeier and Smith, 1958). While annual P was reported in most of the studies and is generally widely available with detailed spatial and temporal coverage, EI30 values were not consistently reported for the PL included in the database and are not available from other data sources (Gabriëls, 2006). As an alternative, the Modified Fournier Index (Arnoldus, 1980; equation 6) has been used as a measure of climatic erosivity (Gabriëls, 2006):

$$MFI = \sum_{1}^{12} \frac{p^2}{P} \tag{6}$$

where MFI = Modified Fournier Index ($mm^2.mm^{-1}$), p = average monthly precipitation ($mm.month^{-1}$), P = average annual precipitation ($mm.yr^{-1}$). MFI was calculated for each of the plot measurement sites, using monthly precipitation data obtained from the CRU CL 2.0 data set (New et al., 2002).

III Results

1 Description of the plot database

The plot database contains data from 227 plot-measuring sites throughout Europe and the Mediterranean region (Figure 1), compiled from 213 individual publications. Annual SL data are available for a total of 1056 PL, corresponding to a total of 7204 PY. Annual R data were available for 804 PL (5327 PY). For 766 of these PL, representing 5013 PY, both annual R and SL data are available. For 673 PL (corresponding to 4583 PY), both R and P are reported, allowing the calculation of annual RC. The distribution of PL and PY over the different countries in the study area and the references to the data sources are given in Table 3.

The first recorded soil loss measurements in the database started in 1950 at Cean-Turda, Romania (Motoc et al., 1998) and later on the number of plots increased until 1994, after which the number of plots started to decline. The earliest publication discussing plot measurements that could be found dated from 1968 (Dubber, 1968), although most of the publications date from 1986 onwards (Figure 2). The average MP of all runoff and soil loss plots is 6.0 yrs (median: 4 yrs, mode: 1 yr) with a minimum of 1 and a maximum of 42 yrs at Podu-Iloaiei , Romania (Bucur et al., 2007) (Figure 3). For most PL (>84% of #PL and >90% of #PY), measurements continued throughout the year for at least one full year. Annual R and SL data calculated for a MP less than 1 yr which were extrapolated to a full year account for less than 3% of all PL and les than 1% of PY (Table 4). The distribution of the number of plots and plot-years over the different land-use types and CZ is given in Table 5, while the distributions of the number of plots and plot-years according to annual P, plot length and plot slope gradients are given in Figure 4. The different land-use types in the database also show different frequency distributions (Figure 5), with cropland and fallow mainly occurring on gentler slopes (<20%), while forest, vineyards, construction sites and tree crop plots are generally situated on steeper slopes (>20%).

2 Effects of plot length and slope gradient on annual runoff, runoff coefficient and soil loss

The range of annual R and SL values recorded in the plot database varies over almost four orders of magnitude (Figure 6). To allow a comparison of the results obtained on plots with different plot lengths and slope gradients, the importance of these topographic variables was examined using the correlation coefficient between plot length and slope gradient and R and RC (Table 6). Annual R was found to be positively correlated with plot length for plots having bare soil, cropland, grassland and tree crops. A significant negative relationship between annual R and plot length was found for plots under forest and plots recently affected by fire. With respect to the relation between slope gradient and annual R only a significant positive correlation was found for post-fire conditions. For grassland and shrubland the relation between R and plot slope gradient was found to be significantly negative. With the exception of vineyards, where a significant negative correlation between slope gradient and annual RC was observed, the same trends, albeit with slightly different r_s values, were found for annual RC.

For annual SL, a significant positive correlation with the LS-factor (equation 3) was found for bare plots, cropland, fallow, shrubland and tree crops (Table 6). For cropland, the correlation was significant with both the L_{PL} and S_{PL}, while for bare and tree crops only a significant correlation with L_{PL} was found. Nevertheless, the correlation between annual SL and S_{PL} is also relatively strong. For shrubland, only S_{PL} was significantly correlated with annual SL, while for vineyards there was only a significant correlation with L_{PL}. Therefore, unit plot SL (SL_u, equation 4) was calculated for plots where the land use was bare, cropland, fallow, shrubland or tree crops. Although the correlation between annual SL and LS_{PL} was not significant for construction sites, this is likely due to the limited number of plots for this land-use type. Nevertheless, annual SL_u values were also calculated for PL on construction sites since these PL all have a bare soil surface.

Table 3. Overview by country in Europe and the Mediterranean of the number of plots (#PL), number of plot-years (#PY) and sources included in the plot database

Country	#PL	#PY	Source
Albania	14	66	Grazhdani, 2006, personal communication 2010; Grazhdani et al., 1996, 1999
Algeria	60	233	Arabi and Roose, 1993; Mazour, 1992; Mazour et al., 2008; Morsli et al., 2004
Austria	3	33	Klik, 2003, 2010, personal communication 2010; Strauss and Klagerhofer, 2006
Belgium	2	17	Bollinne, 1982; Govers and Poesen, 1988; Verstraeten et al., 2006
Bulgaria	43	377	Kroumov and Malinov, 1989; Rousseva et al., 2006
Croatia	2	10	Basic et al., 2001, 2004
Cyprus	7	14	Lenthe et al., 1986; Lüken, personal communication 1986
Denmark	10	41	Schjønning et al., 1995; Veihe and Hasholt, 2006
Finland	20	102	Puustinen et al., 2005, 2007; Tattari and Rekolainen, 2006; Turtola and Paajanen, 1995; Turtola et al., 2007; Uusi-Kämppä, 2005
France	37	277	AREDVI, 2003; Auzet et al., 2006; Ballif, 1989; Brenot et al., 2006, 2008; Clauzon and Vaudour, 1969, 1971; Le Bissonnais et al., 2004; Martin, 1990; Martin et al., 1997; Messer, 1980; Viguier, 1993; Wicherek, 1986, 1988, 1991
Germany	102	330	Ammer et al., 1995; Auerswald, 2006; Auerswald et al., 2009; Barkusky, 1990; Biemelt et al., 2005; Botschek, 1991; Deumlich and Frielinghaus, 1994; Deumlich and Gödicke, 1989; Dikau, 1983, 1986; Dubber, 1968; Emde, 1992; Emde et al., 2005; Engels, 2009; Felix and Johannes, 1993; Fleige and Horn, 2000; Frielinghaus, 1998; Jung and Brechtel, 1980; Kleeberg et al., 2008; Richter, 1985, 1991; Richter and Kertesz, 1987; Saupe, 1990, 1992; Voss, 1978
Greece	36	84	Arhonditsis et al., 2000; Diamantopoulos et al., 1996; Dimitrakopoulos and Seilopoulos, 2002; Kosmas et al., 1996, 2006
Hungary	14	56	Hudek and Rey, 2009; Kertész, personal communications 2009, 2010; Kertész and Centeri, 2006; Kertész and Huszár-Gergely, 2004; Kertész et al., 2007; Pinczés, 1982; Richter, 1987; Richter and Kertesz, 1987
Israel	29	140	Agassi and Benhur, 1991; Inbar et al., 1997, 1998; Kutiel and Inbar, 1993; Lavee, personal communication 2010; Lavee et al., 1998
Italy	80	609	Bagarello and Ferro, 2010; Bagarello et al., 2010a, 2010b; Basso et al., 1983a, 1983b, 2002; Bini et al., 2006; Caredda et al., 1997; Caroni and Tropeano, 1981; Chisci, 1989; Chisci and Zanchi, 1981; De Franchi and Linsalata, 1983; de Vente et al., 2007; Ollesch and Vacca, 2002; Porqueddu and Rogerro, 1994; Postiglione et al., 1990; Rivoira et al., 1989; Torri et al., 2006; Tropeano, 1984; Vacca, personal communication 2010; Vacca et al., 2000; Zanchi, 1983, 1988a, 1988b
Jordan	2	4	Abu-Zreig, 2006; Abu-Zreig et al., 2011
Lithuania	103	792	Feiza et al., 2007; Jankauskas, personal communication 2009; Jankauskas and Fullen, 2002, 2006; Jankauskas and Jankauskiene, 2003a, 2003b; Jankauskas et al., 2004, 2007, 2008
Macedonia	8	36	Blinkov and Trendafilov, 2006; Jovanovski et al., 1999
Morocco	29	164	Chaker et al., 2001; Heusch, 1970; Laouina et al., 2003; Moufaddal, 2002; Yassin et al., 2009; Yassin, personal communication 2009

(continued)

Table 3. Overview by country in Europe and the Mediterranean of the number of plots (#PL), number of plot-years (#PY) and sources included in the plot database]

Country	#PL	#PY	Source
Norway	10	82	Børresen, personal communication; Grønsten and Lundekvam, 2006; Lundekvam, 2007; Øygarden, 1996; Øygarden et al., 2006
Palestinian territories	9	42	Abu Hammad et al., 2004, 2006; Al-Seekh and Mohammad, 2009; Mohammad and Adam, 2010
Poland	10	79	Gil, 1986, 1999; Rejman and Rodzik, 2006; Rejman et al., 1998; Skrodzki, 1972; Stasik and Szafranski, 2001; Szpikowski, 1998
Portugal	52	406	Coelho, 2006; de Figueiredo, personal communication 2010; de Figueiredo and Gonçalves Ferreira, 1993; de Figueiredo and Poesen, 1998; de Figueiredo et al., 2004; Lopes et al., 2002; Nunes and Coelho, 2007; Roxo et al., 1996; Shakesby et al., 1994
Romania	22	568	Bucur et al., 2007; Ene, 1987; Ionita, 2000; Ionita et al., 2006; Motoc et al., 1998; Nistor and Ionita, 2002; Teodorescu and Badescu, 1988
Serbia	6	74	Djorovic, 1990; Kostadinov et al., 2006; Sekularac and Stojiljkovic, 2007
Slovakia	62	104	Chomanicová, 1988; Fulajtár and Janský, 2001; Gajdová et al., 1999; Stankoviansky et al., 2006; Suchanic, 1987
Slovenia	4	19	Horvat and Zemljic, 1998; Hrvatin et al., 2006
Spain	156	876	Albaladejo and Stocking, 1989; Albaladejo et al., 2000; Andreu et al. 1998a, 1998b, 2001; Aspizua, 2003; Bautista et al., 1996, 2007; Bienes et al., 2006; Campo et al., 2006; Castillo et al., 1997, 2000; Cerdà and Lasanta, 2005; Chirino et al., 2006; de Vente and Poesen, 2005; Durán Zuazo et al., 2004, 2008; Francia Martínez, 2006; García-Ruiz et al., 1995; Gimeno-Garcia et al., 2007; Gómez et al., 2004, 2009; Gómez Plaza, 2000; González-Pelayo et al., 2010; Guerra et al., 2004; Ingelmo et al., 1998; Lasanta et al., 2006; Lopez-Bermudez et al., 1991; Martinez-Mena et al., 1999, 2001; Martinez-Murillo and Ruiz-Sinoga, 2007; Martínez Raya et al., 2006; Nadal Romero, personal communication 2010; Puigdefábregas et al., 1996; Rodríguez Rodríguez et al., 2002, 2006; Romero-Díaz and Belmonte Serrato, 2008; Romero-Díaz et al., 1999; Rubio et al., 1997; Sanchez et al., 1994; Schnabel et al., 2001; Solé Benet, 2006, personal communication 2010; Soler et al., 1994; Soto and Díaz-Fierros, 1998; Williams et al., 1995
Sweden	6	52	Ulén, 1997, 2006; Ulén and Kalisky, 2005
Switzerland	12	218	Marxer, 2003; Schaub, 1998; Weisshaidinger and Leser, 2006
Syrian Arab Republic	7	20	Bruggeman et al., 2005; Masri et al., 2005; Shinjo et al., 2000
The Netherlands	3	19	Kwaad, 1991, 1994, personal communication 2009; Kwaad et al., 1998, 2006
Tunisia	9	76	Ben Chaabane and Hamrouni, 2008; Bourges et al., 1973, 1975; Kaabia, 1995
Turkey	84	1233	Erpul, personal communication 2010; Kara et al., 2010; Köse and Taysun, 2002; Köse et al., 1996; Oguz, personal communication 2010; Oguz et al., 2006; Özhan et al., 2005
United Kingdom	46	293	Bhattacharyya et al., 2008, 2009; Boardman and Evans, 2006; Brown, 1996; Fullen, 1992, 1998; Fullen and Booth, 2006; Fullen and Brandsma, 1995; Fullen and Reed, 1986; Fullen et al., 2006; Mitchell et al., 2003; Morgan and Duzant, 2008; Quinton and Catt, 2004

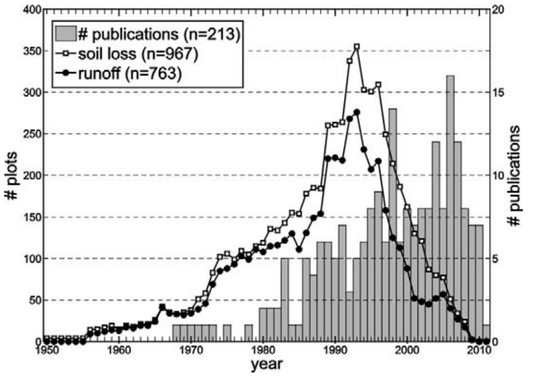

Figure 2. Evolution of the total number of plots (# plots) in operation per year for which annual soil loss and/or runoff were recorded in Europe and the Mediterranean as well as the total number of publications from which plot data were extracted in this study (# publications) per publication year

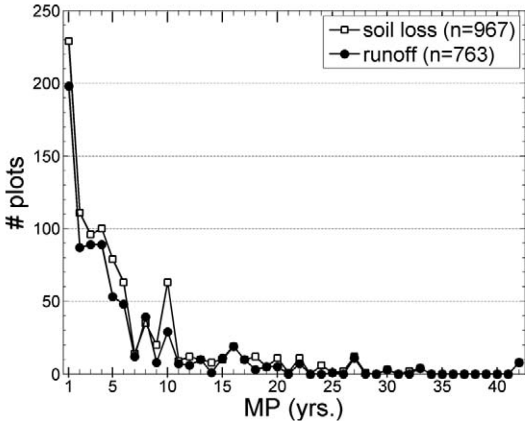

Figure 3. Frequency distribution of the number of plots (# plots) as a function of the measuring period (MP) for which annual runoff or annual soil loss were measured continuously in Europe and the Mediterranean

Table 4. Data collection period of plot data in the plot database. R = annual runoff, RC = annual runoff coefficient, SL = annual soil loss. Number of plots (#PL) and number of plot-years (#PY) for which plot data were collected (1) during full years (Full Year), (2) during a representative part of the year during which almost all of the annual rain was recorded and the authors considered the data to be representative for a full year (Repr. for Full Year), (3) during a measuring period less than one year during which at least 67% of the annual rain was recorded and for which the data were linearly extrapolated to 100% of the annual rainfall (Extrapol. to Full Year).

Data collection period	#PL (% of total)						#PY (% of total)					
	R		RC		SL		R		RC		SL	
Full Year	683	(84.9%)	567	(84.2%)	908	(86.0%)	5016	(94.2%)	4298	(93.8%)	6853	(95.1%)
Repr. for Full Year	110	(13.7%)	95	(14.1%)	122	(11.6%)	281	(5.3%)	255	(5.6%)	306	(4.2%)
Extrapol. to Full Year	11	(1.3%)	11	(1.6%)	26	(2.4%)	30	(0.5%)	30	(0.6%)	45	(0.6%)
Total	804	(100%)	673	(100%)	1056	(100%)	5327	(100%)	4583	(100%)	7204	(100%)

3 Characteristics of the frequency distributions of annual runoff and soil loss for various land uses

Weighted mean values and box-plots indicating the range of annual R, RC, SL and SL_u by land-use type are shown in Figure 7. Weighted mean values are always higher than the median value for annual R, RC and SL, which indicates that annual R, RC and SL have a positively skewed distribution, such as the log-normal distribution (e.g. Bagarello et al., 2010a). Construction sites have consistently the highest annual R, RC and SL. After correction for the plot length and slope gradient, annual SL_u values for construction sites

Table 5. Overview of the number of plots (#PL) and the number of plot-years (#PY) for which annual runoff (R), annual runoff coefficient (RC) and/or annual soil loss (SL) data for Europe and the Mediterranean are available. NA = not available.

		R	RC	SL
Land-use type	Climatic zone	#PL (#PY)	#PL (#PY)	#PL (#PY)
bare	**all data**	**133 (1,362)**	**95 (1,058)**	**182 (1,740)**
	pan-Mediterranean	72 (857)	58 (656)	100 (1,129)
	temperate	59 (490)	35 (387)	80 (596)
	cold	2 (15)	2 (15)	2 (15)
construction sites	**all data**	**3 (11)**	**3 (11)**	**3 (11)**
	pan-Mediterranean	2 (10)	2 (10)	2 (10)
	temperate	1 (1)	1 (1)	1 (1)
cropland	**all data**	**302 (2,018)**	**244 (1,737)**	**397 (2,749)**
	pan-Mediterranean	161 (1,136)	144 (1,035)	174 (1,232)
	temperate	114 (683)	79 (563)	147 (874)
	cold	27 (199)	21 (139)	76 (644)
fallow	**all data**	**47 (221)**	**46 (216)**	**60 (281)**
	pan-Mediterranean	23 (165)	23 (165)	25 (173)
	temperate	21 (46)	21 (46)	26 (86)
	cold	3 (10)	2 (5)	9 (22)
forest	**all data**	**59 (301)**	**55 (277)**	**59 (334)**
	pan-Mediterranean	41 (238)	41 (238)	40 (217)
	temperate	17 (58)	14 (39)	18 (113)
	cold	1 (5)	NA	1 (5)
grassland	**all data**	**69 (506)**	**52 (431)**	**109 (779)**
	pan-Mediterranean	30 (196)	17 (145)	29 (192)
	temperate	34 (296)	31 (277)	24 (233)
	cold	5 (14)	4 (9)	56 (355)
post-fire	**all data**	**54 (223)**	**46 (188)**	**56 (224)**
	pan-Mediterranean	49 (202)	43 (179)	51 (203)
	temperate	3 (9)	3 (9)	3 (9)
	cold	2 (12)	NA	2 (12)
rangeland	**all data**	**14 (59)**	**14 (59)**	**17 (69)**
	pan-Mediterranean	13 (56)	13 (56)	15 (64)
	temperate	1 (2)	1 (2)	2 (6)
shrubland	**all data**	**84 (372)**	**79 (351)**	**111 (589)**
	pan-Mediterranean	77 (357)	72 (336)	101 (559)
	temperate	7 (15)	7 (15)	10 (30)
tree crops	**all data**	**13 (133)**	**13 (133)**	**23 (154)**
	pan-Mediterranean	10 (59)	10 (59)	20 (80)
	temperate	3 (74)	3 (74)	3 (74)
vineyard	**all data**	**26 (123)**	**26 (123)**	**39 (272)**
	pan-Mediterranean	12 (90)	12 (90)	18 (107)
	temperate	14 (33)	14 (33)	21 (165)
Database total		**804 (5,327)**	**673 (4,583)**	**1,056 (7,204)**

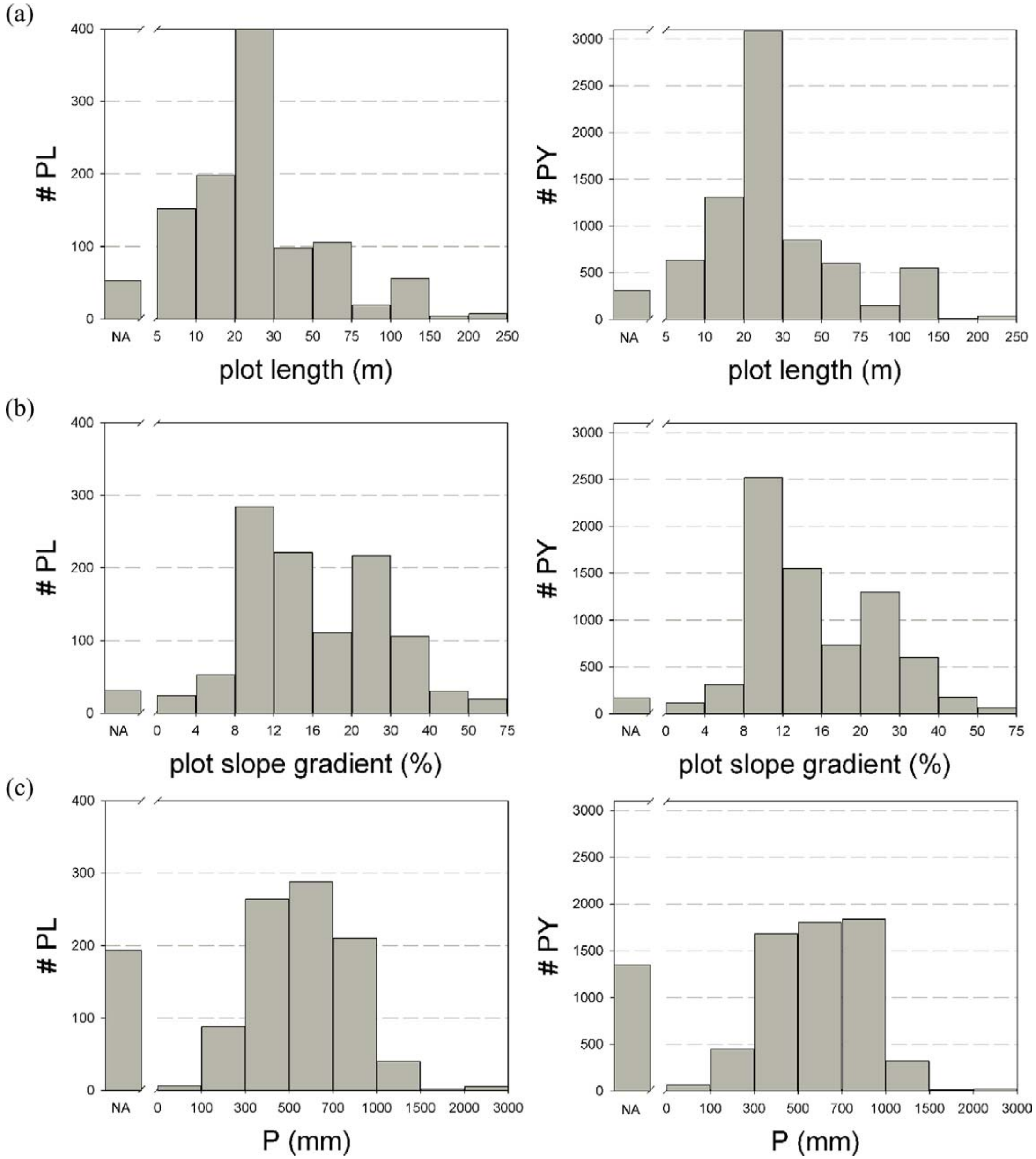

Figure 4. Frequency distribution of the number of plots (# PL) and the number of plot-years (# PY) in Europe and the Mediterranean for which annual runoff and/or annual runoff coefficient, and/or annual soil loss data are available with respect to: (a) plot length; (b) plot slope gradient; and (c) annual precipitation (P). Total #PL = 1 096, total #PY = 7 533. NA = not available (i.e. plot length, slope gradient or P not reported).

are smaller, which is attributed to the steep slopes associated with the construction site plots (Figure 5). Nevertheless, annual SL_u for construction sites remains considerably higher than for other land-use types. However, the number of plots on construction sites is low,

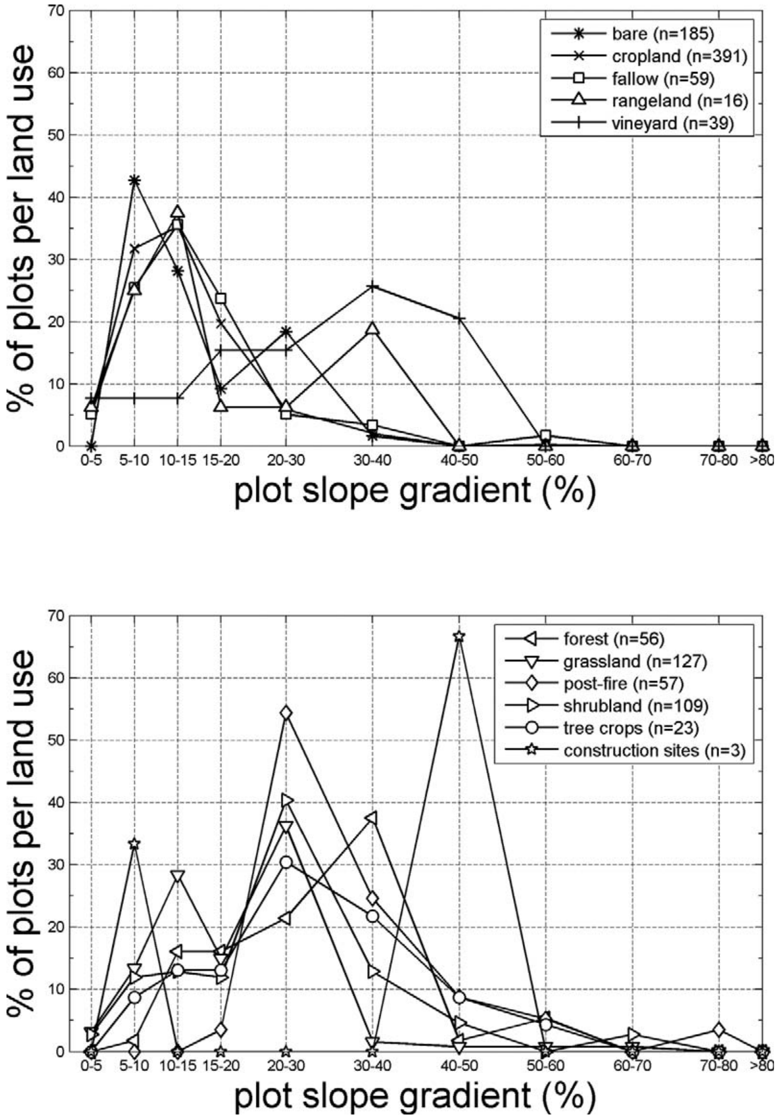

Figure 5. Frequency distribution of the % of plots for the different land-use types in Europe and the Mediterranean according to plot slope gradient class. n = total number of plots for a given land-use type.

so the corresponding mean values for annual R, RC and SL rates should be interpreted with caution, although they do indicate a high vulnerability to erosion of this land-use type. This is attributed to a presence of bare, disturbed soil with a low structural stability on relatively steep slopes causing very high soil loss rates (Borselli et al., 2006). The remainder of the land-use types can be divided into two groups. A first group consisting of bare plots or plots with some type of crop cultivation (i.e. cropland, fallow, tree crops and vineyards) shows mean annual R rates between 30 and 60 mm.yr^{-1}, annual RC rates between 5 and 15% and annual SL rates between 1 and 20 Mg.ha^{-1}.yr^{-1}. The second group of land-use types consists of PL with a

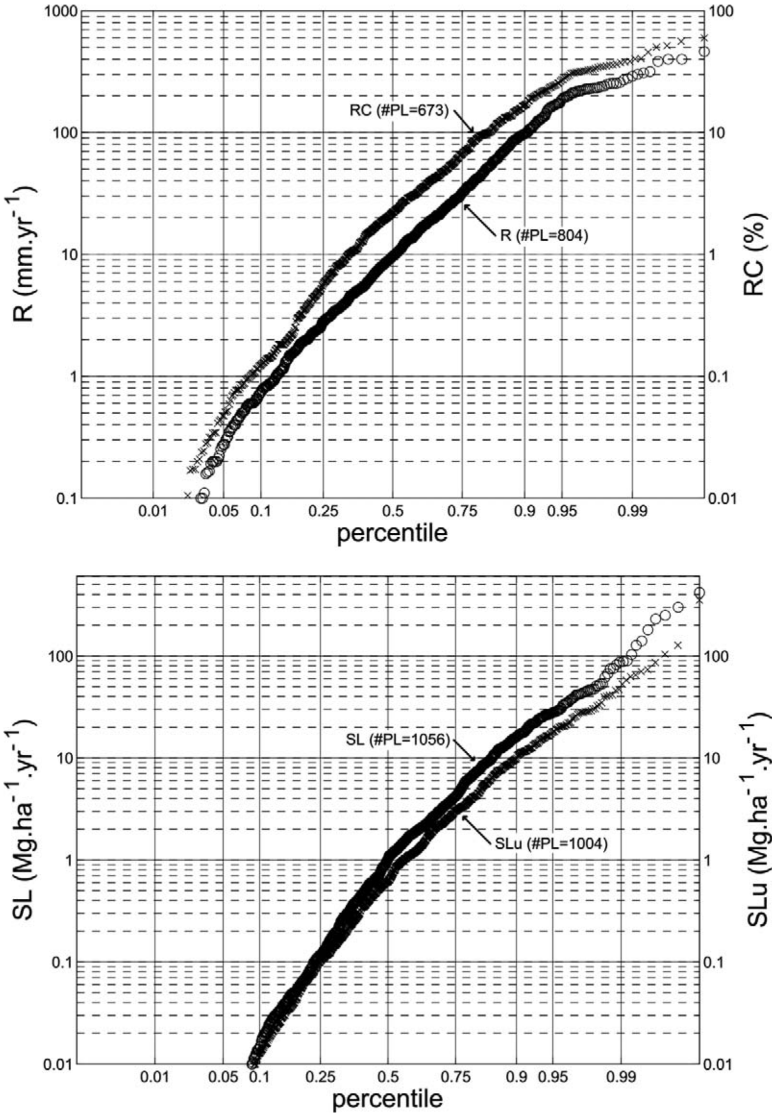

Figure 6. Frequency distribution of annual runoff (R), annual runoff coefficients (RC), annual soil loss (SL) and annual unit plot soil loss (SL_u, equation 4) rates in the plot database for Europe and the Mediterranean. #PL = total number of plots.

(semi-)natural vegetation cover (i.e. forest, post-fire, shrubland, rangeland and grassland), with annual R, RC and SL rates less than 30 mm.yr^{-1}, 5% and 1 Mg.ha^{-1}.yr^{-1}, respectively (Table 7). While bare plots and plots with crop cultivation have consistently higher mean annual R, RC and SL rates than plots with (semi-)natural vegetation, the ranking of the weighted mean values for the different land-use types within these two groups varies for annual R, RC and SL (Figure 7). The difference between these two groups was confirmed by the application of the Kolmogorov-Smirnov test, whereby significant differences between land-use types were mostly observed between land-use types where

Table 6. Spearman's rank correlation coefficient (r_s) and p-values for the correlation between annual runoff (R), annual runoff coefficients (RC) and plot length and slope gradient on the one hand and annual soil loss (SL) and USLE plot length-factor (L_{pl}), slope gradient-factor (S_{pl}) and LS-factor (LS_{pl}) on the other hand for different land-use types in Europe and the Mediterranean. Values in bold indicate significance at $\alpha = 0.05$. NA = not available.

	R				RC				SL					
	Plot length		Slope gradient		Plot length		Slope gradient		L_{pl}		S_{pl}		LS_{pl}	
Land-use type	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p
bare	0.21	**0.02**	0.07	0.45	0.23	**0.03**	0.09	0.41	0.16	**0.04**	0.15	0.06	0.22	**<0.01**
cropland	0.56	**<0.01**	–0.03	0.65	0.56	**<0.01**	–0.07	0.30	0.31	**<0.01**	0.14	**<0.01**	0.28	**<0.01**
fallow	0.16	0.29	–0.13	0.40	0.21	0.16	–0.21	0.17	0.21	0.11	0.25	0.06	0.39	**<0.01**
forest	–0.55	**<0.01**	–0.02	0.90	–0.33	**0.03**	0.08	0.62	–0.13	0.39	–0.08	0.58	–0.04	0.79
grassland	0.30	**0.02**	–0.56	**<0.01**	0.32	**0.03**	–0.59	**<0.01**	0.05	0.61	–0.04	0.66	0.08	0.44
post-fire	–0.58	**<0.01**	0.47	**0.001**	–0.71	**<0.01**	0.38	**0.01**	–0.06	0.69	0.11	0.44	0.09	0.52
rangeland	–0.35	0.24	0.01	0.98	–0.43	0.14	–0.22	0.47	–0.31	0.24	0.10	0.71	0.07	0.79
shrubland	–0.03	0.79	–0.26	**0.03**	0.07	0.57	–0.26	**0.04**	0.13	0.20	0.30	**<0.01**	0.32	**<0.01**
tree crops	0.82	**<0.01**	0.15	0.63	0.80	**<0.01**	0.25	0.41	0.71	**<0.01**	0.24	0.29	0.55	**0.01**
construction sites	NA	NA	0.87	0.67	NA	NA	0.87	0.67	NA	NA	0.87	0.67	0.87	0.67
vineyard	0.20	0.34	–0.23	0.26	–0.16	0.44	–0.60	**<0.01**	0.61	**<0.01**	–0.24	0.15	0.04	0.82

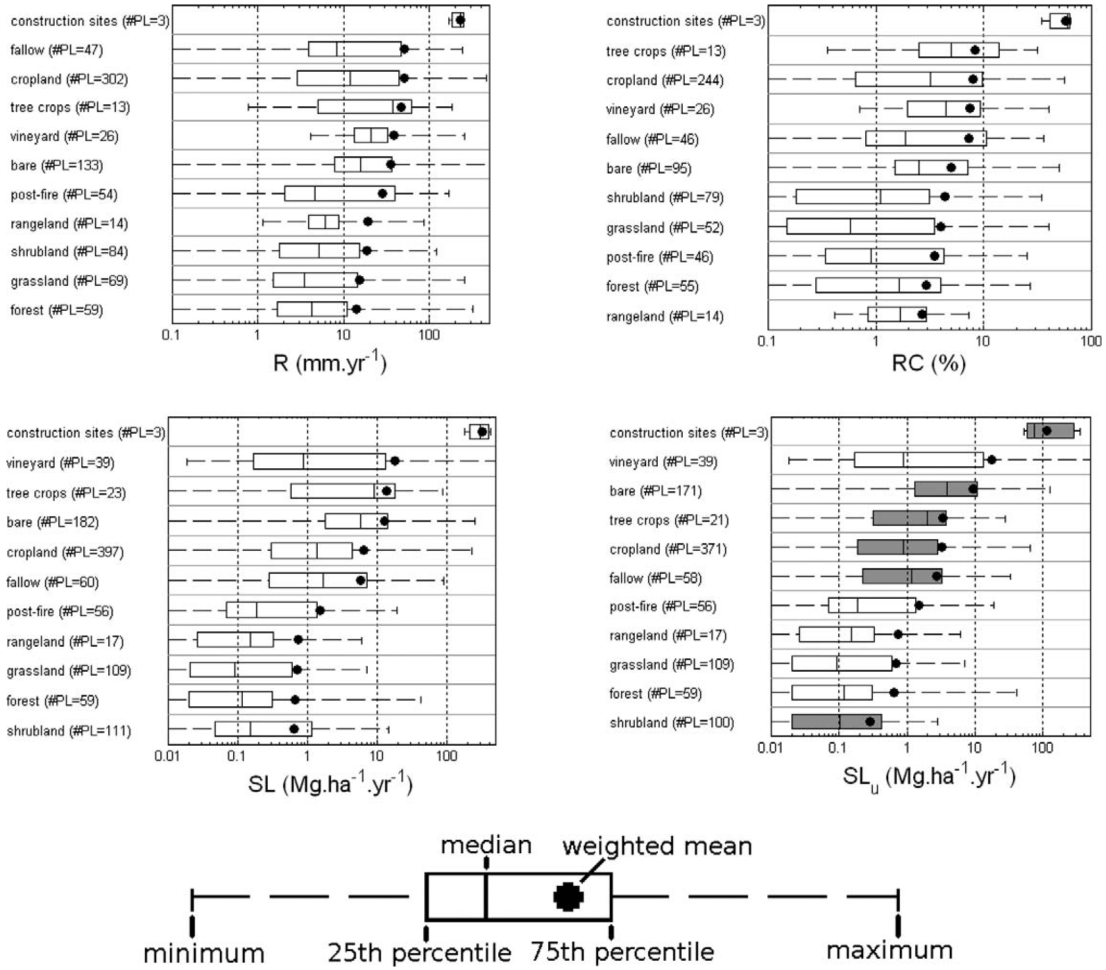

Figure 7. Frequency distribution of mean annual runoff (R), mean annual runoff coefficient (RC), mean annual soil loss (SL), and mean annual unit plot soil loss (SL_u, equation 4) of all plots in Europe and the Mediterranean, grouped by land-use type. Box-plots in grey indicate mean annual soil losses scaled to a unit plot (SL_u: plot length = 22.1 m, plot slope gradient = 9%). For the other land-use types, the original, measured SL was used. Black dots indicate the mean R, RC, SL and SL_u, weighted by number of plot-years (#PY). Box plots are ordered according to descending weighted mean.

crop cultivation was applied and land-use types with (semi-)natural vegetation. Furthermore, for 25 out of 55 pairwise combinations of all the 11 land-use types, the distribution of annual SL data was found to be significantly different, while for annual R and RC only 12 and 8 combinations were found to be significantly different, respectively.

4 Relationships of annual runoff coefficients and soil loss for various land uses

The median and distributions of all available annual RC and SL data for different land-use types are shown in Figure 8. This figure clearly indicates that there is a general trend towards higher median annual SL rates with higher

Table 7. Weighted mean, median and coefficient of variation (CV) for annual runoff (R), annual runoff coefficient (RC), annual soil loss (SL) and annual unit plot soil loss (SL_u) by land-use type for all data and grouped by climatic zone in Europe and the Mediterranean. Weighting was done according to the square root of the number of plot-years. For number of plots and plot-years corresponding to each land use, see Table 5. NC = not calculated because the relation between LS-factor and soil loss for this land-use type was insignificant (see Table 6). NA = no data available.

		R			RC			SL			SL_u		
Land-use type	Climatic zone	mean (mm)	median (mm)	CV (-)	mean (%)	median (%)	CV (-)	mean ($Mg.ha^{-1}.yr^{-1}$)	median ($Mg.ha^{-1}.yr^{-1}$)	CV (-)	mean ($Mg.ha^{-1}.yr^{-1}$)	median ($Mg.ha^{-1}.yr^{-1}$)	CV (-)
bare	all data	35.0	15.8	1.8	5.0	2.5	1.5	12.8	5.7	1.9	9.2	3.9	1.7
	pan-Mediterranean	36.0	20.5	1.9	4.9	3.8	1.4	9.1	3.6	1.5	7.4	3.1	1.5
	temperate	33.1	13.5	1.7	5.2	2.4	1.6	18.9	8.7	1.8	12.4	5.6	1.7
	cold	44.5	45.5	0.3	3.0	3.1	0.3	14.8	15.5	0.6	4.7	5.0	0.7
cropland	all data	50.3	11.9	1.7	8.0	3.2	1.4	6.5	1.3	2.8	3.3	0.9	2.2
	pan-Mediterranean	51.0	17.6	1.7	8.6	4.2	1.2	2.9	1.2	1.8	2.3	0.5	2.2
	temperate	19.3	5.8	1.8	3.3	1.3	1.5	9.6	0.9	2.7	4.1	1.1	2.1
	cold	148.9	199.7	0.6	19.5	28.9	0.6	9.0	3.0	1.3	4.1	1.7	1.3
fallow	all data	50.4	8.3	1.6	7.3	1.9	1.5	5.8	1.7	2.1	2.7	1.1	1.7
	pan-Mediterranean	51.1	25.8	1.1	7.7	3.9	1.0	1.5	0.7	1.5	0.7	0.4	1.4
	temperate	17.2	4.5	2.1	3.6	0.8	2.5	7.1	2.9	1.5	4.1	2.1	1.2
	cold	213.3	221.5	0.2	31.3	31.8	0.2	20.0	15.1	1.3	7.4	3.9	1.4
forest	all data	13.9	4.3	2.5	2.9	1.6	1.5	0.7	0.1	5.2	NC	NC	NC
	pan-Mediterranean	9.6	4.6	1.9	2.8	1.6	1.1	0.4	0.1	2.2	NC	NC	NC
	temperate	28.7	2.0	1.9	3.3	0.9	1.7	1.3	0.0	3.6	NC	NC	NC
	cold	3.9	3.9	NA	NA	NA	NA	0.0	0.0	NA	NC	NC	NC
grassland	all data	15.4	3.5	2.3	4.0	0.6	2.1	0.7	0.1	2.0	NC	NC	NC
	pan-Mediterranean	11.7	3.8	1.3	6.2	1.8	1.9	0.6	0.2	1.6	NC	NC	NC
	temperate	7.7	2.2	1.9	1.1	0.3	2.0	1.0	0.1	2.0	NC	NC	NC
	cold	133.9	131.0	0.6	27.5	26.0	0.4	0.6	0.1	2.1	NC	NC	NC
post-fire	all data	28.3	4.6	1.6	3.5	0.9	1.6	1.5	0.2	2.1	NC	NC	NC
	pan-Mediterranean	26.3	4.0	1.7	3.2	0.7	1.7	1.6	0.2	2.1	NC	NC	NC
	temperate	53.0	41.5	0.8	8.0	8.6	0.3	1.1	1.2	0.9	NC	NC	NC
	cold	41.7	41.7	0.1	NA	NA	NA	0.8	0.8	0.3	NC	NC	NC
rangeland	all data	18.8	6.0	1.8	2.7	1.7	0.9	0.7	0.2	2.2	NC	NC	NC
	pan-Mediterranean	19.6	5.5	1.8	2.8	1.8	0.9	0.8	0.2	2.2	NC	NC	NC
	temperate	6.6	6.6	NA	0.8	0.8	NA	0.3	0.3	1.4	NC	NC	NC

(continued)

Table 7. Weighted mean, median and coefficient of variation (CV) for annual runoff (R), annual runoff coefficient (RC), annual soil loss (SL) and annual unit plot soil loss (SLu) by land-use type for all data and grouped by climatic zone in Europe and the Mediterranean. Weighting was done according to the square root of the number of plot-years. For number of plots and plot-years corresponding to each land use, see Table 5. NC = not calculated because the relation between LS-factor and soil loss for this land-use type was insignificant (see Table 6). NA = no data available.]

		R			RC			SL			SL_u		
Land-use type	Climatic zone	mean (mm)	median (mm)	CV (-)	mean (%)	median (%)	CV (-)	mean ($Mg.ha^{-1}.yr^{-1}$)	median ($Mg.ha^{-1}.yr^{-1}$)	CV (-)	mean ($Mg.ha^{-1}.yr^{-1}$)	median ($Mg.ha^{-1}.yr^{-1}$)	CV (-)
shrubland	all data	18.3	5.1	1.6	4.4	1.1	1.8	0.6	0.1	2.0	0.3	0.1	1.6
	pan-Mediterranean	18.5	5.1	1.6	4.4	1.1	1.8	0.6	0.2	1.9	0.3	0.1	1.6
	temperate	14.3	0.0	1.4	3.4	0.0	1.6	0.5	0.0	2.6	0.2	0.0	2.0
tree crops	all data	46.2	36.9	1.2	8.2	5.0	1.1	13.4	9.0	1.4	3.3	2.0	1.7
	pan-Mediterranean	52.7	34.2	1.2	10.2	5.5	1.0	11.6	7.4	1.5	3.0	1.8	1.8
	temperate	34.7	36.9	0.7	4.7	5.0	0.7	18.4	13.8	1.0	4.2	3.9	0.8
construction sites	all data	227.7	230.0	0.2	57.0	59.7	0.3	325.1	299.0	0.4	115.8	73.4	1.0
	pan-Mediterranean	241.0	241.0	0.1	61.9	61.9	0.1	357.5	357.5	0.2	63.1	63.1	0.2
	temperate	168.0	168.0	NA	34.8	34.8	NA	180.0	180.0	NA	351.3	351.3	NA
vineyard	all data	38.8	21.0	1.5	7.4	4.4	1.2	17.9	0.9	4.1	NC	NC	NC
	pan-Mediterranean	47.6	21.0	1.5	9.8	6.9	1.0	1.8	0.3	1.8	NC	NC	NC
	temperate	25.2	23.1	1.0	3.7	4.3	0.8	32.1	12.4	3.1	NC	NC	NC

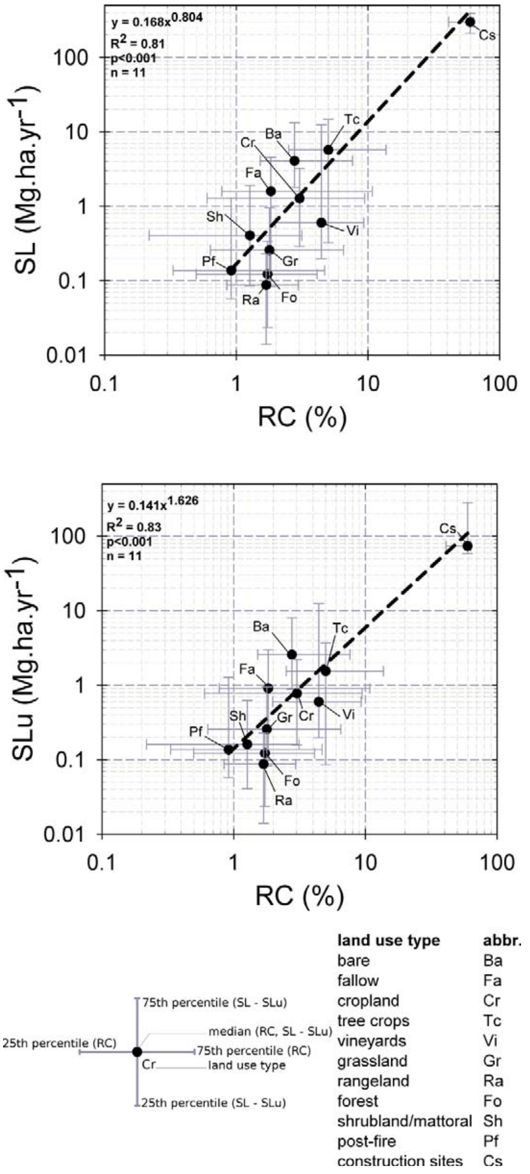

Figure 8. Relation between median annual runoff coefficient (RC), median annual soil loss (SL) and median annual unit plot soil loss (SL_u) of all plots in Europe and the Mediterranean by land use with indication of the 25th and 75th percentile for RC and SL, based on the plot database (for details, see Tables 5 and 7). n = number of land-use types.

median annual RC. For land uses under crop cultivation, tree crops have the highest median annual RC and SL. Vineyards have comparable median annual RC and 75th percentile annual SL values. However, median annual SL is markedly lower for vineyards, indicating that high annual SL rates in the database are more rare for vineyards than for tree crops. The interquartile ranges for cropland and fallow plots are similar for annual RC and annual SL. Median annual RC is lower for fallow plots, however, which indicates that low annual RC are more prevalent on fallow plots. Although annual RC rates on bare and cropland plots are similar, bare plots show higher annual SL rates than cropland plots. Plots with (semi-)natural vegetation are characterized by consistently low median annual SL (0.08–0.3 $Mg.ha^{-1}.yr^{-1}$), but still show somewhat more variation in median annual RC rates (0.5–1.1%).

Using all plot data for which respectively pairs of annual R-SL, RC-SL, R-SL_u and RC-SL_u were available, the best regression correlations (equation 5) are generally observed between annual R and SL (Table 8). Only for plots under grassland and post-fire better correlations between RC and SL were found. As a lack of data on annual P, plot length or plot slope gradient data does not allow the calculation of annual RC or SL_u, respectively, a smaller number of plots was available to calculate annual RC-SL, R-SL_u and RC-SL_u regressions. Nevertheless, the results of the regression analyses did not change using a subdata set of 611 PL where all four variables (annual R, RC, SL and SL_u) are available. In general, regression with unweighted annual R, RC, SL and SL_u data yields slightly better correlation than weighted regression, but weighted regressions were nevertheless considered to be more appropriate as the number of plot-years is taken into account (see section II(3)).

Regressions between annual R and SL were found not to be significant for fallow, vineyards and construction sites and hence these land-use types were not included in Figures 9a and 9b. As a large number of plots is available for cropland and crop type is expected to have an important

Table 8. Coefficients of determination (r^2) and number of plots (#PL) for the unweighted and weighted annual runoff–annual soil loss (R versus SL), annual runoff coefficient–annual soil loss (RC versus SL), annual runoff–annual unit plot soil loss (R versus SL_u) and annual runoff coefficient–annual unit plot soil loss (RC versus SL_u) regressions. Weighting was done using the square root of the number of plot-years. For each land use, the regression with the highest r^2 value is indicated in bold. n.s. = regression is not significant at α=0.05. NA = no regression was calculated as no SL_u values were calculated for these land-use types.

		R versus SL			RC versus SL			R versus Sl_u			RC versus SL_u		
			r^2			r^2			r^2			r^2	
Land-use type	Crop	#PL	unweighted	weighted	#PL	unweighted	weighted	#PL	unweighted	weighted	#PL	unweighted	weighted
bare		126	**0.47**	0.45	89	0.37	0.35	118	0.40	0.37	84	0.34	0.30
cropland	all data	281	**0.19**	0.19	228	0.13	0.12	259	0.16	0.15	217	0.10	0.09
	cereals	132	0.29	0.28	105	**0.29**	0.26	116	0.23	0.22	99	0.22	0.18
	maize	15	n.s.	n.s.	15	n.s.	n.s.	15	n.s.	n.s.	15	**0.27**	n.s.
	sunflower	8	0.54	n.s.	8	0.64	0.56	8	0.54	n.s.	8	**0.64**	0.59
	leguminous	23	n.s.	n.s.	21	n.s.	n.s.	23	n.s.	n.s.	21	n.s.	n.s.
	potatoes + sugar beet	6	n.s.	n.s.	4	n.s.	n.s.	5	n.s.	n.s.	4	n.s.	n.s.
	rotation	77	**0.05**	n.s.	55	n.s.	n.s.	72	n.s.	n.s.	50	n.s.	n.s.
	other	20	**0.38**	0.36	20	0.27	0.24	20	0.25	0.21	20	n.s.	n.s.
fallow		40	n.s.	n.s.	39	n.s.	n.s.	38	n.s.	n.s.	38	n.s.	n.s.
forest		50	0.48	0.47	48	**0.58**	0.58	NA	NA	NA	NA	NA	NA
grassland		47	0.26	0.25	30	**0.28**	0.27	NA	NA	NA	NA	NA	NA
post-fire		53	**0.44**	0.44	45	0.40	0.39	NA	NA	NA	NA	NA	NA
rangeland		14	**0.31**	n.s.	14	0.30	n.s.	NA	NA	NA	NA	NA	NA
shrubland		81	**0.14**	0.08	76	0.12	0.11	71	0.08	n.s.	66	0.08	n.s.
tree crops		13	**0.83**	0.83	13	0.66	0.65	13	0.81	0.80	13	0.62	0.61
vineyard		26	n.s.	n.s.	26	n.s.	n.s.	NA	NA	NA	NA	NA	NA
construction sites		3	n.s.	n.s.	3	n.s.	n.s.	3	n.s.	n.s.	3	n.s.	n.s.

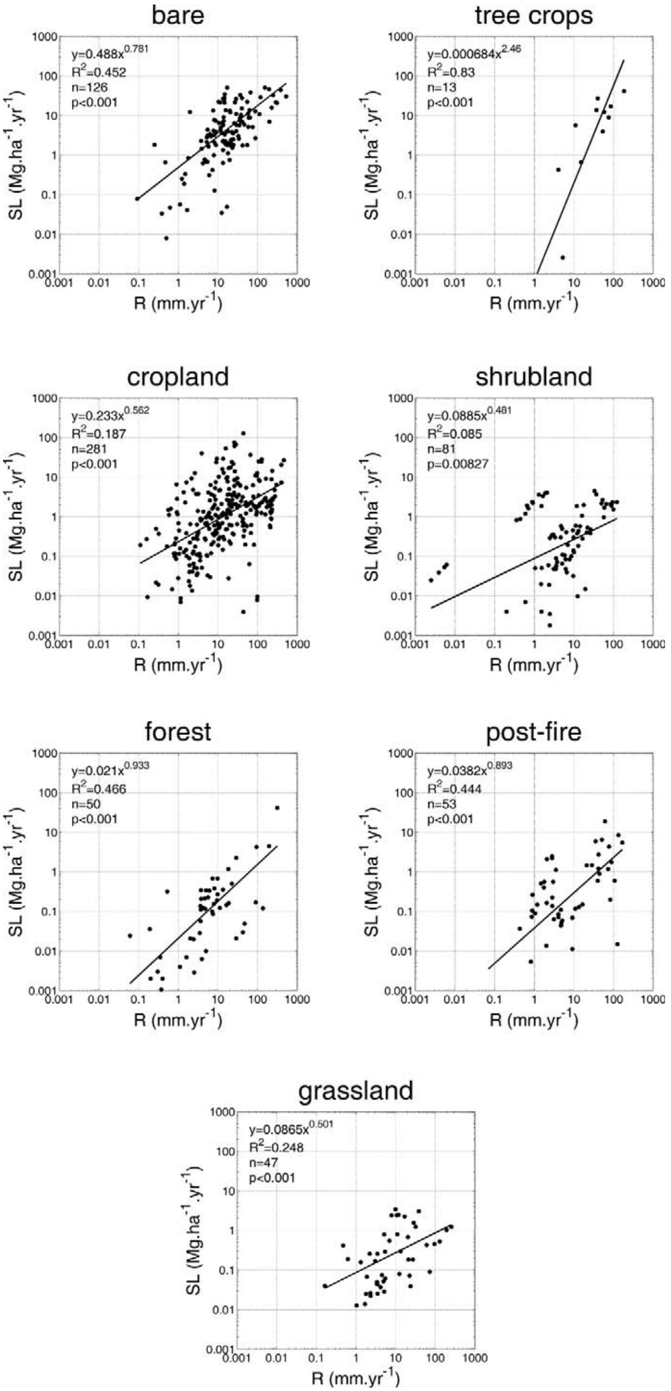

Figure 9a. Significant ($\alpha = 0.05$) relationships between annual runoff (R) and annual soil loss (SL) for different land-use types in Europe and the Mediterranean. Regressions are weighted according to the square root of number of plot-years for each plot. n = number of plots.

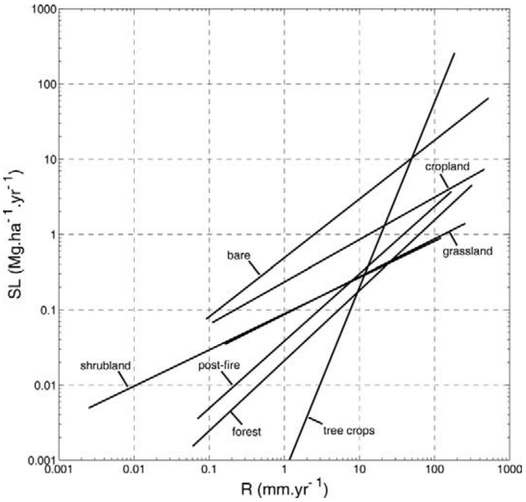

Figure 9b. Comparison of the significant ($\alpha = 0.05$) weighted regressions ($SL = aR^b$) between annual runoff (R) and annual soil loss (SL) for different land-use types in Europe and the Mediterranean. Regressions are weighted according to the square root of the number of plot-years for each plot. For regression parameters, see Figure 9a.

effect on annual SL rates in this land-use type (e.g. Auerswald et al., 2009; Gabriëls et al., 2003), a further subdivision according to crop type was made (Table 2b). The regression between annual R and annual SL was only significant for cereals (Figure 10), most likely due to a lack of sufficient data for the other crop types. Nevertheless, for maize, sugar beet and potatoes the available data show high annual RC and SL rates on nearly all of the plots where these crops were planted (Figure 10).

5 Effects of land use on runoff coefficient and soil loss for different climatic zones

In order to investigate possible impacts of the CZ on the relation between annual RC and SL for different land-use types, plot data were grouped according to CZ. After initial data analysis, the division of all plot data into seven different CZ, some of which contain only a few PL, was found to be too detailed. Therefore, the Mediterranean and Anatolian CZ were grouped in a new CZ hereafter referred to as 'pan-Mediterranean' (M). Likewise, the Atlantic, Continental and Steppic CZ were grouped in a 'temperate' CZ (T) and the Boreal and Alpine CZ in a 'cold' CZ (C). Weigthed mean values, median values and coefficients of variation for R, RC, SL and SL_u for each land use and CZ are given in Table 7. Shrubland, rangeland and post-fire occur mainly in the pan-Mediterranean zone and the few PL in the temperate zone are located relatively close to the pan-Mediterranean zone. Therefore, these land-use types were not further considered in this analysis. Also construction sites were disregarded due to insufficient plot data. For the other land-use types the differences in median value and the distribution of R and SL data by CZ are indicated in Figure 11.

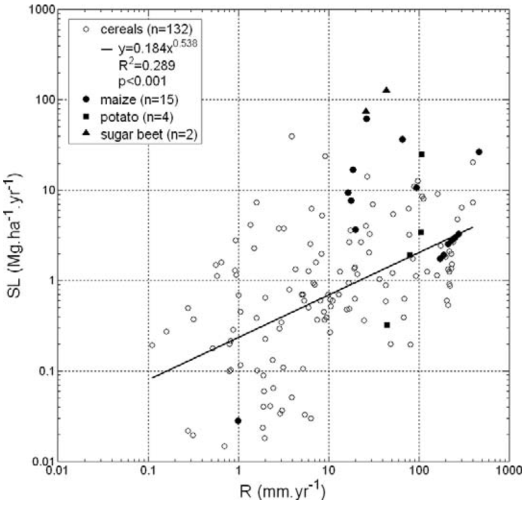

Figure 10. Relationship between annual runoff (R) and annual soil loss (SL) for cereal, maize, potato and sugar beet in Europe and the Mediterranean. Only the regression for plots with cereals was found to be significant ($\alpha = 0.05$) and is given here.

Mean annual SL values are smaller in the pan-Mediterranean than in the other two CZ for all land-use types (Table 7). With respect to the median, median annual SL rates for bare, fallow, tree crops and vineyards are significantly lower in the pan-Mediterranean zone

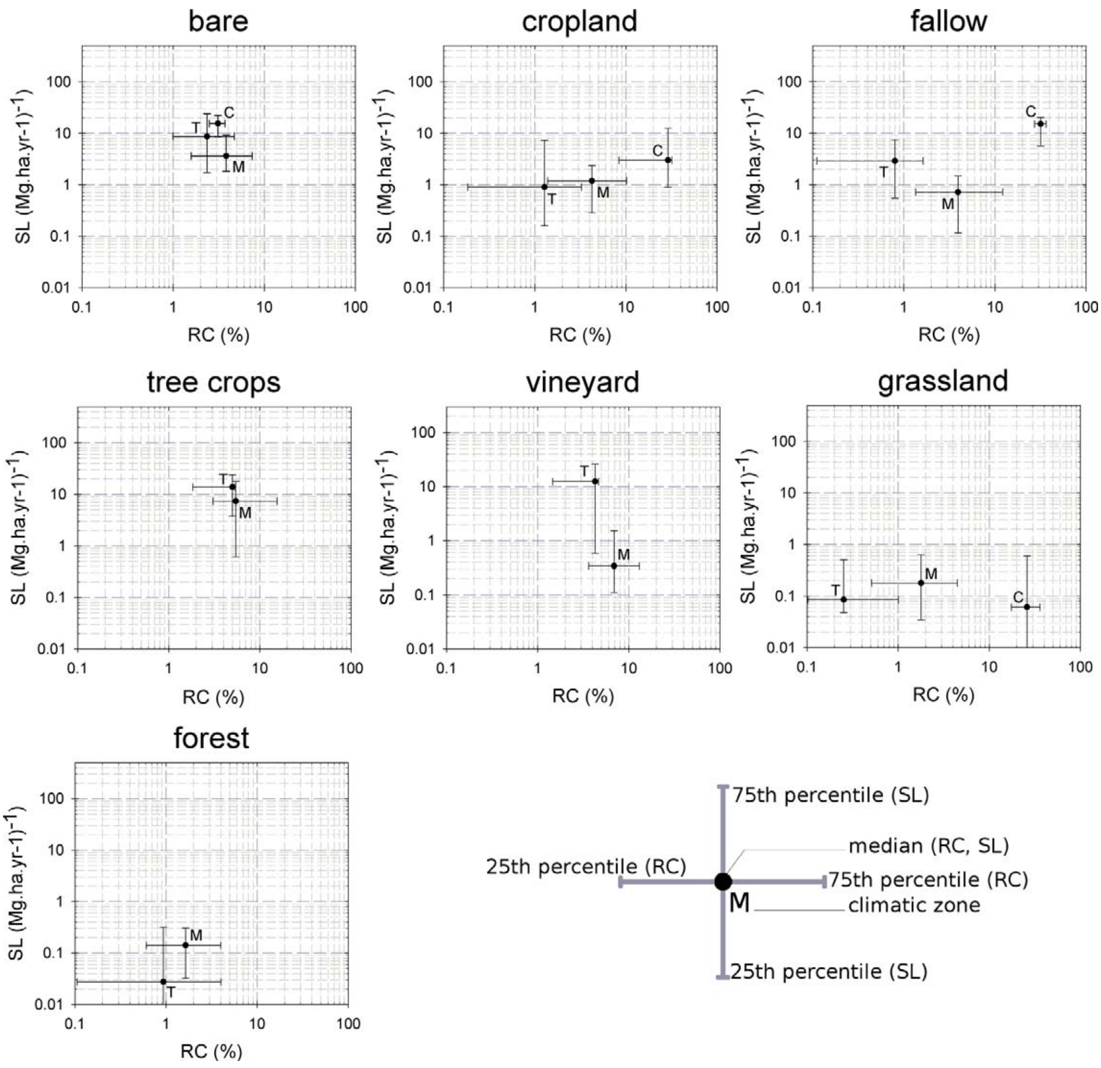

Figure 11. Relation between median annual runoff coefficient (RC) and median annual soil loss (SL) for all plots in Europe and the Mediterranean by land-use type and climatic zone, with indication of the 25th and 75th percentiles for R and SL. M = pan-Mediterranean, T = temperate, C = cold. For the number of plots (#PL) and number of plot-years (#PY), see Table 5, for the division in climatic zones, see Figure 1.

than in the other CZ, except the differences between the pan-Mediterranean and cold CZ for bare PL, and the difference between pan-Mediterranean and temperate CZ for tree crops. These non-significant differences in annual SL are likely due to insufficient data for bare plots in the cold CZ and tree crops in the temperate CZ. Median annual SL in the pan-Mediterranean zone is not smaller for cropland, grassland and forests. However, mean annual SL for all these land-use types is smaller in the pan-Mediterranean zone compared to the temperate zone, indicating that the highest annual SL on cropland occur more frequently in the temperate zone than in the pan-Mediterranean (Figure 11). Only

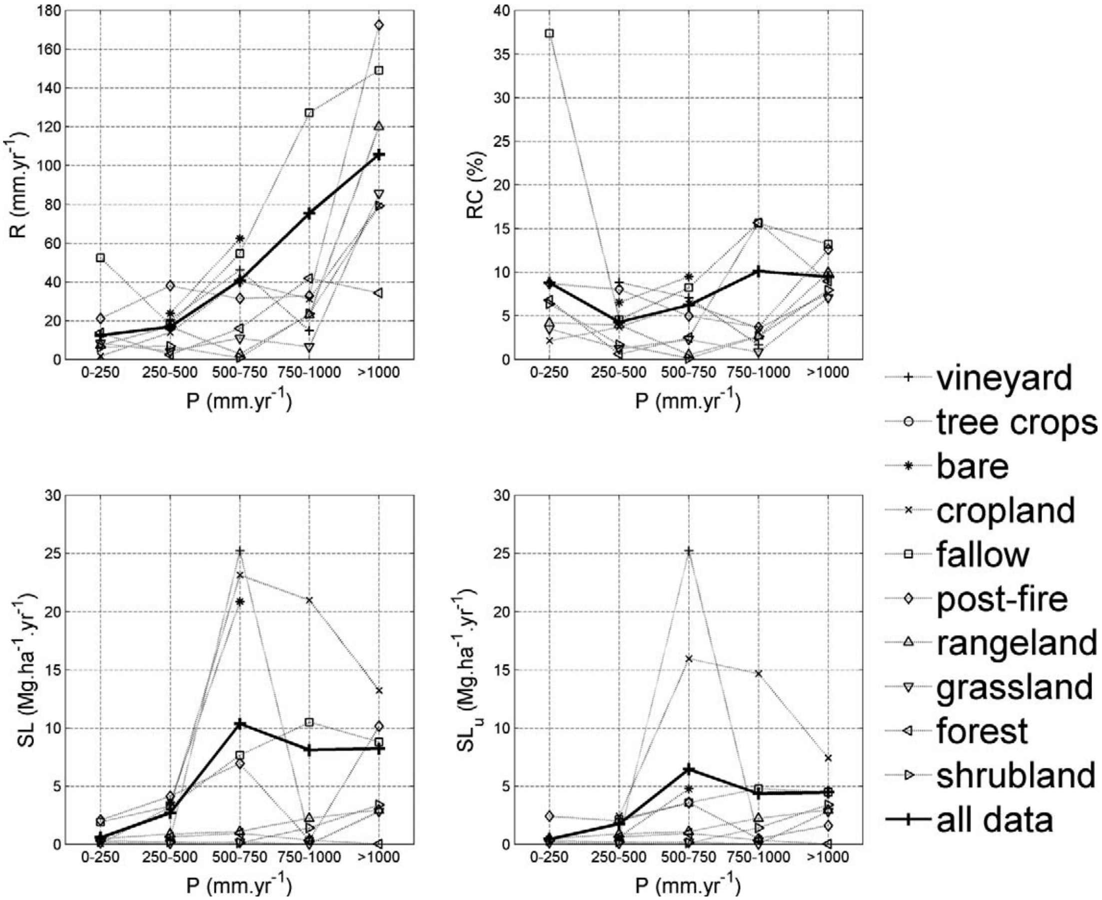

Figure 12. Weighted mean annual runoff (R), annual runoff coefficient (RC), annual soil loss (SL) and annual unit plot soil loss (SL$_u$) for each land-use type in Europe and the Mediterranean as a function of the annual precipitation (P) interval.

differences between the pan-Mediterranean and temperate CZ for cropland and between pan-Mediterranean and cold CZ for grassland were found to be significant.

With respect to annual RC, median annual RC is significantly higher in the cold CZ than in the other CZ for cropland, fallow and grassland. Also, mean annual RC is the highest in the cold CZ for all land-use types. For grassland, there is no significant difference in median annual SL between the different CZ, but differences in median annual RC between different CZ are significantly different, indicating that while grassland has consistently low annual SL rates throughout the study area, annual RC rates differ depending on CZ.

6 Effects of annual precipitation on annual runoff and soil loss for different land uses

Figure 12 displays the relation between P and the weighted mean annual R, RC, SL and SL$_u$ for the different land-use types. As all PL on construction sites fall within the 250–500 mm annual P-class, they were not included in this figure. Separate graphs displaying the annual R, RC and SL by precipitation class for the different land-use types are presented in

Figures 13a, 13b and 13c. It should be noted that for some land-use types only a few PL are available and hence some of the observed trends are uncertain. Nevertheless, clear trends can be observed. For all land-use types, annual R generally increases with increasing annual P (Figure 13a). For plots under cropland, there is already a substantial increase in annual R for 500–750 mm annual P, while for plots with a (semi-)natural vegetation cover, the most substantial increases in annual R occur in the 750–1000 mm and >1000 mm annual P classes. Application of the Kolmogorov-Smirnov test between subsequent precipitation classes indicated that the distribution of R data was only significantly different between the 250–500 mm annual P classes for cropland, fallow, post-fire forest and shrubland plots. For forest, also the difference between the 0–250 and 250–500 mm classes was significant. For annual RC, however, no clear general trend with P over all land-use types can be noted (Figure 13b).

With respect to annual SL (Figure 13c), there is a general trend towards higher annual SL with higher annual P in plots with crop cultivation (vineyard, tree crops, bare, cropland and fallow). Mean annual SL under bare conditions increases between 250–500 mm and 500–750 mm, but levels afterwards and even decreases between the 750–1000 mm and >1000 mm annual P classes. Similarly, annual SL in cropland generally increases with increasing annual P, but mean annual SL for the >1000 mm annual P class is higher than for the 750–1000 mm class. Annual SL increases gradually with increasing annual P for post-fire, rangeland and forest annual PL. For grassland, the highest annual SL are observed in the 500–750 mm class. For shrubland, annual SL first increases to a maximum in the 250–500 mm class, and then declines over the 500–750 mm and 750–1000 mm classes. Mean annual SL increases again between the 750–1000 and >1000 mm classes, but the latter class corresponds to only 3 PL so results are not conclusive. Significant differences in annual SL between subsequent P-classes were found between the 0-250mm and 250-500mm classes for shrubland and between the 250-500mm and 500-750mm classes for bare, cropland and shrubland plots. For cropland, also the 500–750 mm and 750–1000 mm classes were found to have significantly different distributions. Corrections for plot length and slope gradient resulted generally in annual SL_u rates that are lower than the original annual SL rates. Nevertheless, the trends observed in the graph depicting the relation between annual P and annual SL (Figure 13c) were found to persist. Correlating the Modified Fournier Index with annual R, RC and SL did not yield clearer trends than using annual P measured on the plots (Figure 14).

IV Discussion

1 How representative are the available plot runoff and soil loss data for Europe and the Mediterranean?

The assessment of annual R and annual SL rates based on the review of data measured on runoff and soil loss plots is inherently biased since runoff plot experiments are generally set up to answer specific research questions and not to be representative for the entire range of actual hillslope conditions (Auerswald et al., 2009; Cerdan et al., 2006; Vanmaercke et al., 2012). Many plot-measuring sites are located in areas that experience interrill and rill erosion. Furthermore, no plots are located in Iceland or in Scandinavia above 61 degrees latitude (Figure 1), probably due to logistic problems in cold environments and the low population density in these areas. A comparatively small number of runoff plots was found for northeastern Europe (Table 3), since many of these data have not been published in international journals and are not easily accessible. While even more plot data are likely existing, the database compiled in this study is currently the largest compilation of field-measured annual R and SL data at plot scale and for Europe and the Mediterranean region.

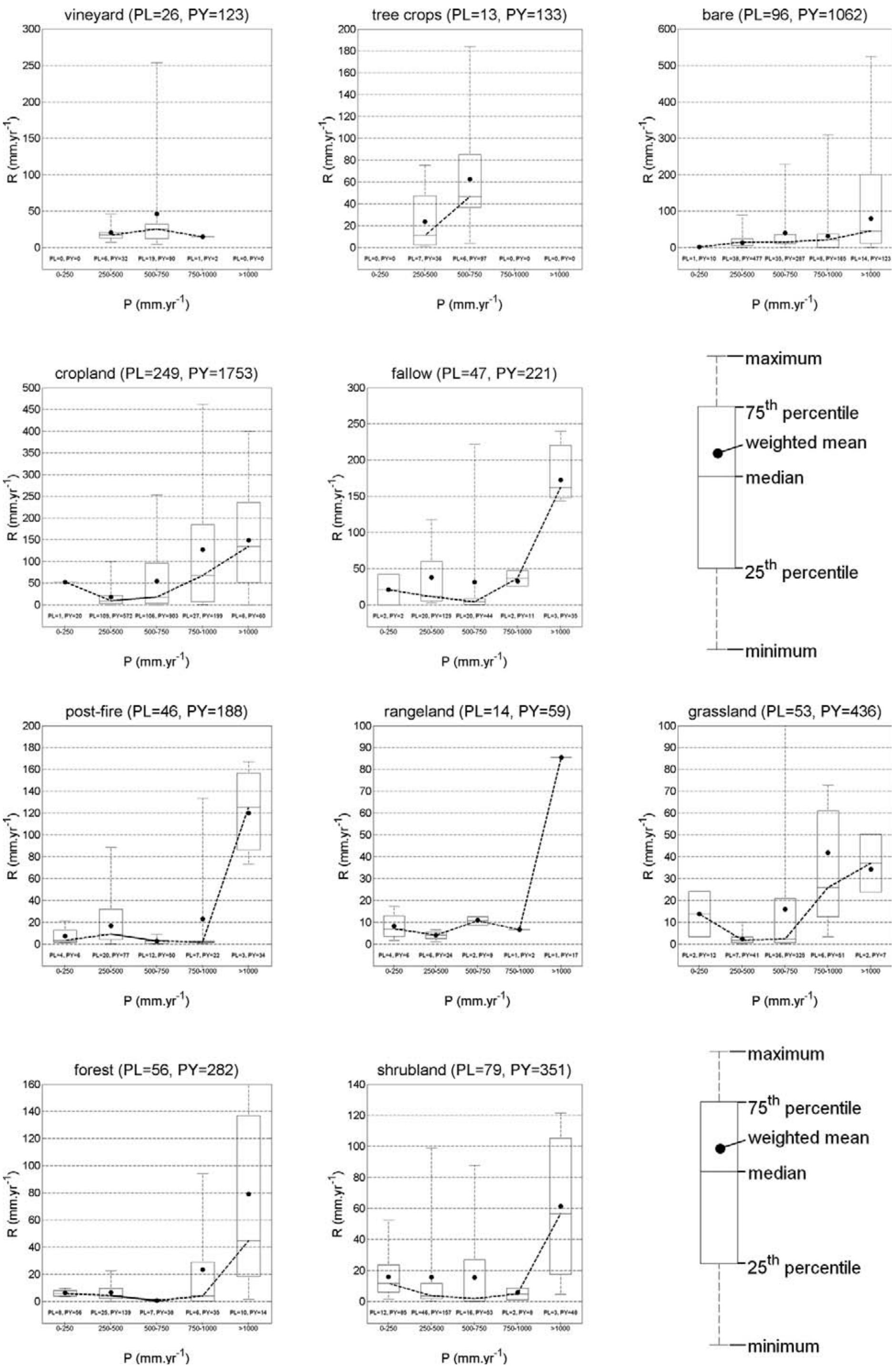

Figure 13a. Median trend, distribution and weighted mean of annual runoff (R) by annual precipitation (P) interval and land-use type in Europe and the Mediterranean. Significant differences (α=0.05) in R between subsequent P classes are indicated by full lines while insignificant differences are indicated by dashed lines. PL= number of plots, PY= number of plot-years.

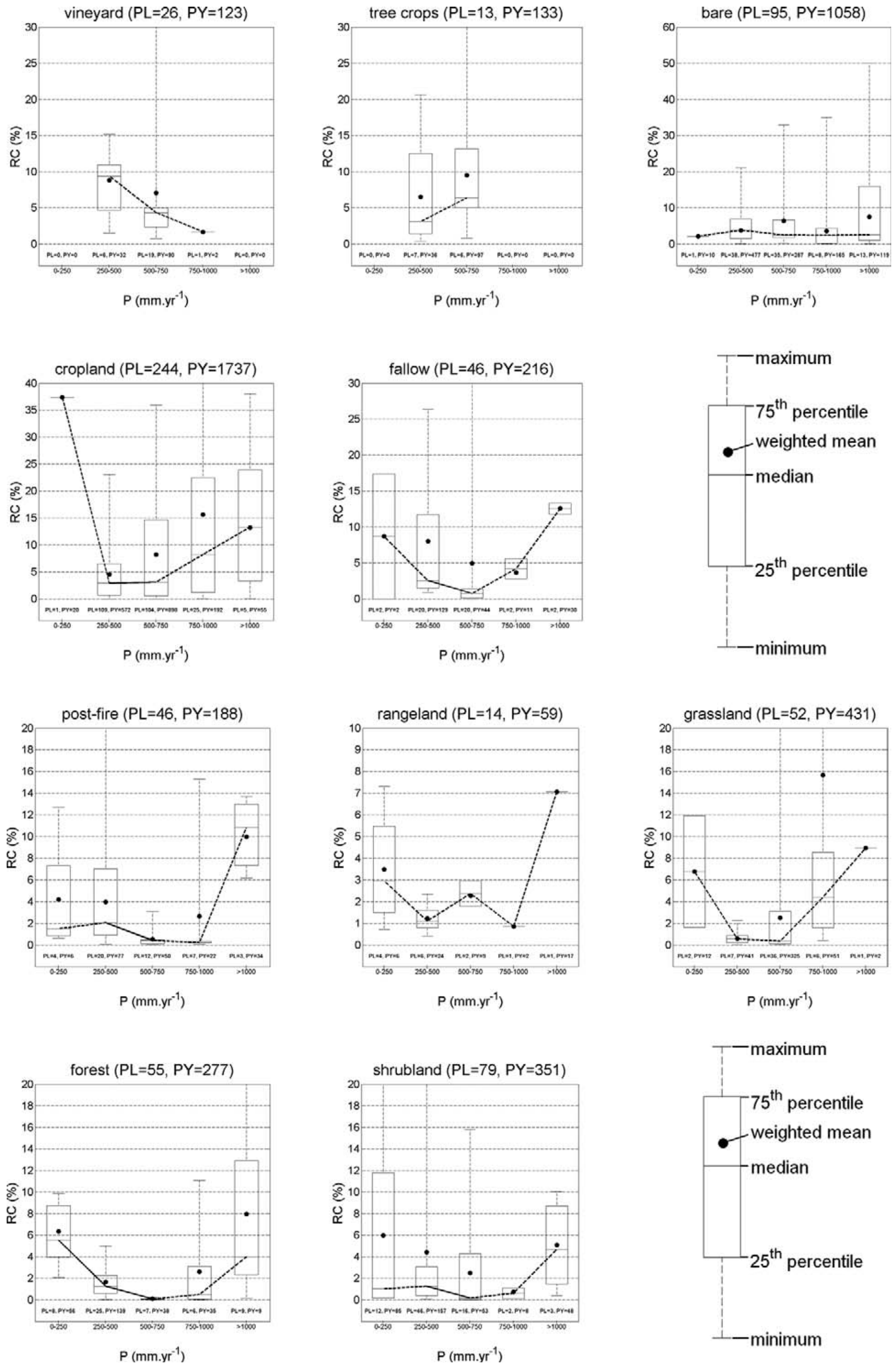

Figure 13b. Median trend, distribution and weighted mean annual of runoff coefficient (RC) by annual precipitation (P) interval and land-use type in Europe and the Mediterranean. Significant differences (α=0.05) in RC between subsequent P classes are indicated by full lines while insignificant differences are indicated by dashed lines. PL= number of plots, PY= number of plot-years.

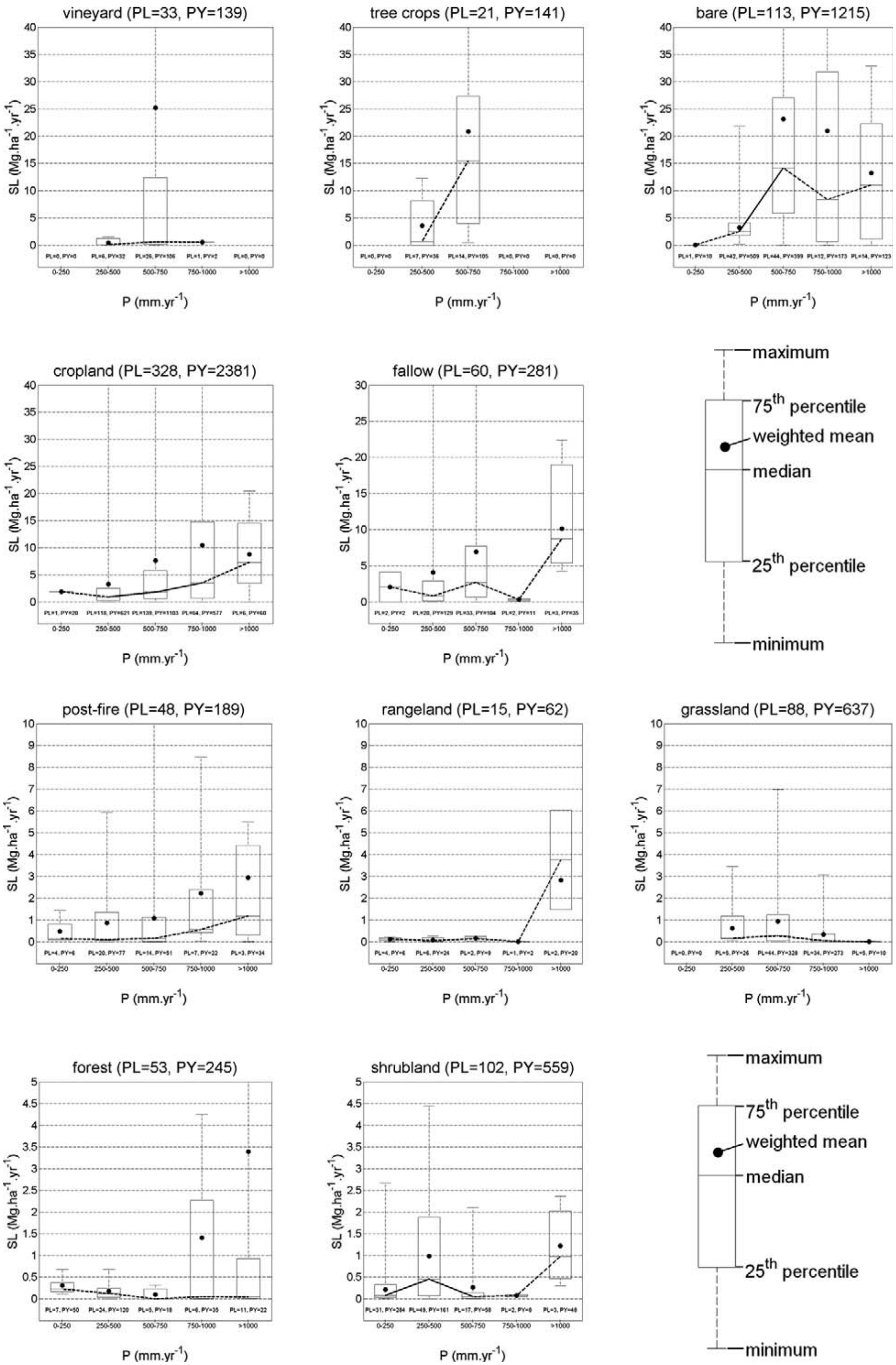
vineyard (PL=33, PY=139)
tree crops (PL=21, PY=141)
bare (PL=113, PY=1215)
cropland (PL=328, PY=2381)
fallow (PL=60, PY=281)
post-fire (PL=48, PY=189)
rangeland (PL=15, PY=62)
grassland (PL=88, PY=637)
forest (PL=53, PY=245)
shrubland (PL=102, PY=559)

Figure 13c. Median trend, distribution and weighted mean of annual soil loss (SL) by annual precipitation (P) interval and land-use type in Europe and the Mediterranean. Significant differences (α=0.05) in R between subsequent P classes are indicated by full lines while insignificant differences are indicated by dashed lines. PL= number of plots, PY= number of plot-years.

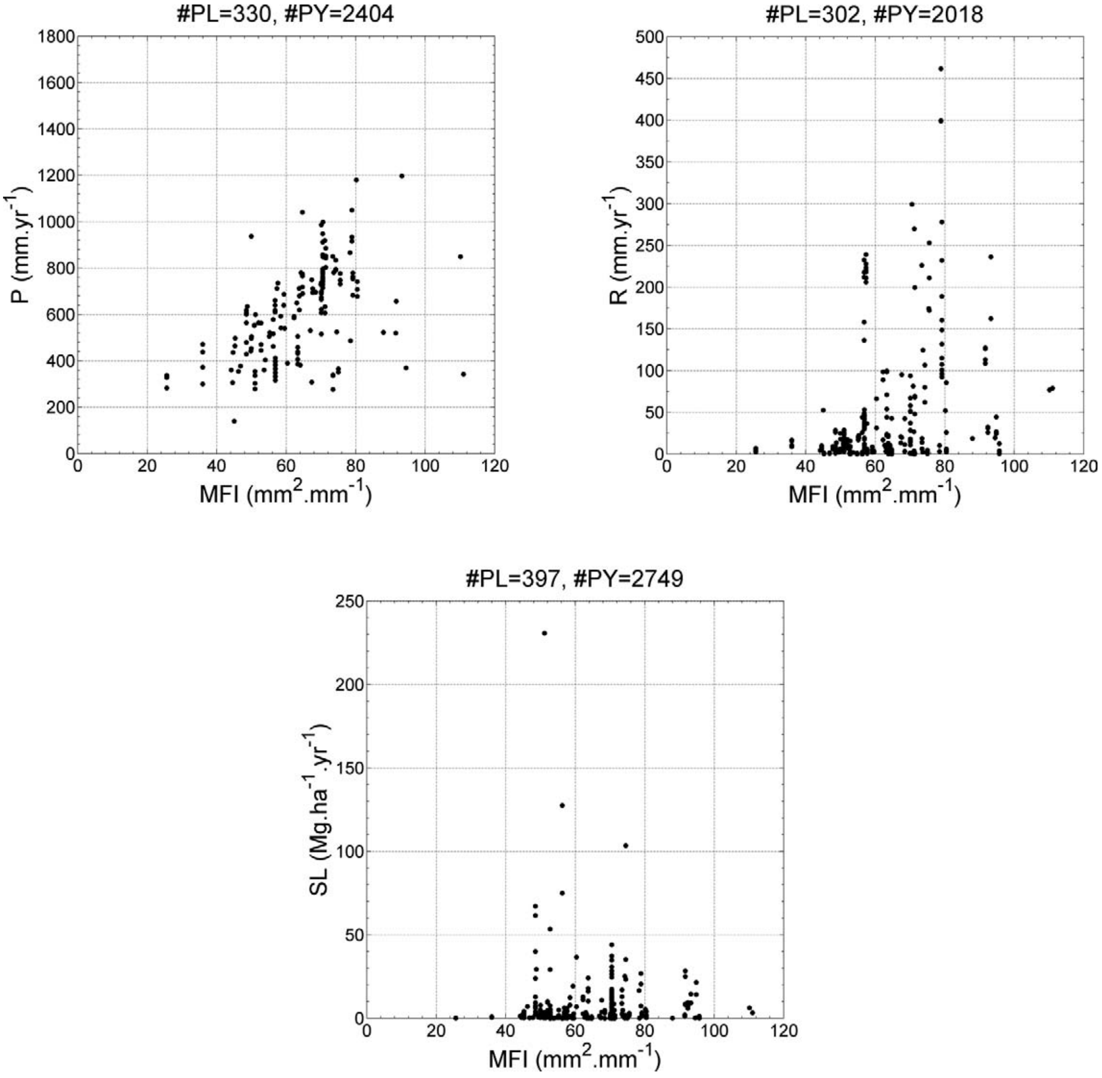

Figure 14. Relations between Modified Fournier Index (MFI) and annual precipitation (P), annual runoff (R) and annual soil loss (SL) for cropland plots in Europe and the Mediterranean

The relatively short measuring periods for the plots (mean: 6 yrs, median: 4 yrs) can be attributed to the relatively short duration of research or PhD projects during which most of the plots are established. This also means that it is difficult to assess temporal variability in R_a and SL_a on the longer term for a specific plot, which is nevertheless an important aspect for conservation planning (Bagarello et al., 2011). Figure 2 shows a clear decline of the number of plots in operation after 1996. This can be attributed to the fact that plot measurements are time- and labour-consuming and field-measured plot experiments are abandoned in favour of modelling studies, which have become more prevalent with increasing and cheaper computing power over the last 20–30 years (Merritt et al., 2003). A similar decline in catchment sediment yield studies was observed by Vanmaercke et al. (2011b), but was already starting between 1970 and 1980 when many large state-led monitoring schemes were abandoned. Most plot-scale studies are conducted by individual researchers however, and the number of publications on runoff and soil loss plots has not decreased in recent years (Figure 2). Moreover, recent publications review previously published data to assess erosion rates and variability under field conditions at national or regional scales (Table 1), to use these data in new spatial analyses (e.g. Cerdan et al., 2010) or to validate erosion models (e.g. Amore et al., 2004; Licciardello et al., 2009; Quinton, 1994; Tsara et al., 2005). Hence, there is an ongoing interest in field-measured annual R and SL data and a review and regular update of existing data sets offers opportunities to use these data in new analyses and thus to give added value to previously published studies (Baade and Rekolainen, 2006).

A large proportion of research has been carried out on bare and cropland plots (Table 5). Runoff and soil loss after wildfires have received considerable attention, despite annual R and SL rates still being low in comparison to those witnessed on some other land uses (Shakesby, 2011; Table 7). Permanent crops (tree crops and vineyards) have received more attention in plot studies in comparison to the areal percentage they represent in the CORINE land-cover map (Vanmaercke et al., 2012). Despite the relatively small area occupied by these land-use types, they are important contributors to total soil loss in Europe (Cerdan et al., 2010) and can be the dominant land-use type in certain regions. Furthermore, some of the highest annual RC (up to 40.2%) and SL rates (up to 151 $Mg.ha^{-1}.yr^{-1}$) recorded in the database occurred on permanent crops (i.e. vineyards and tree crops) (Figure 7, Table 7). The quantitative measurements currently available for these land-use types may still not be sufficient to make a comprehensive assessment of erosion risk in these land-use types (e.g. Gómez et al., 2008).

Also the distribution of plot lengths and slope gradients of the plots shows a research bias (Figure 4). Plots with a plot length between 20 and 30 m, i.e. close to the standard USLE plot (22.1 m; Renard et al., 1997), are by far the most frequent. Plot length is mainly determined by logistic limitations of the studies, and the relation to actual field slope lengths, for which very few data are available, is unknown. On the other hand, observed frequency distributions of the plot slope gradients for different land-use types (Figure 5) show both a difference between slope gradient distributions for different land-use types as they occur in the field as well as a research bias towards steeper slopes. This was demonstrated by Cerdan et al. (2006) who found that mean slope gradient of plots on grassland, forest and shrubland corresponded well to mean slope gradient for these land-use types on the reclassified CORINE land cover map, while mean slope gradients for arable, vineyards, orchard and post-fire plots were found to be steeper than the CORINE average. On the whole, the plots show a relatively steep slope gradient, with the majority of plots having a slope gradient above the 9% of the standard USLE plot (Figure 4). As was shown by Boardman (1998), careless extrapolation or generalization of these data can therefore lead to overestimations of annual SL rates. Therefore, the controlling environmental variables should always be accounted for when evaluating or extrapolating rates of annual R, RC and SL (Cerdan et al., 2010; de Vente et al., 2011). Hence, the rates of annual R and SL presented in this study may not be representative for the flat regions in Europe and the Mediterranean (Cerdan et al., 2010). Nevertheless, the extent of the database compiled in this study allows for the best representation of the relations between measured runoff, soil loss and annual precipitation for different land-use types currently available.

While the use of runoff and soil loss plots allows for a relatively easy assessment of annual runoff, runoff has received considerably less attention than soil loss in the literature as can be noted in the literature review (Table 1) and the number of plots and plot-years (Table 5). One of the problems underlying this discrepancy is the complex relationship between R and environmental variables (Wischmeier, 1966) and as a result also the relation between annual R and SL is less studied. Nevertheless, the assessment of annual R is an important part of many erosion models (Merritt et al., 2003) and hence a better understanding of runoff generation and runoff-soil loss relationships would contribute towards better erosion models (e.g. Kinnell and Risse, 1998). Runoff generation is also an important problem in itself, both on-site (e.g. loss of plant available water; Wallace, 2000) and off-site (e.g. flash floods). For instance, water is a key resource in the Mediterranean (Araus, 2004; Vanmaercke et al., 2011b) and annual RC are often higher than annual RC for comparable land uses in temperate regions, while annual SL rates tend to be lower in the pan-Mediterranean CZ than in the temperate CZ (Table 7, Figure 11), hence excessive runoff may be of more concern than soil loss.

2 Effects of plot length and slope gradient on annual runoff, runoff coefficient and soil loss

Annual SL on bare, cropland and tree crop plots are positively correlated to plot L-factor (Table 6). This finding concurs with results found by Cerdan et al. (2010). For these land-use types, also annual R and RC are positively correlated with plot length (Table 6). This can be attributed to the high connectivity along flow paths under these land-use types, allowing runoff to accumulate along the flow path over longer plot lengths and resulting in higher annual SL due to the increased detachment and transport capacity of the overland flow (Govers and Poesen, 1988; Prosser and Rustomji, 2000). A significant effect of plot S-factor on annual SL was only found for cropland and shrubland, although the correlations between the plot S-factor and annual SL are also relatively strong for bare plots and fallow plots (Table 6, $p = 0.06$).

With respect to climatic zone, Cerdan et al. (2010) found that for arable and bare plots the relation between LS-factor (equation 3) and annual SL was only significant for plot data collected outside the Mediterranean CZ and not for plots in the Mediterranean CZ, which was attributed to the higher surface rock fragment cover in the Mediterranean, especially on steeper slopes (Poesen et al., 1998). In this study, similar results are found for bare plots in the temperate CZ where the relation between the L-factor ($r_s = 0.62$, $p < 0.01$), S-factor ($r_s = 0.25$, $p = 0.03$) and LS-factor ($r_s = 0.44$, $p < 0.01$) was significant, while for plots in the pan-Mediterranean CZ none of these relations were significant. However, for cropland in both the temperate and pan-Mediterranean CZ significant relations between L-factor and annual SL ($r_s = 0.36$, $p < 0.01$ and $r_s = 0.20$, $p = 0.01$, respectively) and between LS-factor and annual SL ($r_s = 0.33$, $p < 0.01$ and $r_s = 0.17$, $p = 0.03$, respectively) were found. This could be due to the inclusion of more pan-Mediterranean cropland plots in the database as compared to the database used by Cerdan et al. (2010). By including more plots, the probability of including low-frequency, high-intensity events for which there is a significant topographic effect increases. Nevertheless the correlation coefficient between LS-factor and annual SL remains smaller for cropland plots in the pan-Mediterranean ($r_s = 0.17$, $p = 0.03$) than for cropland plots in the temperate zone ($r_s = 0.33$, $p < 0.01$).

For grassland, no significant correlations were found between the L-, S- or LS-factor and annual SL. This can be explained by the high root density of the grass, which reduces soil erodibility (De Baets et al., 2006). The correlation between plot length and R was significantly positive (Table 6) however, which may be explained by the fact that runoff is more likely to converge on longer slopes, and the effect of grass cover on annual R retention is often less pronounced and more variable than the effect on annual SL, as is shown by studies on the effectiveness of grass buffer strips (e.g. Blanco-Canqui et al., 2004) and grassed waterways (e.g. Fiener and Auerswald, 2003). Contra-intuitively, a significant negative relation was noted between slope gradient and both R and RC for grassland. This is probably due to the fact that grasslands in the northern regions often lie on gentle slopes but are very wet due to a clayey subsoil. These soils often need drainage (e.g. Øygarden, 1996; Øygarden et al., 1997; Turtola and Paajanen, 1995; Turtola et al., 2007; Warsta et al., 2009). For plots under forest and post-fire a significant negative correlation between plot length and annual R and annual RC was found (Table 6). This is probably related to the heterogeneity of soil cover and macropore distribution in these land-use types, meaning that as plot length increases, runoff is more likely to flow through patches with increased roughness or infiltration capacity. For shrubland, a significant negative correlation between slope gradient and annual R and RC is observed, while the correlation between the S-factor and annual SL is positive (Table 6). An explanation for this can be offered by the reduced tendency in surface sealing of bare patches with steeper slopes (Poesen, 1984, 1986), reducing runoff but increasing splash erosion (Bradford et al., 1987). Nevertheless, plots under shrubland are characterized by a high spatial variability at plot scale and hence the establishment of relations between plot length and slope gradient and annual R, RC and SL is difficult (Cammeraat, 2002).

No significant effect of plot length on annual R or RC was found for vineyards, but the L-factor was significantly correlated with annual SL (Table 6). This is mainly due to the fact that high annual R and RC already occur on short plots, resulting in high runoff rates independent of plot length. For tree crops, which are also considered as a land-use type with permanent cultivation, a positive relation between plot length and annual R and RC was found. This difference with vineyards may be due to differences in soil types or the generally higher vegetation cover associated with tree crops, though no data were available to check these hypotheses. As was already indicated by Cerdan et al. (2010), our results illustrate that the relations between plot length and/or slope gradient and annual SL depend on the considered land use. In addition, our analyses show that also relations of plot length and slope gradient with R and RC depend on land-use type. Plot length and slope gradient may affect annual R and RC differently than they affect annual SL. Furthermore, a further subdivision of the major land-use types analysed by Cerdan et al. (2010) (bare, arable, permanent cultivation and permanent vegetation) reveals that also within these groups, relations between topographic factors and annual SL may vary. For instance, in the permanent vegetation group, no significant relation between LS-factor and annual SL was found for forest, grassland and rangeland plots, but there was a significant relationship between the LS-factor and annual SL for shrubland (Table 6).

3 Frequency distributions and relationships between annual runoff and soil loss for various land uses

Previous studies (e.g. Cerdan et al., 2010; Kosmas et al., 1997) showed the importance of vegetation cover as an important determinant of annual SL on a (sub)continental scale. This study further confirms this, as significant differences between the distributions of SL data were mostly found between land-use types with cultivation and land-use types with semi-natural vegetation. Construction sites have the highest observed annual SL rates (Figure 7, Table 7), although the limited amount of available data (Table 5) does not allow clear conclusions on the frequency distribution of the observed values. Bare plots and plots with crop cultivation (cropland, vineyards and tree crops) form a second cluster with high R, RC and SL rates (Figures 7 and 8). All these land-use types are characterized by severe anthropogenic disturbance (construction sites and bare PL) or intensive tillage of the soil for agriculture (cropland, tree crops and vineyards). On these plots, annual SL regularly exceeds tolerable soil loss rates (T-values) of 5–12 $Mg.ha^{-1}.yr^{-1}$ (Montgomery, 2007). The mean annual SL rate of 11.6 $Mg.ha^{-1}.yr^{-1}$ for tree crops in the pan-Mediterranean zone (Table 7) was found to be much higher than reported in previous studies such as Cerdan et al. (2010) who found an average annual SL rate for orchards in the Mediterranean of 1.67 $Mg.ha^{-1}.yr^{-1}$ and Fleskens and Stroosnijder who concluded that annual SL in olive orchards is unlikely to exceed 10 $Mg.ha^{-1}.yr^{-1}$. Annual SL in olive orchards is often the result of infrequent high-intensity rain events and depends strongly on spatial scale and land management (Gómez et al. 2008). Depending on which data are included in the analysis and the way the available data are analysed they may be deemed low (Fleskens and Stroosnijder, 2007) or frequently in excess of tolerable rates (Gómez et al., 2008). The use of a larger database (20 PL, corresponding to 80 PY) in this study indicates that annual SL in tree crops in the pan-Mediterranean zone can frequently exceed tolerable levels.

Vineyards show a high coefficient of variation for SL_a in addition to a high average SL_a value (Table 7). This is attributed to the high erosion susceptibility of this land-use type after vineyard establishment. Wicherek (1991) reports a sharp decline in soil losses over the first three years after vineyard establishment in the Aisne region, northern France (57.3, 28.7 and 1.4 $Mg.ha^{-1}.yr^{-1}$, respectively). Tropeano (1984) also reports the highest soil loss (8.3 $Mg.ha^{-1}.yr^{-1}$) to occur in the first year after vineyard establishment in the Piemonte region, northwestern Italy, which was reduced to 1.2 $Mg.ha^{-1}.yr^{-1}$ in the following year. This is also illustrated by Engels (personal communication 2009) who notes that soil loss from an old undisturbed vineyard in the Moselle region, western Germany, is considerably lower (0.5 $Mg.ha^{-1}.yr^{-1}$) than that from an adjacent vineyard where vines were removed and roots destroyed (4.4 $Mg.ha^{-1}.yr^{-1}$). Nevertheless, no clear trends in annual SL between 8 and 17 years after vineyard establishment were found for vineyards in the Douro region, northern Portugal (de Figueiredo, personal communication 2010; de Figueiredo and Gonçalves Ferreira, 1993; de Figueiredo and Poesen, 1998). Brenot et al. (2006) measured soil loss by vine stock unearthing (i.e. over the complete period since vineyard establishment) for vineyards of different ages (10–54 years) in Burgundy, France, but no trend in annual SL with respect to vineyard age is observed. In contrast to the high SL_a observed for several vineyards, some vineyards established on very steep slopes (c. 45%) with very stony soils show comparatively very low mean SL_a values in the Douro region, Portugal (0.2–0.5 $Mg.ha^{-1}.yr^{-1}$: de Figueiredo and Gonçalves Ferreira, 1993; de Figueiredo and Poesen, 1998) or the Moselle region (0.02–0.5 $Mg.ha^{-1}.yr^{-1}$: Richter, 1980). Although the number of available plots on which SL data were collected directly after vineyard (re)planting ($n = 1$) or removal of the vines ($n = 1$) is limited, these results indicate that vineyards are in general very vulnerable to soil loss after establishment or periodical replanting of the vines due to the often intense soil disturbances (Borselli et al., 2006). After a number of years, annual SL in vineyards often decreases to relatively low rates as is shown by the median annual SL of 0.9 $Mg.ha^{-1}.yr^{-1}$ for the whole of Europe and the Mediterranean ($n = 39$, Table 7). This is attributed to the stony soils often associated with vineyards which develop an erosion pavement with a high rock fragment cover which drastically reduces SL (Poesen et al., 1994).

Land-use types with a (semi-)natural vegetation generally have mean annual SL values well below the T-value, illustrating the dominant control of vegetation cover over annual SL (Montgomery, 2007). However, SL rates up to 7 $\mathrm{Mg.ha^{-1}.yr^{-1}}$ can be observed on all land-use types and differences between land-use types are mainly situated in the frequency of occurrence for high annual SL values (i.e. above 10 $\mathrm{Mg.ha^{-1}.yr^{-1}}$) (Figure 7). Scaling of annual SL values to unit plot soil loss rates results generally in somewhat lower annual SL_u rates (Figure 6), but does not change the differences between different land-use types observed above (Figure 7, Table 7). Hence, while plot length and slope gradient may have an effect on annual SL values, they cannot fully account for the differences between different land-use types.

The distribution of annual R and RC values follows the same pattern as annual SL, with land-use types with a (semi-) natural vegetation cover having generally lower annual R and RC rates (Figure 7). However, fewer significant differences are observed between different land-use types combinations than for annual SL. There is a larger overlap between the annual R and RC data distributions (Figure 7) which indicates that the effect land-use types have on annual SL is more pronounced than they are on annual R and RC. No standard exists for tolerable annual R and RC levels, but excessive runoff also has several negative off-site effects such as gully formation (Poesen et al., 2006) and flooding (García-Ruiz et al., 2010).

With respect to the relations between annual R/RC and SL/SL_u, the small differences between r^2 values obtained for weighted and unweighted regressions (Table 8) can be explained by the distribution of the number of plot-years since a large part of the number of plots corresponds to a low number of plot-years and hence has similar weights (Figure 3). The generally better correlations between annual R and SL than between annual RC and SL (Table 8) can be explained by the fact that mainly the total runoff volume, rather than the runoff coefficient, determines the erosive power and transport capacity of the overland flow. Nevertheless, the inclusion of differences in annual precipitation makes it easier to compare RC rates between different plots. Hence, both annual R and RC are important variables to consider. The general trend in the relation between annual R and SL is that (semi-)natural land uses show annual SL rates of up to one order of magnitude less than SL values for land-use types with crop cultivation for the same annual R rate (Figure 9b). This is not the case for tree crops, however, where the increase in annual SL with increasing R is much stronger than for other land-use types (Figure 9a). However, this trend should be interpreted with caution as it is based on only 13 PL. For shrubland, clusters of data that correspond to individual plot-measuring sites show a good correlation between annual R and SL (Figure 9a), while the global regression is affected by more scatter in the data, which is most likely determined by local environmental factors that differ from plot site to site. Summer crops like maize, potatoes and sugar beet were found to result in R and SL rates which are among the highest for cropland (Figure 10).

4 Effects of land use on runoff coefficient and soil loss for different climatic zones

The higher annual RC observed in the cold zone may be attributed to the combination of snowmelt and a frozen soil in spring (e.g. Alström and Bergman, 1990; Wade and Kirkbride, 1998) and the generally lower annual evapotranspiration rate at high latitudes (Weiß and Menzel, 2008). Furthermore, annual R and RC rates in the pan-Mediterranean zone are generally higher than in the temperate CZ (Table 7, Figure 11). This is likely due to the combination of soil properties, the often smaller and more discontinuous natural vegetation cover in the pan-Mediterranean region, and the seasonality of the rainfall with a large fraction of the annual rainfall concentrated in a few important events during a short winter season (Altava-Ortiz et al., 2011; Mehta and Yang, 2008).

Nevertheless, these higher annual R and RC rates in the pan-Mediterranean do not result in high annual SL (Figure 11, Table 7). Smaller annual SL rates in the Mediterranean were also observed by Cerdan et al. (2010) and can be explained by the generally higher rock fragment cover in Mediterranean soils which is known to reduce soil loss rates (Poesen and Lavee, 1994; Poesen et al., 1994). Especially for vineyards, which are often located on stony soils, annual SL rates in the pan-Mediterranean CZ are much smaller than those in the temperate CZ (Figure 11). Nevertheless, Sanchis et al. (2008) observed that also for soils with a low rock fragment content (<10% content by mass) soil erodibility was lower in the Mediterranean. This is attributed to a dominance of clay rich soils in arable land in the Mediterranean and the associated low soil erodibility of these soils (Torri et al., 1997). Furthermore, very erodible soil types like loess-derived soils occur almost exclusively in the temperate CZ. Hence, it should be noted that differences between CZ include more than just a climatic effect as CZ is also a proxy for particular soil properties which affect annual R and SL like soil susceptibility to cracking. Apart from differences between precipitation and soil characteristics between the temperate and pan-Mediterranean CZ, differences in conventional land management like tillage frequency and depth in cropland may also account for part of the observed variability. Furthermore, for grassland and forest, there is no significant difference between median SL rates for plots in the pan-Mediterranean zone and plots in the temperate CZ, which again indicates the important effect of vegetation in controlling annual SL.

5 Effects of annual precipitation on annual runoff and soil loss for different land-use types

For all land uses, there is a consistent trend towards higher annual R with increasing annual P which is more pronounced for land-use types with crop cultivation than land-use types with (semi-) natural vegetation (Figure 13a). For all land-use types with crop cultivation, except for vineyards, there is a trend towards increasing annual RC with increasing precipitation, indicating that as rainfall increases there is a larger percentage of excess rainfall (Figure 13b). This may be related to distribution of rainfall patterns throughout the year, with areas with high annual P generally having a more uniform precipitation distribution throughout the year. This causes seasonal saturation of the soil and faster runoff formation (Ponce and Hawkins, 1996).

For annual SL, there is also an increase in annual SL rates with increasing annual P for most land-use types (Figure 13c) but, unlike annual R, the increase is more gradual. For bare and cropland plots, there is even a decrease in annual SL in the highest annual P classes (>750 mm for bare and >1000 mm for cropland). This is likely due to variations in seasonality of the rainfall. The relatively uniform rainfall distribution in regions with high annual P makes these regions less prone to unfrequent extreme rainfall events in periods of the year when the soil is vulnerable to erosion (Edwards and Owens, 1991; Larson et al., 1997).

Shrubland is generally limited to the pan-Mediterranean region and a maximum in SL is observed in the 250–500 mm annual P class (Figure 13c), and both the differences between the lower and higher precipitation class are significant. A similar trend was noted by Kosmas et al. (1997) who attributed this to an initial increase in annual SL with increasing annual P as the erosion potential of the rain also increases, combined with insufficient vegetation cover in drylands. However, as annual

P futher increases the vegetation cover also increases, effectively reducing annual SL for higher annual P. This is similar to the mechanism and trend for sediment yield proposed by Langbein and Schumm (1958). However, this trend is not observed for other land-use types, as vegetation cover in shrubland can be expected to be the most sensitive to changes in annual P. Contrary to the study by Kosmas et al. (1997), this maximum is not noticeable for annual R, which may indicate that, at a Mediterranean-wide scale, runoff volume is more determined by other environmental characteristics than vegetation cover, such as surface sealing and rock fragment cover.

In general, significant differences in the frequency distribution of both annual R and annual SL were mostly found between the 250–500 mm and 500–750 mm P classes (Figures 13a and 13c). This may indicate that significant changes in the rainfall-runoff and rainfall-soil loss relations occur at around these annual P values which are likely related to changes in rainfall regime and distribution throughout the year. Hence, comparison of annual R and SL rates with measures that take rainfall distribution throughout the year into account could improve the analysis. Nevertheless, the use of MFI as an indicator of climatic effect on annual R, RC and SL did not yield better correlations than the use of annual P (Figure 14). The MFI values used in this analysis represent long-term average (i.e. climatological) values which may not be representative for the specific years of plot measurements. This explains why low annual R and SL rates occur regularly in zones with high MFI values. Furthermore, the relation between MFI and annual P (Figure 14) and MFI and EI30 values (Torri et al., 2006) is not straightforward.

VI Conclusions

While a decrease in the number of studies using runoff and soil loss plots under natural rainfall has occurred since the mid-1990s in Europe and the Mediterranean, there is still an interest in plot data. Recently, several studies have assessed the erosion problem by reviewing existing soil loss data from plots and by using these data in empirical studies or erosion model validations. Many of these studies investigated soil loss rates in relation to land use, topography and soil properties. However, plot-scale runoff has been largely neglected in these studies and the relation between runoff and soil loss has not been reviewed on a scale covering Europe and the Mediterranean. Nevertheless, runoff estimation and its relation to soil loss are important parts of many erosion models. On a (sub)continental scale also climatological differences are often not taken into account in overview studies. To address these issues, the largest data set of runoff and soil loss plot data for Europe and the Mediterranean region was compiled in this study, which includes for the first time both annual runoff and annual runoff coefficients at the continental scale. In general, soil loss studies using runoff plots are mainly focused on bare plots and cropland and fewer data are available for construction sites, tree crops and vineyards, in spite of the high soil losses that may be associated with these land-use types. Variation in annual runoff and soil loss rates observed on the plots ranges over several orders of magnitude. While land-use types with crop cultivation (cropland, fallow, tree crops and vineyards) have higher mean soil loss rates than land-use types under (semi-)natural vegetation (grassland, rangeland, shrubland, forest and post-fire), there are still large variations within each of these land-use types, which can only be partly accounted for by topographic (i.e. plot length and slope gradient) differences. Annual runoff rates follow the same pattern as annual soil loss rates, but differences between land uses are less clear. The generally good relations between annual runoff and annual soil loss illustrate the key importance of the relation between runoff and soil loss for a good assessment of soil loss rates. Further quantitative analysis of this relation may also contribute significantly to improve predictions in erosion models. Furthermore, the relation between annual runoff and soil loss also depends on climate, with comparatively high runoff coefficients in cold climates and lower soil losses in the pan-Mediterranean region. This indicates that runoff-soil loss relations may show important regional variations. Apart from the importance of runoff as a causal factor of soil loss, runoff in itself is associated with several problems such as flooding and plant-available water. Techniques specifically aimed at reducing runoff and runoff coefficients can contribute to a more efficient use of rainwater on-site to increase food production, especially in drier regions like the Mediterranean. As expected, annual rainfall was found to be related to annual runoff and soil loss, and the vegetation feedback effect for shrubland proposed by Kosmas et al. (1997) was also observed on a Mediterranean-wide scale for soil loss, but not for runoff. Nevertheless, a large part of the variation in runoff and soil loss rates remains unexplained and better relations between annual precipitation and runoff and soil loss can likely be obtained by accounting for rainfall erosivity, but use of a Modified Fournier Index did not yield better results than the use of the annual precipitation measured on the plots. Hence there are still possibilities to expand the research to better account for rainfall erosivity. Further research may also focus on the effects of several important soil characteristics (e.g. texture, organic matter content) and a more detailed analysis of several relations for which general trends were established in this study (e.g. the relation between annual runoff and plot length and plot slope gradient, the relation between annual runoff and soil loss). In conclusion, this meta-analysis of field plot data for Europe and the Mediterranean allows a quick assessment of the impact of land-use change scenarios on annual runoff, runoff coefficient and soil loss on a continental scale.

Appendix: List of abbreviations and symbols

Abbreviation	Full name	Unit
(#)PL	number of plots	#
(#)PY	number of plot-years	plot-yr
CZ	climatic zone	–
L_{PL}	plot length factor	dimensionless
LS_{PL}	plot LS-factor	dimensionless
MP	measuring period	yrs
MFI	Modified Fournier Index	$mm^2.mm^{-1}$
NA	not available	–
P	annual precipitation	$mm.yr^{-1}$
R	annual runoff	$mm.yr^{-1}$
RC	annual runoff coefficient	%
r_s	Spearman's rank correlation coefficient	–
SL	annual soil loss	$Mg.ha^{-1}.yr^{-1}$
SL_u	annual unit plot soil loss	$Mg.ha^{-1}.yr^{-1}$
S_{PL}	plot slope gradient factor	dimensionless
λ	plot length	m
θ	plot slope angle	°

Land-use types:

Abbreviation	Full name
Ba	bare
Fa	fallow
Cr	cropland
Tc	tree crops
Vi	vineyards
Gr	grassland
Ra	rangeland
Fo	forest
Sh	shrubland
Pf	post-fire
Cs	construction sites

Climatic zones:

Abbreviation	Full name
M	pan-Mediterranean
T	temperate
C	cold

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