



RESEARCH ARTICLE

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Annual water, sediment, nutrient, and organic carbon fluxes in river basins: A global meta-analysis as a function of scale

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Key Points:

- Runoff coefficients tend to increase with spatial scale
- Sediments, organic carbon, and nutrient exports tend to decrease with spatial scale
- Climate is the most important driver of the erosion variables

Supporting Information:

- Supporting Information S1
- Data Set S1

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Abstract Process controls on water, sediment, nutrient, and organic carbon exports from the landscape through runoff are not fully understood. This paper provides analyses from 446 sites worldwide to evaluate the impact of environmental factors (MAP and MAT: mean annual precipitation and temperature; CLAY and BD: soil clay content and bulk density; S: slope gradient; LU: land use) on annual exports (R_C : runoff coefficients; SL : sediment loads; TOC_L : organic carbon losses; TN_L : nitrogen losses; TP_L : phosphorus losses) from different spatial scales. R_C was found to increase, on average, from 18% at local scale (in headwaters), 25% at microcatchment and subcatchment scale (midreaches) to 41% at catchment scale (lower reaches of river basins) in response to multiple factors. SL increased from microplots ($468 \text{ g m}^{-2} \text{ yr}^{-1}$) to plots ($901 \text{ g m}^{-2} \text{ yr}^{-1}$), accompanied by decreasing TOC_L and TN_L . Climate was a major control masking the effects of other factors. For example, R_C , SL , TOC_L , TN_L , and TP_L tended to increase with MAP at all spatial scales. These variables, however, decreased with MAT. The impact of CLAY, BD, LU, and S on erosion variables was largely confined to the hillslope scale, where R_C , SL , and TOC_L decreased with CLAY, while TN_L and TP_L increased. The results contribute to better understanding of water, nutrient, and carbon cycles in terrestrial ecosystems and should inform river basin modeling and ecosystem management. The important role of spatial climate variability points to a need for comparative research in specific environments at nested spatiotemporal scales.

1. Introduction

Sustainable management of river basins requires a variety of tools that can generate predictions of fluxes and pathways of runoff, soil, and nutrient losses over ranges of environments, time, and spatial scales. Such tools are critical in the present and future as the world grapples with issues of climate change, land degradation, water scarcity, and river siltation. In particular, accelerated soil erosion by water has become an enormous threat to humanity and natural ecosystem functioning due to loss of the productive topsoil, together with its constituent nutrients and organic carbon [Chaplot, 2007]. High levels of pollutants linked to soil erosion have already severely degraded some aquatic ecosystems with subsequent impairment of water for domestic, industrial, agricultural, and recreational uses [Chapman, 1996]. Despite the advances in hydrological, soil erosion, organic carbon (OC), and nutrient modeling in recent years, prediction at river basin level remains uncertain [Makela et al., 2000; Beven, 2001; Gerten et al., 2004; Kovacs et al., 2012]. The large uncertainties in modeling are due to poor data quality, inability of models to reproduce all processes involved in the movement of water and sediments, and the difficulties in linking these with environmental conditions [De Vente and Poesen, 2005; Stehr et al., 2008; Duvert et al., 2012; Blöschl et al., 2013]. The processes are dependent on spatiotemporal scales under varying environmental conditions as determined, for instance, by climate, relief, soil type, land management, and land cover.

Soil erosion is primarily driven by lateral movement of water in the landscape involving three main processes: soil particle detachment, transportation, and sedimentation [Kinnell, 2008]. Soil particle detachment in nonchannelized flow systems is mainly caused by raindrop impact under intense rainfall. The loose soil is transported via splash and/or sheet wash. Splash and sheet erosion often occur simultaneously on hillslopes but their relative importance varies spatially and temporally [Chaplot and Le Bissonnais, 2000; Cammeraat,

2004] depending on soil particle size and other factors such as slope gradient [Cerdan *et al.*, 2004; Chaplot *et al.*, 2007]. Splash erosion is a localized process where translocated soil materials do not move far from their points of origin [Legu  dois *et al.*, 2005], while sheet erosion or overland flow erosion involves movement of soil particles over greater distances [Ghahramani *et al.*, 2011]. Sheet erosion requires longer slopes than splash to dominate. It is more effective in sediment transport than splash because it develops from higher-intensity and longer duration rainfall events [Kinnell, 2008]. When the overland flow energy falls below critical levels, due to loss of slope gradient and/or increasing soil cover, sedimentation will occur.

Soil erosion processes are influenced by many factors which make their assessments and linkage to drainage basin yields difficult. Many studies have identified a spatial-scale dependency of hillslope runoff and soil erosion [e.g., Lal, 1997; Van de Giesen *et al.*, 2000], which is often attributed to the variability of infiltration [Wilcox *et al.*, 1997] and rainfall intensity [Viglione *et al.*, 2010]. Beyond the hillslopes, variability of rainstorm characteristics with time is rarely considered. Studies have demonstrated that runoff and sediment yield generally decline with catchment size [Walling, 1983; Correll *et al.*, 1992; Deelstra *et al.*, 2009; Deasy *et al.*, 2011]. However, the rate of decline varies with basin [Walling, 1983] and scientists and practitioners have largely relied on calibrations to minimize uncertainties in applying the sediment delivery ratio concept. This concept is, however, giving way to methods that encompass hydrologic synthesis across process, places, and scales [Bl  schl, 2006], such as the multiple-nested-scale approach. Multiple-nested catchments have already been applied to identify the sources, pathways, and fate of runoff, sediments, organic carbon (OC), and nutrients in selected environments [Le Bissonnais *et al.*, 1998; Cerdan *et al.*, 2004; McGlynn *et al.*, 2004; Rumpel *et al.*, 2006; Mayor *et al.*, 2011; Orchard *et al.*, 2013]. However, results from the studies have largely been inconsistent. For example, Le Bissonnais *et al.* [1998] demonstrated, over 2 years in northern France, that runoff coefficients (R_C), sediment concentrations (SC), and losses (SL) tend to increase before decreasing when moving from point to large catchment scales. However, Cerdan *et al.* [2004] and Mayor *et al.* [2011] observed continuous decline of the same variables with landscape area. Goodrich *et al.* [1997] obtained decreasing R_C in the arid Walnut Gulch of Arizona, USA. In contrast, McGlynn *et al.* [2004] reported increasing R_C from plot to catchment scale in the humid and steep slopes of Maimai catchment, New Zealand. They cited rainstorm intensity as the major driver of the pattern because the two storms monitored were of high intensity and rainfall amounts. Climate appears to be an important controlling factor of the spatial and temporal-scale effect on the erosion variables. There is also much debate on the impacts of R_C and SL on OC and nutrient erosion as the contributing area increases. In the case of OC, Rumpel *et al.* [2006] observed, during a study in Laos, a reduction in sediment OC enrichment with increasing contributing area, which they attributed to oxidation of the OC within catchments to release CO_2 gas.

While the multiple-nested-scale approach has shown potential to detect and quantify relative contributions of different erosion processes at different spatiotemporal scales, the approach has so far been used in few isolated locations with a bias toward assessing the impact of relief. There is, therefore, a need to exploit this approach in quantifying the impacts of other environmental factors on the dynamics of water, sediments, organic carbon, and nutrient fluxes in river basins on a global level. This paper provides a meta-analysis of published data from 86 ISI journal papers representing 446 sites from around the world. Meta-analyses, as instruments of synthesis, are more commonly used in other fields than hydrology, such as medical sciences [e.g., Moher *et al.*, 2009], but it was believed possible to obtain generalizable findings by linking hydrological case studies in the spirit of the comparative assessments of Parajka *et al.* [2013], Salinas *et al.* [2013], and Viglione *et al.* [2013]. The intention was to perform a more in-depth analysis of multiple-environmental factor impacts on erosion and nutrient cycling processes which is often not possible on individual study sites. The data came from numerous observation sites across the world with a wide spectrum of biophysical factors. It was hypothesized that rigorously formulated links could be made between biophysical factors, human impact, and erosion variables through quantitative analysis procedures. The findings may spark new process understanding within catchments, which may in turn inform future research toward unlocking new strategies for safe-guarding soil and water quality [Foy and Withers, 1995; Lal, 2004].

2. Materials and Methods

2.1. Study Selection

Literature on the dynamics of water, sediments, organic carbon (OC), and nutrient fluxes from around the world was explored. The initial target was to examine data from multiple-nested spatial scales. A number of topic-

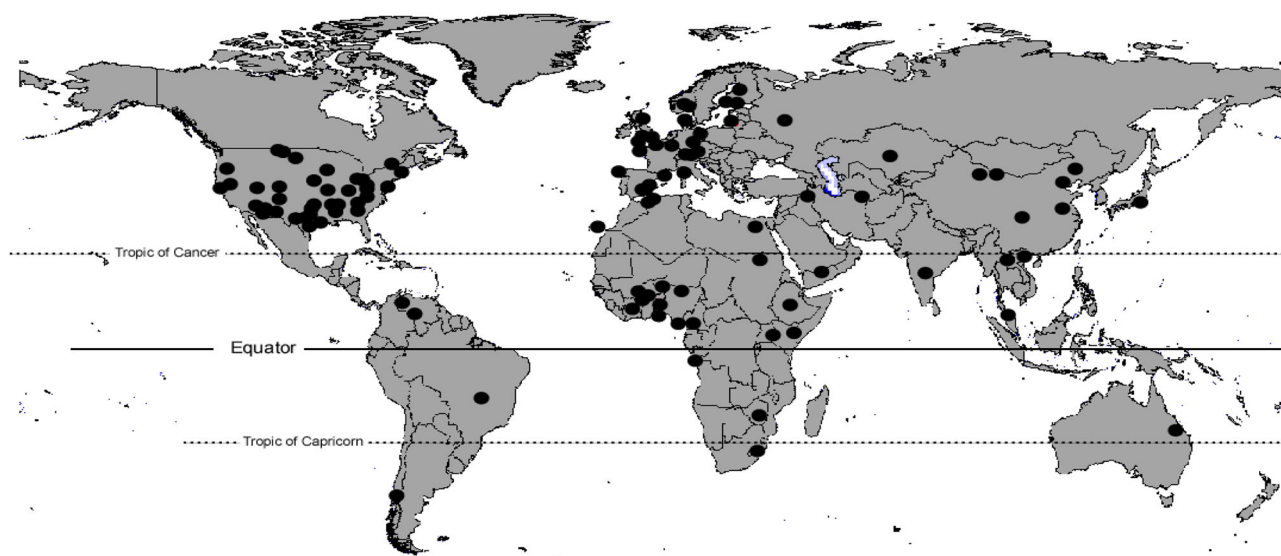


Figure 1. Global distribution of the study sites used in this meta-analysis.

related key words and phrases (e.g., multiple-nested scales; scale effect; sediment, organic carbon, and nutrient erosion; transport of suspended and dissolved substances/pollutants on landscapes; and scaling from local/microlevel to large catchments) were used to search for journal papers in Google, Google Scholar, Science Direct, Springer Link, Scopus, and SciFinder. Only 14 journal papers reporting on at least two nested scales were found, mostly from China, France, New Zealand, and Spain. Moreover, the scale sizes varied so widely that comparisons were difficult. Thus, the search was opened up to include data from nonnested scales and review papers. The final database consisted of 86 peer-reviewed ISI journal papers, yielding 498 observations from 446 sites dotted across the world (Figure 1). The database captured information on author name(s), year the papers were published, location of trial, spatial and temporal-scale size of trial, quantitative information on erosion variable(s), and environmental (controlling) factor(s) considered. Two secondary databases were subsequently compiled and are summarized in Tables 7 and S2 (in the supporting information). Table S1 shows author name(s), year the papers were published, average runoff coefficient (R_C), sediment load (SL), and total organic carbon loss (TOC_L) at the spatial scales considered by the papers. Table 9 shows author name(s), year the papers were published, number of spatial scales (N), spatial-scale range (min and max), location (LONG: longitude, LAT: latitude, and Z: altitude), and other factors. Annual precipitation received during the study period and long-term mean annual precipitation (MAP) were also captured and subsequently used in the analyses. The annual precipitation was used together with reported annual runoff volume to compute the runoff coefficient when it was not provided. MAP was used in stratifying the observation sites (Table 2). Rainfall intensity, a known driver of runoff generation and erosion processes, was not used in the current meta-analysis due to information limitations.

2.2. Definition of Variables

2.2.1. Erosion Variables

The erosion variables in this paper are annual data, based on natural precipitation, corresponding to hydrological years (Table 1). The age of trials, time periods for which experiments had been running, varied from 1 to 45 years [e.g., *Feng and Li, 2008*], with 63% of the studies being 1 year old. In cases where erosion variables were reported for more than 1 year, each year's data were treated as a separate and independent measurement for purposes of this meta-analysis. Trial period slightly less than a year [e.g., *Chaplot et al., 2005; Dlamini et al., 2011*] was treated as a full year in the case where no complementary information was provided to show that the period not included experienced runoff, sediment, OC, and/or nutrient losses. Averages of several years were used in circumstances where it was difficult to isolate data for the different years [e.g., *Andreu et al., 1998; Zillgens et al., 2007*].

Runoff was the most commonly reported variable with 373 observations; 268 of these were for 1 year periods. When the runoff coefficient (R_C) was not provided by a paper, the total runoff volume per unit area

Table 1. Definitions of the Annual Erosion Variables Used in This Paper

Erosion variable	Symbol	Definition
Runoff coefficient (%)	R_c	It is a coefficient relating the amount of surface runoff recorded for a catchment to the amount of precipitation received on the catchment on an annual basis.
Sediment concentration ($\text{g L}^{-1} \text{yr}^{-1}$)	SC	It is a ratio of the total weight of (suspended) solid materials to the volume of water in which the solid materials are found. Annual averages were used in the analysis where applicable.
Sediment load ($\text{g m}^{-2} \text{yr}^{-1}$)	SL	The total amount of solid material that is transported by overland flow systems. In this analysis, it specifically refers to amount of solid material eroded from a unit area of a catchment within a year.
Total organic carbon loss ($\text{g C m}^{-2} \text{yr}^{-1}$)	TOC_L	Total organic carbon loss is the amount of carbon bound in organic compounds in the surface runoff. It includes the dissolved organic carbon determined in the water and the particulate form measured in the sediment load from each catchment within a year.
Total nitrogen loss ($\text{mg N m}^{-2} \text{yr}^{-1}$)	TN_L	Total nitrogen loss is the total amount of nitrogen determined in the sediment load and runoff water from a catchment within a year.
Total phosphorus loss ($\text{mg P m}^{-2} \text{yr}^{-1}$)	TP_L	Total phosphorus loss is the total amount of phosphorus determined in the sediment load and runoff water from a catchment within a year.

(L m^{-2}) was divided by annual precipitation to estimate R_c . The sediment load per unit area (SL) and the concentration (SC) were computed using equation (1)

$$SL = SC \times R \tag{1}$$

where SL is the estimated annual sediment load ($\text{g m}^{-2} \text{yr}^{-1}$), SC is the sediment concentration (g L^{-1}), and R is the annual unit-area runoff volume ($\text{L m}^{-2} \text{yr}^{-1}$).

Data on OC and nutrient erosion were less commonly reported in the papers in comparison to runoff and soil losses. In the cases where they were reported, several methods were used in the estimation of particulate and dissolved components (e.g., Shimadzu TOC-Analyser, Vario-MAX-CN Macro Element-Analyser, Dohrmann DC-180 Carbon Analyser, ICP Atomic Emission Spectroscopy, Bray, Walkley-Black and Kjeldahl Digestion methods). The particulate concentrations were given in such a way that the respective amounts of exports could be computed by equations (2)–(4) for OC, nitrogen, and phosphorus, respectively,

$$\text{POC}_L = \text{POC}_C \times SL \tag{2}$$

$$\text{PN}_L = \text{PN}_C \times SL \tag{3}$$

$$\text{PP}_L = \text{PP}_C \times SL \tag{4}$$

where subscripts L and C stand for load and concentration, respectively. The papers also reported on dissolved components from sieved water samples. The sieve aperture sizes used by the paper authors varied from 0.45 to 0.70 μm . The dissolved components were expressed in parts per million (ppm) and were converted to grams per liter (g L^{-1}) by dividing the ppm by a factor of 1000 for OC, and kept in milligrams per liter (mg L^{-1}) for nitrogen and phosphorus losses. The dissolved losses were computed using equations (5)–(7).

$$\text{DOC}_L = \text{DOC}_C \times R \tag{5}$$

$$\text{DN}_L = \text{DN}_C \times R \tag{6}$$

$$\text{DP}_L = \text{DP}_C \times R \tag{7}$$

Total losses were subsequently obtained by equations (8)–(10)

$$\text{TOC}_L = \text{POC}_L + \text{DOC}_L \tag{8}$$

$$\text{TN}_L = \text{PN}_L + \text{DN}_L \tag{9}$$

$$\text{TP}_L = \text{PP}_L + \text{DP}_L \tag{10}$$

2.2.2. Environmental Factors

The papers identified many environmental control factors. The most frequent ones in the database related to climate (Rain: annual precipitation during the study, MAP: mean annual precipitation, and MAT: mean annual temperature), average relief and topography (Z: altitude and S: slope gradient), average spatial scale (L: characteristic slope length), location (LONG: longitude and LAT: latitude), average soil properties (CLAY:

clay content, SOC_c: soil organic carbon content, and BD: soil bulk density), and land use/cover (LU: land use and Cov: land cover by vegetation). Their magnitudes varied widely and were stratified to aid the analyses (Table 2). The stratification aimed at achieving a balance between common practice and equal number of cases.

Spatial scale was represented by the papers in terms of area (i.e., m², km², and ha) or slope length (L in m). If only catchment area was given, the characteristic space-scale L was calculated as the square root of the given area [Blöschl and Sivapalan, 1995]. L was stratified into five spatial scales; namely microplots (m), plots (p), microcatchments (mc), subcatchments (sc), and catchments (c), which are associated with typical L of the order of magnitude 10⁰, 10¹, 10², 10³, and ≥10⁴ m, respectively (Table 2). The L classes were important because the meta-analysis aimed at improving the understanding of process characteristics as a function of space scale [Blöschl, 2006]. The meta-analysis results are presented and discussed in the context of a river drainage basin where outlets of m and p are located on a hillslope within a headwater catchment, mc is at the toe of the slope, while sc and c are outlets of mid and lower reaches of a basin, respectively.

Generally, one would expect that hydrologic processes change from dominance by runoff and soil erosion on the slope, soil-water exfiltration at the toe, infiltration and sedimentation in midreach sections to sedimentation, and groundwater contributions in the lower reaches of a basin. Typically, the papers reported that surface flow on the hillslopes was nonchannelized, with channelization occurring at mc outlet where flow entered the sc scale. The c scale may also involve floodplain processes. These hydrologic processes are modulated by local biotic and abiotic factors [Weltz et al., 1998; Romkens et al., 2001].

The papers reported that runoff and sediment export at the microplot, plot, and microcatchment scales were measured after each rainstorm using manual methods although automatic equipment was used in some cases [e.g., Feyen et al., 1996; Esteves and Lapetite, 2003]. Typically, gauging weirs were constructed at outlets of subcatchments and catchments and these were equipped with stream stage recorders with auto-samplers, but, again, manual methods were used in some cases [e.g., Deelstra et al., 2009; Bernal and Sabater, 2012]. MAP and MAT are, respectively, long-term (30 year) average precipitation and temperature for the observation sites. The MAP classification was adapted from the Köppen [1936] system. When MAP and MAT were not reported, the 30 year average values were obtained from the WORLDCLIM database with a spatial resolution of 30'' (≈1 km at the equator). CLAY, SOC_c, BD, Cov, and S were catchment averages, while LU was taken as the most dominant land use in terms of fractional area covered. Fallows represented abandoned lands that had previously been under management (e.g., agriculture and mining). Grasslands included both natural grass and improved pastures.

2.3. Database Analyses

A preliminary step of the data analysis was the determination of erosion variable sample size for each environmental factor class (Table 3). Univariate summary statistics of R_c, SL, and TOC_L (Table 4) and environmental factors (Table 5) were calculated to gain insights on their overall variability. The descriptive statistics included minimum, maximum, median, mean, standard deviation (stdev), skewness, 25th and 75th percentiles (Quartile 1 and Quartile 3, respectively), kurtosis, and coefficient of variation (CV).

The next step was a two-tier exploratory analysis involving *bivariate* (Spearman rank correlations) (Table 6) and *multivariate* (Principal Component) analyses (Figure 2). Exploratory analysis was geared at identifying the main controlling factors of the erosion variables. Spearman rank correlations (r_s) were adopted because previous studies indicated monotonic nonlinear relationships between control factors and erosion variables [Nearing, 1997; Cerdan et al., 2010]. Not all the annual fluxes of water and erosion variables were close to a normal distribution as can be seen by the nonzero skewness and kurtosis of the variables in Table 4. The r_s were tested for statistical significance at the 95% confidence level. Principal component analysis (PCA) was used to evaluate the relationships between the erosion variables on the one hand and the environmental factors on the other. It converts actual variables into so-called factors or principal components (PCs), which are linear combinations of actual variables, not correlated with each other linearly (i.e., they are orthogonal) [Jambu, 1991]. The first principal component (PC1) explains the highest percentage of the variance of the data and the second principal component (PC2) corresponds to a lower proportion of the explained variance. Lines in the PCA diagrams show correlations among the environmental factors, while points indicate correlations between environmental factors and erosion variables (Figure 2).

Table 2. Environmental Variables and Their Classes Used in This Paper

Environmental Factor	Symbol	Remarks	Class Definition	Class Name	Symbol
Slope length (m)	L	Hillslope length or square root of catchment area	0–1	Microplot	m
			1–30	Plot	p
			30–200	Microcatchment	mc
			200–3000	Subcatchment	sc
			>3000	Catchment	c
Mean annual precipitation (mm yr ⁻¹)	MAP	30 year average for catchments	0–300	Arid	
			300–600	Semiarid	
			600–850	Moist	
			850–1500	Humid	
			1500>	Wet	
Mean annual temperature (°C)	MAT	30 year average for catchments	<0	Cold	
			0–10	Cool	
			10–20	Warm	
			20>	Hot	
			<10	Sand	
Soil clay content (%)	CLAY	Average for observation site	10–25	Sandy loam	
			25–50	Sandy clay	
			50>	Clay	
			<0.80	Low BD	BD _{low}
Soil bulk density (g cm ⁻³)	BD	Average for observation site	0.80–1.40	Medium BD	BD _{medium}
			1.40>	High BD	BD _{high}
			<1	Flat	
Slope gradient (%)	S	Average for observation site	1–10	Gentle	
			10–20	Moderate	
			20>	Steep	
			Forest	Forests	
Land use	LU	The most dominant in terms of area covered	Grassland	Grasslands	
			Abandoned lands	Fallows	
			Cropland	Croplands	

The last stage was a more in-depth analysis of the impacts of control factors on erosion variables using box and average lines plots (Figures 3–8). The box plots assessed the impact of scale by comparing distributions of the erosion variables as a function of spatial scale. Each box plot shows the 25th and 75th percentile, median value, lower and upper limit of nonoutlier range for the erosion variable data. An outlier is defined as an observation that lies an abnormal distance from other values in a random sample from a population. Lines depicting average values for the erosion variables under each environmental factor class were superimposed on the box plots to show the variability of erosion variables in each class with scale. The average values for each class (Table 8) were also used in discussing the impacts of the environmental factors on the erosion variables.

3. Results

3.1. Variability of Erosion and Environmental Factors Across the Globe

The basic statistics in Table 4 show wide variability of erosion parameters within scales, between scales and from one location to another. For instance, R_C varied from 0.02% in Mediterranean Spain [Mayor et al., 2011] to 114% in Canada [Richardson et al., 2012], with an average of 25%. The high R_C for Canada was attributed to snowmelt contributions. SL ranged from 0.03 g m⁻² yr⁻¹ on a plot in Spain [Rodríguez-Rodríguez et al., 2004] to 15,755 g m⁻² yr⁻¹ for a subcatchment in semiarid Ghana [Amegashie et al., 2011]. TOC_L also varied greatly, from 0.4 mg C m⁻² yr⁻¹ on a plot in Benin [Barthes et al., 2006] to 465 g C m⁻² yr⁻¹ on densely forested steep slopes of the very wet Maimai catchment, New Zealand [McGlynn and McDonnell, 2003], where the riparian zone was considered to be the most significant contributor of TOC_L. The basic statistics in Table 5 also show great variability of environmental factors with, for example, MAP ranging from 241 mm yr⁻¹ in Nevada, USA [Avnimelech and McHenry, 1984] to 4500 mm yr⁻¹ in a South American catchment [Lewis and Saunders, 1989]. MAT varied between -8°C in Russia [Ollesch et al., 2008] and 30°C in Niger [Esteves and Lapetite, 2003].

3.2. Correlation of Erosion Variables With Environmental Factors

3.2.1. Bivariate Analysis

Spearman rank correlations (r_s) in Table 6 reveal significant positive associations between R_C on the one hand and precipitation, MAP, Z, LAT, BD, and S on the other, while associations with L, Cov, CLAY, and SOC_C

Table 3. Sample Sizes for the Environmental Factor Classes^a

Environmental Factor	Environmental Factor Class	Erosion Variable Sample Size					
		R _C	SC	SL	TOC _L	TN _L	TP _L
MAP	Grand total	372	229	351	237	172	117
	Arid	21	18	21	8	0	0
	Semi-arid	31	49	80	44	31	28
	Moist	34	55	82	61	38	25
	Humid	135	82	120	96	94	62
	Wet	51	25	26	28	8	0
MAT	Not classified	100	0	22	0	1	2
	Cold	15	0	0	0	0	0
	Cool	123	33	45	37	90	66
	Warm	124	96	156	78	50	42
	Hot	110	97	125	119	32	6
CLAY	Not classified	0	3	25	3	0	3
	Sand	17	0	27	36	22	15
	Sandy loam	43	37	78	58	23	22
	Sandy clay	94	82	110	78	27	13
	Clay	18	18	21	21	14	0
BD	Not classified	200	92	115	44	86	67
	BD _{low}	11	5	5	3	0	0
	BD _{medium}	89	81	155	153	44	0
	BD _{high}	25	25	32	26	11	0
S	Not classified	247	118	159	55	117	117
	Flat	12	5	10	8	8	0
	Gentle	106	73	81	52	57	56
	Moderate	54	42	58	35	10	0
	Steep	128	85	101	56	14	0
LU	Not classified	72	24	101	86	83	61
	Croplands	158	116	150	115	101	66
	Fallows	69	47	55	13	6	0
	Forests	74	31	67	70	42	33
	Grasslands	63	31	56	35	23	17
	Not classified	8	4	23	4	0	1

^aNumber of erosion variable cases that could not be classified for each environmental factor is also included.

were significant and negative. There were significant positive correlations between R_C and other erosion variables, with r_s varying from 0.23 to 0.28. SC related very strongly to SL (r_s = 0.78), but less strongly to TOC_L, TN_L, and TP_L with r_s ≤ 0.48. SL associated strongly with TOC_L with r_s = 0.57, but related weakly to TN_L and TP_L. TOC_L also related weakly to TN_L and TP_L. However, the TN_L-TP_L correlation was very strong with r_s = 0.94. Climatic (Rain, MAP, and MAT) and topographic factors (S and L) also exhibited significant correlations with soil properties (CLAY, SILT, SAND, and SOC_C).

3.2.2. Multivariate Analysis

The two major PCs in Figure 2 explained 38% of environmental factor variability, with PC1 and PC2 accounting for 21 and 17%, respectively. MAP, CLAY, S, and SOC_C relate strongly to PC1, all showing negative coordinates. Thus, PC1 could be interpreted as the axis of decreasing precipitation and soil clay content. PC2 show negative coordinates for MAT and positive coordinates for LAT and SILT; hence, it can be interpreted as a temperature axis opposing low latitude-high temperature to high latitude-low temperatures and silty soils. The negative PC1 and PC2 coordinates of R_C at p in Figure 2a indicate that R_C at plot scale tends to increase with MAP, MAT, and CLAY. In contrast, the positive PC1 coordinates at other scales suggest increasing R_C with decreasing MAP and CLAY. SL at p and mc scales in Figure 2b also show negative PC1 and PC2 coordinates, while the other scales have positive PC1 coordinates. SL at m scale was close to the center, indicating no influence from the environmental factors. TOC_L at all scales in Figure 2c, except mc, relates closely to PC2, with p and c having positive coordinates while m and sc having negative coordinates. This result suggests temperature as the main regulator of OC erosion. Figure 2d shows close associations of TN_L at m, p, and mc with PC1, with the greatest correlations occurring with S. This point to increasing nitrogen erosion with MAP and CLAY at great slope gradients.

3.3. Erosion Variables as Functions of Environmental Factors and Scales

Figures 3–8 show the erosion variables as a function of spatial scale, stratified by the environmental factors. Table 8 provides additional information on both erosion variables and environmental factors.

Table 4. General Statistics of Selected Erosion Variables (R_C : Runoff Coefficient; SL: Sediment Load; TOC_L : Total Organic Carbon Loss) at Different Spatial Scales (m: Microplot; p: Plot; mc: Microcatchment; sc: Subcatchment; c: Catchment)

	R_C (%)					SL ($g\ m^{-2}\ yr^{-1}$)					TOC_L ($g\ m^{-2}\ yr^{-1}$)				
	m	p	mc	sc	c	m	p	mc	sc	c	m	p	mc	sc	c
Minimum	0.1	0.4	0.2	0.02	0.5	0.9	0.03	0.06	1	3.3	0.7	0.0004	0.01	0.03	0.09
Maximum	60	71	60	72	114	5,264	12,161	8,686.3	15,755	1,782	101	381	440	465	54
Mean	20.9	15.5	25.8	24.8	41.4	508	900.6	1,069.3	1,051.7	241.1	23.7	31.1	24.3	19.9	4.4
Quartile 1	9.5	4.7	1.9	5.7	21.3	27.2	10.3	61.0	82.8	6.4	2.6	1.0	0.6	0.8	0.5
Median	19.7	10.6	23.7	19.3	35.9	71.5	172.5	182.8	291.5	30.8	15.6	6.6	2.0	4.0	1.1
Quartile 3	30.0	22.0	47.3	43.4	54.5	233.2	521	793.8	1386.3	236.7	39.7	17.1	3.2	14.6	4.0
SD	16.6	14.1	23.0	21.2	26.6	1,152.4	2,133.1	2,121	2,253.7	440.4	24.3	78.1	97.9	64.4	9.0
SE	2.4	1.2	4.1	2.4	2.9	163	185	363.8	262	68.8	4.1	9.7	21.9	8.8	1.3
CV	79.4	91.4	89.2	85.4	64.3	226.8	236.8	198.4	214.3	182.7	102.7	251.1	403.1	324.0	204.2
Skewness	0.7	1.5	0.2	0.6	0.9	3.2	3.6	2.7	4.9	2.6	1.1	3.6	4.5	6.5	4.2
Kurtosis	-0.2	2.9	-1.6	-1.0	0.2	10.5	13.7	6.5	28.1	6.2	1.2	12.6	20.0	45.1	20.6

3.3.1. Runoff Coefficients (R_C)

Figure 3 shows the effects of environmental factors on R_C at different scales. R_C clearly increases with mean annual precipitation in Figure 3a, which agrees with the trend of average R_C values for MAP classes in Table 8 and also r_s for MAP- R_C in Table 6. R_C decreases from m to p and then increases to mc, except in the arid zone. Beyond the hillslope, R_C decreases from mc to sc and increases to c. Overall, there is a tendency for R_C to increase with scale with the exception of the arid climates. R_C tends to decrease with air temperatures (Figure 3b) although this is not strictly the case for all scales. At the smallest spatial scales, R_C tends to increase with grain size (Figure 3c) while at larger scales the texture does not seem to affect the R_C . For low-density soils, R_C increases substantially with spatial scale (Figure 3d). Slope has a rather erratic effect (Figure 3e) as land use (Figure 3f). Overall, the box plots in Figure 3 reveal decreasing R_C from m (median 20%) to p (11%), followed by a 2.4 fold increase at mc. R_C is much greater at c (41%) in comparison with the other scales. If scales are combined, R_C increases, from 18% at local scale (microplot and plot), 25% at micro-catchment and subcatchment scale to 41% at catchment scale.

3.3.2. Sediment Concentrations (SC)

Figure 4a shows very high sediment concentrations in the arid zone, while the wet zone has low SC at all scales. Arid and semiarid hillslope SC is also greater than in the moist, humid, and wet zones. This is consistent with trends of average SC for MAP classes in Table 8 and MAP-SC r_s in Table 6. SC decreases with MAT at sc in Figure 4b. All MAT classes have decreasing SC from local scales to the mainstream. Figure 4c shows large sediment concentrations for clay soils at the microplot scale and sandy clay soils at the plot scales, and sandy loam soils at the microcatchment scale. For medium densities there is a tendency for SC to decrease with scale. The increase of hillslope SC with BD in Figure 4d is a reflection of the effects of CLAY on SC. Figure 4e demonstrates that S-SC r_s in Table 6 was largely driven by the impact of S at the p scale. All LUs in Figure 4f show increasing SC with scale from local scales to the stream, but fallows have greater sediment concentrations. Overall, the box plots in Figure 4 suggest a 1.6 fold increase of median

Table 5. General Statistics of Environmental Factors (L: Slope Length; LONG: Longitude; LAT: Latitude; MAP: Mean Annual Precipitation; MAT: Mean Annual Temperature; Z: Altitude; S: Slope Gradient; Cov: Soil Cover by Vegetation) and Soil Factors (CLAY: Soil Clay Content; SILT: Soil Silt Content; SAND: Soil Sand Content; BD: Soil Bulk Density; $SOCC$: Soil Organic Carbon Content)

	L (m)	LONG (°)	LAT (°)	MAP (mm)	MAT (°C)	Z (m)	S (%)	Cov (%)	CLAY (%)	SAND (%)	SILT (%)	BD ($g\ cm^{-3}$)	$SOCC$ ($g\ kg^{-1}$)
Minimum	1.0	-123	-84	241	-8	5	0.01	0	2.5	0.5	0.5	0.40	0.02
Maximum	2,149,127.7	172	102	4,500	30	3,725	100.0	93.0	65.0	90.4	71.4	1.90	265.4
Mean	28,067.1	18	27	983	15	653	20.6	50.5	27.5	40.9	30.5	1.14	20.47
Quartile 1	10.0	-4	14	583	9	221	4.0	32.5	15.0	25.4	15.0	1.00	8.15
Median	152.5	11	34	826	13	516	15.0	53.8	27.0	38.3	29.5	1.00	15.00
Quartile 3	2,140.6	60	42	1,150	22	1,000	30.0	75.6	38.9	58.6	40.2	1.30	22.65
SD	176,807.3	68	28	623	8	610	20.1	28.9	15.1	22.1	16.9	0.27	28.16
SE	7,922.9	3	1	28	0	27	1.0	1.3	0.9	1.6	1.2	0.02	2.04
CV	629.9	386	104	63	55	93	97.7	57.3	55.0	54.1	55.5	24.09	137.5
Skewness	8.5	0	-2	2	0	2	1.5	0.3	0.3	0.5	0.5	0.38	5.19
Kurtosis	80.6	0	5	4	-1	7	2.6	1.0	-1.0	-0.6	-0.7	0.11	35.31

Table 6. Spearman Rank Correlations (r_s) Between Erosion Variables (R_c : Runoff Coefficient; SC: Sediment Concentration; SL: Sediment Load; TOC_L : Total Organic Carbon Loss; TN_L : Total Nitrogen Loss; TP_L : Total Phosphorus Loss) and Environmental Factors (Yrs: Temporal Scale in Years; L: Slope Length; Rain: Annual Rainfall; MAP: Mean Annual Precipitation; MAT: Mean Annual Temperature; Z: Altitude; LONG: Longitude; LAT: Latitude; BD: Soil Bulk Density; S: Slope Gradient; Cov: Soil Cover by Vegetation; CLAY: Soil Clay Content; SILT: Soil Silt Content; SAND: Soil Sand Content; $SOCC_c$: Soil Organic Carbon Content)^b

	R_c	SC	SL	TOC_L	TN_L	TP_L	L	Rain	MAP	MAT	Z	LONG	LAT	BD	S	Cov	CLAY	SILT	SAND	$SOCC_c$	
R_c	1.00																				
SC	0.28 ^a	1.00																			
SL	0.24 ^a	0.78 ^a	1.00																		
TOC_L	0.27 ^a	0.48 ^a	0.57 ^a	1.00																	
TN_L	0.28 ^a	0.47 ^a	0.11	0.16	1.00																
TP_L	0.23 ^a	0.47 ^a	0.24 ^a	0.39 ^a	0.94 ^a	1.00															
L	-0.35 ^a	-0.20 ^a	-0.24 ^a	-0.32 ^a	-0.19 ^a	-0.36 ^a	1.00														
Rain	0.26 ^a	-0.33 ^a	0.20 ^a	0.18 ^a	0.14 ^a	0.12	0.06	1.00													
MAP	0.29 ^a	-0.35 ^a	0.22 ^a	0.18 ^a	0.16 ^a	0.18 ^a	0.15 ^a	0.63 ^a	1.00												
MAT	-0.28 ^a	-0.21 ^a	-0.04	-0.17 ^a	-0.22 ^a	-0.37 ^a	-0.45 ^a	0.30 ^a	0.18	1.00											
Z	0.31 ^a	0.14 ^a	-0.06	0.08	0.23 ^a	-0.33 ^a	-0.25 ^a	0.09	0.17 ^a	0.18 ^a	1.00										
LONG	-0.15	0.15 ^a	-0.04	-0.08	0.60 ^a	0.56 ^a	-0.17 ^a	-0.02	0.17 ^a	-0.08	-0.09	1.00									
LAT	0.13 ^a	-0.04	-0.12 ^a	0.06	0.22 ^a	0.31 ^a	0.35 ^a	-0.23 ^a	0.01	-0.58 ^a	-0.31 ^a	-0.12 ^a	1.00								
BD	0.20 ^a	0.24 ^a	0.14	-0.29 ^a	0.64 ^a	0.10	-0.07	0.00	-0.19 ^a	0.14 ^a	0.19 ^a	0.12	-0.15 ^a	1.00							
S	0.16 ^a	0.10	0.15 ^a	0.14	-0.34 ^a	-0.39 ^a	-0.20 ^a	-0.08	0.08	-0.14 ^a	0.42 ^a	0.26 ^a	-0.02	0.12 ^a	1.00						
Cov	-0.15 ^a	-0.65 ^a	-0.50 ^a	-0.24 ^a	-0.87 ^a	0.11	-0.25 ^a	0.30 ^a	0.57 ^a	0.27 ^a	0.28 ^a	-0.21 ^a	0.10	-0.64 ^a	-0.32 ^a	1.00					
CLAY	-0.15 ^a	-0.19 ^a	-0.21 ^a	-0.23 ^a	0.18 ^a	-0.06	-0.26 ^a	0.42 ^a	0.26 ^a	0.14 ^a	0.20 ^a	0.44 ^a	-0.33 ^a	-0.06	0.44 ^a	-0.06	1.00				
SILT	-0.14	0.13	0.04	0.26 ^a	0.58 ^a	0.33 ^a	-0.17 ^a	-0.24 ^a	-0.25 ^a	-0.40 ^a	0.05	-0.16 ^a	0.47 ^a	-0.01	0.31 ^a	-0.23 ^a	-0.07	1.00			
SAND	0.12	0.19 ^a	0.16	-0.12	0.63 ^a	0.36 ^a	0.18 ^a	-0.27 ^a	-0.20 ^a	0.21 ^a	-0.23 ^a	-0.18 ^a	-0.21 ^a	0.12 ^a	-0.49 ^a	0.03	-0.54 ^a	-0.65 ^a	1.00		
$SOCC_c$	-0.25 ^a	-0.03	-0.27 ^a	0.23 ^a	-0.18 ^a	0.29 ^a	-0.06	0.20 ^a	0.15 ^a	-0.23 ^a	0.35 ^a	-0.09	-0.01	-0.15 ^a	0.71 ^a	0.77 ^a	0.49 ^a	0.14	-0.40 ^a	1.00	

^aStatistically significant determinants at 95% confidence level.

^b+ve: erosion variable and environmental factor values increase simultaneously. -ve: erosion variable decreases with increasing environmental factor values.

SC from m to p, followed by a 1.9 fold decrease to the mc scale. There is another increase to sc and a final decrease to c.

3.3.3. Sediment Loads (SL)

Figure 5a shows increasing sediment loads with MAP at mc, sc, and c scales, which conforms to r_s for MAP-SL in Table 6. The semiarid zone has high hillslope SL, but the arid zone has low SL at all scales due to the low runoff coefficients. SL decreases from sc to c in all MAP classes. Figure 5b shows greater hillslope SL in the warm than in the hot class. SL decreases with CLAY in Figure 5c in consistency with Table 8 and r_s in Table 6. SL increases with the bulk density at all scales (Figure 5d). The SL increase from m to p in BD_{medium} and BD_{high} soils, followed by decreases to mc. In Figure 5f, fallows and croplands have greater SL than forests and grasslands. The SL tends to increase with scale from local scale to sc. Overall, the box plots in Figure 5 exhibit a 2.4 fold increase from m to p, followed by a 1.6 fold increase to mc and sc and a 9.5 fold decrease to c.

3.3.4. Total Organic Carbon Losses (TOC_L)

Figure 6a and Table 8 point to increasing total organic carbon losses with mean annual precipitation, which agrees with r_s for MAP- TOC_L in Table 6. For the smaller spatial scales, there is a clear trend of decreasing TOC_L with scale for all climates. Arid and semiarid zones have decreasing TOC_L in the mainstream, but moist, humid, and wet climates exhibit increases from mc to sc before decreasing at c. TOC_L clearly decreases with air temperature (Figure 6b). For the smallest scales, there is a very clear increase of TOC_L with increasing grain sizes. Figure 6d shows a trend for decreasing TOC_L with bulk density. Hillslope TOC_L for the BD classes decrease with scale. In Figure 6f, forests and grasslands exhibit greater hillslope TOC_L than fallows and croplands. The TOC_L decreases from m to mc, except in forests. Averages for L classes in Table 8 show increasing TOC_L from m ($24 \text{ g m}^{-2} \text{ yr}^{-1}$) to p ($31 \text{ g m}^{-2} \text{ yr}^{-1}$), followed by a sharp decrease to mc ($5 \text{ g m}^{-2} \text{ yr}^{-1}$). On average, m and p scale sediments were enriched in OC compared to bulk soils ($SOCC_c = 20.5 \text{ g C kg}^{-1}$).

3.3.5. Total Nitrogen Losses (TN_L)

Figure 7a shows much greater total nitrogen losses in the moist than the other MAP classes. The MAP- TN_L relationship is not clear despite positive r_s in Table 6. TN_L for warm and hot climates decreases with scale from the local scale to the mainstream. Table 8 shows greater TN_L for sandy-clay and clay than sandy-loam and sand, and Figure 7c shows decreases of TN_L with scale for all texture classes. Steep slopes exhibit decreasing TN_L with spatial scale while this is not the case for flatter terrain. TN_L drops dramatically with

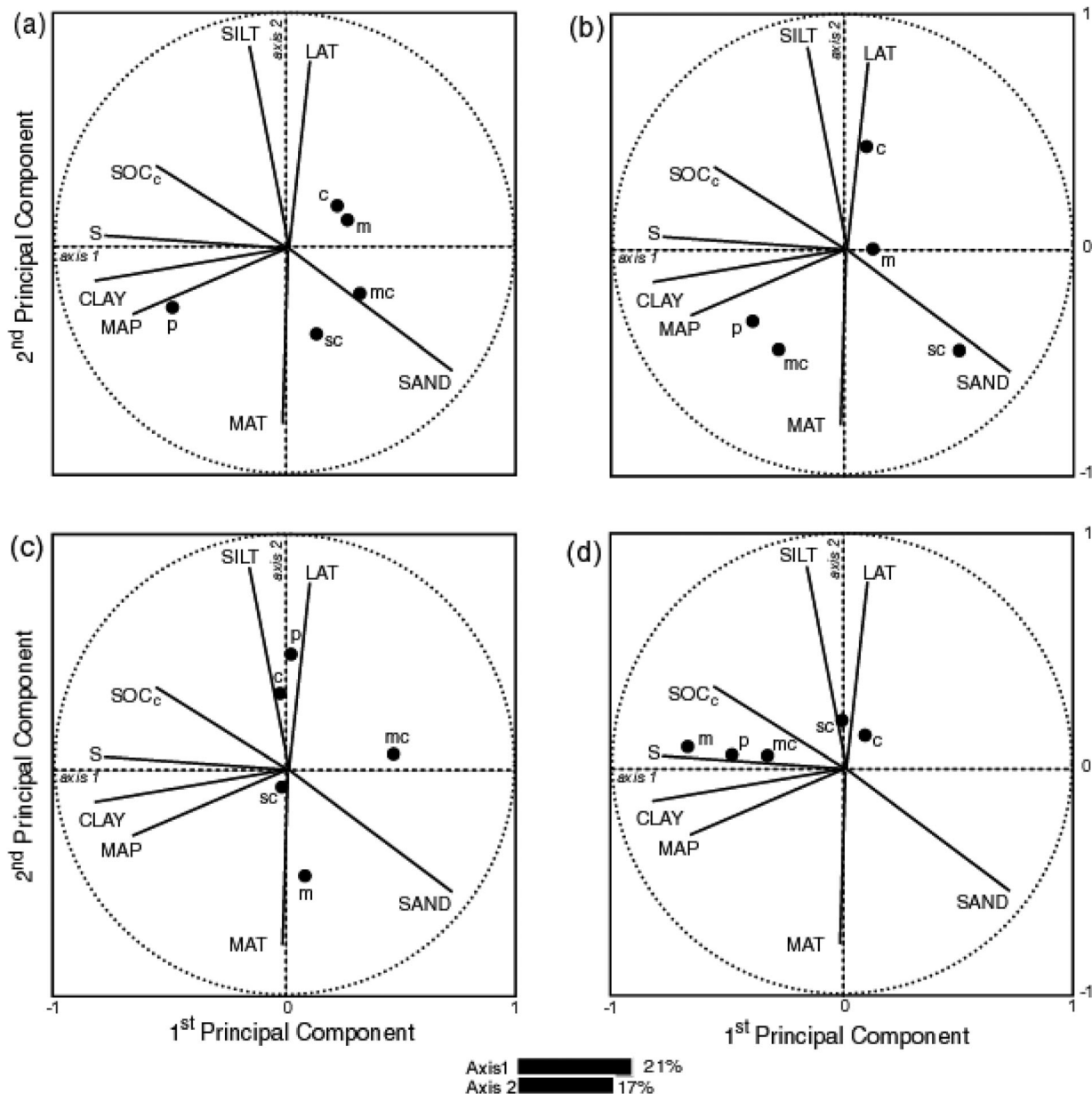


Figure 2. Principal Component Analyses (PCA) of environmental factors (MAP: mean annual precipitation; MAT: mean annual temperature; Lat: latitude; S: slope gradient; Z: altitude; SOC_c: soil organic carbon; CLAY: clay; SILT: silt; SAND: sand content) as active variables and (a) R_c: runoff coefficients, (b) SL: sediment loads, (c) TOC_t: total organic carbon losses, and (d) TN_t: total nitrogen losses, as supplementary variables. The lines show how environmental factors are correlated to each other, while the points show correlations between environmental factors and erosion variables at different spatial scales (m: microplot; p: plot; mc: microcatchment; sc: subcatchment; c: catchment).

scale for the forests while no such trend is apparent for the other land uses. Overall, there is a clear decreasing trend of total nitrogen losses with spatial scale in Figure 7.

3.3.6. Total Phosphorus Losses (TP_L)

Despite positive correlations of total phosphorus losses and precipitation in Table 6, Figure 8a and Table 8 show no clear trends with precipitation. However, Figure 8b shows decreasing TP_L with MAT at mc and sc scales, which agrees with MAT-TP_L r_s depicted in Table 6. The MAT classes also show a trend of decreasing TP_L with scale. The other factors do not indicate a clear pattern which is partly related to the smaller sample size of phosphorus losses as compared to the other erosion variables (Table 3). The scale effect on TP_L exhibited by the box plots and also by Table 8, suggests a 167% increase of TP_L from the local scale to mc, followed by a 27% decrease to sc, and a 58% decrease to the c scale with 24 mg m⁻² yr⁻¹.

Table 7. Definitions of the Annual Erosion Variables Used in This Paper

Erosion Variable	Symbol	Definition
Runoff coefficient (%)	R_c	It is a coefficient relating the amount of surface runoff recorded for a catchment to the amount of precipitation received on the catchment on an annual basis
Sediment concentration ($\text{g L}^{-1} \text{yr}^{-1}$)	SC	It is a ratio of the total weight of (suspended) solid materials to the volume of water in which the solid materials are found. Annual averages were used in the analysis where applicable
Sediment load ($\text{g m}^{-2} \text{yr}^{-1}$)	SL	The total amount of solid material that is transported by overland flow systems. In this analysis, it specifically refers to amount of solid material eroded from a unit area of a catchment within a year
Total organic carbon loss ($\text{g C m}^{-2} \text{yr}^{-1}$)	TOC_L	Total organic carbon loss is the amount of carbon bound in organic compounds in the surface runoff. It includes the dissolved organic carbon determined in the water and the particulate form measured in the sediment load from each catchment within a year
Total nitrogen loss ($\text{mg N m}^{-2} \text{yr}^{-1}$)	TN_L	Total nitrogen loss is the total amount of nitrogen determined in the sediment load and runoff water from a catchment within a year
Total phosphorus loss ($\text{mg P m}^{-2} \text{yr}^{-1}$)	TP_L	Total phosphorus loss is the total amount of phosphorus determined in the sediment load and runoff water from a catchment within a year

4. Discussion

4.1. Correlations Between Environmental Factors and Erosion Variables

The correlation analysis (Table 2) confirms annual precipitation, MAP, altitude, soil bulk density, and slope gradient as the main promoters of runoff generation (indexed by R_c) at global level. This is concordant with findings from several studies [e.g., *Alberts et al.*, 1978; *Chaplot et al.*, 2005, 2007; *Bernal and Sabater*, 2012], however other studies [e.g., *Alfaro et al.*, 2008] reported opposite results. In contrast, MAT, soil clay content, organic carbon content, and cover by vegetation were inhibitors and this agreed with results from many studies [e.g., *Cogle et al.*, 2002; *Brunet et al.*, 2006; *Barthes et al.*, 2006]. R_c was a key driver of erosion processes, as suggested by the significantly positive correlations with SC, SL, TOC_L , TN_L , and TP_L . The overall OC enrichment of sediments at microplot scale and lack of it at bigger spatial scales points to likely oxidation of OC with subsequent production of CO_2 to the atmosphere, as explained by *Chaplot and Poesen* [2012]. The results show that most of the eroded OC and nutrients (i.e., TN_L and TP_L) from microscales (e.g., 87% for OC) do not reach first-order streams. The losses are attributed to several processes which include redeposition, deep infiltration, chemical reactions, microbial attack, and volatilization in agreement with findings from many studies [e.g., *Avnimelech and McHenry*, 1984; *Chaplot et al.*, 2005; *Kaushal and Lewis*, 2005; *Petrone et al.*, 2006].

The multivariate analysis confirmed climate as the key controlling factor of erosion. This result was expected because climate tends to be the main controlling factor on hydrological processes [*Merz and Blöschl*, 2009], not only because higher rainfall climates are likely to be more erosive than dry ones, but also because of the cascading effects of climate on other factors such as soil properties, soil cover by vegetation, and land use. It is the coevolution of vegetation, soil, and climate that gives a lot of explanatory power of hydrologic fluxes to climate variables [*Perdigão and Blöschl*, 2014].

4.2. The Effects of Environmental Factors and Scale on Erosion Variables

4.2.1. Runoff and Runoff Coefficients (R_c)

The increase of runoff coefficients with increasing mean annual precipitation and decreasing air temperatures found in the meta-analysis (Figure 3) would be expected. It is consistent with the Budyko framework for undisturbed environments [*Budyko*, 1974], according to which the evaporation scaled by precipitation increases with the aridity index at large spatial scales. *Donohue et al.* [2007] showed that the accuracy of the Budyko framework at smaller spatiotemporal scales could be improved by including the dynamics of vegetation. Soil properties (especially soil clay content and bulk density) showed consistent relationships with R_c within hillslopes; while $\text{BD-}R_c$ and $\text{LU-}R_c$ relationships reflected the impact of precipitation. In general, the impacts of soil properties, land use, and cover on hydrological responses are considered local-scale phenomena and their effects tend to average out with increasing scale, while climate is considered to be more consistent from local to large spatial scales [*Blöschl et al.*, 2007]. This implies that the impact of soil properties, land use, and cover are expected to dominate at smaller spatial scales while climate becomes dominant at large spatial scales. However, this was not the case in the current analysis as climate (largely defined by annual precipitation and MAP) and human influence were dominant. For instance, forests were predominantly

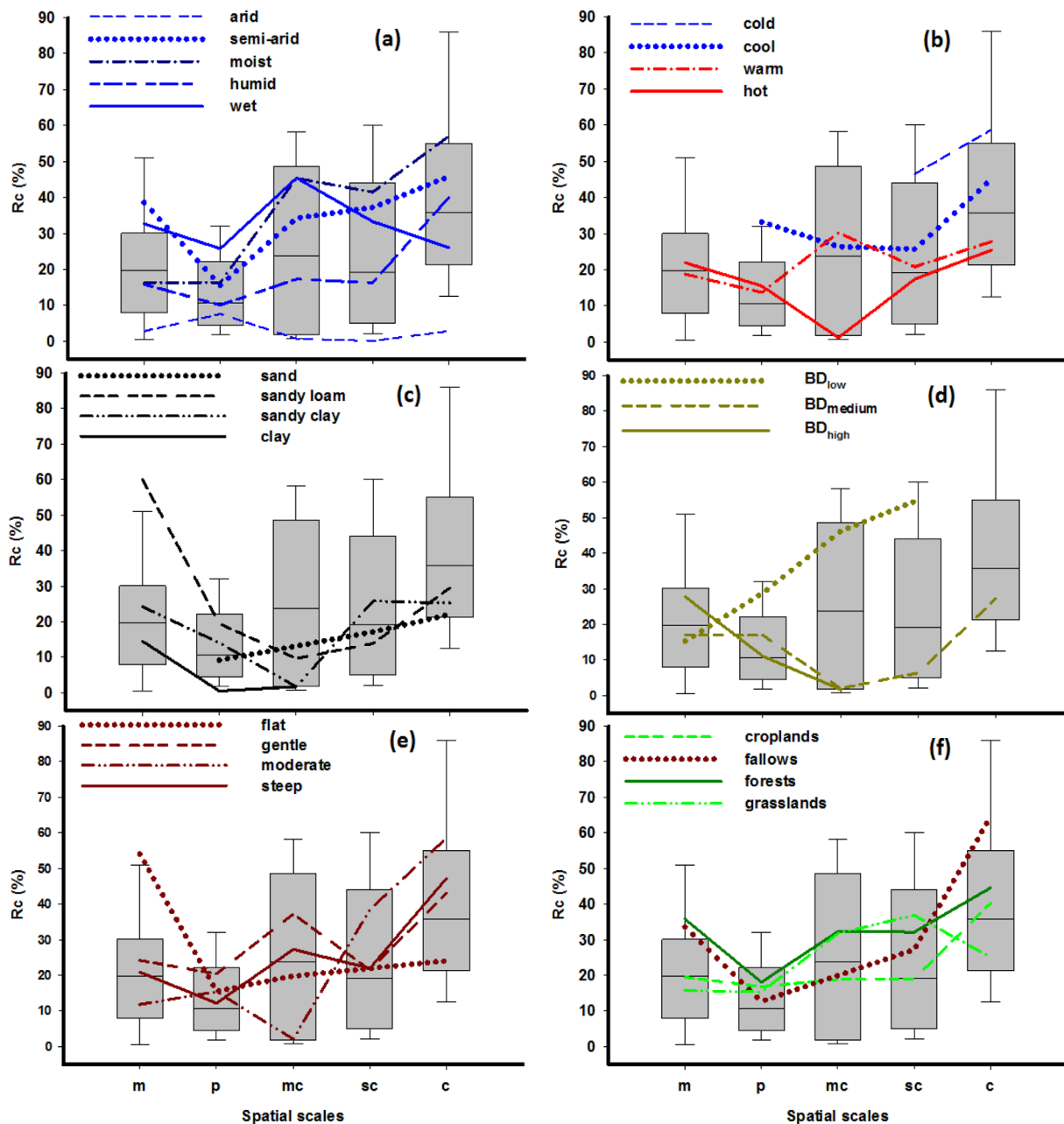


Figure 3. Runoff coefficients (R_c) from the literature for each of the spatial scales (box plots), and stratified by (a) mean annual precipitation, MAP, (b) mean annual temperature, MAT, (c) clay content, CLAY, (d) soil bulk density, BD, (e) slope gradient, S and (f) land use LU (lines). The spatial scales are m: microplot, p: plot, mc: microcatchment, sc: subcatchment, and c: catchment. For classifications, see Table 7. Each box plot shows the median line, 25–75% range, and lower and upper limit of the nonoutlier range.

located on steep slopes of high rainfall areas which are less suitable for farming with resultantly much greater local-scale R_c than other land uses (Figure 3f). Therefore, a combination of high rainfall and steep gradients explains the big R_c under forests [Blöschl et al., 2013], which is the opposite of what empirical relationships that only consider land use would predict. The greater R_c on low bulk density soils may also be explained in a similar way. The other factors and processes were still important, for example high bulk density soils, characteristic of low clay content, are of weak aggregate stability and prone to crusting which restricts water infiltration [Le Bissonnais, 1996; Amézqueta, 1999; Chaplot et al., 2007]. Also, forest fires sometimes create hard soil surfaces which repel water [Doerr and Thomas, 2000; Farley et al., 2005; Rodríguez-Alleres and Benito, 2012]. Though not common, the decrease of R_c with slope gradient in the current analysis is mainly attributable to the high runoff generation on flat loess soils of Northern Europe. The loess soils form dense impervious surface seals under the

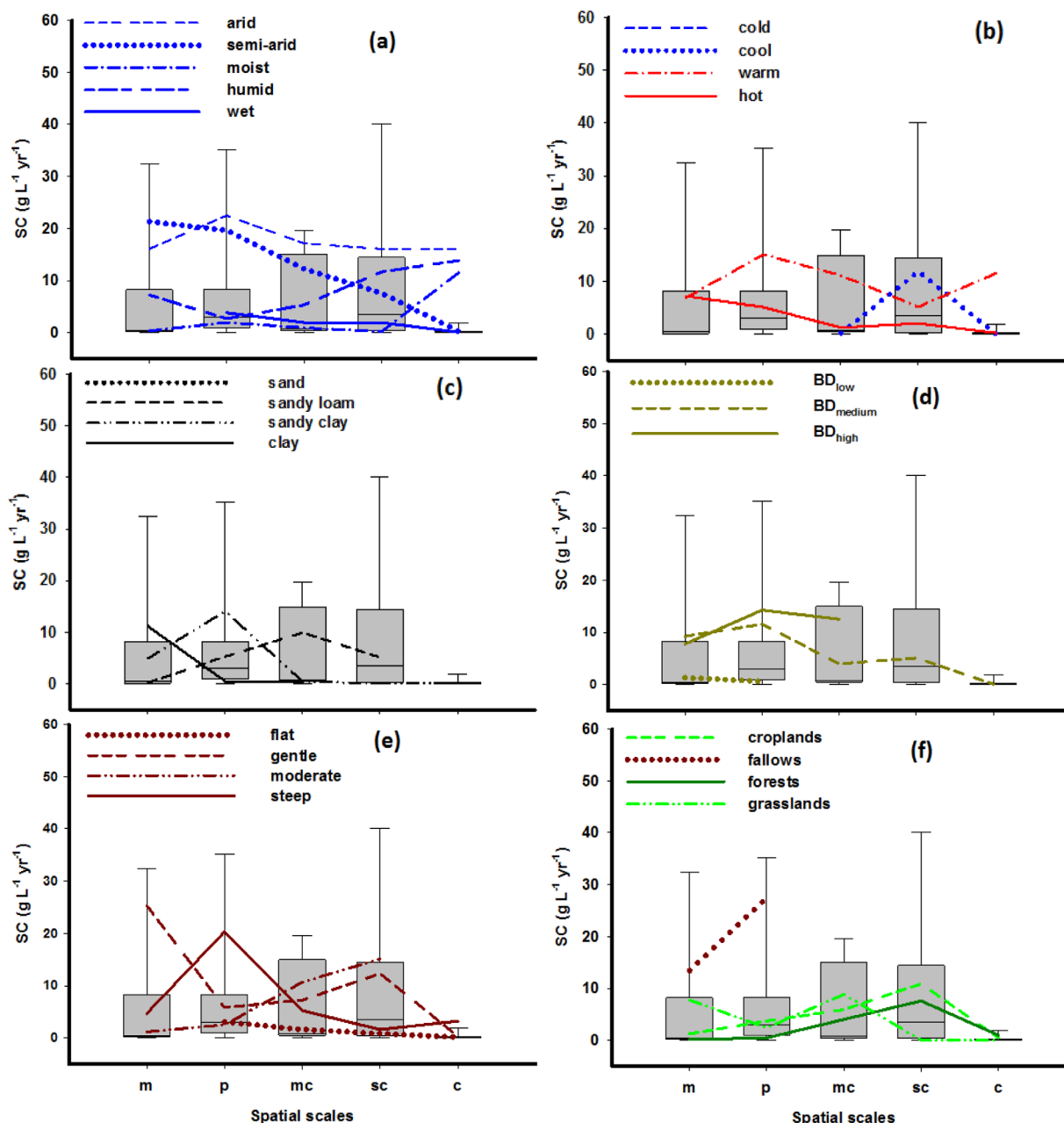


Figure 4. Sediment concentrations (SC) from the literature for each of the spatial scales (box plots), and stratified by (a) mean annual precipitation, MAP, (b) mean annual temperature, MAT, (c) clay content, CLAY, (d) soil bulk density, BD, (e) slope gradient, S, and (f) land use LU (lines). The spatial scales are m: microplot, p: plot, mc: microcatchment, sc: subcatchment, and c: catchment. For classifications, see Table 7. Each box plot shows the median line, 25–75% range, and lower and upper limit of the nonoutlier range.

impact of raindrops [Le Bissonnais et al., 1995; Cerdan et al., 2004]. High clay content soils (e.g., Vertisols) also show high R_C because they collapse upon wetting [Ben-Hur et al., 1985; Reichert and Norton, 1995; Santos et al., 2003]. On the steep slopes of some tropical highlands, Chaplot et al. [2005] and Guzman et al. [2013] reported on high losses of light clay and organic matter particles to water erosion leaving behind high-porosity soils. The high R_C under cold climates can be explained by the lower evaporation and partly by limited infiltration under permafrost conditions [Zhang et al., 2009; Scherler et al., 2011].

The decrease of R_C with scale on hillslopes has been widely reported in the literature [e.g., Bonell and Williams, 1987; Sivapalan et al., 1987; Wood et al., 1988; Lavee et al., 1995; Castillo et al., 1997; Fox and Le Bissonnais, 1998; Cammeraat, 2004; Dunjo et al., 2004; Hearman and Hinz, 2007] and was mostly attributed to losses of surface flow to infiltration driven by the emergence of vegetation patches and soil surface

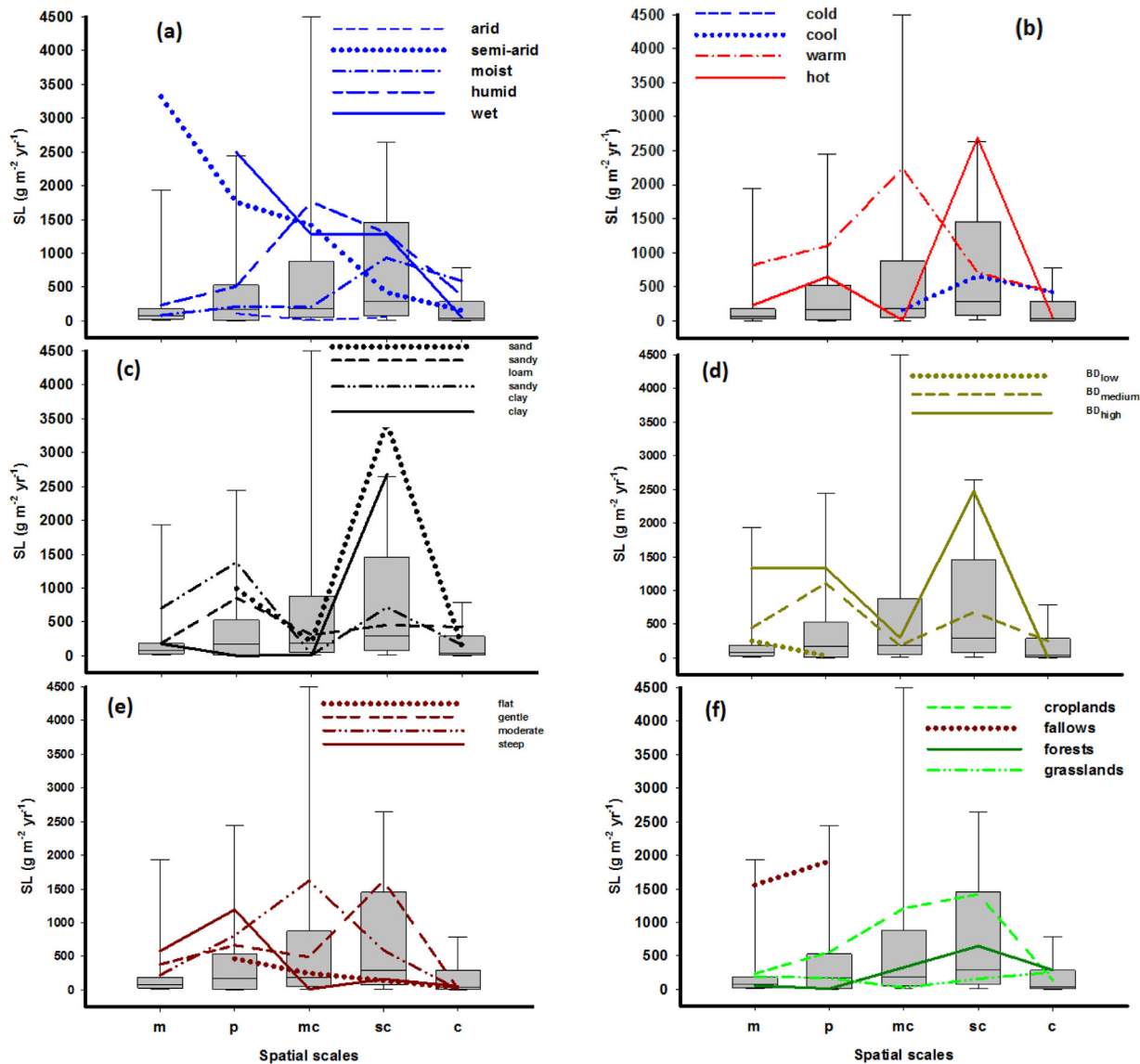


Figure 5. Sediment loads (SL) from the literature for each of the spatial scales (box plots), and stratified by (a) mean annual precipitation, MAP, (b) mean annual temperature, MAT, (c) clay content, CLAY, (d) soil bulk density, BD, (e) slope gradient, S, and (f) land use LU (lines). The spatial scales are m: microplot, p: plot, mc: microcatchment, sc: subcatchment, and c: catchment. For classifications, see Table 7. Each box plot shows the median line, 25–75% range, and lower and upper limit of the nonoutlier range.

roughness. Bare-vegetation patch arrangements on most landscapes create systems where runoff produced from bare surfaces infiltrates under vegetation patches [Mayor *et al.*, 2011], while surface roughness and vegetation barriers increase the infiltration opportunity time of surface runoff by retarding its flow. The overall increase of R_C from plot to larger areas found here is likely a result of additional contributions from interflow and groundwater to streamflow. A number of studies attributed the rise of R_C from the hillslope to first-order streams to interflow contribution [e.g., Castro dos Reis *et al.*, 1999; Burns *et al.*, 2001; Chaplot and Ribolzi, 2013]. Exfiltration also prolongs wet conditions within foot slopes [Uhlenbrook *et al.*, 2005] creating conducive conditions for localized saturation-excess runoff generation and enhancing the spatial connectivity of wet areas [Western *et al.*, 1998]. Mainstream channels are normally marked by high infiltration and sedimentation due to smoothing slope gradients [e.g., Constantz, 1998], but groundwater contributions in lower reaches of basins can also be significant [Clow *et al.*, 2003].

4.2.2. Sediment Concentrations (SC) and Sediment Loads (SL)

The high SC but low SL in the arid zone (Figures 4a and 5a) point to transport limitation of water erosion. Arid zones are often characterized by high-intensity rainstorms, which come after prolonged dry periods.

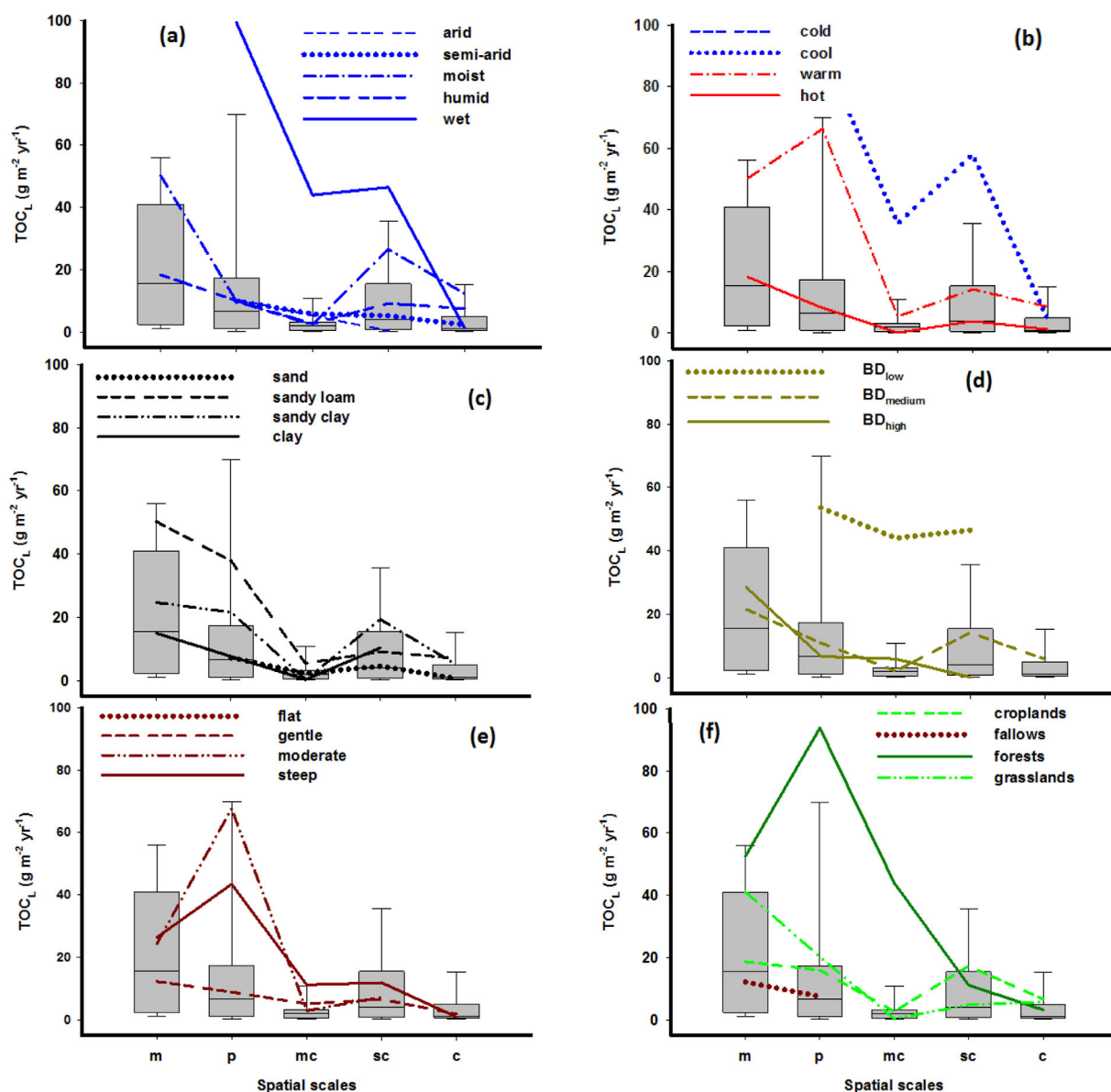


Figure 6. Total organic carbon losses (TOC_L) from the literature for each of the spatial scales (box plots), and stratified by (a) mean annual precipitation, MAP, (b) mean annual temperature, MAT, (c) clay content, CLAY, (d) soil bulk density, BD, (e) slope gradient, S, and (f) land use LU (lines). The spatial scales are m: microplot, p: plot, mc: microcatchment, sc: subcatchment, and c: catchment. For classifications, see Table 7. Each box plot shows the median line, 25–75% range, and lower and upper limit of the nonoutlier range.

Runoff, typically, is dominated by local infiltration-excess mechanisms [Yair *et al.*, 1980], but quick dissipation via infiltration makes it sharply decrease in the downslope to downstream direction [Leguèdois *et al.*, 2005]. Hence, soil losses would sharply decrease with increasing surface area due to redeposition of the entrained sediments. Poor runoff connectivity across spatial scales may also contribute to arid zone rivers being generally dry [Hughes, 1995; Bronstert, 2003; Shadeed and Lange, 2010]. In contrast, the wet zone was marked by low SC and high SL, which suggests erosion processes were detachment rather than transport limited. In general, SC and SL showed tendencies to decrease with annual precipitation at all spatial scales in response to improving soil cover by vegetation, and also improving soil aggregate stability as soil clay content is a function of precipitation-driven weathering. There was a significant impact of soil clay content, soil bulk density, and slope gradient on SC and SL at hillslope level, while land use dominated downstream. Fallows and croplands exported greater amounts of sediment than other land uses due to lower soil cover by vegetation. However, soil losses from croplands vary very widely depending on management practice

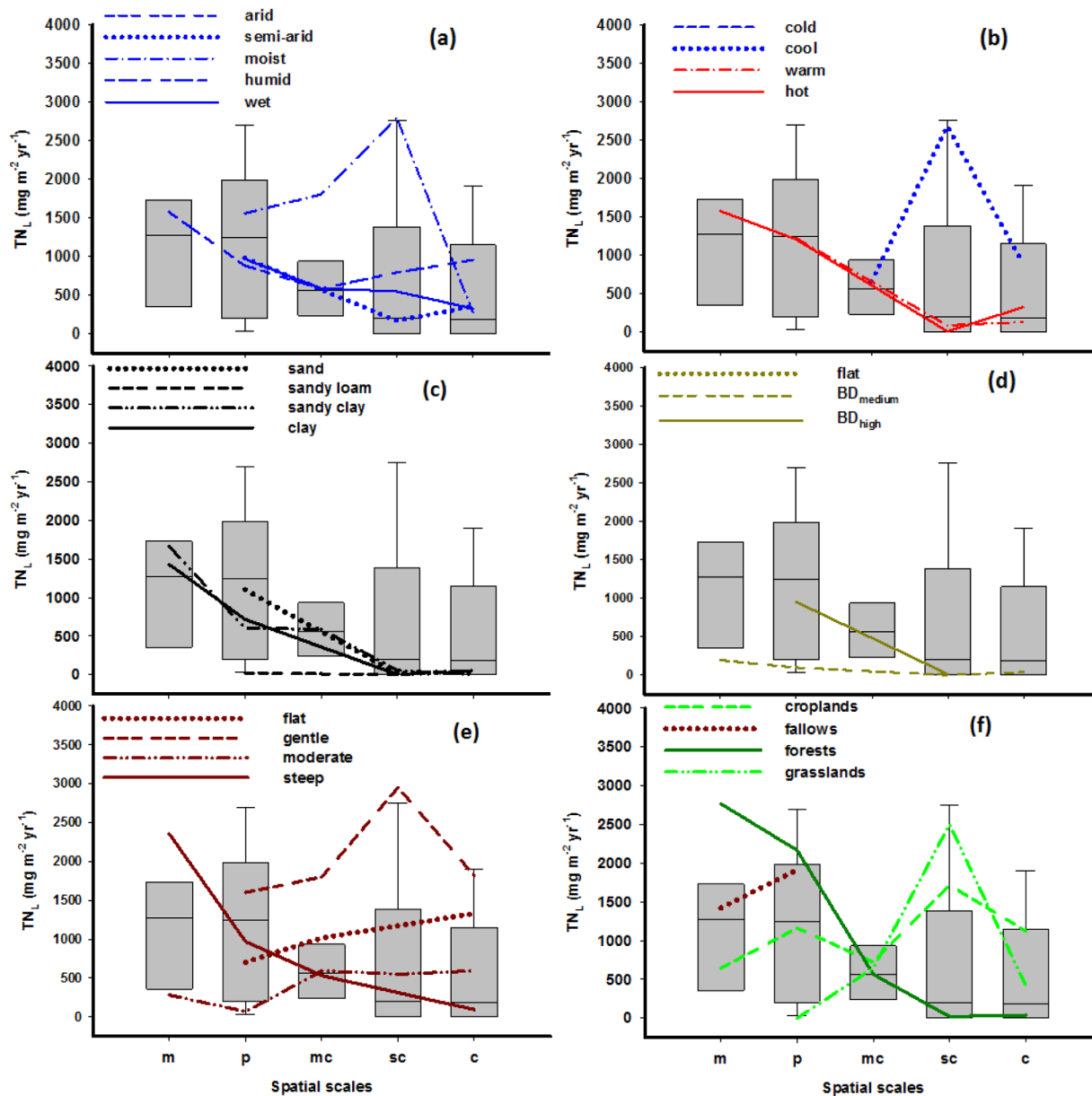


Figure 7. Total nitrogen losses (TN_L) from the literature for each of the spatial scales (box plots), and stratified by (a) mean annual precipitation, MAP, (b) mean annual temperature, MAT, (c) clay content, CLAY, (d) soil bulk density, BD, (e) slope gradient, S, and (f) land use LU (lines). The spatial scales are m: microplot, p: plot, mc: microcatchment, sc: subcatchment, and c: catchment. For classifications, see Table 7. Each box plot shows the median line, 25–75% range, and lower and upper limit of the nonoutlier range.

and season, with for instance soil erosion being higher early in the growing season, when soils are almost bare and low at crop maturity.

The increase of sediment exports from microplot to plot indicates the greater efficiency of transport by rain-impacted flow as flow velocity increases [Kinnell, 2001]. Sediment exports also sharply increased to microcatchment and subcatchment, suggesting massive movements of soil in upper to mid reaches of global river basins. This may be attributed to linear erosion with undercutting and gully retreat processes and to river bank erosion as runoff increases [De Vente et al., 2007]. These sediments are, however, redeposited in lower reaches of basins as slope gradients become smoother [Doble et al., 2012; Eder et al., 2014]. Other factors explaining low sediment exports at river drainage basin outlets include the time lag of flow behind rainstorms [Goransson et al., 2013] and buffering effect by groundwater [Zheng et al., 2011].

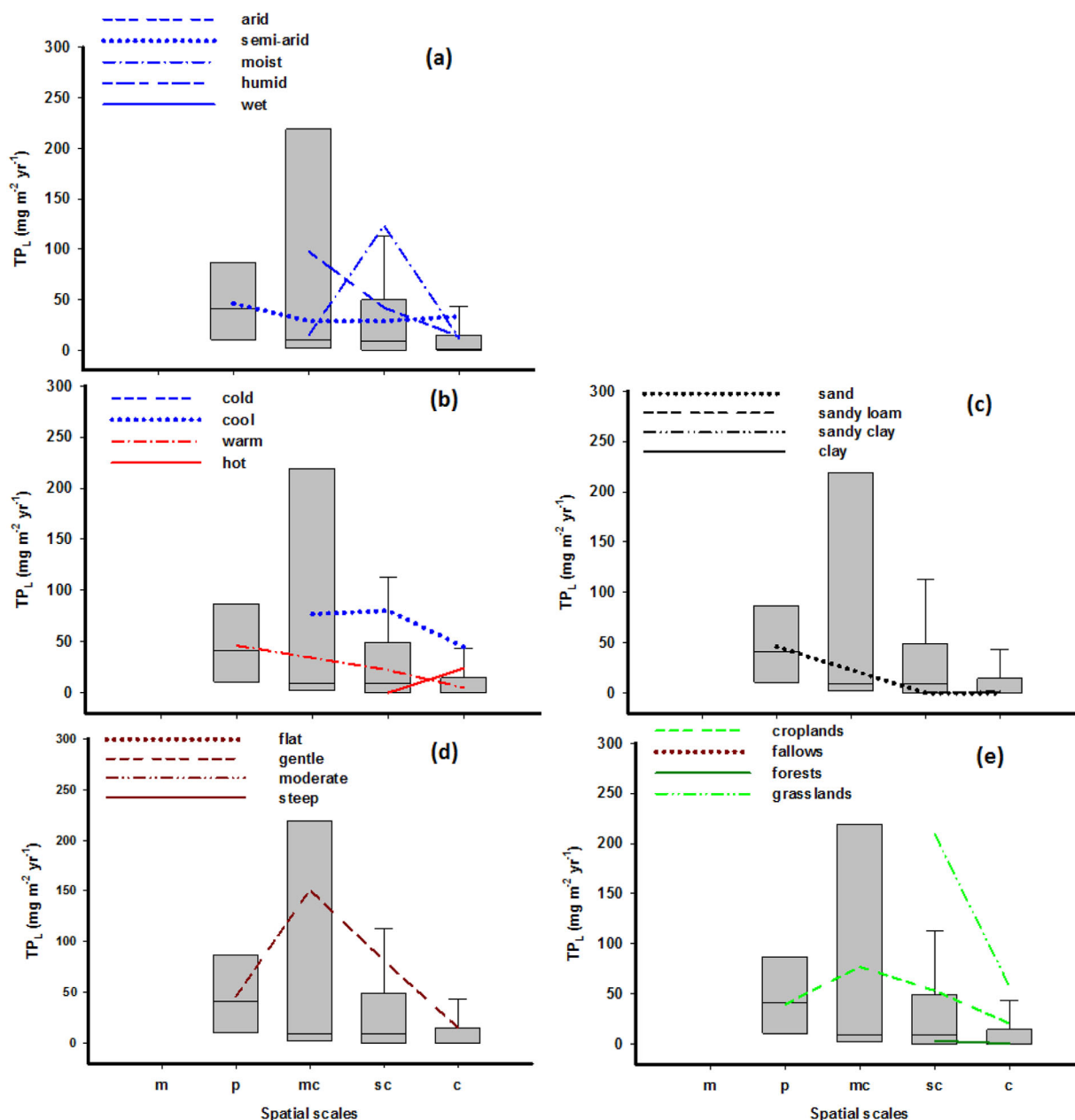


Figure 8. Total phosphorus losses (TP_L) from the literature for each of the spatial scales (box plots), and stratified by (a) mean annual precipitation, MAP, (b) mean annual temperature, MAT, (c) clay content, CLAY, (d) slope gradient, S , and (e) land use LU (lines). The spatial scales are m: microplot, p: plot, mc: microcatchment, sc: subcatchment, and c: catchment. For classifications, see Table 7. Each box plot shows the median line, 25–75% range, and lower and upper limit of the nonoutlier range.

4.2.3. Total Organic Carbon (TOC_L) and Nutrient (TN_L and TP_L) Losses

The increase of TOC_L and TN_L with precipitation (Figure 6a and Table 8) and also with decreasing air temperatures (Figure 6b) reflects the impact of climate on water erosion but also soil stocks. Wet and warm climates foster, indeed, biomass production and subsequent buildup of SOC and nitrogen stocks, while arid climates are expected to have low OC and nitrogen stocks due to low biomass production and rapid oxidation rates. The high TOC_L fluxes from forested areas can be explained by their preferential location on steep slopes of high MAP areas (Table 8). The decrease of TOC_L with soil clay content (Figure 6c) is consistent with results from several studies [e.g., Boix-Fayos *et al.*, 2009; Amegashie *et al.*, 2011] and suggests greater protection of SOC as soil clay content increases. However, other factors, such as declining slope gradient and annual precipitation (Table 8), may also help explain the trend.

Table 8. Computed Average Values for Erosion Variables (R_c : Runoff Coefficient, %; SC : Sediment Concentration, $g L^{-1}$; SL : Sediment Load, $g m^{-2} yr^{-1}$; TOC_L : Total Organic Carbon Loss, $g m^{-2} yr^{-1}$; TN_L : Total Nitrogen Loss, $mg m^{-2} yr^{-1}$; TP_L : Total Phosphorus Loss, $mg m^{-2} yr^{-1}$) and Selected Environmental Factors (Rain: Total Precipitation, mm; MAP: Long-Term Mean Annual Precipitation, $mm yr^{-1}$; MAT: Long-Term Mean Annual Temperature, $^{\circ}C$; BD: Soil Bulk Density, $g cm^{-3}$; S: Slope Gradient, %; CLAY: Soil Clay Content, %; Cov: Soil Cover by Vegetation, %; Z: Altitude, masl; LAT: Latitude, $^{\circ}$) at Different Environmental Factor Classes

Factor Class	Erosion Variables						Environmental Factors								
	R_c	SC	SL	TOC_L	TN_L	TP_L	Rain	MAP	MAT	BD	S	CLAY	Cov	Z	LAT
<i>L</i>															
m	20.9	7.1	468	23.7	1577	*	1015	983	20.7	1.1	30.3	39.0	52.9	818	20.2
p	15.5	11.1	901	31.1	1211	46.3	675	834	19.3	1.2	19.4	23.8	43.2	748	22.8
mc	25.8	5.9	1069	4.5	658	77.1	790	1213	11.0	1.0	18.1	21.2	40.0	378	46.4
sc	24.8	10.3	1052	12.1	1601	56.3	782	994	11.8	1.1	15.7	20.2	41.0	537	41.0
c	41.4	0.7	241	4.4	641	23.9	993	1085	10.4	1.1	26.5	32.7	*	738	41.6
<i>MAP</i>															
Arid	6.5	22.2	102	1.4	*	*	209	271	15.7	1.0	26.7	26.5	40.8	758	37.2
Semiarid	28.2	18.1	1284	4.5	401	28.6	495	486	15.0	1.3	21.0	24.5	38.6	962	28.0
Moist	29.1	1.7	323	16.1	2625	87.8	615	725	13.8	1.1	11.1	22.1	74.2	580	37.5
Humid	21.6	7.5	928	14.1	972	41.5	1024	1098	15.1	1.1	20.7	31.3	60.0	476	35.0
WET	30.1	1.4	1243	38.9	695	24.0	1498	2451	16.4	1.2	41.6	39.3	*	775	29.6
<i>MAT</i>															
Cold	57.1	0.3	16	0.4	*	*	367	665	-3.3	*	5.0	*	*	32	78.2
Cool	33.7	9.7	491	26.6	1829	72.2	730	1114	7.1	1.0	20.8	20.8	*	599	47.1
Warm	18.0	13.1	1030	26.8	195	19.2	635	699	14.6	1.1	20.5	23.6	48.2	810	32.4
Hot	18.8	4.7	733	10.7	1086	4.2	1217	1248	25.9	1.2	20.8	33.1	43.2	571	15.9
<i>CLAY</i>															
Sand	11.6	9.5	1434	5.1	365	12.5	685	707	19.3	1.3	8.0	6.9	29.1	489	30.1
Sandy loam	19.0	5.8	715	22.3	27	1.0	840	983	16.4	1.1	16.3	17.9	58.5	735	31.3
Sandy clay	19.3	8.4	868	15.7	507	0.4	1033	990	19.7	1.2	23.9	36.7	46.0	763	19.3
Clay	13.0	10.0	379	28.6	1074	1.7	1185	1177	22.3	1.0	34.8	53.8	81.0	845	20.2
<i>BD</i>															
Low	28.2	0.6	29	243.5	*	*	1004	915	15.5	0.6	11.1	24.2	43.3	656	37.6
Medium	20.9	7.9	687	19.2	23	0.7	935	1034	18.1	1.1	19.2	29.7	49.6	717	25.5
High	13.3	12.8	1776	7.4	524	0.2	763	804	20.3	1.6	21.2	20.7	12.8	595	18.6
<i>S</i>															
Flat	25.5	2.5	446	8.8	1016	121.1	741	739	22.5	1.5	0.7	11.4	40.8	269	24.6
Gentle	24.5	9.9	1070	12.2	2605	76.9	760	873	15.7	1.1	4.1	23.9	52.8	428	31.7
Moderate	16.9	2.8	899	37.3	390	16.4	795	985	14.5	1.1	15.4	24.5	46.8	683	37.7
Steep	21.8	13.7	867	27.5	1088	1.9	719	1021	14.3	1.2	41.4	34.1	46.1	1001	27.2
<i>LU</i>															
Cropland	23.3	5.1	914	17.2	1394	49.7	909	999	16.0	1.2	12.4	26.2	26.1	436	32.8
Fallow	24.9	25.1	1842	9.6	1669	65.7	588	630	15.2	1.4	31.2	29.3	36.6	624	28.7
Forest	32.2	1.1	363	24.8	191	2.4	855	1351	13.6	1.0	33.7	24.0	42.3	827	36.0
Grassland	23.4	4.8	175	14.6	2189	127.8	737	764	13.9	1.1	18.0	31.5	74.1	917	36.8

TOC_L and TN_L decreased along hillslopes, which points to both possible biogeochemical modifications [Wohl et al., 2012] and redepositions [Smith et al., 2001; Stedmon et al., 2003]. The organic carbon enrichment of sediments from microplots and plots confirms the preferential removal of SOC from soil aggregates by sheet erosion [Schietecatte et al., 2008]. Some studies [e.g., Sharpley, 1985; Fierer and Gabet, 2002] have also reported on the preferential removal of N by splash and sheet erosion. Along streams, TOC_L and TN_L tend to decrease due to biotic uptake and other processes. For example, Wollheim et al. [2006] explains that N is predominantly removed by biotic uptake from the water column and denitrification from sediments, but only denitrification would contribute to net removal because the N in living matter is released back to the water via mineralization. Phosphorus fluxes were found to decrease with scale in this study. Although phosphorus is associated with clay and organic matter particles [Quinton et al., 2001; Schietecatte et al., 2008], it is relatively stable [Benitez-Nelson, 2000; Carter et al., 2003; Zhou et al., 2005; Li et al., 2012] and less prone to biogeochemical modification than organic matter. Therefore, the subsequent decrease in phosphorus fluxes downstream points to losses via redeposition.

5. Conclusions

Understanding the process controls on water, sediment, nutrient, and organic carbon exports from the landscape through runoff across scales is rarely possible in a single operating environment. This paper has therefore performed a meta-analysis based on data from 446 observations around the world published in the literature. The

results allow a number of conclusions. There was a general increase of annual runoff coefficients from hillslopes to basin outlets while sediment, organic carbon, and nutrient exports tended to decrease with spatial scale. These effects point to scale-specific pathways and mechanisms of detachment and transport, which are influenced in a complex way by interactions between hydrological regimes, catchment properties, and human activities. The meta-analysis also suggests that, among the environmental factors, climate appeared to have the most significant effect on the water, sediment, organic carbon, and nutrient fluxes in the river basins. This is because of its direct impact on detachment and transport and its indirect impact on soil properties and land use. The important role of spatial climate variability points to a need for more comparative research in specific environments using nested multiple spatiotemporal scales. There were, however, several limitations to the study which create room for future work. In particular, soil fluxes used may not be representative of the global average because soil erosion measurements are most often carried out in areas where it is an issue of concern. Hence, future research should account for possible observation biases. It was also not possible to explicitly represent the influence of humans (e.g., variability in management practices relating to tillage methods, fertilizer application rates on croplands, crop rotations, and allocation of land uses such as the location of forests on marginal and fragile lands less suitable for farming) due to limited data in the literature. More work is, therefore, needed to incorporate human effects contributing to soil, organic carbon, and nutrient fluxes. In addition to surface flow fluxes, groundwater and interflow also need to be integrated in future analyses. While deciphering spatial patterns from the results may serve as important hypotheses to be tested through future experimental and/or modeling work, the impact of temporal variability and time scales on fluxes requires similar attention. More consistent reporting of the many published catchment research findings to make results more comparable can profit future meta-analyses. The results of this paper are intended to contribute to a better understanding of the processes of water, sediments, organic carbon, and nutrient fluxes in river basins and their main controls, which is important for predicting the cycles at global scale and for enhancing decision making on land use planning for improved ecosystem management. Such a deciphering of processes and their controls especially on soil organic carbon erosion and fate in terrestrial to oceanic ecosystems is likely to be a major future research area.

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