AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2017WR020806

A Global Data Analysis for Representing Sediment and Particulate Organic Carbon Yield in Earth System Models

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Key Points:

- SY should be modeled in ESMs at the event scale with including erosion processes more than interrill and rill erosion
- Seismicity and land management that are rarely considered in current models could be important for controlling global SY
- A statistically significant empirical relationship between sediment and POC yield has been established for simulating them jointly in ESMs

Supporting Information:

- Supporting Information S1
- Data Set S1

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Citation:
Tan, Z., Leung, L. R., Li, H., Tesfa, T., Vanmaercke, M., Poesen, J., . . . Hartmann, J. (2017). A Global data analysis for representing sediment and particulate organic carbon yield in Earth System Models. *Water Resources Research*, *53*, 10,674–10,700. https://doi.org/10.1002/2017WR020806

Received 21 MAR 2017
Accepted 27 NOV 2017
Accepted article online 1 DEC 2017
Published online 21 DEC 2017

Abstract Although sediment yield (SY) from water erosion is ubiquitous and its environmental consequences are well recognized, its impacts on the global carbon cycle remain largely uncertain. This knowledge gap is partly due to the lack of soil erosion modeling in Earth System Models (ESMs), which are important tools used to understand the global carbon cycle and explore its changes. This study analyzed sediment and particulate organic carbon yield (CY) data from 1,081 and 38 small catchments (0.1–200 km^2), respectively, in different environments across the globe. Using multiple statistical analysis techniques, we explored environmental factors and hydrological processes important for SY and CY modeling in ESMs. Our results show clear correlations of high SY with traditional agriculture, seismicity and heavy storms, as well as strong correlations between SY and annual peak runoff. These highlight the potential limitation of SY models that represent only interrill and rill erosion because shallow overland flow and rill flow have limited transport capacity due to their hydraulic geometry to produce high SY. Further, our results suggest that SY modeling in ESMs should be implemented at the event scale to produce the catastrophic mass transport during episodic events. Several environmental factors such as seismicity and land management that are often not considered in current catchment-scale SY models can be important in controlling global SY. Our analyses show that SY is likely the primary control on CY in small catchments and a statistically significant empirical relationship is established to calculate SY and CY jointly in ESMs.

Plain Language Summary Sediment and organic carbon in the rivers produced by soil erosion are ubiquitous. Although they have important effects on the global carbon cycle, current models have limitations in representing sediment and particulate organic carbon (POC) yield at temporal and spatial scales relevant to Earth System Models (ESMs). By analyzing the sediment yield data from over 1000 small catchments across the globe, we identified environmental factors and hydrological processes important for modeling sediment yield in ESMs. Based on the POC yield data, we indicated that sediment yield is likely the primary control on POC yield. Importantly, we also established a statistical significant empirical relationship relating POC yield to sediment yield that can be used in ESMs.

1. Introduction

Recent studies have refuted the traditional view that aquatic ecosystems play a passive role in the global carbon cycle as a "pipe" to transport organic carbon from land to oceans. Increasingly, observational evidence suggests that a considerable fraction of carbon in the aquatic ecosystems is biogeochemically modified in its passage to the oceans (Aufdenkampe et al., 2011; Cole et al., 2007; Kempe, 1982, 1984; Raymond et al., 2013; Richey et al., 2009). Therefore, estimating the magnitude and timing of carbon fluxes from land to rivers is critical for understanding how the carbon cycle responds to perturbations (Regnier et al., 2013) and for modeling large-scale riverine biogeochemistry in Earth System Models (ESMs; Lal, 2003). More specifically, particulate organic carbon (POC) fluxes from land to rivers through sediment yield (SY) should be accounted for.

SY is a process that involves soil erosion, sediment transport, and deposition and is defined by the amount of sediment per unit basin area reaching a river basin outlet during a given period (units: t km^{-2} yr^{-1}; Dialynas et al., 2016; Hilton et al., 2015; Lal, 2003; Martin et al., 2013). SY is important in riverine biogeochemistry because the amount of POC detached in erosion and sediment transport can be large. Assuming 45% of the eroded organic carbon is in particulate form (Ludwig et al., 1996), Lal (2003) estimated that the yield of POC could be as large as 0.9–1.35 pg C yr^{-1}, which is as much as 13.5% of the global net ecosystem production (10 pg C yr^{-1}) by terrestrial ecosystems (Watson et al., 2000). Furthermore, the detached sediment and POC can significantly affect the function of aquatic ecosystems in rivers by changing the river morphology, turbidity, and biogeochemistry (Lacoul & Freedman, 2006; Valero-Garcés et al., 1999; Verstraeten & Poesen, 2002; Vihermaa et al., 2014). Lastly, the erosion and sediment transport processes that produce sediment and POC fluxes are highly sensitive to climate change and human disturbance (Bork et al., 2001; Li & Fang, 2016; Nachtergaele et al., 2001; Syvitski et al., 2005; Vanmaercke et al., 2015, 2016), so gaining a physical understanding of these process is critical for predicting their changes in the future.

Because the dynamics of SY is dependent on catchment area (scale) and catchment characteristics that vary spatially and temporally (heterogeneity), modeling SY at the global scale is challenging. Hence, SY is rarely represented in ESMs although different modeling approaches have been developed for simulating SY in specific catchments (Yu et al., 1999) and global large river basins (Syvitski & Milliman, 2007). According to Poesen et al. (1996), Renschler and Harbor (2002), and others, soil detachment is scale dependent as it could be dominated by splash and interrill erosion at the microscale (mm to m) and plot scale (m to 100 m), rill erosion at the field scale (100–10,000 m), and channel processes (e.g., gully erosion) and mass movement (e.g., landsliding) at the hillslope-catchment scale (>10,000 m). Sediment deposition could be more important in large catchments and river basins due to limited transport capacity (Foster, 1982; Meade et al., 1985). The scale issue is also critical as it influences data availability and quality for modeling (Renschler & Harbor, 2002): high-quality data are less available in small-size fields, entire hillslopes, and small catchments.

Heterogeneity represents another aspect that challenges SY modeling. For different catchments, different environmental factors may dominate the SY. They include topography, land cover, soil texture, soil moisture, soil organic carbon (SOC), rock fragment, lithology, and tectonics (Bryan, 2000; Dialynas et al., 2016; Knapen et al., 2007; Poesen et al., 1994; Renschler & Harbor, 2002; Syvitski & Milliman, 2007; Vanmaercke et al., 2015). Additionally, because land management strongly influence SY (Syvitski et al., 2005; Vanmaercke et al., 2015), there can be large differences between natural catchments and catchments affected by humans.

In the past decades, many studies have published observations of SY across the globe. Synergistic analysis of published data may yield more generalizable findings on SY that are much needed to advance global modeling. Recently, several studies have emerged in this direction to identify significant hydrological processes or environmental factors consistently at the continental or global scale (Mutema et al., 2015; Vanmaercke et al., 2014a, 2014b, 2015). However, some aspects of these studies may limit their values for informing SY modeling in ESMs. For instance, these studies usually did not focus on spatial scales that are relevant to ESMs, and only data with sparse spatial coverage were included in the analysis at the global scale (Mutema et al., 2015). In addition, although observations indicated that event-scale rainfall and runoff are more important than annual rainfall and runoff in determining SY (Beven et al., 2005; Bryan, 2000; Warrick et al., 2015), few previous studies have included these event-scale variables in their analyses. Further, none of these studies focused on linking POC fluxes with sediment fluxes in catchments resolved by ESMs, a relationship that has been established for large river basins (Galy et al., 2015).

This study aims to identify environmental factors that should be represented in ESMs in order to simulate SY globally. It also aims to explore the direction of implementing SY modeling in ESMs. To fill the aforementioned gaps, we analyzed sediment and POC yield data collected from 1,081 and 38 small catchments with a size range of 0.1–200 km^2 across the globe, respectively. This size range is comparable to the spatial scale of processes represented in the land and river components of ESMs that have a typical grid resolution of 15–150 km with subgrid parameterizations of fine-scale processes, such as hillslope water dynamics (Li et al., 2013). Although there are gaps in the geographical coverage, the large number of catchments represent different climate zones, topography, mineralogy, geology, lithology, and land covers, which govern important aspects of the spatial variability of SY globally. As our focus is on upstream catchments, data that were analyzed include low-order streams in the Mediterranean countries, East Africa, New Zealand, the Andes, Puerto Rico and the Southwest of China where SY is very high (Pelletier et al., 2015).

Overall, this study addresses four specific science questions relevant to modeling the yield of sediment and POC in ESMs: (1) What common natural and anthropogenic environmental factors are important for determining SY across different environments globally? (2) Is representing only interrill and rill erosion, as typical in existing SY models, sufficient for SY modeling in ESMs? (3) What is the appropriate time scale to simulate SY processes in ESMs? (4) What control POC fluxes in small catchments resolvable by ESMs? Section 2 describes the data and analysis methods. Results from the synthetic analysis are discussed in section 3. Section 4 discusses the implications of our results and limitations of the study, and section 5 summarizes the key findings and the necessary future studies.

2. Materials and Methods

2.1. Data Sources

Sediment and POC yield data (Figure 1) were obtained from various sources including values published in the literature and data sets (Table 1 and Appendix A). For instance, SY data for the United States were mainly derived from the USGS National Water Information System (NWIS; http://waterdata.usgs.gov/nwis). SY data for Canada, China, and Africa were obtained from the HYDAT database (http://collaboration.cmc.ec.gc.ca/cmc/hydrometrics/www/), the Chinese Hydrology Data Project (Henck et al., 2010, 2011), and the SY in Africa data set (Vanmaercke et al., 2014b), respectively. SY data for Europe were mainly compiled by Vanmaercke et al. (2011) for catchments less than 200 km^2 in size, with reliable outlet coordinates. Other SY data and most of the POC yield (CY) data were obtained from published articles through Google Scholar searches for relevant articles published in peer-reviewed journals in the field. Our search terms include "soil erosion," "sediment yield," "sediment loading," "sediment fluxes," "organic carbon loss," and "organic carbon fluxes." We only included values reported by articles that provided the outlet coordinate and observation period (no shorter than 1 year). The data sets and their detailed references can be found in the supporting information.

For SY that was reported more than 1 year, the data of each year were treated as a separate and independent measurement for temporal analysis. For spatial analysis, mean annual SY of each catchment was used. It was calculated by averaging the observed annual SY over the observational years. The averaging forces an equal weighting for each catchment to guarantee data independence in spatial analysis. Our method is different from Mutema et al. (2015), who treated data from multiple years for the same field as independent data. Figure 1 shows the locations of the catchments with SY and CY data provided at different temporal frequencies and supporting information Figures S1 and S2 show the observed mean annual SY and CY of

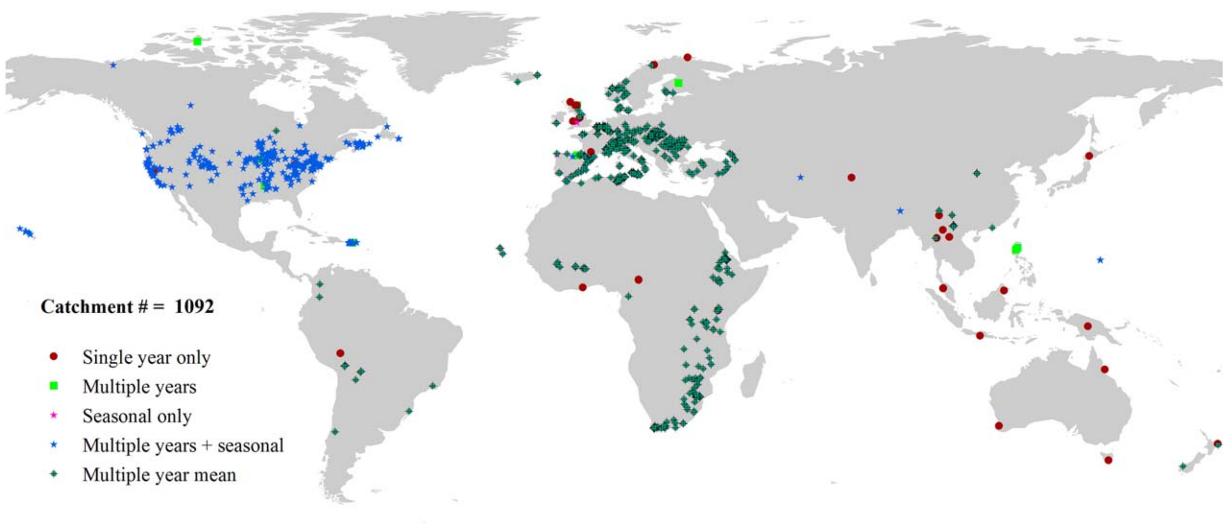

Figure 1. Outlet locations of the catchments with sediment yield (SY) or POC yield (CY) observations used in the study. Symbols indicate the duration and frequency of the SY and CY observations.

Table 1
Description of Response and Environmental Variables

Variable	Group	Description	Derived from	Range	Units
SY		Catchment sediment yield	Publications, data sets or personal communication	0.001–30,000	t km^{-2} yr^{-1}
CY		Catchment POC yield	Publications	0.0001–222.9	t km^{-2} yr^{-1}
CA	Scale	Catchment area	Same as SY	0.01–200	km^2
Q	Climate	Mean annual runoff	Publications, USGS NIWS, Canada HYDAT, or a 50 year 0.25° global data set of surface hydrology simulated by Variable Infiltration Capacity (VIC) model (Sheffield & Wood, 2007)	0.6–7,208	mm
Q_{peak}	Climate	Annual peak runoff	Publications, USGS NIWS, or Canada HYDAT	0.0001–1,801	mm
P	Climate	Mean annual precipitation	Publications or a 50 year 3-hourly 0.25° global data set of meteorological forcings for land surface modeling (Sheffield et al., 2006)	75–9,500	mm
RE	Climate	Average rainfall erosivity	A 50 year 3-hourly 0.25° global data set of meteorological forcings for land surface modeling (Sheffield et al., 2006)	1,135–55057	MJ mm ha^{-1} h^{-1} yr^{-1}
VarSM	Moisture	Soil moisture variability that is defined as the relative difference between the highest and lowest soil moisture, divided by the average soil moisture	A 0.25° global monthly soil moisture data set retrieved from AMSR-E, covering the period from 2002 June to 2011 July (Lu et al., 2009)	1.7–249.1	%
SLP	Topography	Average catchment slope	Publications or a 90 m resolution DEM (Lehner et al., 2008)	0.002–0.602	km km^{-1}
RSLP	Topography	Average river channel slope	Same as SLP	0.0001–0.306	km km^{-1}
PGA	Topography	Peak ground acceleration (a short-period ground motion parameter for the measure of ground movement amplitude) with an exceedance probability of 10% in 50 years	A 0.1° resolution global seismic hazard map (Giardini et al., 1999)	0–9.78	m s^{-2}
Frag	Topography	Topsoil coarse fragments volumetric content	A 1 km resolution global soil data product (Hengl et al., 2014)	0–57	%
Wood	Land use	Woodland coverage	Publications or a 0.05° global gridded land cover data set (Ke et al., 2012)	0–100	%
Grass	Land use	Grassland coverage	Same as wood	0–100	%
Crop	Land use	Cropland coverage	Same as wood	0–100	%
Clay	Soil	Topsoil clay content	Publications or a 1 km resolution global soil data product (Hengl et al., 2014)	3–63	%
Silt	Soil	Topsoil silt content	Same as clay	1–72	%
Sand	Soil	Topsoil sand content	Same as clay	0–90	%
SOC	Soil	Topsoil SOC content	Same as clay	0.5–41.7	%
LITH	Lithology	Lithology erodibility factor, defined by Syvitski and Milliman (2007) that was assigned to each lithology of a global lithology map depending on their erodibility	A 0.1° global gridded lithology map (Dürr et al., 2005)	0.1–3.0	N.A.
POP	Population	Population density of the catchment	A 2.5 arc min gridded population of the world data (GPW) version 3 (Center for International Earth Science Information Network Columbia University & Centro Internacional de Agricultura Tropical, 2005)	0–2,925	people km^{-2}

Note. "N.A." indicates not applicable. Variables are grouped based on the Spearman correlations in supporting information Table S1.

the study catchments, respectively. The U.S., Europe, and East Africa are the regions with higher spatial coverage. The SY data included in this study were measured either at a gauging station ($N = 800$) or calculated from reservoir siltation rates ($N = 281$) over a measuring period of at least 1 year. It should be noted that the SY estimated from reservoir siltation rates could be systematically higher than the estimates from gauging stations (Vanmaercke et al., 2011, 2014b) for two reasons: (1) reservoir surveys usually account for SY from both suspended load and bed load and (2) reservoir surveys overall better represent the importance of infrequent erosion events that often have a large impact on average SY, but that are often missed in gauging station measurements.

2.2. Definition of Variables

The units of sediment and POC yield (expressed as SY and CY, respectively) used here is t km^{-2} yr^{-1}. For data reported as discharge-weighted sediment concentration values, they were converted to yield per unit area using the known outlet runoff discharge and catchment area (CA) values.

Earlier experiments and field investigations identified various environmental factors that could affect sediment and POC yield (Bryan, 2000; Dialynas et al., 2016; Knapen et al., 2007; Ludwig et al., 1996; Poesen et al., 1994; Renschler & Harbor, 2002; Syvitski & Milliman, 2007; Vanmaercke et al., 2015). In this study, we included annual precipitation (P), annual runoff (Q), mean catchment slope (SLP), mean channel slope (RSLP), woodland fraction (Wood), grassland fraction (Grass), cropland fraction (Crop), topsoil (top 10 cm), clay content (Clay), topsoil silt content (Silt), topsoil sand content (Sand), topsoil rock fragment content (Frag), topsoil organic carbon content (SOC), relative monthly variability of soil moisture (VarSM), peak ground acceleration with an exceedance probability of 10% in 50 years (PGA), lithology erodibility factor (LITH), population (POP), and CA in our analysis. To investigate the effects of event-scale rainfall and runoff, we included two event-based environmental variables (Griffiths, 1981; Gonzalez-Hidalgo et al., 2010; López-Tarazóna et al., 2010; Renard et al., 1997; Tropeano, 1991): annual peak runoff (Q_{peak}) and rainfall erosivity (RE). RE is defined as the sum of the kinetic energy of raindrops, which is a function of rainfall intensity (Dunne et al., 2016; Poesen & Savat, 1981). The definition, data source, data range, and units of these variables are listed in Table 1. Based on the spatial correlations in supporting information Table S1, we classified the environmental variables into eight groups: "Scale," "Climate," "Topography," "Land use," "Soil," "Lithology," "Moisture," and "Population" (Table 1).

In most catchments, the data sources did not report all of the required environmental information. For them, we calculated the average values of the environmental factors within their boundaries using several widely used data sets. For each catchment, watershed boundaries were delineated using the Terrain Analysis Using Digital Elevation Model (TauDEM) tools (Tesfa et al., 2011; Wallis et al., 2009) from a global watershed data set that was developed based on the 90 m Digital Elevation Model (DEM) from the Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scale (HydroSHEDS) database (Lehner et al., 2008). In this study, a noncropland catchment is defined as a catchment where the areal fraction of arable land is less than 20% (Vanmaercke et al., 2015). The soil management status of the U.S. cropland catchments was mainly identified using a county-level data set of tillage practices compiled by the Conservation Technology Information Center (CTIC, 2008). This data set was reprocessed into three categories: conventional tillage, conservation tillage, and no-till and gap-filled for 2000–2008 (West et al., 2010). For cropland catchments outside of the U.S., they are recorded as "managed" only if there are specific land management activities (e.g., reduce tillage) reported on the catchments in publications. As shown in Figures 2 and 3, the data sets used in our study cover a broad range of SY and catchment characteristics at the global scale, so they can be used in comprehensive analyses to determine the environmental factors that influence SY and CY consistently across the globe. Figures 2 and 3 also show clearly the skewness of the variables. Like the SY data, only the average values of multiple-year data for each catchment were used in spatial analysis of CY.

2.3. Statistical Analysis

To address our first three questions, the common environmental factors important for determining SY across different catchments and the role of rill and interrill erosion and event-scale erosion were analyzed. To identify the spatial correlations between environmental factors and between environmental factors and SY, we used linear regression and simple principal component analysis (PCA). Linear regression and scatterplots were used to disclose the simple linear correlation and complex nonlinear correlations between the control factors and SY, respectively (Bryan, 2000; Hassan et al., 2008; Vanmaercke et al., 2014b, 2015). The scatterplots were also used to show the degree of consistency between the catchments with Q_{peak} available and all other catchments. For severely skewed variables (e.g., SLP and PGA) shown in Figures 2 and 3, they were log-transformed before being analyzed using linear regression and PCA (Yang et al., 2016) because these analyses only apply to variables with the normal distribution. In the PCA, all variables were *z*-

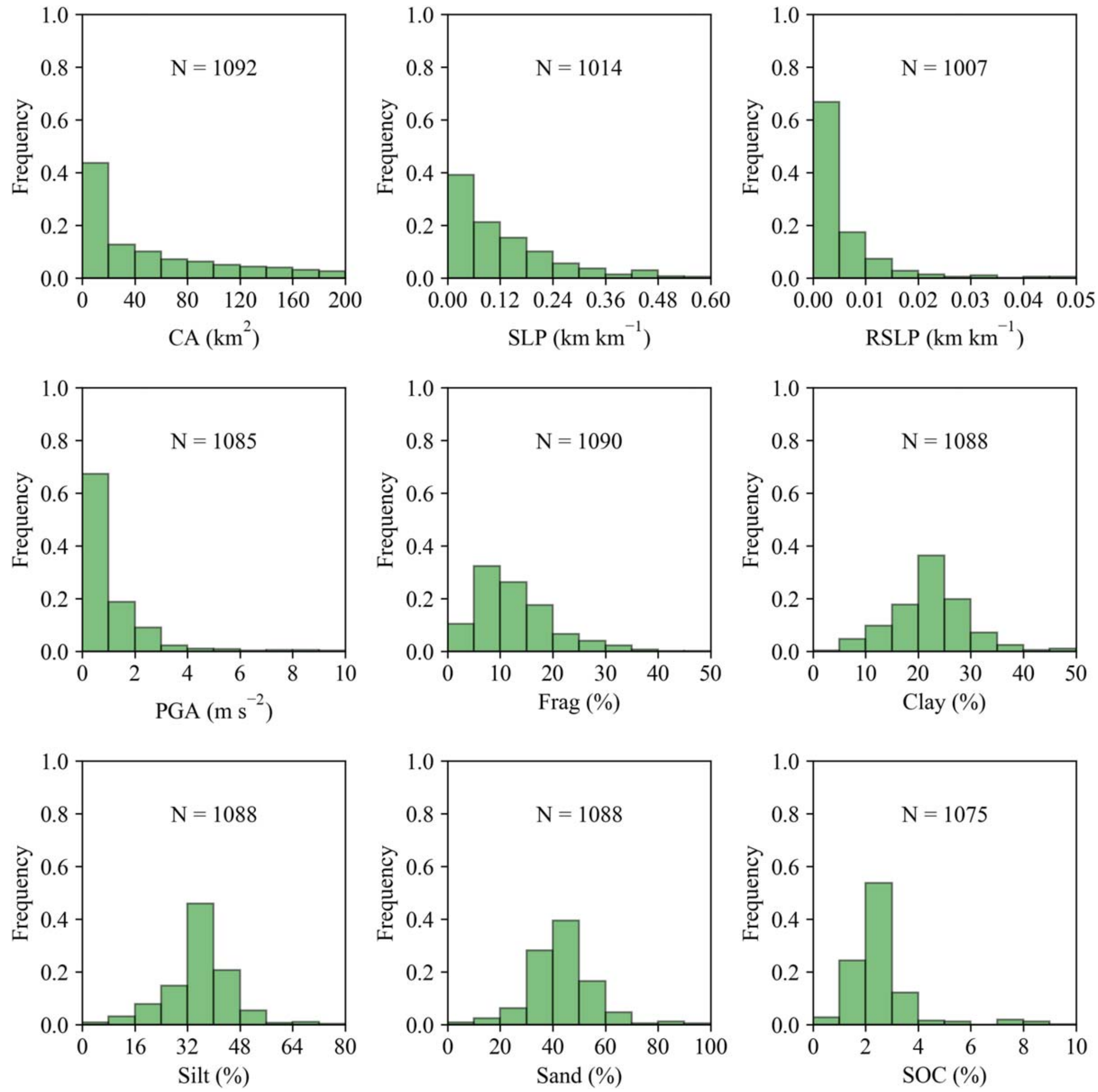

Figure 2. Relative frequency distribution of catchment characteristics, including variables related to catchment scale (CA), topography (SLP, RSLP, PGA, and Frag), and soil (Clay, Silt, Sand, and SOC). The number of catchments involved in each analysis is also presented.

standardized and principal components (PCs) were calculated. Each PC is linearly uncorrelated in the spatial domain and can explain a certain percentage of the spatial variance of environmental factors, called component scores. The first two PCs that have the largest component scores, representing the dominant variance of environmental variables, were used in further analysis. Additionally, by projecting the SY vector onto the PCs, we can compare the dependence of SY on the two PCs (Mutema et al., 2015). The validity of the PCA was tested using the Bartlett tests of sphericity ($p < 0.001$) and the Kaiser-Meyer-Olkin measures of sampling adequacy (Snedecor & Cochran, 1989).

To investigate the impacts of human activities on SY, we used the one-way analysis of variance (ANOVA). The one-way ANOVA test is widely used to check the existence of significant differences between more than two data samples. In ANOVA, we tested the two-tier hypotheses that (1) the mean SYs of the three catchment groups with different land management activities are equal and (2) if the first hypothesis is rejected based on the *F*-statistics ($p < 0.05$), the mean SYs of any two catchment groups are equal based on the Tukey's honest significant difference test.

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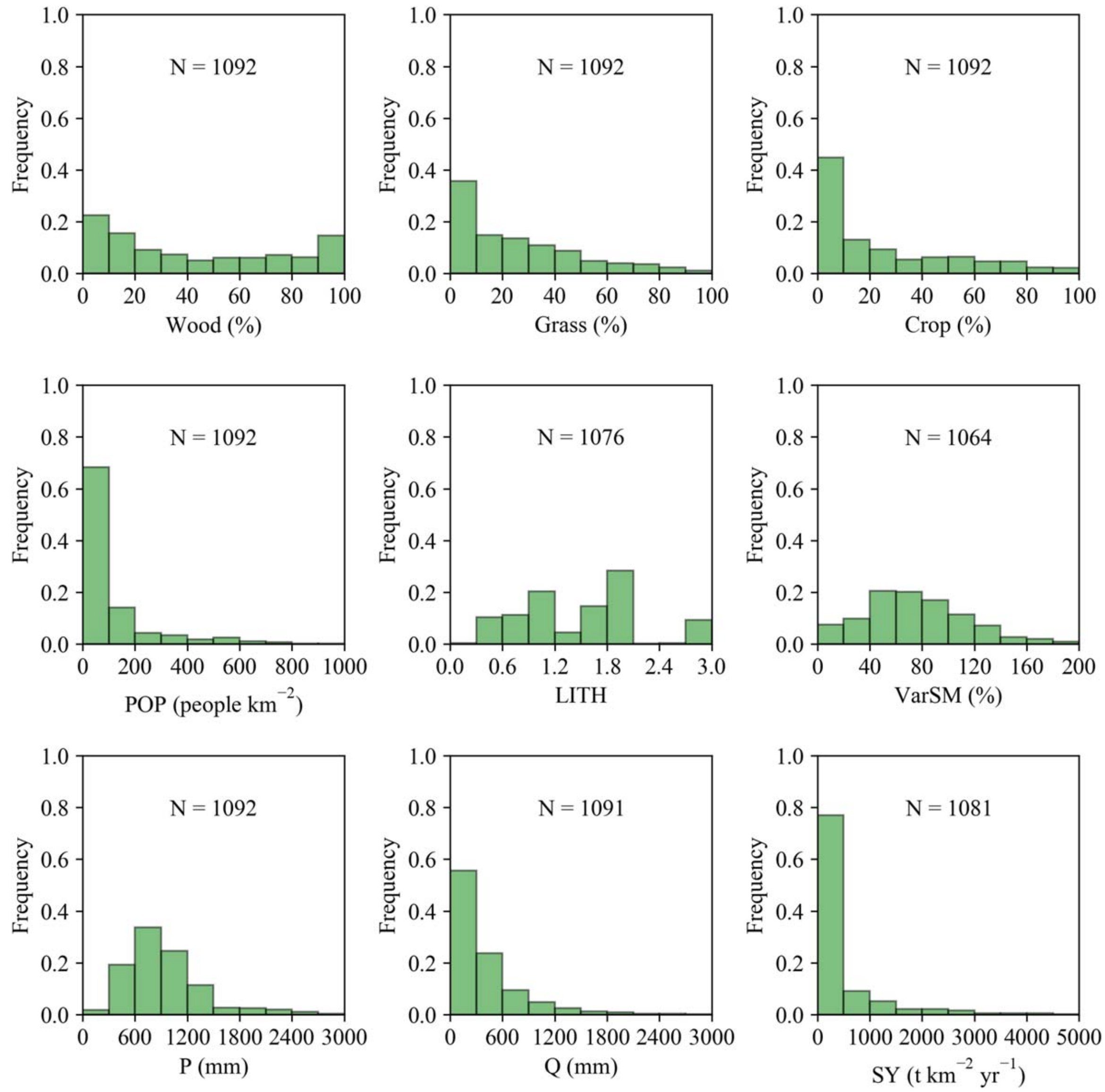

Figure 3. Relative frequency distribution of catchment characteristics, including variables related to land use (Wood, Grass, and Crop), population (POP), lithology (LITH), moisture (VarSM), and climate (P and Q), and relative frequency distribution of sediment yield (SY). The number of catchments involved in each analysis is also presented.

The complex correlations between environmental variables make it difficult to evaluate the important factors in controlling SY across the globe. The partial *r* coefficient and the corresponding *p*-value, calculated by controlling the interfactor effects from less correlated variables (Vanmaercke et al., 2014b), might be instructive on the relative significance of the association of SY with environmental variables, especially the relative significance of highly correlated variables. For the partial *r*, the highly correlated variables were identified and grouped based on the full Spearman correlation matrix of environmental variables (supporting information Table S1), with no requirement for transformation of the skewed variables. Since we are particularly interested in examining the explanatory power of event-scale variables (e.g., Q_{peak} and RE) on the spatial and temporal variability of SY relative to that of Q and P, the partial *r* was only calculated from catchments with Q_{peak} and RE available. For the temporal variability of SY, the partial *r* was calculated from the catchments that have at least three measurements of SY in different years. Further, it should be expected that the partial *r* for temporal correlations would not be affected by many variables that do not vary temporally, such as soil texture.

Lastly, to address the fourth question of what control POC fluxes, multiple linear regression (MLR) models were used to establish the empirical relationships for SY and CY. This analysis can also help evaluate the importance and independence of the environmental factors in controlling SY at the global scale. To construct the optimal MLR of SY, we first employed an ensemble (10,000 times) of backward stepwise model selection (Vanmaercke et al., 2014b) to select environmental variables that have significant *F*-statistics ($p < 0.05$) for different subsets of the study catchments with Q_{peak} available (each subset includes half of the study catchments). Then, we made a single backward stepwise selection using the whole data set to further filter out variables that have less independent explanatory power on the spatial variability of SY. This way, the constructed MLR is less likely to be biased by influential data. For the optimal MLR of CY, because there are limited CY measurements, we only employed a single backward stepwise selection involving all environmental variables and SY. The variables with significant *F*-statistics were selected. As described in section 2.2, all of the above tests except the partial *r* for temporal correlations were based on the average values of the variables in Table 1 for each catchment if the catchment has multiple measurements in different years.

3. Results and Interpretations

3.1. Effects of Environmental Factors on SY

At the global scale, when only the main effect is considered using simple linear regressions (Figures 4 and 5), factors including Clay, Sand, PGA, POP, and VarSM show the strongest spatial correlations with the natural logarithm of the observed SY. More specifically, ln(SY) is positively correlated with Clay, PGA, and POP and negatively correlated with Sand and VarSM. The spatial variability of all environmental factors can be best represented by two PCs in the PCA (Figure 6), with the first PC mainly corresponding to the variability of topography and the second PC mainly corresponding to the variability of climate. Not surprisingly, none of the factors can explain the spatial variability of SY at the global scale as predominantly as those reported in regional-scale analyses or large river basins (Syvitski & Milliman, 2007; Vanmaercke et al., 2014a, 2014b, 2015). But among the study factors, the relationships of PGA, POP, and Wood with SY are almost consistent with the previously reported relationships. The influence of seismic activity (expressed as PGA) on SY (Figure 4 and Table 2) is well documented in different regions (Broeckx et al., 2016; Dadson et al., 2003; Hovius, 1998; Vanmaercke et al., 2014a, 2014b). The weaker correlation between PGA and SY found in this study could be caused by a large fraction of the study catchments being located in regions with low seismic activities, e.g., the U.S. Midwest (Giardini et al., 1999). As shown in Figure 4 and Table 2, PGA has a closer correlation with SY than SLP in the analyses of linear regression and partial *r*. As documented by Hovius (1998), in very active mountain belts, slope/relief can reach a threshold point that an increase in uplift rate beyond the threshold causes further increases in SY without a corresponding increase in slope. It is also possible that active seismicity can weaken substrates/lithologies (Molnar et al., 2007) or cause landsliding (Dadson et al., 2003). Thus, there are very high erosion rates even in regions where topographic relief is low. It is not surprising that POP is positively correlated to SY because human activities (e.g., agriculture, human-induced wildfire, infrastructure construction, and mining) are known to increase SY significantly. The effects of human activities on SY will be discussed in section 3.2. In contrast, because the presence of trees is known to protect soils from both rainfall-driven and runoff-driven erosion (Renard et al., 1997), Wood is negatively correlated to SY globally.

The positive correlation between Clay and SY as shown in Figure 4 is particularly interesting, given that many soil erosion models use clay content as a control factor on erosion even though there is no consensus on its effect. In some models, high clay content in soils is simulated to reduce rill erosion (Flanagan & Nearing, 1995; Renard et al., 1997), as clay content can increase soil aggregation and cohesion (Knapen et al., 2007; Panagos et al., 2014). In other models that include the Clay effect, high soil clay content is simulated to increase SY (Cohen et al., 2009; Coulthard et al., 1996; Temme & Vanwalleghem, 2016), as the occurrence of rill erosion, piping erosion and landsliding was observed to be high in clay soils (Broeckx et al., 2016; Gilley et al., 1993; Verachtert et al., 2011). Here we noted from Figure 6 that the projection of clay fraction and slope on the first PC lies on the opposite side of each other but the projection of clay fraction and runoff on the second PC lie on the same side. So it is possible that the positive correlation between Clay and SY is mainly caused by the increase of flow-related erosion, such as rill erosion and piping erosion, in clay soils (Roering et al., 1999).

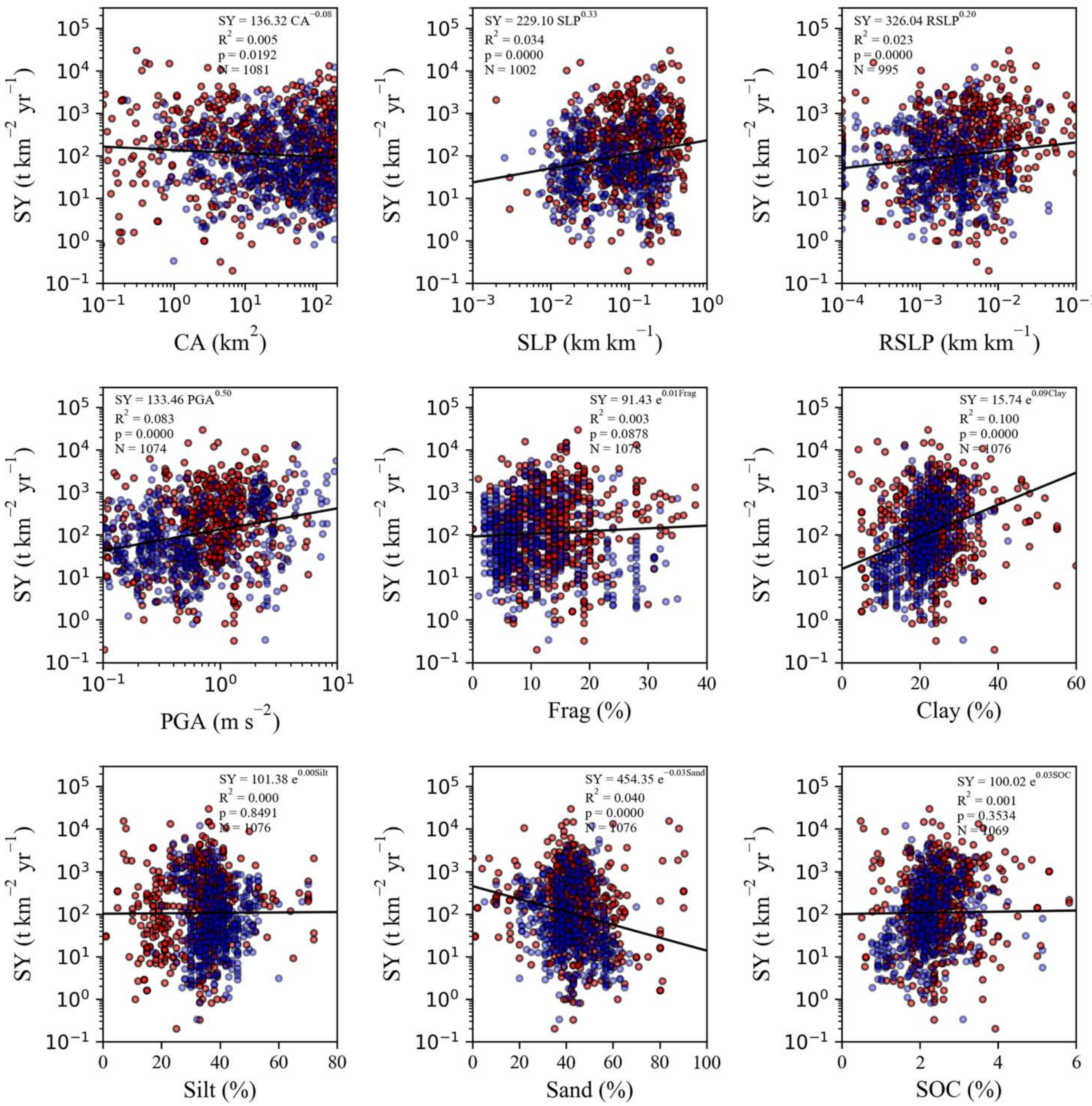

Figure 4. Scatterplots of observed sediment yield versus variables related to catchment scale (CA), topography (SLP, RSLP, PGA, and Frag), and soil (Clay, Silt, Sand, and SOC). Black lines show the linear regression fit which is based on all available catchments. Blue and red dots represent data from catchments with and without available Q_{peak} data, respectively.

The relationship between VarSM and SY shown in Figure 5 is not consistent with some plot-scale experiments (Bryan, 2000). Because soil water content may increase soil resistance to rain splash and concentrated flow (Gilley et al., 1993), intense rainfall occurring days before greening of the land in the arid and semiarid tropics can produce high SY (Nachtergaele et al., 2001). Thus, it is expected that the seasonality of soil moisture (expressed as VarSM) should be positively correlated with SY. But as presented in Figure 5 and Tables 2 and 3, VarSM does not have any positive impacts on the spatial and temporal variability of SY. It should also

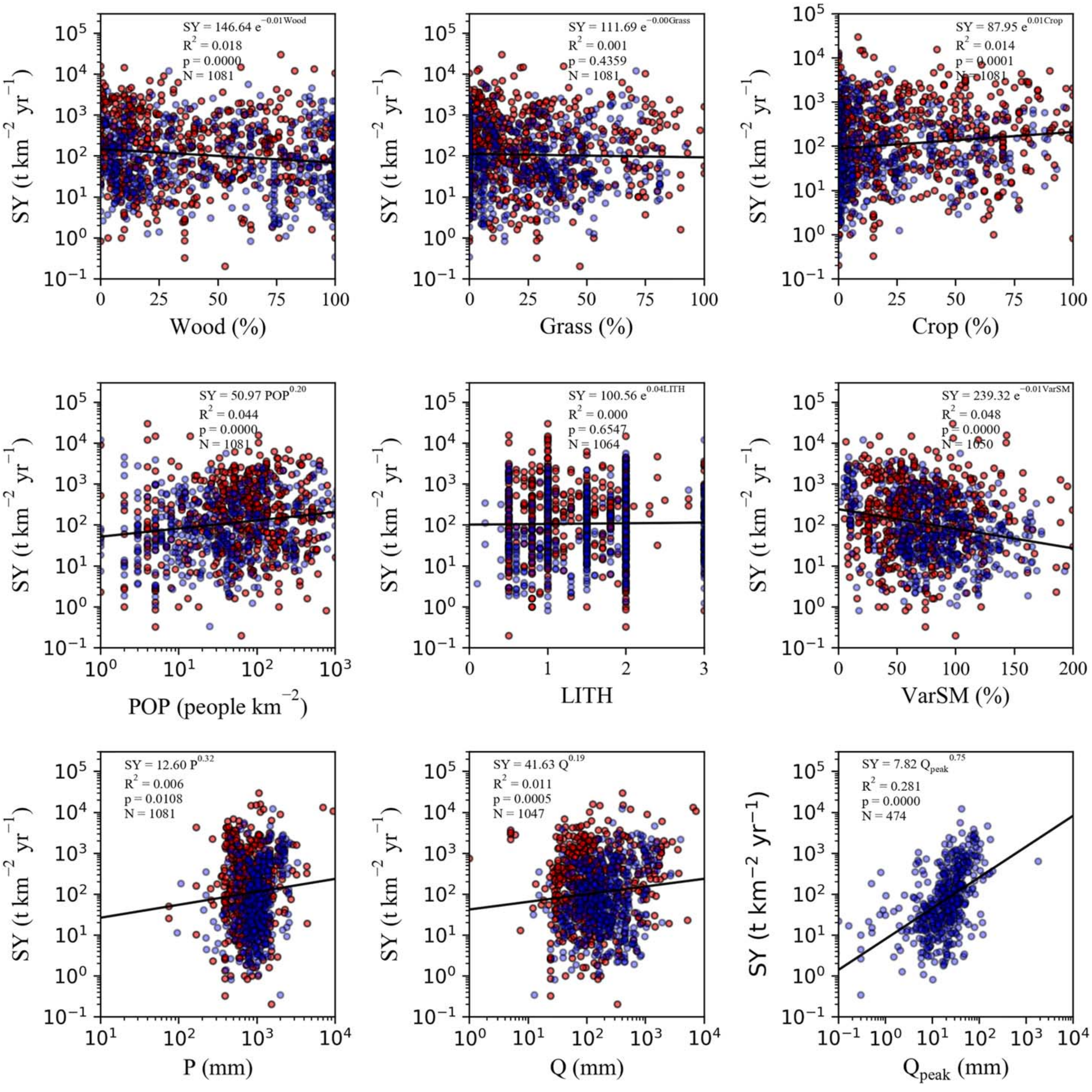

Figure 5. Scatterplots of observed sediment yield versus land use (Wood, Grass, and Crop), population (POP), lithology (LITH), moisture (VarSM), and climate (P, Q, and Q_{peak}). Black lines show the linear regression fit which is based on all available catchments. Blue and red dots represent data from catchments with and without available Q_{peak} data, respectively.

be noted that VarSM is not necessarily a proxy for rainfall intensity and can also be very low in some high-relief terrain, such as the mountainous western U.S. (supporting information Figure S3). Because high-relief terrain usually corresponds to high SY (supporting information Figure S1), it is possible that any positive impacts of VarSM on SY have been cancelled out by the negative correlations between VarSM and topography variables (supporting information Table S1).

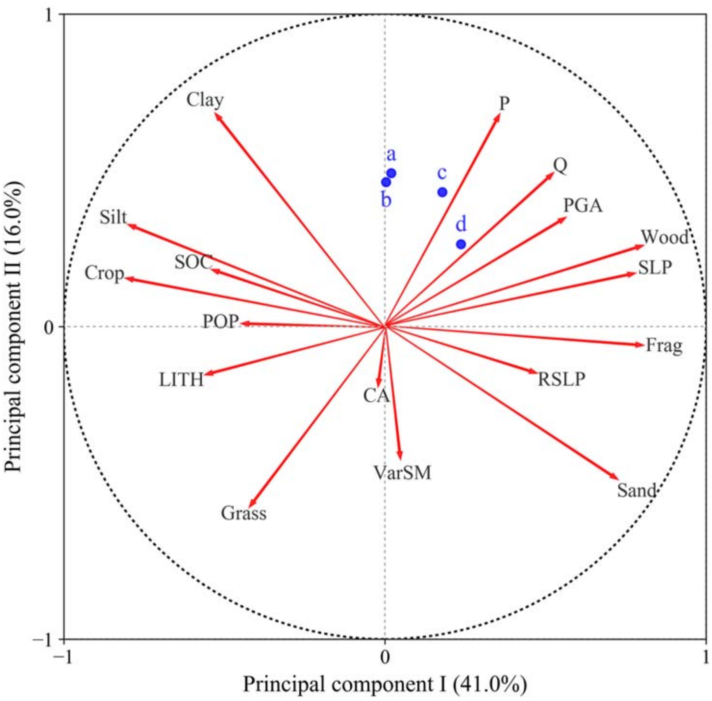

Figure 6. Principal component analysis (PCA) with environmental factors as active variables and sediment yield as supplementary variables. "a," "b," "c," and "d" represent sediment yield from catchments in the size range of 0.1–10, 10–30, 30–100, and 100–200 km^2, respectively. Vectors in red are the loadings of each environmental factor for the first and second PCs. The projection of each vector onto the PCs is a measure of the correlation between the corresponding factor and the PCs. The projection of each blue dot onto the PCs is a measure of the correlation between the corresponding SY group and the PCs.

Catchment scale (expressed as CA) is known to have two opposite effects on SY: in catchments dominated by steep topography, SY could increase with CA due to the effect of larger concentrated water flow, but in catchments where flat topography dominates, SY could decrease with CA due to the effect of larger sediment deposition (de Vente & Poesen, 2005; Foster, 1982; Pelletier, 2012; Poesen et al., 1996). In Figures 4 and 6, CA is negatively correlated with SY and on the opposite side of the four SY scale groups ("a," "b," "c," and "d") in the second PC. These results might indicate the importance of representing sediment deposition in SY modeling in ESMs. However, we are cautious about the explanation because the relationship between CA and SY on the second PC may also be caused by the negative relationship of CA with Q and P (Figure 6).

Several factors including SOC and LITH that were previously known to significantly affect SY in plot or field experiments are not strongly correlated to SY in our analyses (Hassan et al., 2008; Rapp, 1998). Many plot-scale and catchment-scale soil erosion models include SOC as a negative factor to soil detachment (Panagos et al., 2014) because SOC can increase soil aggregation and cohesion (Rapp, 1998). As shown in both Figure 4 and Table 2, the inclusion of SOC for SY modeling in ESMs might not reduce simulation uncertainty. A possible reason is the lack of high-quality fine-scale SOC data to allow incorporation of the SOC effect on SY at the global scale. High erosion rates were documented previously in loess-rich and other regions where substrate strength is weak (Dadson et al., 2003; Syvitski & Milliman, 2007), such as the Loess Plateau of China (Hassan et al., 2008). In this study, we do not find strong correlations between lithology (expressed as LITH) and the spatial variability of SY (Figure 5 and supporting information Figure S3), even though many of the study catchments are located in loess-rich regions. One possible reason is the poor quality of the lithology score data. As shown in Figure 5, the lithology score only varies in the range of 0–3 across the globe in our data set even though rock strength may vary over three orders of magnitude in relatively small regions such as the island of Taiwan (Dadson et al., 2003). In addition, as described by Vanmaercke et al. (2014b), the interaction between lithology and other stronger erosion factors (supporting information Table S1), i.e., topography and land use, may also weaken its main effect on SY.

Importantly, it should be noted that the dependence of SY on the topography and climate PCs in Figure 6 is almost consistent for the four SY scale groups. This might suggest that the correlations between SY and the environmental factors are not significantly dependent on catchment scale in the size range of 0.1–200 km^2. This provides some support for the statistically significant relationships identified in this study to provide a starting point for modeling SY in ESMs.

3.2. Effects of Land Cover and Management on SY

Anthropogenic factors are also known to be important for SY. To examine the global-scale effects of land use and management practices on SY, we used the one-way ANOVA test to evaluate the difference of SY in three land use and management groups: noncropland, traditional cropland, and cropland with soil conservation management (Figure 7). This test rejected the hypothesis that the three groups have statistically equal mean SYs ($p = 9.6 \times 10^{-5}$). In comparison with "pristine" catchments (mean SY: 391 t km^{-2} yr^{-1}), cropland-dominated catchments have significantly larger SY (mean: 569 t km^{-2} yr^{-1}; $p < 0.05$), but cropland with soil conservation management (e.g., reduced tillage, no tillage, and stone lines) has insignificantly smaller SY (mean: 213 t km^{-2} yr^{-1}; $p > 0.05$).

The above results are consistent with the findings of previous studies that human activities can affect SY greatly (Lanckriet et al., 2012; Maetens et al., 2012; Montgomery, 2007; Nyssen et al., 2009; Vanmaercke et al., 2015). First, the development of ephemeral gully on cropland could be significantly faster than that

Table 2
Partial Correlation Coefficient (Partial r) and the Corresponding p-Value for the Mean Annual Value of Each Controlling Variable in Table 1 With the Natural Logarithm of Mean Annual Sediment Yield, ln(SY)

Variable	Factor	Partial *r*	*p*-Value
ln(Q_{peak})	Climate	0.52	4.9×10^{-29}
ln(Q)	Climate	0.32	7.5×10^{-11}
ln(PGA)	Topography	0.27	2.2×10^{-8}
ln(SLP)	Topography	0.23	1.0×10^{-5}
ln(P)	Climate	0.20	6.5×10^{-5}
Wood	Land use	−0.17	0.0012
Clay	Soil	0.15	0.0026
ln(RE)	Climate	0.13	0.0140

Note. Only variables that are significantly partially correlated ($p < 0.05$) are shown and variables in bold are very significantly partially correlated ($p < 0.0001$).

on dense woodland due to the decrease of critical flow shear stress τ_c (Nachtergaele et al., 2001). This may help explain the strikingly higher SY of 569 t km^{-2} yr^{-1} in traditional cropland compared to the mean erosion rate of 90 t km^{-2} yr^{-1} (Cerdan et al., 2010; de Vente & Poesen, 2005) reported for fine-scale plots and fields where sediment mobilization is dominated by rain splash, interrill, and rill erosion. Second, because the τ_c values of no-till soils could be twice as large as the τ_c of tilled soils due to topsoil compaction (Franti et al., 1999; Laflen & Beasly, 1960), soil conservation management, especially no tillage, can clearly decrease the erodibility of topsoils to concentrated flow compared with conventional tillage (Knapen et al., 2007). Overall, the mean SY of conserved cropland is much lower than that of traditional cropland ($p < 0.05$).

It should be noted that in the one-way ANOVA, anthropogenic influence is narrowly defined as agricultural activities including soil and water conservation measures. In fact, other human activities could also increase or decrease SY significantly. For example, the occurrence of fire is often related to human activities and SY was reported to increase significantly after fire (Malmon et al., 2007; Scott et al., 1998; Warrick et al., 2012). By using available global fire data sets (Giglio et al., 2013; Randerson et al., 2012), it is possible to investigate the effect of fire in the future. In addition, as population (expressed as POP) is strongly correlated to SY in the linear regression shown in Figure 5, it is possible that other human activities, e.g., land leveling, logging and mining, are also important in increasing SY (Douglas, 1996; Maetens et al., 2012).

3.3. Effects of Environmental Factors on CY

When only the main effect is considered using simple linear regressions (Figures 8 and 9), factors including Silt, SOC, Wood, Grass, P, and SY show significant spatial correlations (p-value < 0.05) with the natural logarithm of the observed CY. More specifically, ln(CY) is positively correlated with Grass, P, and SY and negatively correlated with Silt, SOC, and Wood. However, the correlations of CY with Silt, SOC, Wood, Grass, and P (especially the negative correlations of CY with SOC) could be misleading because they may result from interactions of those factors with SY. To remove the possible interactions, simple linear regressions were also performed for POC concentration in suspended sediment (CY divided by SY) with the environmental factors (supporting information Figures S4 and S5). The new regressions clearly indicate that POC concentration in suspended sediment is not significantly correlated with the above environmental factors except for SY. Specially, the concentration is not significantly correlated with vegetation productivity related factors (e.g., Wood and SOC), which is consistent with the finding of Galy et al. (2015). These analyses suggest that sediment yield is likely the primary control on POC transport efficiency (Galy et al., 2015).

The decreasing CY at high SY is often explained by the observed decrease in biospheric POC concentration with depth in the soil profiles (Galy et al., 2015; Jobbágy & Jackson, 2000): at low SY surface matrial characterized by high POC concentrations is preferentially detached and exported while at high SY more material in the deeper soil layers with lower POC concentrations is detached and exported. In addition, this relationship can also be explained by the fact that water flow at high SY has much larger shear stress to carry higher fractions of coarse material such as sand and gravel that is characterized by low biospheric POC concentrations (Lal, 2003). A notable strength of the latter interpretation is that it can also explain the lack of negative correlation between POC concentration and SOC shown in supporting information Figure S4.

Table 3
Partial Correlation Coefficient (Partial r) and the Corresponding p-Value for the Time Series of Each Climate Variable (Table 1) With the Natural Logarithm of Sediment Yield, ln(SY)

Variable	Factor	Partial *r*	*p*-Value
ln(Q_{peak})	Climate	0.52	1.3×10^{-101}
ln(Q)	Climate	0.43	2.8×10^{-68}
ln(P)	Climate	0.33	8.8×10^{-38}
ln(RE)	Climate	0.23	2.3×10^{-18}
VarSM	Moisture	−0.05	0.0535

Note. Variables in bold are very significantly partially correlated ($p < 0.0001$) and variable in italic are insignificant ($p > 0.05$).

3.4. Event-Scale Variables

Many existing SY models simulate global and regional SY at the annual time step using annual rainfall and/or runoff as drivers (de Vente et al., 2013; de Vente & Poesen, 2005; Quinton et al., 2006; Tucker & Bras, 2000). However, studies indicated that most of the observed SY in small catchments may be contributed by several large storms (Beven et al., 2005; Dadson et al., 2003; Gonzalez-Hidalgo et al.,

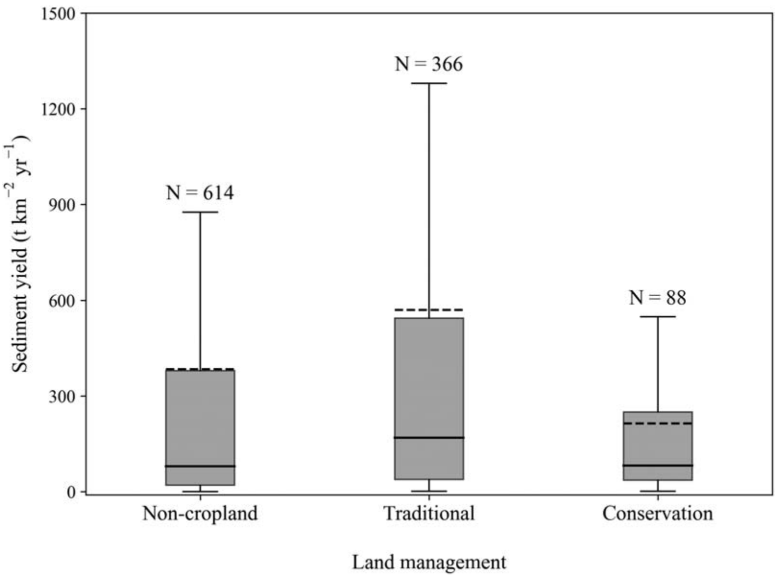

Figure 7. Distribution of SY for different land management groups (noncropland: cropland use is less than 20%; Traditional: cropland with no soil conservation management; Conservation: cropland with some soil conservation management, e.g., reduced tillage). Bold solid lines are the median SY of land management groups and dashed lines are the mean SY of land management groups.

2010). To examine whether SY in small catchments should be modeled at the event-scale, we compared the SY dependence on the two event-scale variables (peak runoff Q_{peak} and rainfall erosivity RE) with the dependence on the two annual-scale variables (annual runoff Q and annual rainfall P) in the partial *r* and MLR analyses. It should be noted that only 472 catchments in our data set have Q_{peak}, RE and all other variables available, and most of these catchments are located in the U.S., Canada, and Puerto Rico. Although the scatterplots in Figures 4 and 5 show that the controlling factors of SY in these catchments do not differ significantly from those in the other catchments, we should be cautious to apply the conclusions drawn from the partial *r* and MLR analyses to other areas. As shown in Tables 2 and 3, Q_{peak} has larger partial *r* coefficients than other climate variables, such as Q, P, and RE. It means that in the study catchments Q_{peak} is more capable of explaining the spatial and temporal variability of SY than other climatic factors. This is consistent with the simple linear regression (Figure 5), in which Q_{peak} shows the largest main effect on the spatial variability of SY.

The results from our event-scale analysis are particularly interesting, given that Q_{peak} represents only the maximum daily runoff in a year and there are broad ranges of climate, topography, land cover, and other variations even in the 472 catchments. There could be two reasons for the explanatory power of Q_{peak}: (1) in most of the catchments where Q_{peak} has dominant effects, SY is overwhelmingly produced by storm-driven erosion (Dadson et al., 2003) or (2) eroded sediment deposited in the channels or lowland (Nyssen et al., 2004) can be more effectively transported downstream during large rain events when sediment transport capacity significantly increases (Dadson et al., 2003; Foster, 1982). In the first case, large storms may trigger gully erosion in low-relief terrain (Palleiro et al., 2014; Poesen et al., 1996, 2003) and landsliding in high-relief terrain (Dadson et al., 2003). In the second case, large storms may trigger debris flow that flushes colluvial sediment from the mountain belt (Dadson et al., 2003).

RE is used in the well-known Revised Universal Soil Loss Equation (RUSLE) to represent the effect of interrill erosion on soil detachment rates (Panagos et al., 2014; Renard et al., 1997). However, as presented in Tables 2 and 3, RE does not achieve comparable explanatory power to Q_{peak}. In fact RE is even worse than annual rainfall in explaining the spatial and temporal variability of the SY subset. It should be noted that the 3-hourly meteorological forcing data set used in the Variable Infiltration Capacity (VIC) model simulation may not be reliable in resolving the short-term variations of rainfall at the small catchment scale. This possibility indicates that SY models that use RE to represent rainfall-driven erosion may require high-quality

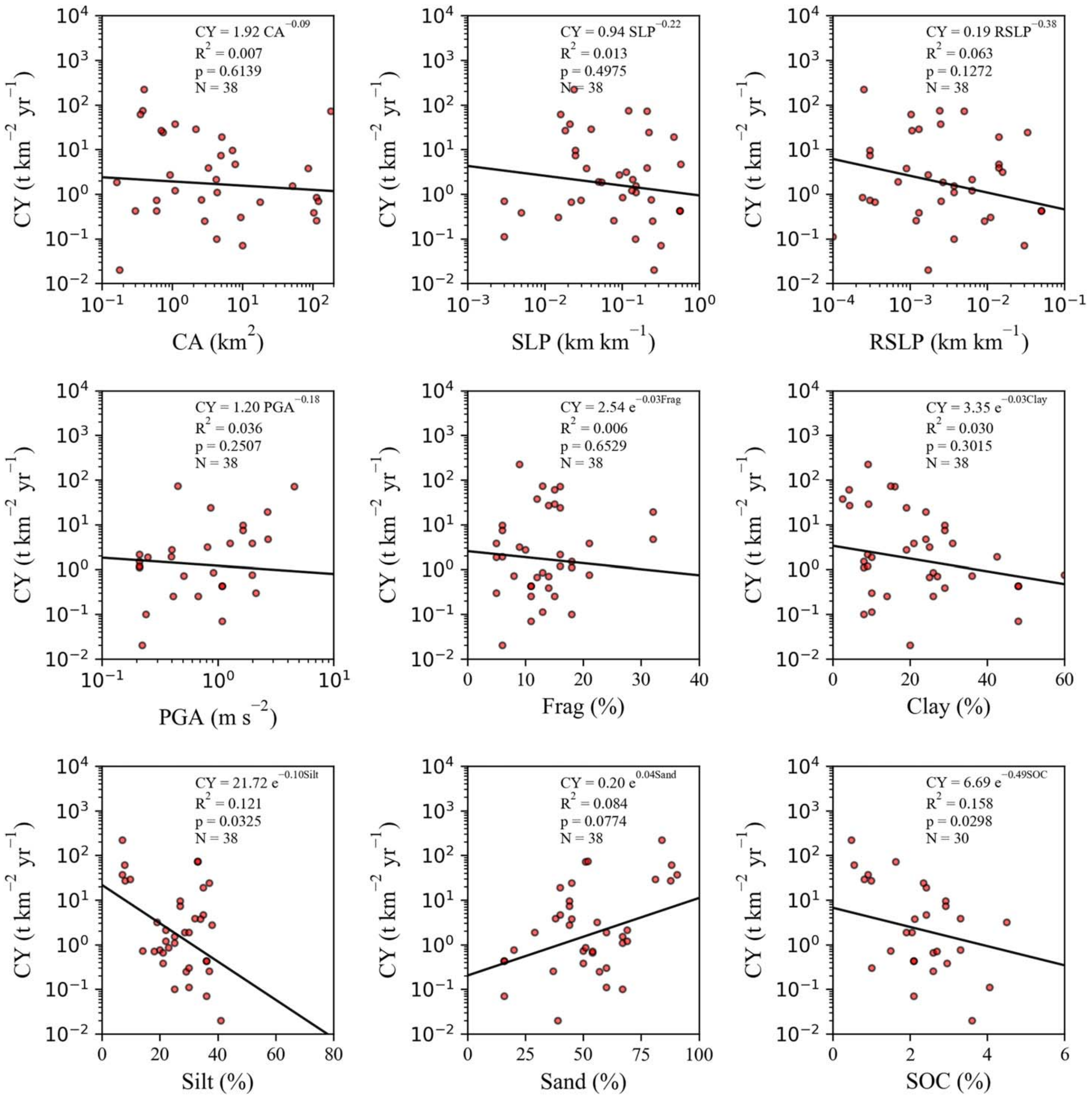

Figure 8. Scatterplots of observed POC yield (CY) versus variables related to catchment scale (CA), topography (SLP, RSLP, PGA, and Frag), and soil (Clay, Silt, Sand, and SOC). Black lines show the linear regression fits.

fine-resolution rainfall data to produce reasonable estimates of SY. In addition, the low contribution of inter-rill erosion to SY may also partly explain the poor performance of RE here (Poesen et al., 2003).

3.5. Regressions of SY and CY

As presented above, the relationships between SY and environmental factors can be very complex because of interactions among processes and environmental variables. By using an ensemble of stepwise backward MLR, we identified seven variables that are influential on the spatial variability of SY, including variables related to topography, land cover, and climate (supporting information Figure S6). Five of the seven variables passed the second-step stepwise backward selection, including Q_{peak}, PGA, Clay, Frag, and Wood. The analysis was processed on the 472 catchments with event-scale variables available, as Q_{peak} appears to be the most influential variable in some of our tests. The optimal MLR for SY can be written as (Figure 10):

$$\ln(SY)=1.44-0.01\ \text{Wood}+0.09\ \text{Clay}-0.03\ \text{Frag}+0.64\ \ln(Q_{peak})+0.49\ \ln(PGA). \quad (1)$$

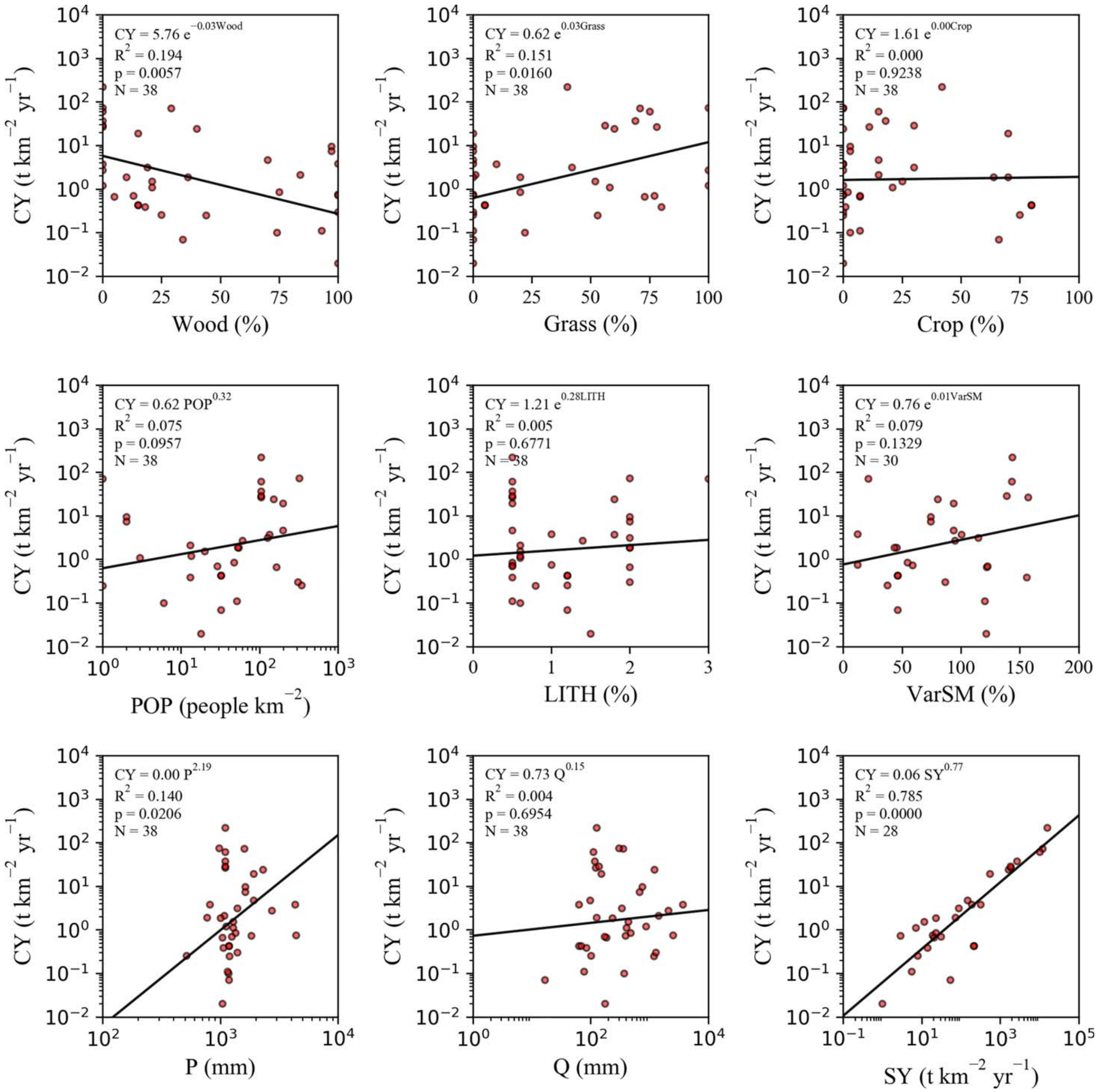

Figure 9. Scatterplots of observed POC yield (CY) versus land use (Wood, Grass, and Crop), population (POP), lithology (LITH), moisture (VarSM), and climate (P and Q), and sediment yield (SY). Black lines show the linear regression fits.

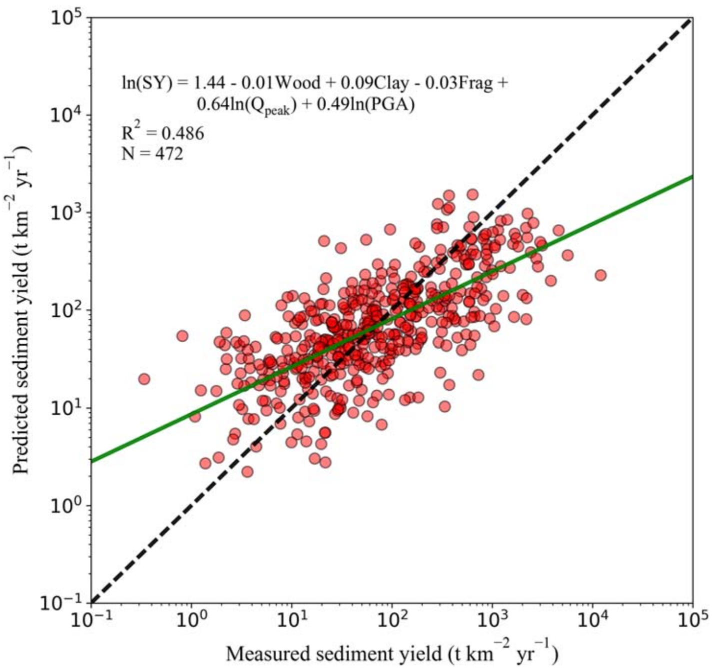

Figure 10. Observed sediment yield versus predicted sediment yield based on multiple linear regression (MLR) models. The shown formula is the MLR model used to predict sediment yield. The black dashed line is the 1:1 reference. The green solid line is the linear regression between the observed and predicted sediment yield.

The *p*-value of the *F*-statistics and the Akaike information criterion (AIC) score for the MLR are 3.68×10^{-45} and 1,612, respectively, indicating that this empirical relationship is significant. The high AIC score indicates that the regression models can achieve the best match with observations using the least number of parameters. The standard error (SE) of the intercept is 0.365 and the SEs of the coefficients for ln(Q_{peak}), ln(PGA), Wood, Clay, and Frag are 0.053, 0.064, 0.002, 0.012, and 0.011, respectively. The Wood and Frag terms in equation (1) are relatively less significant because of their high correlations with each other and also with ln(Q_{peak}) and ln(PGA) (see supporting information Table S1). Because cropland with and without soil conservation management has very different SY values, cropland was not selected as a predictor in equation (1). As discussed in section 3.3, however, human activities are an important factor in determining SY and their effects must be considered carefully based on crop management. In the MLR model, topsoil rock fragment (expressed as Frag) is found to have influence on the spatial variability of SY that is independent of the effects of topography. It is consistent with the findings that Frag increases soil resistance to both rainfall-driven and runoff-driven erosion (Poesen et al., 1994, 1999; van Wesemael et al., 1995). However, its effect is rarely included in empirical and process-based SY models. In equation (1), affected by the changes of climate, land use, and land cover, some terms (e.g., Wood) are possibly not stationary, which can reduce the effectiveness of the MLR as the best linear unbiased estimator. To reduce the impact of this nonstationarity, dynamic land use and land cover data could be useful in future studies.

By comparing Figure 10 with Figures 4 and 5, we can see that the predicted SY is mainly controlled by the spatial variability of Q_{peak}. Meanwhile, there is a visible bias shown in Figure 10 that is related to the overestimates of SY when Q_{peak} is in the range of 10–100 mm (supporting information Figure S7). By plotting the model-data residual as a function of the latitude and longitude (supporting information Figure S8), we notice that the catchments where SY is poorly predicted by equation (1) are mainly located around Lake Tahoe and in Wisconsin and Minnesota where a large amount of runoff is produced by snowmelt. It is possible that peak runoff fed by snowmelt water is less powerful in generating large SY (Puustinen et al., 2007) or frozen soil in those areas is less erodible (Renard et al., 1997).

The optimal MLR for CY was chosen by removing variables recursively with the *p*-value of their *F*-statistics larger than 0.05. This stepwise MLR process identified that CY is only significantly correlated with SY and not any other variables. The optimal regression of CY can be written as (Figure 11):

$$CY=0.061\ SY^{0.766}, \tag{2}$$

which is similar to the relationship reported for large river basins (Galy et al., 2015). When expressed as the natural logarithm of SY and CY, this equation is equivalent to $\ln(CY)=0.766\ \ln(SY)-2.789$. The *p*-value of the *F*-statistics and the AIC score for the regression are 3.65×10^{-10} and 85, respectively, and the SEs of the intercept and the slope of ln(SY) are 0.423 and 0.079, respectively. As POC and sediment yield from bed load and large woody debris are hardly ever measured, equation (2) mainly reflects the relationship between CY and SY from suspended load. The strong correlation ($r = 0.89$) indicates that POC and sediment are physically bound in soils, so they are detached and exported through the same hydrological processes (McDowell et al., 1989; Smith et al., 2013). Further, as the exponent of SY in equation (2) is less than unity, the modeled POC concentration in exported sediment declines with the increase of SY in Figure 12 (Galy et al., 2015; Ludwig et al., 1996). As stated in section 3.3, this relationship is consistent with the findings of much lower POC export efficiency from high yield catchments, especially on steep topography (Kao & Liu, 1997; Kim et al., 2010; Lee et al., 2016; Lloret et al., 2013). As described above, the yield of POC and sediment from bed load and large woody debris may not follow the relationship of equation (2) but they could be important for small catchments.

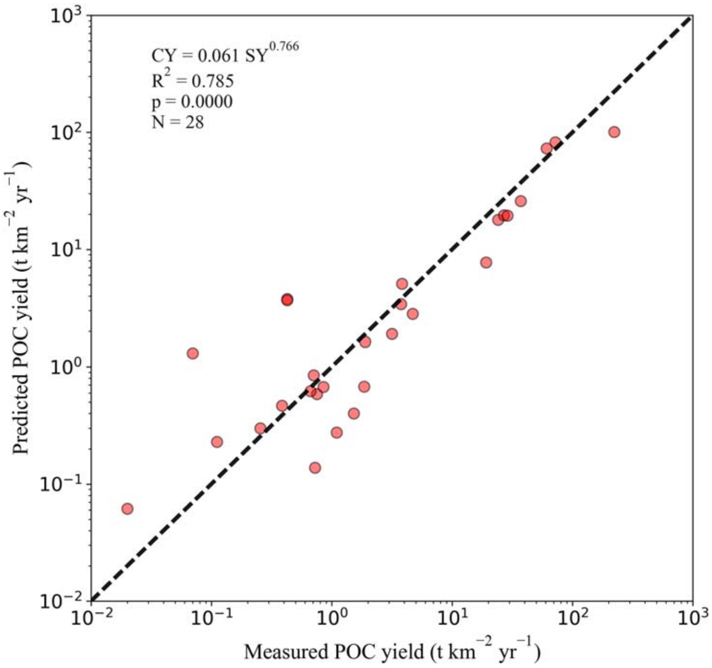

Figure 11. Observed POC yield versus predicted POC yield. The shown formula is the regression model used to predict POC yield. The black dashed line is the 1:1 reference.

In Galy et al. (2015), similar relationships were established separately for both biospheric POC and petrogenic POC using measurements collected worldwide from 70 large river systems. We reanalyzed the data of Galy et al. (2015) for the sum of biospheric POC and petrogenic POC and established a similar relationship for the total POC data (supporting information Figure S9): $CY = 0.042\ SY^{0.753}$. According to the river continuum theory (Vannote et al., 1980), the river mouth data of large watersheds may not reflect the characteristics of low-order streams. Indeed, when comparing the two regressions, POC concentrations measured in small catchments of our data set are higher than those measured in large river basins of Galy et al. (2015). This contrast is confirmed by the *t* test of POC concentrations in suspended sediment between our data set and Galy et al. (2015), as shown in Figure 12 (*p*-value = 0.0079). Possibly a large fraction of POC mobilized at the headwater is biogeochemically modified during transport and the loss cannot be compensated by carbon mobilization through bank and channel erosion (Bouchez et al., 2010; Ward et al., 2015).

4. Discussion

4.1. Implications for Representing SY in ESMs

Empirical and process-based SY models often have limited capability in simulating SY from small catchments at regional and continental scales (de Vente et al., 2013; de Vente & Poesen, 2005). Instead, these models either focus on simulating SY from large river basins at coarse spatial resolutions (de Vente & Poesen, 2005; Pelletier, 2012; Syvitski & Milliman, 2007) or SY from single small catchments (Yu et al., 1999). Using data from over 1,000 small catchments around the world, our analyses focus on the spatial scales relevant to ESMs and suggest some directions to represent SY in ESMs.

First, to represent SY at a grid cell and in subgrid landunits of ESMs, it is not sufficient to simulate only rainsplash erosion, sheet flow erosion, and rill erosion as commonly represented in many existing SY models (de Vente & Poesen, 2005) because rainsplash erosion is unlikely a dominant sediment source at the scale of the grid and subgrid scale of ESMs and shallow overland flow and rill flow have limited sediment transport capacity to produce high SY due to their hydraulic geometry (Gilley et al., 1990; Hairsine & Rose, 1991, 1992a, 1992b). Instead, other more complex erosion processes should be represented. For example, since

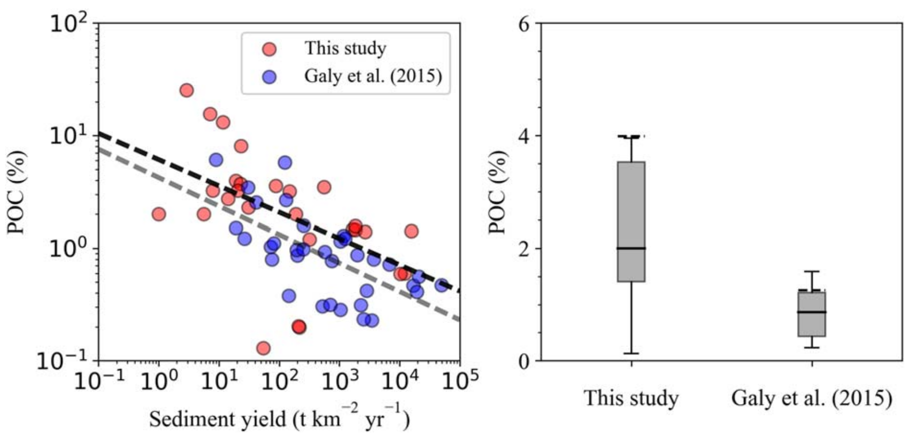

Figure 12. Comparison of observed POC concentration in suspended sediment in this study versus Galy et al. (2015). (left) The black and grey dash line are regressions of POC concentration to sediment yield in this study and Galy et al. (2015), respectively. (right) Bold solid lines indicate the median POC concentration and dashed lines indicate the mean POC concentration.

high SY is linked with traditional agriculture and seismic activities, it is vital to simulate ephemeral gully erosion for cropland-dominated catchments and landslide for steep and tectonic active catchments in ESMs (de Vente et al., 2013). These erosion processes can be implemented separately by either process-based approaches (Arnone et al., 2016; Gordon et al., 2007) or simple empirical relationships (Posner & Georgakakos, 2015; Roering et al., 1999). Otherwise, all erosion processes driven by concentrated flow (e.g., rill flow, gully flow, and channel flow) might be represented using a single method with different hydraulic geometry settings (Morgan et al., 1984). Sediment yield is determined by the balance between soil erosion and sediment deposition. Besides erosion processes, the representation of sediment transport capacity is also needed. The strong correlation between SY and Q_{peak} indicates that most of the detached sediment is likely deposited in gullies and river channels for a year or longer until very strong floods flush the deposited sediment effectively (Dadson et al., 2003).

Second, it is important to model SY in ESMs at the event scale (daily or subdaily time steps) to represent catastrophic mass transport during episodic events. As both storm-driven erosion and sediment transport capacity increase exponentially with the increased intensity of concentrated flow (Bryan, 2000; Dadson et al., 2003; Hairsine & Rose, 1992a, 1992b), modeling SY at the annual or monthly scale in ESMs would cause large uncertainties. In addition, event-scale SY modeling will be more valuable for studying river biogeochemistry as previous works show that major hydrologic events (e.g., flooding) may drive carbon cycling in river networks (Raymond et al., 2016).

Third, as identified by the analyses, several environmental factors should be accounted for when modeling specific soil erosion and sediment transport processes in ESMs. For example, the intensity of seismic activities may be included as a negative factor for the calculation of soil cohesion that is usually a function of soil internal cohesion and root reinforced cohesion in process-based landslide modeling approaches (Arnone et al., 2016). As runoff-driven erosion is likely the dominant sediment source, it is important to carefully evaluate the effect of ground cover on erosion processes. As shown in our analyses, vegetation cover may be a major factor in calculating the impacts of ground cover on SY (Morgan et al., 1984). Other factors such as leaf area index and surface litter that were not analyzed in this study may be also considered (van Dijk & Bruijnzeel, 2001). Soil erosion from cropland catchments is sensitive to land management practices. By changing soil erodibility and ground cover, land management activities can reduce the severity of concentrated flow erosion (i.e., rill and gully erosion) on hillslopes (Knapen et al., 2007). Thus, as a first step, land management should be included in SY modeling to account for its effects on soil erodibility and ground cover in ESMs (Flanagan & Nearing, 1995). Similarly, the factor of topsoil rock fragment can also be included by adjusting the soil erodibility and ground cover (Flanagan & Nearing, 1995; Panagos et al., 2014). It should be noted that as erosion mainly occurs on hillslopes, it would be necessary to process the GIS data related to the above factors in the hillslope fraction of the grid and subgrid cells of ESMs.

Lastly, it may be necessary to remove snowmelt driven runoff from the calculation of SY in ESMs because the analyses of the MLR of SY suggest that this part of runoff is not as effective as rainfall-driven runoff in detaching the top soils.

4.2. Implications for Representing CY in ESMs

This study indicates that for small catchments, SY is the primary control on CY. The likely reason is that POC is physically bound with sediment and the detachment and transport of POC and sediment are driven by the same mechanisms. Similar to large river basins (Galy et al., 2015), an exponential relationship between SY and CY (equation (2)) was established by this study. This empirical relationship may serve as a good starting point for simulating CY in ESMs. For process-based approaches to represent CY in ESMs, our analyses suggest that it may be not sufficient to infer CY from SY by accounting only for the decrease in POC concentration with depth in the soil profiles (Dialynas et al., 2016). Instead, the difference of POC concentrations in soil particles and the dynamics of soil particle distribution in SY should be both considered.

4.3. Limitations and Future Work

The low quality of GIS data could be a large limitation for data analysis and modeling of SY and CY at the global scale (de Vente et al., 2013). For example, the weak correlation between substrate strength (expressed as LITH) and SY could be caused by the severe underestimation of the spatial variability of lithology in the data of Dürr et al. (2005). GIS data related to soil characteristics (e.g., soil texture and SOC) still have large uncertainties despite the high resolutions because these products were produced using less reliable methods, such as limited sampling and extrapolation. Further, high-quality fine temporal-resolution rainfall and runoff data can be vital for event-scale SY modeling in ESMs. Due to the lack of GIS data, not all land management practices are included in our analyses. This lack of land management data can also affect the accuracy of SY modeling in ESMs, especially in regions with large fractions of cropland. Several ongoing global land degradation assessment projects including GLASOD, ASSOD, SOVEUR, and LADA may provide new opportunities for modeling the effect of land use in the future (de Vente & Poesen, 2005).

Several factors (e.g., occurrence of fire and the presence of lakes and reservoirs) that are not included here but were discussed by previous studies could also be important in representing SY (García-Ruiz et al., 2015; Renschler & Harbor, 2002; Warrick et al., 2012). The potential presence of (large and small) reservoirs in the catchments could also strongly influence SY (Renschler & Harbor, 2002), and aquatic systems such as lakes and wetlands could play important roles in processing of eroded organic carbon (Collins, 1996; de Vente et al., 2013). Missing of these factors could contribute to underestimation or overestimation of SY in SY models and data analysis, so they should be further explored in future studies.

As noted, there are several regions in the world (e.g., South Asia and South America) that are underrepresented by our SY data. It is possible that because of the underrepresentation, our explanations for some environmental factors could have large uncertainties. The difference between SY values from gauging stations and from reservoir surveys could be another source of uncertainties for the data analysis of SY. Because reservoir surveys typically result in much larger values (sometimes double) obtained in measurements (Vanmaercke et al., 2011, 2014b), our explanations of the effects of environmental factors on SY in the African and European catchments could be biased. Also, because most of the catchments with available Q_{peak} data are located in the U.S., Canada and Puerto Rico, we caution that the conclusions drawn from the partial *r* analysis and the SY MLR may not be completely applicable for other regions.

Our analyses of CY has provided some valuable information about model development and POC processing in rivers. However, because the analyses are based on far fewer catchments than those used in the analyses of SY, our conclusions can be less robust and characterized by larger uncertainties. In contrast to large river basins, the issue of limited data size may be much more severe for small upland catchments because they each represent only small areas of the land surface. As the dynamics of river POC is an important component of the global carbon cycle, this study motivates more efforts on measuring CY from small catchments across the globe and along the gradients of river corridors. Another drawback of the CY data is that POC in bed load and large woody debris is not included in the data.

Lastly, our study shows that a considerable fraction of the eroded POC could be biogeochemically modified in the rivers during transport. To fully understand the fate of leached POC in rivers, a comprehensive modeling suite including sediment flux, river routing and river biogeochemistry would be needed in future studies (Li et al., 2013, 2015; Pelletier et al., 2015).

5. Conclusions

Sediment and POC yield could have significant impacts on fluvial systems and the global carbon cycle, but they are not yet represented in most ESMs because soil erosion and sediment transport processes depend on the spatial scales and vary greatly in the spatial and temporal dimensions. Existing SY models and data analysis either focus on large river systems that have much coarser spatial scales than ESMs or specific catchments that cannot represent the global variability of SY. By analyzing SY and CY data from 1081 and 38 catchments, respectively, in the size range of 0.1–200 km^2 across the globe using multiple statistical analysis techniques, we investigated possible directions to advance SY and CY modeling in ESMs. Analyses of the environmental control on SY across a large number of catchments showed some relationships that are consistent with and some that are different from those reported in previous studies. But among the many factors examined, we identified several including seismicity, land forest cover, and human activity (land management) that display relationships with SY that are almost consistent with those previously reported. The robustness of the relationships for catchments across very different environments around the globe suggests that these factors are important for SY modeling at the global scale. Among them, seismicity and land management are rarely included in current catchment-scale SY models.

Our analyses also showed that high SY occurs in areas with intense traditional agriculture, seismicity and/or heavy storms. SY is also highly influenced by Q_{peak}. These highlight the limitation of simulating SY by representing interrill and rill erosion alone. Further, our analyses indicated a high capability of event-scale variables in explaining SY variability across a large number of catchments. This suggests that SY modeling in ESMs should be implemented at the event scale to reproduce the catastrophic mass transport during episodic events. The large influence of human activities, particularly cropland management, is well supported by our analyses and should be accounted by SY modeling in ESMs.

Last but not least, we found that SY is the primary control on CY. Our analyses established a statistically significant empirical relationship ($R^2 = 0.785$) to calculate the yield (units: t km^{-2} yr^{-1}) of POC and sediment jointly. Expressed as $CY = 0.061\ SY^{0.766}$, this relationship is similar to that established by Galy et al. (2015) for large river systems, except that the POC concentrations in small catchments are significantly higher, suggesting that it could be important to represent biogeochemistry and other processes for understanding carbon cycling in rivers. Derived using catchments resolvable by ESMs, our relationship could be used as a starting point to model POC fluxes in ESMs, given that SY is modeled with considerations of the natural and anthropogenic factors identified in this study.

Further reasearch is needed to address the weaknesses in our approach, which includes (1) a better representation of catchments in Asia, South America, and Australia; (2) a better recognization of the errors and uncertainties in SY and CY measurements, such as gauging station sampling versus reservoir surveys; (3) a coordinated effort of simultaneous SY and CY measurement in small catchments and along river corridors across the globe; and (4) the incorporation of more accurate GIS data and more human activities.

Appendix A: Database Acknowledgements

We acknowledge the following sources for providing the SY and CY data used in this study. Abaci and Papanicolaou (2009), Alberts et al. (1978), Alvera and García-Ruiz (2000), Balasch et al. (1992), Balasch et al. (2005), Bednarczyk and Madeyski (1996), Beylich et al. (2006), Beylich and Kneisel (2009), Beyer-Portner (1998), Boeglin et al. (2005), Bogardi et al. (1983), Bogen (1995, 1996), Boix-Fayos et al. (2008), Brański and Banasik (1996), Butcher et al. (1993), Cammeraat (2002), Casalí et al. (2008), Cerro et al. (2014), Chaplot and Poesen (2012), Collins (1991, 1996), Csáfordi et al. (2009), Cui et al. (2007), Dawson et al. (2002), Deasy et al. (2011), Descroix (1994), de Vente et al. (2005), Diaconu (1969), Dostál et al. (2006), Douglas et al. (1992), Esteves and Ludwig (2003), Foster and Lees (1999), Fouz et al. (2006), Froehlich and Walling (2005), García-Ruiz et al. (2008), Gergov (1996), Griffiths (1979), Gögüs and Yener (1997), Gomez et al. (2003), Grauso et al. (2008), Guyot et al. (1996), Habersack (1996), Haigh et al. (2004), Harrington and Harrington (2009), Hartmann et al. (2014), Hasholt (1983), Hejduk et al. (2006), Hicks et al. (2000), Hope et al. (1997), Huygens et al. (2000), IAHS (1974), Jacinthe et al. (2004), Jantawat (1985), Jaoshvili (2002), Jauffret and Vérague (1986), Krasa et al. (2005), Kostadinov and Markovic (1996), Labadz et al. (1991), Lamalle et al. (1989), Laubel et al. (1999), Lawler (1994), Lefrançois et al. (2007), Lemin et al. (1987), Lewis et al. (2012), Llovet et al. (1998), Loebis and Taryana (1988), López-Tarazóna et al. (2010), Lu and Higgitt (1999), Mano et al. (2006), Martin et al. (1997), Martínez-Carreras et al. (2010), Marttila and Kløve (2010), Mast (2013), McDowell et al. (1989), McDowell and Asbury (1994), Meybeck et al. (2003), Nadal-Romero et al. (2007), Oeurng et al. (2011), Olefeldt et al. (2013), Olive and Rieger (1986), Olivry and Hoorelbeck (1989), Øygarden et al. (2006), Palleiro et al. (2014), Pavanelli and Rigotti (2007), Pawson et al. (2008), Pepin et al. (2010), Peterjohn and Correll (1984), Petkovic et al. (1999), Pickup et al. (1981), Puustinen et al. (2007), Rădoane and Rădoane (2005), Rai and Sharma (1998), Rapp et al. (1972), Regüés and Gallart (2004), Rejman and Rodzik (2006), Restrepo et al. (2006), Rodríguez-Blanco et al. (2013), Sadeghi et al. (2013), Schröder and Theune (1984), Sharma and Rai (2004), Shibata et al. (2001), Sickman et al. (2007), Sine and Agneessens (1978), Sisák et al. (2007), Smith et al. (2013), Sogon et al. (1999), Steegen (2001), Stone and Saunderson (1996), Stutter et al. (2006), Soler et al. (2008), Tamburino et al. (1990), Thodsen et al. (2004), Torri et al. (2006), Tropeano (1991), Van Dijk and Kwaad (1996), Van Hoestenberghe et al. (2008), Van Rompaey et al. (2005), Verstraeten (2000), Verstraeten and Poesen (2001), Verstraten (1977), Vihermaa et al. (2016), Voet (1997), Vuorenmaa et al. (2002), and White (1996).

Acknowledgments
We are grateful to many researchers and institutions, especially Amanda Henck Schmidt at Oberlin College, USGS Water Resources, Environment and Climate Change Canada, and the Terrestrial Hydrology Research Group at Princeton, for making their sediment yield and ancillary data available for this study. This research is supported by the Office of Science of the U.S. Department of Energy as part of the Earth System Modeling program through the Energy Exascale Earth System Model (E3SM) project. The Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy under contract DE-AC05–76RLO1830. J.H. was supported by the German Science Foundation DFG (Cluster of Excellence "CliSAP," EXC177, Universität Hamburg and DFG-project HA4472/6-1). The SY and CY data set can be accessed in the accompanying supporting information Data Set S1.

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