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Sediment yield along the Andes: continental budget, regional variations, and comparisons with other basins from orogenic mountain belts

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ABSTRACT

We assess the sediment yield at 119 gauging stations distributed from Colombia to Patagonia, covering the different morphotectonic and morphoclimatic settings of the Andes. The most productive areas are the Meta River basin within the northern Andes and the Bolivian and northern Argentina-Chaco systems, which produce an average of 3345, 4909 and 2654 t km^2 y^{-1} of sediment, respectively. The rivers of the northern and central Andes (excluding the Pacific watersheds of Peru, northern Chile, and central Argentina) have a weighted mean sediment yield of 2045 t km^{-2} y^{-1} and produce 2.25 GTy^{-1} of total sediment. A major constraint estimating the Andean continental budget of sediment yield lies in the lack of gauging data for the Peruvian region. Using the available gauge stations, the regional sediment yield appears underestimated. Assuming a higher value of sediment yield for the Peruvian Andes, the total budget for the whole central Andes could range between 2.57 GT y^{-1} and 3.44 GT y^{-1}. A minimum of ~ 0.55 GT y^{-1} and a probable maximum of ~ 1.74 GT y^{-1} of sediment are deposited in the intramontane and surrounding proximal sedimentary basins. The magnitude of sediment yield in the Andes is comparable to other rivers draining orogenic belts around the world.

1. Introduction

Knowledge of river basins sediment yield at a continental scale provides useful information for (i) developing quantitative models of landscape evolution, (ii) studying geochemical and sediment mass balance, (iii) estimating the intensity of continental and regional erosion, and (iv) assessing the volume of solids contributed from continents to the Ocean and the trapping of sediments at the continental scale (Pinet and Souriau, 1988; Summerfield and Hulton, 1994; Harrison, 2000; Hovius, 2000; among many others). Sediment yields for South American rivers have been documented as part of global databases of sediment load into the coastal ocean. Three of the largest river systems draining the Andes (the Amazon, Paraná, and Orinoco) have attracted the most attention (Milliman and Syvitski, 1992; Ludwig and Probst, 1998; Syvitski and Milliman, 2007; Milliman and Farnsworth, 2011; among others). But recently a few small-and medium-sized catchments along the northern Andes (e.g., Magdalena), on the Pacific margin (e.g., San Juan, Patía, Chira, and BioBio), and in the Patagonian region (e.g., Negro, Colorado, and Chubut) also have been added to global databases (Syvitski and Milliman, 2007; Milliman and Farnsworth, 2011). However, these databases do not represent a continental picture of sediment yield near Andean foothills. In addition, data for some Andean catchments are still missing. One attempt to predict erosion rates along the whole Andes by applying a latitudinal gradient of erosion index (Montgomery et al., 2001) fails to predict realistic values when compared to sediment yields obtained from measurements in fluvial systems. Thus, the role of Andean rivers on the global denudation system remains only partially understood.

At the regional scale, sediment yields for the Andean rivers have been collected over the last decades for various regions and catchments of different sizes. Most available studies have attempted to explain regional patterns of sediment yield in terms of the combined effect of local topography, soil properties, climate, vegetation cover, catchment morphology, and land use (Guyot et al., 1994, 1999; Restrepo and Kjerfve, 2000; Latrubesse et al., 2005; Aalto et al., 2006; Restrepo et al., 2006; Laraque et al., 2009; Kettner et al., 2010; Pepin et al., 2013).

While all mentioned datasets and results contain relevant numbers of sediment yield, none has evaluated the variations in sediment yield at a macroscale (i.e., covering the entire Andes). Furthermore, data for a significant number of Andean catchments are still missing in the international literature, notably for rivers draining the northeastern Orinoco and Amazon basins, the central Andes flowing through the Chaco region, and for central Argentina. Thus, our knowledge on the regional variation of sediment yield and its relationship with spatial scale and other environmental factors within the Andes is still limited. We address this knowledge gap by presenting and discussing new sediment yield data and by estimating the continental budget of sediment yield

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Table 1
Drainage basin, measured water and sediment discharges, and calculated sediment yields for the Andean rivers.

Andean region, major receiving basin and river	Area ($\times10^3$ km^2)	Water discharge (m^3 s^{-1})	Sediment load (Mt y^{-1})	Sediment yield (t km^{-2} y^{-1})
Northern Andes				
Colombia				
Caribbean basin				
Suaza[45]	1.01	44.4	0.6	562
Páez[45]	4.76	180.7	2.9	607
Cabrera[45]	2.71	69.8	1.9	682
Sumapaz[45]	2.43	41.2	0.5	206
Bogotá[45]	5.41	38.1	1.3	244
Coello[45]	1.04	41.2	1.6	1575
Recio[45]	0.64	19.0	0.2	249
Gualí[45]	0.46	22.2	0.2	415
Guarino[45]	0.84	31.7	0.5	536
La Miel[45]	2.36	244.2	2.7	1126
Negro[45]	4.58	136.4	8.0	1742
Cocorna[45]	0.79	57.1	0.6	747
Samana[45]	1.71	180.7	0.9	543
Nare[45]	5.56	396.4	2.6	465
Carare[45]	4.90	263.2	16.8	3415
Opón[45]	1.75	88.8	3.4	1912
Suárez[45]	9.78	301.2	3.4	349
Fonce[45]	2.08	85.6	0.6	274
Sogamoso[45]	21.21	434.4	11.2	529
Cauca[45]	66.75	2384.6	49.1	735
Atrato[6]	12.10	1620.4	11.3	933
Chigorodó[6]	0.10	14.6	0.2	1088
León[6]	0.70	63.4	0.8	1000
Carepa[6]	0.15	5.1	0.3	2050
Currulao[6]	0.23	9.8	0.2	1027
Pacific basin				
San Juan[6]	1.60	261.0	2.6	1570
Patía[7]	8.90	225.1	15.4	1714
Mira[8]	9.53	243.5	9.7	1018
Amazon basin				
Caquetá (Angosturas) [&]	5.67	640.1	732	1289
Caquetá (Andaqui) [&]	3.61	408.3	382	1057
Orteguaza[&]	1.57	161.0	238	1508
Guayas[&]	1.46	210.0	191	1308
Guamues[&]	0.638	27.4	004	63
Putumayo[&]	2.9	498.4	168	580
Orinoco basin				
Guape[&]	0.517	71.6	145	2803
Guejar[&]	0.873	30.1	049	560
Guyuriba[&]	2.85	155.5	1131	3958
Negro[&]	1.31	27.0	118	896
Blanco[&]	0.810	46.3	120	1478
Negro[&]	2.48	93.8	445	1793
Somondoco[&]	0.531	18.2	093	1753
Lengupa (San Agustin) [&]	1.64	130.0	942	5739
Lengupa (Paez)[&]	0.774	52.1	503	6498
Upía (Reventonera)[&]	0.911	77.9	357	3914
Upía (Guaicaramo) [&]	7.94	432.2	2773	3492
Cravo Sur[&]	1.10	78.6	257	2339
Catatumbo[&]	1.37	38.4	040	289
Margua[&]	2.60	91.5	051	197
Cobugón[&]	1.26	195.0	365	2884
Ecuador				
Amazon basin				
Pastaza-Napo[9]	36.20	2210.0	42.4	1160
Napo[9]	12.4	1130.0	6.4	515
Coca[9]	5.2	350.0	6.0	1138
Peru				
Amazon basin				
Napo[10]	18.81	2230.0	21.0	770
Napo[10]	100.50	6300.0	54.0	537
Central Andes				
Segment-Peru				
Amazon basin				
Maranon[10]	104.80	4780.0	103.0	890
Huallaga[10]	53.12	2,820.0	42.0	710
Madre de Dios[10]	124.2	5210.0	71.0	570
Ucayali[10]	198.38	11260.0	205.0	570
Pacific basin				
Chira[3]	20.00	158.5	20.0	1000
Segment-Bolivia				
Amazon basin				
Caine[11,12]	9.20	59.0	126.0	13700
La Paz[11,12]	6.50	99.0	119.0	18310
Unduavi[11,12]	0.27	12.0	2.0	7420
Tamampaya[11,12]	0.95	52.0	2.4	2520
Tamapaya[11,12]	1.99	67.0	7.8	4110
Huayllani[11,12]	0.02	0.1	0.1	4060
Achumani[11,12]	0.04	0.2	0.2	5300
Luribay[11,12]	0.81	10.0	6.4	7910
Porvenir[11,12]	0.24	3.0	0.8	3310
Cot[11,12]	5.60	84.0	40.6	7240
Santa Isabel[11,12]	0.20	15.0	0.7	3550
Spe[11,12]	0.32	27.0	3.5	10940
Ico[11,12]	2.30	130.0	11.4	4960
Piray[11,12]	1.42	11.0	2.9	2040
Espejos[11,12]	0.20	3.0	0.4	2070
Chayanta[11,12]	11.20	70.0	14.1	1260
Grande[11,12]	23.70	130.0	154.3	6510
Grande[11,12]	31.20	230.0	206.9	6630
Mizque[11,12]	10.80	47.0	14.1	1310
Azero[11,12]	4.36	32.0	2.2	510
Parapeti[11,12]	7.50	79.0	19.4	2590
Coroico[11,12]	4.70	260.0	7.1	1500
Alto Beni[11,12]	29.90	840.0	115.0	3800
Beni[11,12]	67.50	2170.0	219.0	3200
Piray[11,12]	2.88	12.0	2.3	799
Grande-Abapo[11,12]	59.80	290.0	125.0	2100
Segment-Chaco: Paraná basin				
Pilcomayo[13]	96.00	204.0	141.0	1469
Cachimayo[14,]	1.61	17.8	2.9	1801
San Juan del Oro[*]	19.70	17.3	3.9	198
Cambiaya[*]	43.90	58.0	22.0	501
Pilaya[*]	89.90	90.0	41.6	463
Bermejo[15,*]	25.00	356.0	120.0	4800
San Francisco[13,*]	25.80	356.0	20.4	791
Iruya[15,*]	2.12	24.0	17.7	8349
Valle Grande[15,*]	16.06	16.0	3.8	237
Pilcomayo-Talula[15,*]	6.49	19.6	10.8	1664
Pilcomayo-Villa[*] Quemada[*]	13.5	49.9	24.5	1822
Bermejo[*]	2.26	22.9	4.9	2168
Bermejo[*]	4.85	89.5	15.7	3237
Grande de Tarija[*]	10.46	48.0	14.0	1338
Candelaria[*]	0.37	8.4	1.4	3784
Juramento[16,*]	31.90	29.0	34.0	1066
Salí[16,*]	4.70	15.0	4.9	1043
Dulce[*]	15.00	98.0	23.7	1580
Pescado[15,*]	1.7	50.6	24	14117
Segment-Argentina				
Atuel[*]	3.80	35.2	1.2	323
Grande[*]	6.18	110.7	1.2	197
Tunuyan[*]	2.38	28.6	2.9	1237
Tupungato[*]	1.80	23.6	1.0	553
Diamante[*]	2.75	68.4	2.5	903
San Juan[*]	25.67	65.3	3.9	151
Aconcagua[3]	2.10	31.7	0.5	238
Colorado[*]	15.30	146.4	3.9	258
Southern Andes				
BioBio[17]	24.00	1014.7	22.0	229
Neuquen[*]	30.20		8.0	264
Chubut[3]	40.00	41.2	0.6	15
Colorado[3]	22.00	130.0	6.9	314
Gallegos[3]	5.10	31.7	0.1	20
Negro[*]	89.00	1000.0	18.3	206
Deseado[3]	14.00	4.8	0.5	36

Note: [4–16,*]Regional studies and reports of sediment transport: 4-Restrepo et al. (2006); 5-Kettner et al. (2010); 6-Restrepo and Kjerfve (2000); 7-Restrepo and Cantera (2011); 8-Restrepo et al. (2009); [&]IDEAM, Colombian Institute of Hydrological and Environmental Studies; 9-Laraque et al. (2009); 10-Guyot et al. (2007); 11-Guyot (1993); 12-Guyot et al. (1994); 13-Basile (2004); 14-Guyot et al. (1990); 15-Cafaro et al. (2010); 16-Spalletti and Brea (2002); 17-Link et al. (2002); [*] Sub-Secretary of Water Resources, Argentina.

and its regional variations. We also use these data to determine whether Andean rivers produce similar amounts of sediments when comparing to other fluvial systems draining major orogenic and tectonically active mountain belts.

2. Material and methods

New data sets and reports of sediment transport were collected from hydrological institutes in Colombia, Ecuador, Peru, Bolivia, and Argentina and combined with previous regional studies (Table 1). Using consistent data from national agencies and previous regional studies, we examined 119 representative gauging stations (Fig. 1B). We include unpublished data for at least 48 gauging stations that represent the northeastern Orinoco and Amazon basins, the Chaco region in the upper Paraná basin, and watersheds in central Argentina. Only five gauging stations (or < 5% of the databases) are downstream river sections, including the Chira River in Perú and four rivers in the southern Andes (Table 1). Representative gauging stations (~92%) are located upstream in the Andean mountains and few are at the footslope area, thus avoiding bias in sediment yield values caused from depositional processes on floodplains or fluvial aggradational fans.

Each entry in the database corresponds to one catchment where water discharge and sediment transport were measured and contains at least the name of the river, water and sediment fluxes, the location, the catchment area as reported in the original publication or report, and the area-specific sediment yield. In this study, we only considered the suspended sediment yield because bedload data were unavailable for most gauging stations.

To analyze the collected data, rivers were grouped according to the major tectonic region within the Andes in which they are located (Fig. 1B). The subsequently produced sediment estimations were weighted per each area in relation to the total analyzed Andean area. Only the Peruvian region has gauging stations located in the foothills, therefore yield values for those stations were reestimated as a function of the Andean catchments.

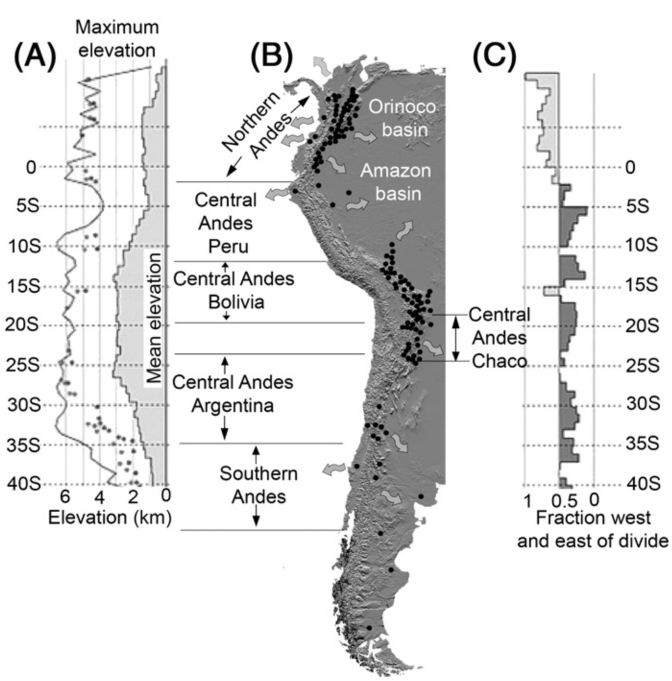

Fig. 1. Main morphological characteristics and regional distribution of sediment yield along the Andes. (A–C) Plots of maximum and mean elevations in 1° latitude bins and cross-range asymmetry (fraction of range volume above sea level that drains to west) (Montgomery et al., 2001). (B) Digital elevation model of the Andes showing the major Andean regions, location of gauge stations analyzed in this study (black circles), and fluvial flux directions from major drainage basins (gray arrows).

To obtain large-scale topographic variations along the Andes and compare them to the observed sediment yield in each major tectonic region, we estimated values of drainage area and elevation by using the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), a 3-arc second resolution model developed by the Consultative Group on International Agricultural Research Consortium for Spatial Information (CGIAR-CSI, http://srtm.csi.cgiar.org/). Each region was delineated using ArcGIS (Fig. 2), then clipped and exported as a DEM, preserving the CGIAR-SRTM geographic projection to minimize errors. The program RiverTools was used to calculate areas and extract elevation data. This approach minimized projection errors by calculating areas in a geodetic space rather than introducing an uncertain amount of error using a planar projection. Additional information was obtained

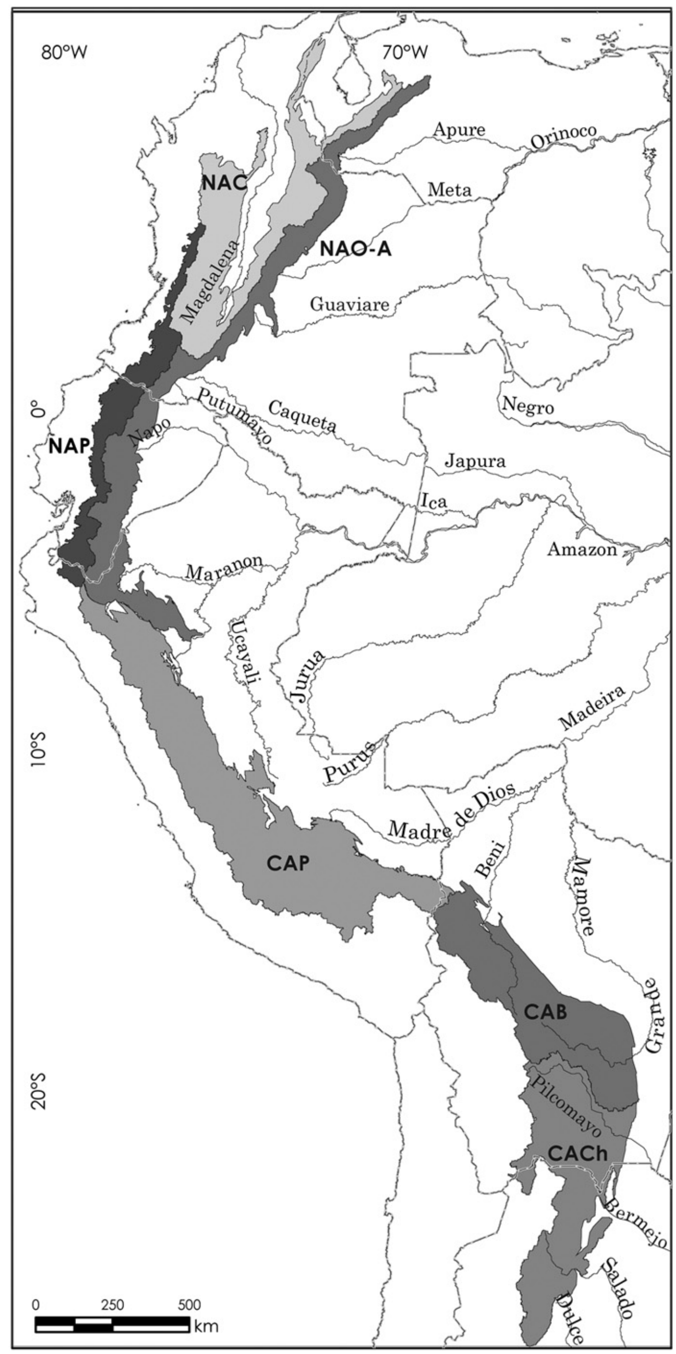

Fig. 2. Major subdivisions of the Andes and corresponding fluvial systems. NAC: Northern Andes–Caribbean; NAO-A: Northern Andes Orinoco–Amazonas; NAP: Northern Andes Pacific; CAP: Central Andes–Peru; CAB: Central Andes–Bolivia; CACh: Central Andes–Chaco.

from plots of maximum and mean elevations in 1° latitude bins and cross-range asymmetry (fraction of range volume above sea level that drains to the west) from Montgomery et al. (2001) (Fig. 1A and C).

The budget and comparisons between sediment yield and the total amount of sediments delivered from the Andes to the foothills were estimated with calculated values of sediment production in the mountain area and the corresponding measured data for each major catchment, as recorded at the most proximal piedmont gauge station available. To make further comparisons of sediment yield between Andean rivers and those draining other orogenic mountain systems in Europe, Asia, Insular Asia, and New Zealand, we obtained sediment yield data from Pinet and Souriau (1988), Milliman and Syvitski (1992), Latrubesse et al. (2005), Milliman and Farnsworth (2011), Vanmaercke et al. (2011), and Andermann et al. (2012).

3. Results and discussion

3.1. Sediment yield along the Andes

Major sections of the Andes were classified according to broad-scale morphostructural segments and the data were grouped according to the major tectonic regions (Jordan et al., 1983; Ramos, 2009) (Fig. 1B). The northern Andes, a region spanning from Colombia down to about 2°S, is represented by the Andean rivers draining (i) the Ecuador–Colombian Cordilleras to the Pacific, (ii) Caribbean basins, and (iii) the Amazon–Orinoco basins. These catchments are characterized by high local relief and intense seismic and igneous activity (volcanism and plutonism). Elevations are moderate, although some volcanic peaks reach more than 5000 m. The mean elevation is ~1870 m asl (Fig. 1A). The Caribbean basins account for 37%, while the Andean area draining to the Amazon–Orinoco basins is ca. 45% (Fig. 2; Table 2), and 18% drains toward the Pacific. Geologic and geomorphic provinces are characterized by large intramontane rivers such as the Magdalena and the Cauca in the Caribbean divide, which collects much of the Andean tributaries, and the Pacific basins with small-sized catchments such as the San Juan, Patia and Mira rivers. Sediment yield for the whole northern Andes averages 1485 t km^{-2} y^{-1}, with higher yields of 6498, 5739, and 3958 t km^{-2} y^{-1} in the Meta River basin in Colombia, a major tributary of the Orinoco River (Table 1).

Sediment yield for the northern Orinoco tributary basin, which covers ~32% of the northern Andean basins, averages 2572 t km^{-2} y^{-1}, almost twice the sediment yields documented for Pacific Colombian watersheds (Restrepo and Kjerfve, 2000; Restrepo, 2012; Restrepo and Kettner, 2012) and almost three times the yields of the Magdalena River and its tributaries (Restrepo and Syvitski, 2006; Restrepo et al., 2006; Kettner et al., 2010). Major sediment yield contributors in the northern Orinoco basin include tributaries of the Meta and Guaviare rivers such as Guyuriba (3958 t km^{-2} y^{-1}), Lengupa (6498 t km^{-2} y^{-1}), Upía (3492 t km^{-2} y^{-1}), and Cobugón (2884 t km^{-2} y^{-1}). In the northern Amazon basin, accounting for 68% of the eastern Orinoco–Amazon catchment, gauge stations along the Caquetá, Putumayo, Pastaza, Napo, and Coca rivers were also considered (Table 1).

The central Andes, from about 2° S to ~5° S was divided into four sections (Ramos, 2009), including (i) the Peruvian and (ii) Bolivian rivers draining into the Amazon, (iii) the tropical Andean rivers draining from the Andes to the Chaco plain, and lastly, (iv) the rivers of central Argentina (Fig. 1B). At this zone the Andes exhibit their maximum mean elevation (ca. 2600 m asl), and many ranges present peaks above 6000 m asl (at Cordillera Blanca, Cordillera Real, and Cordillera Principal) (Fig. 1A). The divide is asymmetric as a high proportion drains to the Atlantic Ocean mainly through the Amazon basin and secondarily through the Parana basin (Fig. 1C). Rivers of central Argentina drain mainly to the Desaguadero–Colorado basin. Average elevation in this Andean area is ~2900 m asl, and the maximum elevation of the Andes is recorded here (Aconcagua, 6962 m). Pacific watersheds were not analyzed in our database because of the strong aridity and small catchment area that contributes little in terms of the total sediment yield.

The mean sediment yield for the gauging stations of the eastern basins of the central Andes is 3032 t km^{-2} y^{-1} but is highly variable throughout the region, ranging from 483 t km^{-2} y^{-1} in central Argentinean rivers to an average of 4909 t km^{-2} y^{-1} for the gauging stations in the Bolivian Amazon basin (Fig. 3). Maximum values of sediment yield were observed in La Paz and Caine rivers within the Beni basin (central Bolivia) and the Pescado and Iruya rivers in the Bermejo basin (Chaco region), with 18,310, 13,700, 14,118, 8349 t km^{-2} y^{-1}, respectively (Table 1; Fig. 3). These are the highest known sediment yields ever documented for any river in South America.

The southern Andes have the lowest mean elevation (below 1500 m asl), high precipitation rates on the west flank, a remarkable rainfall gradient toward the east, and medium-sized rivers draining into the Pacific and Atlantic margins. Rivers from the Atlantic divide have an average sediment yield of 155 t km^{-2} y^{-1}. The smaller localized rivers draining into the Pacific exhibit sediment yields > 73 t km^{-2} y^{-1} and as low as 5.1 t km^{-2} y^{-1} (Pepin et al., 2010). The BioBio in Chile, with a sediment yield of 917 t km^{-2} y^{-1}, shows considerably higher rates of sediment yield compared to the eastern rivers. The BioBio transports 75% of the total sediment transport as bedload, but here we only report sediment yield calculations using suspended load (229 t km^{-2} y^{-1}). Nevertheless, bedload transport in steep southern Andean rivers with high-energy availability can be very high. As a result, southern Andean rivers along the western margin may contribute considerable sediment as bedload transport to the Pacific Ocean (Link et al., 2002).

3.2. Environmental factors, runoff, and sediment yield

Important regional differences in sediment yield are noted along the Andes (Fig. 3). Whereas most basins in the northern and northwestern Andes are characterized by moderately high sediment yields (ca. 30% of the sediment yield > 1600 t km^{-2} y^{-1} and ca. 70% of data > 550 t km^{-2} y^{-1}), the central Andes of Bolivia have higher sediment yield values with around 75% of the data > 2070 t km^{-2} y^{-1}. In the Chaco region, 25% of data have sediment yields > 3237 t km^{-2} y^{-1}. These dissimilarities are based on a significant number of records–especially in the northern and central regions–and they cannot be attributed to data uncertainty but rather to regional factors controlling sediment yield.

Table 2
Area and elevation of the Andes subdivisions.

Region	Area (km^2)	Average elevation (m)	Max elevation (m)	Min elevation (m)	Std deviation elevation (m)
North Andes – Atlantic	199,028	1660	6259	234	1038
North Andes – Caribbean	159,705	1875	5375	138	882
North Andes – Pacific	77,599	2082	5860	158	937
Central Andes – Peru	311,590	2920	6352	402	1288
Central Andes – Bolivia	159,305	2177	6405	266	1158
Central Andes – Chaco	167,883	2680	6342	279	1246
Central Andes – Argentina	171,664	2860	6962	615	1144

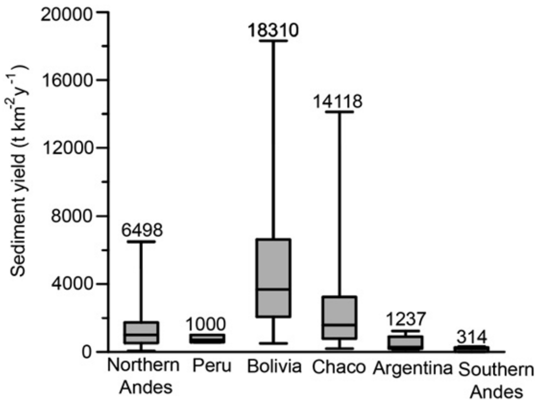

Fig. 3. Box whisker plots of sediment yield for the northern, central, and southern rivers of the Andes. Maximum yields are shown at the top whisker.

In mountain regions, it has been demonstrated that the expected decrease in sediment yield with increasing catchment size is probably overridden by the influence of other sediment-producing drivers (Restrepo and Syvitski, 2006), which explains why no significant trend was found for the Andean rivers. Moreover, sediment budgets in mountain areas are not only controlled by basin relief, lithology, basin morphometry, and climate, but also by the flashy generation of recurrent sediment fluxes from landslides, bank erosion, erosion on agricultural land, and overgrazed steeplands.

The relationship between specific runoff and sediment yield (Fig. 4B) shows to some extent the transport capacity of the fluvial system and the amount of water available for fluvial erosion. A scatter plot reveals clear clusters per tectono-climatic regions in the southern and central Andean rivers of Argentina and the Chaco. Located in the subtropical belt (~15° S–30° S), the Chaco catchments exhibit high discharge variability (Latrubesse et al., 2005), high sediment yields, and relatively lower values of specific runoff. The mean elevation of the Andes in this region is ~2700 m asl. There is ten fold less water production available for erosion and transport processes compared to rivers located in the humid tropics. Sediment production of central Andean rivers in the Chaco is two orders of magnitude greater than high runoff rivers draining the northern Caribbean and Pacific Andes.

As previously mentioned, the weight and the scale of influence (regional-local) of each factor (relief, lithology, climate, and land use changes) need further analysis. Assessing and modeling these factors as control variables of sediment yield at a continental scale is not within the scope of this paper; however, we will briefly discuss some relevant findings on natural and human–induced variables controlling sediment yield in different Andean regions.

The application of a multivariate analysis and the complex BARQT erosion model in the Magdalena basin (Restrepo and Syvitski, 2006; Restrepo et al., 2006; Kettner et al., 2010), the major catchment draining the northern Andes, indicates that yield is relatively well correlated with mean annual precipitation and maximum monthly precipitation.

We find that high values of sediment yield and runoff are recorded along the eastern slopes from Venezuela to Bolivia. Because of their flows across the eastern Andes, mountainous rivers with orographic precipitation in the sub-Andean zone, are characterized by high water discharge variability (Latrubesse et al., 2005). High values of sediment yield observed in the Peruvian and Bolivian basins are owed in part by the result of the orographic influence of the Andes. Incoming air masses from the east are trapped by the Cordillera, thereby increasing precipitation patterns along the eastern slopes from Venezuela to Bolivia. Rainfall can reach more than 6000 mm y^{-1} in parts of the sub-Andean zone in Ecuador, Peru, and Bolivia (Latrubesse et al., 2005; Espinoza et al., 2008), while the central part of the Andes range (~15° S–30° S), located in the subtropical belt (i.e., the Chaco), shows high yields but relatively lower values of specific runoff (Fig. 4B).

Along the Chaco section of the central Andes, the tributaries of the Paraná River show one of the highest sediment yield rates of the whole Cordillera. Wet-dry climate, characterized by very pronounced rhythmic seasonal moisture patterns, is one of the controls on erosion rates. This perennial river, together with other systems such as the Bermejo, display high water discharge variability (Maximum water discharge–Q_{max}/Minimum water discharge–Q_{mean}) as high as 150 (e.g., the Pilcomayo) and 190 (e.g., the Bermejo) (Latrubesse et al., 2005) and 85% of the total suspended sediment is transported from December to March (Martín-Vide et al., 2014). Overall, erosion is enhanced in basins under tropical seasonal climate with an intense rainfall season and subdued in catchments experiencing high rainfall rates and constant climate. Thus, climate plays a complex role on erosion control, mainly because it is influencing other controls like the vegetation cover.

However, the major role of rainfall triggering erosion in the eastern flanks of the northern and central Andes from Venezuela to northern Argentina, is not totally accepted. For instance, the use of different methodologies has produced contrasting interpretations in the Central Andes. While some studies claim that slope and lithology are merely secondary controls of denudation along the Peruvian–Bolivian Andes (Pepin et al., 2013), regional erosion modeling in the Bolivian Andes suggests that the correlation between precipitation and erosion is poor, while slope and lithology are dominant factors (Aalto et al., 2006). In fact, relief-slope and lithology can be important elements affecting sediment yield, at least at regional or local scale, either in the northern or along the central Andes.

Based on a multiyear data set of sediment load from six rivers, including Mira, Patía, and San Juan on the Pacific margin and Magdalena, Atrato, and Sinú on the Caribbean basin, various morphometric,

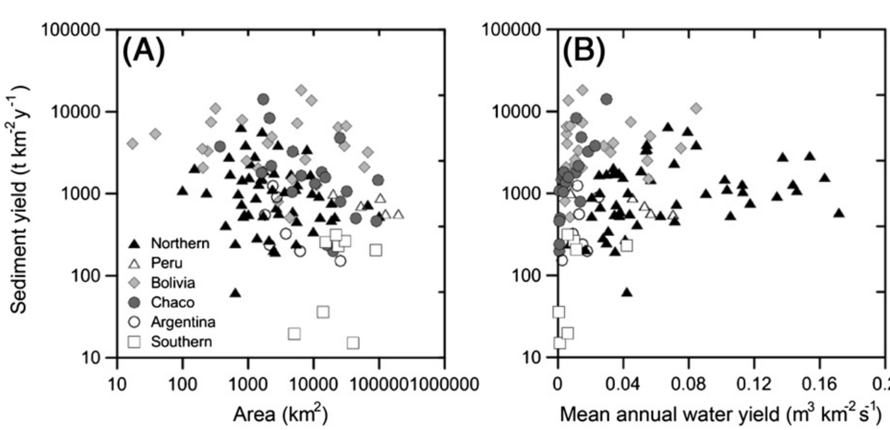

Fig. 4. Scatter plots of Andean sediment yield (A–B). Relationship between sediment yield and drainage basin area (A) and mean annual water production (B).

hydrologic, and climatic variables were estimated in order to understand and predict the variation in sediment yield. At a macroregional scale, a multiple regression model, including two control variables, runoff and relief ratio (the ratio of the maximum height of the drainage basin and the basin length), explains 83% of the variance in sediment yield. Although the model explains the regional characteristics, at a more local scale, lithology plays an important role. The highest yields correspond to tributary basins located on the eastern central Magdalena catchment, which are characterized by fissile sedimentary rocks and highly erodible soils (Kettner et al., 2010). Tributary basins in the western upper Magdalena do not have well-established vegetation cover, and the lithology is characterized by marls and strongly weathered material (e.g., weathered granites). This lithological characteristic causes significantly higher sediment yields compared with catchments in western-central Magdalena that contain mainly high-grade metamorphic and volcanic rocks. In the Chaco, highly erodible and fractured rocks can also be an important control in the extreme sediment yields found in the Pescado and Iruya basins.

Another factor that can affect sediment yield is land use changes. However, our knowledge on the effects of land use on rates of erosion/sediment production in the Andes is almost unknown. Some results are available for the northern Andes. Large-scale changes associated with land use practices and resource exploitation in the Andes are particularly significant for the Magdalena basin where the erosion has increased over the last 10–20 years. Many anthropogenic influences, including a forest-area decrease of 44% in a 20-year period, an increase in agriculture and pasture land of 65%, poor soil conservation and mining practices, and increasing rates of urbanization may have accounted for the overall increasing trends in sediment yield on a regional scale to Restrepo and Syvitski (2006). Our information on the effect of land use change on sediment yield at a regional scale in the central Andes is also unknown. Data from a small catchment, the Paute basin in Ecuador, suggest that surface vegetation cover exerts a first-order control on sediment yield at the catchment scale (Vanacker et al., 2003; Molina et al., 2008).

Overall, continental-scale variance of sediment yield in the Andean basins seems to be conditioned by geomorphic and tectonic influences (relief), climate (runoff), geology (lithology), slope stability (landslides) and human activities (soil erosion), and the role of these factors change as a function of the spatial scale and location. For instance, two of the principal estimators, climate and relief, refer to the relative importance of the fluvial transport component in the sediment routing system; but also we have to consider the design and morphometry of the drainage network. Unfortunately, our knowledge on the morphometry of the Andes and the Andean watersheds is very limited. In addition to the typical rainfall–relief–lithology approach, further detailed morphometric studies and estimations of morphometric parameters, to understand the production and routing of sediments, are more than desirable and necessary.

3.3. From mountain sediment yield to piedmont delivery

The extrapolation of sediment load and sediment yield for whole continents based on data from few representative rivers is very problematic. This approach lacks precision because many environmental factors, such as climate, vegetation, lithology, hydrology, relief, elevation, tectonics, land use, and others, can cause as much as three orders of magnitude variability in sediment load (Meybeck, 1988). As it will be discussed, regional models using regression equations cannot be easily extrapolated to produce estimations and budgets for the whole Andes.

Based on data from gauging stations (Table 1), we first used the drainage area–sediment load algorithms to estimate sediment delivery from each analyzed Andean region (Fig. 5). Regions of central Argentina, southern Andes, and central and southern Pacific basins were excluded from the collective sediment budget because of the lack of data and availability of gauging stations located upstream of Andean footslopes. Sediment flux from the northern Pacific basins was obtained from gauging station data (Restrepo and Kjerfve, 2000; Restrepo et al., 2009; Restrepo and Cantera, 2011; Restrepo, 2012). Sediment flux from northeastern Colombian basins, such as the Meta-Guaviare-Arauca (Orinoco basin) and the Putumayo-Caquetá (Amazon basin), was obtained by new data from 20 gauging stations. A knowledge gap in terms of sediment yield lies in the Peru region. Available gauging stations, including those in the Napo, Marañón, and Ucayali rivers, are located at altitudes <200 m asl and do not represent the sediment yield for upland sections of the catchments. The sediment loads and yield of these rivers and catchments requires more data and further analysis.

To remedy further constraints for calculating the amount of sediment load delivered to the Andean footslopes, we instead used only mountain gauging station data representative of each basin (Fig. 6A). The average yield obtained for the whole northern and central Andes is 2641 t km^2 y^{-1}, but the weighted average yield, which takes into consideration the representation of each Andean region and subregion, is 2045 t km^{-2} y^{-1}. When applying total calculations of sediment delivery for each Andean sector with its specific averaged yields per area, the northern and central Andes, with a combined area of 1.075×10^6 km^2 – from Colombia to the Chaco – deliver a minimum of 2.25 GT y^{-1}. The corresponding sediment yield and transport for the whole central Andes area, based on data of gauging stations at the proximal Andean foothills, are 1415 t km^{-2} y^{-1} and 1698 MT y^{-1}, respectively. The northern Andes transports 0.68 GT y^{-1} of sediment to the Pacific, Caribbean, and Orinoco–Amazon basins. The central region, which comprises Peru, Bolivia, and the Chaco, delivers at least 1.57 GT y^{-1} (Fig. 6B). This total sediment delivery is comprised by 0.34, 0.78, and 0.45 GT y^{-1} in the Peruvian, Bolivian, and Chaco basins, respectively.

These estimations indicate that the sediment flux from the Amazon mountain catchments could be at least 1.42 GT y^{-1}. The amount of sediment produced in the Peruvian Andes is, with high probability, bigger than our conservative estimations. Station data from mountain catchments in the Peruvian Andes are not available. In addition, our interpolation was based on normalized values of sediment transport in the piedmont areas of the Andean catchments. Based on data from the Bolivian Andes, Aalto et al. (2006) suggested an annual sediment flux from the Andes to the Amazon of about 2.3 to 3 GT y^{-1}, a value almost twice our estimation of 1.42 GT y^{-1}. Nevertheless, we consider that the suggested values by Aalto et al. (2006) are feasible because of the lack of data in Peru. The total sediment production in the Amazon watershed fall in between 1.73 and 2.6 GT y^{-1}, assuming that the Peruvian Andes has similar yield values or in between the northern and Bolivian Andes, respectively. As a result, our estimate of the total sediment production within the whole central Andes could range between 2.57 and 3.44 GT y^{-1}. This indicates that within the intermountain basins and Andean footslopes, from the northern Andes to the Chaco regions, between ~0.55 and ~1.74 GT y^{-1} of sediment are deposited in very proximal piedmont alluvial fans, river floodplains, and associated wetlands.

The observed difference between the mountain sediment yield and the recorded loads delivered to the proximal piedmont regions is a consequence of the geomorphologic and tectonic complexities of the Andes (Fig. 6B). A significant amount of Andean rivers have large basins flowing through steep mountainous relief, but intramountain basins trap a large amount of the produced sediments. The combined eastern peripheral basins of the north-central Andes probably represent the biggest continental sediment sink of the planet, particularly the Bolivian and Chaco foreland basins.

3.4. The Andes compared to other orogenic belts with extreme sediment yields

The focus of many global databases has been on the amount of sediments delivered to the coastal ocean rather than documenting

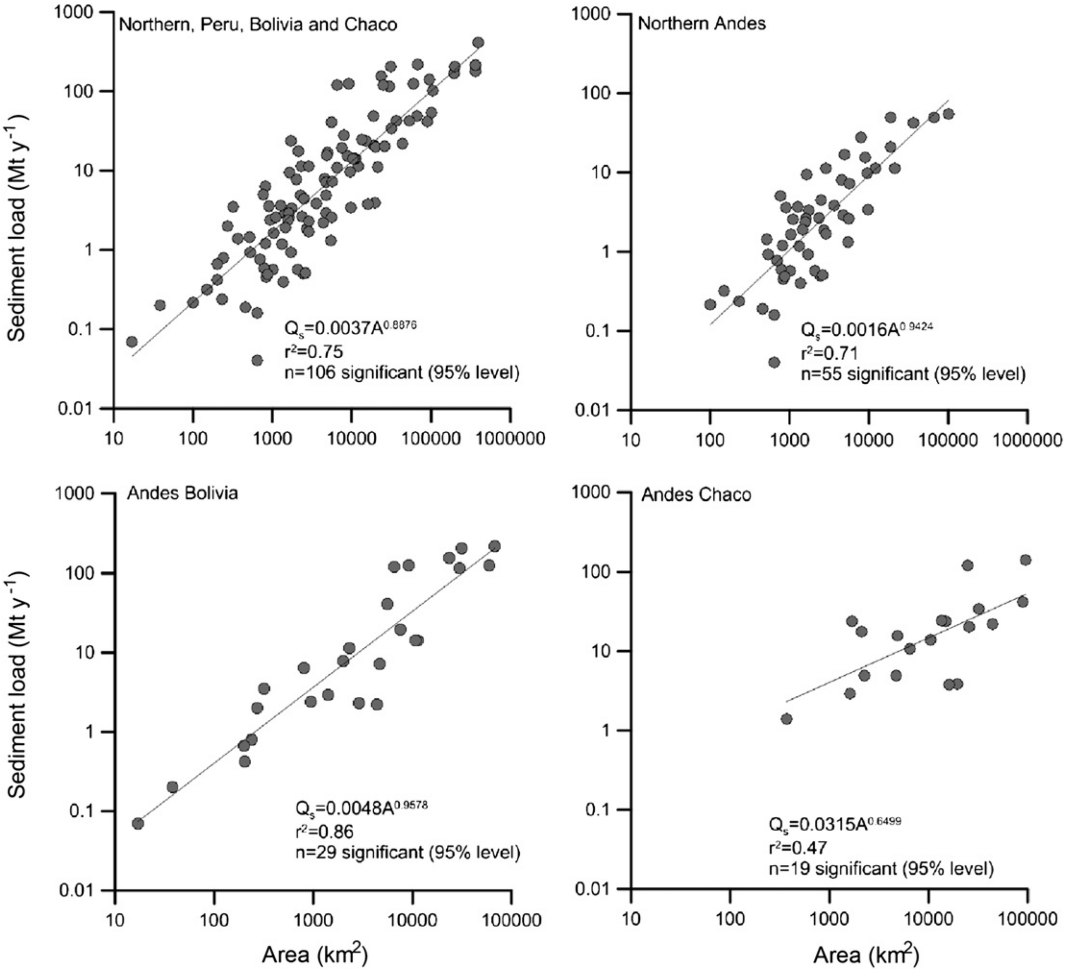

Fig. 5. Relation of sediment load versus basin area for the northern and central Andean rivers. Note the good coefficient of determination (R^2) when grouping the northern, Peruvian, Bolivian, and Chaco rivers.

sediment yields in mountain systems such as the Andes, Himalaya, and Alps. The scarcity of data from the Andean rivers in the seminal global reviews on erosion and sediment in mountain regions is even evident (Dedkov and Moszherin, 1992; Milliman and Syvitski, 1992; Hovius, 2000; among others). As a result, typical values provided for South America (delivery of sediments to the ocean) suggest low sediment production at the continental scale because of the bias produced by sediment storage into the continent. Thus, this picture changes when we compare the sediment yields in the Andes with other orogenic systems around the world.

In an earlier paper, Latrubesse et al. (2005) suggested that the Andean catchments could produce similar amounts of sediment when comparing them to drainage basins in the Himalaya and the mountainous islands of Southeast Asia. Fluvial erosion is remarkable in high relief, young orogenic tectonic belts. Previous global studies of sediment transport ascertained that mountains with easily eroded rocks in the wet mountains of Southeast Asia have sediment loads one to two orders greater magnitude than rivers draining other mountainous areas of the world (Syvitski and Milliman, 2007; Milliman and Farnsworth, 2011). The average yields in New Zealand and Taiwan were postulated to be more than five times the global average (Milliman and Meade, 1983). Relatively small drainage basins of the East Indies (Sumatra, Java, Borneo, Celebes, and Timor), representing about 2% (1.8×10^6 km^2) of the land area draining into the ocean, may possibly discharge about 4200 MT of sediment annually (Milliman et al., 1999). Generally, these estimations for insular Southeast Asia were based on probabilistic curves and, as we previously explained, the application of these methods is imprecise. For that reason, we avoided them. Sediment transport and production by rivers in large islands such as Borneo and other insular regions in Southeast Asia are still poorly understood and their records are far from complete.

Sediment yield estimates of Himalayan catchments come from piedmont stations in rivers such as Kosi, Gandak and Bhuri Gandak, Baghmati, and Kamla Balan, among others (Sinha and Friend, 1994; Latrubesse et al., 2005). These values do not reflect the sediment production in the mountain zone because deposition occurs in the piedmont area where they are located.

We averaged sediment yields in each major orogenic system by selecting rivers measured at mountain and high mountain gauging stations (Fig. 7). Data from fluvial basins such as Karnai, Narayani, and Sapta Kosi, are available in the international literature; and they demonstrate that the production of sediments in the Himalayan basins is high with an average of 4837 t km^{-2} y^{-1} (Andermann et al., 2012) (Fig. 7). Mountainous systems of Europe and Turkey produce an average sediment yield between 385 and 431 t km^{-2} y^{-1} (Vanmaercke et al., 2011), while mountainous southeast insular Asian, New Zealand, and Taiwan catchments produce an average of ~2265, ~1970, and ~7840 t km^{-2} y^{-1}, respectively (Fig. 7).

When analyzing specific rivers with comparable drainage areas ($1000 \leq 70000$ km^2) from the Andes, Himalaya, Southeast Asian, and New Zealand (Pinet and Souriau, 1988; Milliman and Syvitski, 1992; Latrubesse et al., 2005; Andermann et al., 2012), surprising results emerge: (i) the maximum yields in the Andes, such as 18,310 t km^{-2} y^{-1} in Bolivia and 14,117 t km^{-2} y^{-1} in the Chaco,

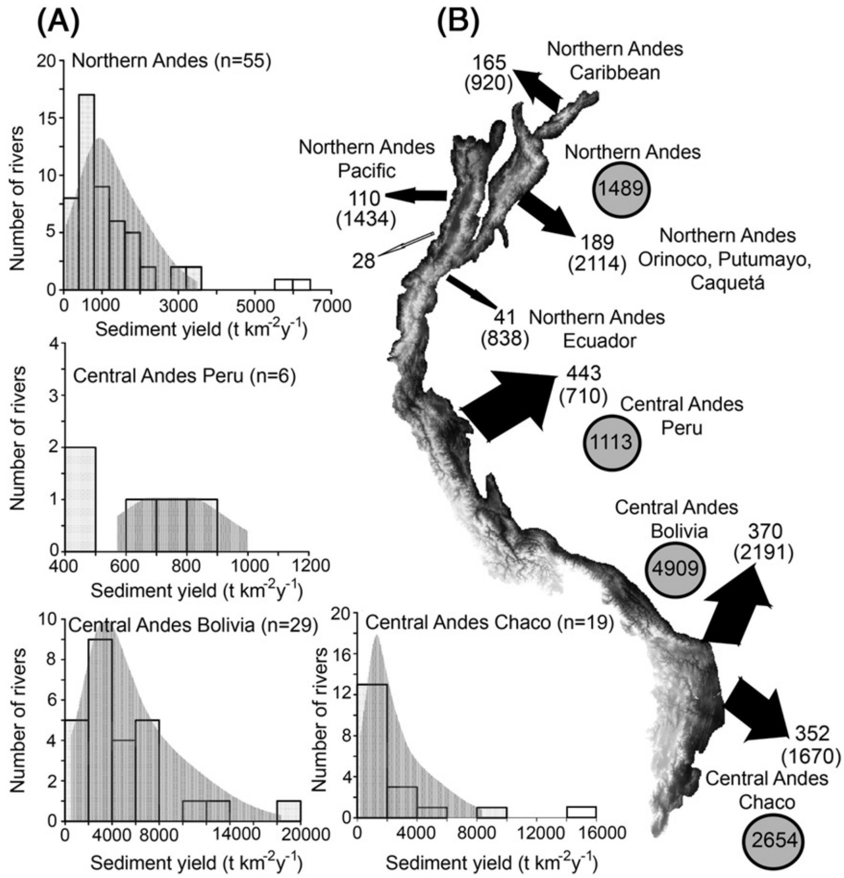

Fig. 6. Sediment yield and load from the most productive regions of the Andes, including frequency distributions of sediment yield for the northern and central regions of the Andes (A) and geographic location of major sediment fluxes ($\times 10^6$ t y^{-1}) (B). Arrow width is proportional to values of sediment load. Average sediment yield (circles) for each Andean region is based on the data set presented in Table 1 and Fig. 3. Values in parentheses indicate piedmont sediment yield after deposition processes in floodplains and aggradational fans. Based on the regional mean sediment yield, we show values of sediment flux from the ungauged northern basins of Ecuadorian Pacific watersheds (white arrow).

are comparable to high yields reported for Asian and New Zealand rivers such as the Huallien (Taiwan, 13,500 t km^{-2} y^{-1}), Peinan (Taiwan, 14,800 t km^{-2} y^{-1}), Choshui (Taiwan, 20,000 t km^{-2} y^{-1}), Aure (Papua New Guinea, 11,000 t km^{-2} y^{-1}), and Haast River (New Zealand, 13,000 t km^{-2} y^{-1}); (ii) 75% quartiles of sediment yield in the Bolivian and Chaco regions, 6630 and 3237 t km^{-2} y^{-1}, respectively, are similar to high yields reported in the upper Himalayas, including the catchments of Cimanuk (7800 t km^{-2} y^{-1}), Bagmati (12,203 t km^{-2} y^{-1}), Karnali (7683 t km^{-2} y^{-1}), Narayani (9333 t km^{-2} y^{-1}), Sapta Kosi (4200 t km^{-2} y^{-1}), Buhri Gandak (1500 t km^{-2} y^{-1}), and Kamla Balan (2670 t km^{-2} y^{-1}); and (iii) average yields in the Andes of 1000, 3675, and 2654 t km^{-2} y^{-1} (Fig. 5B) are quite similar and even larger than yields of other SE insular Asian rivers such as Fly (1086 t km^{-2} y^{-1}), Purari (2424 t km^{-2} y^{-1}), and Sepik (1100 t km^{-2} y^{-1}).

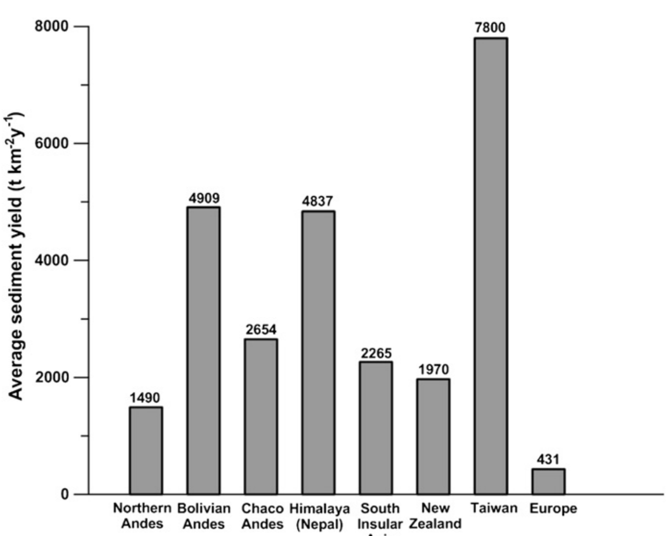

Fig. 7. Average sediment yields of major orogenic systems, showing mean yields for the main Andean regions (n = 109) analyzed in this study. Data from mountain and high mountain rivers in Himalaya–Nepal (n = 13), Europe and Turkey (n = 157), southeast insular Asia (n = 6 islands; calculated from mean sediment yield estimations by Milliman et al., 1999), New Zealand (n = 50), Taiwan (n = 18), and mountainous systems of Europe and Turkey (n = 105) were obtained from Latrubesse et al. (2005), Vanmaercke et al. (2011), Milliman and Farnsworth (2011), Andermann et al. (2012).

4. Final remarks

Based on sediment yield data from 119 gauging stations in Andean catchments, we estimated that the northern and central Andes, accounting for ~46% of the entire Andean area (excluding the Pacific catchments of Peru, northern Chile, and central Argentina), have a weighted mean sediment yield of 2045 t km^{-2} y^{-1} and produce a minimum of 2.25 GT y^{-1} of sediment. Our estimated values suggest a total amount ranging between 2.57 and 3.44 GT y^{-1}.

In between the production in the Andean mountains and the most proximal gauge stations located in the piedmont, the estimated budget indicates that, at least, ~0.55-1.74 GT y^{-1} of sediment are deposited in intermountain basins, piedmont alluvial fans, river floodplains, and associated wetlands. The combined eastern peripheral basins of the north-central Andes represent, perhaps, the largest and most extensive continental sediment sink on the planet.

This first macroscale analysis of sediment yield in the Andes shows that the magnitude of yields for the northern and central regions of the Andes is equivalent to rivers draining other orogenic belts in Asia, Insular Asia, and New Zealand, and one order of magnitude larger than yields reported for the Alps (Vanmaercke et al., 2011). Our results, based on the total sediment yield of the Andes rather than on the average yield of a few major rivers gauged downstream, transform our conception of the role played by the Andes on global sediment erosion.

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