Anthropocene 10 (2015) 13–28

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

Recent deforestation causes rapid increase in river sediment load in the Colombian Andes

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ARTICLE INFO

Article history:
Received 10 June 2015
Received in revised form 29 August 2015
Accepted 2 September 2015
Available online 8 September 2015

Keywords:
Fluvial sediment
Spatial modeling
Erosion
Deforestation
Magdalena River
Andes

ABSTRACT

Human induced soil erosion reduces soil productivity; compromises freshwater ecosystem services, and drives geomorphic and ecological change in rivers and their floodplains. The Andes of Colombia have witnessed severe changes in land-cover and forest loss during the last three decades with the period 2000 and 2010 being the highest on record. We address the following: (1) what are the cumulative impacts of tropical forest loss on soil erosion? and (2) what effects has deforestation had on sediment production, availability, and the transport capacity of Andean rivers? Models and observations are combined to estimate the amount of sediment liberated from the landscape by deforestation within a major Andean basin, the Magdalena. We use a scaling model BQART that combines natural and human forces, like basin area, relief, temperature, runoff, lithology, and sediment trapping and soil erosion induced by humans. Model adjustments in terms of land cover change were used to establish the anthropogenic-deforestation factor for each of the sub-basins. Deforestation patterns across 1980–2010 were obtained from satellite imagery. Models were employed to simulate scenarios with and without human impacts. We estimate that, 9% of the sediment load in the Magdalena River basin is due to deforestation; 482 Mt of sediments was produced due to forest clearance over the last three decades. Erosion rates within the Magdalena drainage basin have increased 33% between 1972 and 2010; increasing the river's sediment load by 44 Mt y^{-1}. Much of the river catchment (79%) is under severe erosional conditions due in part to the clearance of more than 70% natural forest between 1980 and 2010.

1. Introduction

Sediment flux of global rivers is conditioned by geomorphic and tectonic influences – basin area and relief – (Ahnert, 1970; Milliman and Syvitski, 1992; Harrison, 2000), but also by geography – temperature and runoff – (Langbein and Schumm, 1958; Walling, 1997), geology – lithology and ice cover – (Pinet and Souriau, 1988; Milliman and Syvitski, 1992), vegetation cover (Douglas, 1967) and anthropogenic impacts, including reservoir emplacement and human induced soil erosion (Dunne, 1979; Douglas, 1996; Vörösmartry et al., 2003; Syvitski et al., 2005; Restrepo and Syvitski, 2006). These factors often counter balance each other (Syvitski and Milliman, 2007).

Estimating the redistribution of continental substrate through weathering and erosion is one of fundamental goals of geological sciences (Syvitski and Milliman, 2007). The redistribution of sediment loads reflects the agents of erosion, transportation and deposition within landscapes. Transfer of sediment by rivers is a key component of the global denudation system and provides a general measure of the rate of denudation of the continents and of the efficacy of erosion processes in lowering the land surface (Walling and Fang, 2003). Sediment transported by rivers is a primary indication on how the landscape is evolving. Sediment transport can also be used to understand the impact of erosion from mining, deforestation and agricultural practices. Deviations from the ambient sediment flux therefore provide a measure of land degradation and the associated reduction in the global soil resource (Oldeman et al., 1991).

Rivers and their watersheds are systems that evolve over time. Modern river dynamics are influenced both by paleo conditions within the drainage basin and from perturbations of humans (Syvitski, 2003; Reusser et al., 2014). Variability in fluvial fluxes reflects the influence of both long-term (century to millennial) and short-term (annual and interannual) fluctuations in climate. Super-imposed on these influences is the effect of human-induced change on both the drainage basin and the river itself (Farnsworth and Milliman, 2003). For example, landscape-scale erosion rates, estimated by the concentration of ^{10}Be in southeastern

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http://dx.doi.org/10.1016/j.ancene.2015.09.001
2213-3054/

United States river catchments, revealed that soil erosion and sediment transport during the early 1900s, when most of the region was cleared of native forest and was used most intensively for agriculture, exceeded background erosion rates by more than one-hundred fold (Reusser et al., 2014).

There is no doubt that human activity is an effective agent in altering the landscape; affecting erosion rates and consequently fluvial sediment transport. Some studies have documented the relevant role played by the so-called "technological denudation", the human contribution to sediment generation (e.g., Cendrero et al., 2006; Bonachea et al., 2010). Human mobilization of sediments could be one to two orders of magnitude greater than natural denudation rates. In fact, global erosion rates from natural processes are between 0.1 and 0.01 mm y^{-1}, while soil denudation due to human activities accounts for 1 mm y^{-1} (Bonachea et al., 2010). Overall, humans have increased the rate that sediment is delivered to the global oceans by 2.3 ± 0.6 Gt/y (Syvitski et al., 2005; Syvitski and Kettner, 2011).

Humans modify global runoff through aquifer mining, surface water diversion, changes in inland lakes, desertification, wetland drainage, channelization of rivers, and dam building, and global sediment yield with urbanization, agricultural practices, mining, deforestation and sediment trapping by dams. Medium ($100–400 \times 10^3$ km^2) and small sized rivers ($1–100 \times 10^3$ km^2) are most impacted where humans can overwhelm pristine conditions (Syvitski, 2003; Walling and Fang, 2003; Syvitski et al., 2005; Syvitski and Kettner, 2011). Forest clearing for wood products and agriculture, can dramatically increase the pace at which sediments move into river systems, thus, increasing sediment yield above natural levels (Meade and Trimble, 1974; Reusser et al., 2014). The tropics are regions most influenced by increased sediment loads largely because of deforestation (Syvitski and Kettner, 2011).

While the clearing of forests began more than 10,000 years ago, the rate of clearing has accelerated since the 1900s when the area of cropland doubled (Houghton, 1994). Deforestation accelerated again since the 1960s, coinciding with rapid global population growth, especially in the tropics (Etter et al., 2006a). The rate of net forest loss globally is presently 125,000 km^2 y^{-1}, and increasing by 2000 km^2 y^{-1}. Of all the deforestation, 85% occurs in the tropics (Hansen et al., 2013) where forests are being converted to cropland and pasture for the production of soy, beef, palm oil, and timber (Ferretti-Gallon and Busch, 2014).

In the tropical Andes of Colombia, 80% of the natural vegetation was cleared by 2000, with 20% remaining as remnants of forests (Etter et al., 2008). Some 180,600 km^2 (69%) of the Andean forests and 203,400 km^2 (30%) of the lowland forests were cut down by 2000 (Etter et al., 2006b), with the highest rates of forest clearing corresponding to the Andean region. The total national deforestation rates rose from an estimated 10,000 ha y^{-1} to more than 230,000 ha y^{-1} between 1500 and 2000. Thus the Andean forest belt has been constantly cleared over the last 500 years, with clearing accelerating to 1.4% y^{-1} during the second half of the 20th century (Etter et al., 2008).

During the industrialization and urbanization that took place in Colombia between 1970 and 2000, the socioeconomic and policy changes were associated by an increase in deforestation, at average annual rates in excess of 230,000 ha. The area of transformed landscapes now exceeds 41 Mha or approximately 40% of the country. The highest proportion of new clearing continued to occur in the Andean region (Etter et al., 2008). For instance, the clearing between 1970 and 2000 was mainly concentrated in the Magdalena and Amazon basins (Etter and van Wyngaarden, 2000).

A recent deforestation assessment in 34 tropical countries, that account for the majority of tropical forests (Kim et al., 2015), reveals 62% acceleration in net deforestation in the humid tropics from 1990s to the 2000s. Tropical Latin America showed the largest acceleration of annual net forest area loss. Colombia has the highest rate of deforestation with an increase of 179% from the 1990s to the 2000s. Brazil showed the second largest increase in deforestation with 33%.

Clearance of natural vegetation for cattle ranching, land cultivation and mining is known to have increased rates of soil erosion by several orders of magnitude (Walling and Fang, 2003). Quantitatively determining the human contribution on erosion rates in fluvial catchments remains a difficult task, albeit critical for environmental decision making, such as setting allowable levels of suspended sediments and developing soil conservation strategies for reducing sediment yields so that they are closer to the rates at which landscapes evolve and erode naturally (Reusser et al., 2014).

Our inability to accurately model the human impact on sediment transport and erosion in fluvial systems remains one of the bottlenecks of the study of human-landscape interactions (Etter et al., 2006c; Syvitski and Milliman, 2007). Many algorithms to model the influence of human on sediment flux (Syvitski and Milliman, 2007), including the Soil Conservation Service curve number method (Mishra et al., 2006), the revised universal soil loss equation (Erskine et al., 2002), and the water erosion prediction project model (Croke and Nethery, 2006), are all designed to plot scale or, at best, small catchments and are not easily adapted to simulate human impacts on erosion for medium–large river basins (Syvitski and Milliman, 2007). Also, determining the magnitude of the composite human disturbance is like trying to hit a moving target as each decade brings a new environmental situation (e.g., Restrepo and Syvitski, 2006; Wang et al., 2006; Syvitski and Milliman, 2007).

The tropical Andes of Colombia and its main river basin, the Magdalena (Fig. 1), have witnessed dramatic changes in land-cover and further forest loss during the last three decades (Restrepo and Syvitski, 2006). The Magdalena River, one of the top 10 rivers in terms of sediment delivery to the ocean (184 Mt y^{-1}) (Restrepo and Kjerfve, 2000; Restrepo et al., 2006), and its tributaries, have experienced increasing trends in sediment load during the 1980–2000 period; increases in close agreement with trends in land-use change and deforestation (Restrepo and Syvitski, 2006). Now the relevant questions are: (1) what are the cumulative impacts of the destruction of tropical forests on soil erosion? and (2) what are the effects of deforestation on sediment production and availability, and transport capacity of Andean rivers?

This paper estimates the amount of sediment load explained by deforestation in the Magdalena basin (Fig. 1). We use a scaling model BQART that combines natural and human forces, like basin area, relief, temperature, runoff, lithology, ice cover, and sediment trapping and soil erosion induced by humans (Syvitski and Milliman, 2007). The BQART model has a bias of 3% and accounts for 96% of the between-river variation in long-term (±30 years) of global sediment loads (Syvitski and Milliman, 2007). The BQART model has already been successfully applied to the Magdalena River basin (Kettner et al., 2010), to explore anthropogenic erosion due to deforestation during the 1980–2000 period. Here we extend this analysis for another decade, to investigate rates of change and continued trends in sediment load for the main tributaries during the last three decades. We compare these results to trends in deforestation, economic indicators related to soil degradation, and sedimentation rates in the lower Magdalena basin.

2. The Andes of Colombia and the Magdalena River

The Andes is a tectonically active region characterized by active volcanism, ongoing uplift, earthquakes, and high magnitude mass movements (Vanacker et al., 2003; Harden, 2006; Molina et al., 2008). Uplift has caused rivers to incise and denudation rates to be high. In this region of steep slopes, mass movements are mostly

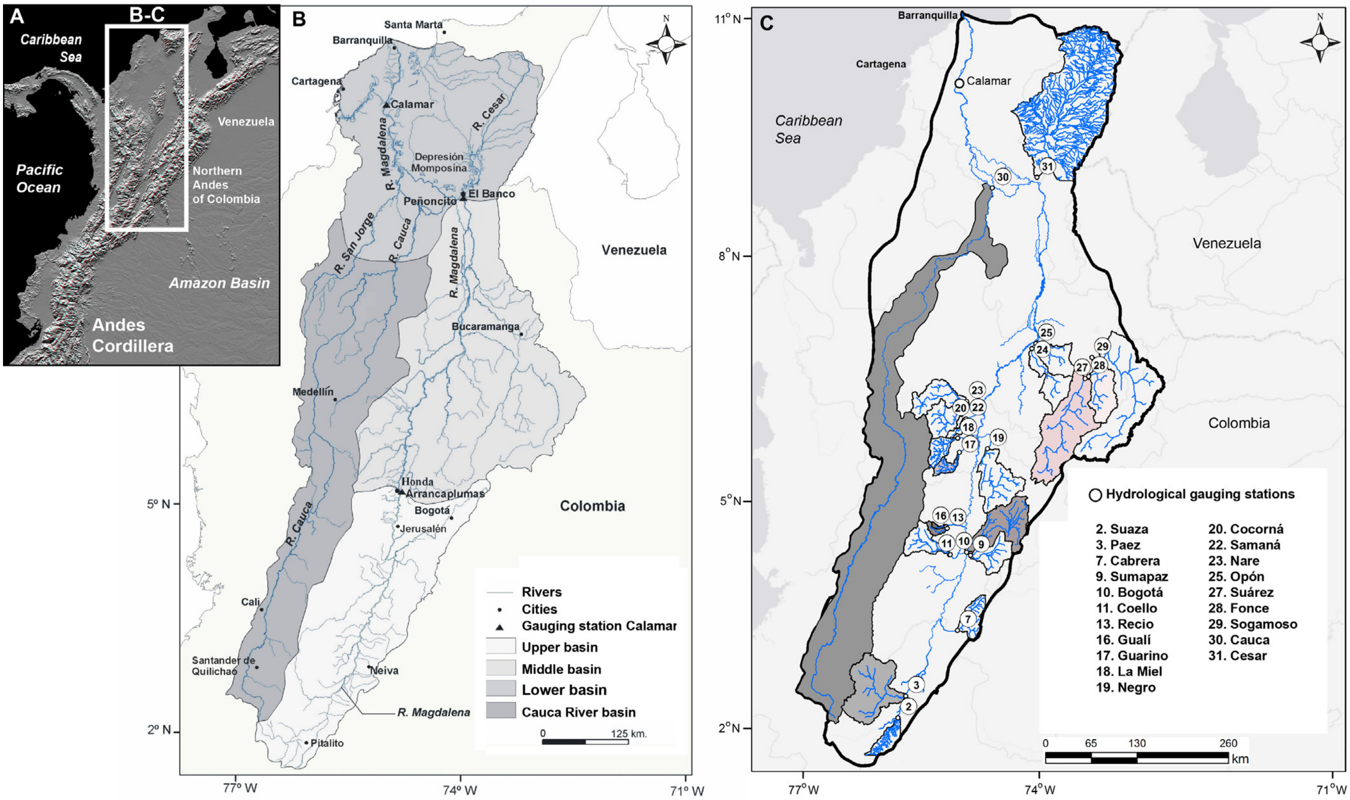

Fig. 1. Location of the Magdalena drainage basin in the northern Andes (A), showing the upper, middle and lower sections of the catchment (B), and the 21 analyzed tributary basins and their hydrological stations (C).

triggered by wet conditions and by earthquakes (Aalto et al., 2006; Harden, 2006). Tropical catchments located in the cordilleras of the Andes are susceptible to soil erosion due to their topography and erosive climate, and due to the occurrence of extreme geologic events (Hess, 1990; Milliman and Syvitski, 1992; Dadson et al., 2003).

The Andes of Colombia consists of three nearly parallel and north–south-oriented mountain ranges, the Western, Central, and Eastern Cordilleras, which merge into a single range near the Ecuadorian border (Fig. 1A). Between these ranges lie two river valleys: the high and narrow Cauca valley to the west and the low and broad Magdalena valley to the east. The Magdalena River is the largest river system of the northern Andes of Colombia (Fig. 1B), with a length of 1612 km. The drainage basin area covers 257,438 km^2 (24% of Colombia), with headwaters located at an elevation of 3685 m. The geomorphic setting of the Magdalena comprises subsiding foreland areas, an anastomosing river pattern, and tributary systems with high vertical aggradation (Latrubesse et al., 2005). The Andean part of the Magdalena basin is vulnerable to natural erosion processes, with 19% of the basin area being influenced by hillslopes exceeding 35°; 26% of the land has moderate slope angles (16–35°); and 55% of the area with lower slope angles (0–15°). Tributary basins (71% of the drainage area) are in elevations higher than 1000 m. The mountainous section of the catchment is characterized by landslide activity over fissile sedimentary rocks. Most tributaries drain basins less than 6000 km^2 and are responsive to both natural and human-induced change (Restrepo and Syvitski, 2006).

Besides the natural factors that lead to excessive erosion, including high runoff over steep slopes undergoing tectonic activity, forest cover in the Colombian Andes has greatly decreased due to population expansion and changes in land use. The first studies assessing the human impact on soil erosion in the Andes of the Magdalena basin (Restrepo and Syvitski, 2006; Restrepo et al., 2006), show that most of the erosion can be explained by natural variables, including runoff and peak discharge. These two estimators explain 58% of variance in erosion rates. The study also indicated that deforestation, poor soil conservation and mining practices, and increasing rates of urbanization, have accounted for the remaining trends in erosion on a regional scale.

Many socioeconomic features demonstrate that the Magdalena basin drives the economic growth of Colombia. Eighty percent of the population lives in the catchment and 86% of the Colombian GDP is produced here. Recent economic indicators at a national level show that the basin produces 75% of its agricultural products, 70% of its hydroelectricity, 90% of its thermal energy, and 80% of its coal mining (Restrepo, 2013).

The percentage forest cover in the Magdalena basin was estimated to have declined from 66% in 1980 to 22% in 2000, with an annual deforestation rate of 274,000 ha y^{-1} (Restrepo and Syvitski, 2006). An assessment of deforestation by IDEAM (National Institute of Hydrology and Environmental Studies) between 2000 and 2010 indicates that the national rate of forest loss is 336,000 ha y^{-1} (IDEAM, 2011), with a percentage forest reduction from 22% in 2000 to 13% in 2010. When compared to global rates of deforestation (FAO, 2010), Colombia, with an area of 1.14 million km^2 and representing ~0.1% of the global land, contributes ~5% to the global forest loss (Restrepo, 2013).

3. Materials and methods

The BQART model is an analytical model modified with empirical algorithms (Eq. (1b)) designed to capture geomorphic-, geographic-, geologic features, and human influences (Eqs. (1a) and (1b); Syvitski and Milliman, 2007). Only minor model adjustments, discussed below, are applied in the process of downscaling *BQART* methodology to a sub-basin scale.

$$\overline{Qs} = \overline{\omega} B \overline{Q}^{0.31} A^{0.5} R \overline{T} \quad \text{for } \overline{T} \geq 2\,^{\circ}\mathrm{C} \tag{1a}$$

where B is defined as:

$$B = IL(1 - T_{\mathrm{E}})E_{\mathrm{h}} \tag{1b}$$

where $\overline{Qs}$ is long-term suspended sediment (kg s^{-1}, using the unit conversion ω a dimensionless constant of proportionality = 0.02), $\overline{Q}$ is long-term water discharge (km^3 y^{-1}), A is basin area (km^2), R is maximum relief (km), $\overline{T}$ is basin-averaged temperature (°C), I is the glacier erosion factor, L is the basin-wide lithology factor (−), T_{E} is the trapping efficiency fraction of lakes and man-made reservoirs (−) and E_{h} is the human-influenced or anthropogenic factor, here adjusted to deforestation rates (−).

In this study, monthly water and suspended sediment load data (17–32 years in length) were obtained for 21 sites throughout the Magdalena basin from the Hydrological Institute of Colombia, IDEAM (IDEAM, 2014) (Fig. 1C, Table 1). The long-term annual average observed sediment load is derived from monthly data to validate intra-basin *BQART* simulations for the 1980–2010 period. The gauging stations in each major tributary system correspond to the lowest point in the sub-basin for which water discharge and sediment load data are available, although this is not always near where the tributary joins the main course of the Magdalena (Fig. 1C). The 21 selected catchments capture the variability of topography, lithology, land cover, and human induced pressures that the Andes represent (Kettner et al., 2010).

Morphometric variables (drainage basin area, relief and longitudinal profile) of the selected tributary catchments of the Magdalena basin (Table 1) were obtained using Shuttle Radar Topography Mission data (3 arc-seconds horizontal and a vertical resolution), ranging from ±1.1 to 2 m in the lowlands to ±6 m in the highland regions (Farr et al., 2007; Berry et al., 2007). The network pattern was explored to assess patterns of sediment retention throughout the river network (Fig. 1). Basin-averaged temperature and precipitation data for each analyzed sub-basin were assessed using climate archives of the Center for Climatic Research, University of Delaware (http://climate.geog.udel.edu/~climate/html_pages/archive.html).

A 1:500,000-scale geologic map of Colombia (Gómez et al., 2007) was analyzed to determine the lithology for each of the drainage basins. The lithologic classification was converted into six broad basin-averaged lithology classes according to the global lithologic composition (Dürr et al., 2005) and the lithology categories presented by Syvitski and Milliman (2007) and Syvitski and Kettner (2008). An area-weighted lithology factor was established for each tributary sub-catchment of the Magdalena River basin (Table 2) (Kettner et al., 2010). BQART model implementation in terms of trapping efficiency of man-made reservoirs (T_{E}) and the glacial erosion factor, the latter insignificant for the Magdalena tributaries, were followed according to Kettner et al. (2010).

Minor model input adjustments were made to establish the anthropogenic-deforestation factor (E_{h}) for each of the sub-basins of the Magdalena River (Kettner et al., 2010). Syvitski and Milliman (2007) employed a relation based on population density and Gross National Product (GNP) per capita to determine variation in human disturbance globally, resulting in a 16% more accurate sediment flux estimates, on a global basis. The algorithm however was never developed to capture human disturbance for national or subnational sediment flux simulations. To simulate the influence of human induced activities on sediment flux for the Magdalena, we employed a dimensionless vegetation–erosion index that is equivalent to the anthropogenic factor (E_{h}) used by Kettner et al. (2007). The factor accounts for the effect changes to the vegetation cover have on erosion rates and sediment yield (Table 3).

Table 1

Physical characteristics of the Magdalena River basin as a whole and the 21 analyzed tributary catchments. Numbers in front of the tributary names indicate the location of each tributary basin (Fig. 1). Water discharge, mean annual runoff and sediment yield are based on data for the 1980–2010 period.

Tributary	Area[a] (km^2)	Length[a] (km)	Water discharge[b] (km^3 y^{-1})	Mean annual runoff[a,b] (mm y^{-1})	Sediment yield[a,b] (t km^{-2} y^{-1})	Rating curve exp.[c] C (−)	# of data (y)
Magdalena River	*257.438*	*1.612*	*245.4*	*880*	*710*	*1.71*	*38*
2. Suaza	1.014	89	1.4	1.351	464	2.40	24
3. Páez	4.760	127	5.5	1.206	626	2.20	24
7. Cabrera	2.713	115	2.2	824	571	1.79	25
9. Sumapaz	2.433	137	1.4	551	156	1.96	27
10. Bogotá	5.409	305	1.3	226	250	2.62	33
11. Coello	1.041	108	1.2	1.217	1114	2.66	23
13. Recio	643	76	0.7	960	249	2.60	28
16. Gualí	458	96	0.8	1.585	568	1.86	16
17. Guarino	840	92	1.6	1.229	679	2.48	20
18. La Miel	2.363	104	7.8	3.250	982	2.02	34
19. Negro	4.575	214	4.4	936	1550	1.91	24
20. Cocorna	790	86	1.8	2.231	620	1.69	28
22. Samana	1.713	111	5.8	3.330	525	1.96	17
23. Nare	5.564	187	12.8	2.244	404	2.33	24
24. Carare	4.909	274	8.4	1.699	3064	2.03	22
25. Opón	1.752	179	2.8	1.574	1878	1.68	20
27. Suárez	9.775	220	9.4	968	338	1.86	23
28. Fonce	2.083	106	2.7	1.273	302	2.15	32
29. Sogamoso	21.211	348	13.8	647	514	2.00	22
30. Cauca	66.751	1183	76.0	1.127	727	1.20	32
31. Cesar	18.827	379	1.7	89	7	0.76	32

Italic letters correspond to physical characteristics for the whole Magdalena River drainage basin.

[a] Morphometric variables were obtained from a 3 arc-seconds horizontal and a 1 m vertical resolution Shuttle Radar Topography Mission data (SRTM). Basin averaged-temperature and precipitation data for each analyzed sub-basin were assessed from the climate archives of the Center for Climatic Research. University of Delaware (http://climate.geog.udel.edu/~climate/html_pages/archive.html).

[b] Monthly and daily water and suspended sediment load data for the 21 sub-catchments (Fig. 1) in the Magdalena basin were obtained from the Hydrological Institute of Colombia (IDEAM, 2014).

[c] The rating curve exp. C (−) is estimated following Morehead et al. (2003) and is based on the temperature, relief, and long-term sediment load of each sub catchment.

Table 2
Averaged lithology factor of each tributary catchment within the Magdalena drainage basin based on the geological classification.

Tributary	Pa–Pr[a] (%)	Mt[a] (%)	Vb[a] (%)	Ss[a] (%)	Assigned *L* factor[b] (−)
2. Suaza	15	35	50		0.75
3. Páez	50	16	16	18	0.85
7. Cabrera		2	1	97	1.96
9. Sumapaz				100	2.00
10. Bogotá				100	2.00
11. Coello	18	80	1	1	0.52
13. Recio	50	35	15		0.58
16. Gualí	2	68	30		0.65
17. Guarino	7	45	45	3	0.77
18. La Miel	26	70		4	0.56
19. Negro				100	2.00
20. Cocorna	7	90		3	0.55
22. Samana	55	30		15	0.73
23. Nare	70	25		5	0.58
24. Carare				100	2.00
25. Opón				100	2.00
27. Suárez		4	1	95	1.93
28. Fonce	2	30	3	65	1.49
29. Sogamoso	2	5	2	91	1.88
30. Cauca	12	20	35	33	1.17
31. Cesar	7	5	5	83	1.77

Note: the lithology within the catchments was characterized from 1:500,000 scale geological maps of Colombia (Gómez et al., 2007) and the Magdalena drainage basin (IDEAM, 2001).

[a] The lithologic classification was converted into six broad basin-averaged lithology classes according to the global geologic map (Dürr et al., 2005). Pa: igneous intrusive rocks comprising mainly granites, granodiorites and quartz-diorites; assigned lithology factor $L = 0.5$; Pr: rocks from the middle and lower crust in the Precambrian basement, consisting of medium to high-grade metamorphic rocks (granodioritic-granitic character) ($L = 0.5$); Mt: middle-grade regional metamorphic rocks not classified as Precambrian basement rocks ($L = 0.5$); Vb: acid and intermediate volcanic rocks including basalts of different genetic origins, or mixture of hard and soft lithologies ($L = 1.0$); Ss: siliclastic rocks including siltstones, sandstone and conglomerates. It is assigned to tributaries draining a significant proportion of sedimentary rocks, unconsolidated sedimentary cover, or alluvial deposits ($L = 2.0$). The percentage lithology cover of each class in each catchment is obtained from the geological maps of Colombia and the Magdalena drainage basin (Gómez et al., 2007; IDEAM, 2001).

[b] After Syvitski and Milliman (2007).

Table 3
vegetation–erosion index used in this study to assign an anthropogenic factor (E_h) to each of the tributary basins within the Magdalena River. Land cover analysis 1980–2000 for each catchment was prepared from the classification of MSS and TM LANDSAT images (Restrepo and Syvitski, 2006). Forest covers and percentages of deforested areas during the 2000–2010 period were obtained from Armenteras and Rodríguez (2005), Restrepo (2005, 2008), and IDEAM (2014). The latter describes a deforestation assessment based on MODIS images classification for the 2005–2010 period.

Tributary	Low erodible area [a] (%)	Medium erodible area [b] (%)	High erodible area [c] (%)	Total highly erodible area [d] E_T (%) 1980–2010	Assigned anthropogenic E_h factor (−) [e] 1980–2010
2. Suaza	55.3	26.4	22.3	48.7	0.3
3. Páez	52.2	33.1	19.5	52.6	0.7
7. Cabrera	47.0	25.2	29.9	55.1	0.7
9. Sumapaz	63.4	17.5	19.6	37.1	0.3
10. Bogotá	20.8	17.4	62	79.4	1.4
11. Coello	17.0	21.0	64.3	85.3	1.4
13. Recio	72.5	10.8	17.1	27.9	0.3
16. Gualí	67.1	9.6	23.5	33.1	0.3
17. Guarino	80.2	3.5	21.6	25.1	0.3
18. La Miel	15.9	50.2	38.1	88.3	1.4
19. Negro	34.0	23.4	45.7	69.1	0.7
20. Cocorna	39.7	36.5	30.4	66.9	0.7
22. Samana	55.2	22.6	26.1	48.7	0.3
23. Nare	48.9	38.4	15	53.4	0.7
24. Carare	23.7	14.6	66.7	81.3	1.4
25. Opón	18.1	45.4	43.7	89.1	1.4
27. Suárez	25.8	61.4	14.4	75.8	1.4
28. Fonce	–	–			0.7[f]
29. Sogamoso	14.4	27.1	59.2	86.3	1.4
30. Cauca	24.5	30.7	46.6	77.3	1.4
31. Cesar	18.8	13.5	68.2	81.8	1.4

[a] Area of catchment with forests. Also, this category includes soils and rocks having no active erosion and low values of deforestation (<25%) during the 1980–2010 yr period.

[b] Area of each sub-basin with secondary forests, scrubs and homogeneous areas of exposed soils. Percentage deforested area in this class is 25–50% during the 1980–2010 yr period.

[c] Proportion of catchment with cultivated lands, pasture for cattle ranching, grassland and perennial crops. This class also consists in high steep terrains exposed to landslide events. The percentage of deforestation in this category is >50% for the 1980–2010 period.

[d] The total percentage of highly erodible lands (E_T) for each sub-basin is obtained by adding the percentages of medium [b] and high [c] erodible areas.

[e] Assigned anthropogenic factor (E_h) for each sub-basin: $E_h = 0.3$ for sub-basins with $E_T < 50\%$; $E_h = 0.7$ for sub-basins with E_T values ranging between 50 and 75%. This category contains a mixture of influences of soil erosion, deforestation and conservation; $E_h = 1.4$ for sub-basins with high values of soil erosion deforestation and poor farming and mining practices ($E_T > 75\%$) (after Kettner et al., 2007; Syvitski and Milliman 2007; Kettner et al., 2010).

[f] Assigned anthropogenic factor $E_h = 0.7$ for upstream stations and sub-basins with no data.

Land-cover analysis for each sub-catchment during the 1980–2000 period was prepared from classification of MSS and TM LANDSAT images, providing total area of deforestation and estimates of change throughout the period 1980–2000 (Restrepo and Syvitski, 2006). Erosional areas during the same period were obtained from the Environmental Assessment of the Magdalena Drainage Basin (IDEAM, 2001). Forest covers and percentages of deforested areas during the 2000–2005 yr-period were obtained from Armenteras and Rodríguez (2005), Restrepo (2005, 2008), and IDEAM (2011). Finally, we estimated forest cover change 2005–2010 for each tributary basin using deforestation maps from the National Assessment of Deforestation (IDEAM, 2014), which are derived from MODIS MOD13Q1 Vegetation Indices with a 250 m resolution.

To obtain the E_h deforestation factor for each tributary basin, integrated data of land-use cover analysis during the 1980–2010 yr-period was converted into three classes (Kettner et al., 2010) (Table 3): (1) low-erodible cover, the area of each basin with soils and rocks having no active erosion and low values of deforestation (<25%) during the 1980–2010 yr-period; (2) medium-erodible cover, the proportion of a catchment with secondary forests, scrubs and homogeneous areas of exposed soils. The percentage of deforested area in this class is 25–50%; and (3) high-erodible cover, the area of each basin with cultivated lands, pasture for cattle ranching, grassland and perennial crops. This class also consists in high steep terrains exposed to landslide events. The proportion of deforestation in this category is >50%. Total area (%) of highly-erodible lands (E_T) for each basin is obtained by adding the areas of medium and high erodible covers. Following the original range in E_h values of Syvitski and Milliman (2007), we assigned $E_h = 0.3$ for basins with $E_T < 50\%$ and $E_h = 0.7$ for basins with E_T values ranging between 50 and 75% where the land area contains a mixture of the influences of soil erosion, deforestation and conservation. $E_h = 1.4$ for basins with high values of soil erosion, deforestation and poor farming and mining practices ($E_T > 75\%$) (after Kettner et al., 2007, 2010; Syvitski and Milliman 2007).

A nonparametric Mann–Kendall (M–K) test is applied to detect trends of sediment load for 1980–2010 and these are compared with observed deforestation rates. The M–K test, is considered a robust method to identify and estimate linear trends in environmental data, including time series analyses of river fluxes (e.g., Yue et al., 2002; Milliman et al., 2008; Restrepo et al., 2014). The test does not assume any special form for the distribution function of the data and can be used for the analysis of non normally distributed data (Yue et al., 2002). The Sen's method was used to test the correlation between magnitude of slope changes and sediment load (Mann, 1945; Kendall, 1955; Kendall and Stuart, 1967). We also applied a modified M–K test (Hamed and Rao, 1998) to avoid possible errors associated with positive autocorrelations in the analyzed sediment load series (Constantino, 2013). The C values calculated with progressive and retrograde series are named $C1$ and $C2$, respectively. The intersection point of the two lines, $C1$ and $C2$ ($k = 1,2 \ldots n$), located within the 95% confidence interval provides the beginning of a step change point within a time series. Assuming a normal distribution with a significant level of $P = 0.05$, a M–K statistics $C > 1.96$ indicates a significant increasing trend; while a C lower than -1.96 indicates a significant decreasing trend (Gao et al., 2015).

To make comparisons between sediment load trends and human activities that promote sediment production in the Magdalena River basin, including deforestation, agriculture, mining, urbanization, and energy, we analyzed data of a global nature (FAO, 2010; Ferretti-Gallon and Busch, 2014), or more regional such as the humid tropics (Geist and Lambin, 2001, 2002; Kim et al., 2015), and national Colombian deforestation assessments (Etter et al., 2005, 2006a,b,c, 2008; IDEAM, 2014). Other regional studies consulted included those on agriculture (e.g., illegal cocaine crops; Dávalos et al., 2011; MacSweeney et al., 2014), mining (Alvarez-Berríos and Aide, 2015), and economic indicators of human activities in the Colombian Andes (Restrepo and Syvitski, 2006; Restrepo, 2013).

To assess the combined processes of sediment transport and deposition for the whole Magdalena basin, we analyzed time series of sediment load 1972–2011 in the most downstream station at Calamar (Fig. 1C). The Continuous Wavelet Transform (CWT) was used to examine the time series, using generalized local base functions (i.e., mother wavelets) that were stretched and translated with both a frequency and time resolution (Torrence and Compo, 1998; Restrepo et al., 2014). This time series was evaluated for non-stationary functions with different frequencies, providing a time-scale localization of the signal. CWT was applied on monthly de-seasonalized sediment load at Calamar 1972–2011, and used to estimate the periodicities and variability patterns, to distinguish temporal oscillations in sediment load, and identify the intermittency of each time-scale process (Restrepo et al., 2014).

4. Results

4.1. BQART model results: the amount of sediment produced by deforestation

The BQART model accounts for 86% of the between-tributary sediment flux variance (Fig. 2A, Table 4). When the anthropogenic-deforestation factor is not included in the BQART model simulations (i.e., $E_h = 1$), only 77% of the variance in sediment load is captured (Fig. 2B). Eighty-six percent of the individual tributaries is simulated within a factor of 2; remaining tributaries are all located on the east slope of the Magdalena river basin (Fig. 2C, Table 4). Three tributaries (Sogamoso, Bogotá, and Suárez) are overpredicted by a factor ≥ 2 (Fig. 2C). These low sediment yield tributaries (Table 1) contain very gradual gradients in their longitudinal profiles, surrounded by lakes, reservoirs and wide floodplains, and offer areas of high sediment retention not explicitly parameterized in BQART. High-sediment-yield tributaries like the Cabrera and the Fonce (Table 1) contain few sections of low-gradient slopes in their longitudinal profiles, with limited alluvial plains and no lakes or reservoirs; they lack potential sediment-storage areas. The observed overprediction for the Sumapaz is well captured once the anthropogenic-deforestation term is employed.

Land cover in the Magdalena basin has undergone considerable change. Forest cover decreased by 40% over the period of study, while the area under agriculture and pasture cover (agricultural lands 1 and 2) increased by 65% during the same 20-yr period (Fig. 3A). Many Magdalena sub-catchments, including the C auca, Opón, Suarez, Negro, and Páez rivers, witnessed an order-of-magnitude higher deforestation rates compared to other tributaries during 2005–2010 (Fig. 3B).

The total forest clearance in the Magdalena basin of 5106 km^2 between 2005 and 2010 represents 24% of the combined deforestation in Colombia (Fig. 3C). When including these deforestation rates 1980–2010 in the BQART model (Table 3), there is good agreement between model simulations and sediment load observations for the Cauca, the largest tributary system of the Magdalena drainage basin (66,751 km^2) (Fig. 2C and D, Table 4).

4.2. Trends in sediment load 1980–2010

Time series analysis of sediment load 1980–2000 for 21 gauging stations for the Magdalena basin indicates that 17 watersheds (68%

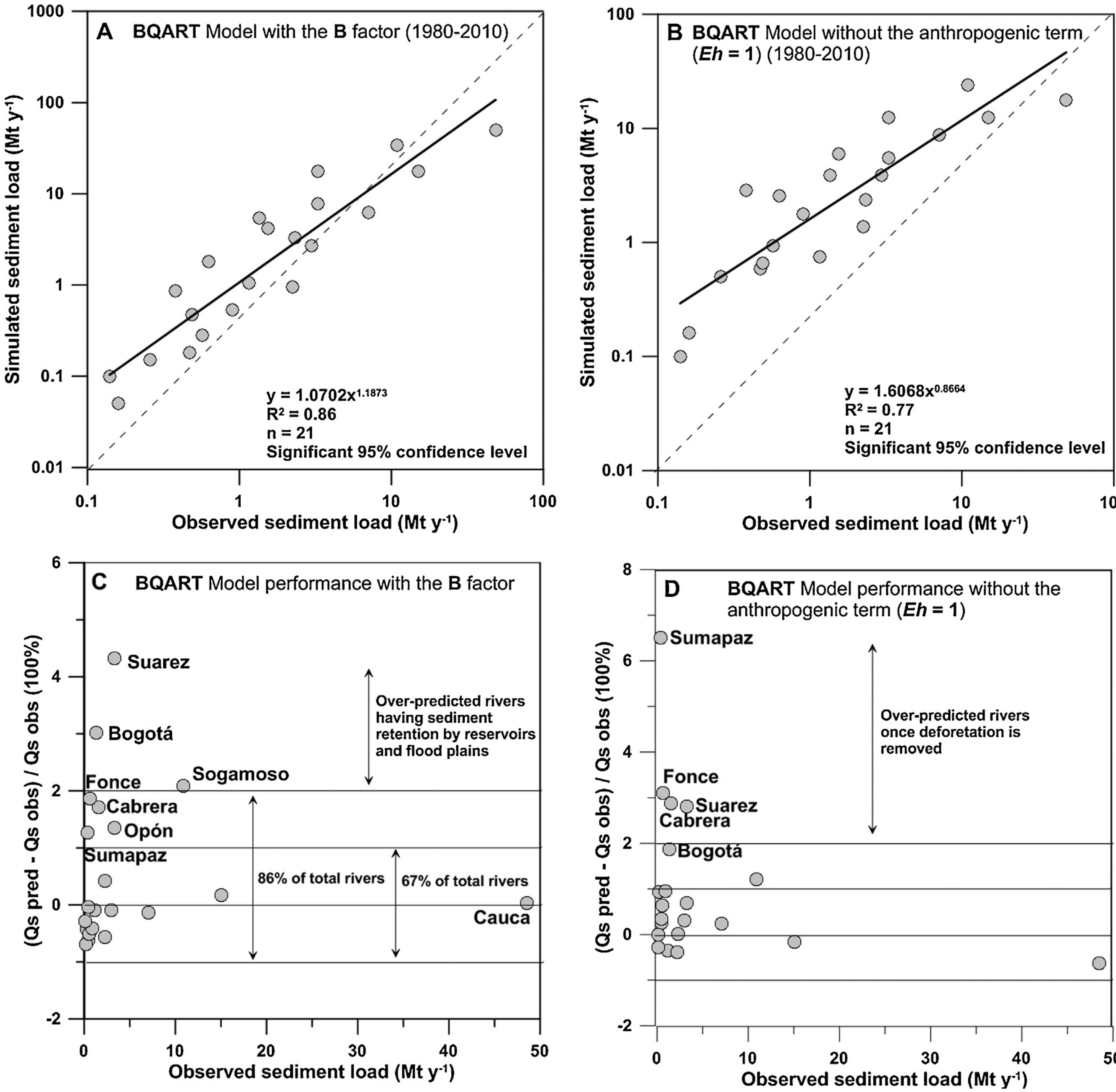

Fig. 2. BQART model simulations compared with sediment flux (Qs) observations from 21 sub-basins within the Magdalena basin. (A) BQART model simulations including the lithology and anthropogenic factors capture 86% of data variance. (B) BQART model simulations without including the deforestation term ($E_h = 1$) capture 77% of data variance when compared with observations from 21 tributary rivers within the Magdalena basin. Scatter plots of observed *Qs* versus BQART model performances for different simulations are also provided, including once were the whole *B* term is considered (C) and when the deforestation has been excluded ($E_h = 1$) (D).

of the drainage basin area) included in the regional database show increasing trends, whereas 12 locations or 31% of the land basin area display decreasing trends (Table 5). Only three stations, representing 1% of the drainage basin area, show no significant trend in sediment load. Most of the tributaries in the upper Magdalena basin between 1990 and 2000 have experienced significant increases in sediment load. The Opón River, located in the central and eastern part of the Magdalena basin, has witnessed sediment load increases starting since the 1990s.

Modified M–K tests were applied to test the statistical significance on upward and downward trends in sediment load 1980–2010 (Fig. 4). Some tributaries witnessed upward trends during the 1980s, 1990s and post-2000, including the Páez, the Carare, the Gualí, the Opón, the Sogamoso, the Guarinó, and the Suárez (Fig. 4A). The Cauca River, the main Magdalena tributary, saw its sediment loads increase by 30% from 1979 to 1999. Between 1979 and 1989, the average sediment load was 44 Mt y^{-1}. Since 2000, the average load increased to 59 Mt y^{-1}. Statistically significant upward trends at the 95% confidence level are seen for the Cauca between 1995 and 2002 as well as during the 2005–2010 period (Fig. 4B).

Further M–K tests on sediment load series for the 21 tributary systems during the 2005–2010 yr-period show that six tributaries, representing 55% of the analyzed Magdalena basin area, have witnessed increasing trends in sediment load (Fig. 4E). The Cauca experienced an increase in sediment load of 1.7 Mt y^{-1}. Further

Table 4
Natural and human induced factors used to simulate spatial variability of sediment load within the Magdalena drainage basin. Definition and source of catchment variables are explained within the text.

Tributary	Discharge ($km^3\,y^{-1}$) 1980–2010	Area (km^2)	Relief (km)	Temp (°C)	Observed sediment load[a] ($Mt\,y^{-1}$) 1980–2010	Simulated sediment load[b] ($Mt\,y^{-1}$) 1980–2010	Simulated sediment load[c] ($Mt\,y^{-1}$) $E_h = 1$ 1980–2010
Magdalena River	*245.4*	*257.438*	*5.4*	*21.8*	*188.2*	*149*	
2. Suaza	1.4	1.014	1.6	17.9	0.47	0.18	0.59
3. Páez	5.5	4.760	3.6	12.9	2.98	2.71	3.87
7. Cabrera	2.2	2.713	3.6	20.0	1.55	4.2	6
9. Sumapaz	1.4	2.433	3.7	10.8	0.38	0.86	2.85
10. Bogotá	1.3	5.409	2.9	12.3	1.35	5.43	3.88
11. Coello	1.2	1.041	3.5	17.1	1.16	1.05	0.75
13. Recio	0.7	643	4.7	4.3	0.16	0.05	0.16
16. Gualí	0.8	458	4.6	12.7	0.26	0.15	0.5
17. Guarino	1.6	840	2.9	14.9	0.57	0.28	0.93
18. La Miel	7.8	2.363	2.5	19.9	2.32	3.29	2.35
19. Negro	4.4	4.575	3.3	21.9	7.09	6.17	8.82
20. Cocorna	1.8	790	2.1	27.6	0.49	0.47	0.66
22. Samana	5.8	1.713	2.7	18.7	0.9	0.53	1.76
23. Nare	12.8	5.564	2.9	21.3	2.25	0.96	1.37
24. Carare (d.str)	8.4	4.909	3.6	20.1	15.04	17.52	12.51
25. Opón	2.8	1.752	1.9	22.8	3.29	7.74	5.53
27. Suárez (d.str)	9.4	9.775	3.7	13.9	3.3	17.58	12.56
28. Fonce	2.7	2.083	3.2	14.0	0.63	1.8	2.58
29. Sogamoso	13.8	21.211	3.7	12.3	10.91	33.73	24.09
30. Cauca	76.0	66.751	4.2	21.6	48.51	50.1	17.79
31. Cesar	1.7	18.827	1.8	25.0	0.14	0.1	0.1
Sum	**catchments**					**104**	**155**
110							

The tributary numbers 2–31 indicate the location of each tributary basin in Fig. 1.
Italic letters correspond to physical characteristics for the whole Magdalena River drainage basin.
[a] Observed annual sediment load for each of the tributaries over the observed period listed in Table 1.
[b] Simulations applied to all listed tributary basins including basin averaged lithology and anthropogenic factors in the *B* term.
[c] Simulations applied to all listed tributary basins without including basin averaged anthropogenic factor ($E_h = 1$) in the *B* term.

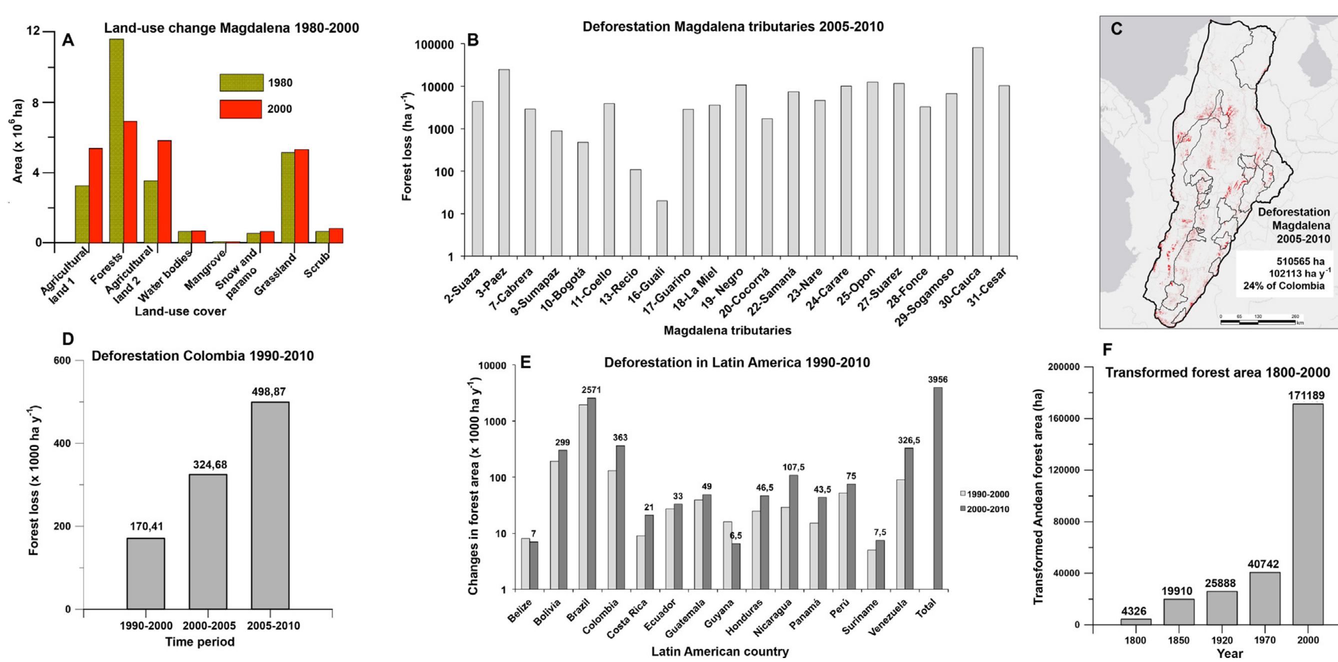

Fig. 3. (A) Area (in ha) occupied by each of the land cover types obtained from the classification of the 1980 and 2000 TM Landsat images (Restrepo and Syvitski, 2006). (B) Deforestation rates for the 21 tributary basins of interest for the 2005–2010 period, based on MODIS image classification by IDEAM–Colombia. (C) Map of deforestation in the Magdalena basin during the 2005–2010 period. (D) Deforestation rates in Colombia during the 1990–2000, 2000–2005, and 2005–2010 periods (data from Kim et al., 2015). (E) Changes in forest area in Latin America during the 1990–2000 and 2000–2010 yr-periods (data from Kim et al., 2015). (F) Transformed forest area in Colombia between 1800 and 2000 (data from Etter et al., 2008).

Table 5
Total simulated sediment load for the 1980–2000, 1980–2010, and 2000–2010 periods in each analyzed tributary basin, including the amount of sediments produced by deforestation during the last 30 years.

Tributary	Total simulated sediment load[a] (Mt y^{-1}) 1980–2000	Total simulated sediment load[a] (Mt y^{-1}) 1980–2010	Total simulated sediment load[a] (Mt y^{-1}) 2000–2010
2. Suaza	3.6	5.4	1.8
3. Páez	23.4	81.3	57.9
7. Cabrera	84	126	42
9. Sumapaz	16.8	25.8	9
10. Bogotá	105.8	162.9	57.1
11. Coello	21.2	31.5	10.3
13. Recio	1	1.5	0.5
16. Gualí	3	4.5	1.5
17. Guarino	4.8	8.4	3.6
18. La Miel	65.6	98.7	33.1
19. Negro	122.2	185.1	62.9
20. Cocorna	9.4	14.1	4.7
22. Samana	10.4	15.9	5.5
23. Nare	19	28.8	9.8
24. Carare (d.str)	349	525.6	176.6
25. Opón	153.6	232.2	78.6
27. Suárez (d.str)	176	527.4	351.4
28. Fonce	36	54	18
29. Sogamoso	674	1011.9	337.9
30. Cauca	994.6	1503	508.4
31. Cesar	2	3	1
Sum catchments	**2875.4**	**4647.2**	**1771.6**
Deforestation[a]	**230.0**	**418.2**	**159.5**

[a] Total sediment load due to deforestation when adding 9% of the explained variance of the E_h factor in the B term.

analysis of standardized sediment load series reveals that 12 tributary basins experienced more pronounced positive deviations during the 2000–2010 period compared to pre-2000 period.

These regional analyses of land use (Fig. 3) and sediment load trends (Fig. 4) appear to indicate that the extent of erosion within the Andes of Colombia has severely increased over the last 30 years. The last decade has been a period of increased pulses in sediment transport as seen by the statistical significant trends (Fig. 3), during a time of a dramatic (241%) increase in forest clearance, from 1700 $km^2 y^{-1}$ between 1990 and 2000 to 4990 $km^2 y^{-1}$ during the 2005–2010 yr-period (Fig. 3D).

4.3. Sediment load for the Magdalena River 1972–2011

Monthly series of sediment load 1972–2011 were obtained at the most downstream station of the Magdalena River at Calamar (Fig. 1C). The modified M–K test for the Magdalena reveals significant upward trends in annual sediment load during the mid 1980s, 1990s, and post-2000 (Fig. 4C). Between 2000 and 2010, the annual sediment load increased 33% with respect to the pre-2000 period and more positive deviations are observed during this period (Fig. 4D). The Magdalena drainage basin has witnessed an increase in mean erosion rates from 550 t $km^{-2} y^{-1}$ before 2000 to 710 t $km^{-2} y^{-1}$ for the 2000–2010 yr-period. The average sediment load for the whole Magdalena basin increased 44 Mt y^{-1} during the last decade (Fig. 4E and F).

To estimate the periodicities and variability patterns and to distinguish temporal oscillations in sediment load of the Magdalena River at Calamar, the continuous wavelet transform was applied on monthly de-seasonalized time series of sediment load (Fig. 5A). Sediment load series show an annual signal during the mid 1970s, late 1980s and 1990s, and at the end of the 2005–2010 yr-period (Fig. 5B). These annual oscillations are significant at the 95% confidence level (Fig. 5C). Similarly, the average variance of sediment load at the 2–8 y band shows peaks during the late 1980s and 1990s, and a progressive upward trend between 2005 and 2010 (Fig. 5D).

There are other 2–4 y oscillation patterns over the periods 1995–2000 and 2007–2010 and a quasi-decadal oscillation between 1985 and 1995 (Fig. 5B), but of less statistical significance (Fig. 5C). Nevertheless, the conjugation of strong annual, interannual (2–4 y), and quasi-decadal (8 y) signals of sediment load from the lower Magdalena suggest that the mechanism of sediment fluxes has a large spatial scale. Sediment fluxes show large temporal variability as noted earlier by Restrepo et al. (2014). Large-scale atmospheric processes and local-scale natural and human induced factors (e.g., basin size, relief, vegetation cover, soils, land-use change, deforestation, mining), operate at the basin scale and produce strong temporal fluctuations in sediment fluxes.

4.4. Underlying drivers of increasing sediment load trends

The Magdalena may be one of the few medium-sized world rivers experiencing such strong increases in sediment load during the last decade (Fig. 4F). The intra-decadal fluctuations of sediment load are more pronounced at the end of the 1980s and 1990s, and for the 2005–2011 period (Figs. 4 and 5).

When analyzing the participation (million pesos) in the gross domestic product of human activities that promote soil erosion in the Magdalena basin for the 1927–2000 period, including agriculture, mining, energy, and urbanization (Fig. 6A–E), a large part of the land conversion and further deforestation resulted from agriculture activities (Fig. 6F). All human drivers show clear increases during the 1970s, 1980s, and 1990s. The trends match well with the observed increasing trends in sediment transport of the Magdalena tributaries (Fig. 4) and with the main Magdalena River at Calamar (Figs. 4C and 5B). Cattle ranching and population in the Andes of Colombia also increased exponentially during the last two centuries, with major increases between 1970s and 2000 (Fig. 6G and H).

During the 2010–2011 La Niña event, Colombia including the Magdalena, experienced the worst flooding event on record, the so-called “wet wave”. Economic losses were close to US $7.8 billion (Hoyos et al., 2013), twice the economic losses of the last major earthquake in the coffee region in 1999. Environmental

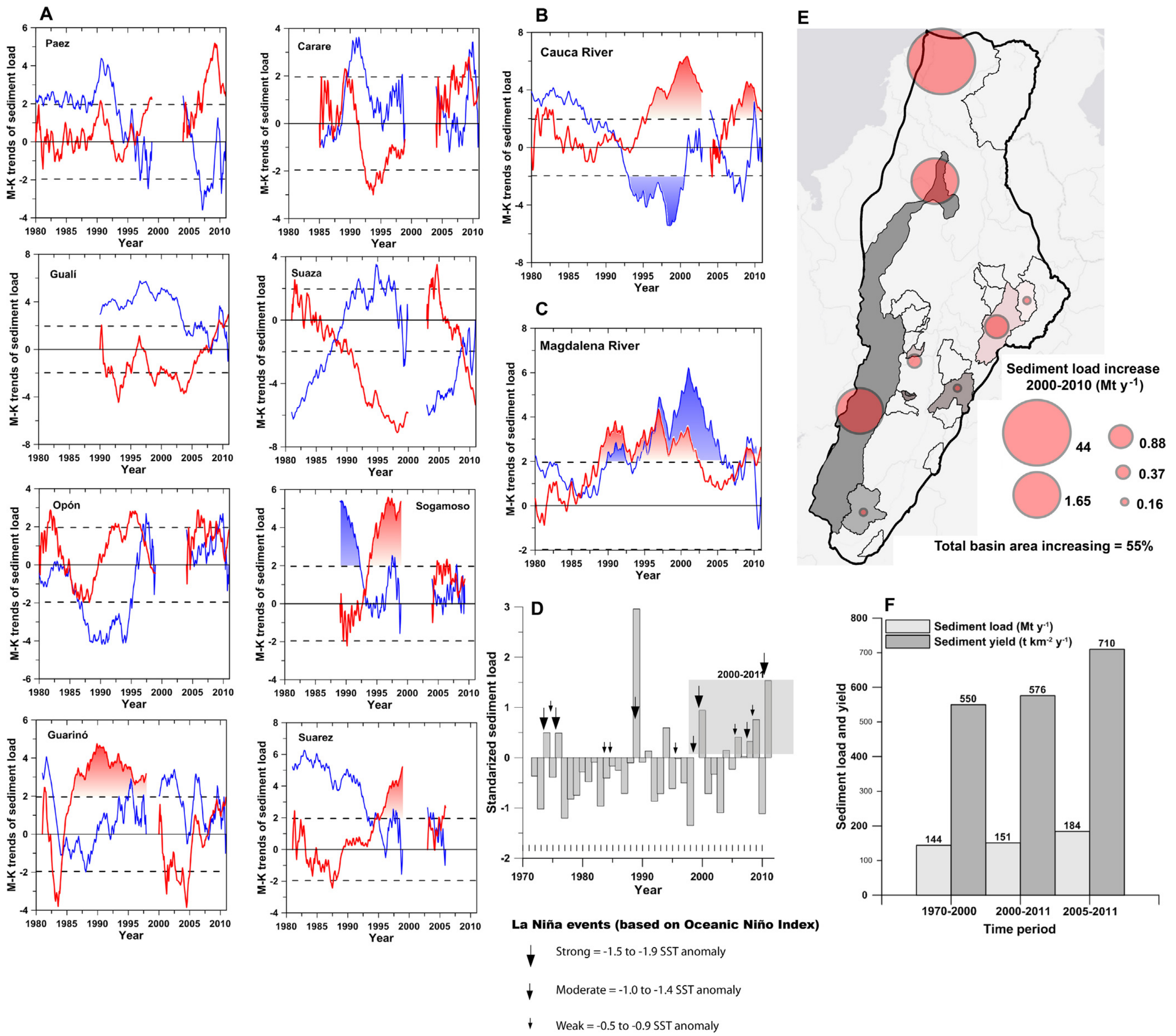

Fig. 4. The M–K trends of sediment load for selected Magdalena tributaries (A), the Cauca River (B), and the most downstream station of the main Magdalena at Calamar (Fig. 1) (C). Progressive and retrograde series are shown in red and blue, respectively. (D) Standardized sediment load of the Magdalena River at Calamar showing the occurrence of major La Niña events based on the Oceanic Niño Index. (E) Regions of the Magdalena drainage basin experiencing upward trends in sediment load during the 2000–2010 yr-period. (F) Sediment load and yield for the whole Magdalena River 1972–2011, as measured at Calamar. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

institutions, including the Ministry of Environment and Sustainable Development, the National Environmental System (SINA), the regional corporations, and the central government, blame climate change as the major trigger of the “wet wave”. In the last decade, scientific studies by Eafit University of the Andean rivers of Colombia formulated a different hypothesis. They suggest that there is an increase in the rate and magnitude of natural disasters (floods, landslides) that most likely is mainly due to growing land–surface modification caused by human activity, and to a lesser extent, by climate change. If this hypothesis is proved for the Andean region, it could have a major impact on mitigation strategies, since funds could be directed towards soil conservation rather than to climate change mitigation. The first approach has a regional impact, and its results are more measurable at local and regional scales, while the second is a global issue that depends on more developed countries and economies.

Human capability to alter soils, land erosion and sediment fluxes in rivers, trigger a geomorphic response in the form of increased rates of natural disasters such as landslides and floods, and produce other associated environmental changes like soil denudation, desertification, habitat loss, and sedimentation (Bonachea et al., 2010). According to this global picture of human intervention on the territory, a relevant and unsolved issue for the Andean region, as well as for other river catchments, is whether land-use change or climate change is the main trigger of accelerated erosion-accumulation processes and related extreme events (i.e., floods and landslides).

For the Andes of Colombia, human activities appear to have played a more prominent role compared to rainfall (climate change) to mobilize sediment. Deniers of land-use change and its impact on floods argue that climate change is the main trigger of the floods experienced during the last 4 years. Nevertheless, recent

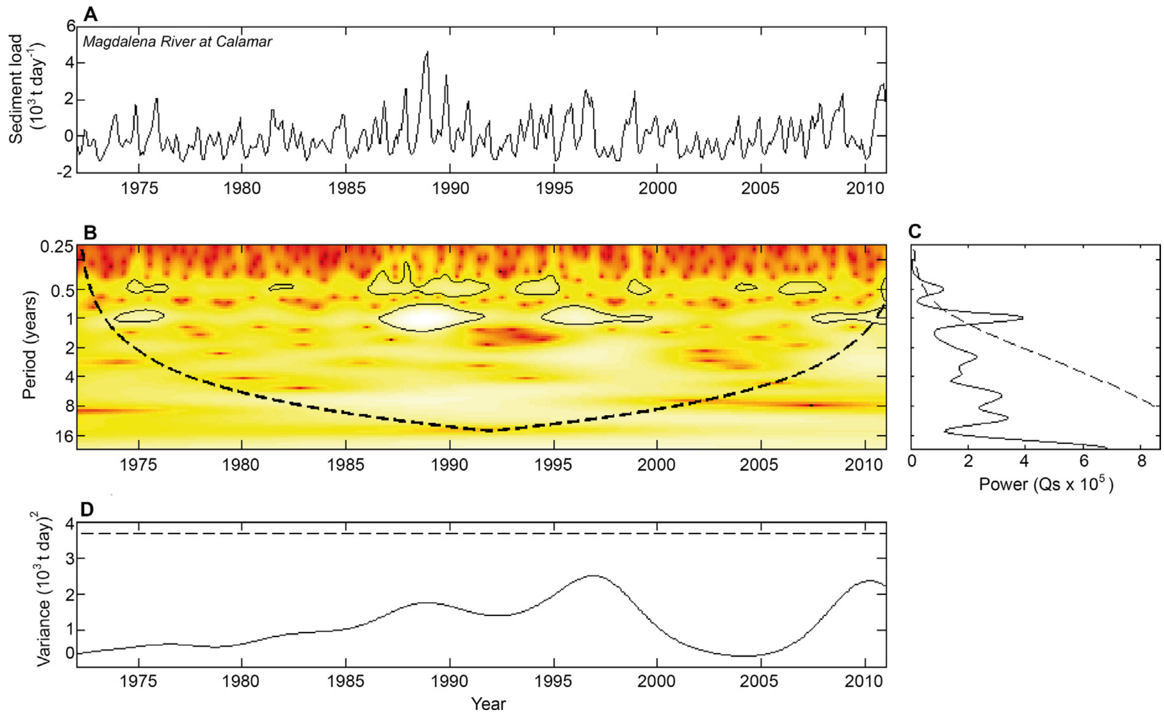

Fig. 5. Sediment load wavelet analysis of the Magdalena River at Calamar (Fig. 1). (A) Monthly standardized sediment load 1972–2011. (B) Continuous wavelet transform spectrum, showing high values of the transform coefficients (white) and the 95% confidence level (dashed line). (C) Global wavelet spectrum. (D) Power analysis of sediment load in the frequency domain at average variance of 2–8 year band.

studies on precipitation trends in Colombia during the last three decades (Carmona and Poveda, 2014) show no regional signs of increasing trends in rainfall in the central Andes. In addition, Andean rivers of Colombia exhibit increasing trends in sediment transport and water discharge. Thus, it appears that rivers transport more water through their channels for the same or less amount of precipitation received in their catchments (Restrepo, 2005; Restrepo et al., 2006, 2014). Evidently, deforestation, sediment load and sedimentation rates (and therefore, denudation) show signs of acceleration in the basin and some significant sub-basins within it. That augmentation can hardly be attributed to rainfall change alone, which in the northern part of South America shows an increase of around 5–7% during the last two decades (Bonachea et al., 2010).

Tropical South America is largely controlled by the meridional oscillation of the intertropical convergence zone (ITCZ), though spatial variability is introduced by the presence of the Andes and the Amazon River basin, by the surrounding tropical Pacific and Atlantic Oceans, and by land–atmosphere feedbacks. At longer timescales the region exhibits coherent hydroclimatic anomalies during both phases of the El Niño or Southern Oscillation (ENSO) (Aceituno, 1989; Ropelewski and Halpert, 1987, 1996). With minor regional exceptions in timing and amplitude, tropical South America historically has exhibited negative anomalies in rainfall and river discharges during the warm phase of ENSO (El Niño) and positive anomalies during the cold phase (La Niña). Both large-scale forcing and land surface hydrology play a key role on the dynamics of ENSO over the region (Poveda and Mesa, 1997; Poveda et al., 2001).

All South American Rivers, independently of size, display a strong seasonal signal of discharge and sediment load variability, typically by a factor of 5–10, comparing low to high monthly discharge. The interannual variation of discharge and sediment load associated with the ENSO or El Niño–La Niña cycle can almost be equally great, typically by a factor of 2–4, comparing low to high annual discharges (Richey et al., 1986; Depetris et al., 1996; Vörösmartry et al., 1996; Restrepo and Kjerfve, 2000). In Colombia, relationships between river discharge anomalies and the ENSO have been found in the Magdalena (Restrepo and Kjerfve, 2000; Restrepo, 2005) and Caribbean rivers, including the Sucio, Sinú, Canal del Dique, and Magdalena, which exhibit higher water discharge during La Niña and lower flows during El Niño (Restrepo et al., 2014). Further statistical analysis on annual streamflow data and ENSO anomalies show that the ENSO might be responsible for up to 65% of streamflow interannual variability in rivers such as the Magdalena, Cauca, Cesar, Rancheria, and Sinú (Gutiérrez and Dracup, 2001; Restrepo and Kjerfve, 2000; Restrepo et al., 2014). In addition, the annual and interannual variabilities of soil moisture in drainage basins are highly intertwined during strong El Niño and La Niña events, with greater positive anomalies during La Niña (Poveda et al., 2001).

Previous analysis on the interannual variability of sediment load of the Magdalena River at Calamar (Fig. 1B) showed an interannual oscillation well correlated with the ENSO cycle. Regression analysis of the low frequency sediment load on the smoothed SOI yielded a coefficient of variation of $R^2 = 0.54$, significant at 95%, indicating that variations in the Southern Oscillation Index (SOI) explain 54% of the variability in sediment load (Restrepo and Kjerfve, 2000). The Oceanic Niño Index (ONI) is used here to compare the occurrence of La Niña events and sediment delivery of the Magdalena at Calamar. Major positive deviations occurring in 1989, 2000, 2006, 2009 and 2011 coincide with strong La Niña events. 10 out of 13 La Niña events between 1972 and 2011 witnessed positive deviations in sediment load (Fig. 4D). Clearly, the Magdalena sediment load is strongly coupled to the El Niño–La Niña cycle, a condition also observed in the wavelet analysis with periodicities ranging between 2 and 7 years (Fig. 5).

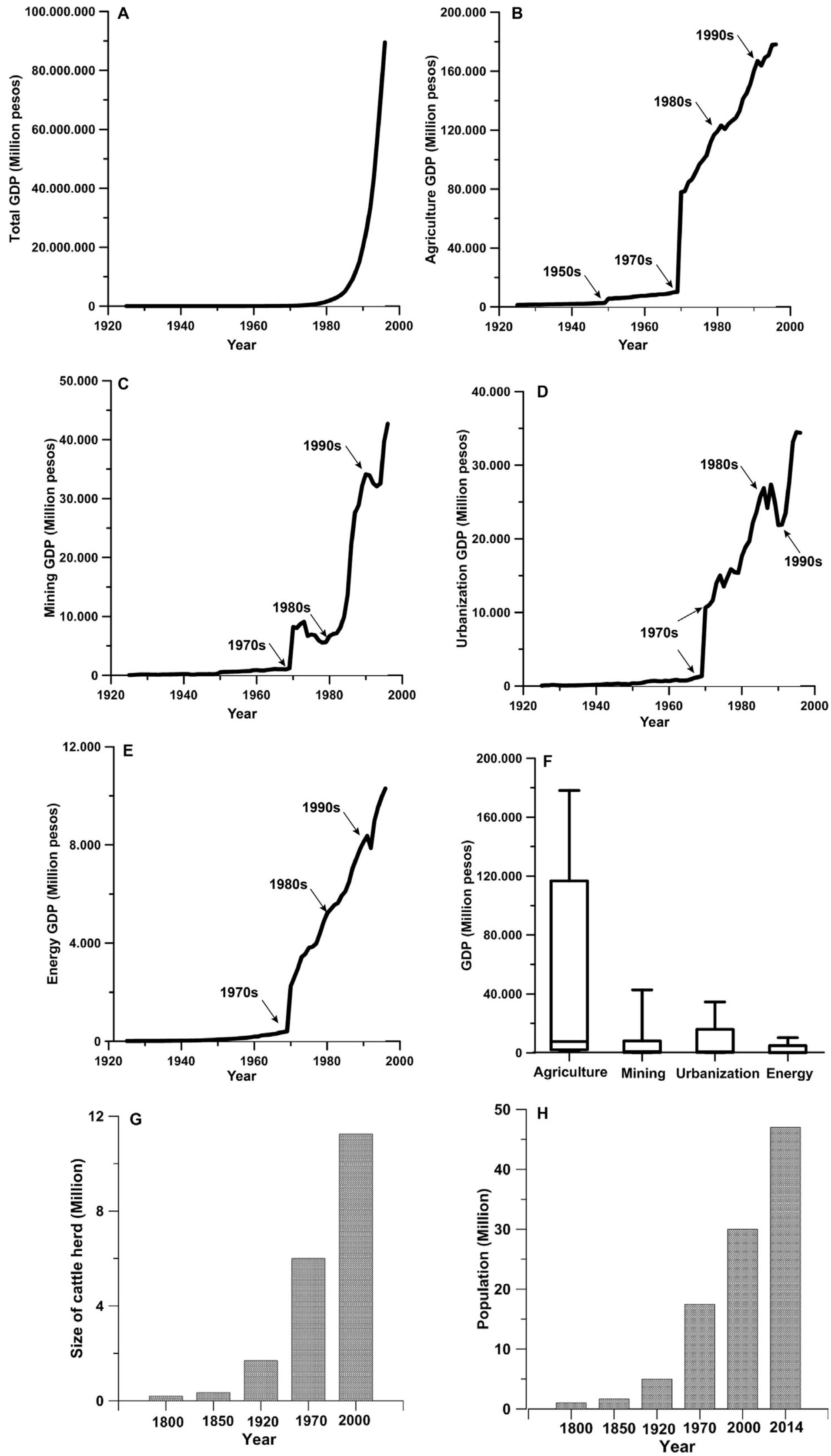

Fig. 6. (A–E) Major economic activities in the Magdalena drainage basin and their participation (million pesos) in the Gross Domestic Product (GDP). (F) Box whisker plot of major economic activities altering soils within the Magdalena catchment (data from Republic Bank of Colombia). (G) Size of cattle herd in the Andes of Colombia during the 1800–2000 yr-period (data from Etter et al., 2008). (H) Population of Colombia between 1800 and 2014 (data from Etter et al., 2008).

5. Discussion

The vulnerability of soils to human-induced erosion is highly variable in space and time; dependent on climate, geology, the type and duration of land use, and topography. Although our knowledge of the relationships between soil erosion, land use, and climate is established, the global heterogeneity of land use history and other relevant factors such as climate variability have limited us from fully understanding the global patterns of long-term soil erosion (Hoffmann et al., 2015). We present a proxy for estimating the amount of sediment produced by human activities in the Andes of Colombia (e.g., deforestation), by applying a robust model (BQART) that integrates natural and human drivers to simulate changes in sediment loads.

A previous implementation of the BQART model in the Magdalena drainage basin (Kettner et al., 2010) shows that the model overestimates the cumulative sediment flux of 21 tributaries by 25% compared with observations ($R^2 = 0.82$). Possible causes affecting the goodness of fit of the comparisons are the short durations of the observations of each of the tributaries (6–25 y), in combination with rapidly changing subbasin environments, including human activities such as deforestation and mining intensification. Having validated the BQART model for the Magdalena for the 1980–2000 yr-period (Kettner et al., 2010), we applied the BQART to estimate the contribution of human activities to soil erosion, once the dataset of model parameters was extended to the last three decades. This study indicates that natural and human induced factors account for 86% of the between-tributary sediment flux.

When applying the BQART to anthropogenic issues, uncertainties regarding the goodness of fit of the model and the long-term load of rivers are of equal magnitude in both observations and predictions (Fig. 2A). As noted by Syvitski et al. (2003), for rivers where agreement is not good, it is not always possible to assign "fault" with either the model or the observations. Observational uncertainties include (1) the length of observations, especially where monitoring does not capture the high-energy events, (2) measurement methods, and (3) human impacts. Simulation uncertainties are introduced by the variables considered in the model and those related with spatial variability of e.g., geography and lithology.

The sediment-load fluxes of the Opón, Cabrera, Bogotá, Sogamoso, and Suárez are overpredicted (Fig. 2C). These tributaries drain the eastern margin of the Magdalena basin. In general, the eastern Magdalena tributaries drain a significantly higher proportion of sedimentary rocks. In contrast, catchments in the western upper and central parts of the Magdalena basin drain metamorphic and volcanic rocks. To examine this impact (Kettner et al., 2010), the dataset was divided into two categories: eastern and western basins. Taking lithology into account, regression analyses for the western and eastern tributaries indicate that the BQART model captures 92% and 66% of the data variance, respectively. Thus, BQART predictability improves at intrabasin scale when spatial variability in lithology is accounted for.

For the Magdalena tributaries, an explanation as to why there could be an offset between observed and simulated long-term sediment loads might be the fact that small drainage basins have relatively large interannual variability in sediment dynamics. Smaller drainage basins are extremely responsive to episodic events and can deliver large portions of their sediment loads in relatively short periods. When observational records are too short, these episodic events will bias the average observed sediment load and therefore create an offset between observed and simulated long-term sediment loads. The importance of infrequent events makes small basins both interesting and frustrating to study because their long-term-averaged loads may depend on a few scattered events within decades, so long-term (decadal) records are needed to establish a valid representation of the long-term average sediment load (Farnsworth and Milliman, 2003; Kettner et al., 2010). For the Magdalena basin, between 36 and 88% of the total sediment load variability is attributed to flashy peak events. Tributaries like the Carare, the Opón, and the Sogamoso have recorded daily sediment loads greater than 50 kt d^{-1}, with yields often exceeding 5000 t km^{-2} y^{-1} during large events (Restrepo 2005; Restrepo and Syvitski 2006). Deviations from the 10 to 25-y averaged sediment load indicate that the upper and middle basin tributaries experience between 5 and 13 significant deviations from their interannual mean (Restrepo, 2005), and also, 12 analyzed rivers in this study had more positive deviations during the 2000–2010 yr-period.

There is no doubt that deforestation in the Andean section of the Magdalena River has strongly increased soil erosion and sediment transport. Our simulation results from the BQART model shows that the anthropogenic-deforestation factor accounts for 9% of the between-tributary loads. The estimated 160 Mt of sediments produced by forest clearance in the Magdalena during the last decade must be taken as a conservative value. A possible reason for this may be the underestimated rate of deforestation 2005–2010 used in this study, which is on average 145% lower that the more accurate value obtained by Kim et al. (2015). For instance, the highest peak of forest loss on record in Colombia occurred during the 2005–2010 period (Fig. 3D) (Restrepo, 2013; Kim et al., 2015). Further discussion on the observed human impacts in the Andes of Colombia is presented as supplementary material.

Strong human impacts on tropical Andean drainage basins have been recently documented. In highly degraded Andean catchments in southern Ecuador, land cover conversions are often followed by a phase of intense soil degradation that further exacerbates the anthropogenic impact on surface hydrology. For example, high erosion rates of 24 and 150 t ha^{-1} y^{-1} are observed in pastures and croplands, respectively (Molina et al., 2008; Vanacker et al., 2014). In addition, observed changes in streamflow during the last four decades are not the result of long-term climate change. Despite increased precipitation in some Ecuadorian river basins, there is a remarkable decrease in streamflow that very likely results from direct anthropogenic disturbances after land cover change (Molina et al., 2015). Further analysis of landslide frequency and area distribution after forest conversion in the tropical Andes demonstrates that the majority of landslide-induced sediment is coming form anthropogenic environments. Thus land cover change plays an important role in enhancing the overall soil denudation rates in tropical mountain regions (Guns and Vanacker, 2013, 2014).

Increases in fluvial sediment loads towards the ocean due to deforestation have been reported in other studies. Numerical simulations presented by Xing et al. (2014) indicate that for the Ebro River, Spain, sediment had to increase by 35% due to deforestation. Similar but more dramatic trends were found for the Waipaoa River, New Zealand by Kettner et al. (2007), were sediment loads increased more than 6 times and were mostly addressed to the wholesale deforestation. In this perspective the 9% increase due to human induced deforestation for the Magdalena River seem almost insignificant. However, both examples refer to relatively small responsive river systems. For larger systems like e.g., the Magdalena River, sediment fluxes measured at the river mouth tend to show no to less impact by deforestation occurring higher upstream (Walling, 1997). This, as for larger catchments, it is more likely for free erodible material to get deposited again before it reaches the river transport network. So a 9% increase due to deforestation for such a large system as the Magdalena river is very significant (Table 5).

It is now accepted that the rate of anthropogenic soil erosion exceeds the rate of soil production by several orders of magnitude (Syvitski et al., 2005; Bonachea et al., 2010; Hoffmann et al., 2015). Levels of sediment transport in the Magdalena, one order of magnitude higher in modern times than during pre-human conditions, were previously documented by a study to estimate the amount of sediments produced under modern and pre anthropocene conditions on a global scale (Syvitski et al., 2005). The differences between pre-human and modern sediment load in South American rivers were more pronounced for the Magdalena River, with a difference ranging between -100 and $-150\,\mathrm{Mt\,y^{-1}}$. Thus, during pristine conditions and according to the observed total load of the Magdalena estimated in this study, $184\,\mathrm{Mt\,y^{-1}}$, the Magdalena could have had an annual sediment load between 34 and $84\,\mathrm{Mt\,y^{-1}}$ during pre-human times.

6. Conclusions

Comparisons between observed and simulated sediment load of the Magdalena sub-basins indicate that the BQART model (1) replicates successfully spatial distribution of sediment load with only a ~10% bias over 2 orders of magnitude, (2) captures for 86% the between-tributary spatial variation in the 25–30 yr-period of observations of the 21 tributaries, (3) attributes 9% between-river variability in sediment flux to deforestation, and (4) offers a useful method to estimate the amount of sediments produced by deforestation in tropical drainage basins.

Regional analyses of land use and sediment load trends indicate that the extent of erosion within the Andes of Colombia has severely increased over the last 30 years. For example, the last decade has been a period of increased pulses in sediment transport and rates of deforestation as seen by the statistical significant trends in load (Fig. 4) and by a marked increase of 241% in forest clearance between 1990 and 2000 and 2005–2010 yr-periods (Fig. 3D). As a whole, the Magdalena drainage basin has witnessed an increase in erosion rates of 33%, from $550\,\mathrm{t\,km^{-2}\,y^{-1}}$ before 2000 to $710\,\mathrm{t\,km^{-2}\,y^{-1}}$ for the 2000–2010 period.

When discussing possible connections between the observed trends–oscillations of fluvial fluxes and upstream human activities, both trends and fluctuations in sediment load are in agreement with the detected increases in deforestation and economic activities that promote sediment production. Steep upward increases in sediment load and clear pulses in the wavelet spectrums are present during the decades of major human intervention, including 1980–1990 and 2000–2010. During the 2005–2011 interval, six tributaries, representing 55% of the analyzed Magdalena basin area, witnessed increasing trends in sediment load.

In general, potential drivers related to the modification of land surface by human activities show, at basin and sub-basin levels, growth patterns and magnitudes that are well resembled by the observed sedimentation rates in the lower reach of the Magdalena River. Such signs of increasing sediment fluxes and rates of sedimentation should not be attributed to climate change and rainfall variability alone.

The new launched PAGES program "Global Soil and Sediment transfers in the Anthropocene (GloSS)" seeks to analyze the global pattern of past and present anthropogenic soil erosion, aiming to determine the sensitivity of soil resources to different land use conditions and under a wide range of climate regime and socio-ecological settings (Hoffmann et al., 2015). Our exercise on estimating the amount of sediment produced by human activities in the tropical Andes could be used by the GloSS program to develop new proxies for human impacts on rates of soil erosion. In addition, our results on sediment load trends 1980–2010 and their spatial variability prove to be valuable when identifying hot spots of soil erosion during the Anthropocene.

Acknowledgments

This study was carried out with support from the Fundación para la Promoción de la Investigación y la Cultura-Banco de la República, Colombia (Grant 3276) and also from the International Development Research Center (IDRC-Canada, Grant 107756-001) in the BASIC Project, Basin Sea Interaction with Communities, Cartagena-Colombia. We want to thank both reviewers for their constructive comments and suggestions that have improved the quality of this paper. Special thanks to one of the reviewers for providing Fig. 4D with major La Niña events according to the Oceanic Niño Index. Finally, we thank professor Veerle Vanacker, associate editor of the Anthropocene Journal, for her constructive editing corrections.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ancene.2015.09.001.

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