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