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Regional soil erosion in response to land use and increased typhoon frequency and intensity, Taiwan

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A R T I C L E I N F O

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A B S T R A C T

Reservoir sedimentation data and sediment yields from Taiwanese rivers show increased soil erosion in response to both 20th century changes in land use and a more recent increase in typhoon frequency and intensity. Decadal variations of up to 5- to 20-fold in suspended-sediment rating curves demonstrate supply-limited transport and correspond to increased sediment delivery from hillslopes due to changes in land use, regional ground shaking during the Chi-Chi earthquake, and post-2000 changes in typhoon frequency and intensity. While accelerated erosion in central Taiwan after the Chi-Chi earthquake has been documented previously, our results show that periods of increased upland erosion also occurred earlier, in response to 20th century changes in land use. Analyses of rainfall records and typhoon frequency for the period 1900–2009 further point to an island-wide increase in erosion rates corresponding to increased typhoon frequency and intensity after 1990.

Introduction

Regional soil loss historically plagued societies around the world and continues today at a global pace far above rates of soil production (Nearing et al., 2004; Montgomery, 2007). Historical episodes of soil loss preceded systematic measurements of sediment yield, and thus studies that assessed regional erosion have generally relied on indirect methods and modeling efforts. Taiwan offers an opportunity to investigate directly the potential interactions between land use, climate change, and soil erosion because of the availability of long-term government sediment data records. While recent studies of erosion rates in Taiwan have focused on increased sediment delivery to river systems from the magnitude 7.6 Chi-Chi Earthquake that struck central Taiwan in 1999 (Dadson et al., 2003, 2004; Lin et al., 2006, 2008; Goldsmith et al., 2008; Meunier et al., 2008; Chen and Hawkins, 2009; Chuang et al., 2009; Hovius et al., 2011), understanding the effects of land use and climate change in tropical drainage basins is central to evaluating potential global effects on soil erosion, carbon cycling, and agricultural productivity. To date, however, the effects of climate change and human activity on upland erosion rates in Asia have received relatively limited attention [see Kao and Liu (2002) for a notable exception] even though the steep terrain of tropical islands in the western Pacific produces a disproportionate share of sediment delivered to the world oceans (Milliman and Syvitski, 1992). Here we investigate these connections using multi-decade, region-wide records of reservoir sedimentation and suspended sediment discharges in Taiwan.

Methods

We compiled century-scale data on typhoon frequency, rainfall, and reservoir sedimentation rates from Taiwan government data (WRA, 2009, 2011; CWB, 2012a). Rainfall data from 1900 to 2009 were analyzed in terms of typhoon frequency, expressed as the number of named typhoons in the government database that delivered an average of more than 65 mm of rainfall per day to at least one rain gauge station on the island; this encompasses 75% of all typhoons in the database (CWB, 2012a, 2012b). The average daily rainfall intensity during each typhoon was determined by dividing the total (cumulative) rainfall for the typhoon by its duration (in days) for the station with the maximum reported rainfall for that typhoon. We also compiled recently published sedimentation data for 50 reservoirs for the period 1921–2011 from Taiwan government reports (WRA, 2009, 2011) and stratified our analysis into three regions: northern (17 reservoirs), central (14 reservoirs), and southern (19 reservoirs) (Fig. 1); in eastern Taiwan only minimal data spanning several measurements were available for just several reservoirs, precluding a meaningful analysis of trends over time for that region. We determined a time series of erosion rates for the area upstream of each reservoir by taking reported sediment volumes and dividing by the upstream drainage area contributing runoff (and thus sediment) to each reservoir, and then dividing by the number of years over which the sediment accumulated (the time between sediment volume measurements). We then estimated regional erosion rates by calculating an area-weighted average of all the drainage basin erosion

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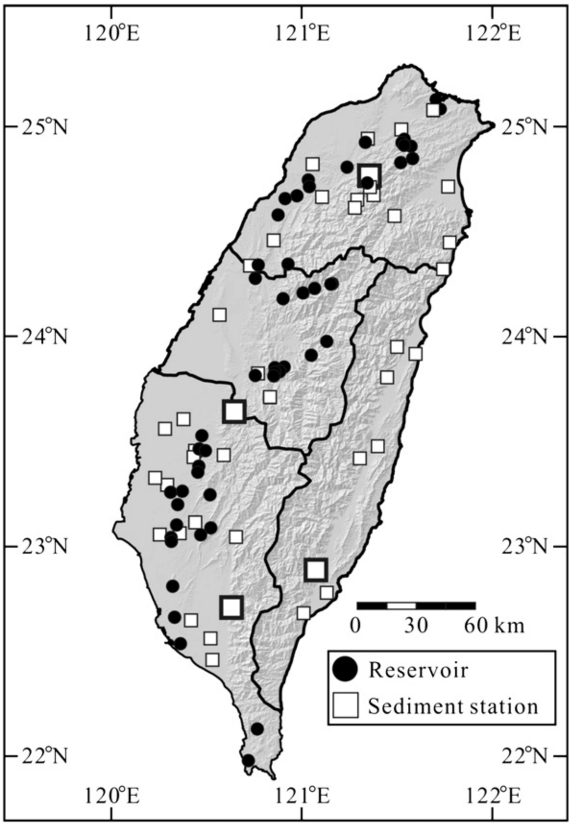

Figure 1. Location of 50 reservoirs and 43 gauging stations included in our data analysis and discussed in text. Boundaries between areas defined as northern, central, southern, and eastern Taiwan are also shown. Large open squares show locations of gauging stations shown in Fig. 4.

rates within each region (i.e., each drainage basin's rate was multiplied by the fraction of the total area of all the analyzed basins that it accounted for, and the resulting values were then summed). Data on timber harvest volumes for 1912–1956 were compiled from Chen and Chen (2005); data after 1956 are from Yao (2011). Locations of sugar cane factories in the 1930s, a proxy for the density of intensively cultivated sugar cane plantations in that era, are from Chao (2008). Ground acceleration data from the Chi-Chi earthquake were obtained from Taiwan government data (CWB, 2012b). Data on suspended sediment loads and river discharge were obtained for gauging stations with records >35 yr from Taiwan government hydrologic reports (WRA, 2010) in northern (13), central (8), southern (13), and eastern (9) Taiwan.

Adapting the methods of Hovius et al. (2011), we compared suspended sediment concentrations (and thus suspended sediment loads) over different decades using a power law regression of the form $C = KQ^b$, where C is sediment concentration, Q is water discharge, and K and b are the regression coefficient and exponent. In order to evaluate changes in K over time, power-law regressions using the b value determined for the entire (long-term) data set for each gauging station were fit to the data from each decade for that gauging station. Although large events can also influence b values (Huang and Montgomery, 2013), holding the b value determined in this manner constant for each station allows comparing values of the resulting regression coefficients (K) between decades for each station, larger coefficients indicating a greater sediment load, and thus greater sediment delivery from hillslopes. Standardizing the form of the regression in this manner allows comparing regression coefficient values through the ratio of decadal values to the lowest decadal value for each gauging station. This ratio scales differences in sediment loads for comparable discharges, and thereby for changes in basin-scale sediment supply over time.

Results

Reservoir sedimentation

Reservoir sedimentation is thought to be an effective trap for the majority of the sediment load transported by a river and an effective way to track human impacts on basin-scale erosion (Walling and Webb, 1996). Reservoir sedimentation data from individual drainage basins in Taiwan show substantial variability in annual sedimentation, and thus in the calculated erosion rates from upstream drainage basins. Local annual erosion rates for individual drainage basins ranged from <1 to >100 mm yr^{-1} (Fig. 2). While all regions had high rates of erosion after 2000, the timing of earlier periods of high regional erosion rates varied, with peaks in the late 1930s and 1940s in southern Taiwan, the late 1950s in central Taiwan, and the 1960s and 1970s in northern Taiwan. In all three regions, however, initial rates of soil erosion of <5 mm yr^{-1} rose dramatically after 2000 when rates in individual basins exceeded 40 mm yr^{-1} in all three regions. These values greatly exceed long-term rates of erosion determined from fission track dating, which range from 3.0 to 6.0 mm yr^{-1} in the steep topography of eastern Taiwan but are generally <3 mm yr^{-1} in western Taiwan (Dadson et al., 2003).

Aerially-weighted, decadal average erosion rates for northern and central Taiwan record transient, several-fold increases followed by erosion at roughly double the initial rates, and a further rise in erosion rates after 2000. In southern Taiwan, the regional erosion rate peaked in the 1930s and then declined before increasing somewhat in the 1970s through 1990s, and more dramatically after 2000 (Fig. 3). The regionally averaged erosion rate in central Taiwan peaked in the 1950s, a decade before it peaked in northern Taiwan. This pattern grossly corresponds to the progressive development of Taiwan, which proceeded from south to north (Liou, 2004). Averaged across the island, reservoir-

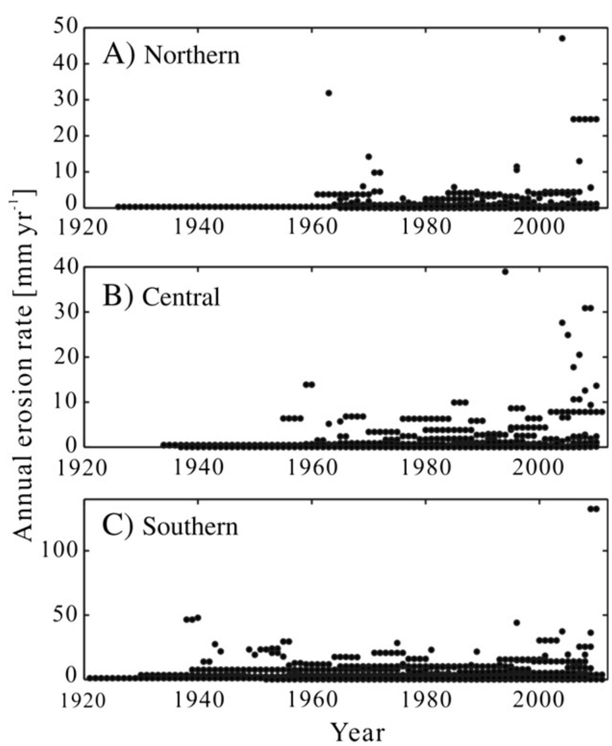

Figure 2. Annual erosion rates for drainage basins in northern, central, and southern, Taiwan based on annual reservoir sedimentation; lateral strings of single points represent annual values averaged over the time period between measurements.