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

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ABSTRACT

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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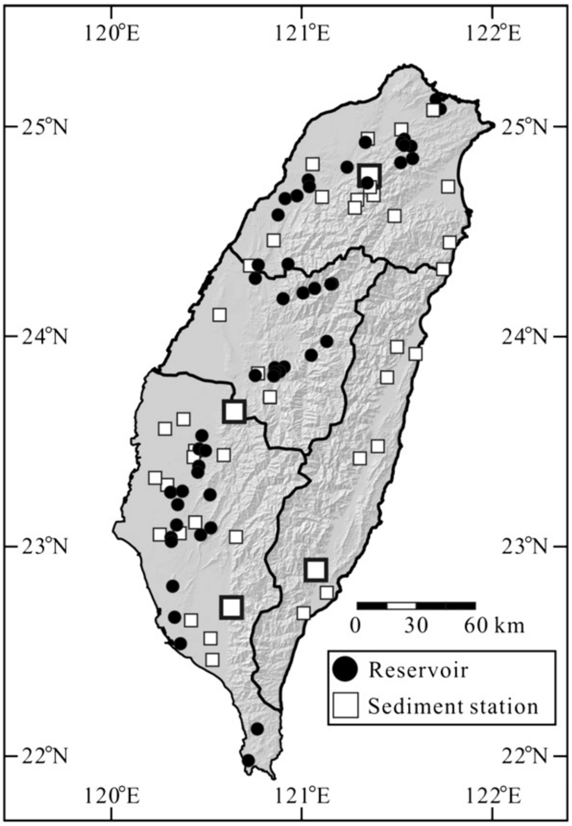

Figure 1. Location of 50 reservoirs and 43 gauging stations included in our data analysis and discussed in text. Boundaries between areas defined as northern, central, southern, and eastern Taiwan are also shown. Large open squares show locations of gauging stations shown in Fig. 4.

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-

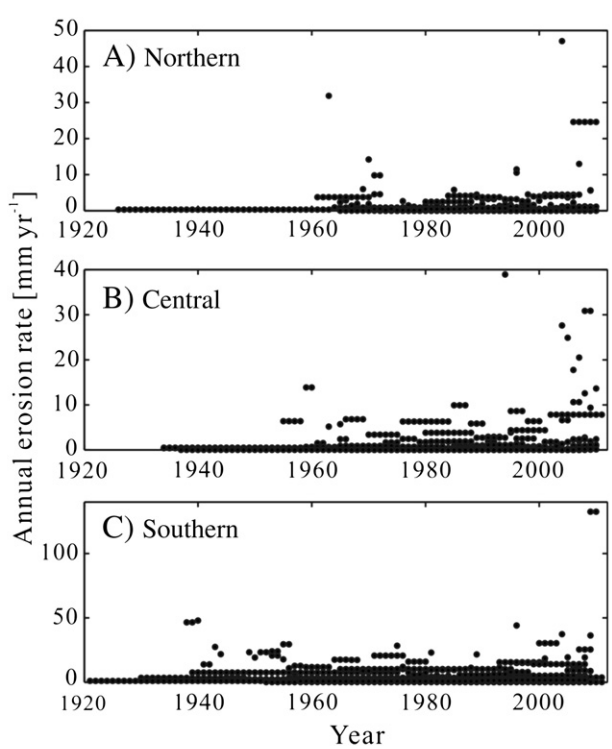

Figure 2. Annual erosion rates for drainage basins in northern, central, and southern, Taiwan based on annual reservoir sedimentation; lateral strings of single points represent annual values averaged over the time period between measurements.

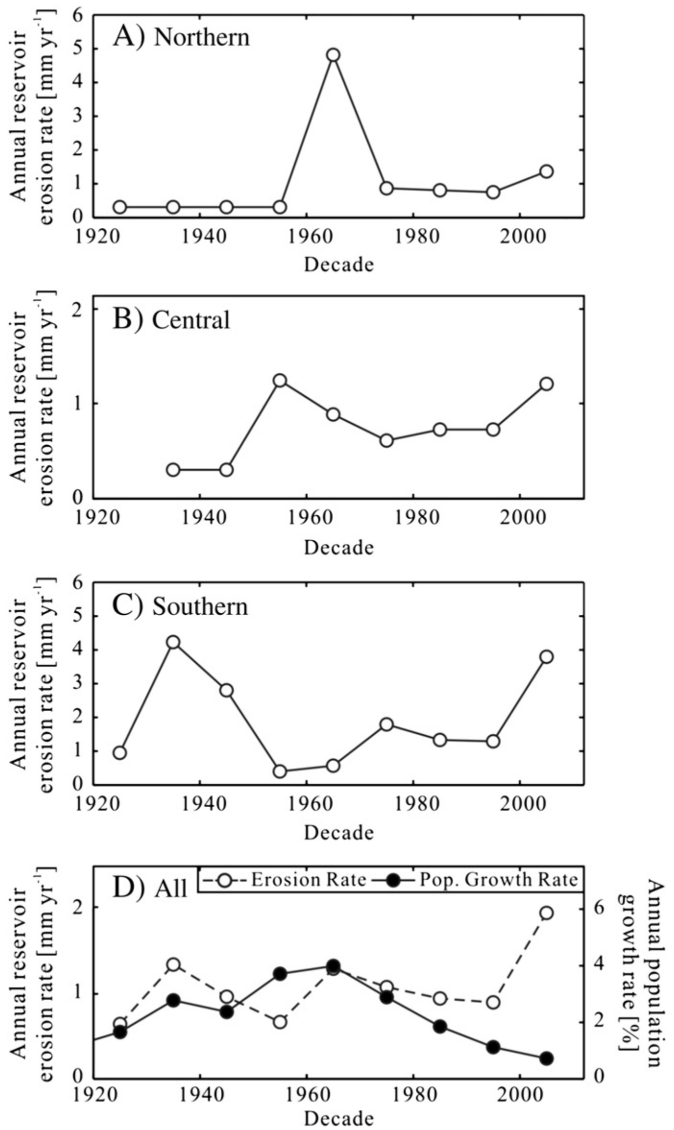

Figure 3. Decade-average erosion rates determined from aerially weighted reservoir sedimentation data for (A) northern, (B) central, and (C) southern Taiwan, as well as (D) average annual erosion rate for all of Taiwan plotted with decadal variations in the annual population growth rate.

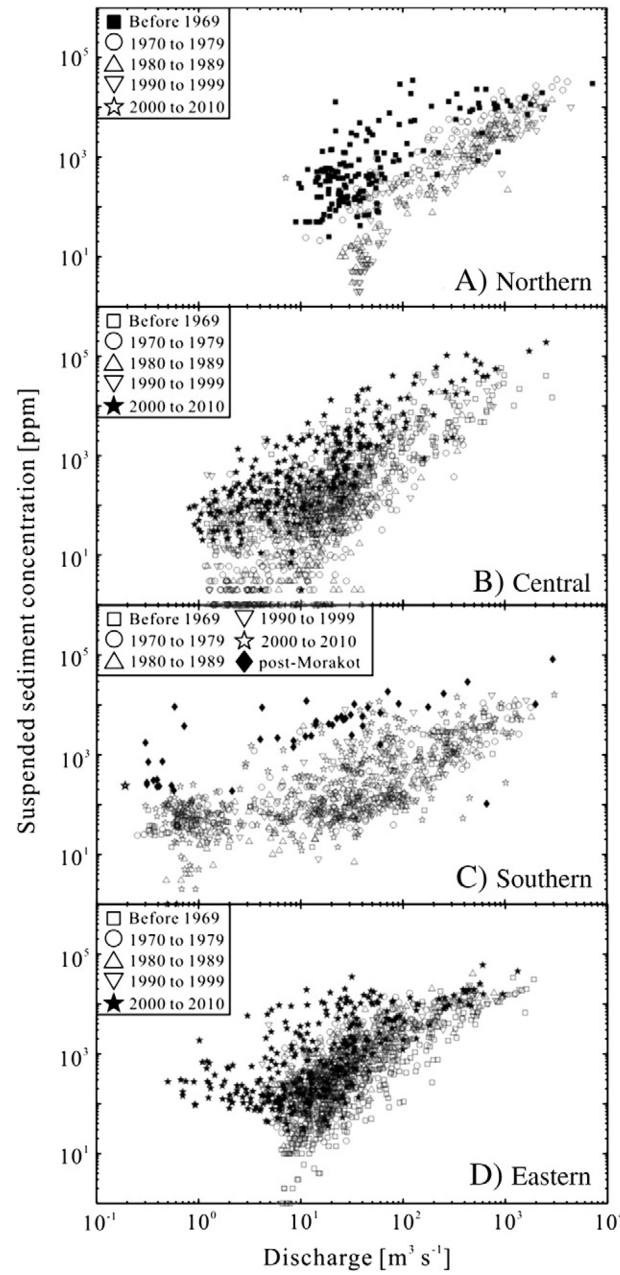

Figure 4. Suspended sediment concentrations as a function of river discharge for data from different decades for an example gauging station in (A) northern (Hsia-Yun), (B) central (Tung-tau), (C) southern (San-Ti-Men), and (D) eastern (Yen-Ping) Taiwan. Black symbols in each panel correspond to periods of greatest sediment concentrations per given discharge value.

sedimentation-based erosion rates roughly tracked the population growth rate until 2000, with area-weighted values of 1–5 mm yr^{-1} characterizing each region of Taiwan. These values span the island-wide 3.9 mm yr^{-1} suspended-sediment derived erosion rate reported previously for the period 1970–1999 (Dadson et al., 2003).

Suspended sediment

Sediment rating curves for gauging stations exhibit substantial decadal variability in suspended sediment loads for all four regions (Fig. 4). Because rating curves account for variability in discharge they allow comparison of sediment loads across storm events of different magnitude. Systematically higher sediment concentrations at any given discharge indicate greater sediment delivery as influenced by storm intensity, land use, or slope weakening resulting from strong ground shaking.

All three effects appear in the suspended sediment data records from individual gauging stations. An example from northern Taiwan, the Hsia-Yun station in the Tanshui River basin, had its greatest sediment concentrations (for a given discharge) in the 1960s during rapid regional development, after which sediment concentrations systematically declined through the 1990s (Fig. 4A) [see Kao and Liu (2002) for another, similar example from northern Taiwan]. In central Taiwan, the Tung-tou station in the Choshui River basin had its greatest sediment concentrations after 2000 (Fig. 4B), an observation widely attributed to aftereffects of the Chi-Chi earthquake on sediment delivery by subsequent typhoons (Dadson et al., 2003, 2004; Lin et al., 2006, 2008; Chuang et al., 2009). In southern Taiwan, the San-Ti-Men station in the Kaoping River basin had its greatest sediment concentrations in the aftermath of Typhoon Morakot, which triggered widespread landsliding in 2009 (Fig. 4C). Likewise, in eastern Taiwan the Yen-Ping station in the Peinan River basin had its greatest sediment concentrations after 2000 (Fig. 4D). While the suspended sediment records do not extend back in time as far as do the reservoir sedimentation records, the systematic decadal variations in suspended sediment concentrations in all four regions demonstrate both the supply-limited nature of sediment transport in Taiwanese rivers and comparable response to several different forcing mechanisms.

Suspended sediment concentrations varied by decade over all discharges and not just by individual storm events, indicating extended basin-wide changes in sediment supply (Fig. 5). The timing of rating curve changes across Taiwan supports the interpretation of changing land use in response to regional development as a major control on sediment yields before 2000, as sediment loads generally declined from the 1960s through the 1990s. Sediment loads then increased from the 1990s through 2000s. This pattern of regional swings in sediment rating curve coefficient values implicate regional factors, such as land use or climate trends, as underlying the decadal variations of 5- to 20-fold in sediment load.

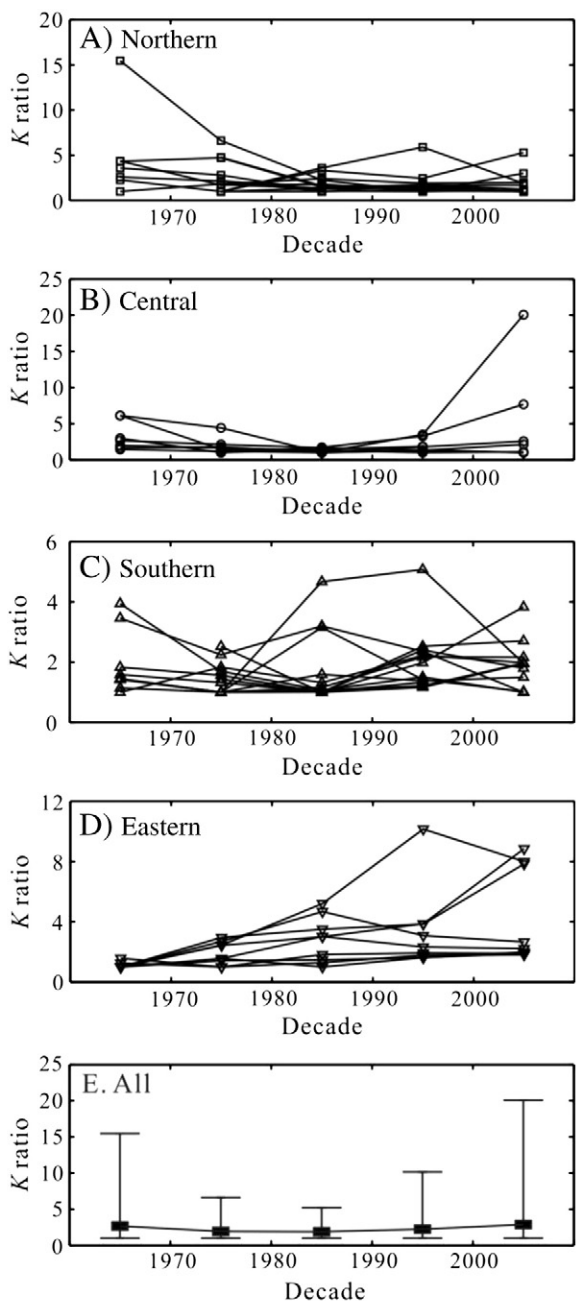

Figure 5. Decadal variations in the ratio of regression coefficients (K values) in the relationship between suspended sediment concentration (C) and fluvial discharge (Q), determined from $C = KQ^b$, where K and b are the regression coefficient and exponent, respectively.

Storm intensity

The number of large typhoons (i.e., those delivering more than 65 mm of daily precipitation) striking Taiwan per year increased in the 1990s and 2000s (Fig. 6A), indicating systematic changes in typhoon frequency and intensity. Early in the 20th century, 2 to 3 large typhoons landed each year; over the past several decades this increased to 3 to 5. Previous analyses of typhoon occurrence in Taiwan from 1970 to 2006 also noted increased typhoon frequency and intensity after 2000 (Tu et al., 2009a, 2009b). While the number of rain gauge stations used to create the typhoon database increased over the period of measurement (Fig. 6B), the number of stations doubled in the period when little change occurred (i.e., before 1950) and the period of rising typhoon frequency and intensity occurred after the greatest increase in the number of stations (i.e., after 1950). Hence, our analysis strengthens and extends the conclusion that both the average daily rainfall intensity during typhoons and the maximum typhoon size (total cumulative rainfall) increased over recent decades.

Discussion

The observed decadal variations in sediment delivery recorded in the rating curves from Taiwanese rivers confirm supply-limited sediment transport, and thus the expectation of substantial changes in sediment transport in response to variations in sediment delivery to channels due to land use, strong ground shaking during earthquakes, and increased typhoon frequency (Hovius et al., 2000; Dadson et al., 2003; Huang and Montgomery, 2012).

Land use

While the effects of these influences are apparent in suspended sediment records from individual gauging stations, island-wide patterns provide further context for interpreting regional influences on erosion rates and sediment yields. The shift of the peak decade-scale erosion rates from south to north tracks development and changes in land use driven by a growing population. Intensive forestry and upland sugar cane plantations in southern Taiwan resulted in extensive erosion during the Japanese colonial era (1930s and 1940s) (Liou, 2004; Lin, 2006; Chao, 2008). In the 1930s the limited number of reservoirs, fully half of which were in southwest Taiwan, record erosion rates of 1 to 46 mm yr^{-1}, far greater than the erosion rates for reservoirs in central and northern Taiwan (Fig. 7A). Extensive post-World War II upland development in central (1950s) and northern (1960s) Taiwan is mirrored in the sequential rise in regional erosion rates. Island-wide timber harvest volumes rose dramatically in the late 1950s, peaked in the 1960s and then subsequently declined through the 1990s (Fig. 8). Unfortunately, we lack more detailed data on spatial patterns of land use change over time.

Earthquakes and typhoons

The dramatic post-2000 increase in sediment yields at two gauging stations in central Taiwan has been attributed previously to after-effects of the Chi-Chi earthquake, through the hydrologic influence of co-seismic fracturing of hillslopes on sediment delivery and routing during subsequent typhoons of material from seismically-induced landslides out of upland channels in the epicentral region (Dadson et al., 2003, 2004; Lin et al., 2006, 2008; Chuang et al., 2009). We note, however, that the post-2000 jump also apparent in sediment yields in northern, southern, and eastern Taiwan (Figs. 2, 3, & 5) cannot be due

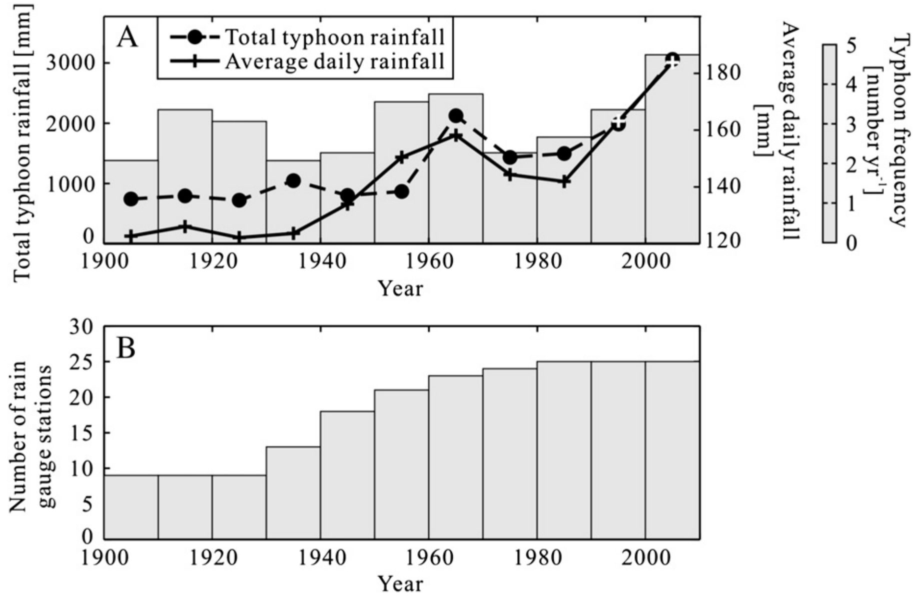

Figure 6. (A) Gray bars represent the number of typhoons per decade with total rainfall greater than 65 mm reported in the Central Weather Bureau typhoon database (CWB, 2012a, 2012b). Black circles with a dashed line represent maximum total (cumulative) event rainfall for reported typhoons from 1900 to 2009. Crosses with a solid line represent average daily rainfall during typhoon events in each decade for events included in the typhoon count. (B) The number of rain gauge stations used to compile the typhoon rainfall database.

to the Chi-Chi earthquake because these regions did not experience significant peak ground acceleration during that event (Fig. 7B). Hence, another explanation is called for to account for increased post-2000 erosion rates in these other regions of Taiwan. One possibility that warrants further investigation is suggested by how the post-2000 rise in erosion rates in regions across Taiwan post-dates significant land use changes, but corresponds to the regional increase in typhoon intensity and frequency.

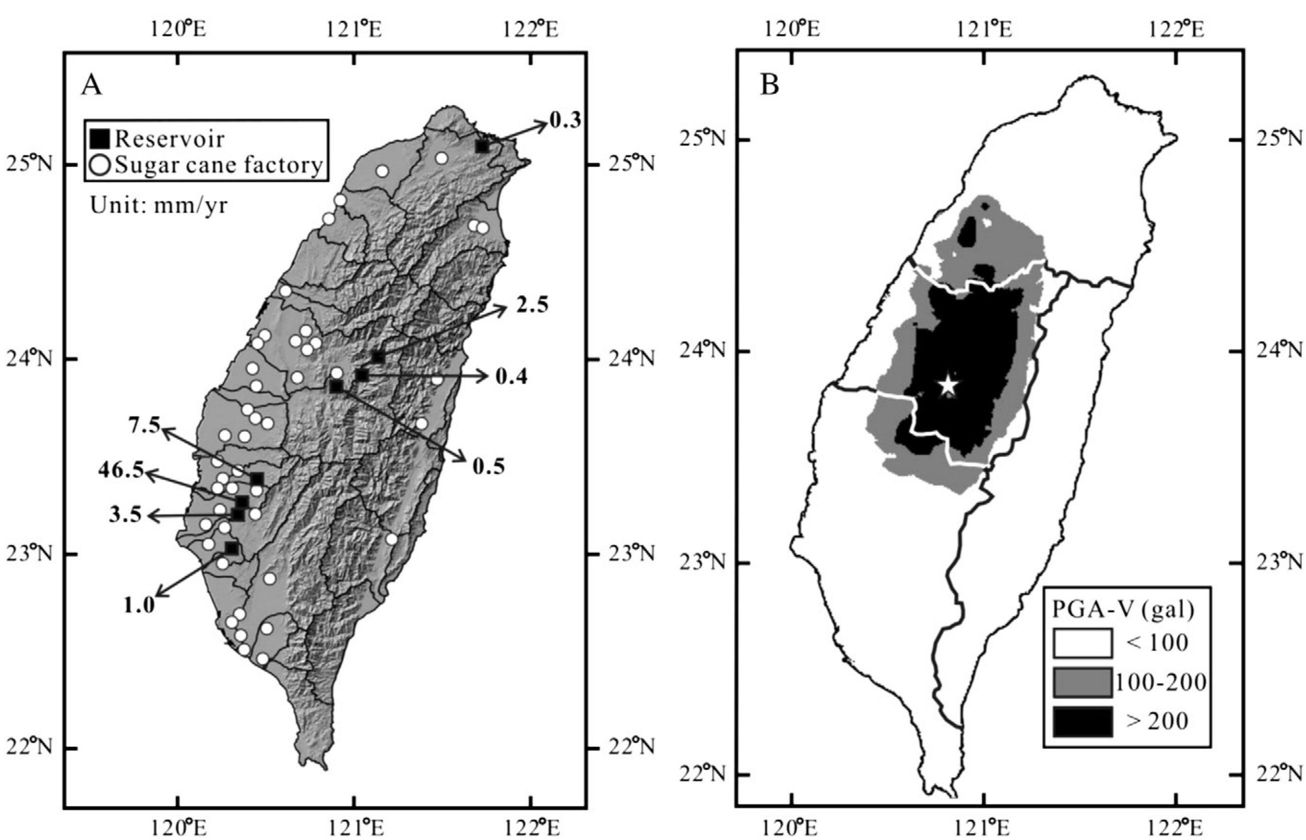

Figure 7. (A) Catchment erosion rates (mm/yr) for the 1930s for the eight reservoirs with data extending that far back (black squares). White circles portray the locations of sugar cane factories, and thereby the high density of sugar cane plantations in southwestern Taiwan. (B) Map of peak vertical ground acceleration during the Chi-Chi earthquake showing the concentration of significant ground motion in the epicentral area of central Taiwan; white star shows the location of the earthquake epicenter in central Taiwan (data from CWB, 2012b). Boundaries separating four regions of Taiwan are as in Fig. 1.

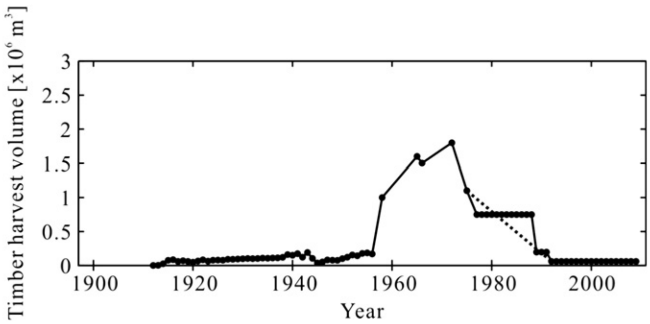

Figure 8. Timber harvest volume in Taiwan from 1912 through 2009; dashed line represents an interpolated linear decline in harvest volume for the period in which annual data represent an average over a multi-year period. Data for 1912–1956 from Chen and Chen (2005); data from after 1956 from Yao (2011).

Conclusions

All together, we conclude that the systematic variations of erosion rate in Taiwan document regional effects of changing land use from an increasing human population on the erosion of a soil-mantled tropical upland, and point to accelerating soil loss in response to increased typhoon frequency and intensity. Our analysis illustrates how continued population growth and increased typhoon frequency hold the potential for synergistic interactions between regional land use and climate change in setting the pace of regional soil loss, a confluence of influences that will become increasingly important in the coming decades.

Acknowledgments

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