

## Developing and applying a soil erosion model in a data-poor context to an island in the rural Philippines

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**Abstract** Soil erosion in many parts of the developing world poses a threat to rural livelihoods, to the sustainability of the agricultural sector, and to the environment. Most erosion prediction models are mechanistic and unsuited to quantify the severity of soil erosion in a data-limited developing world context. The model developed in this paper for Negros Island, in the central Philippines, is based on the Revised Universal Soil Loss Equation, but contains important innovations such as the movement of eroded soil over the landscape, simulating deposition on lower slopes and in waterways. It also includes a term describing farmer strategies to reduce soil erosion, which are typically ignored in erosion prediction models. A two-sample *t*-test found that model-predicted sediment loading values were not significantly different from field-measured sediment loading values when corrected for watershed size ( $P = 0.857$ ). The model predicts an annual loss of 2.7 million cubic meters of sediment to waterways such that by 2050 more than 416,000 ha of agricultural land will be rendered unproductive due to erosion. Farmer behavior conserves soil, but on the steepest slopes soil conservation practices are not adequate to prevent erosion. Of two proposed strategies to control soil erosion in the rural Philippines, the model suggests that a complete switch to tree crops would conserve more soil than universal terrace adoption. However, even under these conservation scenarios, erosion threatens the areal extent of upland agriculture on Negros, and hence the sustainability of the island's food supply.

**Keywords** Farmer technology adoption · Modeling · Philippines · Productivity · Soil erosion · Sustainability

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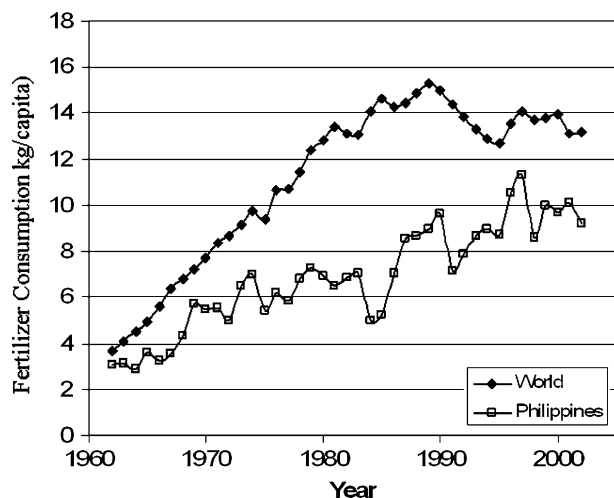
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## 1 Introduction

Soil erosion, especially in combination with population growth and the rising costs of agricultural inputs, is one of the most severe threats to the livelihoods and economies of people in the rural developing world (Pimentel et al. 1976, 1995; Larson et al. 1983; Alfsen et al. 1996). Yet policymakers have often been slow to act on the erosion issue because cheap petroleum inputs to agriculture can temporarily compensate for nutrient loss, masking productivity losses due to soil degradation (Tharakan et al. 2001). It is also difficult for local and national officials to understand the scope of the erosion problem, because of the difficulties involved in extrapolating plot-level data on soil properties and erosion to a landscape scale, especially in data-poor areas of the developing world. Once policymakers decide to act, they must choose between a number of different plans for achieving soil protection without unduly burdening the poor or creating perverse incentives. Often, there is no way to know how well these plans will work in a given context until significant amounts of money and personnel have been devoted to their implementation.

In the Philippines, soil erosion has been labeled the country's worst environmental problem (Tujan 2000). The Philippine Forest Management Bureau estimates that between 71 and 84 million tons of soil are eroded from the country's agricultural lands every year (Philippine Forest Management Bureau 1998). In addition to agricultural productivity losses, this eroded soil leads to landslides, lower water quality and diminished biodiversity in rivers and lakes, loss of hydroelectric generation capacity, and damage to the country's coastal reefs (Cruz et al. 1988; Solandt et al. 1999). The country's poor are both especially vulnerable to and significant contributors to the problem of soil erosion, because they tend to farm in marginal environments and to depend on agriculture for their livelihoods. The Philippines' continued access to the petroleum resources that fueled its Green Revolution is becoming increasingly uncertain, and it is no longer clear whether farmers will be able to compensate for productivity loss through fertilizer application. World fertilizer use per capita is already declining from its peak rate in 1990, and Philippine fertilizer use per capita appears to be stabilizing below global rates (Fig. 1). It is therefore timely to reconsider an approach to quantifying the severity of erosion on a landscape scale, meaning

**Fig. 1** Fertilizer consumption in kilograms per capita from 1960 to 2002 for the Philippines and globally. Data sources: the Fertilizer Institute, Washington DC ([www.tfi.org](http://www.tfi.org)); United States Census Bureau ([www.census.gov/ipc/www/worldpop.html](http://www.census.gov/ipc/www/worldpop.html)); UNFAO



an area over which a policymaker might have jurisdiction—such as a province—and which is large enough to display geographical patterns of soil loss.

Soil erosion models of varying degrees of sophistication have been developed to quantify erosion at the landscape level. The most widely used models that have integrated plot-level studies of erosion with predictions for the landscape are the Water Erosion Prediction Project (WEPP) and the Revised Universal Soil Loss Equation (RUSLE). Both of these models have been applied in the tropics. The WEPP is a process-based model that predicts erosion as the result of a single rainfall event, which can then be projected over a year using detailed rainfall data to generate annual soil loss predictions (Ascough et al. 1995). It includes soil movement and deposition processes both on land and in channels. It also requires detailed information about the system being modeled, including daily climate data, physiological characteristics of the crop plants at several stages of development, channel shape, substrate, and depth. For use in the data-poor tropics, therefore, the WEPP presents daunting challenges.

The RUSLE generates a prediction of average annual soil loss from a plot (or, by extension, a landscape) based on six input factors: rainfall erosivity, soil erodibility, slope length, slope steepness, crop cover, and support practices (Renard et al. 1996). These are termed the *R*, *K*, *L*, *S*, *C*, and *P* factors. The RUSLE was developed using field parameters from US agricultural land. Researchers' attempts to use it in the tropics have been criticized by some soil scientists who argue that erosion processes in the tropics are sufficiently different from those in the temperate zone to render tropical RUSLE predictions inaccurate (Lal 1990). There have been few tropical applications of the RUSLE on a landscape scale, and most have not been validated (Mongkolsawat et al. 1994; Romero and Stroosnijder 2001). This is mainly because tropical soil erosion models are used to quantify the soil erosion problem in areas with low availability of field data to validate a model. One modeling study using RUSLE in Mexico was successfully validated with field data (Millward and Mersey 1999). This model generated categorical, rather than quantitative data by identifying areas of minimal, low, moderate, high, and extreme erosion. Another study generating categorical data using the RUSLE was conducted in Brazil by Lu et al. (2004). The rainfall erosivity and support practice factors were not included in this model (Lu et al. 2004). Categorical model output can be very useful for identifying areas of high soil erosion risk, but it does not generate total overall estimates of soil loss from the landscape; nor does it allow different soil management strategies to be compared.

Another limitation of previous studies applying a spatially distributed RUSLE at a landscape scale is that they typically ignore the support practice factor. This is understandable, because it is difficult to gain an understanding of how farmers mitigate or increase soil erosion through their farming strategies in a way that can be mapped. Some modelers have solved this problem by averaging the effects of observed support practices over the landscape (Angima et al. 2003). This technique effectively includes farmer practices, but does not link them to spatial factors influencing soil erosion.

Attempts to compare RUSLE predictions with model output from WEPP in the tropics have been limited. Typically, the RUSLE is not expected to generate accurate predictions at the landscape level because it is missing some important processes (such as deposition) that are included in the WEPP. However, the RUSLE may generate more accurate results compared to the WEPP in watersheds with low erodibility, due to the WEPP's tendency to over-predict runoff for small rain events (Cecilio et al. 2004).

Any researcher studying tropical erosion must consider the challenges in using the predictive soil erosion models described above. On the other hand, it is unproductive for researchers to be completely paralyzed by the paucity of field data in their systems of study

and to avoid any attempt to quantify soil loss on the landscape scale. Clearly the best approach for model construction is to use data from the field whenever possible to initialize and validate the model parameters. It is also important to develop a model that is appropriate for the scale of inquiry and the parameters under investigation. The present study is primarily concerned with soil loss from agricultural land over an island landscape of 1.2 million hectares. To quantify this soil loss, I chose to use the RUSLE in combination with my own spatial computer model that generates soil movement over a landscape grid, replicating what is arguably the most important feature of the WEPP model—without its highly detailed data requirements.

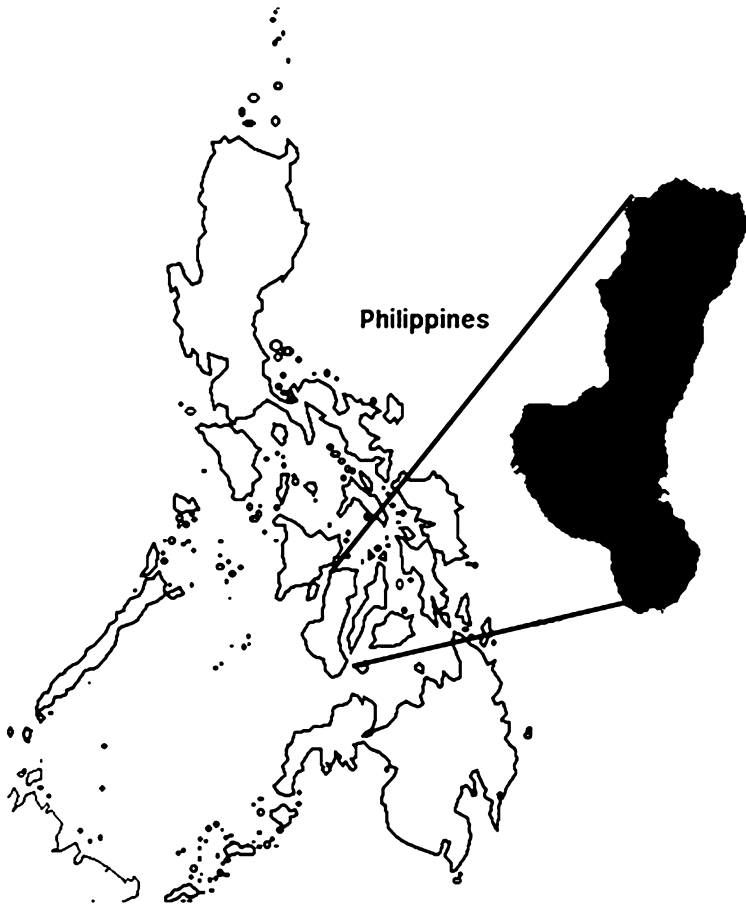
There are two strategies for combating soil erosion in the Philippines that are generally espoused by the Philippine government, non-governmental organizations, and researchers. The first is what I will call the ‘plant more trees’ approach; the second may be termed a ‘technology’ approach (in some cases, both of these approaches are adopted in the same program).

The ‘plant more trees’ approach may take many forms. In some areas, farmers are encouraged to practice agroforestry on their land, or to plant trees across a hillslope as an erosion barrier (Shively 1999a). Other researchers advocate macroeconomic policies designed to encourage farmers to switch from farming erodible grain crops to farming less erodible tree crops such as coconut and fruit trees (Coxhead 2000). In a more forceful version of the ‘plant more trees’ strategy, some poor Philippine farmers squatting on government land have told me stories of government officials threatening them with eviction if they do not devote part of their land to planting tree crops.

Even more widespread than the ‘plant more trees’ strategy is the ‘technology’ strategy. This strategy focuses on technology introduction programs developed by non-governmental organizations, agricultural extension programs, or researchers (Coughlan and Rose 1997; Cramb 2001; Daño 2002; Lapar and Ehui 2003). These programs usually include creating hedgerows, grass strips, rock walls, or other erosion barriers (Pattanayak and Mercer 1998; Shively 1999b) or on-farm reforestation projects (Shively 1999a). The assumption behind these programs is that there is a need for farmers to conserve soil in the face of extremely erodible conditions, but that there are constraints to these farmers adopting technologies on their own. These constraints are typically identified as economic—the long-term benefits which farmers would realize from soil conservation are exceeded in the short-term by the establishment costs of the technologies. Risk aversion associated with a new, introduced technology may also be a barrier to implementation for some farmers (Nelson and Cramb 1998; Lapar and Pandey 1999; Shively 1999b).

In a country like the Philippines, where soil is one of the few resources available for economic exploitation, it is important to choose the most effective strategy to preserve that resource. So far there has been no study devoted to weighing the ‘plant more trees’ strategy versus the ‘technology’ strategy in terms of effectiveness. In this study, I have undertaken such an evaluation. In addition, both of these soil conservation strategies focus on the individual farm or small farming community. With this model, I have adopted a broader, systems view of the biophysical and economic drivers of erosion in the Philippines.

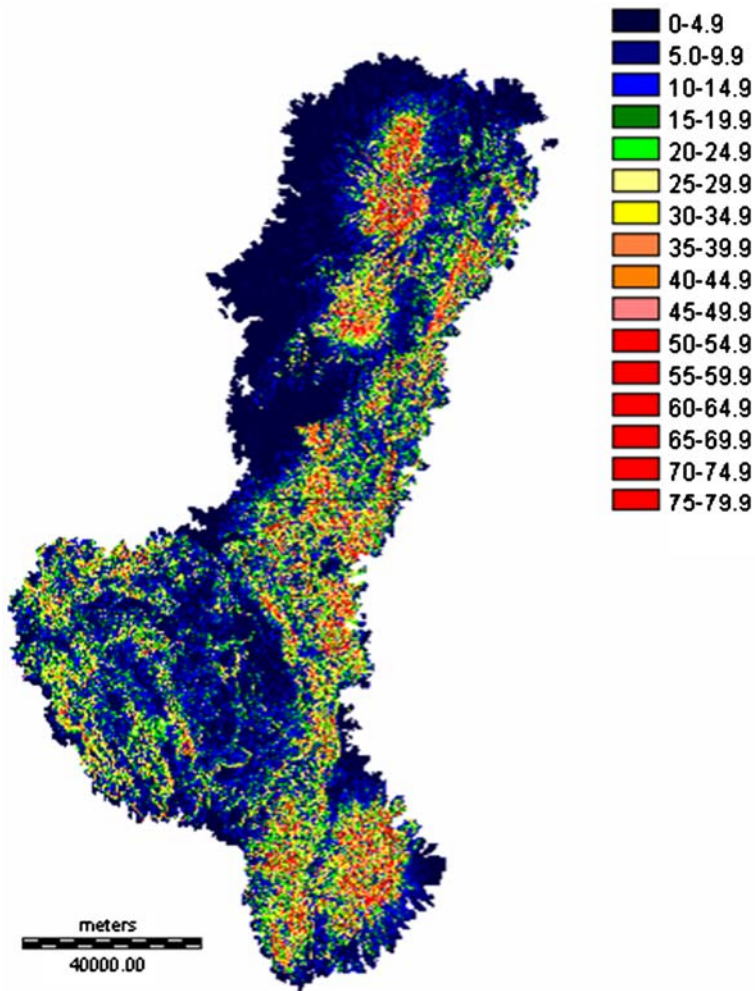
Negros Island, located in the central Philippines, is an ideal location for an erosion study (Fig. 2). Thirty-five percent of the island’s land area consists of erodible uplands (the ‘uplands’ are defined in the Philippines as lands of >18% slope) (Fig. 3). The agricultural patterns on Negros are typical of those found in many areas of the Philippines, in which most of the land is owned by a few wealthy families and the remaining, often marginal land is intensively farmed by poor and middle-income peasants. For example, sugarcane lands on Negros, which are generally located in the most fertile areas, are heavily skewed in



**Fig. 2** Map of the Philippines showing location of Negros Island

distribution, with 78.8% of the land owned by 4% of the population (Lopez-Gonzaga and Bañas 1986). This is because of the island’s history as a center of Philippine sugar production beginning in the mid-1800s, during which time land-grabbing by Spanish nobles was sanctioned by the colonial government for the purpose of building the country’s sugar export industry (Lopez-Gonzaga 1987). Consequently, as one moves farther into the mountains on Negros, where land is less suitable for sugarcane cultivation, one encounters increasingly smaller farms and poorer households. The central Philippines (a region that includes Negros) is an especially intensively farmed area, with high population density and high poverty rates (Philippine Department of Agriculture 1991).

Erosion has the potential to reduce agricultural output on Negros not only through lowering productivity, but through eliminating land from production altogether. When traveling in the mountains, one can already see former croplands that are now unproductive due to erosion and are often abandoned. Rural families that can no longer make their living farming these lands tend to migrate to urban centers in search of employment. Most urban centers in the Philippines are already experiencing an influx of poor rural people with



**Fig. 3** Map of Negros Island depicting slope in %

limited education and few job skills. Housing, schools, health care and employment in urban areas are currently insufficient for the growing population, and the failure of more small scale farms in the rural areas could further overwhelm urban resources. In addition, rural families produce most of their own food, but upon transitioning to the urban areas they need to buy food. This has the potential to strain the Philippines' agricultural production and its foreign exchange (in 2004, the Philippines imported more than 1 million metric tonnes of rice, or 7% of the country's production, according to the FAO). The farms that are abandoned because of topsoil loss generally do not support native forest, nor can they be used to produce food; in most cases, they become overgrown with *kogon* grass. The landscape of Negros, which was predominantly tropical seasonal forest as recently as the 1950s, has already been dramatically changed through deforestation and intensive agriculture, with consequences for the island's biodiversity, water quality and forest resources.

Negros Island, therefore, displays the typical problems facing the Philippines as a whole (high-population density, poverty, agricultural degradation, rural-urban migration, and deforestation) but to a greater degree. Soil erosion has the potential to degrade agricultural lands to the point at which they are no longer productive, with serious ecological, social and economic consequences for Negros and for the Philippines. This study is the first to examine comprehensively the extent to which erosion might render Negros' agricultural sector unsustainable, and the time scale over which this might occur.

The objectives of this study are as follows:

1. To develop and test a model of soil erosion that predicts soil loss from the uplands and suspended sediment transport off of Negros Island, and to validate the results with field measurements of erosion.
2. To incorporate farmer behavior into this model, and to quantify how farmer efforts at soil conservation are currently reducing the impacts of erosion on Negros.
3. To produce a quantitative assessment of the threat of soil erosion to the sustainability of upland agriculture on the island.
4. To test two alternative strategies proposed by policymakers and researchers to combat soil erosion in the Philippines: encouraging farmers to adopt terracing technology versus encouraging farmers to plant trees or switch to agroforestry.

Research questions for this study are: can a RUSLE-based soil erosion model incorporating deposition accurately predict soil loss rates and sediment loading rates compared with field measured values? Does the incorporation of farmer practices into the model (as the '*P*' factor in the RUSLE equation) result in soil loss predictions that are significantly lower than model predictions without the farmer practice factor? Over what time scale and at what magnitude might soil erosion render Negros upland agriculture unproductive? What quantitative impact will technology adoption or agroforestry development have on soil loss from the uplands of Negros Island?

## 2 Methods

My study consisted of two fieldwork stages. One stage involved gathering data for map generation and model calibration, and the second stage for model building, validation and sensitivity analysis. My research team of local college students and a community health worker<sup>1</sup> surveyed farmers on Negros about their farming practices and soil conservation strategies during the first fieldwork period (September–December 2004). We also visited farms to observe cropping patterns. During the second fieldwork stage (June–July 2005), we collected total suspended sediment (TSS) data for validating the model at three rivers on Negros. During the model building stage, I constructed and assembled the input maps for the RUSLE calculations and developed the computer program to model sediment movement over the landscape. I then subjected the model to validation using the TSS data and published data from field studies on soil erosion at the plot scale and at the landscape scale. Lastly, I ran the model under the different policy scenarios (terrace adoption and agroforestry practice) to determine their impact on erosion.

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<sup>1</sup> Girly Julinao, Noralyn Mayagman, and Joy Soreño

## 2.1 Field surveying

We surveyed five villages within *barangay* Bato (a *barangay* is the smallest government unit in the Philippines), located in the municipality of Mabinay, on a plateau in the center of the island. Bato was selected as a representative sample of the island's agricultural patterns, containing all of the major crops grown on Negros, with a large range in topography, farmer affluence, and farm size. The *barangay* is intensively cultivated, includes a flat plain as well as steeply sloping hillsides, and 387 households. The total land area is  $\sim 630$  ha, and nearly all of it is farmed. The main agricultural products include corn, rice, sugarcane, and coconut; other crops grown include cassava and other root crops, banana, and vegetables.

We conducted our survey between September and December, 2004 (the end of the rainy season in the Philippines). We contacted all 378 households, of which 351 engaged in farming. These households farmed a total of 749 plots. The average family in Bato had five members, farming on an average of 1.8 ha of land. Mean annual household income was about \$560 (US), or \$1.53/day. Incredibly, the average slope of a cultivated plot in Bato was  $23^\circ$ . Rates of fertilizer application ranged widely; some farmers were unable to afford any fertilizer, but the average rate of fertilizer use was 175 k/ha.

Interviews typically took between 15 and 30 min, and were conducted in the local language by myself and three local residents. We followed the interview with an on-site farm visit, during which we measured the slope of the plot and recorded which soil conservation technologies were in place. During the interviews, we collected physical and socioeconomic information about the farm, but for the purposes of this study we concentrated on 'mappable' variables, such as slope, type of crop grown, irrigation status, and ownership status.

Farmers implemented a variety of technological strategies to improve soil quality and reduce erosion, and nearly every farmer used some kind of technology in addition to chemical inputs. Only three of these strategies, however, were practiced with the stated goal of reducing erosion. These are, in order of decreasing effectiveness, terracing (construction of rock, earth or vegetative barriers at regular intervals, typically between 5 and 10 m apart, running perpendicular to the slope), constructing erosion barriers (planting a line of trees or constructing an earth barrier across a slope), and cover cropping (planting sweet potato or other 'creeping' ground cover during the fallow season or as a crop rotation to reduce the impact of raindrops on the soil surface). Farmers practicing any of these strategies were recorded as adopters of soil conservation technology; farmers practicing none of them were recorded as non-adopters, although they may have used other soil improvement strategies such as green manuring. Although this distinction between adopters and non-adopters is somewhat arbitrary, it is supported for the central Philippine landscape because terracing, cover cropping and erosion barriers are the strategies typically introduced by government and NGOs in extension programs designed to educate farmers in erosion prevention (Coughlan and Rose 1997; Cramb 2001). Thus, the commonly held view is that these are the technologies that constitute erosion prevention. If the goal of this project is to determine rates and probability of soil conservation technology adoption for both scientific and policy purposes, it is logical to use local definitions of soil conservation technology.



## 2.2 Rainfall erosivity factor

Ideally, the rainfall-runoff erosivity factor should be constructed from daily rainfall records maintained over a number of decades that include storm intensity and duration. However, there is no weather station in the central area of the Philippines, and only one in the entire country, that maintains daily precipitation records. That station is at Clark Air Force Base (AFB) on Luzon Island, north of Manila. The Clark AFB records show that there are on average 39 rainfall events per year that exceed the minimum erosivity threshold of 50 mm total rainfall (Ascough et al. 1995). Unfortunately, the intensity of these rainfall events was not recorded at Clark. Soil erosion experiments on Leyte Island, to the east of Negros, recorded the average total rainfall intensity (in mm/h, averaged over the entire rain event) and the amount of rain for ten rain events occurring between 1989 and 1991 on the site (Presbitero et al. 1995). I derived a relation between rainfall rate and the inverse power of rainfall amount for the Leyte data ( $i_m = 123.35/P^{0.5}$ , where  $i_m$  = total rainfall intensity and  $P$  = rainfall amount in mm). Intense rainfall events with high rates of fall result in less total rain compared to longer rainfall events that drop a larger total rain amount. Combining this information with the data from Clark AFB, which recorded daily rainfall amount (but not rainfall rate), I was able to calculate the total rainfall intensity for each of the 39 yearly rainfall events. The assumption involved in this calculation is that the daily rainfall at Clark came from one storm. This is a reasonable assumption, because in the tropical Philippines during the rainy season, there is frequently only one daily storm. Erosive energy for a rain event may then be calculated using the following equation (Renard et al. 1996):

$$e = 0.29[1 - 0.72 \times \exp(-0.05 \times i_m)],$$

where  $e$  is kinetic energy for the storm and  $i_m$  is the total rainfall intensity in mm/h.

The erosion experiments on Leyte also reported an average mean *peak* rainfall intensity (as distinct from the total rainfall intensity) of 68.8 mm/h, or 34.4 mm/30 min, recorded over 85 storm events during the mid-1990s, using 1-min interval measurements (Coughlan and Rose 1997). The storm erosivity is simply the product of the storm energy ( $e$ , calculated above), and the maximum 30-min intensity (34.4 mm/30 min) (Renard et al. 1996). To find  $R$ , all storm erosivities were then summed over the year for the 39 events recorded at Clark. This yielded an  $R$ -value of  $335.85 \text{ m} \times \text{mT} \times \text{mm}/\text{ha} \times \text{year}$ , assuming that Negros experiences a pattern similar to Clark: 39 yearly rain events with a maximum intensity of 68.8 mm/h. For comparison,  $R$ -values calculated for a tropical rainforest environment in Thailand ranged from 200 to 800  $\text{m} \times \text{mT} \times \text{mm}/\text{ha} \times \text{year}$  (Srikhajon et al. 1984).

## 2.3 Soil erodibility factor

The Philippine Department of Agriculture drew up a detailed soil map of Negros Island with accompanying soil surveys and soil descriptions including chemical analyses in 1960 (Barrera 1960, Philippine Department of Agriculture 1989). The scale of the original paper map was 1:250,000. I digitized the paper map of soil polygons, and then constructed a  $K$ -factor map using the following equation from (Renard et al. 1996):

$$K = [2.1 \times 10^{-4}(12 - \text{OM})M^{1.14} + 3.25(s - 2) + 2.5(p - 3)]/0.0759,$$

where  $K$  is the soil erodibility factor in  $(\text{metric tons} \times \text{ha} \times \text{h}) / (\text{ha} \times \text{megajoules} \times \text{mm})$ ; OM is percent organic matter in the soil;  $M$  is  $(\% \text{silt}) \times (\% \text{silt} + \% \text{sand})$ ;  $s$  is an integer representing the structure class of the soil, and  $P$  is the soil's permeability class, based on the soil texture. This  $K$ -factor represents how easily the soil is eroded; for example, sandy soils tend to be less easily eroded than clay soils and therefore have a lower  $K$ -factor.

## 2.4 Length-slope factor

The digital elevation model (DEM) used for the slope length and steepness factor calculations was obtained from the NASA Shuttle Radar Topography Mission website. The data are 'finished,' meaning that they have been edited for 'spikes' and 'wells,' and water bodies have been defined. DEM resolution is 3 arc s, or  $\sim 90$  m.

The  $L$  (length) factor, in the original version of the USLE, from which the RUSLE is derived, was the 72.6-foot length of the experimental plots on which the USLE was developed (Wischmeier and Smith 1978). Conceptually, when applied to a landscape,  $L$  represents the uninterrupted slope over which water running downhill accumulates erosive energy (Moore and Burch 1986). What precisely constitutes an 'uninterrupted slope' is often difficult to determine, and many researchers have developed algorithms to describe the hydrology of water moving across a complex landscape. Some modelers have used an upslope contributing area approach, in which water flow generated by rainfall is routed through downslope cells to determine the length of the water's path as it erodes soil (Desmet and Govers 1996). Others have computed the length of the maximum downhill slope from a local ridge or high point (Hickey 2000). Because the landscape on Negros is highly fragmented, with rapidly changing land cover, I decided to modify the maximum downhill approach by considering each raster cell a slope segment of uniform slope and landcover (the scale of the raster cells approximately corresponds to the size of an individual farm, so farmer practice is also considered uniform). I therefore calculated the  $L$  and  $S$  factors for each individual raster cell.

The  $L$  and  $S$  factors in the RUSLE equation are calculated as follows (Renard et al. 1996):

$$S = 10.8 \times \sin(\theta) + 0.03,$$

for slopes  $< 9\%$ ;  $\theta$  represents slope angle

$$S = 16.8 \times \sin(\theta) - 0.50,$$

for slopes  $\geq 9\%$

$$L = (\lambda/72.6)m,$$

where  $\lambda$  is the slope length in feet (300.7 feet for one raster cell)

$$m = \beta / (1 + \beta)$$

$$\beta = (\sin \theta / 0.0896) / [3.0(\sin \theta)^{0.8} + 0.56].$$

Although these calculations are in feet, the *LS* factor is unitless. I calculated *LS* for every cell of the DEM, treating each cell as a uniform slope.

## 2.5 Crop cover factor

A land cover map for Negros was created from a Landsat image available through the Global Land Cover Facility at the University of Maryland. The image is from 2001, but the area on Negros classified by the government as ‘alienable and disposable’ (i.e., agricultural) has not changed since 1970, reflecting the island’s long-time, intensively farmed state (PDENR, n.d.). I classified the satellite image into nine categories using the IDRISI software’s maximum likelihood classification procedure. I was given some training data by the National Mapping and Resource Agency of the Philippine government, and I was able to select additional training sites from the image itself based on my knowledge of the island. The classification categories are: urban, forest, water, coconut, sugarcane, rice, corn, disturbed forest, and mixed canopy/agriculture. These last two classes represent a mixture of agriculture and tree canopy, whether natural or artificial. This is common in the mountainous uplands, where farmers may leave some tree cover on ridgelines, or plant trees as an erosion barrier. The ‘disturbed forest’ and ‘mixed agriculture’ classes, because they contain more than one vegetation type within a cell, could not be identified by dominant vegetation type. However, the ‘disturbed forest’ spatial signature was recognizably closer to the ‘forest’ signature than that of other vegetation types, while the ‘mixed agriculture’ class had a spatial pattern between that of maize and coconut. These two classes constituted about 20% of the land cover on the island. While the inability to determine the dominant vegetation for these cells undoubtedly impacted the analysis, I felt confident in assigning the erodibility value of coconut to the ‘mixed’ class and of forest to the ‘disturbed forest’ class, because this would render a conservative estimate of erosion.

The values for the RUSLE ‘C’ factor were taken from the literature on tropical crop systems. Unfortunately, no research on the cropping factor has been conducted in the Philippines itself. Measured *C* factor values from Nigeria of 0.5, 0.01, and 0.2 were used for the corn, grassland, and coconut palm, respectively (Roose 1977); a *C*-factor of 0.28 from India was used for rice paddies (Singh et al. 1981), and a *C*-factor of 0.06 from Thailand for forest cover (Srikhajon et al. 1984). Sugarcane land was given the same erodibility factor as maize land. For the forest/agriculture and canopy/agriculture classes, I used *C*-values for coconut and dipterocarp forest, respectively, which are certainly conservative estimates because agricultural planting under canopy cover is more erodible than undisturbed forest land. *C*-values for urban areas and water were set at 0.

## 2.6 Practice factor

The *P* factor map was constructed using a new technique to apply models of farmer decision making from a survey population to a landscape scale of analysis. The objective of this procedure was to use the results of a survey conducted in a limited geographical area (the five-village study site) to derive a pattern of behavior over a larger geographical area (Negros Island), as it would have been impossible to survey the entire island. A probability model representing farmer behavior as a function of spatial variables such as slope and crop type was generated for the survey data from the study area, and I assumed that the same patterns determining farmer behavior (i.e., adoption of soil conservation technology)

apply over the whole island. This allowed me to predict farmer behavior in areas I had not surveyed using the spatial variables that were found to be significant determinants of decision-making behavior in a binary logistic model. Significance was measured by the *P*-values of the coefficients associated with the spatial variables. This process resulted in an extrapolation of functions derived from data collected in a limited geographical area to a larger geographical area.

Essentially, the technology with the highest probability of being adopted in a given cell was assigned to that cell (terracing, cover cropping, erosion barriers, and no technology adoption). Then, a *P*-value for that technology was determined from experiments that had been conducted on field sites on Cebu, Negros' neighboring island. While every individual cell does not necessarily represent a farm, the scale of the map (0.8 ha/cell) approximately corresponds to average farm size on the island. This makes the decision model extrapolation a good approximation of farmer decision-making over the landscape, but by no means should it be taken as an accurate predictor of behavior in any particular cell.

I analyzed the responses to the farmer survey using a binary logistic regression in Minitab. The farmers were separated into two groups: technology adopters and technology non-adopters. Slope was the best predictor of farmer adoption of technology; farmers on steeper slopes are more likely to adopt soil conservation strategies than farmers on low slopes. In addition, rice farmers are less likely than other farmers to use soil conservation strategies. This is because rice grown on Negros is paddy rice, which has a much lower erodibility than grain crops, due to the construction of rice paddies on flat fields surrounded by berms. Rice farmers therefore do not usually feel the need to conduct erosion prevention measures on their land. The results of the binary logistic model are summarized in Table 1. The two independent variables, slope and rice area, are negatively correlated, because rice is grown on lower slopes. However, the model correctly predicted nearly 83% of the paired adopting/non-adopting farmers for the predictive model with slope and rice area as independent variables. This indicates that the model fit was very good.

I also analyzed the quality of soil conservation technologies adopted using an ordinal logistic regression, ranking the technologies from one (terracing) to three (cover cropping) in declining effectiveness, as measured in Philippine field experiments. Farm area in coconut, farm area in sugar, and farm population density were the best predictors of technology quality adopted, with a positive relation (Table 2).

Raster maps of the independent variables selected as input to the binary logistic model were used as input to the map probability model. This model, which I wrote in Visual Basic for Applications (VBA), calculated the probability of farmer adoption of soil conservation technology in a given cell of the map. Equations were drawn from Wooldridge (2001):

**Table 1** Output from binary logistic regression in Minitab with 'adoption of soil conservation' as dependent variable. 'Rice' refers to number of hectares planted in rice

Predictor	Coefficient	P	Odds ratio
Constant	-0.05	0.85	
Rice	-0.83	0.01	0.44
Average slope	0.04	0.00	1.04

Soil conservation adopters: 235; Non-adopters: 124

Log-likelihood = -197.722

Test that all slopes are 0: *P*-value = 0.000

Measures of association concordant pairs = 82.9%

**Table 2** Output from ordinal logistic regression in Minitab with ‘technology quality’ as dependent variable. ‘Sugar and Tree crop’ refer to number of hectares planted in sugar and coconut, respectively

Predictor	Coefficient	P	Odds ratio
1st Constant	-0.31	0.15	
2nd Constant	2.51	0.00	
Sugar	0.64	0.01	1.89
Tree crop	0.59	0.05	1.81
People/ha	0.04	0.07	1.04

Terracing adopters: 152; Erosion barrier adopters: 106; Cover-crop adopters: 13

Log-likelihood = -219.421

Test that all slopes are 0: *P*-value = 0.002

Measures of association concordant pairs = 61.4%

$$P(\text{row, col}) = (\text{Exp}(a_0 + a_1 \times x_1(\text{row, col}) + a_2 \times x_2(\text{row, col}) + \dots a_n \times x_n(\text{row, col}))) / (1 + (\text{Exp}(a_0 + a_1 \times x_1(\text{row, col}) + a_2 \times x_2(\text{row, col}) + \dots a_n \times x_n(\text{row, col}))))$$

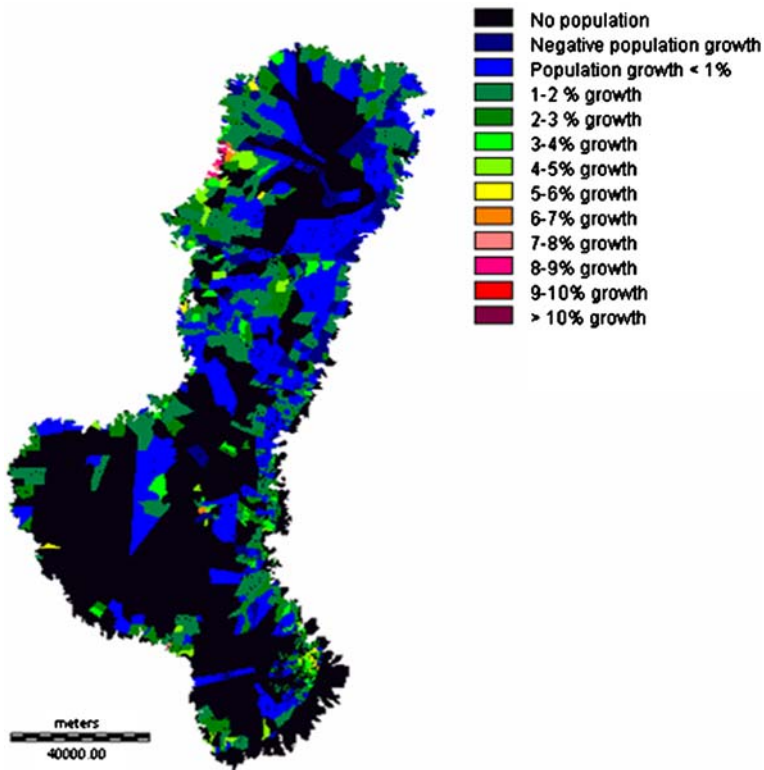
where *P*(row, col) represents the probability of farmers in a given cell adopting the technology; *a*<sub>0</sub>...*a*<sub>*n*</sub> represent coefficients generated by the binary logistic model; *x*<sub>0</sub>(row, col)....*x*<sub>*n*</sub>(row, col) represent the mapped input variables. For each cell, if the probability of technology adoption was greater than 0.5, the cell was labeled an ‘adopter.’ Then, a technology type was assigned using the probability equations derived from the ordinal logistic model, with sugar area, coconut area and population density as independent variables.

I created a population density map from a digitized map of *barangay* boundaries in 2000, available from the provincial office of the Department of Environment and Natural Resources. Population by *barangay* was enumerated in the 1960 and 2000 censuses by the National Census and Statistics Office. I used this information to construct a population density map by *barangay* for the years 1960 and 2000. I then calculated the population growth rate by *barangay* between 1960 and 2000, and adjusted this 40-year average rate based on decadal estimates of the island’s population (which were not spatially distributed). Dividing by the areal extent of each *barangay* (typically a few to a few hundred hectares) yielded population growth by raster cell. The result was a population growth model that was distributed spatially over the island; urban areas, for example, had a much higher growth rate than rural areas; however, the *average* growth rate over the whole island was ~2.3% annually (Fig. 4). The probability map could then be calculated yearly based on the new population estimates.

*P*-values were assigned to the generated technology map based on field experiments from the Philippines (Daño 1992; Presbitero et al. 1995; Shively 1999a). These values were 0.22 for terraces, and 0.7 for erosion barriers.

### 2.7 Map processing

All of the input maps were reprojected into Universal Transverse Mercator coordinates using the Luzon datum. They were clipped to the dimensions of the island, and a mask was applied to exclude any areas outside of the island from processing.



**Fig. 4** Population growth rates by cell between 1960 and 2000. Cells colored black indicate areas with less than one person per cell average in both 1960 and 2000

## 2.8 Computer model

Watersheds on the island were defined using the IDRISI WATERSHED module (Eastman 1999). If a watershed defined by the module did not drain into the ocean, it was combined with its receiving watershed to create a larger one that did enter the ocean. The maps of the individual RUSLE factors were multiplied together to produce a map of annual erosion in metric tons per hectare. I multiplied this map by the area of the map cells to produce a map of erosion per raster cell per year. Then I divided this map by a soil bulk density map to generate soil loss per year by volume (soil bulk density values were also measured in the 1960 island soil survey). The 1960 soil survey also contained information on the depth of each soil type, which the researchers determined by digging soil pits. From the digital soil map, I was able to construct a map of soil depth in 1960 using the soil survey information. The depth multiplied by the area of each cell yielded a map of initial soil volume per cell in 1960.

The computer model removed the eroded soil from each cell at the beginning of each year and ‘moved’ the soil down a flowpath until the total sediment load was deposited on land or in a waterway. The model was run for 90 years, with 1960 chosen as the initial year, because the soil depth data derived from the soil survey map dates from

that year. The algorithm used to move the soil was the moving window approach, facilitated by the IDRISI module FLOW (Jenson and Domingue 1988). The program went through the map, searching for cells immediately surrounding a cell that flowed into it. If the slope of the receiving cell was less than the slope of the contributing cell, all eroded soil from the contributing cell was deposited on the lower slope. If the slope of the receiving cell was greater than or equal to the contributing cell, all of the eroded soil was presumed to progress uninterrupted and the erosion of the receiving cell joined that of the contributing cell in moving downslope. If the receiving cell was a waterway, the waterway identification number, watershed identification number, and amount of soil lost to the waterway were recorded. The volume of the eroded soil was subtracted from the soil volume of the 'donating' cell, and a new soil depth value was calculated by dividing the new (eroded) soil volume by the cell area. Thus, eroded soil moved down across the DEM until it encountered a flatter slope, at which point the total sediment load was deposited, or a waterway, where the total sediment load was lost. New maps of soil volume by cell and soil depth by cell were calculated every year, reflecting the movement of the topsoil.

Once the soil in a given cell eroded to the point where the soil depth was below 15 centimeters, the cell was assumed to be unproductive. If it was designated as cropland, its status became grassland, with a very low erosion rate (very little land on Negros is used for pasture). The erosion map was then adjusted for the following year.

## 2.9 Validation data: literature

Several sets of data were used to validate the model—data collected in the field, on Negros, and data from published studies. The data from the literature were collected in the Philippines, Malaysia, Thailand, Costa Rica, and Sri Lanka (Daño 1992; Presbitero et al. 1995; Coughlan and Rose 1997; Krishnaswamy et al. 2001; Hewawasam et al. 2003). These data were used for two different validation tests: one to compare model output of soil loss from individual cells, or plots, with experimental data, and the other to compare model prediction of soil export from the watersheds with measured values.

The model's prediction of soil loss from individual cells as determined by the annual RUSLE calculation was compared with field experiments in the Philippines. Because of the limited number of studies that have focused on measuring erosion in tropical environments, only eight data points were available for comparison with the model. Field values from an experimental station in Los Baños and two stations in Leyte were chosen for the validation data because these stations have similar rainfall, soil type and topography to that of Negros (Daño 1992; Presbitero et al. 1995; Coughlan and Rose 1997). All of these studies were conducted on plots planted in maize. The number of validation points was too small to perform most statistical analyses. Instead, I compared the field-measured values to the mean values of the model-predicted erosion plus or minus two standard deviations, to determine if the field values fell within the range of 95% of the model values.

For the watershed output validation, I chose the Costa Rican and Sri Lankan data from the literature based on the similarity of the watersheds in the study compared with the watersheds and climate on Negros (in terms of topography, soils and rainfall). The literature data were necessary for validation because of the impossibility of gathering enough data from Negros waterways to generate a data set covering a variety of watershed scales.

## 2.10 Validation data: field

Field data collected on Negros were used to validate the watershed export portion of the model. To collect the field data from Negros, the field team measured TSS during July and August, 2005. We chose three tributaries that drain the upland areas where the field surveying took place, so that we could more closely link farmer practices with resulting soil erosion.

Our sampling strategy was to capture the storm events during which almost all erosion occurs (Edwards and Glysson 1999). On the first sampling day, before the rains began, we set up transects at each of the rivers and measured the width of the waterways. Each river was divided into five width-increments stretching across the channel, and we measured depth and base flow with a flow meter in each of these increments, totaling five measurements per sampling. We also measured the flood height and depth of the waterways (clearly visible from marks on the bank or from the extent of the floodplain).

When a rain event began, we proceeded to the sampling sites to take measurements. We repeated the width, depth and flow measurements in each width increment, and took a 100 ml sample in a plastic bottle for suspended sediment analysis in the laboratory. Measurements were repeated every 2–3 h after the rain event, which typically lasted only 30–60 min.

During 1 month of sampling, we captured four rain events of varying sizes at each river. Dr. Estela Cequiña's laboratory at Central Mindanao University analyzed the samples taken during these events according to standard USGS protocol for measuring TSS, filtering the samples and oven drying them (Guy 1969). This gave a measurement of sediment weight per liter of water for each sample. To determine how much total sediment passed by the sampling point during the measurement, I calculated the volume of water flowing by the sampling point using the stream depth, cross-sectional area, and flow rate, then multiplied the resulting number (in liters) by the sediment concentration in the sample (in mg/L). The instantaneous measurements of sediment loading in metric tons/h generated using this method were plotted on a timeline. I integrated the area under this time curve to find the total amount of sediment in metric tons being transported by that stream over the 1-month sampling period.

The amount of rainfall received during our measurement period was divided by the total amount of rainfall estimated for the year using the Clark AFB measurements to determine the proportion of erosive rainfall that occurred during the sampling period. The sediment load calculated for the 4-week period was divided by this rainfall proportion to generate an annual sediment load for each waterway.

After determining total annual sediment transport out of the three watersheds on Negros, I combined these data with the literature data from Costa Rica and Sri Lanka to generate a validation data set of 17 watersheds. I corrected both the field-measured and model-generated sediment transport values for watershed size by taking the residuals of the linear regression of sediment yield on watershed size. Because the validation watersheds all had an average slope of between 5 and 15%, I limited the comparison with the model output to the 119 watersheds on Negros that had average slopes within this range. I then used a two-sample *t*-test to compute a confidence interval for the difference between the mean sediment yield of the modeled watersheds versus the mean sediment yield of the validation watersheds, corrected for size.



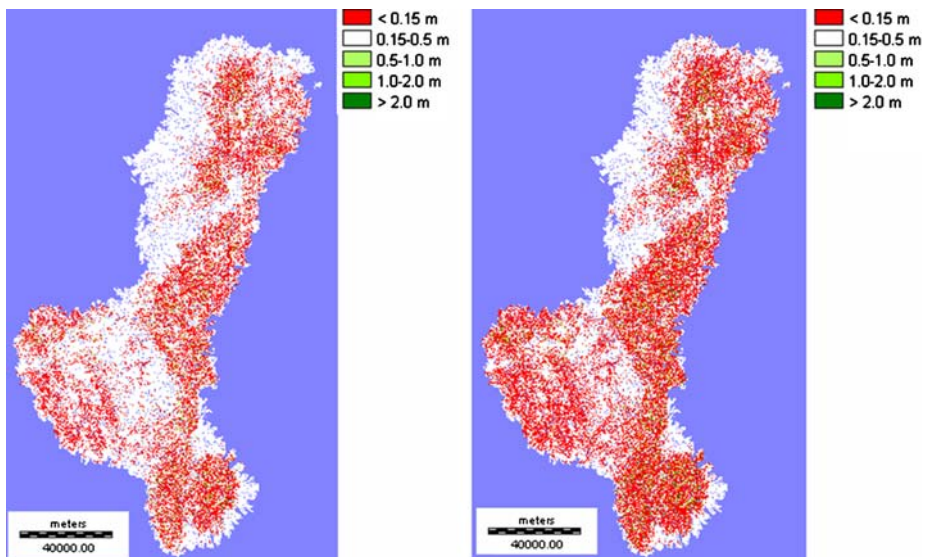
## 2.11 Policy scenarios

I re-ran the erosion prediction model with different erosion input maps created with the RUSLE to account for the different policy scenarios mentioned previously (universal terrace adoption, and agroforestry adoption over all of the island's agricultural lands). I also ran the model without any farmer adoption of soil conservation technology. The input maps altered by these policy scenarios were the  $P$  and  $C$  maps, as listed in the model scenarios below:

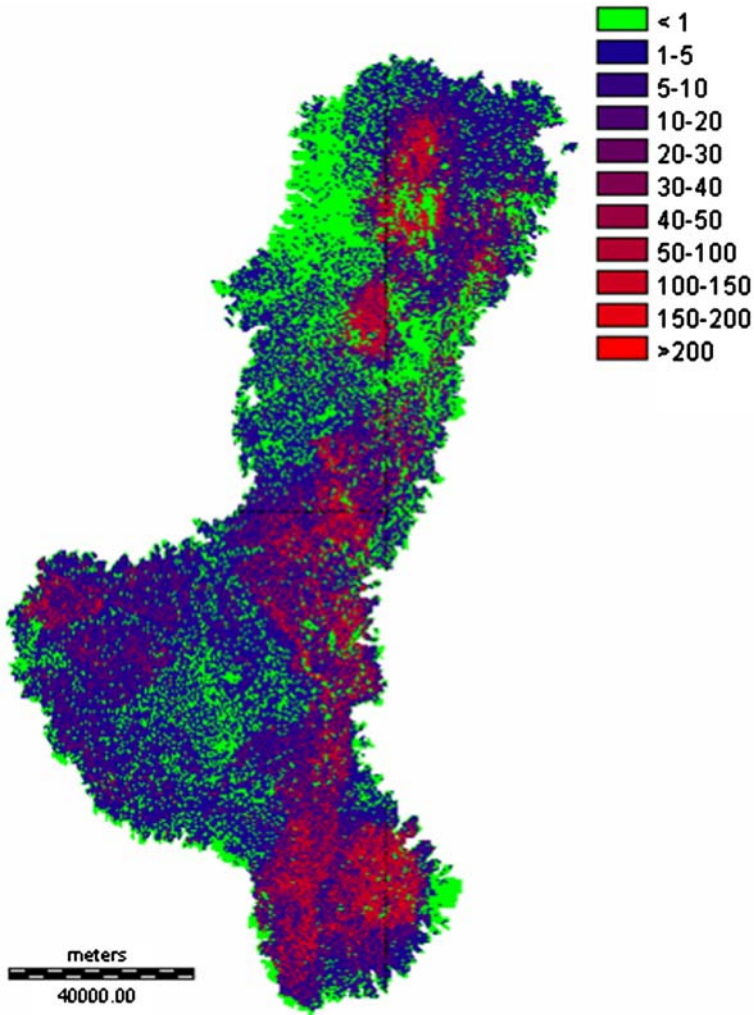
1. No soil conservation technology adoption at all ( $P$  map = 1);
2. All agricultural lands adopting terraces ( $P = 0.22$ );
3. All agricultural lands cultivated in coconut ( $C = 0.2$ ).

## 3 Model results

The model predicted severe soil erosion on Negros leading to the long-term degradation of more than one-quarter of the island's agricultural land (Fig. 5). Soil erosion from  $\sim 23\%$  of the island's agricultural land appeared to be occurring at sustainable rates ( $<1 \text{ mT ha}^{-1} \text{ year}^{-1}$ ), while 30% of the island had soil loss rates considered 'high' by the United States Department of Agriculture ( $>10 \text{ mT ha}^{-1} \text{ year}^{-1}$ ) (Troeh et al. 1999) (Fig. 6). According to the model, planting coconut on all agricultural lands was more effective at reducing erosion than the universal adoption of terraces, although neither of these strategies curbed erosion on the steepest slopes. All but one of the eight data validation points for soil loss from individual fields were within two standard deviations of the mean model predictions for fields of corresponding slope, crop type and farming practice



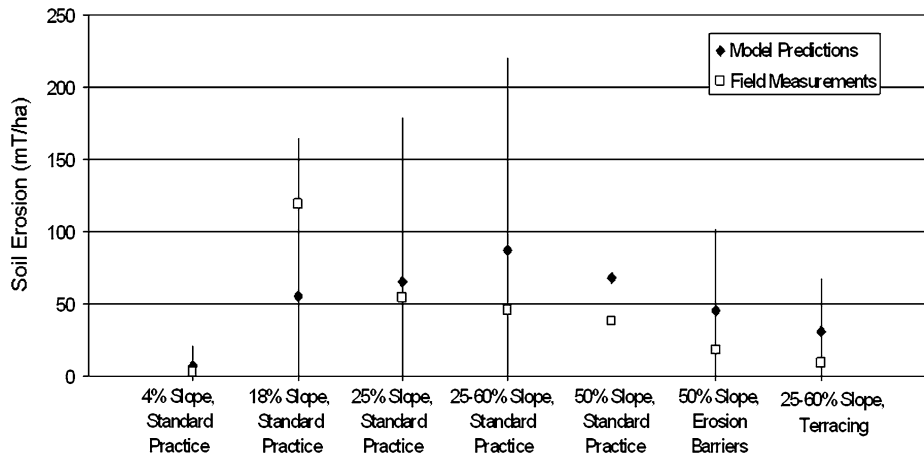
**Fig. 5** Soil depth in meters in model year 2000 (left), and in model year 2050 (right). Red cells indicate depths of  $<15 \text{ cm}$ ; these areas total 276,027 ha in 2000 and 416,970 ha in 2050



**Fig. 6** Soil erosion in metric tons per cell per year from Negros Island

(Fig. 7). The two-sample *t*-test of field measured sediment export versus model predicted sediment export failed to reject the null hypothesis that the model mean was the same as the field-measured mean.

Model predictions of soil loss from the island declined over the 90-year model period, due to the reversion of agricultural land to grass/scrub land, following the erosion of topsoil to a depth of <15 cm and the consequent abandonment of agriculture. For the year 1961, the model predicted total soil *erosion* (not including deposition) to be 23.1 million cubic meters—adjusted for soil bulk density, this is equivalent to 29.4 million metric tons. The vast majority of this soil was not lost to waterways, but deposited downslope. By model year 2050, the amount of soil detached (eroded) declined to 13 million cubic meters, or 18.9 million metric tons of soil.



**Fig. 7** Modeled annual soil erosion for maize fields compared with published soil erosion values from the literature (Dano 1992; Presbitero et al. 1995; Coughlan and Rose 1997). The vertical lines represent two standard deviations of the mean values predicted by the model

A map of soil erosion generated by the model in 2004 (a little less than mid-way through the simulation) showed some areas of extremely high soil loss—greater than 200 metric tons/hectare (Fig. 6). However, these highly erodible lands constituted <0.2% of the island’s total area. Twenty-three percent of the island area had soil erosion rates of <1 mT ha<sup>-1</sup> year<sup>-1</sup>, considered a sustainable rate (Troeh et al. 1999). About 30% of the island’s land area was eroding at rates greater than 10 mT ha<sup>-1</sup> year<sup>-1</sup>. In 2004, total soil erosion from agricultural land was 14.3 million cubic meters; however, total soil loss to waterways was 2.7 million cubic meters, less than one-fifth of this figure, due to deposition.

Some cells were predicted to have <15 cm of topsoil left after 90 years of simulated erosion (Fig. 5). Most areas on the island, in contrast, had no net loss of soil after 90 years. Some gained topsoil as the result of deposition. Without farmer soil conservation practices, 4,204,743 m<sup>3</sup> of soil would be transported out of the watershed during the year 2004, as predicted by the model (Table 3). This indicates that farmers are ‘saving’ 1,492,799 m<sup>3</sup> of topsoil per year (about 36% of the topsoil lost) through terracing and constructing erosion barriers. The model-predicted total sediment export from the island with all farmers

**Table 3** Model-predicted yearly soil export and average erosion on 50% slope for all policy scenarios

	Export from watersheds on island in cubic m/year in 2004	Average soil erosion on 50% slope (mT/0.8 ha)
Original model prediction	2,711,944	55.9
Without soil conservation practices	4,204,743	78.3
Universal terrace adoption	2,607,276	54.5
Coconut on all steep lands	2,173,058	51.1

adopting terraces would be 2,607,276 m<sup>3</sup>; with all lands planted in coconut it was 2,173,058 m<sup>3</sup>. Therefore, the highest soil loss prediction occurred under the scenario depicting no farmer effort to conserve soil, and the lowest prediction was generated by the scenario depicting widespread coconut cultivation.

Average soil loss from slopes of more than 50% was extremely high under both the no-conservation practice scenario and the original model run. On the steepest lands, universal terrace adoption and tree cropping reduced average erosion by only 3 and 9%, respectively, to 54.5 and 51.1 mT cell<sup>-1</sup> year<sup>-1</sup> (Table 3).

### 3.1 Model validation

Model output for a given slope (or slope range), crop type, and farmer practice varied due to soil type over the island. Seven of the eight validation measurements from various field experiments in the tropics were within two standard deviations of the mean predicted model value, and four of the validation points were within one standard deviation of the mean (Fig. 7). However, both model predictions and field values varied considerably. Model-predicted soil loss from land grown in maize without any conservation practices averaged 55.1 metric tons per hectare annually for an 18% slope, while field experiments yielded soil loss rates of 90.3–119 mT ha<sup>-1</sup> year<sup>-1</sup> for an 18% slope. Model predicted soil loss from terraced land planted in maize averaged 31 mT ha<sup>-1</sup> year<sup>-1</sup> for slopes between 20 and 60%, while data from the field was much lower (9 mT ha<sup>-1</sup> year<sup>-1</sup>). Erosion barrier technology reduced model-estimated average soil loss to 45.2 mT ha<sup>-1</sup> year<sup>-1</sup> for 50% slopes, compared to 18.55 mT ha<sup>-1</sup> year<sup>-1</sup> from the published data.

The two-sample *t*-test comparing mean model-predicted sediment loss from Negros watersheds with mean field values of sediment loss from Negros, Costa Rica and Sri Lanka failed to reject the null hypothesis that the two populations (field and model) were not significantly different ( $P = 0.86$ ) at a confidence level of 90%.

## 4 Discussion

The model output suggests that soil erosion is a serious threat to the sustainability of Negros' agricultural systems. Even accounting for deposition, more than 890,000 ha of land (76% of the island) is losing soil at a rate greater than the 'sustainable' rate at which soil can be replenished (1 mT ha<sup>-1</sup> year<sup>-1</sup> or less Troeh et al. (1999)]. More than 225,000 ha (19% of the island) are losing soil at rates greater than 20 mT ha<sup>-1</sup> year<sup>-1</sup>, accounting for deposition. At these soil loss rates, after 90 years more than 416,000 ha of the island would have topsoil depths of <15 cm, which is assumed to be the minimum amount needed to produce a crop (Pimentel et al. 1995) (Fig. 5). This is 36% of the island's total land area, an alarming figure considering the island's 2.3% average annual population increase, which drives the need for more productive agricultural land to sustain rural families.

The areas of extreme soil loss are almost entirely located in the uplands, where the poorest island residents with the least access to capital and technology are located. A loss of agricultural viability in these areas would cause the collapse of small-scale farms, exacerbating the exodus of farming families to the island's urban centers.

The enormous range in the field data points to the difficulties involved in calibrating and validating a soil erosion model. For example, why should empirical measurements of

erosion on similar soil types be higher on an 18% slope (from Los Banos, Philippines), than on a 50% slope (Leyte, Philippines) (Fig. 14)? It is likely that this difference has to do with plot-level differences; perhaps micro-topography that encourages rilling, or differences in soil erodibility within a soil type. The range of field-measured erosion values should caution researchers about applying the results of a field-level erosion study to an entire landscape. Modeling may provide a way to 'even out' these plot-level differences in order to form a landscape-scale understanding of erosion patterns. The watershed loss data indicate that the model predictions are not significantly different from field measurements of sediment loss from watersheds, with 90% certainty. The model therefore appears to be predicting the mechanism of sediment detachment and transport reasonably well over the landscape.

There was only one cell in the entire island landscape with 50% slope that was not predicted to have a terrace or erosion barrier, so the standard deviation of the model output could not be calculated for this point. Field measured values of erosion from slopes this high were only 56% of the model prediction, but erosion from extreme slopes is poorly studied. The RUSLE was originally calibrated for much lower slopes, so results on slopes this steep may be suspect; however, other researchers have used the model to predict erosion on extreme slopes (Srikhajon et al. 1984; Mongkolsawat et al. 1994). Clearly more field research and more research on the behavior of the RUSLE are needed for slopes of 50% or more.

It is important to emphasize the extent of soil deposition on Negros. Because geographical soil loss is not one-dimensional, some downslope areas of the island gained soil over 90 years, while others both gained and lost soil, resulting in no or little net loss. Using the RUSLE to estimate soil loss without incorporating a depositional element would therefore result in gross overestimations of soil loss from some areas.

The model results indicate that encouraging farmers to switch to coconut farming would prevent more soil export from the watershed than encouraging upland farmers to adopt terraces. In fact, the small difference in sediment loss and export under the universal adoption of terraces compared to the 'standard scenario' may be attributed to the fact that under the 'standard scenario' most farmers had already adopted soil conservation technology. Seventy-five percent of the survey respondents in the study area adopted soil conservation technologies even without technology introduction programs, and according to the model farmers who do so are 'saving' about 1.5 million cubic meters of soil from being eroded from the island yearly, compared with the 'no technology adoption' scenario. This suggests that the large amounts of time, resources and personnel devoted to technology education programs in the uplands might be better spent on other projects, as farmers already know how to conserve soil. Another implication of this finding is that models that do not consider farmer strategies to prevent soil erosion will overestimate both erosion and the potential positive impacts of programs to introduce soil conservation technology. One limitation of the model in this study is that it does not consider how farmer conservation strategies might change over time, in response to economic or environmental factors (other than population growth, which is included). Future development of this model should incorporate such dynamics by utilizing the results of repeated farmer surveys conducted over years or even decades in one location.

In spite of the conservation attributed to farmer practices, soil erosion in the steepest areas of the island continues at rates that threaten the sustainability of upland agriculture. More research is needed on how effective terracing and other strategies are at very high slopes (>50%), and how the RUSLE should be calibrated on these slopes. Although farmers may do everything in their power to conserve soil, ultimately it is not sustainable

in the long-term to farm in the uplands, especially not on slopes of greater than 50% (although this practice was not uncommon in the field study area). Rather than addressing farmer practices or even which crops farmers should grow, those concerned with slowing the pace of soil erosion should consider the broader social and political dynamics that force farmers into the marginal uplands. Unfortunately, the two main drivers of upland farming activity—unequal land distribution and high rates of population growth—are politically charged topics in the Philippines and are unlikely to be addressed by policy makers in the near future.

## 5 Conclusions

Soil erosion is a serious threat to the sustainability of agriculture on Negros, because it would render 36% of the island's land area unproductive by 2050. This would put pressure on the remaining agricultural land to produce more to feed the growing population; alternatively, the loss of agricultural land could lead to greater rates of rural-urban migration. The innovations to the standard RUSLE model developed in this paper allowed for the successful incorporation of depositional elements and soil movement over the landscape, and of farmer practices to conserve soil. Farmers are already responding to the threat of soil erosion with strategies that are reducing soil loss significantly, indicating that models that do not take into account farmer practices to reduce erosion will tend to overestimate soil loss. Soil conservation strategies can be improved in quality in some areas, but the positive effects of this strategy are likely to be minimal. Encouraging farmers to plant tree crops rather than grain crops would conserve more soil, but this strategy would also take more time and expense to implement. Neither of these strategies (terrace adoption or a switch to tree crops) would result in sustainable soil retention on the island's steepest lands. The very fact that poor farmers are using the steepest areas of the island for agriculture is the result of broader social and economic patterns that must be addressed if soil erosion is to be reduced significantly.

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