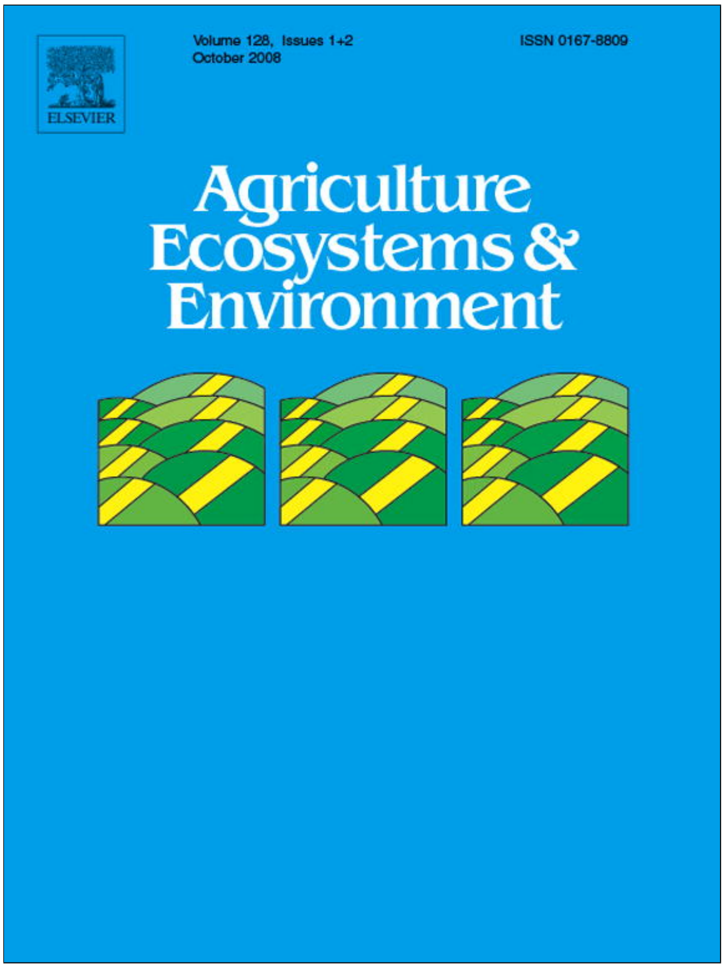
Volume 128, Issues 1+2
October 2008
ISSN 0167-8809
ELSEVIER
Agriculture
Ecosystems &
Environment

Agriculture, Ecosystems and Environment 128 (2008) 12–20

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

A multi-scale assessment of hurricane impacts on agricultural landscapes based on land use and topographic features

Stacy M. Philpott [a,*], Brenda B. Lin [b,1], Shalene Jha [c], Shannon J. Brines [d]

[a] Department of Environmental Sciences, University of Toledo, 2801 W. Bancroft Street, Mailstop 604, Toledo, OH 43606, United States
[b] The Earth Institute, Columbia University, Hogan Hall B-19, 2910 Broadway, MC 3277, New York, NY 10025, United States
[c] Department of Ecology and Evolutionary Biology, University of Michigan, 830 North University, Ann Arbor, MI 48109, United States
[d] School of Natural Resources and Environment, University of Michigan, 440 Church Street, Dana Building, Ann Arbor, MI 48109, United States

ARTICLE INFO

Article history:
Received 14 March 2008
Received in revised form 28 April 2008
Accepted 30 April 2008
Available online 12 June 2008

Keywords:
Chiapas
Mexico
Coffee agroecosystem
Ecosystem service
Erosion
Global change
Heavy rainfall
Landslides

ABSTRACT

Agricultural systems are increasingly vulnerable to the effects of extreme climate events. Yet strategies to reduce risk and vulnerability have not been greatly explored. Here, we examine the vulnerability of coffee agroforestry systems varying in management intensity (e.g. land use) and topographic features to disturbance related to Hurricane Stan in Chiapas, Mexico—a hurricane categorized by heavy rains and mild winds. An approximately 50 km^2 area was chosen within a coffee-growing region where data were collected on a variety of topographic and landscape features (aspect, slope, elevation, distance to river) and vegetation characteristics (canopy cover, vegetation structure, tree density) as predictive factors of vegetation, economic, and landslide damage at three distinct spatial scales. At the plot level, we collected vegetation data later compiled into a vegetation complexity index. At the farm level, we collected data to understand the effect of the hurricane on economic damage and farm area affected by landslides. We also recorded number and volume of roadside landslides as a measure of post-hurricane disturbance. We then conducted a geo-spatial analysis to determine which factors contribute most to landslide occurrence at landscape scales. We found no effect of coffee management on vegetation damage or on economic losses at the plot or farm scale. At the farm scale, increasing management intensity (i.e. reduction in vegetation complexity) correlated with increased proportion of farm area affected by landslides ($P = 0.014$). Additionally, reduction in vegetation complexity was correlated with increased number ($P = 0.0224$) and volume ($P = 0.062$) of roadside landslides at the landscape level. Topographic and landscape features, such as distance to river ($P = 0.004$) and wind exposure/aspect ($P = 0.044$) strongly influenced landslide frequency at the landscape scale. Forest proximity and proportion of forest cover did not significantly influence the frequency or extent of landslide damage. We created hazard maps using the vegetation complexity index, distance to river, and wind exposure as the heaviest weighted factors to assess areas of the terrain with the greatest vulnerability. These maps present a practical result of this study, and offer a template in which land management policy can develop to lower regional vulnerability to landslide risk. These results show that farmers may be able to reduce vulnerability to extreme storm events by carefully managing their farms. Although farmers may not be able to control negative topographic features of their farms, increasing vegetation complexity within farms may be an efficient strategy to reduce some susceptibility to hurricane disturbance.

1. Introduction

There is great urgency to understand the impact of global climate change on agriculture. These top issues may be directly linked by hurricanes. In recent years hurricane frequency and intensity has increased, and although there is considerable debate about the causes, some attribute these patterns to global climate change (Emanuel, 2005; Webster et al., 2005; Shepherd and Knutson, 2007). Agriculture is a main driver of habitat destruction, covers half of arable lands (McNeely and Scherr, 2003), and may increase susceptibility to hurricane damage (e.g. Perotto-Baldiviezo et al., 2004). Yet, tropical agroecosystems vary widely in management practices. For example, coffee agroecosystems fall along a management intensification gradient, from farms cultivated under a native forest shade canopy (most vegetatively

* Corresponding author. Tel.: +1 419 530 2578.
E-mail addresses: stacy.philpott@utoledo.edu (S.M. Philpott), bl2249@columbia.edu (B.B. Lin), sjha@umich.edu (S. Jha), sjbrines@umich.edu (S.J. Brines).
[1] Tel.: +1 212 854 8253.

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doi:10.1016/j.agee.2008.04.016

complex) towards farms characterized by lower density, diversity, and height of shade trees, lower canopy cover, and higher coffee density (least vegetatively complex) (Moguel and Toledo, 1999). Vegetatively complex coffee farms are prized for contributions to ecosystem services such as biodiversity preservation, pest control, pollination, and erosion control (Beer et al., 1998; Perfecto et al., 2007). Because coffee often grows on steep, largely deforested, mid-elevation mountain ranges, vegetation complexity may be especially important in buffering against the devastating effects of hurricanes. Here, we investigate environmental and economic impacts of hurricanes on coffee agroecosystems varying in vegetation complexity at three spatial scales.

Hurricanes dramatically affect forests, but very few studies examine the role of agricultural landscape management on vulnerability to hurricane-related environmental and economic damage. To our knowledge, only three studies have examined whether differences in agricultural type alter hurricane impacts. Uriarte et al. (2004) examined hurricane impacts on plant communities in abandoned pastures, mixed plantations, abandoned cacao, and forests. Areas with more complex vegetation were least resistant to hurricane damage losing larger and more trees. Yet, land uses with low human impact (cacao and forest), experienced faster increases in species richness and tree density following the hurricane. A second study demonstrated that hurricane impacts (erosion, economic loses, and vegetation damage) were less severe in farms using trees, live fences, terraces, and contour planting in agricultural fields (Holt-Gimenez, 2002). Perotto-Baldiviezo et al. (2004) examined landscape scale relationships between landslides, topographic features, and land use. Landslide probability was significantly higher in steeper areas, especially those in active or recently harvested swidden agricultural fields. Thus, what little evidence exists indicates that farms managed with increased tree cover, and with agroecological practices better resist and recover from the effects of hurricanes.

Research on landslide frequency has shown that both storm events and anthropogenic disturbance can increase risk. Landslide disturbance severely affects economic stability of agricultural regions due to damage to crop plants, arable land, and on-farm infrastructure, as well as disturbance of public services (Laing, 2003). In Puerto Rico, the leading cause of landslides has been attributed to intense and prolonged rainfall (Larsen and Simon, 1993). In the Luquillo Experimental Forest in Puerto Rico, landslides and uprooted trees triggered by Hurricane Hugo covered roughly 1.25% of the study area (Scatena and Larsen, 1991). Torrential rains accompanying Hurricane Mitch in 1998 triggered thousands of landslides throughout Central America (Crone et al., 2001), with as many as 11,500 landslides in east-central Guatemala (Bucknam et al., 2001).

Landslides attributed to anthropogenic disturbance are generally associated with changes in land use and vegetation structure. Landslide frequency in tropical mountains in Puerto Rico is five times greater within 85 m of roadsides than outside road zones (Larsen and Parks, 1997). Soil mass movement associated with roads can be 300 times greater than rates in undisturbed forest (Sidle et al., 1985), leading to greater rates of landslides. Other disturbances, like logging, are also associated with increased frequency of landslides (Guthrie, 2002).

Hurricane Stan hit the coffee-growing Soconusco region of Chiapas, Mexico in October 2005, just as the coffee harvest was beginning. The hurricane timing particularly affected the agricultural economy disrupting all aspects of the harvest, from preventing the arrival of migrant laborers, and slowing the harvest, to severely affecting transportation. The extensive rainfall (>500 mm) and wind (130 km/h) (Pasch and Roberts, 2006) led to widespread fruit drop before workers could reach the fields for harvest. Additionally, the onslaught of precipitation (>10% of the annual average in a few days) created massive landslides and floods, heavily damaging roads and bridges and submerging entire villages. Up to 50% of the Soconusco coffee harvest was lost, an estimated 170,000–280,000 ha of land were damaged, and 50–90% of farm infrastructure was affected (Perez, 2005). The extent of damage caused by this and other recent storms raises questions concerning risk and vulnerability for those dependent on agricultural livelihoods. Specifically, there is increased interest in understanding those factors that may reduce hazards and increase resilience of agricultural landscapes to the vagaries of extreme climate (Turner et al., 2003; Dale, 1998).

Despite the importance of hurricanes and landslides for farms and for farmer livelihoods, we lack a systematic evaluation of hurricane impacts in a range of agricultural management types at both farm and landscape scales. At the farm level, the potential for vegetation damage, soil erosion, infrastructural, and economic losses are evident, whereas a landscape perspective may be necessary for assessing the influences of topography and land use on landslide probability. In this study, we examine several key factors that may influence hurricane impacts in coffee-growing regions. We worked at three distinct scales to examine the importance of land use and several topographic factors including elevation, slope, aspect, and distance to rivers, in determining environmental and economic impacts of hurricanes. First, using plot level data from coffee farms and forests, we examined how vegetation characteristics of the coffee farms before the hurricane influenced vegetation damage and landslide occurrence as a result of the storm. Second, using data from government surveys and local field surveys, we examined how overall farm-level vegetation management relates to economic losses and total farm area affected by landslides. Finally, using topographic map data, satellite imagery and roadside landslide data, we examined which topographic and land use factors are most important in predicting the occurrence and size of landslides.

2. Materials and methods

2.1. Study region

We worked in the Soconusco region of Chiapas, Mexico in a mosaic of small forest fragments and coffee agroecosystems varying in vegetation complexity. All field sites are located between 600 and 1400 m elevation, approximately 40 km north of Tapachula between 15.202N, 92.383W (NW corner) and 15.144N, 92.297W (SE corner) (Fig. 1). The geology of this area of Chiapas can be generally characterized as comprised of volcanic rocks and sediments derived from volcanic rocks, which are quite prone to landslides, and also widely variable in character (Mora et al., 2007). The study area is approximately 51.8 km^2 including both coffee farms and forest fragments. Coffee accounts for approximately 93.7% of the study area and forest (generally less than 2 ha each) for the remaining 6.3% of land area (Table 1). Coffee farms cultivate both *Coffea arabica* and *Coffea canephora* in the understory, and most incorporate some sort of mixed-shade canopy over coffee.

2.2. Plot scale analyses

For local analyses we worked in 10 farms and associated forest fragments within the Tapachula watershed region. Between December 2005 and January 2006, we established between two and six 25 m × 25 m plots in each farm ($n = 30$). The number of plots depended on the size of the farm and area in active coffee production. Additionally, we established between one and three

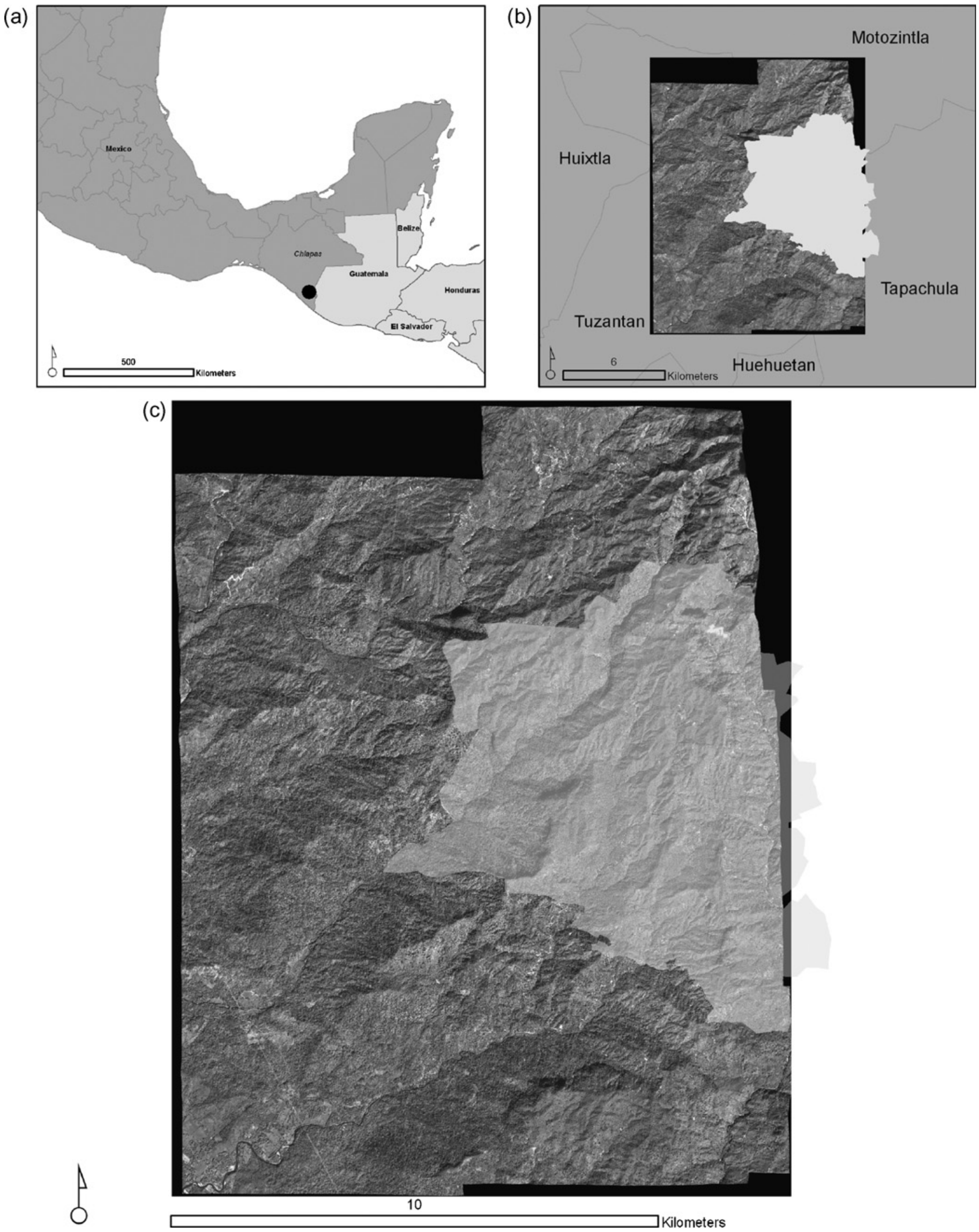

Fig. 1. Area of study: (a) country level; (b) state level; (c) landscape level.

Table 1
Description of land use types found in Soconusco study region

	F	SF	R/TP	TP/CP	CP	CP/SM	SM	Sun
Vegetation complexity index[a]	0.74	0.61	0.40	0.36	0.30	0.26	0.16	0.07
Percent canopy cover	78.26	77.80	53.58	56.05	56.50	23.15	18.87	3.03
Number of tree species per plot	20.39	10.00	7.00	5.96	6.17	4.50	2.17	2.00
Tree density (no. per m^2)	0.10	0.09	0.02	0.03	0.03	0.02	0.01	0.01
Coffee density (no. per m^2)	0.000	0.000	0.173	0.342	0.433	0.270	0.407	0.619
Stand basal area (m^2/m^2)	0.005	0.003	0.001	0.001	0.001	0.001	0.000	0.001
Area of satellite image (km^2)	0.617	0.008	0.073	12.509	12.483	1.889	5.929	0.377
Percent of classified landscape	0.02	0.02	0.22	36.91	36.84	5.58	17.50	1.11

Land use types are as follows: F = forest, SF = scrub forest, R/TP = rustic, traditional polyculture coffee, TP/CP = traditional/commercial polyculture coffee, CP = commercial polyculture coffee, CP/SM = commercial polyculture, shade monoculture coffee, SM = shade monoculture coffee, and Sun = sun coffee.

[a] The vegetation complexity index reflects higher vegetation diversity and structure with higher values.

plots in each of seven forest fragments ($n = 15$) scattered in between coffee farms. Forest plots were smaller (20 m × 20 m) because the forest fragments were smaller in breadth. We took GPS points of each plot to map the exact location on the geographic and altitudinal gradient of the various plots (Trimble, Sunnyvale, CA).

We sampled vegetation in each plot during January–February 2006. The objectives of the vegetation surveys were to (a) describe the vegetation complexity and management style of each site and (b) assess the hurricane damage sustained. In each plot we recorded percent canopy cover using a vertical tube densiometer (Geographic Resource Solutions, Arcata, CA), taking 50 measurements per plot and averaging them for a per plot canopy cover measure. We counted and identified all standing and fallen trees and measured their diameter at breast height (DBH). We used DBH to calculate stem and stand density for each plot, and converted these values to stand density (m^2) per hectare. We also counted standing and damaged coffee plants in each plot and calculated the percentage of damaged trees or coffee plants per plot.

We classified sites according to a numerical vegetation complexity index and a standard land management classification system, which included the following categories: forest, rustic coffee, traditional polyculture coffee, commercial polyculture coffee, shade monoculture coffee, and sun coffee (Moguel and Toledo, 1999; Philpott et al., in press). Where sites did not fall cleanly into a management system, we created borderline systems to capture this variation (e.g. rustic/traditional polyculture). We classified forests as either forest or scrub forest based on vegetation density. Scrub forests were composed of low density, primary colonizing tree or shrub species, while forest patches exhibited clear canopy and understory layers, composed of primary forest species. In the land management classification system, sites with highest vegetation complexity (i.e. forest) were assigned to the lowest land management number, and sites with the lowest vegetation complexity (i.e. sun coffee) were assigned to the highest land management number. For each site we created a vegetation complexity index (Mas and Dietsch, 2003). Raw data for each vegetation variable measured (tree richness, number of trees per m^2, number of coffee plants per m^2, stand basal area, and canopy cover) were converted to a scale from 0 to 1. For most variables, we divided each measurement by the highest possible value and subtracted by one. For coffee density, which generally increases as overall canopy complexity decreases, we divided by the lowest measurement and subtracted by one. We summed values for each variable and divided by number of variables measured to obtain an index value between 0 (least-intensive) and 1 (most-intensive).

2.3. Farm scale analyses

All farms in the region supplied data to the Consejo Mexicano de Café regarding economic losses and landslide impacts resulting from the hurricane. Data from 27 farms, including 8 farms in which we collected plot-level data, were made available to us. The data collected included estimates of expected and actual coffee harvest, the area of the farm affected by landslides, and total coffee production area. From this, we calculated the percent coffee harvest lost and percent farm area affected by landslides. We examined these two dependent variables in relation to the vegetation complexity index of each farm.

To classify the land use of farms included in this analysis, we used the following methods. We retained the same classification for the eight farms included in the plot-level analysis. For two additional farms (Guadelupe Zaju and Santa Elena) we used other available vegetation data (Philpott, 2006; Lin, unpublished data). We visited all other farms for which survey data were available during July 2007. In each farm, we took data on number of shade strata, approximate percent canopy cover, canopy height, and common canopy species observed, and made comparisons to other farms in which vegetation data were collected. We then categorized farms according to methods outlined above. We examined the relationships between percent of harvest lost, proportional area affected by landslides and coffee land use classification using simple linear regressions.

2.4. Landscape scale analyses

To assess the impacts of vegetation complexity and topographical features on hurricane-induced landslides, we used field data, digitized topographic map data, and satellite image analysis. Within the study region, dirt roads are the main thoroughfare for transport. Generally, roads have major influences on landslide frequency with much higher incidence of landslides nearby to roads (Larsen and Torres-Sanchez, 1996; Larsen and Parks, 1997). Thus, we chose to sample the impacts of land use and topographic features in mediating roadside landslides. Along roads, we established a total of 18 transects located within forest and coffee management types. Each transect within the selected farm was 300 m long, and along each transect we measured and mapped all landslides. We recorded landslide locations with a GPS unit (Trimble GeoExplorer 3), and measured landslide length, width (at 4 points along the length) and depth (at 4 points coinciding with width measurements) in order to estimate the total size (volume) of each landslide. We measured landslides both uphill and downhill from the road, as some landslides spanned across the roadway.

For the satellite land use analyses, we purchased a multispectral and panchromatic IKONOS® image as well as a digital elevation model, hydrography layer, and transportation layer (Land Info Worldwide Mapping, 2007). The image was taken on 10 December 2005 two months after hurricane Stan. The image was orthorectified and double-checked using a series of ground-truthing points. We created a land use map using the visual aid of the panchromatic image (1 m spatial resolution) and with the textural and reflectance patterns of a chlorophyll composite provided by the multispectral image (spectral bands 4-3-1, 4 m spatial resolution). We created a total of six terrain and land use layers based on (a) distance to rivers, (b) elevation, (c) slope, (d) aspect, (e) land use and (f) vegetation complexity index to determine whether topography, hydrology, coffee management and interactions among these factors contribute to relative landslide risk.

We used linear regressions to measure relationships between each factor (elevation, aspect, slope, vegetation complexity index, and distance to rivers) and both the number of landslides per transect and the volume of land lost per landslide. For each set of regressions, we used buffer scales of 1 km, 500 m, 100 m, and 20 m. These particular scales of analyses were chosen to correspond to the range of sizes from a farm management unit to the highest available scale of resolution. Specifically, many farms in the study region range from 250 to 350 ha in size, a size roughly equivalent to the area a 1 km radius circle (314 ha). Furthermore, farms in the region are commonly divided into management units called *pantes*, in which shade tree pruning, coffee pruning, weed removal, etc. will occur on similar schedules. Although the sizes of *pantes* vary, they range in size from approximately 75 to 100 ha in size in the farms studied, a similar size to the area of a 500 m radius circle (78 ha). Mean size of forest fragments in the study area is 1.4 ha and for scrub forest is 2.3 ha, sizes that correspond roughly to a 100 m radius circle (3.14 ha). The smallest scale, 20 m radius, was chosen because this was scale of the smallest resolution of the digital elevation model used in the analysis. As we wanted to examine the importance of land use management, presence of and nearness to forest fragments, topographic features, and rivers, selecting these scales of analysis was relevant. To generate data for the regression from the image, we took the mean value of the elevation, slope, distance to rivers, and vegetation complexity index within a given buffer zone. We chose the mean value for analyses as data for each of these variables was normally distributed. Generally, the force of sustained winds from a hurricane should be greatest in a direction perpendicular to the hurricane track, but many other factors such as vegetation height, composition, slope, and wind tunneling affect the damage inflicted (Gresham et al., 1991; Frangi and Lugo, 1991; Foster and Boose, 1992). We ranked the aspect according to wind exposure by assigning the greatest exposure to aspects facing the direction of the hurricane winds perpendicular to the angle of hurricane entry. The hurricane was moving from the NE, thus in a general sense highest exposure hazard ranking for this storm and region in particular was assigned for the NW facing slopes, with decreasing hazard moving away from this aspect (Pasch and Roberts, 2006). For the final regression model, the most predictive scale for each independent factor was used. Because of the recent emphasis placed on forest fragments in providing ecosystem services, we also examined whether distance to forest or the proportion of buffer zones with forest cover correlated with lower landslide number or size.

We created two types of hazard maps to visualize hurricane risk. First, we created an a priori landslide hazard map from literature-based assumptions: (1) hazard increases at lower elevations, (2) hazard increases with steeper slopes, (3) hazard increases with nearness to rivers, and (4) hazard increases on the aspect with highest wind exposure (as defined above). We then added to this to a land use hazard layer where risk increased with decreasing vegetation complexity. Finally, we created two post-priori terrain hazard maps using the coefficients from our regression analysis to weight the influence of each factor according to its calculated importance based on field data. We selected for inclusion in the hazard maps those layers that had significant influences on landslide size or number in regression analyses.

3. Results

3.1. Plot scale analyses

Individual vegetation variables and the vegetation complexity index varied reflecting a general decline in vegetation structure and diversity along the management intensification gradient (Table 1). We found minimal vegetation damage as a result of the hurricane, and no small landslides within the study plots. We counted a total of one fallen tree (in a shade monoculture farm) and three defoliated shade trees (two in a shade monoculture farm, and one in a sun coffee farm). We recorded three snapped coffee plants (in a traditional/commercial polyculture farm), and nine defoliated coffee plants in another traditional/commercial polyculture farm. There was no damaged vegetation within forest plots. Thus, total percentages of damaged vegetation at all points along the coffee intensification gradient were very small and did not warrant further statistical analyses. Likewise, we found no small landslides within study plots resulting from Hurricane Stan.

3.2. Farm scale analyses

There were significant effects of vegetation management on landslides, but not on coffee harvest lost. There were strong linear relationships between the expected and actual harvest (Fig. 2a, $R^2 = 0.9866$, $y = 0.7286x - 65.423$, $P < 0.001$), with all farms reporting yield loses between 18 and 40%. However, there was no significant relationship between the vegetation management

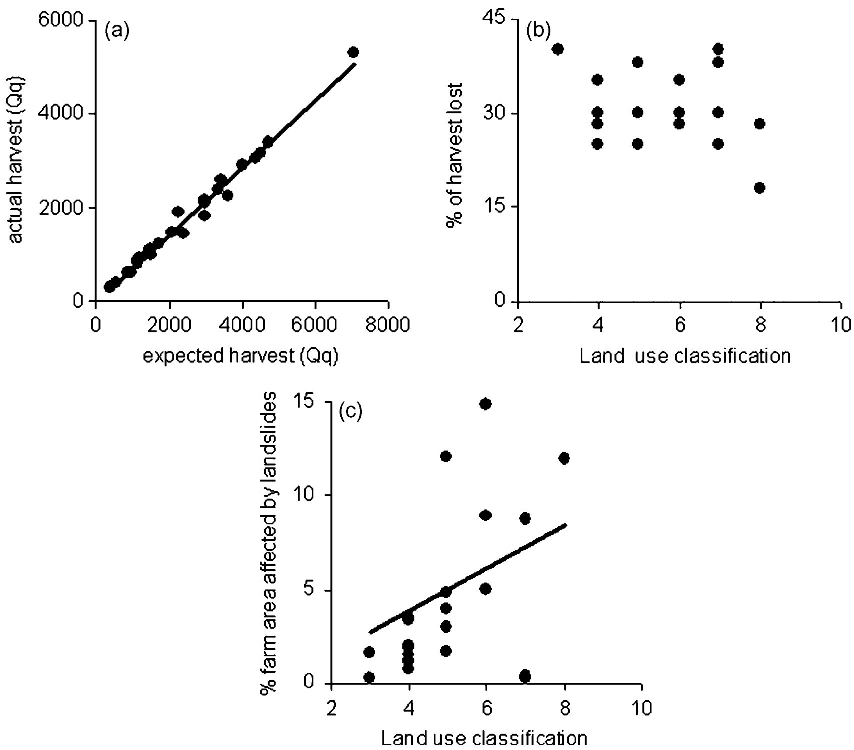

Fig. 2. Farm-scale relationships between (a) actual and expected harvest, (b) harvest lost based on land use type, and (c) farm area affected by landslide based on land use type. The six forest and farm land use types included in the farm scale analysis were ranked where land use classification number increases as vegetation complexity decreases. Regression results are presented in the text. Harvest information is provided in quintales (Qq).

and yield losses (Fig. 2b, $R^2 = 0.0843$, $y = -1.1152x + 36.536$, $P = 0.142$). In contrast, the area affected by landslides significantly increased with management, such that landslides affected a higher proportion of farm area on farms with less complex vegetation (Fig. 2c, $R^2 = 0.0827$, $y = 1.164x - 0.8312$, $P = 0.014$). Analyses using the vegetation complexity index were not possible due to the small sample size.

3.3. Landscape scale analyses

Of the 18 road transects surveyed across the coffee farms, 12 transects had at least one landslide. Transects with landslides had an average of 6.25 landslides per transect (±1.052 SE). Average landslide size was 188.52 m^3 (±74.459 SE). The number and size of landslides varied with transect. The numbers of landslides per transect varied from 0 to 15, and the combined size of all landslides on a single transect varied from 0.36 m^3 to 4101.22 m^3. Most of the landslides can be generally characterized as shallow slumps, where vegetation is left on top of the fallen soil and rock.

Regressions examining relationships between the number of landslides and landscape factors were most significant at the largest scale (1 km), and the best model was a combination of 500 m and 1 km scales for the five factors (ANOVA, $F = 3.88$, $R^2 = 0.618$, $P = 0.025$) (Fig. 3a). Elevation, slope, distance to river, and aspect were not significant predictors of roadside landslide frequency at any scale. Vegetation complexity index negatively

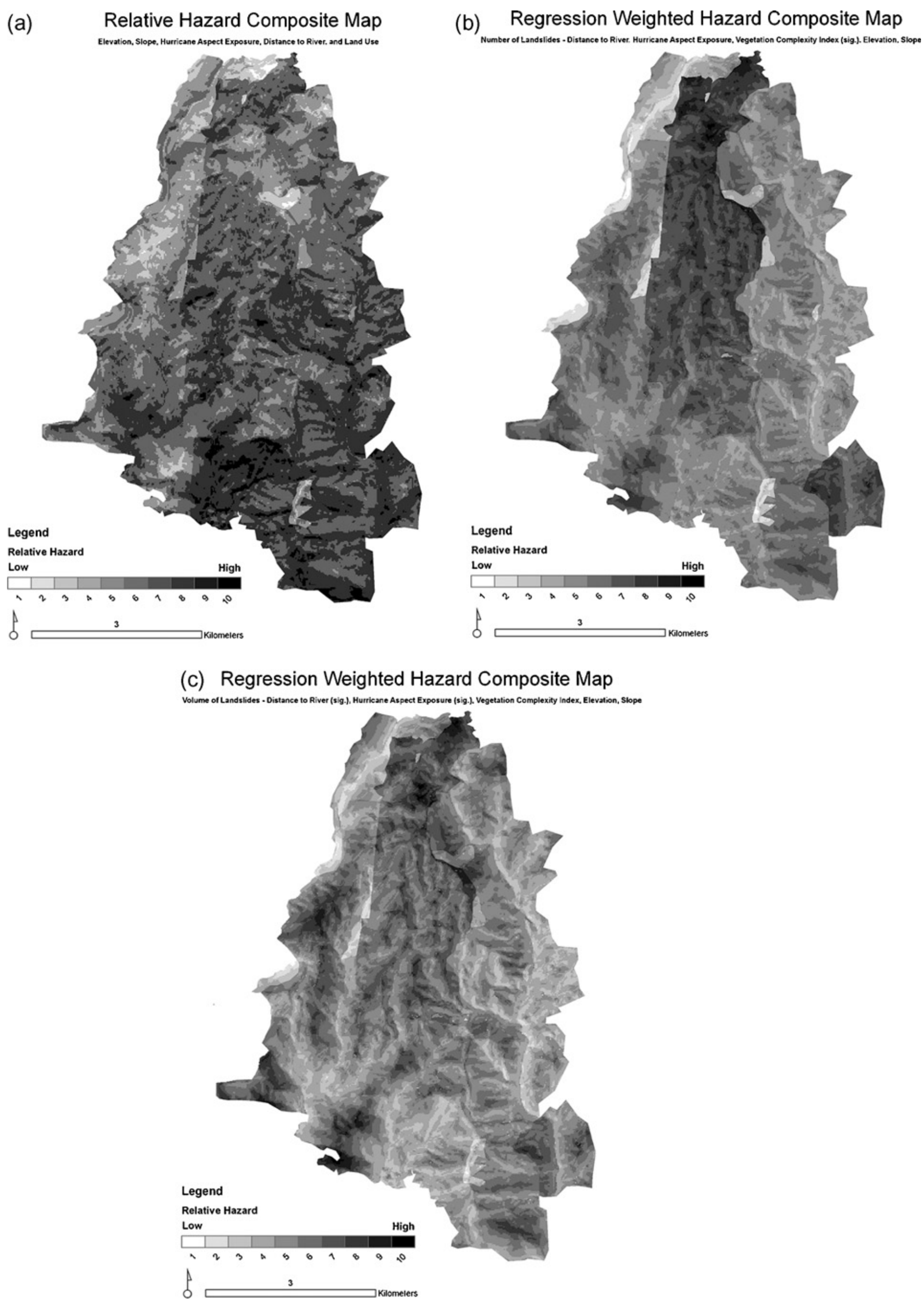

Fig. 3. Landslide hazard maps from the Soconusco region of Chiapas, Mexico based on topographic, landscape, and land use features including elevation, slope, hurricane aspect exposure, distance to rivers, and vegetation complexity index. (a) An a priori relative hazard composite map created from an equal-weighted linear combination of all five-factor layers. (b) A post-priori hazard map created from a combination of factor layers weighted based on the regression examining the number of landslides. (c) A post-priori hazard map created from a combination of factor layers weighted based on the regression examining the volume (size) of landslides.

correlated with the number of roadside landslides observed, but only at the largest scale ($P = 0.0224$). Forest proximity and the proportion of forest cover at multiple scales did not significantly influence the number of landslides per transect (*regression results*—forest proximity: $R^2 = 0.095$, $y = -0.002x + 5.163$, $P = 0.212$; proportion of forest cover at 100 m scale: $R^2 = 0.057$, $y = 0.001x + 3.590$, $P = 0.339$; proportion of forest cover at 500 m scale: $R^2 = 0.0122$, $y = 0.00003x + 2.59$, $P = 0.155$; proportion of forest cover at 1 km scale: $R^2 = 0.005$, $y = 0.000003x + 3.671$, $P = 0.773$).

The scale of analysis was also important in determining the influences of landscape factors on landslide size. Regressions predicting landslide size became more significant with increasing scale, and the best model was a combination of 500 m and 1 km scales for the five factors (ANOVA, $F = 2.549$, $R^2 = 0.158$, $P = 0.036$) (Fig. 3b). Elevation and slope did not predict landslide frequency at any scale. Landslide size tended to decrease as vegetation complexity increased at the 500 m scale ($P = 0.062$), and negatively correlated with distance to rivers at the 500 m scale ($P = 0.004$) and wind exposure (aspect) at the 1 km scale ($P = 0.044$). Forest proximity and the proportion of forest cover did not significantly influence the size of the landslides at any spatial scale (*regression results*—forest proximity: $R^2 = 0.011$, $y = -0.194x + 234.808$, $P = 0.380$; proportion of forest cover at 100 m scale: $R^2 = 0.001$, $y = 0.001x + 180.30$, $P = 0.854$; proportion of forest cover at 500 m scale: $R^2 = 0.002$, $y = -0.001x + 228.683$, $P = 0.695$; proportion of forest cover at 1 km scale: $R^2 = 0.028$, $y = -0.001x + 367.970$, $P = 0.158$).

3.4. Hazard maps

We created conceptual a priori and regression-weighted post-priori versions of hazard maps to visualize hurricane risk. In each case we standardized the range of the histogram for each predictive factor and then combined the layers to create composite maps. This methodology is akin to what is typically referred to as a multi-criteria evaluation employing a weighted combination of factor layers. The first map (Fig. 3a) is an a priori relative hazard composite map created from an equal-weighted linear combination of factor layers. The second map (Fig. 3b) is a post-priori hazard map created from a combination of factor layers weighted based on the regression examining the number of landslides. The third map (Fig. 3c) is a post-priori hazard map created from a combination of factor layers weighted based on the regression examining the volume (size) of landslides. In all three maps, the grayscale from white to black represents increasing relative hazard.

4. Discussion

The results from our study demonstrate that both land use and topographic features influence certain types of environmental damage sustained by hurricanes, and that the observed impacts vary with the scale at which impacts are measured. Most of the damage from Hurricane Stan seemed to stem from excessive rainfall, rather than wind damage, particularly evident from the lack of damage to foliar vegetation. The majority of the damage, such as fruit drop, damage to buildings and infrastructure, and landslides were triggered by heavy rainfall, as is commonly seen with other storms. For example, during Hurricane Mitch, some areas of Central America received nearly half of their annual rainfall in a week (Kok and Winograd, 2002). At the scale of farm and forest plots, there was minimal to no vegetation damage and no landslide damage. In contrast, farm-level data showed that vegetation complexity (and thus management style) of the farm was significantly correlated with landslide damage. At the landscape scale, increases in vegetation complexity correlated with fewer landslides, but only at the 1 km scale. Distance to river and vegetation complexity index were predictive of landslide volume at the 500 km scale, while wind exposure (aspect) was significant at the 1 km scale.

4.1. Topography and hurricane risk

There are many natural factors that can influence slope stability. Among these factors are geomorphology, soil properties, hydrology, vegetation and seismic activity. In the case of our measurements, we have taken into account differences primarily in slope and vegetation. Because of the great variation in soil due to geologic and topographic variation, we have not been able to capture soil differences at the various scales. Hydrology in this region can be generally characterized as dendritic, but is relatively unexplored at the scale of this analysis. We therefore have not taken into account detailed differences in hydrology in different areas of the region. This region does experience consistent small seismic events that probably contribute to slope instability and make hillside soil more susceptible to landslides due to micro-liquefaction. But these recent seismic events have not produced landslide damage that has equaled that of the hurricane.

A combination of landscape level features certainly contributes to the susceptibility to landslides. In one study in Puerto Rico (Scatena and Larsen, 1991), landslides occurred on the Northeast and Northwest facing slopes of the topographic terrain—this may be a factor of the direction of rainfall and the soil structure of the system as well. In our study, aspect was an important factor for landslide occurrence in all but the largest scale. We found that the Southwestern slope experienced greater landslides than the Southeastern slopes, perhaps because of the direction of the tropical storm. Because of the high level of rainfall intensity and the wind direction of the Hurricane Stan, the Southwestern slopes may have received the brunt of the storm effect, therefore exceeding the rainfall intensity threshold of the soils and triggering more landslides (Larsen and Simon, 1993). Although aspect was an important predictor of landslide frequency, its importance as a factor for a predictive map of future hurricane risk is less clear due to the unpredictability of storm effects.

Scatena and Larsen's (1991) work in Puerto Rico found that landslides were not associated with anthropogenic disturbances such as roads, pastures, or cropland. Rather, landslides were highly associated with elevation and slope gradient. We found the opposite conclusion in our study, where roadside disturbance was highly influential for landslide frequency, while elevation and slope were not significant. However, the role of slope may be important in other situations, depending on the variation of other factors that contribute to landslide frequency. For example, Bucknam et al. (2001) found that slope played a large role in determining landslide susceptibility because steeper areas required less rainfall to trigger landslides.

The significance of aspect and distance to river to landslide risk at only one scale is likely the result of the actual landscape morphology in this region. The mountainous terrain of Chiapas has many rivers running through topographic lows. High intensity storms will bring large volumes of water towards the rivers creating regions of mass water and soil flows. In the case of our results, distance to river may reach a maximum at 500 km, and these regions may be the most protected from landslides because they experience fewer drainage flows. Directional shifts in landscape aspect also occur at large scales, and therefore the wind exposure (aspect) contribution may only be detected at 1 km scales and greater.

4.2. Land use and hurricane risk

Because of the large range of management variation experienced in this region, we focused attention on the effect of land management for landslide frequency. Unlike the topographic factors mentioned above, where farmers will have little to no control to change their circumstances, farmers can actively manage their farms to maximize agricultural production. Our results show that farmers can also actively manage their farms to reduce their environmental vulnerability to landslide damage on both the farm and landscape scale. Farms managed with higher vegetation complexity suffered less damage from landslide occurrence and farm area affected by landslides thus providing a potential management strategy to lower risk to extreme storm events.

Within the farm scale survey data, landslide information was collected in coffee field sites as well as alongside roads. In our study, we found no landslides directly within the coffee field sites. However, landslides were abundant along roadsides in most farms. This may be because roadsides present a human-induced instability that allows for greater landslide vulnerability due to the increased weight on hill slopes, alteration of surface runoff paths, and enhanced run off rates (Sidle et al., 1985). Roads can have a large spatial impact on watersheds and contribute to slope instability (Guthrie, 2002). In previous hurricane occurrences within Latin America, roadside landslides presented the greatest structural damage to rural areas (Crone et al., 2001). These conclusions support our results of finding a majority of the landslides along the road.

Of the roadside landslides found, fewer landslides occurred in farms with more complex canopy vegetation. The influence of complex on-farm vegetation management as a landslide deterrent may be attributable to the stabilizing effects of plant root systems. Plant root systems and their contribution to hill-slope soils has received considerable attention, especially as many habitats have been transformed due to natural resource extraction, such as logging and mining. Although agriculture retains greater vegetative structure than either of these anthropogenic changes, the removal of multiple layers of vegetation structure will certainly influence regional resilience to extreme events. Megahan (1978) showed that landslide occurrence increased as the vegetation crown cover decreased, occurring more rapidly with tree removal than with shrub removal. At the landscape scale, the mean vegetation complexity index in a 1 km buffer was more important than the amount of forest around transects in predicting landslide volume and number. It appears that maintaining high levels of vegetation complexity on-farm, rather than only relying on ecosystem services from small patches of nearby forests is important to reduce risks from hurricanes. Thus, in general, our findings support that farm management decisions, such as removal or reduction in shade canopy structure, can lead to greater landslide risk.

Our results follow the conclusions reached by Holt-Gimenez (2002) that found that "sustainable" farms with more labor- and knowledge-intensive land management had more topsoil and vegetation, less erosion, and lower economic losses than "conventional" farms after Hurricane Mitch in 1998. In other words, those farms with more agroecological practices suffered less from hurricane damage. In a similar field situation, Starkel (1972) found that the conversion from forest to tea gardens in India led to major vulnerability for farmers during a large storm. Slopes of 25–40° within the gardens led to landslides covering 20% of the agricultural land, while the forested land lost only 1% to landslide cover.

The coffee region in the Soconusco still maintains a wide range of coffee management styles and provides an ideal platform to explore how different land characteristics affect the resilience and resistance of coffee systems to environmental change. Because of the economic dependence of many farmers in this region on coffee production, reducing risk exposure to greater climate change and variability may offer farmers a more sustainable livelihood. With increases in hurricane intensity and frequency becoming a distinct possibility in the near future, evaluations of how the agricultural landscape may affect resistance and resilience to hurricane damage at the local and regional scale will be necessary to inform further management decisions.

4.3. Landslide susceptibility and hazard maps

The development of landslide susceptibility maps and hazard maps have been used to inform policy decisions on land use in many high-risk regions of the world (Crone et al., 2001, Ayalew and Yamagishi, 2005). In central Mexico, hazard maps have been implemented into municipal and regional construction codes used to inform mitigation planning in highly vulnerable regions (Cuanalo et al., 2006). Other landslide susceptibility maps have attempted to model susceptibility threshold equations that were primarily based on the contributing factors to garner some predictive power of high-risk regions to tropical storms (Bucknam et al., 2001). For our hazard maps, the relative risk of areas based on predictions from the literature appears qualitatively different than the weighted hazard maps created from our data observed during Hurricane Stan. Because it is impossible to predict the types of hurricanes that will hit in the study region in the future, our hazard maps may be most useful at visualizing the impact of vegetative complexity index (i.e. management of land use) on the relative hazard. Specifically, we would recommend using these hazard maps as a guide towards restoring vegetation, or increasing on-farm vegetation complexity in areas that may also be highly susceptible to landslide risk either based on those topographic and landscape factors that were important in this storm (aspect and distance to rivers) or based on these and additional factors that are important during hurricanes generally (slope, elevation). Although it is difficult to predict when, where, and what types of hurricanes will occur in the future, it is fairly certain that hurricanes will occur, thus working with landowners and land managers in the region to reduce their relative risks in the future is warranted.

5. Conclusion

In sum, we demonstrate two important factors relating to susceptibility of agricultural landscapes to hurricanes using a case study of Hurricane Stan in the Soconusco region of Chiapas. First, for our case, the scale at which the impact of the hurricane was measured was important to understanding which landscape factor most strongly influenced landslide incidence and severity. We found no measurable effects of coffee management at the smallest spatial scale in terms of vegetation damage or landslides, but did find that management including reducing the complexity of the shade canopy increased the area of farms affected by landslides and the number of roadside landslides at farm to regional level scales. Furthermore, topographic features of the landscape most strongly influenced landslide risk at larger scales. Second, we demonstrated that vegetation complexity in agricultural areas was important in predicting landslide risk in coffee-growing areas. Based on our results for this slow-moving storm with heavy rainfall, those farmers in high-risk areas based on topographical assessments may be able to reduce their susceptibility to some types of hurricane damage (e.g. landslides) by increasing on-farm vegetation complexity.

Acknowledgements

We thank G. Lopez Bautista, G. Dominguez, J.A. Garcia-Ballinas, and B. E. Chilel for assistance in collecting field data. G. Ibarra Nunez from El Colegio de la Frontera Sur provided logistical support. We thank all of the farm owners for access to their property and for providing information on economic losses sustained during the hurricane event. A. Rodriguez Camacho and the members of the Unión de Café Tacaná generously provided access to their damage reports. Thanks to C. Taylor, P. Bichier, J. Vandermeer, I. Perfecto, and R.A. Rice for their support with image classification and study design. M. Castaneda, D. Stierman, and M. Uriarte all provided helpful comments on the manuscript. The L'Oreal U.S.A. for Women in Science Fellowship to SMP provided funding for this project.

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