Landslides and Their Contribution to Land-cover Change in the Mountains of Mexico and Central America[1]

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ABSTRACT

Landsliding is a natural process influencing montane ecosystems, particularly in areas with elevated rainfall and seismic activity. Yet, to date, little effort has been made to quantify the contribution of this process to land-cover change. Focusing on the mountains of Mexico and Central America (M-CA), we estimated the contribution of landsliding to land-cover change at two scales. At the scale of M-CA, we classified the terrain into major landforms and entered in a GIS historical data on earthquake- and rainfall-triggered landslides. At the scale of the Sierra de Las Minas of Guatemala, we investigated Landsat TM data to map rainfall-triggered landslides. During the past 110 yr, >136,200 ha of land in the mountains of M-CA have been affected by landslides, which translates into disturbance rates exceeding 0.317 percent/century. In Sierra de Las Minas, rainfall associated with hurricane Mitch affected 1765 ha of forest, or equivalently, landslides triggered by storms of this magnitude transformed between 0.196 (return time of 500 yr) and 1.290 (return time of 75 yr) percent of forest/century. Although landsliding results in smaller rates of land-cover change than deforestation, we hypothesize that it has a stronger impact on ecosystems, both in qualitative and quantitative terms, given its influence on vegetation and soil. Moreover, interactions between landsliding and deforestation may be altering the expression of this complex process such that the few protected areas in the mountains of M-CA may represent the only possibility for the conservation of this process.

RESUMEN

Los deslizamientos de tierra representan un fenómeno natural que afecta a todos los ecosistemas montañosos, particularmente aquellos que se encuentran en áreas de elevadas precipitaciones y actividad sísmica. Sin embargo, hasta el presente los esfuerzos por cuantificar la contribución de este proceso a cambios de cobertura de suelo han sido limitados. Enfocados en las montañas de México y Centro America (M-OA) estimamos que la contribución de los deslizamientos de tierra con cambios de cobertura de suelo a dos escalas. A la escala de M-CA, clasificamos el terreno basado en clases mayores de relieve e incluímos datos históricos de sismos y tormentas que han provocado deslizamientos de tierra en un SIG. A la escala de la Sierra de Las Minas en Guatemala, investigamos datos Landsat TM para identificar y localizar deslizamientos de tierra disperados por lluvia. Durante los últimos 110 años >136,200 ha de tierra han sido transformados por deslizamientos de tierra en las montañas de M-CA, lo que se traduce en tasas de perturbación >0.317 por ciento/siglo. En la Sierra de Las Minas, las lluvias asociadas con el huracán Mitch transformaron 1765 ha de bosque, lo que es equivalente a tasas de perturbación por deslizamientos de tierra entre 0.196 (tasa de retorno de 500 años) y 1.290 por ciento/siglo (tasa de retorno de 75 años). A pesar de que las tasas de cambio de cobertura vegetal por deslizamientos son menores que las causadas por deforestación, hipotetizamos que tienen un mayor impacto en estos ecosistemas tanto en términos cualitativos como cuantitativos por su influencia sobre la vegetación y el suelo. Además, interacciones entre los deslizamientos de tierra y la deforestación podrían estar afectando la expresión de este complejo proceso de tal forma que las pocas áreas montañosas de México y Centro América que están protegidas representan la única posibilidad para la conservación de este proceso.

Key words: Central America; land-cover change; landslides; Mexico; tropical mountains.

CONVERSION OF FORESTS TO MANAGED ECOSYSTEMS is considered a major activity impacting the carbon cycle (Houghton *et al.* 1998, Schimel *et al.* 2001). Many studies have emphasized land-cover and land-use change in lowland tropical areas, given their large areal extent and consequently, potential effect at a global scale (Melillo *et al.* 1996). Tropical mountains representing <25 percent of the Earth land surface have often been overlooked in these studies, yet they may play an unappreciated role in regional, and perhaps global carbon budgets. Deforestation has been, and still is, a prevalent process transforming these ecosystems (Ochoa-Gaona & Gonzalez-Espinosa 2000, Munroe *et al.* 2002). Yet, a combination of steep topography, heavy rains, and seismic activity results in landsliding, a process transforming land cover in qualitatively and quantitatively different ways. Unlike deforestation, landsliding results in the removal of soil and weathered bedrock in addition to vegetation (Zarin & Johnson 1995a,b).

Changes in land-cover associated with landsliding differ in other ways from deforestation. First, landsliding is a rapid process, whether triggered by precipitation, seismic events, or both (Thomas 1994). This translates into abrupt, and sometimes extensive, changes in land-cover, depending on the location and magnitude of the triggering event. Second, each triggering event can result in populations of tens to thousands of landslides exhibiting an enormous variability in size (Stark & Hovius 2001). This variability in size may have profound consequences for ecosystem recovery, since "patch size" influences rates of ecological processes (Pickett & White 1985). Lastly, landslides can affect ecosystems in irreversible ways in areas where bedrock is underlain by soils derived from volcanic ash. The removal of ash-derived soils may expose substrates that differ greatly in composition, influencing the recovery of ecosystems (Restrepo *et al.* 2003).

Landsliding is a complex process that can be strongly influenced by attributes of the vegetation (Sidle *et al.* 1985). Therefore, changes in land cover and land use resulting from human activities and climate can interact with landsliding to influence the large-scale dynamics of montane ecosystems (Diez *et al.* 1996, Glade 2003).

This may explain why landslides have become an increasing hazard to human lives and infrastructure in densely populated mountains (Dai *et al.* 2002), and why extensive landsliding in protected tropical mountains has been treated as major ecological disasters (Figueroa *et al.* 1987). On the other hand, landsliding can modify land cover, but to date, there have been limited efforts to quantify this effect.

Focusing on the mountains of Mexico and Central America (M-CA), we take a twofold approach to evaluate the role of landsliding in land-cover change. First, we examine historical data on landslide-triggering events and the total area of land transformed by landslides, to provide a regional estimate of land-cover change associated with landsliding. Second, we examine remotely sensed data for a single landslide-triggering event, to establish its usefulness in evaluating and monitoring land-cover change associated with landslides at local scales. Ultimately, the combination of both approaches will help us gain a better understanding of the large-scale dynamics of tropical mountains mediated by landsliding.

METHODS

STUDY SITE.—Our study area comprises M-CA, a region characterized by an enormous diversity of life-forms and forest types, resulting from its latitudinal position, and unique tectonic, geological, and biogeographical history (Weyl 1980, Darwin & Welden 1992; Fig. 1a). This region is representative of many others found in tropical and subtropical areas around the world that, in addition to being tectonically active, are subjected to precipitation events of variable intensity (Fig. 1b). In the past, interactions among the several tectonic plates that meet here originated the main topographic features observed today (Weyl 1980, Ferrusquia-Villafranca 1993). Currently, interactions among the same plates are the source of the many shallow earthquakes that trigger landslides across the region (Bommer & Rodriguez 2002). Several mountainous systems are recognized in M-CA, each having a different origin, age, geology, and climate (Weyl 1980, Ferrusquia-Villafranca 1993). This variation is likely to influence ecosystem attributes and the formation of landslides within each mountainous system. In this article, we use the term "landslide" in a broad sense to describe the usually fast movement of vegetation, soil, saprolite, and rock under the influence of gravity, which results in patches of bare ground with variable characteristics. It is important to emphasize that gravity determines the downslope movement of material from hillslopes (Thomas 1994).

We focused on the Sierra de Las Minas to investigate the impact of landsliding on land cover at a local scale (Fig. 1c). This mountain system in eastern Guatemala with elevations up to 3015 m above sea level is one of the several subparallel high ranges comprising the Northern Sierras of Central America (Weyl 1980). It harbors an enormous diversity of species and vegetation types, and it was declared a Biosphere Reserve in 1990 .The Sierra de Las Minas
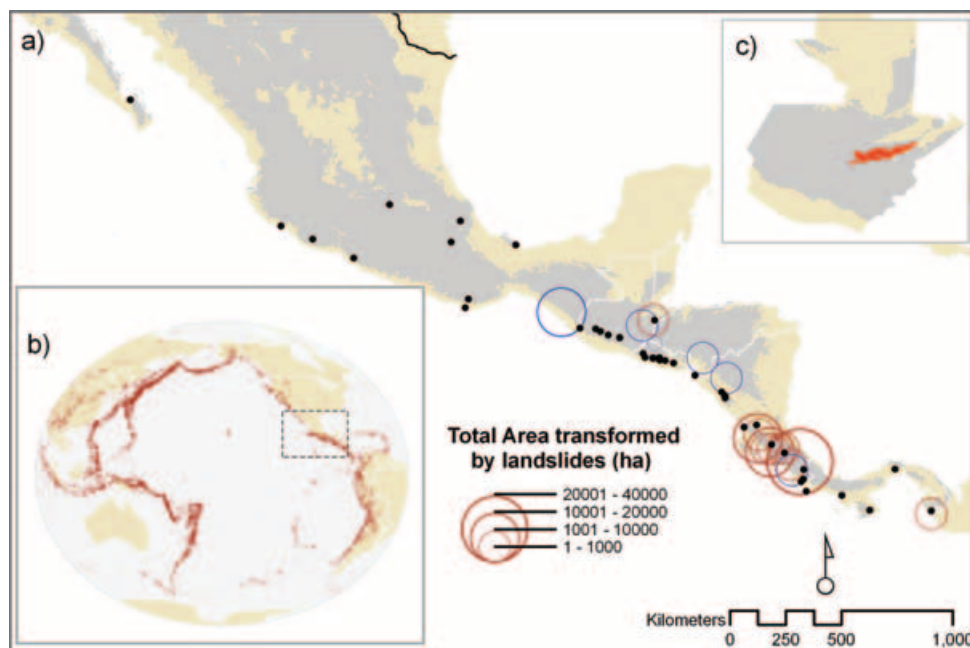
FIGURE 1.   (a) Mexico and Central America lie within one of the most (b) active seismic zones in the world (small red points are earthquakes). In particular, the convergence of several tectonic plates is the source of the many shallow earthquakes that trigger landslides across the region (red circles in a); M-CA is also influenced by storms of variable magnitude, which can generate extensive landslide activity (blue circles in a). The size of the circles denotes the total area covered by landslides (*a* in Eq. (1)); landslide-triggering events for which this information is unavailable are shown as small black points. (c) In the Sierra de Las Minas, a small mountain range in eastern Guatemala (shown in red), earthquake- and storm-triggered landslides have left a strong imprint on the landscape. In (a), Mexican and Central American hills and mountains are in gray.

is flanked to the north and the south by the Polochic and Motagua faults, respectively, two important sources of seismic activity in M-CA, and therefore of landslide activity (Weyl 1980, Harp *et al.* 1981). The Motagua fault, in particular, is where the Caribbean and North American Plates meet. In addition to earthquakes, the Sierra de Las Minas can also be affected by intense precipitation events associated with tropical storms and hurricanes, such as Hurricane Mitch in October–November 1998 (Bucknam *et al.* 2001). Rains of this magnitude, in combination with soils derived from metamorphic and Ultrabasic rocks, may explain the elevated number of landslides that were recorded in the Sierra de Las Minas in 1998. Strong winds seemed to have had a negligible effect in the Sierra de Las Minas due to the trajectory followed by Hurricane Mitch in M-CA (F. Hernandez, pers. comm.).

REGIONAL IMPACT OF LANDSLIDES ON LAND-COVER CHANGE.—To evaluate the contribution of landslides to land-cover change, we followed a three-step procedure. First, we classified M-CA into major relief classes or landforms. This not only depicted areas more susceptible to landslides, but also constrained our study area for the purposes of calculating disturbance rates (see below). We used a classification scheme based on digital elevation data, which combines elevation and terrain roughness to define major landforms (Meybeck *et al.* 2001). We derived an index of terrain roughness, representing the difference between the maximum and minimum elevation within a 60 × 60 cell neighborhood divided by the neighborhood's radius, using the GTOPO 30 DEM (resolution 0.5 min or *ca* 1 km; http://edcdaac.usgs.gov/gtopo30/gtopo30.asp). The elevation and terrain roughness maps were reclassified using Meybeck *et al.*'s

(2001) classes, and used in a matrix analysis to yield a thematic map showing the coincidence of two input classes. The unique combinations of roughness and elevation define major landforms in this new thematic map (Table 1).

Second, we estimated human population size per landform. This opened the possibility to discuss the extent to which human activities and landsliding may interact. We used the Population of the World (GPW2) grid map, in which the values of each cell (resolution ~4.5 km at low latitudes) represent the estimated population size for the year 1995 (Ciesin *et al.* 2000). This map was used in combination with a rescaled version of the landform map that matched the resolution of the population grid in a matrix analysis. This resulted in a new thematic map depicting the population of M-CA per landform.

Finally, we gathered historical data from published and unpublished reports to build a data base of earthquake and rainfall events known to have triggered landslides in M-CA, and entered it in a GIS. The data base covers *ca* 110 yr and includes information on (1) characteristics of the triggering events (date, location, type, magnitude); (2) characteristics of the areas impacted by landslides (geological substrate and ecoregion); and (3) characteristics of landslides (total area over which landslides were triggered, total area covered by landslides, total number of landslides, statistics of landslide size). Most of this information has been generated in response to local and regional landslide-triggering events that have impacted directly or indirectly human populations and their infrastructure, including protected areas. We believe that the inventory of earthquakes known to have triggered landslides is relatively complete, in part because of a recent comprehensive inventory of earthquakes

TABLE 1. *Landforms of Mexico and Central America. Numbers indicate extent of landform in km² for M-CA (parentheses and regular font), CA (square brackets and regular font), and population size (italics). In gray are landforms included as mountainous terrain in the context of this study. Classification based on Meybeck* et al.*'s (2001) scheme.*

Relief roughness (‰)	Mean elevation (m)							
	0–200	200–500	500–1000	1000–2000	2000–3000	3000–4000	4000–5000	5000–6000
<5	Plains (187,644) *(6,84,244)*	Mid-altitude plains (2785) *(59,553)*	High-altitude plains (9)					
5–10	Lowlands (199,217)	Platforms (47,707)	Low plateaus (2534)	Mid-altitude plateaus 24,244				
10–20	*(4,851,052)*	*(495,058)*	*(22,027)*	*(465,875)*	High plateaus (100,015) *(3,675,038)*		Very high plateaus	
20–40	Rugged lowlands (320,300) *(13,237,872)*	Hills (287,169) [92,726] *(9,700,909)*	Low mountains (342,650) [94,093] *(15,330,467)*	Mid-altitude mountains (719,512) [62,241] [62,241] *(35,028,708)*				
40–80					High mountains (226,857) [14,498]		Very high mountains (159)	
80–160					*(32,337,524)*		*(28,162)*	
>160								

known to have triggered landslides in this region during the last *ca* 500 yr (Bommer & Rodriguez 2002). On the other hand, the inventory of rainfall events known to have triggered landslides is incomplete, in part reflecting the rainfall's more local character and therefore accessibility of information. Combining historical data of different qualities and biases may seem of limited use in ecological studies; yet it is one of the few methods available for landscape-change studies (Bürgi 2004). To determine the extent to which landslides have transformed land cover per major ecosystem types, we used the "major habitat types" category of the World Ecoregion digital map (Olson *et al.* 2001).

LOCAL IMPACT OF LANDSLIDES ON LAND-COVER.—We used two Landsat TM images taken within 20 mo of Hurricane Mitch (Path 19 Row 50 of 3/28/2000 and Path 20 Row 50 of 12/30/1999; Fig. 2a) to evaluate the local impact of rainfall-induced landslides on land-cover in the Sierra de Las Minas, Guatemala. These images were purchased with a radiometric, geometric, and precision correction for which ground control points and a digital terrain model had been used to improve the satellite model and remove inaccuracies resulting from local terrain elevation. In addition, we performed an absolute atmospheric correction based on the dark object substraction approach (Chavez 1988) and reprojected the images to the Universal Transverse Mercator system (zone UTM 16) on the WGS 84 datum to fit complementary GIS coverages used in the classification. The two satellite images were subset using a GIS coverage depicting the hillslope and fluvial areas impacted directly and indirectly by landslides prior to the classification.

To classify landslides in Sierra de Las Minas, we followed a three-step approach. First, we masked out from the images clouds and cloud edges, and all pixels with slopes below 15°. Clouds and cloud edges were eliminated from the images through the collection of training sets on these features and the assignment of a value of zero to the corresponding pixels so that they would not be included in future calculations. In the Sierra de Las Minas, only 4 percent of the landslides that were triggered by Hurricane Mitch occurred in slopes below 15° (Bucknam *et al.* 2001). In addition, most of these pixels corresponded to agricultural areas in floodplain features, including alluvial fans, which are spectrally similar to landslides and therefore could influence the accuracy of the supervised classifications. We used NASA's SRTM DEM (resolution ~90 m; http://srtm.usgs.gov/) to create a binary map showing slopes above or below 15° (Fig. 2b,c), and masked out the pixels in slopes below 15°.

Second, we selected a pilot study region (PSR) in the Sierra de Las Minas, where the USGS had identified an elevated number of landslides (Bucknam *et al.* 2001) to evaluate the performance of two factors, degree of landscape heterogeneity and different band combinations, on image classification. In tropical mountains, gradients in temperature and precipitation translate into changes of vegetation over short distances (Kappelle & Brown 2001), and this heterogeneity may influence the detection of landslides. We run the supervised classifications on the PSR which encompassed six forest types after eliminating slopes below 15° (heterogeneous landscape; 251,207 ha), and one area of Tropical evergreen seasonal mixed al-

timontane forest (homogeneous landscape; 14,900 ha; TESMAF). Information on forest types came from the Ecosystems Map of Guatemala (TECSULT Foresterie Inc. 2000).

We used three band combinations to explore their ability to recognize landslides in the heterogeneous and homogeneous landscapes. These included (1) bands 1–5 and 7; (2) Normalized Difference Vegetation Index (NDVI), and Texture for bands 1 and 2; and (3) bands 2, 4, 5, and three band ratios (TM 5/7, 5/4, 3/1). From now on, we will refer to the third combination as the 2, 4, 5, mineral composite treatment. The NDVI enhances the greenness reflectance differences between vegetation and bare land, and the texture enhances variability among pixels, and therefore differences between cover types (Schott 1997). The texture metrics used in this study characterized the variance around each pixel in a 3 × 3 neighborhood. The combination of NDVI with the Texture for bands 1 and 2 was successfully used to identify landslides of different ages on infrared aerial photographs (Restrepo *et al.* 2003). Bands 2, 4, 5 have been shown to visually capture subtle differences in spectral signature between landslides of different ages and vegetation in the mountains of Bolivia (Blodgett 1998). Moreover, these were used to collect training sets and run a supervised classification on bands 1–5 and 7 aimed at mapping landslides in the mountains of Argentina (Paolini *et al.* 2002). Mineral ratios are widely used in geological studies, because they readily map onto field and laboratory spectrometer measurements and they reduce brightness effects associated with topographic slope and aspect effects (Rajesh 2004). Three band ratios have been useful for displaying and distinguishing between clays and micas (TM5/7), ferrous (TM5/4), and iron oxides and hydroxides (TM3/1), minerals, plus vegetation (Carranza & Hale 2002, Rajesh 2004). The underlying geology of the Sierra de Las Minas includes minerals of these types (Harp *et al.* 1981).

We ran a supervised classification of the images using the Maximum Likelihood classifier (Schott 1997). The satellite images were visually interpreted (Fig. 3) to collect training sets representative of forests, shrublands, pastures, crops, water, landslides, vegetated landslide scars, and fire scars for both the PSR and the TESMAF regions. We used black and white aerial photographs (1:40,000) taken between January and March 2000 (Fig. 2d), a digital map of Guatemala forest types (http://www.ccad.ws/documentos/mapas.html), and a GIS coverage of landslides triggered by Hurricane Mitch in Guatemala (Bucknam *et al.* 2001, Fig. 2e) to help the visual interpretation of the satellite images. The accuracy of the location of landslides in the GIS coverage was within 50–100 m, which often translated into a lack of overlap between the landslide polygons and the landslides seen on the satellite images. In these cases, we gathered the training sets from the closest elongated forest clearing that because of its morphology was indicative of a landslide. To assess the accuracy of the classifications, we recoded the PSR and TESMAF classified images in two classes of interest, landslides and nonlandslides areas. From each of the recoded images, we randomly selected an average of 50 (TESMAF) and 200 (PSR) points and compared their cover type with that seen in the original satellite images (Fig. 2a), aerial photographs (Fig. 2d), and the landslide GIS coverage (Fig. 2e). Based on this selection, we estimated the producer's, user's, and overall accuracy and Kappa
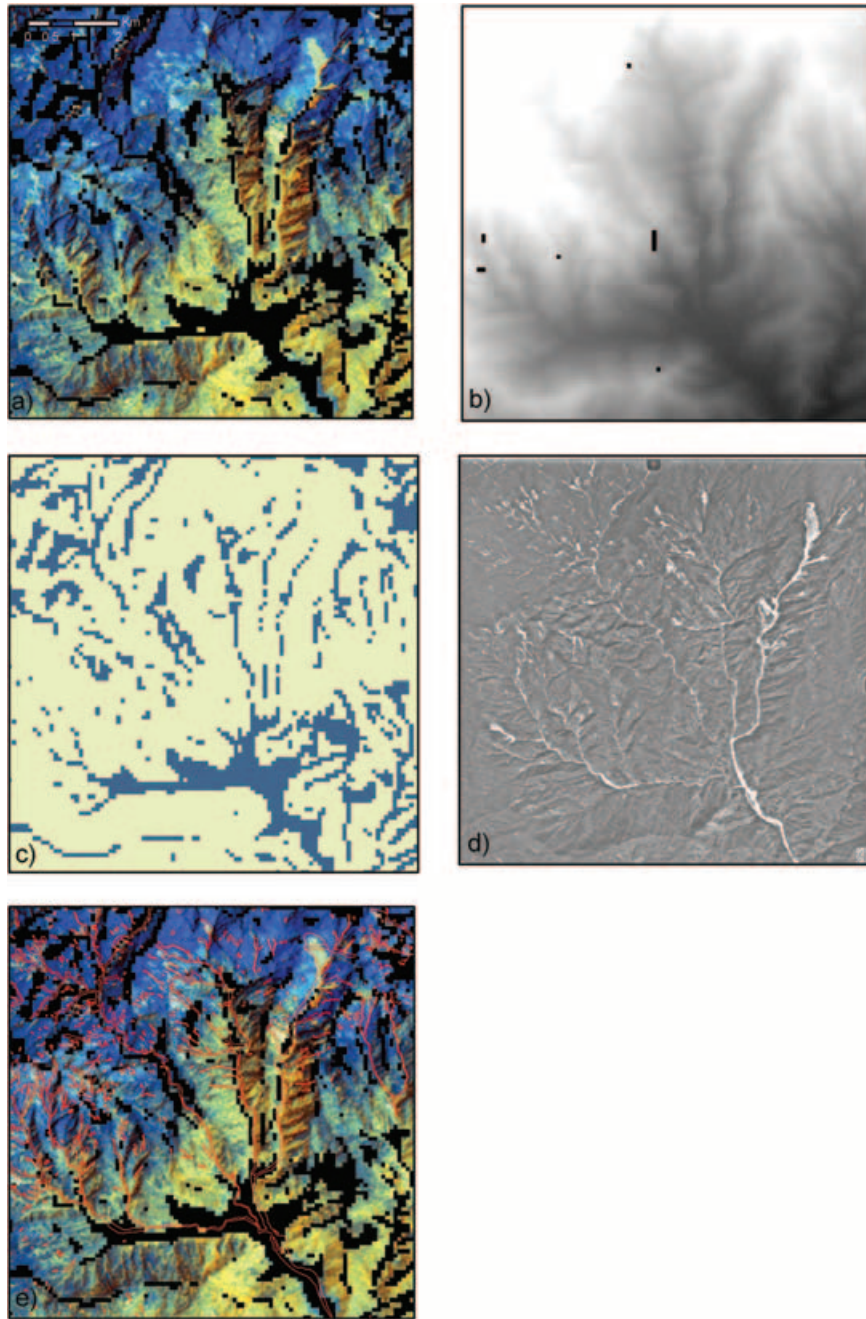
FIGURE 2.   (a) The analysis of Landsat TM images may provide useful information to study landsliding at local and regional scales (RGB: 5/4, 5, 4). Ancillary information, such as (b) a DEM to segment the images into (c) slopes $<15°$ and $\geq15°$, was used in combination with (d) aerial photographs taken after Hurricane Mitch, and (e) published landslide coverages to classify the images.

coefficients (Congalton & Green 1999). Finally, we used the band combination x landscape heterogeneity treatment that resulted in the highest overall accuracy, and Kappa coefficient to classify the Sierra de Las Minas and obtain an estimate of the total area covered by landslides. The two scenes were classified separately to minimize errors due to different atmospheric conditions.

IMPACT OF LANDSLIDING ON LAND-COVER CHANGE.—The impact of landslides on ecosystems have traditionally been evaluated in terms of disturbance rates (D), which is the extent of land denuded by landslides over a given period of time:

$$D = (a/A) \times \frac{1}{t} \times 100 \qquad (1)$$

where a is the total area covered by landslides, A is the total area over which landslides are recorded after a given landslide-triggering event, and t is the time elapsed between periods of observation or triggering events, usually expressed on a per-century basis
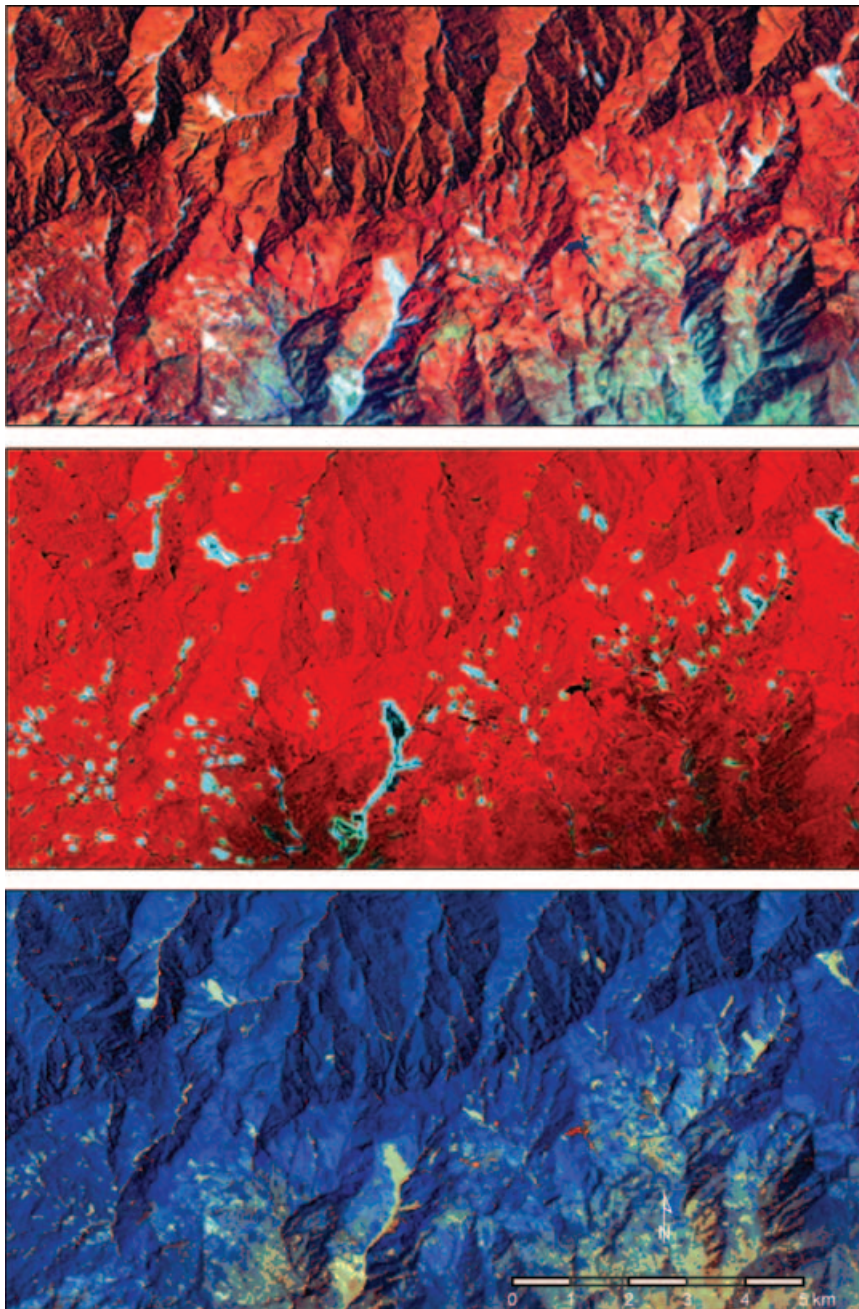
FIGURE 3.   Different band combination treatments were used to visually inspect and classify the Landsat images. (a) Bands 1–5 and 7 (RGB: 4, 5, 3), (b) NDVI and Texture for bands 1 and 2 (RGB: NDVI, T2, T1), and (c) Bands 2, 4, 5, and mineral composite (RGB: TM 5/4, 5, 4).

(Gardwood *et al.* 1979). In this regard, disturbance rates are identical to estimates of land-cover change, usually expressed as percentage of change on a per-average year basis (Lambin *et al.* 2003). To estimate rates of land-cover change associated with landslides at a regional scale, we added up the total area affected by landslides per triggering event, *a*, and used the total area covered by mountains, *A*, and the time period covered by the records, *t*, for which data on *a* existed in our data base. To estimate rates of land-cover change associated with landsliding in the Sierra de Las Minas, we searched for reports

estimating return times for precipitation levels of the magnitude that fell during hurricane Mitch. Meteorological data for stations in the neighborhood of the Sierra de Las Minas show that the 1998 cumulative October precipitation levels were large as compared to the cumulative October mean estimated over a 10-yr-period (Albores station: 705 mm vs. 208 mm and Coban station: 529 mm vs. 242; http://www.insivumeh.gob.gt/principal/alertas.htm). Yet, the quality of the data did not allow Lopez (1999) to estimate return times for precipitation levels of Mitch's magnitude in Guatemala. Instead,

the author used historical data on hurricanes and concluded that "large meteorological events capable of producing major disasters occur every twenty years." Not all hurricanes are associated with large precipitations; so we made use of calculations from Nicaragua on return times for cumulative monthly precipitations, such as those that fell in October during passage of hurricane Mitch. These calculations based on Gumbel's probability distribution for extreme events showed that the return times for the unusual October cumulative precipitations varied between 75 and 500 yr depending on site (INETER 1998). We used these figures in our estimates for the Sierra de Las Minas, acknowledging the enormous variability that this variable can take in space.

RESULTS

We identified five landforms corresponding to mountainous terrain: hills and low, mid-altitudinal, high, and very high mountains (Table 1). These landforms cover 1,576,347 km^2, or equivalently 64 percent of the total area of M-CA. Mid-altitudinal mountains covered the largest area, followed by low mountains and hills (Table 1). Of an estimated population of 121,616,489, 76 percent live in mountainous terrain as defined above. Mid-altitudinal mountains harbor the largest percentage of the population, followed by high and low mountains (Table 1).

REGIONAL IMPACT OF LANDSLIDES ON LAND-COVER.—At least 62 landslide-triggering events in the last 110 yr (1888–1998) have affected the mountains of M-CA (Fig. 1a; Appendix); 56 of these correspond to earthquakes and 6 to storms. Data on the total area covered by landslides (*a* in Eq. (1)) were available for 17 triggering events (14 earthquakes and 3 storms) and ranged between 300 and 38,300 ha per event (Fig. 1a; Appendix). Adding up the total area covered by landslides yields a figure of >136,200 ha of land transformed by landslides. This is a minimum figure, since we lack information on total area covered by landslides for the remaining 45 triggering events (Fig. 1a). The ecosystems more heavily impacted by landslides, whether we look at the number of triggering events or total area affected by landslides, were the Tropical/Subtropical Moist Broadleaf, followed by the Tropical/Subtropical Coniferous forests (Table 2). Since all but one event (El Triunfo Biosphere Reserve,

TABLE 2. *Major ecosystem types affected by landslides in Mexico–Central America. Information on ecosystem type was obtained for the mapped earthquake epicenters.*

Ecosystem type	Number of landslide-triggering events	Total area affected by landslides (ha)
Tropical/Subtropical moist broadleaf forest	33	>119,310
Tropical/Subtropical dry broadleaf forest	11	
Tropical/Subtropical coniferous forest	18	>7949
Deserts and xeric shrublands	2	>8830
Unknown	1	NA
Total	65	>136,089

Mexico) for which information on total area covered by landslides are located in Central America, we base our estimates of landcover change on the mountains of CA for the time period covered by the records (110 yr) (Fig. 1a; Appendix). We kept El Triunfo in our calculations due to its proximity to Guatemala, and more importantly its geological relationship with the rest of CA. Based on the above considerations, at least 0.00317 percent of land/yr, or 0.317 percent of land/century, is being affected at any given time by landslides.

LOCAL IMPACT OF LANDSLIDES ON LAND-COVER.—The different image treatments used to identify landslides yielded overall accuracy values ranging between 75 and 91 percent, and overall kappa values between 0.500 and 0.825 (Table 3, Fig. 3), suggesting differences among the treatments in terms of their ability to correctly discriminate landslide from nonlandslide pixels. In general, the supervised classifications of the homogeneous (TESMAF) landscape yielded better results than the heterogeneous (PSR) one, as indicated by the higher overall accuracy and kappa values (Table 3). For the homogeneous landscapes, the supervised classification that combined NDVI with Texture for bands 1 and 2 showed the highest overall

TABLE 3. *Results of a supervised image classification for detecting landslides in the Sierra de Las Minas, Guatemala. Two Landsat TM images taken within 20 mo of Hurricane Mitch were used to evaluate the performance of automated image analysis in the detection of landslides. Producers (PA), users (UA), and overall (OA) accuracy. The heterogeneous landscape included six ecosystem types, whereas the homogeneous landscape one, the Tropical evergreen seasonal mixed altimontane forest.*

	Heterogeneous landscape					Homogeneous landscape				
	PA (%)	UA (%)	OA (%)	Kappa (κ)	Overall kappa κ	PA (%)	UA (%)	OA (%)	Kappa (κ)	Overall kappa κ
All spectral bands	96	52	75	0.343	0.500	86	81	84	0.646	0.680
NDVI, Texture 1 and 2	97	66	82	0.485	0.640	94	88	91	0.774	0.825
2, 4, 5, 5/7, 5/4, 3/1	100	79	89	0.648	0.787	97	76	87	0.607	0.740

accuracy and kappa values (Table 3, Fig. 3b). The lowest values corresponded to the classification that used all spectral bands over the heterogeneous landscape (Table 3, Fig. 3a).

The supervised classification of the two Landsat TM images using bands 2, 4, 5, and the mineral composite applied over each forest type showed that approximately 1765 ha of land in the Sierra de Las Minas were impacted by landslides triggered in 1998 by Hurricane Mitch (Table 4). Some ecosystems were affected more than others by landslides, with the Tropical evergreen seasonal mixed upper-montane and altimontane forests exhibiting the largest impact (866 and 498 ha of forest affected by landslides; or 1.3% and 1.1% of their area; Table 4). Using the total area affected by landslides shown above, we estimated disturbance rates between 0.194 percent/century (return time of 500 yr) and 1.290 percent/century (return time of 75 yr; see Methods).

DISCUSSION

Mountains are a prevalent feature of Mexican and Central American landscapes, and they currently harbor most of the population reported for this region. More importantly, for the first time, historical and remotely sensed data are combined to examine the contribution of landsliding to land-cover change in tropical and subtropical mountains. This opens the possibility for investigating the large-scale dynamics of these ecosystems, including possible interactions between landsliding, a natural process modeling mountains worldwide, and deforestation.

LANDFORMS AND HUMAN POPULATION.—The proportion of land covered by mountains in M-CA (64%) is not only greater than other estimates for the same region (44%) (Kapos *et al.* 2000), but also global figures showing that mountains represent 20–36 percent of the Earth land surface (Denniston 1995, Kapos *et al.* 2000, Meybeck *et al.* 2001). In addition, we show that 76 per-

cent of the population of M-CA live in hills and mountains, which contrasts with global estimates indicating that between 10 and 39 percent of the world population live in similar areas (Denniston 1995, Meybeck *et al.* 2001). The figures for M-CA reflect in part the location of the densely populated capitals and main cities of this region in hills and mountains. While the M-CA human population living in hills and mountains derive direct benefits from them, the remaining fraction occupying the lowlands receives indirect benefits, such as those represented by hydropower and water production.

Current patterns of human occupation of Mexican–Central American mountains are interesting in three ways. First, archeological evidence indicates that prior to the arrival of Europeans, the lowlands and rugged lowlands sustained higher population densities than mountains contrary to what we see today (Culbert & Rice 1991, Dunning 1992). Second, there has been a dramatic overall increase of population size in M-CA (Denevan 1992). Thirdly, the pattern observed in M-CA is opposite to what is found in temperate regions where cities occur mostly in the lowlands and rugged lowlands, a trend that is currently being reinforced as people abandon the mountains (Piussi 2000). In M-CA then, patterns of human occupation may have two major consequences. On one hand, it increases the vulnerability of people and their infrastructure to landsliding. On the other, it opens up the possibility for interactions between landsliding and human activities at a variety of scales.

LANDSLIDING AND LAND-COVER CHANGE.—We estimated that 0.31 percent/century of land is transformed by landslides in CA, and 1.29 percent/century in the Sierra de Las Minas. Globally, rates of land-cover change associated with landsliding are estimated at 8.2 $\pm$ 4.8 percent ($N = 5$) and 1.6 $\pm$ 1.0 percent/century ($N = 4$; mean $\pm$ SD) for earthquake- and precipitation-triggered landslides, respectively (Wright & Mella 1963, Simonett 1967, Pain & Bowler 1973, Gardwood *et al.* 1979, Veblen 1979, Guariguata 1990, Peterson *et al.* 1993, Dalling & Iremonger 1994, Restrepo *et al.* 2003). Whereas our estimate of 0.31 percent/century for CA falls below these figures, that of 1.29 percent/century for the Sierra de Las Minas is within the range for rainfall-triggered landslides. A comparison with global rates of deforestation in tropical areas (0.60 $\pm$ 0.20 percent/yr or 60 $\pm$ 20 percent/century) (Achard *et al.* 2002, Lambin *et al.* 2003) and the mountains of Central America (range 2.3–4.0 percent/yr or 230–400 percent/century; Ochoa-Gaona & Gonzalez-Espinosa 2000, Nagendra *et al.* 2003, Solorzano *et al.* 2003) show that disturbance rates by landsliding are below those resulting from deforestation. These differences are not surprising, given that rates of land-cover change associated with deforestation and landsliding are estimated over vastly different time scales. In particular, rates of deforestation are estimated over short periods of time in regions undergoing accelerated changes in land cover and land use. Recent studies, however, have shown that deforestation is highly variable in space and time due to the complex dynamics of human socioeconomic activities, and that over long periods of time, deforestation rates can be reversed to yield secondary forests over vast areas (Grau *et al.* 2003).

TABLE 4.   *Sierra de Las Minas forest types showing the area affected by landslides.*

Forest type	Total area (ha)	Area in landslides (ha)
Tropical evergreen broad-leaved submontane forest	19,015	0
Tropical evergreen seasonal mixed submontane forest	18,878	145
Tropical evergreen seasonal mixed lower-montane forest	32,900	255
Tropical evergreen seasonal mixed upper-montane forest	66,829	866
Tropical evergreen seasonal mixed altimontane forest	44,004	498
Total	181,626	1,764

The spatial and temporal extent of our data base, including its completeness, clearly had a major effect on the resulting estimates of land-cover associated with landsliding. These estimates are likely to improve as we obtain critical information for each event reported in our data base. In particular, landsliding events triggered by rainfall are underrepresented in this data base, and those triggered by earthquakes lack information on the total area covered by landslides (*a* Eq. (1); Appendix). In this latter case, it is possible to build a model relating earthquake magnitude with *a*, to predict total area covered by landslides for events from which this information is lacking. Using data from Costa Rica, we found a good correlation between these two variables (C. Restrepo, pers. obs.), but certainly, more data is needed to see if this model applies to larger areas. Similar models exist for total area over which landslides are triggered, that is, the area encompassing the farthest observed landslide (*A* in Eq. (1); Appendix) (Bommer & Rodriguez 2002) and volume of soil and bedrock removed (Keefer 1994).

THE SIERRA DE LAS MINAS.—The uncertainties surrounding our regional estimates of land-cover change associated with landslides reflect the scarcity of information on total area covered by landslides, *a*, associated with each triggering event. In Central America, this information has been obtained in two ways: assigning known areas of land to a few landslide percent damage classes (Mora & Mora 1994) and mapping landslides using aerial photographs (*e.g.*, Harp *et al.* 1981). Whereas the first approach allows a quick, inexpensive, but rough estimate of total area covered by landslides, the second offers a slow, expensive, and precise method.

The automated classification of remotely sensed data has the potential to bridge the gap between the two approaches mentioned above, providing in addition baseline data for future studies on land-cover change, as shown by our work in the Sierra de Las Minas. We found that the use of NDVI with Texture for bands 1 and 2 yielded very good results for locating landslides, but it excluded the interior of big landslide from the calculations of landslide area, because the latter were sufficiently homogenous, and thus not enhanced by the texture filter. On the other hand, the use of bands 2, 4, 5, and the mineral composite was helpful for differentiating subtle variations between landslides and spectrally similar features such as exposed soils in recent and old fire scars, and land with reduced vegetation cover but it required several iterations to refine the classification. We suggest that a classification based on NDVI with Texture for bands 1 and 2 could be used in cases in which landslide mapping needs to be done fast and over vast areas, and/or to segment the original images and then run a new classification, using bands 2, 4, 5, and the mineral composite to obtain good estimates of landslide area.

At least two additional issues need to be evaluated before we can make extensive use of remotely sensed data to investigate the contribution of landsliding to the large-scale dynamics of tropical and subtropical montane ecosystems. First, the topographic normalization of the images can help eliminate the uneven illumination of the slopes that is characteristic of complex terrain (Riaño *et al.* 2003), therefore allowing the identification of landslides and other valuable features in slopes that are shadowed. Second, an investi-

gation of remotely sensed data with different spatial and temporal resolutions can help characterize better the size distribution of landslides (Stark & Hovius 2001), and therefore the total area covered by landslides (*a* in Eq. (1)), as well as their spatial attributes. In addition, in combination with field studies it may help understand changes in the spectral signature of landslides in response to the recovery of plants and soil.

THE LARGE-SCALE DYNAMICS OF M-CA MONTANE ECOSYSTEMS MEDIATED BY LANDSLIDING AND CONSERVATION IMPLICATIONS.—At least 0.31 percent of M-CA montane ecosystems are in an early stage of succession each century as a result of the formation of landslides, some ecosystems being more influenced than others by this process (Table 2). Although this figure is low when compared with deforestation rates, it is important to realize that landsliding influences ecosystems in ways that are qualitatively and quantitatively different from deforestation. First, changes in land cover associated with landsliding are abrupt and often extensive. In M-CA, for example, a single earthquake or storm can remove the equivalent of 120 to 38,400 ha of forest at once, in areas ranging from 1500 to 1,600,000 ha (Appendix). Second, a single triggering event can generate hundreds to thousands of "patches" of bare ground that differ greatly in size and upon which ecosystems, including soil, will develop. In fact, a diverse array of organisms thrive in these new substrates, and these together with the variability in patch size may explain the elevated levels of *diversity* found in tropical and subtropical mountains (Burger 1980, Gentry 1992). Third, the removal of both vegetation and soil, and its mobilization and deposition along the hillslope–fluvial interface may play an unappreciated role in *biogeochemical cycles*. For example, when landslides occur, the organic carbon in the vegetation and soil is transferred to the hillslope–fluvial interface, where it can remain stored for hundreds to thousands of years (Kelsey 1982). Meanwhile, in the landslide scars, new carbon is fixed while ecosystems undergo succession (Zarin & Johnson 1995a; Restrepo *et al.* 2003). To date, however, the landscape-level consequences of this rich dynamics remains poorly understood.

Unfortunately, population growth in these areas may be *threatening* the *process* of landsliding itself, and therefore our ability to understand the role it plays in these ecosystems. First, land-cover/land use (Glade 2003) and climate change (Thomas & Thorp 1995, Diez *et al.* 1996) may influence the frequency and magnitude of landsliding. Second, landsliding is a complex process controlled by climatic, geologic, and biotic attributes that are highly variable in space. This variability is currently represented in a limited way in the few protected areas of M-CA. In recent years, El Triunfo Biosphere Reserve in southern Mexico, the Sierra de Las Minas Biosphere Reserve in eastern Guatemala, and La Amistad Biosphere Reserve in Costa Rica/Panama among others have been struck by earthquakes and storms that have triggered thousands of landslides. In some instances, the impact was so extensive both on the hillslopes and fluvial systems that people referred to them as major "ecological disasters," prompting plans of reforestation and management of individual landslides. Surprisingly, the ecological knowledge gained from these events was extremely limited. These protected areas may

give us a unique opportunity to understand the process of land-sliding, and at the same time to conserve this threatened process. In a region like M-CA, where earthquakes and storms are common, the combination of historic, remotely sensed, and field data will ultimately help us understand the large-scale dynamics of mountain ecosystems mediated by landsliding.

ACKNOWLEDGMENTS

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APPENDIX. *Landslide-triggering events in Mexico and Central America for which data on total area over which landslides were triggered (A), total area covered by landslides (a), and total number of landslides (n) have been estimated. The epicenter of the triggering event is given by its latitude (LAT) and longitude (LON). Landslide-triggering events (TE) are earthquakes (E) and rainfall (R); some of these are identified by their names (TEN) and dates of occurrence (TED). Estimation of a is based on two methods: assigning known areas of land to a few landslide percent damage classes (D) and mapping landslides using aerial photographs (M) (see discussion); we used other (O) for cases in which the method was not described.*

Country	Site	LAT	LON	TE	TEN	TED mm/dd/yy	A (km^2)	a (km^2)	n	Method	Reference
Mexico	Reserva Biosfera El Triunfo	15.57	−92.88	R	Javier Storm	09/xx/1998	1192	119		O[1]	(12, 17)
Guatemala	Los Amates	15.28	−89.19	E		2/4/1976	16,000	51	>10000	M[2]	(10)
Guatemala	Motagua and Polochi rivers	14.00	−89.50	R	Mitch Hurricane	10/xx/1998	10,000	88	11,500	M[3]	(2, 18)
Honduras		14.72	−86.88	R	Mitch Hurricane	10/xx/1998	4430	39	500,000	M[4]	(8, 9)
El Salvador	San Salvador	13.70	−89.20	R	Mitch Hurricane	10/xx/1998	12,313	4		M	(5)
Nicaragua		12.67	−85.23	R	Mitch Hurricane	10/xx/1998	1324	36	3364	M	(3)
Costa Rica	Pejibaye-enjambre	9.80	−83.60	E	Pejibaye	7/9/1989	20	3		D	(1, 11, 14, 16)
Costa Rica	Sarchi, San Juan, and Trojas rivers	10.25	−84.30	E	Sarchi	6/6/1912	74	5		D	(1, 14)
Costa Rica	Bajos del Toro	10.22	−84.30	E	Bajos del Toro	8/29/1911	19	5		D	(1, 14)
Costa Rica	Bajos del Toro	10.25	−84.25	E	Bajos del Toro	8/31/1951	52	9		D	(1, 14)
Costa Rica	Cerro Doan, near Pejibaye-El Humo	9.17	−83.57	R		7/1/1983	25	17		D	(11, 15)
Costa Rica	Guatuso	10.61	−84.89	E	Guatuso	10/10/1911	96	17		D	(1, 14)
Costa Rica	Patillos	10.05	−83.92	E	Patillos	12/29/1948	139	25		D	(1, 14)
Costa Rica	Along Poas river	10.02	−84.33	E	Fraijanes	12/30/1888	225	41		D	(1, 14)
Costa Rica	Enjambre Puriscal	9.81	−84.83	E	Enjambre Puriscal	3/24/1986	399	64		D	(1, 14)
Costa Rica	Divison-Buvis (Pacific slope)	9.40	−83.65	E	Perez-Zeledon	7/2/1979	579	100		D	(11, 13, 14)
Costa Rica	Tronadora and Rio Chiquito rivers, Tilaran	10.47	−84.97	E	Tilaran	4/13/1969	768	123		D	(1, 14)
Costa Rica	Grande river	9.80	−84.70	E	Orotina	3/3/1920	956	169		D	(1, 14)
Costa Rica/Panama	Limon (Atlantic slope)	9.50	−83.25	E	Limon	4/21/1987	2,000	383		D, M	(1, 4, 11, 14, 19, 20)
Panama	Jaque, Darien	7.48	−78.28	E		7/10/1972	450	64		D	(6, 7)

[1]The report states that 10–12 percent of the El Triunfo Biosphere Reserve was affected by landslides.

[2]Landslides from the published maps were digitized to obtain *a*.

[3]This figure was derived from adding up the areas of mapped polygons, which included the source and depositional areas, including the areas damaged along the river channels.

[4] Landslides were mapped in this area; yet the figure on *a* was provided by E. L. Harp (pers. comm.).

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