Reports

Earthquake-Caused Landslides: A Major Disturbance to Tropical Forests

Abstract. *Earthquakes occasionally denude large areas of tropical forest: for example, 54 square kilometers in Panama in 1976 and 130 square kilometers in New Guinea in 1935. Earthquake rates in New Guinea, but not in Panama, are sufficiently high so that substantial areas of disturbed, nonclimax forest may accumulate. In New Guinea, earthquake-caused landslides are as important as tree falls in the disturbance regime.*

The high species diversity of tropical rain forests has long been causally associated with the stability of the rain forest; without disturbance, niche diversification (*1*) or low extinction rates (*2*) supposedly lead to the accumulation of many species. However, all tropical forests are not stable. Pleistocene climatic changes converted rain forest to savanna (*3*), and hurricanes and windstorms level large tracts of rain forest (*4*, *5*).

It has recently been argued that disturbance, at some intermediate level of severity, size, and frequency, maintains high diversity by delaying competitive exclusion (*6*), and, alternatively, that disturbance inevitably reduces diversity through random extinctions unless balanced by immigration (*7*). The lack of quantitative data on disturbance from tropical forests precludes tests of these disturbance-diversity hypotheses. In this report, we demonstrate that earthquake-caused landslides, severe but often ignored disturbances, can maintain substantial portions of some tropical rain forests in successional stages and, compared to other types of disturbance, are an important component of the disturbance regime in these forests.

Two shallow earthquakes, 6.7 and 7.0 on the Richter scale, struck 33 km and 5 km ($\approx$ 7°N, 77°W), respectively, off the sparsely populated southeastern coast of Panama (Darien Province) in 1976 (*8*). Landslides associated with these shocks caused extensive deforestation and initiated succession over a wide area of low elevation and steep terrain originally covered by tropical rain forest (Fig. 1). The total region affected was at least 450 km^2 (*9*). On the basis of estimates of the amount of damage along the coast and from aerial photographs, we calculate that slides denuded approximately 54 km^2 (12 percent) of the affected region of 450 km^2 (*10*). This is an underestimate of earthquake-caused damage because we do not include corrections for slope, extensive areas where trees were felled but the slopes not denuded, or damaged flood plains.

The simultaneous creation of many landslides over a large region during an earthquake has important ecological consequences, even if it occurs rarely. The abundance of successional, nonclimax species will increase on a regional, not local scale; the abundance or number of climax species will decrease in the remaining patches of undisturbed forest because of "island effects" (*11*); the creation of large even-aged, species-poor (*12*) stands of trees over a wide area may facilitate outbreaks of disease and pests, which are rare in species-rich tropical forests; and local extinction may increase because individuals of tropical tree species are clumped (*7*). The extremely patchy distribution and the size of landslides are shown in Fig. 2.

In the Panama-Colombia region between 6° to 8°N and 77° to 79°W, earthquakes greater than or equal to 6.0 on the Richter scale occur at a rate of 0.4 quake per 10^3 km^2 per century, based on a 75-year record (*8*), or an average of one quake every 250 years in an area of 10^3 km^2. Rate of disturbance (RD) can be calculated by multiplying frequency of disturbance by the mean size of disturbance. If forest damage by the 1976 quakes is typical, quakes disturb 2 percent of the forest per century (*13*).

The only quantitative report of earthquake-caused landslides in tropical regions other than Panama comes from northern Papua New Guinea, where two shallow quakes, 7.9 and 7.0 on the Richter scale, denuded 130 km^2 (8 percent) of a region 1662 km^2 ($\approx$ 3°S, 142°E) in 1935 (*14*). The earthquake rate of this region was estimated to be 0.9 to 1.8 quakes per 10^3 km^2 per century (*15*), based on a 30-year record, or an average of one quake every 56 to 111 years in an area 1000 km^2. Assuming that the average quake damage is only 100 km^2, 8 to 16 percent of the forest would be denuded per century (*13*). In contrast, landslides caused by normal weathering processes (erosional landslides) denuded only 3 percent of the forest per century in the same region (*14*).

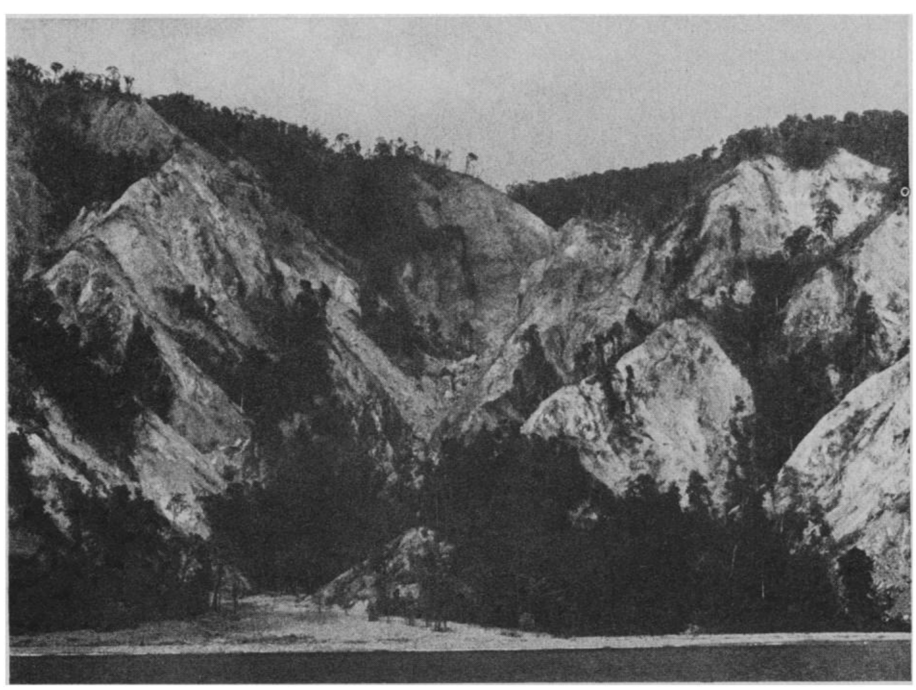

Fig. 1. A coastal landslide in the highly damaged central area, 8 months after the earthquakes occurred.

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Approximately 18 percent of tropical rain forests lie in zones of high seismic activity, including about 38 percent of the Indo-Malayan and 14 percent of the American, but less than 1 percent of the African rain forest (*16–18*). These regions are characterized by rugged mountains and uplands (most are plate margins with active mountain building or volcanism, or both) and receive high rainfall throughout the year, two conditions that facilitate landsliding when local topography and parent material are appropriate. Because earthquakes also cause extensive tree falls in less rugged lowland forests (*5*), earthquake damage might be common in these regions.

The severity of disturbance in forest systems can be measured by the time required to recover the predisturbance species diversity and structural complexity of the habitat. Recovery time (RT) on agricultural land in the tropics is several centuries (*18*). The following evidence suggests that succession on earthquake-caused landslides will be slower and greatly increase recovery time. (i) On a 2-ha slide in Panama 20 months after the earthquakes, individuals of *Trema micrantha* (L.) Blume, an early successional tree and the most abundant species on the slides, were chlorotic, had low growth rates, and were much shorter on the denuded slopes than on adjacent areas where the trees were merely toppled (*12, 19*). (ii) The percentage of cover of the 2-ha slides was still low after 20 months (*20*), while a closed canopy is formed within a year after agricultural land is abandoned (*17*). (iii) In New Guinea, large landslides are undetectable and revegetated within 40 years, although very large landslides (comparable in size to those formed during the 1935 quake) are still detectable after 50 or 60 years (*14*).

The total area disturbed (TD = RD × RT, assuming no overlap of disturbances), the total percent of forest in some stage of recovery from a disturbance at any time, combines measures of frequency, size, and severity of disturbance. We list the total areas disturbed for several probable recovery times and rates of disturbance for Panama and New Guinea in Table 1. We assumed that rates of disturbance by tree falls approximates that of mature forests elsewhere in Panama and Costa Rica (*21*), that recovery time for tree falls is at least 20 to 30 years, the time required for canopy closure in Panama (*22*), and that erosional landslide rates of New Guinea and Panama are similar. Because hurricanes are extremely rare in Panama and northern New Guinea (*23*), as are extensive natural fires in tropical rain forests (*18*), and human disturbance is presently slight (*18, 24*), we assume that their contributions are less important. Although there are no estimates of windstorm damage, and past human disturbance is difficult to ascertain (*18, 24*), we think that Table 1 is a useful first approximation of the disturbance regime in the Panama and New Guinea forests considered.

Table 1. The disturbance regimes of Panama and New Guinea. From data and sources given in the text.

Type of disturbance	Rate*	Recovery time (years)	Total area disturbed (%)
Tree falls	62–125	20	12–24
		30	19–38
		50	31–62
Earthquake landslides			
New Guinea	8–16	200	16–33
		300	24–49
		500	41–89
Panama	2	200–500	4–10
Erosional landslides	3	200–300	6–15

*The percent of area per 100 years

Fig. 2. Diagram of a portion of an aerial photograph taken 3 days after the earthquakes occurred showing the patchiness of landslides within the highly damaged central area. Black areas are landslides, dashed lines represent clouds on the photograph, and *A* is an approximately 100-ha denuded area. The irregular lower edge is the Pacific coastline. The top is north, and the scale bar represents 1 km.

Tree falls disturb more forest per century than landslides. However, the total area disturbed by earthquake-caused landslides in New Guinea, but not Panama, is equal to or greater than that of tree falls, depending on recovery time. Even if mean quake damage is halved (which proportionally decreases RD and TD), the ranges of total area disturbed still overlap. This supports White's suggestion (*25*) that earthquake-caused landslides are an important disturbance in New Guinea.

The only previous study of earthquake-caused landslides in which the total area disturbed is considered is a study of the temperate rain forests of southern Chile, where most of the vegetation is maintained in an early successional stage by earthquake-caused landslides and volcanism (*26*).

The total area disturbed by earthquake-caused landslides in Panama, which would be considered a "rare" disturbance, is similar to that of erosional landslides, an oft-mentioned "common" cause of disturbance. This cautions against nonquantitative comparisons.

The total area disturbed, not rate of disturbance, is the appropriate measure of disturbance when considering the ecological maintenance of species diversity, since it is a measure of the distance from a state of no disturbance. Unless the total area disturbed varies between regions, a particular disturbance cannot be related to differences in species diversity between regions. Earthquake damage varies regionally, is ecologically significant, and must be considered in discussions of disturbance-diversity hypotheses. Regional comparisons of more widespread disturbances, such as tree falls, will require accurate determination of both rates of disturbance and recovery time.

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8. Data from the National Geophysical and Solar-Terrestrial Data Center, Environmental Data Service, National Oceanic and Atmospheric Administration, Washington, D.C.
9. We observed landslides along 45 km of the coast from Jaqué to the Colombian border and 10 km inland in the Rio Jaqué valley. Observations further inland were not feasible at the time and Landsat photographs are unavailable for the region after the quakes: damage may be more extensive.
10. We distinguished a highly damaged central zone (160 km^2), less damaged peripheral areas (193 km^2), and river plains and mangroves with few slides (97 km^2). Mean percent of denuded ground in eight sections (1 by 3 km) of an aerial photograph (Fig. 2) from the central zone was 20 ± 6.2 [standard deviation (S.D.)]; the percent of the two least damaged, adjacent sections, used as an estimate for the less damaged peripheral areas, was 11 ± 2.4 (S.D.).
11. E. O. Wilson and E. O. Willis, in *Ecology and Evolution of Communities*, M. L. Cody and J. M. Diamond, Eds. (Harvard Univ. Press, Cambridge, Mass., 1975), pp. 522–534.
12. The most abundant [*Trema micrantha* (L.) Blume] and five most abundant species included 66 and 91 percent, respectively, of 539 individuals in 18 species in a transect 30 m^2 on a 2-ha slide in Panama, 8 months after the quakes.
13. Calculated over a square degree of latitude and longitude ($\approx$12,000 km^2). A cut-off point of 6.0 on the Richter scale was used by Brooks (*15*) and was maintained in the analysis of the Panama data.
14. From or calculated from data in D. S. Simonett, in *Landform Studies from Australia and New Guinea*, J. N. Jennings and J. A. Mabbutt, Eds. (Australian National Univ. Press, Canberra, 1967), pp. 64–84.
15. J. Brooks, unpublished report, cited in Simonett (*14*).
16. Distribution of seismic zones from B. Gutenburg and C. F. Richter, *Seismicity of the Earth* (Princeton Univ. Press, Princeton, N.J., 1954). Distribution of tropical rain forests from the following maps: A. W. Küchler, *Vegetation of the World* (Rand McNally, Chicago, Ill., undated); figure 2 in (*17*); and figure 1.1 in (*18*).
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19. Mean and maximum height of *T. micrantha* were 94 ± 6.8 [standard error (S.E.)] cm ($N = 152$) and 4.5 m, respectively; individuals in less disturbed areas ranged up to at least 6 m. Growth was 65 ± 5.7 (S.E.) cm ($N = 152$) from 8 to 20 months after the quake.
20. Percent cover, visually estimated through a transparent grid, was 2 percent after 8 months and 23 percent after 20 months on the upper two-thirds of the slide, and 19 and 43 percent on the lower third.
21. G. S. Hartshorn, in *Tropical Trees as Living Systems*, P. B. Tomlinson and M. H. Zimmermann, Eds. (Cambridge Univ. Press, Cambridge, England, 1978), pp. 617–638; N. Brokaw, unpublished data.
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27. We thank R. Foster, R. Lawton, E. Leigh, A. S. Rand, A. P. Smith, J. Teeri, two anonymous reviewers, and others for comments and discussion; G. Angehr, J. Bryan, L. Cruz, N. Franks, D. Glanz, W. Glanz, R. Lawton, and G. VanVliet for field assistance; H. Janos for figure assistance; R. Steward and J. Steward for bringing the landslides to our attention; and the Smithsonian Tropical Research Institute (STRI), especially I. Rubinoff and A. S. Rand. Funds for the Panamanian expeditions were provided by STRI and, for operation of the R.V. *Stenella*, by the George Becker Fund of the Smithsonian Institution (SI). Supported by an NSF graduate fellowship and the Hutchinson Fund of the University of Chicago (to N.C.G.), by an SI postdoctoral fellowship (to D.P.J.), and by the Coulter and Hutchinson Funds (University of Chicago) and STRI (to N.B.).
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Observation of a Subsurface Oil-Rich Layer in the Open Ocean

Abstract. *A layer of water at a depth of 200 meters containing 3 to 12 milligrams per liter of oil was found during February and March 1978 over a distance of 800 nautical miles in the southwest North Atlantic and the eastern Caribbean. The geochemistry and carbon-14 activity of the oil shows it to be a weathered crude, probably from a submarine seep. Although the dimensions of the oily layer were not determined, conservative estimates indicate that more than 1 megaton could have been present.*

During February and March 1978, on a cruise investigating the chemistry of the subtropical underwater (*1*), we found an extended layer of unusually oil-rich water about 200 m below the surface of the southwestern North Atlantic Ocean and the eastern Caribbean Sea (Fig. 1). At stations 11 to 24, a transect of 800 nautical miles, hexane extracts of seawater obtained from depths of 150 to 250 m yielded 3 to 12 mg of weathered oil per liter (average of 6 mg per liter). Extracts of samples from both above and below the oily layer at stations 11 to 24 and from all depths at stations 26 to 38 had hydrocarbon concentrations (micrograms per liter) and distributions typical of the open ocean (*2*). Because the sampling at each station was centered about the subtropical underwater, the discovery of the oily layer was serendipitous.

Water was collected in a 90-liter polyvinyl chloride drop-top sampler and transferred into 20-liter glass bottles through steel tubing. Forty liters of each sample was batch-extracted with hexane within 1 hour of collection. The extracts were concentrated by means of a vacuum within 1 hour of collection, esterified with boron trifluoride-methanol reagent,

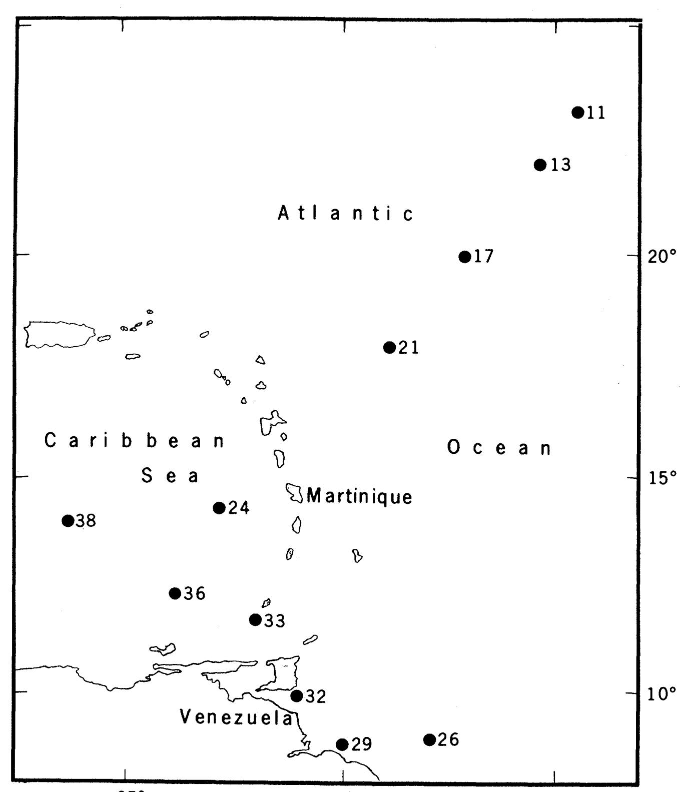

Fig. 1. Sampling stations of NOAA *Researcher* cruise R-78-1. The oily layer was found at stations 11 (12.6 mg, 200 m), 13 (5.8 mg, 200 m), 17 (9.6 mg, 270 m), 21 (3.2 mg, 145 m), and 24 (2.8 mg, 150 m and 5.7 mg, 200 m).