Impact of Forest Harvesting on Slope Stability in Managed Forest Catchment, Nara Prefecture, Japan

Fumitoshi Imaizumi[1)] and Roy C. Sidle[2)]
1) Graduate School of Life and Environmental Science, University of Tsukuba, 1621-2, Ikawa University Forest, Ikawa, Aoi, Shizuoka, 428-0504, Japan (imaizumi@sakura.cc.tsukuba.ac.jp)
2) Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto, Japan (sidle@slope.dpri.kyoto-u.ac.jp)

Abstract

Forest harvesting that induces the root decay of logged trees and the root recovery of replanted trees affects stability of slopes over time; these factors influence the occurrence of shallow landslides. Landslides cause loss of life and property; thus, the occurrence of landslides is considered to be one of the most detrimental effects of forest harvesting. Although many studies have been carried out to evaluate the effect of forest harvesting on the occurrence of landslides, the impact of harvesting differs in each study due to dissimilar site conditions (i.e., geology, physiography, and climate). Thus, field data that can neglect the influence of these complex conditions is necessary for testing simulation model predictions of the effects of forest harvesting on landslide occurrences. Using aerial photograph investigations and field surveys, we examined the occurrence of landslides with regard to forest harvesting in the Sanko catchment (Nara prefecture, central Japan), where rotational management yields a mosaic of different forest ages over the years. In the Sanko catchment, geology and slope gradient are rather uniformly distributed, allowing the evaluation of the forest harvesting effect by ignoring other factors. The trends in the landslide frequency in the managed forests correspond to changes in slope stability; this is explained by root strength decay and recovery. The impact of landslide occurrence can be summarized to be strongest for 1–10 yr after forest harvesting and smaller impacts continue up to 25 yr after harvesting. In the Sanko catchment, the influence of forest harvesting on landslide occurrence is more evident in steep slopes as compared to gentler slopes. Only smaller landslides (< 100 m^3) whose slide surface might be shallower than root depth are accelerated by forest harvesting, while the effect of forest harvesting is not obvious for larger landslides (> 100 m^3). These characteristics of landslide frequency relevant to forest harvesting can be demonstrated by landslide models based on infinite slope stability.

Keywords: landslide, forest harvesting, slope stability, root strength

Introduction

Acceleration of landslides with destructive power instantaneously supplies enormous volumes of sediment into streams. These landslides are considered to be the most significant impact of the forest harvesting. An increase in the frequency of landslides may cause disasters in mountainous regions. Thus, the effect of forest harvesting, including clear cutting and forest regeneration, on the occurrence of landslides needs to be investigated in order to develop better measures for mitigating disasters.

The quantification of the effects of forest harvesting on landslide rates has been conducted, particularly in the Pacific Northwest (Jacob, 2000; Brardinoni et al, 2002; Guthrie, 2002). Although these studies revealed that clear cutting accelerates the occurrence of landslides, the impact of logging differs in each study. For example, the number and volume of landslides in clear cut terrains is more than 10-fold higher than that in undisturbed forests in some catchments, while the effect of logging on the occurrence of landslides is unclear in other catchments located in the same region (Jacob, 2000; Brardinoni et al, 2002; Guthrie, 2002). These studies evaluated the effects of forest harvesting by comparing the landslide frequency (or volume) in logged forests with that of undisturbed forests located in other areas. However, not only forest harvesting but also other factors (i.e., geology, physiography, and climate) affect the occurrence of landslides (Sidle et al., 1985; Brardinoni et al, 2002). Thus, the influence of forest harvesting on the occurrence of landslides in certain terrains cannot be elucidated by comparing the landslide frequency with the different geology, physiography, and climate.

The overall aim of this study is to clarify the effects of forest harvesting (i.e., clear cutting and subsequent regeneration of artificial forests) on the occurrence of landslides in the Sanko catchment, central Japan. In the Sanko catchment, the geology and slope gradient are rather uniformly distributed, thereby

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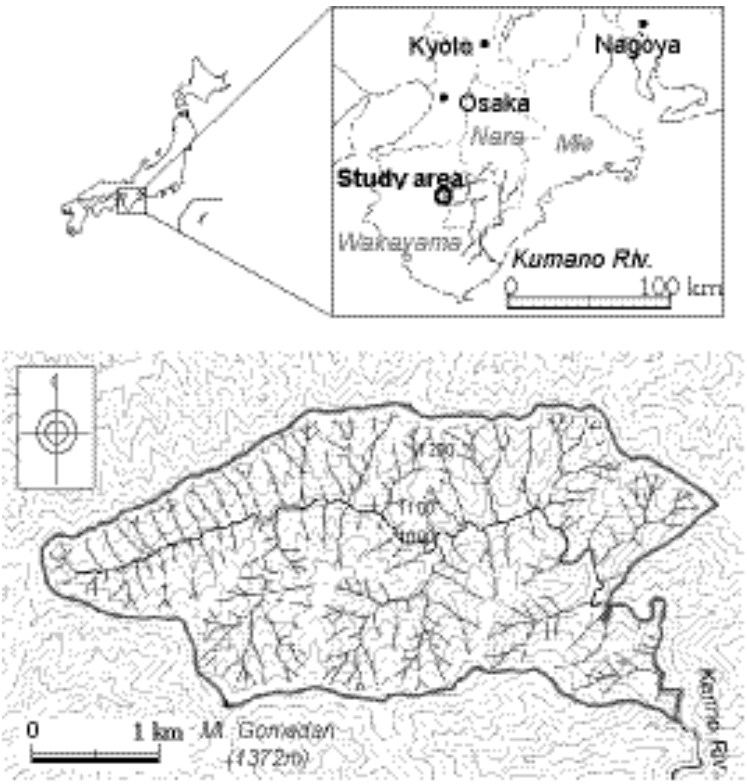

Fig. 1. Topographic map of Sanko catchment.

enabling the evaluation of the effect of forest harvesting without considering the other factors. The specific objectives include: (i) assessing the occurrence of landslides in the managed forest, (ii) examining the effects of forest harvesting on the occurrence of landslides, and (iii) investigating the influence of forest harvesting on hillslope stability based on physical analysis.

Study area

Site description

The Sanko catchment is drained by Kanno River, a headwater tributary of the Kumano River; this catchment is located in the southwestern Nara prefecture, central Japan (Fig. 1). This catchment has an area of 8.50 km^2 with tributaries flowing in the north-south direction. The lowest point of the catchment is located in the southeast end of the catchment (750 m a.s.l.) and the highest point is the peak of Mount Gomadan (1372 m a.s.l.) in the southwest region of the catchment. The area is underlain by the Cretaceous Shimanto belt comprised of sandstone and clay, and the area is homogeneous throughout the catchment. Hillslope gradients are also relatively homogeneous throughout the catchment (typical gradients 30°–50°, Fig. 1); thus, the effect of differences in the hillslope gradient on the distribution of landslides may not be significant. The channel gradient is 2°–5° for the main stream (Kanno River) and 5°–35° for tributaries. The soils are shallow, typically ranging 0.5–1.0 m, because of the steep hillslopes.

An annual rainfall of 2500 mm occurs at the Wakayama Experimental forest of Kyoto University, about 3 km west of the Sanko catchment. Heavy rainfall events (i.e., total storm rainfall > 100 mm) occur during the Baiu rainy season (June and July) and in the autumn typhoon season (from late August to early October). Winter snowfall occurs at higher elevations within the catchment, but precipitation from December to February is only about 10% of the total annual precipitation. Thus, snowmelt is typically not a significant landslide-triggering mechanism in this area.

Forest management

About 95% of the Sanko catchment has been converted into an artificial forest (largely sugi (Japanese cedar) with minor amounts of hinoki (Japanese cypress) and the remainder comprises secondary broadleaf

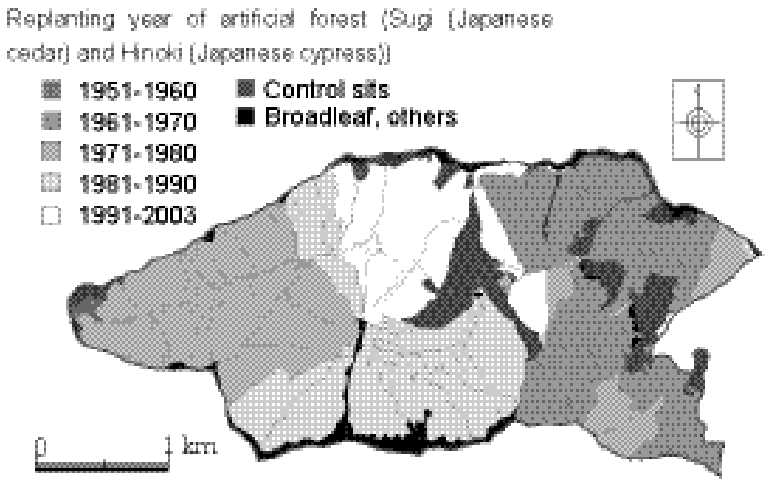

Fig. 2. The year of replanting in Sanko catchment.

forests, forest roads, and log landings. Broadleaf forests and log landings are mainly located on mountain ridges. In this study, we did not compare the occurrence of landslides in broadleaf forests and log landings with those in artificial forests because of their different geographic conditions. Clear cutting has been the only harvesting method used in the catchment. Typically, replanting is carried out one or two years after logging. In the Sanko catchment, both sugi and hinoki forests are cultivated in rotation in intervals of about 80 yrs; thus, regenerating forests with different ages (representing different periods of clear cutting) exist during years of abundant as well as scanty rainfall (Fig. 2). By averaging landslides rates within the various age classes of forest stands over long periods we can evaluate the effects of forest harvesting with the influence of rainfall minimized. Because only skyline logging has been conducted in the Sanko catchment, the influence of logging methods on landslide occurrence (e.g., Roberts et al., 2004) cannot be expected. Old-growth artificial forests (both sugi and hinoki), which were replanted from 1912–1916, are investigated as a control area spanning across 0.78 km^2 (about 9% of the entire catchment). The influences of logging and replanting appear to be minimal in the control area because the forest ages from 1964–2002 are 38–90 yr.

Methodology

Monochrome aerial photographs for nine periods (1964, 1965, 1967, 1971, 1984, 1989, 1994, 1998, 2003) and color aerial photographs for 1976 were used to assess the location and area of landslides in the Sanko catchment. These landslides were confirmed by stereo photograph pairs and were mapped on 1:5000 forest management maps. Most of the aerial photographs were taken in March (before the Baiu season); thus, almost all the mass movements confirmed by aerial-photo stereographs probably occurred prior to December of the previous year. New occurrences of landslides for each period (1964, 1965–1966, 1967–1970, 1971–75, 1976–1983, 1984–1993, 1994–1997, 1998–2002) were confirmed by comparing earlier and later aerial photographs. Expanded landslides were not considered to be new landslides in this study. Mapped landslides were scanned and their location and areas were analyzed using Arc GIS software.

Volumes of 11 landslide scars, including their initiation and transportation zones, were measured in the field to develop a preliminary volume-area relationship for landslides within the catchment. The landslide size ranged from 50–4,000 m^2, thereby including most landslide sizes in the catchment, as confirmed by the aerial photograph investigations. This relationship was used to estimate the landslide volume from the landslide area obtained from the aerial photograph interpretations. To estimate volume of sediment supply from expanded landslides, volume of the landslide in the prior period was subtracted from volume of the later landslides.

Result

A total of 873 landslides were confirmed from the aerial photograph investigations in the period from 1964–2002. Since 256 landslides were confirmed from the aerial photographs obtained in 1964 (the first period), 617 new landslides occurred from 1964–2002. In the Sanko catchment, forest roads exist mainly along the mountain ridgelines and in the valley bottom along the stream. These roads sometimes have the greatest

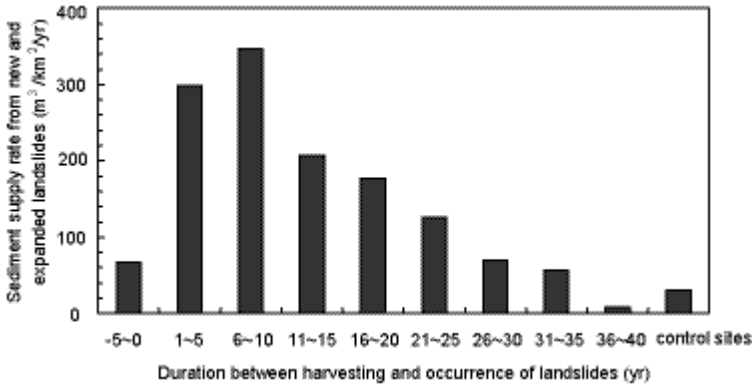

Fig. 3. Changes in sediment supply rate from new/expanded landslide with increase in duration between forest harvesting and occurrence of landslides.

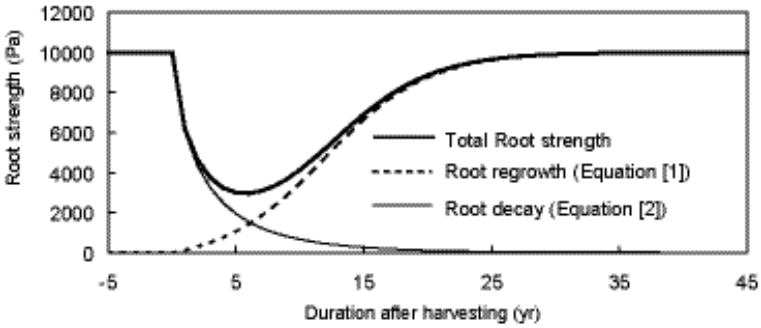

Fig. 4. Changes in root strength estimated from Sidle (1992). Maximum root strength = 10,000 Pa was assumed. Root regrowth curve estimated from equation [1] and root decay curve estimated from equation [2] are also illustrated in the figure.

special impact on landslide initiation (Wemple et al., 2001; Brardinoni et al., 2002; Grthrie, 2002), and 124 landslides were initiated from roads in the Sanko catchment in the period from 1964 to 2002. The landslides initiating from roads were excluded from assessments in this study in order to clarify the impact of clear cutting and subsequent forest regeneration on landslide occurrence. Aerial photograph investigations cannot confirm smaller landslides, and the threshold scale of non-visible landslides depends on forest cover conditions (Brardinoni et al, 2003; Brardinoni and Church, 2003). Sugi and hinoki (both conifers) are typically replanted in an evenly distributed pattern in the study catchment, thus facilitating the recognition of smaller landslides in aerial photographs. Intensive field surveys conducted in some sub-catchments revealed that landslides with sizes exceeding approximately 50 m^2 are likely to be detected in aerial photographs; thus, landslide sizes documented in our study range approximately from 50–5000 m^2. Based on both aerial photographs and field investigations, landslides typically occur at the bedrock surface or shallower depths at an average depth of only 0.6 m. However, only a few landslides are associated with bedrock failure.

In order to help quantify the effect of forest harvesting on the occurrence of landslides, the duration between forest harvesting at headwalls of landslides and their occurrence were investigated using GIS software. Sediment supply rate from the new/expanded landslides — calculated from the annual volume of new/expanded landslides divided by the area of each duration categories — is the largest in forests 6–10 yr after harvesting (Fig. 3).The sediment supply from landslides in the forests 1–10 yr after harvesting is about nine times higher compared to the control sites. The sediment supply in the forests more than 26 yr after harvesting is similar to that of the control sites, indicating that slope stability almost completely recovered within 25 yr after harvesting.

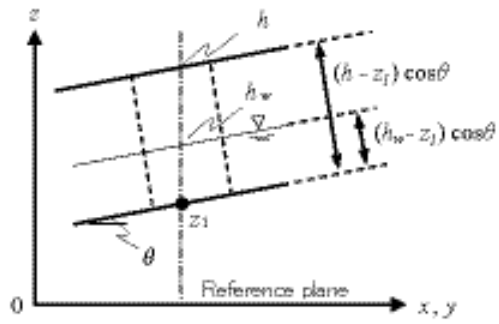

Fig. 5. Schematic diagram of slope stability.

Discussion

Influence of root strength on slope stability

Sidle (1991) quantified the general shape of a conceptual root strength regrowth curve using the following equation:

$$R = (a + be^{-kt})^{-1} + d \tag{1}$$

where R (dimensionless) is the actual root cohesion divided by the maximum root cohesion (dimensionless), t is the time elapsed since the harvesting years (yr), and a, b, d, and k are the empirical constants. The empirical coefficients based on the uprooting tests for sugi trees are $a = 0.952$, $b = 19.05$, $d = -0.050$, and $k = 0.250$ (Sidle, 1991). Sidle (1992) predicted the root strength decline (D) using the following equation:

$$D = e^{-ltn} \tag{2}$$

where D is the actual root cohesion divided by the maximum root cohesion (dimensionless) and l and n are the empirical constants. Unfortunately, the decay coefficients for sugi and hinoki were unavailable. However, the decay coefficients for coastal Douglas firs ($l = 0.506$ and $n = 0.730$; Sidle, 1992) with root strength decline trends similar to sugi (Tsukamoto, 1987) can be substituted for those of sugi. The changes in R and D in the Sanko catchment are estimated using equations [1] and [2] and the empirical coefficients of Sidle (1991, 1992). The changes in the total actual root cohesion after harvesting are estimated from the sum of R and D multiplied by the estimated maximum root strength (= 10,000 Pa). The changes in hillslope instability assumed from the changes in the frequency of landslides (Fig. 3) are antithetical to the changes in the estimated net root strength (Fig. 4). Thus, the temporal changes in frequency of landslides in the Sanko catchment can be explained by the root strength models proposed by Sidle (1991, 1992).

Inference of slope gradient on slope stability

The factor of safety (FS) for slope stability is the ratio of shear strength to shear stress and is given by

$$FS = \frac{c + c' + [\int_{h_w}^{h} \{(1-n)\gamma_s + nS\gamma_w\}dz + \int_{z_1}^{h_w} (1-n)(\gamma_s - \gamma_w)dz]g\cos^2\theta\tan\phi}{\int_{z_1}^{h_w} \{(1-n)\gamma_s + nS\gamma_w\}dzg\cos\theta\sin\theta} \tag{3}$$

where c is the effective soil cohesion (Pa), c' is the cohesion attributed to the root system (Pa), n is the porosity of soil (dimensionless), S is the degree of saturation (dimensionless), γ_s is the mass density of sediment (or soil) particles, γ_w is the mass density of water, θ is the slope gradient, ϕ is the effective internal angle of friction (degree), z_1 is the height of slide surface from the reference plane; h_w is the height of ground water surface from the reference plane, h is the height of slope surface (Fig. 5). Under the assumption that parameters in equation [3] are constant along depth direction, the following values estimated for each parameter were used for investigating the effect of slope gradient and root strength on slope stability in the Sanko catchment: $c = 3000$ (Pa), $n = 0.4$, $S = 1$, $\gamma_s = 2600$ (kg /m^3), $\gamma_w = 1000$ (kg /m^3), $g = 9.8$ (m/s^2), $\phi = 38$ (degree), $h - z = 0.6$ (m), and $h_w - z = 0.6$ (m). The average root strength from 0–10 yr (when slopes are the most unstable in the Sanko catchment in Fig. 3), 11 to 25 yr (when the slope stability is recovering), and greater than 25 yr after harvesting (when the slope stability has almost recovered) in Fig. 4 were used to calculate the slope stability using equation [3] (Fig. 6). Parameters in the site exhibit variance around the mean values and are distributed throughout the catchment. Although the calculated FS always exceeds 1 (Fig. 6), landslides possibly occur on

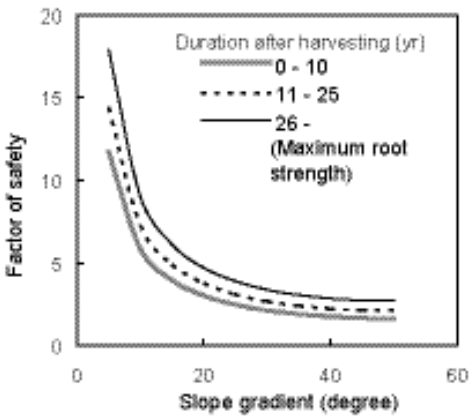

Fig. 6. Changes in the factor of safety with increasing in slope gradient.

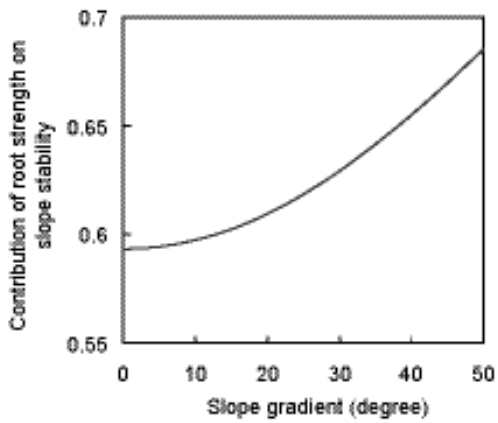

Fig. 7. Contribution of root strength to slope stability.

the slopes with negative parameters with regard to slope stability as compared to the mean values. For any duration considered after harvesting in Fig. 6, the FS decreases and approaches 1 with an increase in the slope gradient. This indicates that steeper slopes are more unstable compared to gentler slopes if parameters with the exception of slope gradient are similar. Differences in FS for each duration are greater in gentler slopes (Fig. 6); however, the contribution of root strength to the total slope stability is not clear. The contribution of root strength to the total slope stability of forests more than 25 yr after harvesting was calculated using the root strength of the matured forest ($\approx$ 10,000 Pa) divided by the sum of the numerator in the equation [3]. Root strength in the numerator of the equation [3] was also assumed to be 10,000 Pa for the calculation. The contribution of the root strength to the total slope stability of steeper slopes is greater as compared to the gentler slopes (Fig. 7), indicating that the stability of the steeper slope is more sensitive to the changes in the root strength caused by root decay and regrowth. In the Sanko catchment, increases in the frequency of occurrence of new landslides — calculated from the number of new landslides per year divided by the area of duration category — with slope gradient are not clear for forests 26–40 yr after harvesting (Fig. 8). However, the frequency of occurrence of new landslides for forests 0–10 yr after harvesting increases with the slope gradient, indicating that the influence of harvesting on landslide frequency is more evident for steeper slopes. This larger effect of forest harvesting on slope stability of steeper terrains agrees with the larger contribution of root strength to the total slope stability elucidated by infinite slope model (Fig. 7).

Landslide sizes induced by forest harvesting

Frequency of smaller landslides (< 100 m^3) in the forests, 1–10 yr after harvesting, is more than 8-fold greater than that in forests 26–40 yr after harvesting, while the frequency of larger landslides in the forests 1–10 yr after harvesting is only 3.4-fold greater in forests 26–40 yr after harvesting (Table 1). The area-depth relationship of landslides developed by field surveys predictably shows that the depth of smaller landslides is

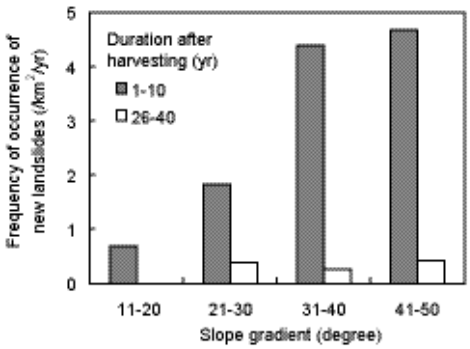

Fig. 8. Changesin frequency of new landslides for each volume category with increase in duration between forest harvesting and occurrence of landslides.

Table 1. Acceleration in frequency of occurrence of new landslides for each landslide volume category.

Landslide volume (m^3)	Frequency of occurrence of new landslides ($/km^2/yr$)		A/B
	1-10 years after logging (A)	26-40 years after logging (B)	
< 100	2.38	0.28	8.6
100-200	0.41	0.08	4.9
200>	0.28	0.08	3.4

shallower than that of larger landslides. The average depth of smaller landslides (< 100 m^3) measured in the study site was about 40 cm lesser than the depth of sugi roots (50–60 cm for lateral roots, and 1 m for vertical roots; Tsukamoto, 1987). Thus, the effect of forest harvesting on slope stability is sensitive at depths shallower than those of tree roots.

Conclusions

As demonstrated in this study, changes in frequency of landslides in the Sanko catchment can be explained by the root strength models proposed by Sidle (1991, 1992). This indicates that the landslide frequency trends are greatly affected by changes in root strength in managed forests. Magnitude and duration of the influence of forest harvesting differ depending on both site conditions (i.e., geology, physiography, and climate) and tree conditions (i.e., species and environmental conditions for tree growth; Sidle, 1991; Sidle, 1992). Analysis of infinite slope stability can demonstrate that the acceleration of landslide occurrence induced by forest harvesting is more evident in steeper terrains; thus, landslide models may be useful for estimating the effect of physiography on the occurrence of landslides. However, information on other factors that affect the occurrence of landslides is scarce, particularly information related to tree conditions. In order to estimate the magnitude and duration of forest harvesting on slope stability in other regions, information for other factors should be investigated.

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