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Effects of forest harvesting on the occurrence of landslides and debris flows in steep terrain of central Japan

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Abstract

Landslides and debris flows associated with forest harvesting can cause much destruction and the influence of the timing of harvesting on these mass wasting processes therefore needs to be assessed in order to protect aquatic ecosystems and develop improved strategies for disaster prevention. We examined the effects of forest harvesting on the frequency of landslides and debris flows in the Sanko catchment (central Japan) using nine aerial photo periods covering 1964 to 2003. These photographs showed a mosaic of different forest ages attributable to the rotational management in this area since 1912. Geology and slope gradient are rather uniformly distributed in the Sanko catchment, facilitating assessment of forest harvesting effects on mass wasting without complication of other factors. Trends of new landslides and debris flows correspond to changes in slope stability explained by root strength decay and recovery; the direct impact of clearcutting on landslide occurrence was greatest in forest stands that were clearcut 1 to 10 yr earlier with progressively lesser impacts continuing up to 25 yr after harvesting. Sediment supply rate from landslides in forests clearcut 1 to 10 yr earlier was about 10-fold higher than in control sites. Total landslide volume in forest stands clearcut 0 to 25 yr earlier was $5{\cdot}8 \times 10^3$ m^3 km^{-2} compared with $1{\cdot}3 \times 10^3$ m^3 km^{-2} in clearcuts >25 yr, indicating a fourfold increase compared with control sites during the period when harvesting affected slope stability. Because landslide scars continue to produce sediment after initial failure, sediment supply from landslides continues for 45 yr in the Sanko catchment. To estimate the effect of forest harvesting and subsequent regeneration on the occurrence of mass wasting in other regions, changes in root strength caused by decay and recovery of roots should be investigated for various species and environmental conditions.

Keywords: slope stability; forest management; landslide; debris flow; hydrogeomorphological processes

Introduction

Forest harvesting, particularly clearcutting, affects various hydrogeomorphological processes in forest terrain, including enhancement of surface erosion (Roberts and Church, 1986; Edeso *et al.*, 1999), changes in hillslope or catchment hydrology (Keim and Skaugset, 2003; Dhakal and Sidle, 2004), and increases in landslides and debris flows (Brardinoni *et al.*, 2002; Jakob *et al.*, 2005; Sidle and Ochiai, 2006). Just after initiation, landslides and debris flows attributable to the effects of timber harvesting exert significant destructive forces and supply large volumes of sediment to streams, thus increasing catchment sediment (Gomi and Sidle, 2003; Constantine *et al.*, 2005), changing channel structure and stream ecosystems (Hartman *et al.*, 1996; Gomi *et al.*, 2002; Gomi and Sidle, 2003), and threatening property and human habitation downstream (Sidle and Chigira, 2004; Sidle and Ochiai, 2006). Thus, the influence of forest management, including clearcutting and forest regeneration, on landslide and debris flow occurrence needs to be assessed to preserve the integrity of stream ecosystems as well as to develop better mitigation measures for preventing disasters.

Numerous investigations of the effects of forest harvesting on landslide rates have been conducted, especially in the Pacific Northwest of North America (Fiksdal, 1974; Swanson and Dyrness, 1975; Swanson *et al.*, 1977; Swanston and Marion, 1991; Jacob, 2000; Montgomery *et al.*, 2000; Brardinoni *et al.*, 2002; Guthrie, 2002). Even though most of these studies revealed that clearcutting accelerates the occurrence of landslides and debris flows, the impact of logging is different for each area. For example, the number and volume of landslides in clearcut terrain is more than 10-fold higher than in undisturbed forests in some catchments, whereas the influence of logging on landslide occurrence is not clear 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 landslide frequency (or volume) in logged forests with that of undisturbed forests. However, interpretations from such types of comparisons are complicated by differences in environmental factors such as geology, soils, physiography and local climate anomalies (Sidle *et al.*, 1985; Brardinoni *et al.*, 2002; Sidle and Ochiai, 2006). Thus, the influence of the forest harvesting on the occurrence of landslides and debris flows in any specific terrain cannot be elucidated by comparing landslide frequency among sites with different environmental characteristics. Effects of forest harvesting on landslide occurrence for controlled site settings can be examined by landslide models (Sidle, 1992; Montgomery *et al.*, 2000; Dhakal and Sidle, 2003). However, field data on factors that affect slope stability are typically limited, thus assumptions are often made in landslide models related to such parameters.

In Japan, many residents live in mountainous areas that have been logged and replanted with commercial forests of sugi (Japanese cedar, *Cryptomeria japonica*) and hinoki (Japanese cypress, *Chamaecyparis obtusa*); both residents and foresters are interested in the effects of the forest harvesting on repeated natural hazards that occur in these areas. Both statistical and physical modelling studies of the impacts of forest harvesting on landslide occurrence have been conducted since the 1970s (Tsukamoto, 1987; Hiramatsu *et al.*, 2002; Ohsaka *et al.*, 2002; Numamoto *et al.*, 2004).

The overall aim of this study is to clarify the effects of forest management (i.e. clearcutting and subsequent regeneration of artificial forests) on the occurrence of landslides and debris flows in the Sanko catchment, central Japan. Specific objectives include: (i) assessing the occurrence of landslides and debris flows in the managed forest; (ii) examining the effects of forest harvesting on occurrence of landslides and debris flows; (iii) investigating the contribution of forest harvesting and other environmental factors on hillslope stability; and (iv) elucidating the magnitude and timing of various impacts of landslides and debris flows induced by forest harvesting.

Study Area

Site description

The Sanko catchment is an 8·50 km^2 basin that forms the headwaters of the Kanno River, a tributary of the Kumano River in southwestern Nara Prefecture, central Japan (Figure 1). Elevation of the catchment ranges from 750 to 1372 m a.s.l. The area is underlain by the Cretaceous Shimanto belt comprised of sandstone and claystone and is relatively homogeneous throughout the catchment. Even though the east end of the catchment is a bit steeper than other portions, hillslope gradients are relatively homogeneous and steep throughout (typical gradients 30°–50°, Figure 2b). Thus, the effect of differences in hillslope gradient on the distribution of landslides and debris flows is not so significant. Channel gradient is 2°–5° for the main stream (Kanno River), and 5°–35° for tributaries. Because of the steep hillslopes, soils are shallow, typically ranging from 0·5 to 1·0 m in depth.

Annual rainfall of 2500 mm occurs at Kyoto University's Wakayama Experimental Forest about 3 km west of 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 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 to artificial forest (largely sugi with minor amounts of hinoki) and the remainder is secondary broadleaf 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 and debris flows in broadleaf forests and log landings with those in artificial forests because of their different geographical positions. Clearcutting has been the only harvesting method used in the catchment, and replanting typically occurs 1 or 2 years

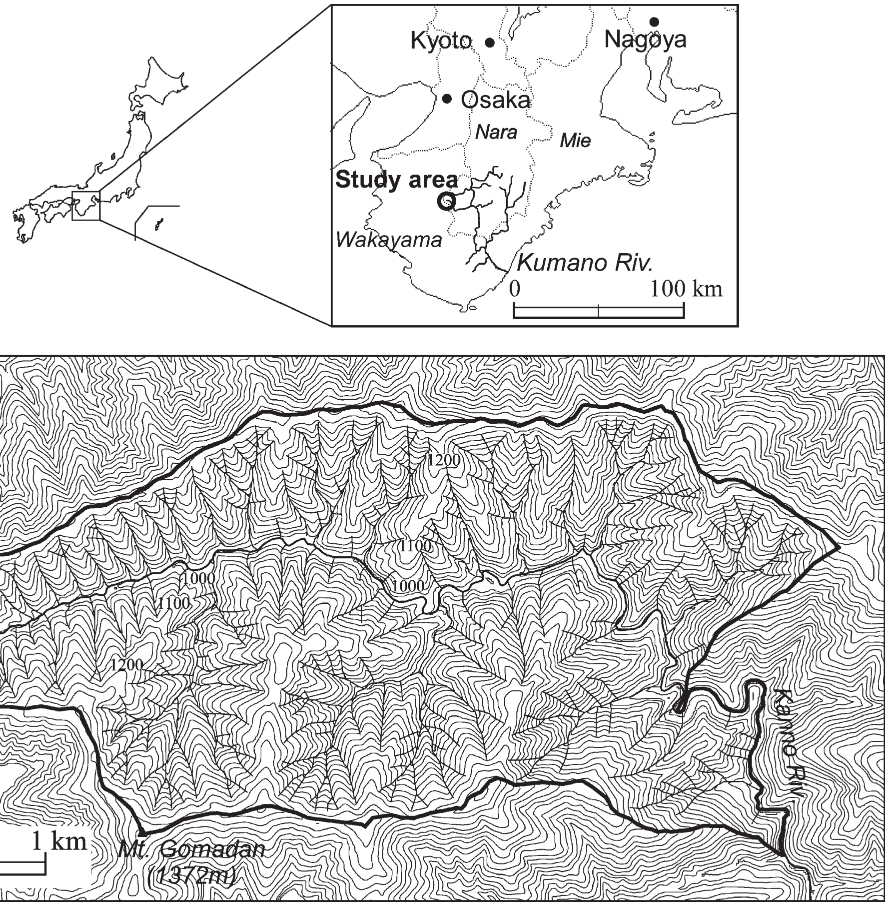

Figure 1. Topographic map of the study area, Sanko catchment, Japan.

after logging. In the Sanko catchment, records of the forest (harvesting and replanting) are available from 1912. Both sugi and hinoki forests are managed with rotation intervals of about 80 yr in this catchment. A mosaic of different ages of regenerating forest stands (representing different periods of clearcutting) exist in years which had both abundant and little rainfall. Thus, by averaging landslide rates within various age classes of forest stands for long periods, we can minimize the effect of rainfall episodes when assessing the effects of forest harvesting on landslide initiation. Because timber harvesting basically coincides with subcatchment boundaries, both the clearcutting and replanting periods are almost the same throughout each subcatchment (Figure 2a). Thus, changes in frequency of debris flows related to forest age (and elapsed time after clearcutting and replanting) can be analysed in the Sanko catchment. Because only skyline logging has been conducted, we expect that yarding did not affect the occurrence of many landslides (e.g. Sidle, 1980; Roberts *et al.*, 2004). The clearcut area has remained relatively constant from the 1960s to the 1980s (Figure 3). Both clearcut and replanted areas decreased starting in the 1990s.

Older artificial forests (both sugi and hinoki), which were replanted from 1912 to 1916, are considered as control areas; these sites occupy 0·78 km^2 (about 9% of entire catchment). The influences of logging and replanting on landslide initiation are assumed to be minimal in these control areas because forest age in these earlier logged sites ranged from 38 to 90 yr during our period of aerial photograph assessment (from 1964 to 2002).

In the Sanko catchment, forest roads (widths generally <5 m) exist mainly along mountain ridgelines and in the valley bottom for the purpose of forest management. Forest roads, particularly mid-slope roads, often exert the greatest unit area impact on landslide initiation (Wemple *et al.*, 2001; Brardinoni *et al.*, 2002; Guthrie, 2002; Sidle and Ochiai, 2006). Landslides initiating from roads were excluded from assessments in this study in order to clarify the impact of clearcutting and subsequent forest regeneration on landslide occurrence. Drainage from forest roads may affect the stability of slopes below the road (Sidle and Ochiai, 2006). Because slopes in the Sanko catchment are rather short (typically <100 m), the effect of the ridgeline road on landslide volume is limited.

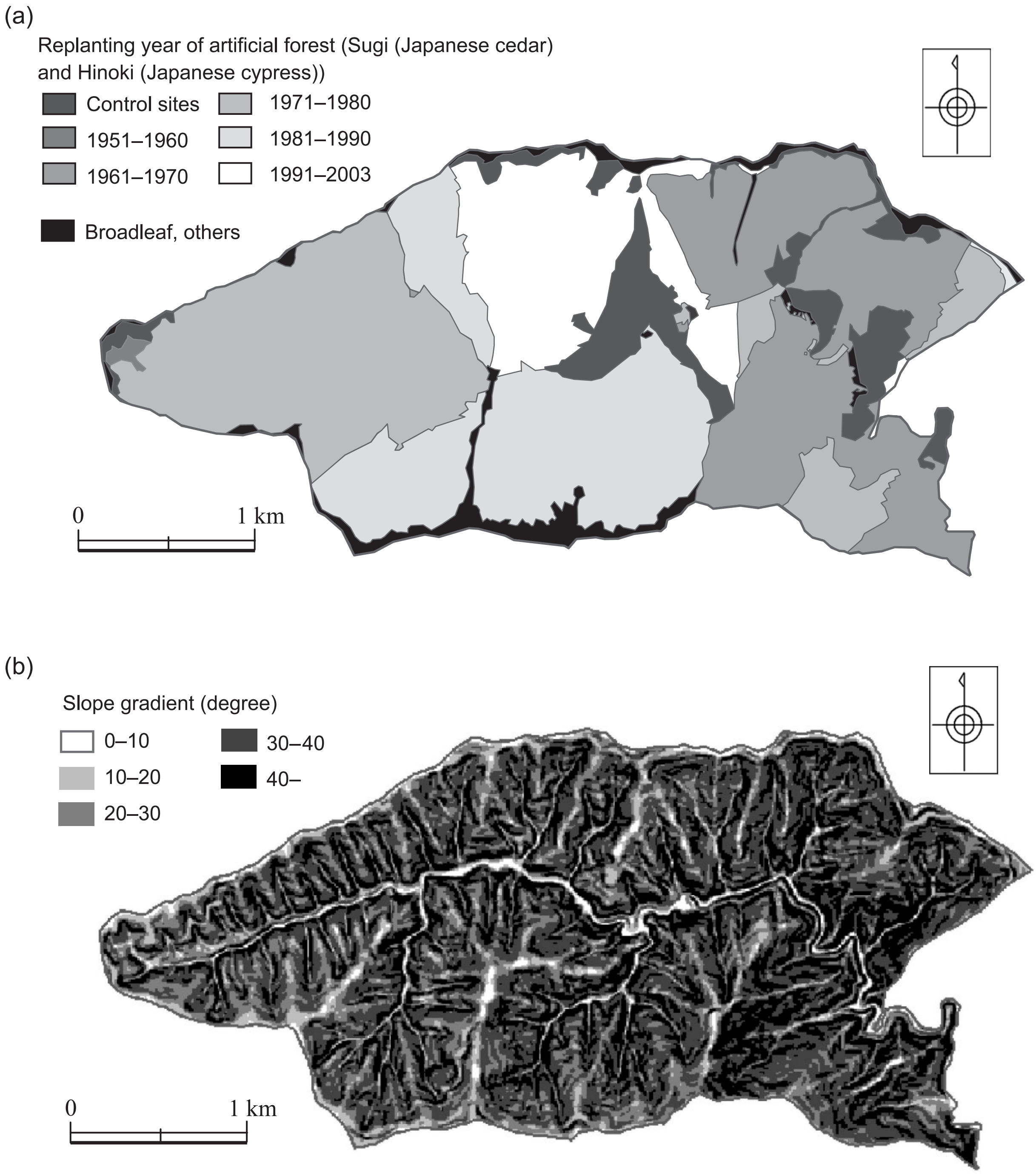

Figure 2. (a) Map of Sanko catchment showing the year in which artificial forests were replanted. Trees in the control sites were planted between 1912 to 1916. (b) Distribution of slope gradient in Sanko catchment.

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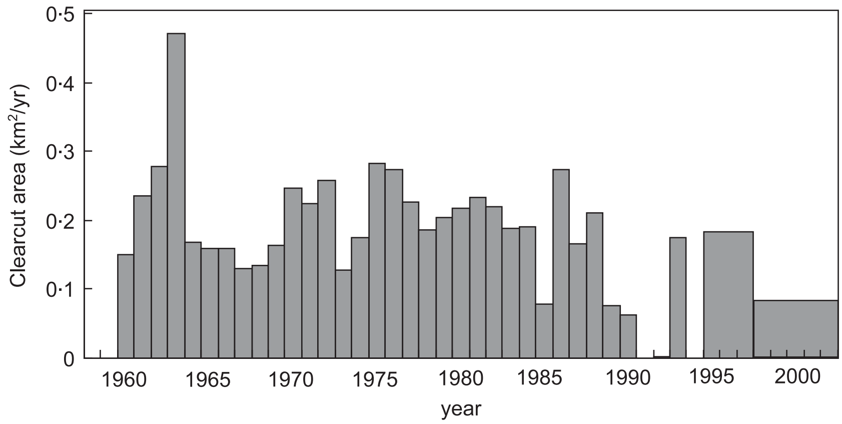

Figure 3. Areas that were clearcut harvested in Sanko catchment from 1956 to 2000. Clearcut areas from 1956 to 1994 are derived from forest management records; clearcut areas from 1995 to 2002 are based on aerial photograph investigation. Time periods represented by bars from 1995 to 2002 indicate aerial photograph periods.

Methodology

Aerial photograph interpretations

Monochrome aerial photographs for nine different years (1964, 1965, 1967, 1971, 1984, 1989, 1994, 1998 and 2003) and colour aerial photographs for 1976 were used to assess the location and area of landslides and debris flows in the Sanko catchment. Landslides and debris flows were identified by stereo photograph pairs and mapped on 1:5000 forest management maps. Most of the aerial photographs were taken in March (before the Baiu season), thus almost all of the mass movements (i.e. landslides and debris flows) identified by aerial photo-stereographs probably occurred prior to December of the previous year. New occurrences of mass movements for the following inclusive years were identified by comparing successive aerial photographs. Mass movements were divided into slope and channel components. All mass movements on hillslopes are designated as landslides and all in-channel mass movements are designated as debris flows. Based on our definition, landslides deliver sediment from hillslopes to channels and debris flows move down channels. Even though other definitions exist to distinguish landslides and debris flows (e.g. Cousssot and Meunier, 1996; Hunger, 2005), the definition adopted in this study appears most appropriate for distinguishing sediment supply from hillslopes and transport in channels using aerial photographs. We ignore travel distance of mass movements. Where landslides coalesced, landslide area downslope of the point of coalescence was added to the area of the larger of the two landslides.

Field survey

Volumes of 11 landslide scars, including their initiation and transport zones, were measured in the field to develop an approximate volume–area relationship for landslides within the catchment ($V = 0{\cdot}19 \times A^{1{\cdot}19}$: V, volume (m^3); A, area (m^2); $R^2 = 0{\cdot}86$, p value $<0{\cdot}01$). The landslides sampled ranged in size from 50 to 4000 m^2, covering the range of areas of most landslides in the catchment as identified by aerial photograph investigations. This relationship was used to estimate landslide volume from landslide area obtained by aerial photograph interpretations.

GIS analysis

Mapped landslides and debris flows were scanned and their location and areas were analysed using Arc GIS software. In this study, we define 'channels' as geomorphological features where sediment and water accumulate, identified by a line that continuously crosses slope contours at an angle less than 90° on the 1:5000 forest management maps (Figure 2b). Hollows are not classified as channels because their topography is not linear, and are by definition, not channelized (e.g. Tsukamoto and Ohta, 1988). Channels and hollows are distinguished by contours around them; contours of hillslopes on both sides of a valley are parallel alongside channels, whereas contours are not parallel and flow lines (lines perpendicular to contours) come from various directions to the valley bottom in and around hollows.

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Landslide and debris flow maps were overlain on forest management maps by GIS in order to analyse the impact of forest management on mass movements. Rainfall data monitored during the past 29 yr near the ridge of Sanko catchment (beside the summit of Mount Gomadan) were also compared with landslide data sets in order to clarify the relationship between rainfall and occurrence of landslides.

Results

Occurrence of landslides and debris flows

A total of 713 different landslides were identified in the 8·5 km^2 Sanko catchment on a series of aerial photographs taken from 1964 to 2002. Because 210 landslides were noted on aerial photographs taken in 1964 (the first period), 503 new landslides occurred from 1964 to 2002. A total of 121 landslides were initiated from roads in the Sanko catchment during the 1964–2002 period; these landslides were excluded from assessments in this study in order to clarify impact of clearcutting and subsequent forest regeneration on landslide occurrence. One limitation of aerial photograph investigations is that they cannot be used to identify smaller landslides; the threshold scale of non-visible landslides depends on forest cover conditions (Brardinoni and Church, 2003; Brardinoni *et al.*, 2003). Smaller landslides in older forests may be easily missed by aerial photograph surveys compared with those in younger forests; however, the relationship between forest age and minimum size of landslides identified by aerial photographs (ranging appropriately 20–45 m^2) was not clear in the Sanko catchment. Landslides in mature forests in the study site where sugi and hinoki (both conifers) were typically replanted in evenly distributed patterns can be identified easily on aerial photographs because landslides disrupt the regular pattern of trees. Differences in scale of aerial photographs among photograph periods (ranging from 1:15 000 to 1:20 000) may also affect the minimum size of visible landslides. Intensive field surveys conducted in some subcatchments revealed that landslides larger than about 50 m^2 were likely to be detected on aerial photographs. Thus, we set a minimum size of landslides for analysis as 50 m^2 to prevent error caused by differential recognition of smaller landslides amongst photograph periods. Based on both aerial photograph and field investigations, landslides typically occur at the bedrock surface or shallower depths, with an average depth of only 0·6 m. As such, these relatively rapid failures would mostly be classified as debris slides and debris avalanches (Sidle and Ochiai, 2006). Only a few landslides are associated with bedrock failure.

In the Sanko catchment, 146 debris flows originated in the period from 1964 to 2002, including 77 debris flows that were directly initiated by landslides (about 20% of the total landslides) and 69 debris flows that were caused by mobilization of channel deposits or bank failures.

Maximum daily rainfall and maximum hourly rainfall are highest in the period from 1984 to 1988; annual volumes of new and older landslides (which grew in size from the previous photograph period) were also highest in this period (Figures 4 and 5). However, the relationships between the annual volume of new landslides plus those that increased in size and rainfall factors (i.e. maximum hourly rainfall, maximum daily rainfall and maximum rainfall in rainy season) are not very clear (Figure 6). Therefore, other factors (i.e. influence of forest harvesting) should be considered when we discuss occurrence of landslides in the Sanko catchment.

Influence of forest harvesting on occurrence of landslide

To help quantify the effect of forest harvesting on occurrence of landslides, the time lag between forest harvesting around headwalls of landslide areas and occurrence of landslides was investigated using GIS. Because units of harvesting coincide with subcatchment boundaries, the entire landslide complex, including initiation and transport zones, resides in the same age forest. Both number and volumes of landslides in harvesting–landslide time categories (duration of 5 yr) were investigated. Because the areas associated with the specified harvesting–landslide time categories are not constant, volumes and numbers of landslides should be divided by respective land area of each category to establish a clear relationship between the time after harvesting and the number (and volumes) of landslides (Figure 7). Sediment supply rate from new or expanded landslides, calculated from the annual volume of new or expanded landslides divided by the area related to each time category is at a maximum 6–10 yr after forest harvesting while the frequency of landslides, calculated from the number of new landslides per year divided by the area related to each time category, is highest 1–5 yr after harvesting (Figure 7). Consequently, managed forests in Sanko catchment are most unstable in the period of 1 to 10 yr after forest harvesting. Sediment supply rate from landslides and frequencies of landslides in forests clearcut 1–10 yr earlier are about 10-fold and 6·5-fold higher, respectively, compared with control sites. Intervals of aerial photographs used for investigations range from 1 to 8 yr (average 4 yr); thus, estimated times between harvesting and landslide occurrence may include inherent differences of up to several years (Figure 7).

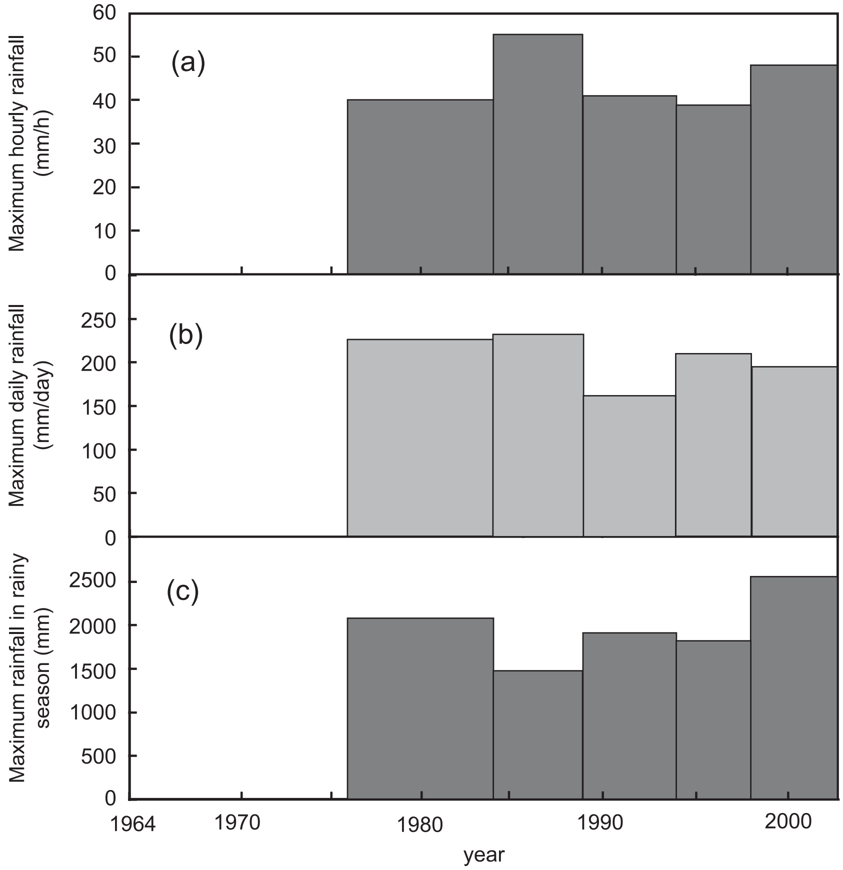

Figure 4. (a) Maximum hourly rainfall, (b) maximum daily rainfall and (c) maximum rainfall in a given rainy season (1 June to 31 October) for the various periods of aerial photograph interpretation in Sanko catchment.

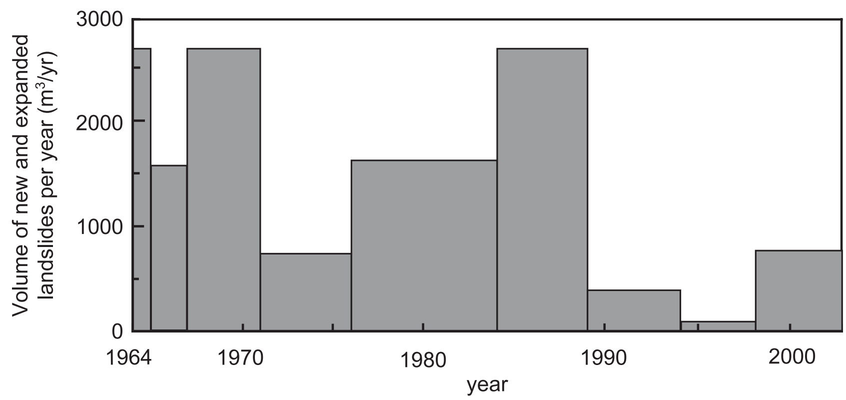

Figure 5. Total volume of new and expanded landslides (older landslides which grew in size from the previous photo-period) for the periods examined.

Tsukamoto (1987) investigated the strength of sugi roots and showed that roots begin to decay several years after cutting with most strength disappearing within 10 years. Therefore, root decay in 1–10 yr old forests accelerates occurrence of landslides (Figure 7). Both sediment supply rate and frequency of landslides decrease with increasing time after harvesting, particularly from 10 to 25 yr. Frequency of landslides in forests clearcut 26 to 40 yr earlier (average 0·50 km^2 yr) is similar to that of control sites (0·43 km^2 yr), indicating that slope stability almost completely recovers within 25 yr after harvesting.

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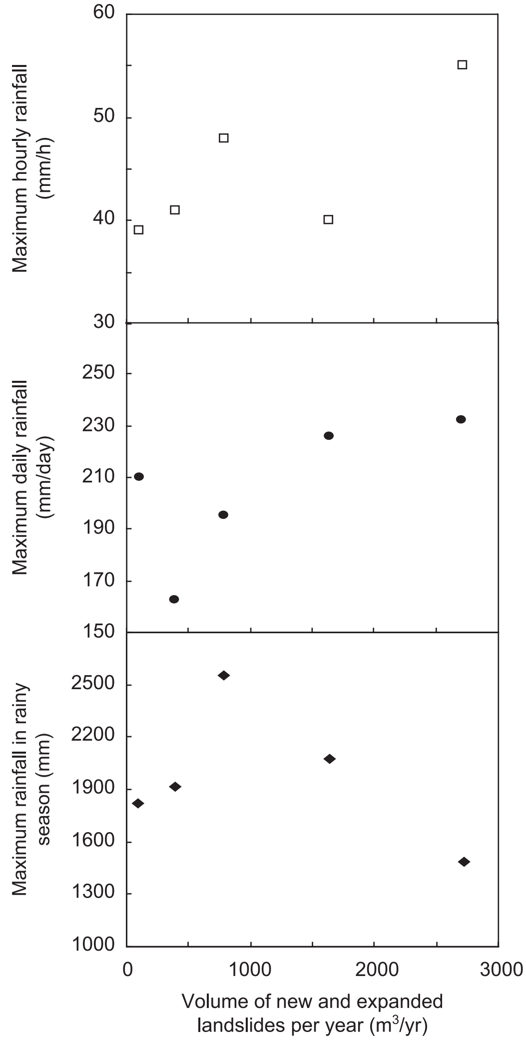

Figure 6. Comparison of rainfall attributes (i.e. maximum hourly rainfall, maximum daily rainfall and maximum rainfall in a given rainy season) and volume of new and expanded landslides (older landslides which grew in size from the previous photograph period).

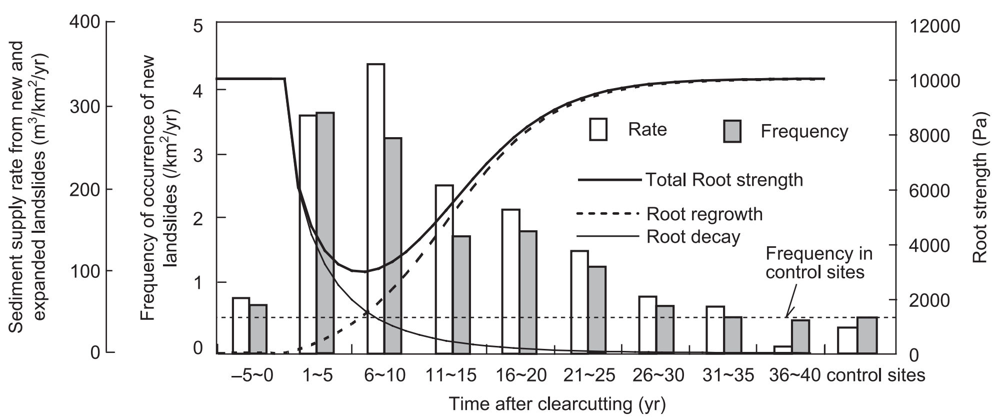

Figure 7. Changes in sediment supply rate from new or expanded landslides and frequency of occurrence of new landslides with time after clearcutting. Landslide rate and frequency are compared with the dynamic root strength values estimated by Sidle's (1991, 1992) model.

This hillslope stability recovery time in Sanko catchment is similar to that of recovery of the sugi root-strength (about 20 yr; Kitamura and Namba, 1981; Tsukamoto, 1987). Clearcutting may also change rainfall inputs and hydrology of hillslopes, thereby affecting slope stability (Keim and Skaugset, 2003; Dhakal and Sidle, 2004); however, our data are insufficient to investigate the effect of clearcutting on hillslope hydrology. Total landslide volume in forest stands clearcut 0 to 25 yr earlier (the period when effects of forest harvesting could be detected) was $5{\cdot}8 \times 10^3$ m^3 km^{-2}, whereas landslide volume in clearcuts older that 25 yr was $1{\cdot}3 \times 10^3$ m^3 km^{-2}, indicating that harvesting increases landslide volume by about fourfold compared with control sites.

The frequency and sediment supply rate of smaller landslides (<100 m^3) in forests clearcut 1 to 10 yr earlier (the period when hillslopes are the most unstable) is much higher than that in forests clearcut 25 to 40 yr earlier (the period when hillslopes stability fully recovers), while the frequency and rate of larger landslides (>200 m^2) does not change much between the two periods (Table I). Similar increases in numbers of smaller landslides in clearcuts have also been observed in other studies (Brardinoni *et al.*, 2002; Guthrie, 2002). The area–depth relationship of landslides developed by field surveys predictably shows that smaller landslides are shallower than larger landslides. Average depth of smaller landslides (<100 m^3) measured in the study site was about 40 cm. Lateral roots of sugi are generally restricted to depths of <50–60 cm in the soil profile and vertical roots affecting hillslope stability typically extend to <1 m (Tsukamoto, 1987). Roots of hinoki are mainly <1 m deep (Ishitsuka *et al.*, 2002). Thus, the depth of landslides that are exacerbated by clearcutting corresponds with depth of sugi and hinoki roots.

Comparison of maximum daily rainfall and rates of sediment supply suggest that many landslides occurred in years with high daily rainfall events in both young and older regenerating forest stands (Figure 8). Heavy rainfall events

Table I. Landslide frequency and sediment supply rate of various landslide volume categories in forests clearcut 1–10 yr earlier (the period when hillslopes are the most unstable) and in forests cleacut 26–40 yr earlier (the period when hillslope stability has recovered).

	Frequency of occurrence of new landslides (km^2 yr^{-1})			Sediment supply rate from new landslides (m^3 km^2 yr^{-1})		
Landslide volume (m^3)	**1–10 yr forests (*A*)**	**26–40 yr forests (*B*)**	***A*/*B***	**110 yr forests (*C*)**	**26–40 yr forests (*D*)**	***C*/*D***
<100	2·08	0·28	7·5	110	16	7·0
100–200	0·41	0·08	4·9	58	14	4·1
>200	0·28	0·08	3·4	57	23	2·5

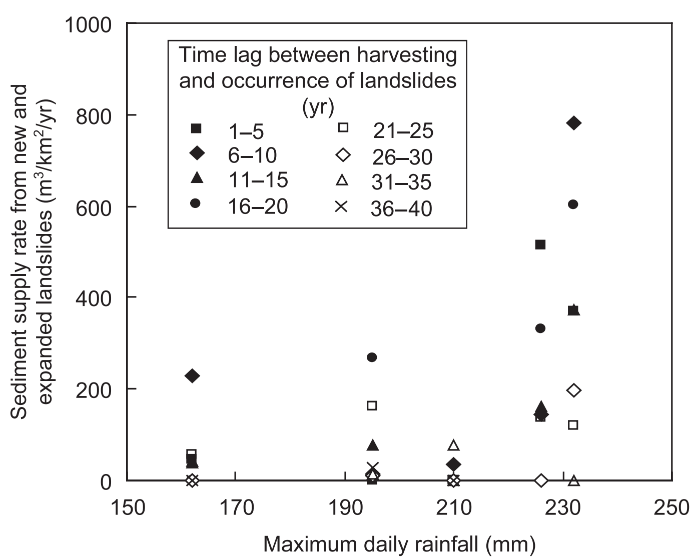

Figure 8. Comparison of maximum daily rainfall and sediment supply rate associated with new and expanded landslides which occurred in various age classes of forests.

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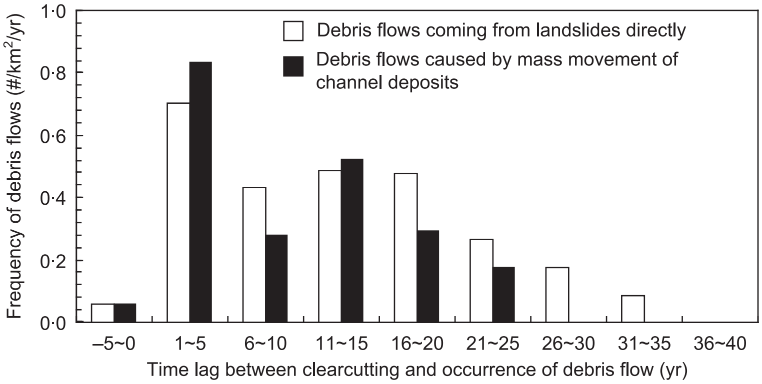

Figure 9. Frequency of new debris flows. Two types of debris flows are distinguished: those directly initiating from hillslope landslides and those occurring in and around channels.

augment pore pressure response that triggers slope failure (Sidle and Ochiai, 2006). Thus, rates of sediment supply are affected not only by forest harvesting, but also by rainfall factors.

Influence of forest harvesting on occurrence of debris flows

To clarify the relationship between forest harvesting and debris flow occurrence, the time lag between clearcutting and debris flow occurrence was investigated by GIS. Because harvesting units closely coincided with subcatchment boundaries, forest ages along debris flow paths were usually uniform (Figure 2a). Forest ages in initiation zones were used to calculate time lags for cases where forest ages along debris flow paths were not uniform. Because the areas associated with the specified harvesting–landslide time categories (duration of 5 yr) are not constant, frequencies of debris flows are calculated from the number of debris flows divided by the respective land area of each category (Figure 9). The frequency of debris flows in control sites was not studied because control sites did not coincide with subcatchment boundaries. The frequency of debris flows originating from landslides is distributed similarly to that of landslides (compare Figure 9 with Figure 7); frequency of debris flows initiated by landslides is greatest 1–5 yr after clearcutting and decreases with increasing forest age (Figure 9). The trends of frequencies of debris flows that initiated in and around channels is similar (Figure 9). For debris flows to initiate in a supply-limited basin, a sufficient volume of sediment must be stored in the valley (Bovis and Jacob, 1999); therefore, timing of debris flow occurrence near channels may coincide with direct sediment supply and/or accumulation from landslides. However, in some cases additional landslides may be needed to trigger a debris flow (e.g. Sidle and Ochiai, 2006).

The percentage of landslides with sediment that has travelled down through the channel system as debris flows differed according to the size of landslides; these percentages for landslide volumes of <100, 100–200 and >200 m^3 were 6, 17 and 30%, respectively. Thus, most of the smaller landslides that were exacerbated by harvesting do not directly cause debris flows, indicating that environmental impact in channels is not as great as for larger landslides.

Discussion

Forest harvesting effects

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

$$R = (a + b\mathrm{e}^{-kt})^{-1} + d \qquad (1)$$

where R (dimensionless) is the actual root cohesion divided by the maximum root cohesion (dimensionless), t is the time elapsed since harvesting (yr), and a, b, d and k are empirical constants. The empirical coefficients based on the uprooting tests for sugi trees are $a = 0{\cdot}952$, $b = 19{\cdot}05$, $d = -0{\cdot}050$ and $k = 0{\cdot}250$ (Sidle, 1991). Sidle (1992) predicted the root strength decline (D) using the following equation:

$$D = \mathrm{e}^{-lt^{n}} \qquad (2)$$

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where D (dimensionless) is the actual root cohesion divided by the maximum root cohesion and l and n are empirical constants. Unfortunately, the decay coefficients for sugi and hinoki were unavailable. However, the decay coefficients for coastal Douglas fir ($l = 0{\cdot}506$ and $n = 0{\cdot}730$; 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). 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 kPa). Changes in hillslope instability attributed to both changes in landslide frequency and sediment supply rates from landslides are inversely proportional to the changes in net root strength calculated by Sidle's model (Figure 7). Thus, the temporal manifestation of landslides in the Sanko catchment can largely be explained by the root strength model.

Many statistical studies revealed that clearcutting accelerates the occurrence of landslides and debris flows; however the impact of logging is different for each area (Jakob, 2000; Brardinoni *et al.*, 2002; Guthrie, 2002). To explain such differences in the magnitudes of forest harvesting effects, the mechanics of root reinforcement related to slope stability should be considered. The factor of safety (FS) for slope stability is given by the following equation (Sidle, 1992):

$$FS = \frac{C + C_R + \left\{\left[(Z - h)\gamma_m + h\gamma_{sat}\right]\cos^2\alpha - u + W\cos\alpha\right\}\tan\phi}{\left[(Z - h)\gamma_m + h\gamma_{sat}\right]\sin\alpha\cos\alpha + W\sin\alpha} \tag{3}$$

where C is the effective soil cohesion, C_R is the cohesion attributed to root systems, γ_m is the unit weight of soil at field moisture content, γ_{sat} is the unit weight of saturated soil (γ_m and γ_{sat} may not vary much in the same area), Z is the vertical soil thickness, h is the vertical height of the water table relative to the base of the soil, α is the slope gradient, u is the pore water pressure on a saturated failure plane, W is vegetation surcharge and ϕ is the effective internal angle of friction. Several sensitivity analyses of the effects of realistic changes in vegetation surcharge (due to harvesting) on FS suggest that the contribution of W is negligible for most potentially unstable site conditions (Gray and Megahan, 1981; Sidle, 1984, 1992). As demonstrated in Equation 3, slope stability is affected by C_R, as well as other factors, i.e. α (related to physiography of the forest landscape), ϕ (reflecting properties of soils and weathered bedrock), Z (soil depth) and h (related to both magnitude of rainfall and hillslope topography). Furthermore, the effect of C_R on FS changes with different values of Z, h and α that appear in denominator of Equation 3. To demonstrate the multiple influences of forest harvesting and other factors on slope stability, the relation between landslide frequency and slope gradient was investigated for each forest stand age (Figure 10). The difference in landslide frequency between 1–10 yr old forests (the period when hillslopes are the most unstable) and 26–40 yr old forests (the period when hillslope stability has recovered) is more obvious in steeper terrain. In steeper terrain, the third term in the numerator of Equation 3 decreases with increases in α, indicating that the relative contribution of C_R on slope stability increases.

As demonstrated here, the effects of forest harvesting are confounded by other factors, such as differences in geology, soils, physiography and climate that affect slope stability. In the Sanko catchment, average values and variances of Z, ϕ and α in Equation 3 would be nearly constant for each harvesting-landslide time lag category

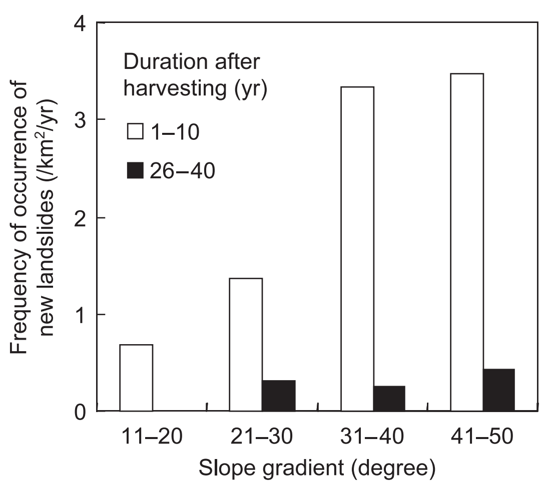

Figure 10. Landslide frequencies for various slope gradient categories in 1–10 and 25–40 yr old forests.

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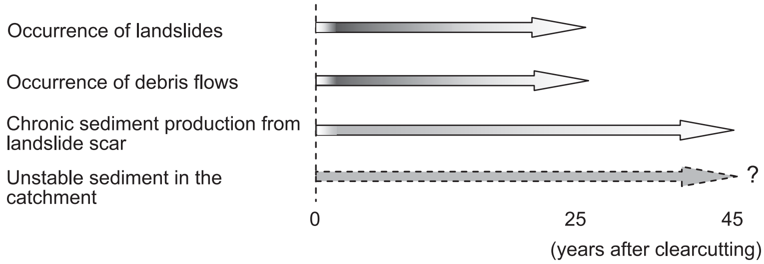

Figure 11. Impacts of landslides and debris flows induced by the forest harvesting: darkness of arrows indicates the relative magnitude of the impact and length of arrows indicates timing of impact.

because of the rather uniformly distributed geology, soils and slope gradients. The rotational forest management employed within the catchment yields a mosaic of different forest ages over the years, including years with abundant rainfall and years with little rainfall. Therefore, forests in each age category were exposed to various magnitudes of rainfall events, effectively averaging the influence of h in this study. Thus, our results directly reflect the effect of forest harvesting (Figures 7–10).

Timing of forest harvesting impacts

Landslides and debris flows induced by forest harvesting can cause natural hazards due to their destructive power; furthermore occurrence of landslides and debris flows cause other impacts in managed catchments, including subsequent sediment supply from landslide scars and increases in unstable sediment in the catchment (i.e. channel deposits, colluvium and debris fans). The timing and magnitude of each impact is required to evaluate the total and cumulative effects of forest harvesting (Figure 11).

The direct impact of landslide occurrence in the managed forests of Sanko catchment can be summarized as strongest for 1 to 10 yr after forest harvesting with progressively lesser impacts continuing up to about 25 yr after harvesting (Figure 7). Temporal patterns of debris flow frequency are similar to those of landslide frequency (Figure 9). The simultaneous occurrence of landslides and debris flows creates the most severe impacts because of the destructive power and large, instantaneous supply of sediment to channels associated with debris flows. We deduced such simultaneous linkages between landslides and debris flows for 20% of the total landslides that were documented in the catchment.

Because landslide scars continue to produce sediment after initial failure (Gomi *et al.*, 2004; Sidle and Ochiai, 2006), sediment supply from landslide scars must be considered in the long-term related to catchment sediment yields. Aerial photograph analysis in Sanko catchment showed that vegetation typically covers landslide scars about 20 yr (on average) after landslide occurrence. Because some influence of forest harvesting on landslide occurrence continues up to 25 yr after cutting, active sediment supply from landslide scars may continue until surrounding forest stands are about 45 yr old (20 yr + 25 yr; Figure 11). Channel deposits derived from landslides and debris flows may also continue to affect sediment yield in the catchment. The timing and magnitude of the impacts of channel deposits are affected by the volume and position of the deposits (Gomi *et al.*, 2004); however, it is difficult to estimate volume and position of deposits using aerial photographs. These factors may be important for the evaluation of longer term forest harvesting impacts.

Conclusion

Occurrence of landslides cause natural disasters by their destructive power as well as by increasing sediment yield in catchments (Chappell *et al.*, 2004; Gomi *et al.*, 2004; Constantine *et al.*, 2005). Thus, understanding the effects of forest harvesting on the occurrence of mass movement is important not only for natural hazard mitigation, but also for sediment control and aquatic habitat in and downstream of the catchment. In this study, the effects of forest age (after clearcutting and subsequent replanting) on mass wasting processes were investigated based on aerial photograph investigations and field surveys.

As demonstrated, trends of new landslide and debris-flow frequency correspond to changes in slope stability that can be explained by root strength decay and recovery (e.g. Kitamura and Namba, 1981; Tsukamoto, 1987; Sidle,

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1991). Magnitude and the timing of forest harvesting effects differ depending on both site (i.e. geology, soils, physiography and climate) and forest conditions (i.e. species and environmental conditions for tree growth; Sidle, 1991, 1992). Environmental factors that affect root strength decay and recovery are poorly understood, while effects of the geophysical conditions at a site have been modelled in previous studies (Sidle, 1991; Montgomery *et al.*, 2000). Because the respective shapes of the root strength recovery and decay curves can be quantified by the same functions independent of environmental conditions and species (even though coefficients are affected by those conditions; Sidle, 1991, 1992), the general trends of temporal changes in slope stability related to forest harvesting obtained in the Sanko catchment (except magnitude and timing) may be similar in other areas. To estimate magnitude and timing of forest management impacts on occurrence of landslides and debris flows in other regions, changes in root strength caused by decay and recovery should be investigated for various species and environmental conditions.

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