

## CASE STUDY:

# SLOPE STABILITY: BENEFITS OF FOREST VEGETATION IN CENTRAL JAPAN

Prepared by Dr Roy Sidle, Disaster Prevention Research Institute, Kyoto University, Japan, for the report *“The Role of Environmental Management and Eco-Engineering in Disaster Risk Reduction and Climate Change Adaptation”* (ProAct Network 2008), available at [www.proactnetwork.org](http://www.proactnetwork.org)

## 1. BACKGROUND INFORMATION

Much controversy and confusion exists related to the role that woody vegetation plays in stabilizing hillslopes. A clear understanding of the benefits of woody vegetation and the conditions under which it can and cannot stabilize hillslopes are essential for planning revegetation projects in unstable areas and managing existing forests in a sustainable manner. What has been lacking in most previous studies is a long-term perspective on the effects of forest cutting and regeneration on slope stability with an area of similar geology, soils, and climate. Here landslides are examined over a 40-year period in the relatively small, unstable catchment in central Japan. This case study is unique because soils, lithologies, rainfall, vegetation type, and slope conditions are very similar throughout the catchment, and 95% of the area has been harvested for timber production at various times within smaller sub-catchments with accurate records dating back to 1912.

Woody vegetation, particularly trees, can stabilize hillslopes in two ways: (1) modifying the soil moisture regime through evapotranspiration processes; and (2) providing root cohesion to the soil mantle. The first factor is generally not very important for shallow landslides and debris flows that occur during an extended rainy season, except possibly in the tropics and sub-tropics where evapotranspiration is high throughout the year (Sidle and Ochiai, 2006). In most temperate regions, soils are nearly saturated and evapotranspiration is low during autumn and winter rainstorms when slope failures typically occur, thus, soil water content is only minimally affected by the small water losses attributed to evapotranspiration (Sidle et al., 1985). A study on Vancouver Island, British Columbia revealed that reduced evapotranspiration following logging may increase pore water pressures during moderate-sized winter storms, but for the large storms in which landslides generally occur, differences in pore water pressure due to logging were difficult to detect (Dhakal and Sidle, 2004). However, evapotranspiration facilitated by trees could extend the “window of susceptibility” for shallow landslides and debris flows if a large storm occurred near the beginning or end of the rainy season (Megahan, 1983; Sidle et al., 1985). Also, when large and high intensity storms occur during drier conditions, evapotranspiration may reduce the susceptibility to landsliding (Sidle and Ochiai, 2006). Depth of rooting also affects soil moisture depletion; deep-rooted species can sustain maximum transpiration rates for greater durations, thus drying the soil at greater depths compared to shallow-rooted vegetation (McNaughton and Jarvis, 1983). The benefits of such deeper soil water withdrawals on landslide susceptibility have not been investigated, but could alter the timing and reduce the movement of deep-seated landslides in the tropics where evapotranspiration is high year-round (Sidle and Ochiai, 2006). Conifer trees can also modify the soil moisture regime by

interception and subsequent evaporation of snow from canopies; this reduces the recharge of water into soil during snowmelt (Golding and Swanson, 1986). Thus, areas without forest cover would have deeper snowpacks than if conifer forests were in place and this greater snow accumulation could raise shallow groundwater levels during snowmelt, thereby increasing the probability of landslides (Megahan, 1983). Additionally, the timing of snowmelt would generally occur later with conifer cover than without conifer cover (Sidle and Ochiai, 2006).

A more significant contribution of woody vegetation to the stability of hillslopes is the additional strength imparted within the soil mantle by root systems. In shallow soils, tree roots may penetrate the entire soil mantle and anchor the soil into more stable substrate (e.g., Wu et al., 1979). Dense lateral root systems in the upper soil horizons form a membrane that stabilizes the soil (e.g., Schmidt et al., 2001), and larger tree roots can provide reinforcement across planes of weakness along the flanks of potential slope failures (Sidle et al., 1985). As such, the contribution of roots to soil strength has been considered as an additive cohesion component by numerous investigators (e.g., O'Loughlin and Watson, 1979; Abe and Ziemer, 1991; Sidle, 1991). Additionally, tree trunks may provide arching and buttressing support within the soil (Gray and Megahan, 1981). Most of this field and experimental evidence suggests that root strength contributes significantly to the reinforcement of shallow soil mantles (i.e., < 1 to 2 m deep), but does not significantly affect deeper (> 5 m depth) landslides.

Only cursory evidence has been presented for cases where trees may actually destabilize soils; most of these cases are very site specific and speculative. While root systems and organic matter from canopies support high infiltration rates in forest soils, there is no evidence that such natural mechanisms promote landslide occurrence by increasing soil moisture. Tree root systems often enhance the drainage of hillslopes via preferential flow paths, thus dissipating accretions in pore water pressure that could induce landslides (Chandler and Bisogni, 1999; Sidle et al., 2001). In certain isolated cases, trees may impose mechanical instability on slopes because of the effect of their weight and wind shear (Thorne, 1990; Millard, 2003). Generally, environments susceptible to such slope failures (e.g., oversteepened river banks, exposed ridgelines near canopy openings) can be easily identified and managed accordingly.

Past studies of the effects of timber harvesting (particularly clearcutting) provide insights into the benefits of reforestation of unstable sites. Field investigations in various areas of the Pacific Rim found that landslide rates increased by 2 to more than 10 times during the period of 3 to 15 years after clearcut timber harvesting (Bishop and Stevens, 1964; Endo and Tsuruta, 1969; O'Loughlin and Pearce, 1976; Megahan et al., 1978; Wu and Sidle, 1995; Jakob, 2000). This increase in landslide frequency and volume is related to the period of minimum rooting strength after clearcutting and prior to substantial forest regeneration (Figure 1). Such empirical field findings have been supported by research on mechanical straining tests of roots, both in the laboratory and in the field (Burroughs and Thomas, 1977; Ziemer and Swanson, 1977; Wu et al., 1979; Abe and Ziemer, 1991), as well as uprooting tests in the field (Kitamura and Namba, 1981; Phillips and Watson, 1994). During storms or intense periods of snowmelt when hillslope soils are in a tenuous state of equilibrium, the reinforcement from woody roots may provide the critical difference between stable and unstable site conditions, especially when soils are partly or completely saturated (Sidle, 1992). However, most of these field investigations have spanned areas of different soils and even lithologies, not to mention climate and vegetation conditions. Furthermore the length of most of these studies is not sufficient to remove the confounding effects of temporal climate patterns. Thus, a long-term perspective on the interactions of forest vegetation and slope stability is needed in an area with similar topography, geology, soils, and climate to confirm these prior empirical observations.

The project detailed herein was conducted while the author was employed as a Professor at Disaster Prevention Research Institute, Kyoto University, Japan, and was partly funded by a grant from the Japanese Society for the Promotion of Science. The land owner, Sanko Forestry Company, gratefully provided access into this catchment area and supplied records of past timber harvesting.

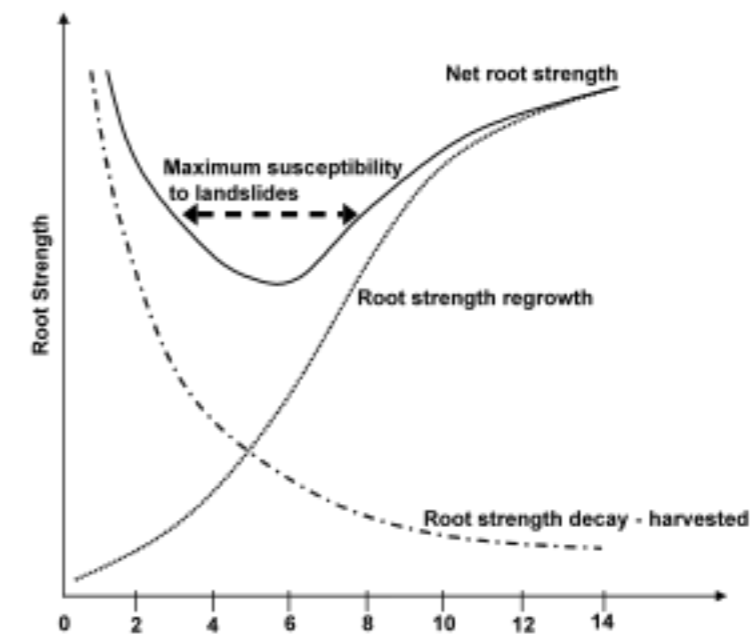


Figure 1. Conceptual changes in root strength after clearcut timber harvesting. Root decay and recovery curves are based on numerous data worldwide compiled by Sidle (1991, 1992). Net rooting strength is the sum of the decay and recovery curves.

## 2. PROJECT DESCRIPTION

The principle objective of the project was to quantitatively assess the effects of different forest stand ages on landslide frequency and sediment production from landslides. Associated with this major study objective is the application of knowledge gained to other forest management systems, such as reforestation of degraded lands and sustainable forestry management alternatives for unstable terrain.

This study was conducted within the 8.5 km<sup>2</sup> Sanko catchment, in southwestern Nara Prefecture, central Japan (Figure 2). This catchment is within the headwaters of Kanno River, a tributary of the larger Kumano River. Elevation within Sanko catchment ranges from 750 to 1372 m above sea level and slopes are steep (typical gradients 30°–50°) and relatively uniform throughout the catchment. The overall catchment is comprised of many smaller elongated and narrow sub-catchments of similar size (Figures 2 and 3). Annual rainfall is about 2500 mm, with heavy rainfall occurring during the Baiu season (June and part of July) and autumn typhoon season. Winter snowfall occurs at higher elevations within the catchment, but precipitation from December to February is only about 10% of total annual precipitation and typically does not contribute to landslide processes. Surface geology in the area consists of sandstone and claystone and is relatively homogeneous throughout the catchment. Soils are shallow cambisols, typically ranging from 0.5 to 1.0 m in depth.

The entire area is owned by Sanko Forestry and has been continuously managed since 1912. While the catchment is uninhabited, forest managers and laborers frequently work in this area. About 95%

of the catchment has been converted to Japanese cedar (sugi) with minor amounts of hinoki (Japanese cypress); the remaining area is secondary broadleaf forests, forest roads, and log landings. Landslides from these minor landscape features were not considered in this investigation because of their unique topographic locations. Since 1912, only clear-cut harvesting has been practiced within this catchment, and replanting typically occurs one or two years after logging. Both the sugi and hinoki forests are managed on rotation intervals of about 80 years. The forest management unit consists almost exclusively of the small (several hectare) subwatersheds (Figure 3). As such, there consists a unique mosaic of different ages of regenerating forest stands (representing different periods of clearcutting) that have experienced a wide range of rainfall conditions (that would trigger the landslides). Thus, by averaging landslides rates within various age classes of similar forest stands for long periods, the effect of rainfall episodes can be minimized related to assessing the effects of forest harvesting on landslide initiation. Because only low-impact, skyline logging has been conducted, we expect that timber yarding did not affect the occurrence of many landslides (e.g., Roberts et al., 2004). The older sugi and hinoki forests, which were replanted from 1912 to 1916, are considered here as control areas. These forests occupy about 9% of the entire catchment. The impact of logging in these older forest stands is assumed to be negligible.

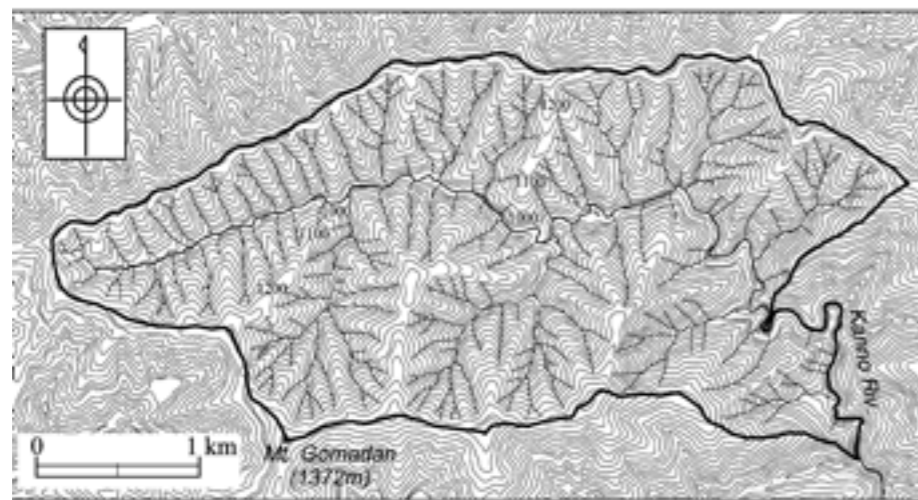


Figure 2. Map of the Sanko catchment in southwestern Nara Prefecture, Japan (from Imaizumi et al., 2008).

To assess the long-term effects of clearcutting on landslide occurrence in Sanko catchment, aerial photographs for ten different years (1964, 1965, 1967, 1971, 1976, 1984, 1989, 1994, 1998, and 2003) were analyzed. Both the location and area of landslides and debris flows within the various subcatchments were determined. Because most of the aerial photographs were taken in March (before the Baiu season) almost all of the landslides and debris flows identified by aerial-photo stereographs likely occurred prior to December of the previous year (i.e., during the summer Baiu or autumn typhoon seasons). Landslides and debris flows for each interval were assessed by comparing successive

aerial photographs. All failures on hillslopes were designated as landslides and all in-channel mass movements were considered debris flows.



Figure 3. Photograph showing several of the small, elongated subcatchments within Sanko catchment. Recent and past landslides and debris flows are evident.

Volumes of eleven landslides were measured in the field to develop an approximate volume-area relationship for landslides within the catchment. The sampled landslides varied in size from 50 to 4000 m<sup>2</sup> 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 (Figure 4).

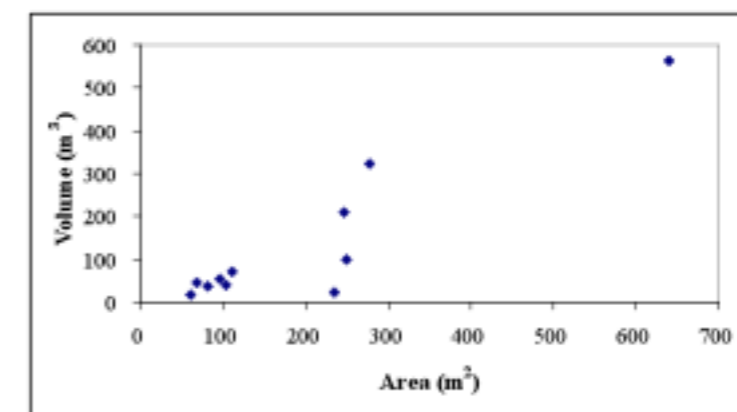


Figure 4. Relationship between landslide area and volume based on field investigations of 11 landslides of various sizes. Relationship is:  $V = 0.19 A^{1.19}$  where  $V$  is landslide volume (m<sup>3</sup>) and  $A$  is landslide area (m<sup>2</sup>);  $R^2 = 0.85$ .

### 3. RESULTS

To evaluate the effect of time since clearcutting on landslide frequency and volume of sediment produced, volumes and numbers of landslides were divided by the respective land area associated with successive 5-year intervals of timber harvesting – landslide time categories. The sediment supply is then the annual volume of new (or expanded) landslides divided by the area related to each time category. Sediment supply rate is at a maximum 6 to 10 years after timber harvesting, while the frequency of landslides is at a maximum 1 to 5 years after harvesting (Figure 5). Furthermore, the rates of both sediment supply and landslide frequency remain substantially higher than pre-logging rates for up through 21 to 25 years after clearcutting. These values correspond well with previously estimated effects of increased landslide susceptibility – i.e., a ‘window’ of about 3 to 15 years after harvesting when sites are more susceptible to landsliding. Total landslide volume per unit area in forests that were harvested from 0 to 25 years prior to the aerial photo identification was 4.46 times higher than similar landslide volumes in clearcuts that were greater than 25 years old.

Thus, the effects of clearcutting in the sugi and hinoki forests in Sanko catchment appear to disappear within 25 years after harvesting with increasing root strength of regenerating stands. Assuming that landslides frequencies and sediment supply rates from landslides in forests older than 25 years represent recovered conditions, a ratio of increase can be calculated for the most susceptible period (1 to 10 years after clearcutting) for different landslide volume classes (Table 1). The largest increase in both landslide frequency and sediment supply rates occurred for landslides smaller than 100 m<sup>3</sup> (7.5 - fold and 7.0 - fold, respectively). The smallest increases in landslide frequency and sediment supply rates in the first 10 years after clearcutting was observed for landslides larger than 200 m<sup>3</sup>: 3.4 - and 2.5 - fold increases, respectively (Table 1). Thus, it is apparent that trees provided the greatest stability benefits against smaller landslides. Since such landslides are the most numerous worldwide (Sidle and Ochiai, 2006), this is an important benefit of forest vegetation in controlling sediment releases in catchments. For all landslide size categories combined, the ratio of landslide frequency between forests 1 – 10 years in age and those 26 – 40 years in age was 6.3; this ratio was 4.2 for sediment supply rate.

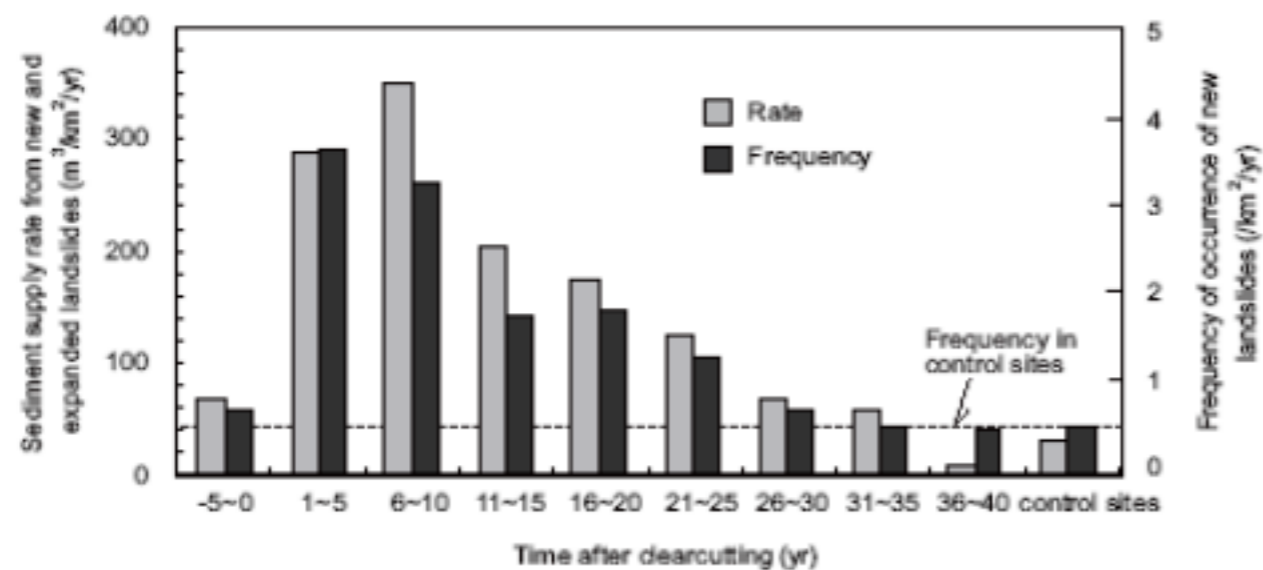


Figure 5. Frequency of landslides and sediment supply rate from new and expanded landslides for different time periods after clearcutting (modified from Imaizumi et al., 2008).

Landslide volume (m <sup>3</sup> )	Landslide frequency (number km <sup>-1</sup> yr <sup>-1</sup> )		Ratio of increase	Sediment supply rate from landslides (m <sup>3</sup> km <sup>-2</sup> yr <sup>-1</sup> )	
	Forests 1-10 yr old	Forests 26-40 yr old		Forests 1-10 yr old	Forests 26-40 yr old
< 100	2.08	0.28	7.5	110	16
100 – 200	0.41	0.08	4.9	58	14
> 200	0.28	0.08	3.4	57	23
<b>all landslides</b>	<b>2.77</b>	<b>0.44</b>	<b>6.3</b>	<b>225</b>	<b>53</b>

Table 1. Comparison of both landslide frequency and sediment supply from landslides in forests that were recently clearcut (age 1 – 10 years) and those which were harvested 26 – 40 years prior (modified after Imaizumi et al., 2008).

The frequency of landslides was also assessed for different slope gradient categories in both recently clearcut (1 – 10 years previously) forests and older (26 – 40 years ago) clearcuts. These findings showed large increases in landslide frequency in younger clearcuts for all slope gradient categories, especially on slopes steeper than 30° (Figure 6).

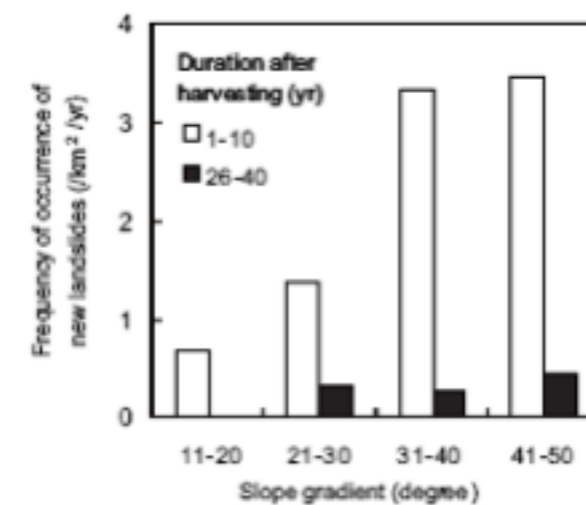


Figure 6. Landslide frequencies for various slope gradient categories in recently clearcut (1 -10 year ago) and 25 -40 year old forests (after Imaizumi et al., 2008).

### 4. SUSTAINABILITY

The findings of this case study have important implications for sediment hazard reduction in unstable areas where forest cover has been converted to other vegetation types with weaker rooting systems (e.g., pasture, agricultural crops, exotic plantations). Such cases are currently prominent in developing nations of Southeast and East Asia, Africa, and Latin America. Such land conversion scenarios have great impact on landslide susceptibility in steep terrain compared to careful and long-term planning of forest harvesting. The short-term benefits associated with growing agricultural crops and exotic plantations on steep slopes that are realized by rural residents in developing regions are strongly outweighed by the long-term declines in site productivity and increases in erosion, both surface erosion and landslides (Sidle et al., 2006). This case study clearly shows that forest cover can reduce landslide erosion by a factor of 4-5 compared to sites without substantial tree root strength.

These benefits appear to be primarily associated with reducing the frequency of smaller landslides. By establishing forests in steep terrain (which were formerly forested), we can regain the original stability of the land and gradually build up soil organic matter to prevent surface erosion and runoff. Once forests are successfully established on such lands, it is possible to manage them to support local incomes. Of course harvesting large blocks of trees will increase the susceptibility of landslides for a period of about 3 to 20 years after cutting (mostly during the first 10 years), but if other silvicultural practices are employed (e.g., partial cutting, leave areas in the steepest and most susceptible terrain), landslide erosion can be dramatically reduced (e.g., Sidle and Wu, 1999).

## 5. LIMITATIONS ON THE USE OF ECOSYSTEMS IN THIS PARTICULAR HAZARD

A major limitation to achieve successful reforestation of unstable lands in developing nations is dealing with the poverty cycle that land users are caught up in. An example is the situation in Sumber Jaya, Sumatra, where current residents were forced to transmigrate from Java during the Suharto regime several decades ago. Many of these people were coffee farmers and brought with them their original methods of monoculture coffee farming from Java where they cleared the soil surface in flat areas and established coffee plantations. These practices in the steep terrain of Sumber Jaya enhance runoff, surface erosion, and even cause landslides (Sidle et al., 2006); however, the residents wanted to earn more short-term income from coffee plantations than they could derive from the native rainforest. When coffee prices precipitously declined during the past decade due to the flooding of coffee markets by Vietnam, the farmers in Sumber Jaya could no longer sustain the profits they anticipated and subsequently started to convert coffee plantations on steep hillsides to vegetable gardens. These gardens have even more dire consequences for runoff, erosion, and landslides, not to mention the extensive site disturbance needed to remove coffee trees and establish vegetable crops. In such cases it is necessary for government agencies and international donors to step in and support sustainable forestry and reforestation programs. To control landslides and promote sustainability, it is necessary for governments to take a long-term, practical view of the projected demand for forest products and recognizing how this can be best realized by planning forest harvesting in the most sustainable manner (Sidle et al., 2006). Such schemes need to supply farmers with short-term subsidies or incomes in the interim while forests establish to break this vicious cycle.

## 6. CARBON BENEFITS

Any reforestation scheme has carbon benefits based to the dynamic sequestration of carbon in root biomass, soils, and above ground biomass. For degraded lands, this benefit may accrue for some time as carbon stocks in soil accumulate; however, the benefit will be greatest during the initial cycle of tree establishment. Some releases in carbon to the atmosphere will occur later during the decomposition of organic materials on the forest floor, but these will be outweighed by carbon sequestered in tree biomass production and the photosynthetic process.

## 7. CONCLUSIONS AND LESSONS LEARNED

It is clear that forest cover provides the most effective protection against shallow landslides compared to all other types of vegetation. The maintenance of that cover can be achieved with careful management objectives that will allow land owners to derive economic benefits from the forests. While clearcutting has the greatest impacts on slope stability of all silvicultural practices, it can still be successfully executed providing that leave areas be established in particularly susceptible sites like steep slopes (e.g.,  $> 40^\circ$ ) and concave slope depressions (hollows) that accumulate subsurface water. The harvested portion of the forest will be more susceptible to shallow landsliding for a period of about 3 to 20 years after clearcutting (particularly the first 3-10 years), but the utilization of leave areas will greatly reduce the overall landslide vulnerability. Additionally, other silvicultural practices can be employed (e.g., partial cutting) that will retain more root strength on hillsides and thus further reduce the impact of harvesting on landslide initiation. Benefits of forest cover related to deep-seated landslides are not so great, except possibly in the tropics.

In this case study, older forest vegetation with mature root systems reduced landslide erosion and sediment delivery to streams by 4 to 5-fold compared to young forests with little root strength. These findings are significant as this is one of the only studies which took a long-term perspective of landslide initiation in a contiguous area of similar topography, soils, geology, and climate. These reported differences would be even greater for scenarios where forests in similar terrain were converted to agricultural crops or exotic plantations with little root strength. And the effects would persist as long as the converted vegetation was in place, not the 3-20 year 'window' of susceptibility typical of managed forests. Thus, substantial benefits can be achieved by reforestation of steep terrain that has already been converted to cropland or exotic plantations.

It should be noted that the important issue of road-related landslides was not addressed herein, as the focus of this study was to assess the benefits of forest vegetation on slope stability. In any project that attempts to reduce the overall effects of land management practices on landslide initiation, mountain roads must be considered as they represent the most prodigious source of landslide erosion per unit area impacted (Sidle and Ochiai, 2006). Combining sustainable forest management practices together with stable and well-maintained road locations is the best combination to reduce overall landslide hazards and associated sediment losses to streams.

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