RAP PUBLICATION 2011/19

Forests and landslides

The role of trees and forests in the prevention of landslides and rehabilitation of landslide-affected areas in Asia

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by

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in collaboration with

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FOREWORD

Understanding the roles that trees and forests can play in preventing landslides is becoming more important as sloping areas in Asia are further developed and climate change impacts loom. Roles of trees and forests in rehabilitating landslide affected areas are similarly important because of the impacts of landslides on water resources and water quality, in particular. Against this background, much attention is being given to climate change adaptation in the region. Current rural development trends and predictions of increasing incidence of extreme weather events heighten the need for consolidated information on the roles of forests and forestry in relation to landslides.

With natural disasters becoming increasingly frequent in the region, interest in maintaining forests for the environmental services they provide is growing. In several countries in Asia, floods, droughts and landslides have precipitated major policy realignments that have centred on forests and forestry. The resulting policies have, however, often attracted criticism for their poor technical foundation and disregard for socio-economic considerations. Such experience emphasises the need for policies to be based on sound science and balanced assessments of the distribution of costs and benefits to across society.

FAO is pleased to contribute to increased awareness and understanding of the roles of trees and forests in the prevention of landslides and rehabilitation of landslide affected areas through this publication. It is hoped that by bridging the gap between science and policy and providing a sound basis for decisions involving forests and landslides, a safer and greener future will result. It is intended that the information provided will be used in conjunction with economic, social and environmental information to improve management of forests on sloping land both in Asia and elsewhere in the world.

Hiroyuki Konuma
Assistant Director-General and
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ABSTRACT

The potential for loss of life and assets from landslides is increasing in many mountainous and hilly areas of Asia. Logging, residential and infrastructure development and other activities continue to expand on slopes with high risk of landslides. Excessive soil water content is the primary cause of slope failure while steep slopes, weak soils, or topography that concentrates water are the main factors contributing to landslide risk. Poorly constructed roads and the loss of soil reinforcement and water extraction by tree roots increases the probability of landslides during triggering events such as prolonged heavy rainfall or earthquakes. Climate change predictions suggest that landslide frequency will increase in some areas of Asia as the frequency of extreme storms increases. Drought may also affect some areas resulting in root dieback, pest and disease outbreaks and wildfire – all of which are likely to reduce soil root reinforcement and increase landslide incidence.

Scientific studies confirm the crucial role of trees and forests in preventing landslides, not only by reinforcing and drying soils but also in directly obstructing smaller slides and rock falls. The role of trees and forests in relation to deep seated landslides is considerably less although soil drying by tree roots can still help avoid excessive soil water pressures. During extreme events, involving copious rainfall, very weak slopes or seismic activity, forest cover is unlikely to have any effect. Policies encouraging land uses which reduce soil disturbance and retain a high degree of forest cover can, however, reduce landslide risk. Tree planting on susceptible slopes can also reduce risk while natural regeneration and tree planting on failed slopes can help control landslide after effects such sediment release into rivers. Fast growing trees and shrubs are best suited but socio-economic and conservation related factors should also be considered. Above all, however, identifying and mapping high landslide risk zones and avoiding activity within these areas is an essential step in reducing risk posed to life and assets by landslides.

1. BACKGROUND[†]

Steep terrain, vulnerable soils, heavy rainfall and earthquake activity make large parts of Asia highly susceptible to landslides.[19] With population growth, expansion of infrastructure, and increased forestry and agricultural activity in sloping areas, the significance of landslides is set to increase in the coming years. In temperate and tropical Asia, projected climate change related impacts, including increased frequency of extreme rainfall events, and heightened risk of forest dieback and wildfire, are likely to result in compound effects on landslide incidence.[40]

In Asia, as natural disasters have become more frequent, major natural resource-related policy realignments have been triggered. In the 1990s, Asia suffered 75 percent of global deaths from natural disasters.[223] Water related issues - floods, landslides and droughts - have been perhaps the most significant driver of forestry-related policy change (Box 1). For example, the logging bans in Thailand, the Philippines, and in China were largely the result of the perception that landslides, floods, and droughts were consequences of deforestation. However, there is a lack of precise understanding of the role of forests in relation to these disasters and in watershed management in general.[65, 91] In this context, it is clear that reference to accurate technical information is essential if policy prescriptions are to provide benefits in economic, social and environmental terms and avoid unnecessary costs.

As well as causing fatalities and damaging residential and commercial areas and infrastructure, landslides cause environmental problems. For example, by damaging or destroying forest and agricultural resources, removing topsoil and reducing land productivity, blocking rivers and increasing downstream sedimentation.[165,129,18] Bursting of rivers blocked by landslides has also caused downstream disasters.

By understanding the factors that influence landslide incidence, damage can often be avoided by relocating settlements or activities away from high risk areas or, by adopting precautionary measures. The preponderance of landslide deaths in poorer countries and experience in the region successfully mitigating landslide risk suggest that much can be done to limit future losses associated with landslides.[19,101]

The objective of this publication is to describe the extent to which

(i) the preservation of forests or planting of forests can reduce the incidence of landslides; and

(ii) forestation projects are valuable in land rehabilitation and stabilization after landslides occurrence.

This section includes an overview of the distribution of landslide incidence and recent trends in landslide frequency in Asia while Sections 2 and 3 detail why landslides are a growing hazard and how trees and forests are useful in landslide reduction. Section 4 outlines the implications of climate change on landslide incidence and Section 5 reviews the practices for managing landslide risk, including rehabilitation of landslide affected areas. Sections 6 and 7 include key findings and recommendations for policy-makers.

1.1. Forests and landslide prevention

Landslides encompass a wide range of phenomena including slumps, rock falls, debris slides, and earth-, debris- and mud-flows. Landslides may be shallow or deep-seated and are caused by changes in slope stability resulting from undercutting, changes in water saturation or loss of woody vegetation. Activities that increase erosion and slope instability in uplands include logging, road and trail construction and forest conversion. In undisturbed forest catchments landsliding is usually

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[†] Citations indicated by numbers in superscript are listed at the end of the publication.

low.[196]

Figure 1.1. Patterns of old logging on 40-45° slopes associated with high landslide density on Kamanshi River, Yamanashi Prefecture, Southern Japanese Alps. Logging took place 5 years before the photo was taken. Notice clogging of river channel and overrun check dams

Source: Yuichi Onda

Landslide risk and the selection of stabilization measures depend on bedrock characteristics, hillside hydrology, slope gradient, length and curvature, and soil depth and type. Vegetation cover also plays an important role. Deep-rooted trees and shrubs can reduce the occurrence of shallow rapidly moving landslides by strengthening soil layers and improving drainage.[91,177] In shallow soils, roots may penetrate the entire soil mantle, providing anchors into more stable layers while dense lateral roots stabilize soil surface layers against landslides.[173] Transpiration via extensive root systems also reduces soil water content and landslide risk.[177,45] Additionally, forests can play a role in attenuating and blocking smaller debris flows and rock falls by forming a physical barrier.[87]

Deep landslides resulting from continuous heavy rainfall or earthquakes are less likely to be affected by vegetation.[91] Vegetation is also of little use on undeveloped and unstable soils which support few trees, such as volcanic deposits which cover a significant area in Asia.

Landslide risk is greatly increased by slope disturbance especially where appropriate precautions are lacking. Roads, which are often built in conjunction with agricultural or forestry activities, contribute the largest landslide losses compared to other land uses – one to two orders of magnitude higher than in undisturbed forests on steep land.[177] Across much of rural Asia, upland roads are often built without adequate attention to engineering standards and as such are a frequent cause of landslides.

With respect to vegetation removal, studies in temperate regions have shown that clearance of forests on sloping land increases landslide risk by reducing rooting strength for up to two decades.[177] Landslides begin to increase when roots decay at around three years after forest clearance and susceptibility remains high until around 15 years when regenerating roots mature. Rates of root recovery are likely to be significantly lower outside tropical areas.

Conversion from trees to crops or grazing land significantly reduces rooting depth and strength, and also means that soils are dried to a lesser depth and degree due to shallower rooting patterns and lower levels of transpiration. These alterations increase landslide risk and may be compounded by activities and factors associated with agriculture such as tillage and terracing, low soil cover and reduced infiltration.[177,123,73] Given these impacts, maintenance of forest cover is particularly important in areas where slopes are greater than 45-55 percent or are concave, or where soils have low cohesion, or cover bedrock or an impermeable layer.[124]

1.2. Forests and landslide rehabilitation

Following landslides, timely stabilization of affected sites can help mitigate ongoing sedimentation of streams, prevent further landslides and mudflows, and re-establish livelihoods of local communities. Appropriate techniques depend on the substrate and slopes must also be sufficiently stable if slope stabilization work is to be carried out. Microbial and nutrient biomass takes time to redevelop and different species may be more suited to new conditions than those previously present.[181] Rapid, successful reforestation with larger seedlings shortens the period without vegetative cover or root reinforcement and higher seedling densities may result in more rapid canopy development and root recovery. Although individual species play an important role, higher levels of plant diversity generally associated with natural regeneration, may increase slope stability above that offered by monospecific and single age plantings.[73]

In addition to ecological factors, a range of other issues are also of importance in rehabilitation following landslides including the economic and social benefits of trees in comparison with other vegetation types or engineered ground stabilization measures. Land tenure and regulatory conditions prevailing in the target area are also of importance in determining the suitability of different slope stabilization options.

1.3. Landslide trends in Asia

Assessing trends in the incidence of landslides is hindered by the fact that accurate records on landslides are rarely collected. Damage due to landslides is also often recorded as damage due to other natural disasters with which landslides are commonly associated, such as earthquakes, floods or cyclones.[19, 147] As such, the extent of damage done by landslides is underreported. Available statistics nonetheless imply that the decadal frequency of landslides causing death or affecting people in Asia has increased more than five-fold since the 1970s with 88 recorded landslides resulting in 5 367 mortalities between 2000 and 2009 (Figure 1.2). Some of this increase is likely to be due to better communication and reporting in more recent decades, in addition to increased activity in sloping areas and climatic changes.

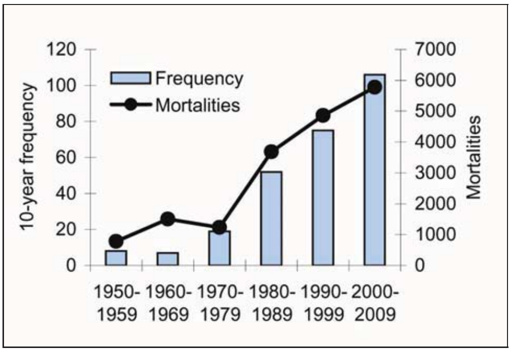


Figure 1.2. Decadal frequency of landslides and mortality rate in Asia
Source: International Disasters Database: http://www.emdat.be

Between 1950 and 2009, the frequency of fatal landslides was highest in China, followed by Indonesia, India, the Philippines, Japan, Pakistan and Nepal. These seven countries accounted for 87 percent of the 17 830 landslide-related fatalities reported in Asia between 1950 and 2009 and 82 percent of the total 267 reported landslides. Relative to population in 2000, total fatalities between 1950 and 2009 were highest in Nepal (71.1 per million), followed by Philippines (35.4), Indonesia (10.6), Republic of Korea (7.4), Malaysia (6.5), Sri Lanka (6.4) and Japan (6.3).

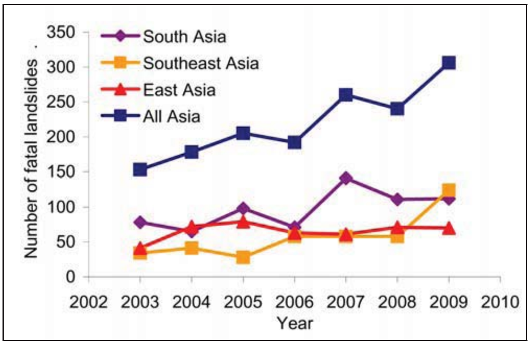


Figure 1.3. Number of fatal landslides in Asia by subregion 2003, 2009 (excl. earthquakes)

Source: David Petley

Information from the Durham Fatal Landslides Database (DFLD)[146] independently shows rising incidence of fatal landslides over the past decade, particularly in Southeast Asia (Figure 1.3). The annual average number of fatal landslides recorded in Asia between 2003 and 2009 was 219, more than three times the number recorded in the International Disasters Database for the same period.[145] The difference results primarily from the inclusion of landslides with fewer than 10 fatalities in the DFLD. Both databases indicate an increasing frequency of landslides over time. The increase is thought to be due to increasing precipitation frequency, intensity and/or duration; deforestation, population growth; urbanization; and infrastructure development.[145]

Observed total mortality in landslides triggered by precipitation is estimated to be approximately six times higher than in landslides triggered by earthquakes.[101] In general, poor countries have significantly higher levels of landslide mortality than wealthier countries due to lower prevailing levels of human development.[101] The occurrence of fatal landslides is heavily influenced by high rates of tectonic processes, the occurrence of monsoon rainfall and the presence of a vulnerable population.[146] The total number of people potentially exposed to landslides is estimated to be greatest in India, followed by Indonesia, China, the Philippines, Japan and Taiwan Province of China.[101] In Indonesia and the Philippines exposure to landslides resulting from precipitation is proportionately greater whereas in Japan and Taiwan earthquakes are of greater significance. Excluding landslides associated with earthquakes, the annual number of fatalities resulting from landslides in Asia between 2003 and 2009 is 2,585. [145] For the same period, an annual average of only 538 fatalities are recorded in the International Disasters Database.[225]

Mortality risk from precipitation triggered landslides, estimated by combining information on hazard type and destructivity, population exposure and vulnerability, demonstrate relatively high levels of risk in many parts of Asia (Figure 1.4). Five key landslide locations in Asia have been identified:[145] (i) the southern edge of the Himalayan arc' (ii) Central and SE China; (iii) Philippines and Taiwan (iv) Indonesia/Java; and (v) southern India and Sri Lanka. All of these areas are associated with high seismic hazard. In national terms, risk is estimated to be highest in China, Indonesia, Myanmar, Philippines, India and Nepal.[101] In DPR Korea, Japan, Viet Nam, Bangladesh and Pakistan mortality risk is also estimated to be high. Per unit population, Timor-Leste and Bhutan are assessed as having the highest levels of risk in Asia, followed by Brunei, Lao PDR and Nepal.

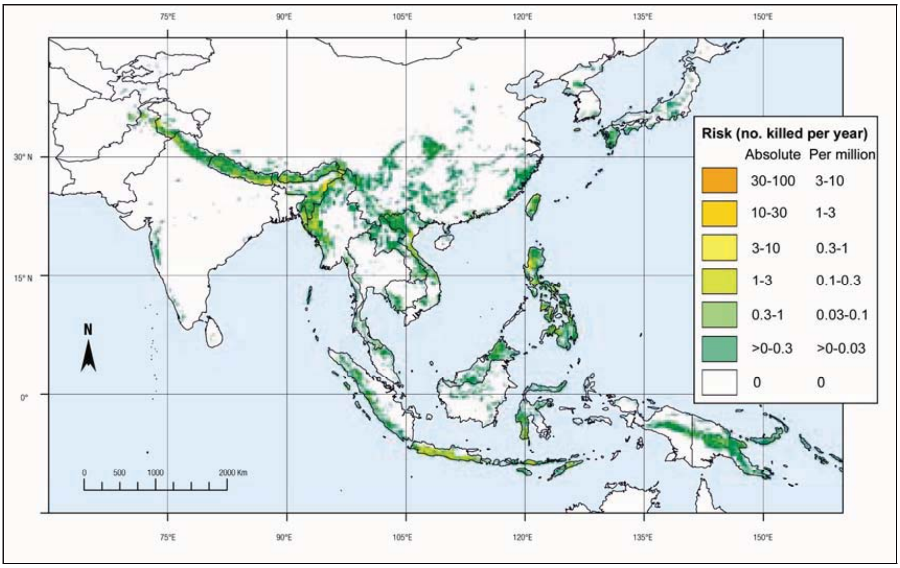


Figure 1.4. Mortality risk distribution for landslides triggered by precipitation

Source: ISDR 2009.

With population in Asia set to expand by 10 percent, from 3.8 to 4.1 billion, between 2010 and 2020, the impacts of landslides will likely increase. This is demonstrated in the experiences of Hong Kong, as records clearly show increases in landslide frequency as the territory became more densely populated and hillside cutting increased.[19]

1.4. Climate change links

The close association between landslides, rainfall and other climatic variables make future changes in climate particularly important in estimating the future significance of landslides. Changes observed in extreme events and climate anomalies in Asia over past decades, although not necessarily evidence of climate change, have included increased occurrence of extreme rains causing flash floods in Viet Nam; landslides and floods in the Philippines in 1990 and 2004; and floods in Cambodia in 2000.[40] Generally, the frequency of occurrence of more intense rainfall events in many parts of Asia has increased, causing severe floods, landslides, and debris flows and mud flows.[40] Other changes in past decades have included:

- In western and southern China extreme rains have been increasing in the last decade. An increase in the intensity of summer rains in eastern China has also been recorded;
- In Japan, extreme rains have become more frequent over the past 100 years and an increase in maximum rainfall has also been recorded;
- In South Asia, and in Bangladesh, Nepal and North-East India in particular, increases in extreme rainfall events have been reported and increases in the intensity of cyclones in the Bay of Bengal have been recorded in recent years;
- More frequent cyclones in the Philippines and stronger as well as more frequent cyclones in China have been recorded.

Rapid thawing of permafrost and decrease in depths of frozen soils due largely to rising temperature has threatened many cities and human settlements and has caused more frequent landslides and degeneration of some forest ecosystems in China and Mongolia.[40]

In the period to 2039, precipitation is expected to increase over most of Asia, particularly during the northern hemisphere winter. Most regional climate change studies project changes in the seasonal distribution of rainfall, with drier and/or longer dry seasons and shorter, more intense wet seasons.[104] In South Asia, increased rainfall during the northern summer is expected, while in Southeast Asia little change is foreseen until 2040.[40] An increase in occurrence of extreme weather events including heat waves and precipitation events is predicted in South Asia, East Asia, and South-East Asia. In Japan significant increases in temperature and precipitation are predicted. Increases in tropical cyclone intensities by 10-20 percent are also expected in Asia while temperature is projected to increase by 0.7-1.8°C in South, Southeast and East Asia and 1.5-2.9°C in the Tibetan plateau and North Asia.[40]

Changes in climate are expected to cause increase in extreme rainfall events are likely to directly increase the frequency of landslides in sloping areas while cyclone winds may induce landslides by toppling trees, exposing bare soil and increasing saturation failures.[165] Also expected to raise the incidence of fire, forest dieback, and spread of pests, pathogens and invasive species, and are also likely to directly affect tree physiology, forest growth and biodiversity.[182, 40] By inducing root decay slope stability may be affected and fire is also likely to directly affect soil stability and permeability.[174] At the same time, increased road development and rising levels of human activity in forest areas are likely to increase the incidence of fire and may result in increasing cycles of forest devastation.[167] Maintenance of forest health and vitality is therefore likely to become increasingly important in slope protection as well as other climate change related goals.[45,236]

1.5. Protection forests extent and status

Figure 1.5 shows the proportion of national land area covered by forest and by protection forest in Asian countries.[66] Bhutan, Indonesia, Japan, Lao PDR, Viet Nam and Timor-Leste – some of the more landslide vulnerable countries in the region – all have significant proportions of their land area covered by protection forests. In other higher risk countries – China, India, Nepal, Pakistan, Philippines, Sri Lanka, and Thailand – protection forests have a smaller role. In the Republic of Korea, Malaysia, Myanmar, DPR Korea and Brunei where landslide risk is also significant, protection forests are less extensive although in these countries total forest cover is greater.

In China, the Republic of Korea, Myanmar, Thailand and Viet Nam the area of forests designated for protection has expanded significantly over the past 20 years, often as a result of programmes aimed directly at watershed protection.[57,58]

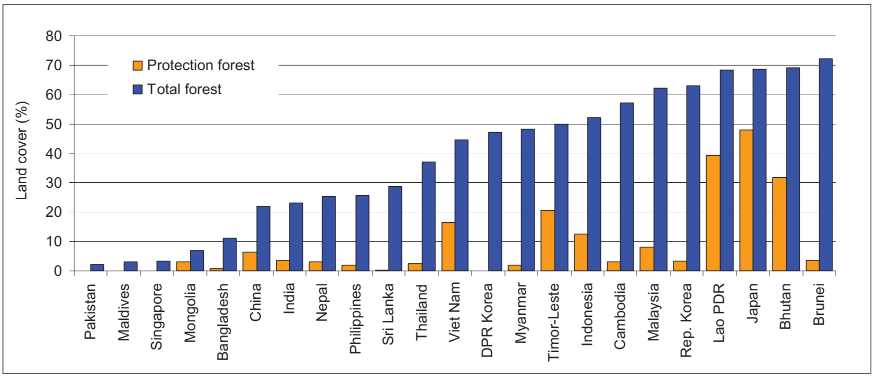


Figure 1.5. Total forest cover and cover of forest designated for protection Asian countries, 2010.[66]

Box 1. Policy responses to natural disasters

In several countries in Asia, natural disasters have prompted fundamental realignments of policy. In China, following water shortages in the Yellow River catchment in 1997 and catastrophic flooding of the Yangtze River in 1998, two major national programmes were implemented. The Natural Forest Protection Program (NFPP) and the Sloping Land Conversion Program (SLCP) included logging bans and reductions, conversion of sloping croplands and reforestation activities in several provinces.[31] The ban is controversial, however, with authorities having been accused of making excessive claims in relation to the downstream impacts of deforestation in northwest Yunnan.[103] The drought and flooding periods also coincided with strong El Niño and subsequent La Niña events, which may have contributed.

In the Philippines, recurrent devastating floods and landslides were attributed to illegal logging and land conversion and led to the pronouncement of logging moratoria, most recently in 2011.[86,122,178] The poor location of settlements and lack of flood adaptation accounted, however, for some of the most devastating effects, which were associated with debris flows. Reforestation, although proposed as a major response was perhaps inappropriate in relation to deep-seated landslides that occurred in primary forests within the affected area.

In Thailand, landslides in the south of the country following heavy rains in 1988 were linked to deforestation of steep slopes and, as most of the damage was on land cleared for cropping, a logging ban was subsequently implemented (Figure 1.6). Some reports suggested, however, that landslide density was independent of vegetation cover and that rainfall intensity had overwhelmed the stabilizing properties of vegetation.[148] Forest clearance and replacement with vegetation less capable of securing the soil – rubber in particular – was also suggested to have been of greater importance than logging.[155,33]

In most cases where radical policy changes have been adopted in response to natural disasters the technical basis has been challenged and knowledge on the nature of relationships between disasters and human activities – road building, deforestation, logging, agriculture, etc. – is still being refined.[65,91] Predicted increases in extreme weather events and natural disasters in the coming years can be expected to further influence policies related to forests and the environment. To avoid unwanted costs it is important that future policy responses should be based on a sound technical understanding.

Figure 1.6. Landslide scars in Southern Thailand following heavy rains in 1988

Source: Masakazu Kashio

2. WHY LANDSLIDES ARE A GROWING HAZARD

The causes of landslides are many and often complex, acting over timescales of minutes to millennia. Landslides occur when the force of gravity causes hillslopes fail and, as such, they are often associated with regions experiencing intense geological uplift, weathering and water-related erosion. The occurrence of a landslide is usually a direct response to one or more ‘trigger factors’ or external events of high magnitude that cause the slope to fail. Rainfall and earthquakes are the most common trigger events.

Throughout Asia, intense storms and rains extending over long periods trigger landslides, although drier regions are also subjected to landslides associated with earthquakes. Copious rainfall together with earthquakes compounds the problem, such that even small tremors can initiate landslides.

Longer-term changes to a slope, termed ‘preparatory factors’, also gradually change its stability state.[39] Frequently, changes in land use that result in soil excavation or loss of forest cover predispose slopes to failure. As development has extended into hilly and mountainous areas, alteration of hill slopes has raised landslide incidence over and above the natural "background" level. For example, 80 percent of landslides in China result from human activities, with dam-building and road construction the most significant causes.[188]

Activities most associated with increases in landslide frequency include road and rail construction, hill-side construction, water impoundment, agriculture and livestock rearing, logging and surface mining. The activities themselves, however, rarely initiate a landslide without the occurrence of other contributory factors, such as high rainfall or earthquakes. However, the activities are critical because they lower the thresholds for landsliding to different degrees, depending on the activity.

It is likely that changes in climate or weather will exacerbate many of these problems. Already it may have altered rainfall patterns and increased storm frequency and intensity, both of which have direct effects on landslide incidence. Also, with higher mean temperatures and associated increases in fire hazard and forest loss, landslide risk may be further multiplied where rainfall is also expected to increase. Landslide hazard may fall, however, where lower rainfall is expected and higher temperatures are likely to reduce soil moisture.

2.1. Changing rainfall and snowmelt patterns

Copious amounts of water entering the soil mantle can destabilize hillslopes such that a large storm or typhoon/cyclone can initiate hundreds of slides. The scale of the impact and the potential for disaster is greatly increased by contributory factors such as land use and proximity to settlements or infrastructure. Intense storms are a primary cause of landslides, but much events of much lower intensity can trigger landslides if forest removal has increased susceptibility to water saturation. Without reduction of soil moisture through forest evapotranspiration, a long period of rainfall causes soils to become saturated and additional rainfall or seismic activity can trigger slides. This is particularly likely at the end of the rainy season when high soil moisture content and water pressures create instability. In monsoonal areas, exceptional pre-monsoon rains may also produce this antecedent effect at the beginning of the rainy season. Similar effects may occur at the end of snowmelt when rising temperatures cause rapid melting or rain-on-snow events to release excessive amounts of water. Consequently, the seasonality and pattern of rainfall and snowmelt, in addition to storm intensity and duration, are critical determinants of sliding.

2.2. Earthquakes and seismic activity

The impacts of earthquake-induced landslides are escalating because of rising population densities and economic development in areas once thought remote or too steep for development. Widespread landsliding due to earthquakes is restricted to rare large earthquakes. Earthquakes smaller than magnitude six contribute negligible amounts to total landslide volumes.[111] However, a single large earthquake can initiate thousands of landslides in an area up to 250 km or more from the epicenter,[175] although the vast majority occur on or near the fault-line.[203] Slopes that do not fail, may become predisposed to landsliding in the event of another tremor or arrival of moderate rainfall.[112]

In some areas, such as western New Guinea and to a lesser extent in Turkey, central Japan, Iran and Tibet, earthquake-induced landslides are the main agents of slope erosion.[111] They occur periodically in many other countries of all Asian sub-regions, but in humid areas their importance is below that of rainfall-induced landslides. In dry climates, earthquake-induced landslides are relatively more frequent, and occur especially at times of the year when soil moisture content is high.[211]

It is important to note that landslides triggered by earthquakes are typically deep-seated and frequently cause failures along planes of weakness within the bedrock in which the forces involved are so large that the presence of forests has little or no effect on most slope failures.

Figure 2.1. Deep seated landslide resulting from 2008 Sichuan earthquake. Trees had no mitigating effect

Source: Patrick Durst

2.3. Road and railway construction

Roads and railways are important contributors to increased landslide incidence.[183, 107] Road and railway construction frequently involves cutting slopes and removing soil from hillsides. Trees are removed for broad right-of-ways, even when there is no soil excavation. The removal of soil and trees results in a significant reduction in lateral support, and landsliding often occurs. Road at mid-slope and at the base of the hill constitute the highest landslide risk due to subsurface water interception, and overloading and undercutting slopes,[177] Construction of roads, trails and tracks is associated with many economic activities such that the destabilizing effects of forest clearing and soil excavation are often seen over large areas, if soil stabilizing counter-measures are not also employed.

Ideally, railways and major roads are designed to higher standards than smaller trails and logging roads and there are frequently requirements for engineering works to stabilize affected slopes and minimize landslide hazard. Yet, rapidly constructed roads often do not reach required standards of engineering.[188]

Trails and tracks associated with agricultural development and forestation programmes, although associated with much less soil excavation, are also a significant cause of landslides.[178,198] Concentrated storm flows associated with trails and tracks often lead to gully erosion and landsliding.[198] Landslides can occur where water discharges onto slopes from the track or trail, or from culverts associated with larger roads. Landslides can also result where gullies are created due to the accelerated rates of infiltration.[158]

Figure 2.2. Landslide following road construction in Bhutan

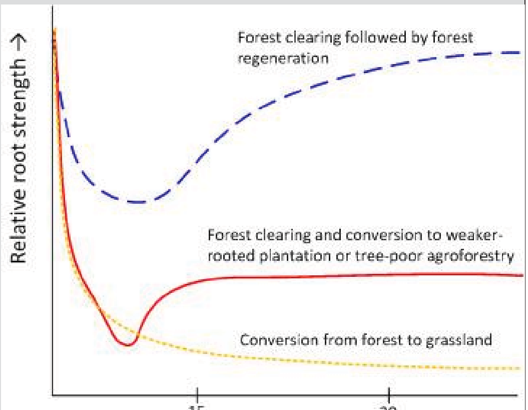
Source: Patrick Durst

2.4. Deforestation and land use conversion

Many activities associated with increasing economic development - agriculture, logging, mining, residential development, tourism, etc. - bring land-use/land-cover change and the loss of forests from hillslopes. 1 the loss of roots and the reinforcement they provide may significantly increase the likelihood slope failure.[172,16,110] Removal of forest or brush cover and replacement with grass or crops has often been found to substantially increase the susceptibility of hillslopes to landsliding.[159,77,144,178,98,1] Although the replacement land use type determines relative slope stability, most land uses are inferior to forest. Deforestation is a contributory causal factor that unlike weathering, groundwater content, rainfall or earthquakes can be addressed through development policy and potentially controlled on relatively short timescales.

In Asia, deforestation is primarily being driven by rising demand for agricultural land, both for subsistence farming and, increasingly, for commercial and industrial agriculture. Forest degradation also results from the expansion of logging – legal and otherwise – and shifting cultivation, which may end in conversion of forest to some other land use. Migration into and development of forested areas is facilitated in particular by the opening of roads – often to support logging or plantation development.

BOX 2. A Window of susceptibility



The removal of trees and shrubs from hill-slopes makes slopes susceptible to landslides. Loss of protective function persists until woody vegetation is re-established and sufficient stem and root density is achieved. The 'window of susceptibility' commences when roots begin to die and decay. Within 3–5 years small roots may lose over half their original tensile strength and significant increases in landslides can be expected after this.[139,138]

Where forested slopes are converted to cropland, pasture or other land uses, the effect will be permanent and even in newly established coffee, tea and timber plantations, landslides are still likely to be common. Where vegetation removal occurs cyclically, such as in logging or shifting cultivation, the window-of-susceptibility is open until roots re-establish.[116, 13] Where logging takes place, susceptibility is substantially reduced if selective silivicultural systems are employed instead of clear cutting.[217]

The window of susceptibility (corresponding to the dip in the figure above) may remain open for 15-20 years;[218,113,217,22] less in the humid tropics where regeneration is quicker (5-7 years),[207,116] and longer at high altitudes in temperate regions where it is slower.[5] Because shifting cultivation will temporally arrest natural succession, with the planting of crops for 3-4 years—which also results in significant depletion of soil nutrients—regeneration will be delayed, so that the window of susceptibility may become longer.

3. CLIMATE, LANDSLIDES AND THE ROLE OF FORESTS

3.1. Relevant landslide types

Several extremely common types of landslide can be affected by forests. A simplified landslide classification includes three broad categories: 1) shallow, 2) deep-seated wasting, and 3) rock failures.[180] Deep-seated movements occur below the depth of tree roots and above bedrock; while shallow slides occur within the rooting zone (or assumed rooting depth if trees are no longer present). Landslides resulting from failure within bedrock are not considered to be influenced by vegetation.

Trees/shrubs and forests can have the greatest beneficial effect in preventing or mitigating shallow landslides. Initiated by failure along layers of weakness – either parallel to the slope or in rotation about a point – they consist of soil or debris (rock and soil) transported down slope at varying velocities. The slide velocity is determined primarily by the amount of water incorporated in the slide and the slope gradient. Great destructive forces are associated with high velocities and large volumes of material. Run-out distance and whether the slide reaches streams, habitation, roads or other infrastructure affects the scale of the impact. People may be able to escape slow moving slides (<3 m/second), but higher speeds of onset and movement increase the potential hazard.

Deep-seated slides were considered to be insensitive to human influence, but it is now thought that timber harvesting, road building, and changes in surface hydrology promote displacement.[41,75] Drying of soil, through transpiration by forests, slows the rate of creep and shortens the 'season' of movement - normally during the rainy season when water content in the soil is high.[180]

Deep-seated slope deformations extend to great depths and such movements are much slower than those associated with shallow slips. Lives are rarely lost and impacts are usually related to damage to buildings, pipelines and other infrastructure, water ways and natural resources.

Finally, rock falls of the type considered here are small and localized, but can be very disruptive, particularly to transportation. Resulting from dislocation of rock, usually on very steep, treeless slopes, they strike with little warning and can be extremely hazardous. Areas with pronounced and erratic freeze-thaw cycles are particularly at risk. Where infrastructure developments cannot avoid rock fall hazards, some form of protective barrier may be employed. In this respect, trees can act as a barricade or obstruction to smaller rock falls and limit run-out distance.[46] Larger rock falls cannot, however, be mitigated by forests and require conventional engineering works or relocation of development.

3.2. Topography, geology and climate

3.2.1. Topography

Slope gradient and curvature are the most relevant topographic factors controlling terrain susceptibility to landslides. Although steeper gradients are generally more prone to landslides, geologic and climatic factors may make gentler slopes more susceptible to failure. For example, slopes facing a particular direction may be subjected to more intense storms. Deeply incised landforms and topographic depressions are also susceptible during rain storms and snowmelt events due to water convergence and saturation. Slopes with lower gradients that have been altered by road construction are also more susceptible to sliding [79].

On natural slopes, gradients where shallow landslides initiate are commonly 15°-25° for earth flows and 20°-45° for debris flows.[109] Slopes steeper than 45° usually have insufficient soil to be vulnerable to sliding. Rock falls are associated with cliffs and very steep slopes of 45° or more. Topography is less of a factor in deep-seated movements, which normally occur on a much wider range of slopes (5° to 25°), although they have been recorded on slopes as little as 1.3° and greater than 25°.[27,67]

In the Western Ghats of India, slopes greater than 20° are the most susceptible to shallow landslides,[115] but without woody vegetation, some prediction models suggest that slopes as low as 15° can fail.[116] In a number of case studies from coastal British Columbia, average slope for landslide initiation in recently harvested areas was found to be about 10° lower than in forested areas.[21] On slopes with relatively weak soils or weathered bedrock threshold gradients drop even further.

Adding weight, particularly at the top of the slope, or cutting, especially at or near the base of the slope also increase susceptibility to land sliding.[99,219] Common examples include the building of structures, adding earth fills, rocks, mine tailings, and also the planting of trees on the steep, upper slopes. Additional weight at the base of a slope, however, adds shear strength and enhances stability.

The loss of trees at slope bottom seriously affects slope stability by eliminating the fixing effect of extra weight, lateral support and buttressing effect. It also removes barricade protection against smaller slides and rock falls.

3.2.2. Geology and soils

Dominant geological factors controlling landslide activity include tectonic activity, bedrock type, relative orientation of bedding planes with respect to the orientation of the sloping surface, degree of bedrock fracturing, presence and thickness of surface materials. Volcanic ash and loess, which cover a large proportion of some parts of Asia such as Japan and China, are especially prone to slope failure, for example. Vegetation provides important protection to loess, but the role of trees in volcanic ashes is less clear.

Some types of underlying bedrock are prone to high rates of chemical weathering and fracturing, which weakens the substrate and creates flow paths for subsurface water that may converge in critical areas and cause slides. In tropical Asia, high rates of weathering result in the layering of rock and clays which may act as slip planes.

Soil thickness and type influence vegetation growth[70] and physical properties of slopes[204] thereby affecting overall slope stability. Rooting depth relative to soil thickness is critical to stability and while thin soils may have dense root networks, deeper soils often provide for healthier root development. Undisturbed natural forest areas in the tropics may have much greater soil thickness, even on steep slopes.[119]

3.2.3. Climate and weather

Asia encompasses several broad climatic zones within which the impacts of climate change are expected to vary. The zones, together with climatic variation associated with altitude and aspect, determine to a large extent the degree of weathering, soil development, and type of vegetation cover.

Patterns of rainfall and snowmelt, storm intensity and duration, and recharging of soil moisture over the rainy season directly influence landslides incidence. Also high winds can increase loading on trees and play a role in slope failure. On the other hand, higher temperature, increased wind speed and lower relative humidity lead to the drying of soils and an increase in slope stability.

With respect to weather, tropical disturbances and storm systems in the mid-latitudes of Asia are major producers of landslide triggering events. Cyclones are the most important of these, but other less severe weather systems also cause landslides. Other important sources of variability in precipitation include the South Asian and East Asian monsoons and the El Nino-Southern Oscillation (ENSO).

The El Nino-Southern Oscillation (ENSO) affects the tropical Pacific and returns every two to seven years (three or four years on average), with each episode lasting 9-12 months. The effect of ENSO on precipitation is greatest in Southeast Asia and the western Pacific. ENSO effects are strongest between December and April.[228] Different effects are associated with ENSO depending on the phase – El Nino or La Nina:

- **La Nina** increases the severity of storms and causes wetter than normal conditions in Indonesia, Malaysia and surrounding areas during December-February, and over the Philippines, eastern Indonesia, Papua New Guinea and South Asia in June-August.[164,90] Landslide frequency escalates in these countries during La Nina episodes.
- **El Nino** (March-May) produces drier conditions by June-August with increased the risk forest fire in insular Southeast Asia (especially Indonesia and Philippines). [234,90] South Asia is drier June to August, except South India and Sri Lanka where it is wetter in September to November.[231] El Nino usually brings more rain in East Asia in December-February.

Strong El Niño years when landslide frequency falls in most countries are usually followed by several years of La Niña. In last few decades El Nino has been more frequent than La Nina. Drought and fire may increase landslide hazard when rains return due to root degradation or die-back, particularly of the fine roots that provide the greatest strength.[229] This is a growing concern in some parts of Asia such as Indonesia, India, Philippines, Papua New Guinea and Australia.[234, 220] Slopes made vulnerable may be quickly saturated with rainwater, overcoming the reduced resistance to failure.

3.3. Role of forests and trees in prevention

In hilly and mountainous areas in Asia, hillslopes with healthy and intact forests receive protection from landslides. Forests, and in particular trees and shrubs, have a direct impact on the stability of hillslopes. The ability of the forest to provide these functions depends on the composition, density and health of the forest. Species mix, tree height and weight, stand density, rooting depth, root architecture, and tree and root health all have an impact on slope stability. Forests can have both positive and negative effects on slope stability depending on the combination of the above factors and their relative contribution to reducing shear stresses and increasing shear strengths. Empirical evidence shows that the effects of forests are mostly positive and that natural forests provide the greatest level of slope protection compared to other forms of land use.

3.3.1. General processes

The most important landslide protection service that forests provide is in relation to the mechanical and hydrological properties and processes in hill slope soils (see Figure 3.1). Mechanical attributes at the soil-root interface that improve slope stability include: root anchoring, root tensile strength, soil-root friction, root elastic strength, root cross-sectional area, lateral traction and buttressing and arching. The weight of trees on the lower part of slopes and other areas with low gradients can also contribute to slope stability. The primary mechanical effects of vegetation on slope stability are reinforcement of soil by roots, and protection of soil surface from surface erosion and gullying.

Though the net effects of vegetation in preventing landslides are positive, there are a few negative effects that in some circumstances reduce the protective functions of trees and forests. Mechanical factors and events associated with trees that may increase shear stress or reduce shear strength include: wind loading, uprooting, tree weight acting on the slope, and bedrock fracturing by roots. Hydrologic properties associated with trees and forests that may have a negative impact include increased surface roughness and resulting higher levels of infiltration.

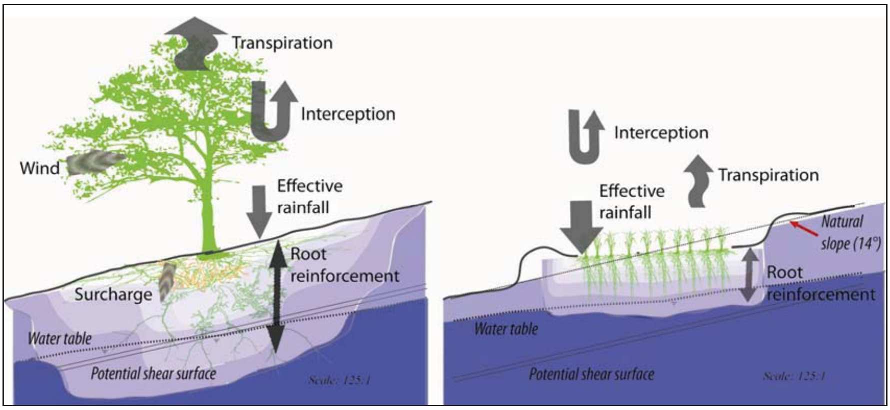


Figure 3.1. Relative influence of trees and upland rice on slope stability. The zones of root reinforcment and soil drying (lighter shade) will extend the length of the slope parallel to the surface with sufficient tree stocking. With shrubs, wind and surcharge forces are reduced, but soil reinforcement and drying remains comparable to trees

3.3.2. Mechanical effects

The stabilizing effect of roots in soil is supported by assessments that note an increase in landslide frequency following vegetation removal.[169] Mechanical effects of vegetation on slope stability include reinforcement and anchoring of soil mantle by roots, surcharge, wind-loading and surface protection.

Soil reinforcement and anchoring

Roots of shrubs and trees penetrate to greater depths than other vegetation and may pass through potential slip surfaces, thereby anchoring the soil. Small roots also bind the soil to a distance of at least 1.5 times the canopy radius.[83] Consequently, forests' effectiveness in protecting slopes depends on rooting depth relative to potential failure planes and density and distribution of roots. Branching, root elasticity and strength, and root-soil cohesion also affect the reinforcement properties of roots.

Root depth and distribution are most important for slope stabilization as more planes of weakness are traversed and bound with increased rooting depth.[30,194,133] Tropical species such as *Tectona grandis* and *Coffea arabica* show rooting depths up to 4 m.[114] However, root biomass and consequently root reinforcement decrease rapidly with depth depending on species and climatic and soil conditions.[194,185] Forest vegetation still can significantly increase soil strength at depths of greater than one metre, depending on the species.[16,149]

Thicker roots require more force to be pulled out of the soil but thinner roots are significantly stronger than thick roots relative to their cross-sectional area.[224] Consequently, loss of thin roots through fire or drought can significantly reduce slope stability.

The bond between root and soil is an important factor and probably second only to rooting depth and distribution in terms of contribution to slope stability. Root-soil cohesion decreases rapidly as water saturation increases; roots will more commonly slip rather than break, especially under saturated conditions.[201]

In shallower soils, tree and shrub roots may anchor the soil mantle to the slope and increase shear strength.[192] Forests not subject to disturbance may have much deeper rooting although in some tropical forests with highly weathered soils, there may be very few roots below about 20-30 cm deep. In such scenarios, as in southeast Brunei, removal of the forest cover would make little difference to the incidence of rainfall-triggered shallow landslides.[48]

Buttressing and soil arching

Buttressing and associated soil arching action are important functions of trees.[83] Particularly at the bottom or "toe" of the slope, trees help immobilize soil behind the tree extending upwards.[205,82] The buttress effect also extends laterally, creating supporting arches to near-by trees. Furthermore, traction at the outer boundary of a potentially sliding mass or "raft" connecting it with firm adjacent ground stabilizes the slope over a broad area.[215] *In situ* tests showed a tremendous traction effect exerted by lateral roots of *Pinus yunnanensis* in the upper 60 cm of soil.[216]

Figure 3.2 Ponderosa pine tree buttressing a slope above a forest road. Unprotected portion of road cut to the left has failed. Mendocino National Forest, California, 1978

Source: Donald H. Gray

Surcharge

The weight of a mature tree on a slope, plus any accumulated snow or rain, increases shear stress in the slope. For example, surcharge combined with lowering of soil cohesion from heavy rainfall is believed to have contributed to slides on forested slopes near Santos, Brazil.[42,189]

In general, however, the effect of surcharge is small because the weight is usually distributed uniformly so that force per unit area may be negligible. It even can be positive and enhance slope stability, when soil cohesion is low, ground water table high, or slope angles are low.[84] Gravitational forces are countered somewhat by the increased weight causing soil particles to lock together, fixing the tree in place. And though tree removal on upper slopes may reduce the small amount of surcharge, the lost benefits of root reinforcement and soil moisture reduction probably would be greater.

Wind loading

At times, the force of wind on trees can be significant, for example during tropical storms and cyclones.[189] Wind loading does not lead to landslides directly but the additional force may tip the balance; for example, if wind and intense rainfall act in unison. Wind loading can cause roots to be pulled out, reducing soil cohesion, and increase shear stress. Furthermore, wind may uproot trees and expose mineral soil, allowing large amounts of water to infiltrate, increasing soil water pressure, and triggering a landslide. Wind throw may also rip up bedrock and create new potential slip surfaces.

Wind loading forces and uprooting increase with tree height. For this reason, shrub species that have rooting depths comparable to trees may provide superior landslide protection in areas prone to high winds. Coppiced trees would also be less susceptible to wind loading and are also likely to impose less surcharge on a slope.

3.3.3. Hydrological effects

The main beneficial hydrological effects relate to forests' ability to remove water from the soil and transpire it back into the atmosphere, and to intercept rainfall and snow, allowing it to evaporate before reaching the soil. Modification of subsurface water flow through piping and enhancement of permeability may also improve slope stability. These effects reduce soil moisture content, and thereby delay the onset of soil saturation levels at which landslides are triggered. The delay may be sufficient to offset a susceptible period, such as a monsoon season, without a landslide incident. Forests are a particularly good land use with respect to landslide prevention because of their high rates of interception and transpiration.

Interception and evaporation

Intercepted rainfall is stored on leaves and stems and reduces the volume of effective rainfall reaching the ground. Water that doesn’t make it to the ground is lost to evaporation with frequency of rainstorms more important than amount, duration or intensity.28, 106 In a light rain most, if not all, of the rainfall may be stopped from reaching soil and even in high intensity storms, trees intercept about 15-25 percent of rainfall.[37] For example, in the U.S. Pacific Northwest, the amount of interception in old-growth Douglas-fir (*Pseudotsuga menziesii*) ranges from 100 percent for light rain, to 15 percent for storms around 75 mm.[166] Different species have different interception capacity. For example, the maximum value for beech (*Fagus spp.*) and spruce (*Picea spp.*) have been measured at 2.6 mm and 4.7 mm, respectively.[193]

As a percentage of annual precipitation, typical interception loss rates are as follows:

- cool-temperate hardwood forests 10-15 percent;
- temperate deciduous forests 15-25 percent,
- temperate coniferous forest and tropical rainforests 25-35 percent.[189]

Coniferous trees intercept larger amounts of rain and snow during periods when deciduous trees are without foliage. In broadleaf plantations in India, interception rates of 40 percent have measured.[76] In secondary or fallow vegetation in the tropics, rates range between 3.1 percent[170] and 21 percent.[29] Even in drier, open forest ecosystems there can be significant interception by leaf litter.[24]

Typically, grasses and crops intercept 20-48 percent of rainfall during the growing season,[214] while grazed grassland interception rates are about half and sparse crops like maize less than half again.[120] However, on an annual basis the percentage is much smaller compared to forests as such vegetation either dies, loses mass or is grazed or harvested.

Forests, if harvested, loose most rainfall interception. One example from northwest California estimates that clearcut logging of redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*) would increase effective annual rainfall by 20-30 percent, and most of the increase would occur during large storms, potentially influencing slope stability.[156]

Suction and transpiration

Trees have more extensive root systems than most other plants and are able to extract moisture from the soil at considerable depth and reduce moisture levels at distances of up to three times the radius of the crown.[83] Though most roots are in the top meter of the soil, tap roots and sinkers extend much deeper. For example, a 25-year old *Pinus radiata* in New Zealand had roots with an average depth of 2.4 meters, and a maximum depth of 3.1 meters.[206] Feeder roots may extend very deep:

- sclerophyllous brushland and forest - 5.2±0.8 m;
- temperate coniferous forest - 3.9±0.4 m,
- temperate deciduous forest - 2.9±0.2 m;
- tropical deciduous forest - 3.7±0.5 m; and
- tropical evergreen forest - 7.3±2.8 m. 235

The global average for maximum root penetration depth for trees is around 7 m, while for herbaceous vegetation it is only 2.6 m. Most importantly, because trees are able to access water at depth and maintain transpiration for longer than other types of un-irrigated vegetation [97,214] soil water depletion is maximized and the onset of soil saturation delayed when rains recommence.

Where precipitation considerably exceeds potential evapotranspiration, such as in cool temperate and sub-alpine regions, the reduction in soil moisture through transpiration and evaporation is small and soil drying is minimal. At this point, the effect of vegetation is minimal.[82]

Infiltration and subsurface flow

Forest lands generally have high infiltration rates, but they may reduce soil moisture through subsurface flow facilitated by pipes and channels formed by root decay and burrowing animals. Tree roots (both dead and alive) contribute to soil pore formation and form networks that can help slopes drain faster than if the channels were absent.[131,180] However, root channels also raise infiltration rates and soil moisture content, which can increase landslide hazard. The net effect depends on vegetation type and cover, degree of soil compaction, presence of impervious layers and the nature of the channel network.

Soil compaction reduces infiltration and can lead to overland flow which although removing water from the slope also causes surface erosion and gully formation, the latter being a significant precursor to land sliding. Natural forests are generally not affected by soil compaction and surface and gully erosion. Shade and large amounts of organic matter associated with forests also retard soil cracking in clay-rich soils. But if forests are cleared, cracking may lead to excessive infiltration rates.

3.3.4. Additional effects

Protective barrier

Trees and forests also provide a protective barrier against smaller avalanches or slides of rock, debris and soil, as well as limiting the run-out distances of material with respect to streams, roads and lines of infrastructure.[46, 20] Landslides are not prevented, but the effect of standing trees obstructing the downward movement of landslide material or rock fall may mitigate some or all of the potential damage. For example, debris flows deposited much of their load when hitting a forest boundary and stopped entirely within 50 meters of that boundary in 72 percent of the 1,700 cases examined in coastal British Columbia.[87]

The effect of tree buffers will depend on width, spacing and tree diameter. Species may show differences in protection against rock fall and in the French Alps, for example, European beech (*Fagus sylvatica*) showed greater resilience to breakage or toppling than Norway spruce (*Picea abies*) and silver fir (*Abies alba*).[186]

Wildfire propensity

Relative to other landuses, some forest types have a propensity to destructively burn. Wildfires occur with some frequency in unmanaged coniferous forests found North, Central and East Asia, as well as submontane and montane forests and plantations elsewhere in Asia.[64] Fires in deciduous forests such as teak (*Tectona grandis*) in Thailand and Myanmar occur in dry areas of Asia. With widespread forest degradation in Asia and shifts in climate this frequency of devastating fires may increase in coming years if fuel loads are not adequately managed.

Besides removing the protective function of vegetation against surface erosion and landsliding, intense fires weaken bedrock and increase landslide susceptibility.

3.3.5. Net effect at critical levels of saturation

When soil moisture levels rise close to full saturation, the hydrological and mechanical effects of trees diminish. Although remaining effects can make a crucial difference to slope stability, the stability threshold or factor-of-safety (FOS) of forested slopes is much less when the soil is near full saturation. Saturated soil conditions can occur after a long period of rain or at the end of the rainy season, when subsurface flow is impeded or during an intense storm where the soil mantle is shallow. When slopes are at a high level of saturation, even moderate rainfall can trigger a landslide.

Furthermore, if a rain storm coincides with a period of dormancy in forest plants – when transpiration levels are at their lowest – the stability threshold is reduced. Coniferous forests, however, are able to maintain large evaporative surface area even during this period. Forests can slow the onset of critical levels of saturation, even to the point where the rainy season ends and the landslide hazard falls, thus offering protection in all but exceptional years.

Even under saturated conditions, soils reinforced with roots are stronger than those without. For example, three times more shear stress would be required to cause failure in saturated colluvial soils containing roots than equivalent soils without roots.[50] The elasticity of the soil-root system is an additional component that contributes to strength prior to failure.[130] During failure, fine roots act in tension and if roots extend beyond the shear plane, trees may provide the last available resistance and restrain material from sliding downhill.

3.4. Evidence of landslide prevention

Because landsliding is a natural geomorphic process, most hillslopes eventually fail with large storms and earthquakes the most common triggers. Such events occur periodically when thresholds of resisting forces - including those provided by forests - are surpassed. During the most extreme events, factors such as copious rainfall, cutting or excavation at the toe of the slope, weak underlying regolith/bedrock, seismic activity, or other factors discussed above, are likely to override the effects of vegetation. In these situations, forest cover is unlikely to make a difference.

However, there are also many cases where landslides would have occurred if it were not for the lower levels of soil moisture and additional soil reinforcement provided by forests. This contribution can make a critical difference and prevent slides where destabilizing forces are less extreme. Moreover, once forests are cleared, less extreme events –which are also more frequent – are likely to be sufficient to initiate slides on a greater number of slopes due to lowered resistance thresholds.

Consensus among land managers and scientists is that forests lower the probability of shallow landslides, and to a lesser extent deep-seated movements, in upland areas. This is reflected in the reduced amount of eroded soil and rock material that is dislodged and transported down slope in forested areas. Even though landslides still occur in undisturbed forests, the annual mass erosion rates per hectare are substantially less in forested catchments compared to those where deforestation and forest degradation is severe. Most of the reduction results from the fewer number of landslides on forested slopes, but forests also store sediment and limit the amount of material reaching streams.

The effectiveness of forests in stabilizing slopes is demonstrated by empirical data on landslide incidence following sudden removal of forest. One of first studies to evaluate the effect of clear-felling on landslide incidence reviewed data from southeast Alaska.[17] Both frequency and cumulative area of slides showed drastic increases after logging took place. Increases began 2-3 years after logging, coinciding with root decay and loss of root strength (see Figure 3.3). Frequency of debris avalanches and debris flows increased substantially for 9 years until forest vegetation re-established. The area affected by landslides during this period was 5 times greater than the estimated area disturbed by landslides during a 100-year period prior to logging. Over half the recorded landslides were initiated by a major storm 6 years after logging.

A more recent study in the Sanko catchment in central Japan,[98] which was periodically logged between 1964 and 2003, confirmed that changes in slope stability were correlated with root strength decay and recovery following harvest. The direct impact of forest removal on landslide occurrence was greatest in forest stands clearcut 1-10 years earlier, with lessening impacts continuing up to 25 years after harvesting. Sediment supply rate from landslides in forests clearcut 1-10 years earlier was about ten-fold higher than in control sites. In addition to forest recovery, the drop in sediment release is also likely to be associated with there being progressively less soil material remaining on the slope. The stabilizing effect of roots is supported by landslide inventories that note an increase in landslide frequency following vegetation removal.[169, 71, 17,137,125, 209, 108]

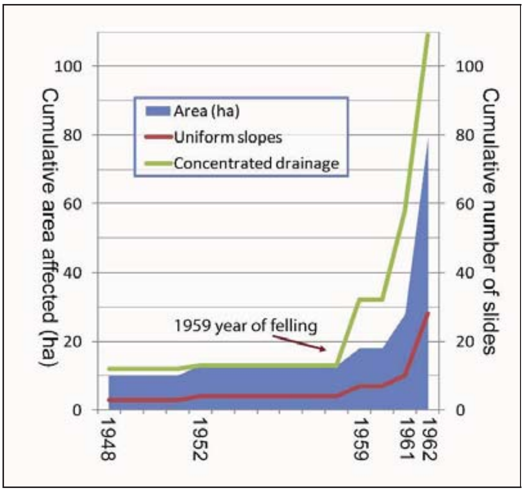


Figure 3.3. Clearcut logging in Hollis, Alaska shows a link to substantial increases in landslides frequency and size of affected area for two different slope types. Authors suggested root decay and loss stabilization by roots was the cause [17]

Other studies from North America, New Zealand, Japan and elsewhere show similar upward trends in the number of landslides following forest cover removal. In general, rates of mass erosion in steep forested terrain can be expected to increase two- to more than ten-fold 3-15 years after timber harvesting, although rates on highly erodible soils may increase much more.[272, 273,274,275,276,277] This increase in landslide frequency and volume is related to the period of minimum rooting strength after clearcut harvesting and prior to substantial regeneration (see Box 2).

Evidence from Nepal supports the view that causes other than just logging, namely grazing and agriculture, also lead to increased landslide incidence. Between 1972 and 1986 in Lele catchment in the Middle Hills of Nepal, 650 shallow landslides were recorded in areas cleared for grazing, agriculture and firewood. Most of these took place on steep (>33°) deforested slopes during an intense rain storm, whereas only a few landslides occurred in the thickly vegetated headwater area.[25] In New Zealand, a review of five published studies to assess soil loss associated with post-deforestation landslide erosion, conclusively showed that most landslides would not have occurred if the forest had remained,[43] Many other surveys have also reported increases in landslide incidence following deforestation and land use conversion.[88]

With conversion of natural forests to land uses other than forest plantations, slope stability is permanently diminished. This is particularly evident when forests are converted to pasture or grassland. In southern California, USA, the clearing of brushland for pasture led to 5-fold increase in both area and numbers of soil slips after a series of major storms.[38] Elsewhere in California on areas converted to perennial grass and annual grass, mass movement rates are 1.5 and 2.5 times, respectively, higher than natural brush cover.[160]

In the western Uluguru Mountains, Tanzania, converted grassland and cultivated farmland accounted for nearly 94 percent of landslide erosion after a major storm, while natural forest or brushland accounted for less than 1 percent, on an equal area basis:

> "Grasslands were not overgrazed and cultivated soils were not excessively depleted, which indicated that the differences in landsliding observed were mainly caused by the effective rooting strengths of forest and brushland."[190]

At Lake Waikapiro in Hawke Bay, North Island, New Zealand, analysis of pollen in lake sediments showed that "although the effect of climate change cannot be excluded [...] land use change is the most important factor leading to increased landslide initiation in this region."[49] Today, erosion rates from pasture lands in the area are 8-17 times higher than indigenous forest.[140]

Furthermore, it has been observed that undisturbed forested slopes are often significantly steeper than the maximum angle of a stable slope with the difference most likely attributable to the stabilizing influence of forest vegetation.[152] Field tests on wooded slopes in Hong Kong showed that the additional cohesion brought by tree roots increased the slope stability threshold by 29 percent.[85]

Relative to other land-uses, undisturbed forests exhibit the lowest levels of landsliding. For other upland land uses, such as coffee and tea growing, grazing, cultivation and recently cleared swiddens/shifting cultivation areas, surface erosion and landsliding rates are many times higher.[92,26,198] Tree plantations or tree-rich agroforests once fully established may provide nearly as much erosion and landslide protection as natural forests, provided they are managed for the purpose, i.e. with sufficient stocking and undergrowth presence and not harvested. In the Potwar Upland in Pakistan, for example, runoff and sedimentation due to sheet erosion fell 55 percent and 78 percent five years after tree-planting and the closure of slopes to grazing.[93] If grazing can be controlled, higher rates of protection can be expected as forests grow. Consequently, intact natural forests and appropriately managed plantations and agroforests are the most effective ways of stabilising soils in upland areas.

4. IMPLICATIONS OF CLIMATE CHANGE

Climate and associated weather is responsible for altering landslide frequency. Though, relative to development pressures, the impacts of climate change are less immediate and uncertain, the need to address climate change in policy and mitigation strategies will become increasingly important.

Climate change factors relevant to landslide incidence are:

1) changes in annual and seasonal precipitation,
2) increased mean air temperature, and
3) increased frequency and intensity of extreme events (severe storms, cyclones/typhoons, droughts,).

With excessive amounts of rain, thresholds of slope stability are quickly surpassed and landslides usually are triggered. Rising temperature causes more extreme storms, speeds up soil and bedrock weathering, and elevates risk of wildfire that denudes slopes and further hastens weathering.[35] On the other hand, higher summer temperatures accelerate evapotranspiration rates and lower soil moisture content, thereby reducing landslide risk. Predicted increases in variability in daily precipitation, may have impacts if, for example a long period of rain preceded a storm such that a much smaller storm is necessary to trigger landslides.

All sub-regions of Asia are expected to see a significant acceleration of warming over that observed in the past century.[168] The predicted changes in temperature and precipitation will not, however, be uniform across Asia. Similarly the intensity of storms, cyclones and precipitation will rise in some areas and decline in others. Higher temperatures accompanied by reduced rainfall raise the risk of wildfire, which kills vegetation and can also weaken bedrock. Yet, if fires can be controlled, reduced soil moisture would reduce landslide incidence providing drought does not damage vegetation and weaken root reinforcement.

Based on the IPCC Fourth Assessment Report[100] the following predictions are made for seven sub-regions of Asia as delineated by IPCC. Discussion focuses on the near-term period, 2010-2039.[191]

4.1. North Asia

The northern parts of China and Mongolia will probably experience the greatest increases in temperature and precipitation relative to other parts of Asia. Temperatures are expected to be up to 2.7-2.9°C higher in the winter and 1.7-2.2°C higher the rest of the year. Significant melting of permafrost over vast territories,[105] and perhaps completely in the southern fringe of North Asia,[143] will result in extensive rock falls and slides, debris flows, thermal erosion, ground surface subsidence and pounding. A greater frequency of extreme summers is likely to lead to significant increases in seasonal thaw depths.[94] Winter and spring precipitation is expected to increase between 10 percent and 16 percent and rise between 4 percent and 7 percent in summer and autumn. Increased snow and likelihood of rain-on-snow events in the warmer springs will increase landslide incidence.

Predictions for the summer are less clear. Though rainfall is higher, so are temperatures and evapotranspiration, such that the net effect on soils is difficult to predict. Predictions of fire hazard are for the same reason unclear. Nevertheless, one study suggests that for an average temperature increase of 1°C, the duration of the wildfire season in North Asia could increase by 30 percent.[200] Also, warmer winter temperatures would reduce winter kill, and lead to explosion in insect populations that can kill forests over vast areas. Beside the loss of soil reinforcement once roots begin to decay, standing dead trees are highly susceptible to wildfire.

4.2. Tibetan plateau

The Tibetan Plateau will experience similar impacts of permafrost loss and increased landslide incidence as North Asia. Year-round temperatures may increase 1.5-2.1°C and cause progressive shrinkage of the permafrost area.[208] Glaciers are also melting at very high rates. Combined with significantly greater snow and rain (10-14 percent in winter and 4-7 percent the rest year) landslide and debris flow incidence can be expected to increase, particularly during spring-melt period and the plateau monsoon starting in May.

4.3. East Asia

China, Japan, Republic of Korea and DPR Korea will likely experience moderately high year-round temperature increases (1.3-1.8°C). Winter precipitation may be 5-6 percent higher and spring/summer rainfall may rise 2-3 percent (change in autumn rainfall is negligible). While these changes are not severe, many parts of East Asia are already very susceptible to landslides, due to high rainfall and unstable soils, and small changes could drastically increase landslide hazard. For example, areas of loess – accounting for some 6.63 percent of China – are highly erodible and can disaggregate instantaneously when saturated if vegetation is absent.[44] Japan also has many areas with fragile geology that is easily weathered and susceptible to sliding, volcanic soils in particular.[35] East Asia is also subjected to tropical cyclones/typhoons of increasing frequency and intensity.[55] During these extreme events landslides will be numerous and widespread, particularly in coastal areas.

4.4. South Asia

In India, southern Pakistan, Nepal, Bhutan, Bangladesh, Myanmar, and Sri Lanka, moderately high precipitation increases can be expected with temperature increases of 1°C or less. Increases in pre-monsoon rains (7-8 percent) and monsoon rains (5-7 percent) could lead to a significant rise in landslide incidence in the Himalayas, Sri Lankan highlands and Western Ghats of India. Furthermore, the period of elevated landslide risk will lengthen because increased pre-monsoon rain in April and May will cause soil moisture to build up sooner. In Sri Lanka and southern India, landslide incidence is greatest during the retreating monsoon between October and December. At this time, the expected increase in rainfall is only 1-3 percent. But in Kerala, like Nepal and Bhutan, where most of annual precipitation falls during the monsoon, a small amount of additional rainfall, particularly at end of the season, may lead to significant number of landslides if soils are near saturation. Additionally, the severity of South Asia tropical cyclones and storms is increasing although their frequency appears to be declining.[117]

4.5. Southeast Asia

The countries of Southeast Asia will experience the smallest increases in temperature (0.7-0.9°C) and negligible changes in precipitation. However, because hot, humid conditions are conducive to high rates of biological and chemical weathering of bedrock slight changes in precipitation and temperature may still significantly alter landslide frequency. On the other hand, in relatively drier parts of the sub-region higher temperatures will cause soils to dry, thus reducing landslide incidence. Nevertheless, both humid and drier areas will be susceptible to the predicted increase in frequency and intensity of cyclones and convection storms. The combined effects of flooding, debris flows and high winds could potentially lead to catastrophic events in densely populated coastal areas.

5. TOWARDS EFFECTIVE MANAGEMENT OF LANDSLIDE RISK

A number of complementary actions are available to manage landslide risk. Typically they are applied at two geographic scales: 1) individual slopes within a sub-catchment, and 2) upland landscapes ranging in size from sub-catchments to entire river basins.

At the landscape level, forest-related options include retention, rehabilitation or restoration of forest. The latter two are referred to as “protective forestation”. Retention of intact natural and plantation forests in upland areas is the first and best means of protecting uplands from landslides.

At the level of the individual slope, the options are to reduce landslide hazard through the use of plants including trees and shrubs, or mitigate landslide impacts through site reclamation also using trees and shrubs. At the catchment scale, the issues are more complex, particularly with regard to the interaction between hillslope stability and channel stability.

5.1. Protection of landslide-prone landscapes

Control of landslides in upland areas requires an integrated approach. Tree planting alone will not solve the problem of increasing incidence of landslides and erosion. There also needs to be landscape-level planning of land use, good land management practices in cropping, grazing and forestry, careful road construction, terracing and other contour-aligned practices in fields and plantations, and participation of local communities.[9]

Within agricultural and other areas, individual slopes with unstable soils or perched water tables in topographic depressions are best left as forest, or reforested if already cleared, due to the high risk of landsliding. One of the best approaches to enhancing slope stability, while also promoting biodiversity conservation, involves restoration of upland forest ecosystems. A greater diversity of forest species improves slope stability through more complete use of available rooting zones. Inclusion of fruit trees or species that provide products without the need for felling can also support socio-economic needs.

Unstable slopes will almost always require protective forestation. Protective forestation, however, does not necessarily imply large-scale reforesting, which may be unrealistic in areas where there is heavy reliance on land for subsistence production. Because landslide hazard is not uniformly distributed, but concentrated in critical areas of topography, soil and land use, reforestation targeted at high risk areas could result in disproportionately large reduction in landslide incidence and sediment yield.[14] For instance, it has been calculated that reforestation in the Waipaoa catchment, North Island, New Zealand of just 9.3 percent (159 km^2) could decrease the total sediment inputs from landslides by about 20 percent.[157]

Whether large-scale or targeted, protective forestation on the severely degraded soils found in many parts of Asia will probably require soil fertility treatment. To a lesser or greater degree, planting will also be required in many areas to restore species composition, forest structure and the ecological functions typical of mature natural forests.[34]

5.1.1. Forestation options

At the landscape level, there are several alternatives depending on the ecology of the region and local socio-economic conditions. The options range from encouraging natural regeneration and providing protection that allows forest recovery – as pursued in China under the ‘mountain closure’ scheme[188] – to intervening directly by planting indigenous and/or exotic species.[149]

Managing upland forests, including planning and implementation of protective forestation activities, is a complex task. The ITTO Guidelines for the Restoration, Management and Rehabilitation of Degraded and Secondary Tropical Forests recommend a holistic approach taking into account other local landscape components.[102] The guidelines should help decision-makers identify strategies that benefit local communities while preserving the site-specific ecosystem integrity.[223]

Protective forestation is not a one-off “plant and run” affair. Policies and practices that can be continually improved by monitoring and learning are far superior to rigid management. Putting in place management structures, which include local participation from the outset of the planting programme is a best practice to be emulated.

Box 3. Species selection

On slopes susceptible to landsliding there is a need to select appropriate species for land stabilization. Species characteristics that have proved effective for erosion control are also desirable for rehabilitation of landslide areas. In order of importance, these are as follows:[53,212]

1. Good survival and growth on impoverished sites
2. Ability to produce a large amount of litter
3. Strong, deep and wide-spreading root system with dense, numerous fibrous roots
4. Ease of establishment and need for minimal maintenance
5. Capacity to form a dense crown and to retain foliage year-round, or at least through the rainy season
6. Resistant to insects, disease, drought, and animal browsing
7. Good capacity for soil improvement, such as through high rate of nitrogen-fixation, appreciable nutrient content in the root system
8. Provision of economic returns or service functions, preferably fairly quickly such as fruit, nuts, fodder or beverage products
9. Absence of toxic substances in litter or root residues
10. Low invasiveness

Tolerance to soil infertility, acidic or toxic soils and exposure to desiccating wind and sun is critical. Erosion reduces soil fertility, and high rainfall causes leaching, acidity and sometimes aluminum toxicity. Species known to have exceptional physiological tolerances belong to genera Acacia, Eucalyptus, and Pinus.[54] In Malaysia, *Melastoma malabathricum* and *Leucaena leucocephala* have shown to be suitable for slope stabilization and have superior resistance towards acidity and aluminum toxicity.[132,163,162]

5.2. Slope protection and reclamation of landslides

Trees, shrubs and other plants may be employed to stabilize landslide-prone slopes as preventative measures.[188,37,83] By use of trees and other woody vegetation - often supplemented by conventional engineering solutions - landslide hazard to economic activities such as forestry, agriculture and infrastructure development is minimized. On slopes that have already failed there is generally a need to curtail continued impacts from the slide, such as sediment release into rivers where fisheries resources may be damaged. There may also be pressure to quickly rehabilitate productive assets, such forests or agricultural lands. In these cases, reclamation techniques may be appropriate.

5.2.1. Protecting agricultural landscapes

Deforestation does not always lead to large soil losses from erosion and landsliding; much depends on how the land is subsequently managed.[74] People in upland areas have lived for many years with the risks of landsliding and other erosion hazards. Over time cultivation technologies that minimize risk and reduce degradation of land, such as terracing and agroforestry, have been often implemented. Such innovations, though primarily developed to maintain soil fertility by controlling surface erosion and capturing nutrients and organic matter,[136] can also reduce landsliding in some cases. Throughout Asia, they have been employed in a multitude of forms as a local response to climate, ecosystem and socio-economic circumstances.

Many production systems in the uplands of Asia are characterized by multiple land use patterns in typically marginal, stressed agricultural ecosystems.[225] These systems range from pure agriculture with cultivation of herbaceous plants to forest production from either planted or natural forests. In between are found the agroforestry systems, which mix herbaceous and woody plants and in some cases livestock as well.[230] In their numerous and diverse forms, agroforestry includes most of the traditional systems practiced in Asia.[11]

In terms of landslide protection, agricultural systems with a high proportion of trees or shrubs may provide increased root density with depth to reinforce the soil mantle. Generally, systems mimicking natural forest with respect to plant diversity and multilayered structure above and below ground will provide the greatest levels of landslide protection.

Shifting cultivation transitions

Slash and burn agriculture periodically opens a "window of susceptibility" to landslides when patches of forest are cleared for cropping. Depending on how quickly roots rot and new woody vegetation re-establishes, this period may last from 3 to more than 20 years. Forest regeneration after swidden abandonment may be slower than after logging as a result of nutrient depletion resulting from burning and crop production.[179] In cases of severe surface erosion and nutrient depletion, vegetation more suited to drier and more fire-prone environments such as grassland may develop. Frequent burning of Imperata (*Imperata cylidrica*) grasslands in Philippines and elsewhere in Southeast Asia constitutes a barrier to succession, preventing forest re-establishment.[52] While such grasslands may, however, provide some protection from landslides, Imperata grasses are of little use to farmers and as a result, additional pressure may fall on remaining forests. Rehabilitation of Imperata grasslands may be achieved through assisted natural regeneration of forests including fire suppression, restrictions on grazing or establishment of agroforestry.

Modern agroforestry

Much of the impetus behind current agroforestry development in tropical uplands has been in response to intensification of shifting cultivation and related land degradation.[153,72,11] Attempts to provide alternative cultivation systems in the mountain areas of Yunnan [213], and rehabilitate abandoned fields colonized by Imperata grass in Philippines and Indonesia through "agroforestation" [68,195] are two examples.

Surface erosion, gullying and landsliding can be mitigated by a type of alley cropping that incorporates rows of contour planted trees, which help level the slope between rows over long periods of time.[199,212] Among the Ikalahan people of the northern Philippines, former swidden farmers plant rows of nitrogen-fixing trees 5 to 20 m apart depending on the gradient.[10] On the steepest slopes, SALT (Sloping Agricultural Land Technology) guidelines suggest spacings of 3-5 m.[141] While planting crops along the contour without alternating pasture or rows of woody vegetation can cut soil losses (t/ha/yr) by half, incorporating trees can reduce losses by 90 percent.[15] SALT design also includes the use of diversion ditches to prevent runoff from flowing onto the slope;[32] the first line of defence against landsliding and surface erosion. Improper contour alignment, however, may cause concentrated flow leading to gullies and landsliding.

Tree-rich agroforestry systems offer a greater degree of slope stabilization. Though conversion of forest to agroforest makes hill slopes more susceptible to landsliding,[177] the ultimate effect depends on the type of system established. If there is sufficient density of trees or shrubs (stems/ha and root biomass with depth), slope stability may not be significantly altered. Closely spaced tress also put down deeper roots than trees in alley cropping systems. Some systems such as home gardens, multilayer tree garden,[126] and some types of forest farming,[47] will likely have levels of protection close to forests once mature. However, if systems are associated with roads and terraces, as is the case of coffee and tea plantations, susceptibility to landsliding will rise, as seen in Darjeeling, India[184] and Tanzania.[89]

Forest farming

Within the agricultural landscape, slopes susceptible to landsliding (steep areas, depressions and other areas of water convergence, and areas close to valley heads) are generally left under forest cover by farmer when land is not scarce. Such areas are also often less accessible. With increasing demand for land these areas are increasingly being developed, leading to higher rates of landsliding and erosion if alternative productive uses for land that do not lead to deforestation are not found.

One possible solution may be improved forms of the traditional practice of forest farming. The production of food, forage and other products from the forest without cropping has been practiced in natural and semi-natural tropical forests for millennia, such has been the case with the ikalahan people in the Kalahan Forest Reserve in Northern Luzon in the Philippines.[238] Newer forms, termed "closed-canopy high-diversity forest farming system" or "rainforestation", are being employed in the Leyete Islands, Philippines as a means to replace environmentally destructive forms of land use between the lowland areas and the protected mountain forests.[127,78,171] Albeit production levels are normally lower than conventional agriculture or shifting cultivation, when suitable markets exist or can be created for the non-timber forest products that are typically produced, forest farming may be a viable alternative that retains forest cover and slope stability.

Yet, gallery forests along inland valleys, where landslide susceptibility is greater and hence where forest farming would be most suited[47,81] are also favoured for irrigated rice production.[128] Though such terraced systems may have slope stability comparable to forest, slope degradation can occur at a greatly accelerated rate if terraces are not maintained, as has been documented in Nepal.[237]

Land use rationalization

Rationalization of land use according to productive capacities and biophysical constraints is necessary to avoid or reduce landslide risk while maintaining production where possible. Such land evaluation and resulting zonation would suggest:

> "continuous annual crop production in level, high-productivity areas; use pastures and production-oriented agroforestry on gently sloping land and agroforestry systems more closely resembling the native forest on steeper slopes; and leave undisturbed forest cover on extremely erosion-prone soil and watersheds. Less suitable sites are protected from degradation, while maximizing production on the most stable, productive sites will reduce pressure on receding forests and over-utilized shifting cultivation sites."[10]

Land evaluation guidelines have been produced for different purposes including rainfed agriculture, irrigated agriculture, extensive grazing and forestry.[57,58,59,61,63] Because 'top-down' approaches are not always successful, participatory approaches including farming systems analysis (FSA) have also been introduced.[60,62] These have resulted in the development of methods and applications for ecosystems and landscape analysis in agroforestry [161,154] and the Land Use Planning And Analysis Systems (LUPAS) methodology,[96] which are suitable for resolving landuse conflicts in upland areas.

5.2.2. Reclamation of landslide scars

Individual slopes that have recently failed and continue to cause major off-site impact or are likely to slide again may be selected for reclamation. In such cases, reclamation aims to restore the economic and biological productive capacity of the land. Reclamation may also serve to mitigate further impact as landslide scars can continue to produce sediment and resulting negative effects for years after initial failure. In the Sanko catchment in Central Japan, sediment supply from some landslides has continued for 45 years.[98] Usually because of the expense and difficulty of reclaiming land only the most essential slopes are considered for reclamation.

Objectives of landslide reclamation

Restoring productivity and livelihoods and/or curtailing off-site impacts are the primary objectives of landslide reclamation. Other overarching objectives such as aesthetic, socio-economic or conservation considerations may also be important depending on the location of the site and the local situation.

In national parks, reclamation would normally not be considered because landslides provide areas for development of early successional habitats that can enhance biodiversity and increase habitat richness. If slides are caused by human activities such as road building, however, or if sliding is extensive and biological resources are at risk, then landslides areas may need to be reclaimed.

Outside parks, options for reclamation are likely include the use of exotics because of their frequently superior ability to establish in inhospitable sites and stabilize slopes. They may be eventually thinned out, however, to allow native species to recolonize.

Due to poor soil and exposure to desiccating sun and wind, plus a requirement for rapid revegetation, the range of tree, shrub and other plant species available for reclamation work is limited. Typically these are exotic species, but research into native species known to possess the necessary attributes for reclamation purposes progresses. At present, socio-economic and biodiversity related objectives of reclamation may have to be put aside.

Vegetation establishment

Because larger/older seedlings are best for successful establishment, reclamation may be expensive. In areas difficult to access, aerial seeding has been used although success rates are often low. Compared to conventional engineering solutions, however, planting of trees and shrubs is generally the most economical means to reclaim landslide scars.

Without additional erosion control measures, tree planting on eroding slopes stands a high chance of failure. Slopes where vegetation has been stripped and the subsoil is exposed are highly erodible, particularly during the rainy season when landslides are most likely to have occurred. Therefore, it is crucial that some form of physical barriers be erected to prevent soil movement so that roots are given a chance to anchor themselves.

Tree planting usually requires site preparation variously including terracing, contour trenching or bund construction. Rehabilitation of the denuded Swat River catchment in Pakistan illustrates that planting chir pine (*Pinus roxburghii*) mixed with broadleaved tree species and also constructing stone check dams is effective in reducing surface runoff and soil erosion compared to tree planting alone.[7] Controlling soil movement is particularly important in mountain regions where torrents are frequent and cause both direct soil erosion and soil saturation, which increases landslide risk.

Natural regeneration versus planting

The choice between natural regeneration of vegetation or tree/shrub planting is likely to depend on the degree of disturbance, the total landslide-affected area, the proximity to recolonizing vegetation, and the urgency with which the land needs to be stabilized. Where quick stabilization is not urgent, assisted natural regeneration may be best and in many parts of Asia, high rates of rainfall and weathering promote rapid regrowth.[176,69,35] These factors also increase susceptibility to surface erosion and landsliding, however, which makes reclamation more difficult.

> “Promotion of the recovery of self-sustaining [plant] communities on landslides is feasible by stabilization with native ground cover, applications of nutrient amendments, facilitation of dispersal to overcome establishment bottlenecks, emphasis on functionally redundant species and promotion of connectivity with the adjacent landscape. Arrested succession through resource dominance by a single species can be beneficial if that species also reduces persistent erosion, yet the tradeoff is often reduced biodiversity.”[202]

Severe degradation and exposure of the infertile subsoils will slow natural regeneration. Regeneration will also be limited where distance to unaffected forest areas is large such that recolonization is impeded. If the need to stabilize land is urgent, then rapid establishment of vegetation through planting may be necessary.

Tree and shrub species suitable for land stabilization will differ from those used for forest rehabilitation. Characteristics outlined in Box 3 also apply but species need to process even greater robustness. Because of the difficulty in establishing vegetation on inhospitable sites, proven exotic species are usually used. Testing of native species is, however, growing in countries including China, Thailand and India and new possibilities may come available.

In general, nitrogen-fixing species have been used successfully as many can tolerate harsh environment and nutrient-deficient substrates, typical of landslides scars. Some genera or species are more suited to some sites than others. One study of trees planted on mining waste in India finds that acacias fare better than eucalypts in improving the soil on such sites.[151]

5.3. Identification and monitoring of landslide hazards

Most Asian countries have regions susceptible to landslides. Because many Asian countries are geologically and geomorphologically active and socio-economic conditions may be poor, levels of vulnerability are often high.[2] Poor populations in marginal areas are especially at risk and vulnerability is increased by rapid and uncontrolled expansion of industry, agriculture and settlements in landslide-prone areas.

Consequently, there is a need to develop programmes to minimize risks associated with landslides. Strategies to manage landslide risk should include maintenance of an up-to-date landslide inventory, permanent monitoring of natural processes, research on natural phenomena, and geomorphological mapping.[95] Estimation of risk is based on identification of landslide hazards and estimation of consequences if landslides do occur. Developing risk mitigation options and planning their implementation is the next logical step, followed by monitoring to facilitate programme improvement.

Zoning of potential landslide areas according to risk, together with regulations excluding some activities and requiring geotechnical evaluation for others, are the most common measures for mitigating landslide risk. Zoning backed by regulation is a fundamental component of disaster management and an important basis for promoting safe human occupation and infrastructure development in landslide-prone regions.

Remote sensing for continuous monitoring of landslide-prone areas and information systems for decision support are becoming increasingly sophisticated. GIS-based systems are of great practical use in assessing landslide susceptibility, hazard and risk, and in supporting land management decisions to reduce vulnerability. Even in countries with limited financial, technical and data resources, such systems are proving to be cost-effective and well suited to such purposes.[6]

Maps are the primary tools for decision support and can be used to delineate zones of varying landslide susceptibility, hazard or risk. Susceptibility mapping aims to differentiate land into areas according to factor-of-safety (FOS) estimates.[197] Based on the susceptibility map, hazard maps identify slopes where there is potential for causing negative impacts with respect to ‘elements at risk’ (people, buildings, engineering works, economic activities, public services, utilities, infrastructure and environmental features). Risk maps attach probabilities and economic and social costs associated with such consequences. These exercises rely on understanding mass movement processes and require high quality data.[8]

The ability to accurately predict landslides is of great importance if hazard assessments and zoning regulations are to prove useful. High levels of accuracy will primarily depend on the quality of the data and the model employed. The predictive accuracy of current hazard assessments is reasonably good in Asian countries where landslide risk is being studied. Verification of model results against inventories of actual landslides showed accuracies in the range of 70-90 percent, depending on the type of model used and how well it represents a particular geomorphic setting.[134,135,150,36]

6. CONCLUSIONS

Evidence shows that forests have a significant role in preventing landslides, as well as mitigating off-site damage. The presence of trees and shrubs increases slope stability mainly through mechanical reinforcement of soil by roots, rainfall interception and drying of soils through transpiration. Without these effects, stability thresholds are reduced, making slopes more susceptible to intense or long-duration rainfall, earthquakes or other triggering events.

Both the mechanical and hydrological effects of forests are relevant to shallow landslides, while for deep-seated landslides where failure occurs below the rooting zone the effects of forests are primarily hydrological. Forest cover also indirectly reduces landslides incidence by inhibiting surface erosion and the formation of gullies. Soil and subsoil exposed by gully erosion have much higher water infiltration rates, which frequently triggers landslides and debris flows. Ultimately, the presence of forests in upland regions reduces the probability of slope failure, which extended to the scale of a watershed or basin implies fewer number of slides the greater area of forest coverage.

Forests and trees also have a role in providing a physical barrier to the movement of landslide material, as well as trapping material and gradually releasing it with reduced impact. The ultimate effect will depend on the width, age and density of the tree stand and the magnitude of the forces involved in the landslide. For smaller slides, forests are likely to be an effective barrier in protecting water courses, infrastructure and habitation. With larger slides and rock falls, however, trees could create logjams in rivers.

Continued development in upland areas will result in construction of roads and trails, forest clearance and expansion of land uses with shallow rooting depths, and building of settlements and industries. Although slope stability is usually regained within 10-20 years following forest re-establishment, logging roads and forest management constitute a significant cause of landslides and careful road construction following available codes is therefore warranted.[234]

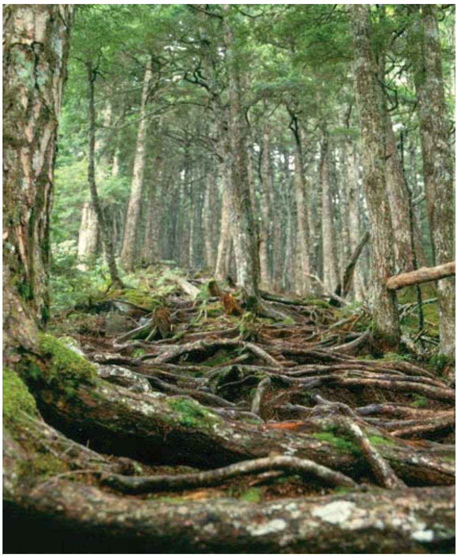


Figure 6.1. Tree roots stabilizing steeply sloping soil surface
Source: Masakazu Kashio

Because of these and other developments, including climate change, the number of landslides experienced in the region is likely to increase. If effective steps are not taken to minimize risk, the impact associated with landslides may rise as population densities and the value of property and resources increase. In areas affected by landslides, development gains will be lost and families, businesses and communities will become more vulnerable to future disasters, including landslides. If alternative low-risk areas are not available nor affordable, new settlement would take place in high-risk areas such on steep slopes, alluvial fans, or flood plains and a vicious circle could develop.

Climate change is likely to increase the incidence of landslides in parts of Asia where increases in storm frequency and intensity are expected. In regions subject to drought and root die-back or wildfire, subsequent loss of root reinforcement and lower stability thresholds are also likely to make slopes susceptible to landslides triggered by minor earthquakes or moderate rainfall.

Appreciation of economics of natural hazards and disaster risk reduction is growing. While the economic costs of individual landslide events are typically much lower than flood or earthquake events, they are rising because of changes in climate and activity expanding into landslide-prone areas. Although individual landslides are mostly small, the cumulative impact can be large and impacts often extend offsite and are long-lived. In the case of sediment release causing damage to fisheries and livelihoods for example.

Consequently, mitigation of landslide hazard follows a two-pronged approach. Firstly, lives, property, natural resource assets and investments need to be protected. For example, top soil is of critical importance in natural resource based economies and cannot be replaced while the cost of disaster and loss of life can never be adequately measured. Secondly, there is often a need to re-establish production and livelihoods following landslides. Though rehabilitation can be expensive and difficult, quick stabilization of failed slopes and re-establishment of productive assets will minimize costs. Funds for prevention and rehabilitation are likely to be most effectively used by targeting the most sensitive or hazardous sites.

7. RECOMMENDATIONS

Application of knowledge of the climate-vegetation-landslide nexus can reduce risks associated with development in upland areas. With the uncertainties of climate change and its impacts, margins of safety need to be widened. Four complementary approaches are necessary to reduce risk and maintain slope stability:

1. establish and implement guidelines for suitable land use in upland landscapes;
2. establish and enforce standards of practice for slopes that have been altered by human activity;
3. management of vegetation on natural slopes; and
4. rehabilitation of landslide affected lands and livelihoods and curtailment of off-site impacts.

Zoning: Cases throughout Asia have shown that policies supporting total exclusion from upland forests are ineffective in preventing encroachment and forest clearing. Instead, land use regulations should allow economic uses of forests that are compatible with landslide risk management objectives. Flexibility to allow for differences in degree of landslide hazard among slopes should be the aim, although this does require spatially precise estimates of hazard.

Delineating parcels of land based on their suitability for different uses with respect to slope stability may proceed in two stages:

1. The degree of landslide hazard is estimated based on current land use and the inherent properties of topography, geology, soils, vegetation, weather and other factors. Hazard zones are classified with the support of GIS and remote sensing technologies, together with models to estimate slope stability. Maps of the hazard zones are produced to guide appropriate land use. Also, vulnerable land, infrastructure, or settlements within or downslope of highly hazardous zones are identified.
2. Types of development or land use that do not reduce slope stability are specified for each of the identified zones.

Such guidelines are made available to planners and decision-makers when developing plans for upland landscapes.

Standards of Practice: Altered or engineered slopes, such as those that result from the construction of roads, railways and other types of infrastructure, buildings or agricultural terraces, are susceptible to failure. The problems of concentrated water flow, increased water infiltration, ponding, loss of lateral support, etc. that cause landsliding must be addressed by the adoption of appropriate standards of practice and the development of specific technologies to facilitate the adoption. Soil bio-engineering that utilizes the root reinforcement and hydrologic drying properties of trees/shrubs is one technology that is gaining acceptance as a cost-effective method of enhancing slope stability.

Standards for the construction of roads and railways need to recognize the role trees and shrubs play stabilizing slopes and emphasize retention where possible. This especially important at the toe of slopes, where trees provide lateral support for the upper slope and protect infrastructure from damage by smaller rockfalls and landslides. Consideration of the age (stem diameter), width and density of the tree buffer is necessary.

Skid trails associated with logging and paths or trails established in and around agricultural areas also require special attention and measures to reduce risk, and in the case of logging, implementation of specialized techniques may be necessary.[234] Concentrated water flow, which leads to gullying and landslides, should be managed through alignment of trails along contours and other standard means. Planting or retaining trees below culverts and other seepage areas to provide root reinforcement and soil drying is also recommended. These measures apply equally in relation to roads and railways.

Vegetation management: Prevention of landslides will require management of vegetation at the landscape level. Due to the scale of hydrologic and geomorphic processes, off-site impacts, and other related objectives of water management the river sub-basin is the appropriate unit of management. On natural slopes unaltered by construction or engineering, forest conversion to another land use is the most important factor determining changes in slope stability. Consequently, development plans for upland areas must consider the impact of such changes in land use.

Policies to control development in the uplands, and especially headwater areas, have relied on the creation of protection forests. Slopes with steep gradients are inherently unstable and should continue to be classified as protection forest. In headwater areas, sedimentation from gullying and landslides is a particular problem and such areas should remain under forest. Similarly, treeless slopes with high landslide hazard ratings should be targeted for protective forestation programmes and appropriate vegetation management. Such a targeted approach precludes the need to plant forests for an entire catchment, with attendant expense and disruption to existing land uses.

Shrub species in addition to trees should be included in the mix because they provide comparable soil reinforcement to trees without negative effects of weight surcharge and wind-loading forces of larger and taller vegetation.

Vegetation management should be extended to controlling surface erosion, in addition to direct control of landslide risk. Vegetation cover limits soil erosion and the formation of gullies, which increase water infiltration and landsliding.

The policy to exclude all economic activities from protection forests, whether natural or planted has been applied whether or not the activity involves tree removal. In terms of managing landslide risk, however, it is only necessary that the vegetation provides continuous rooting of sufficient density and depth, and above-ground cover for interception and transpiration to reduce soil moisture content and maintain slope stability. Consequently, new activities may be incorporated into standard watershed management objectives.

Because protection forests cannot usually be harvested for timber, other benefits that can be derived from standing forests should be focused upon. These could include production of fruits or other non-wood forest products with high local value, marketing of carbon emissions reduction and water resources protection, ecotourism opportunities, etc. Selection cutting of high-grade trees may be possible, if large areas are not opened up and high-lead yarding or other means to limit road and trail construction such as helicopter logging are employed.

Rehabilitation: Livelihoods, and associated natural resources, need to be quickly re-established after a landslide, while continuing offsite impacts also need to be managed. Landslides may be localized and few in number, or widespread and numerous, as would result from a large storm or earthquake. Landslide reclamation and rehabilitation of livelihoods requires the financial resources and technologies to successfully re-establish vegetation. Though the task is difficult and not always successful, disaster relief funding is becoming increasingly available and forestry activities should not be overlooked both as a means to rehabilitate affected areas and restart economic activity.

As final word, it can be concluded that landslide management and recognition of the role that forests and trees play should be integral part of climate change adaptation and disaster risk reduction. Landslide incidence and associated impacts are expected to rise because of climate change and expanding development in upland areas. The impacts of landslides can be widespread, resulting in loss of life, settlements, infrastructure, agricultural land, natural resources, heritage sites and more. The solution to minimize the problem, however, simply involves identification of hazardous slopes, management of vegetation and land use on these slopes, and implementation of engineering practices when altering slopes. Forests, and in particular trees and shrubs, play a key role in maintaining and enhancing slope stability, and should be considered an integral part of upland management.

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