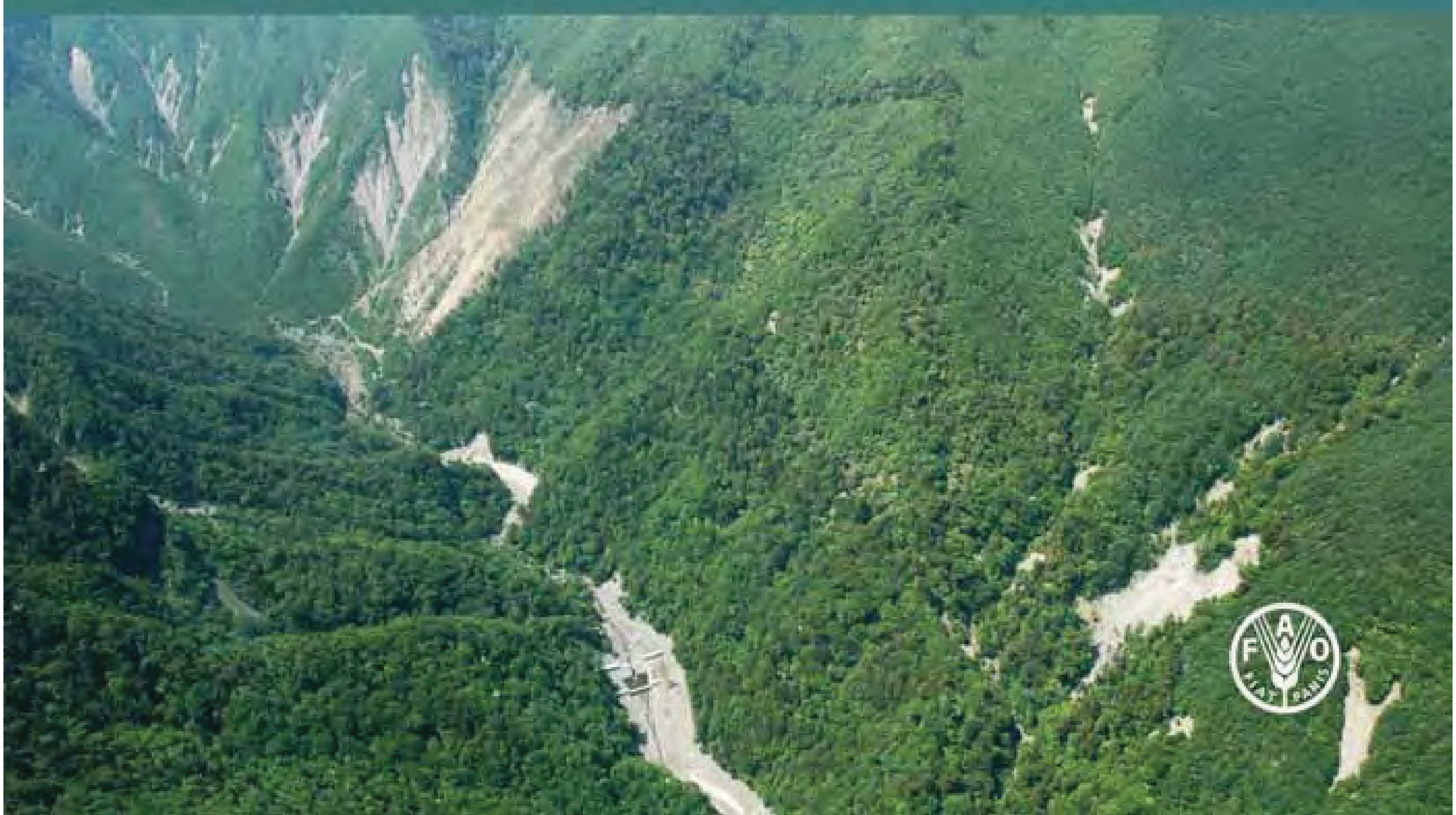
Forests and landslides

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



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

Second edition

by Keith Forbes and Jeremy Broadhead

In collaboration with: Gian Battista Bischetti, Francesco Brardinoni, Alan Dykes, Donald Gray, Fumitoshi Imaizumi, Sekhar L. Kuriakose, Normaniza Osman, Dave Petley, Alexia Stokes, Bruno Verbist and Tien H. Wu

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Foreword

Understanding the roles that trees and forests can play in preventing landslides is increasingly important as sloping areas in Asia are further developed and the impacts of climate change affect the region. The roles of trees and forests in rehabilitating landslide-affected areas are also important because of the impacts of landslides on water resources and water quality. Against this background, climate change adaptation in the region is receiving considerable attention. Current rural development trends and predictions of more extreme weather events heighten the need for consolidated information in these contexts.

With natural disasters becoming increasingly frequent in Asia, interest in maintaining forests for the environmental services they provide is growing. In several Asian countries, floods, droughts and landslides have led to major policy realignments that have centred on forests and forestry. However, the resulting policies have often been criticized for their poor technical understanding and disregard for socio-economic considerations. This emphasizes the need for policies to be based on sound science and balanced assessments of the distribution of costs and benefits 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 affected areas through this publication. The contents should 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. 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.

Hiroyuki Konuma
Assistant Director-General and
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Abstract

The potential for loss of life and destruction of assets through landslides is increasing in many mountainous and hilly areas of Asia. Logging, residential and infrastructure development and other activities continue to expand on slopes highly prone to 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 trigger 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 die-back, pest and disease outbreaks and wildfire – all of which are likely to reduce soil reinforcement provided by trees and increase landslide incidence.

Scientific studies confirm the crucial role of trees and forests in preventing shallow 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 smaller although soil drying by tree roots can still help to avoid excessive soil water pressures. During extreme events, involving heavy rainfall, very weak slopes or seismic activity, forest cover is unlikely to have any effect. Policies encouraging land uses that 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 to control the after-effects of landslides such sediment release into rivers. Fast growing trees and shrubs are best suited to this purpose but socio-economic- and conservation-related factors should also be considered. Above all, identifying and mapping high landslide risk zones and avoiding activity within these areas is an essential step in reducing the risk to lives and assets posed by landslides.

1.Background*

Steep terrain, vulnerable soils, heavy rainfall and earthquake activity make large parts of Asia highly susceptible to landslides.[18] With population growth, expansion of infrastructure and increased forestry and agricultural activity in sloping areas, the significance of landslides is set to increase in coming years. In temperate and tropical Asia, projected climate change-related impacts, including increased frequency of extreme rainfall events, and heightened risk of forest die-back and wildfires, are likely to increase the number and severity of landslides.[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 fatalities from natural disasters.[38] Water-related issues – floods, landslides and droughts – have been perhaps the most significant driver of forestry-related policy change. For example, logging bans in Thailand, the Philippines and China were largely the result of perceptions 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.[66, 93] 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, they may also damage or destroy forest and agricultural resources, remove topsoil and reduce land productivity, block rivers and increase downstream sedimentation.[169,131,17] 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 prevalence of landslide deaths in poorer countries and regional experience in successfully reducing landslide risks suggest that much can be done to limit future losses associated with landslides.[18,103]

*Citations indicated by numbers in superscript are referenced at the end of the publication.

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 can assist in land rehabilitation and stabilization after landslides have occurred.

This section includes a review of trends in landslide frequency and the distribution of landslides in Asia as well as an assessment of policy responses to natural disasters in Asia. Sections 2 and 3 detail how trees and forests are useful in landslide reduction and why landslides are a growing hazard. Section 4 outlines the implications of climate change on landslide incidence and Section 5 reviews practices for managing landslide risk, including rehabilitation of landslide-affected areas. Sections 6 and 7 contain conclusions and recommendations for policy-makers.

1.1 Landslide trends in Asia

Assessing trends in landslide incidence is hindered because accurate records 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.[18, 150]

Available statistics nonetheless imply that the frequency of landslides causing death or affecting people in Asia has increased more than five-fold since the 1970s; between 2000 and 2009, 88 recorded landslides resulted in the deaths of 5 367 people (Figure 1.1).[51] The increasing trend is supported by independent data held in the Durham Fatal Landslides Database, which also demonstrate an increase in smaller landslide events. Some of the increase in recorded data is likely to be due to better communication and reporting in more recent decades but also results from increased human development of sloping areas and observations of climatic changes (Box 1).

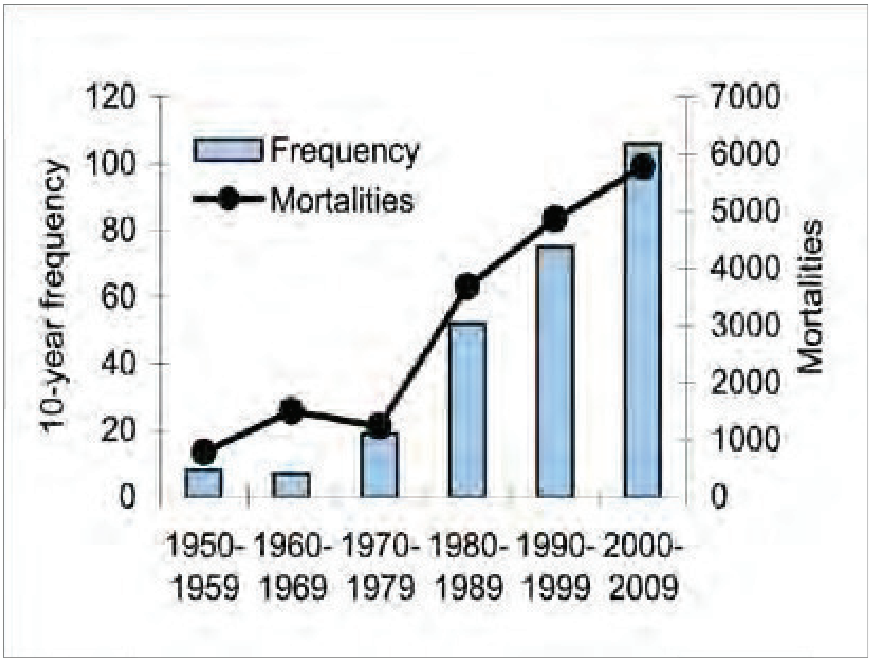

Figure 1.1. Decadal frequency of landslides and mortality rates in Asia
Source: International Disasters Database <http://www.emdat.be> [(51)].

The occurrence of fatal landslides is heavily influenced by tectonic processes, monsoon rainfall and the presence of a vulnerable population.[149] In some countries such as Indonesia and the Philippines exposure to landslides resulting from heavy rainfall is proportionately greater than in others where earthquakes are of greater significance, for example Japan and Taiwan, Province of China. Regardless of the triggering mechanism, however, poor countries have significantly higher numbers of landslide deaths than wealthier countries due to lower levels of human development.[103]

Risks of mortality through landslides triggered by precipitation can be estimated by combining information on hazard type and destructivity, population exposure and vulnerability. Assessments demonstrate relatively high levels of risk in many parts of Asia (Figure 1.2). In particular, five key landslide locations in Asia have been identified, all of them associated with high seismic risks:[148]

(i) The southern edge of the Himalayan arc;

(ii) Central and southeastern China;

(iii) The Philippines and Taiwan, Province of China;

(iv) Indonesia/Java; and

(v) Southern India and Sri Lanka.

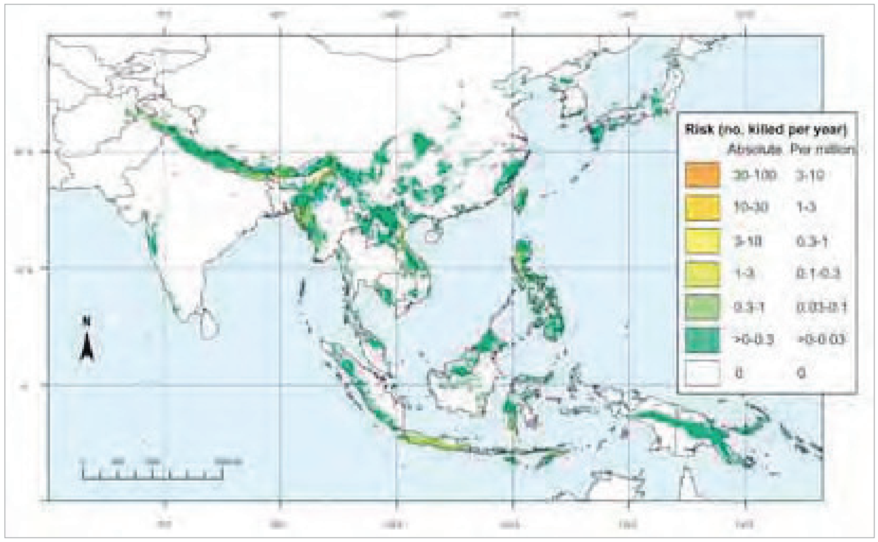

Figure 1.2. Mortality risk distribution for landslides triggered by precipitation
Source: ISDR, 2009. (103)

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

With the population in Asia set to expand by 10 percent, from 3.8 to 4.1 billion between 2010 and 2020, the impacts of landslides are likely to increase. The experience of Hong Kong Special Administrative Region (S.A.R.) provides an example, where landslides increased when the territory became more densely populated and hillside cutting increased.[18] In this context there is a clear and increasing need to address landslide risk in Asia and also the roles that forests and forestry can play in risk reduction.

BOX 1 - The Durham Fatal Landslides Database

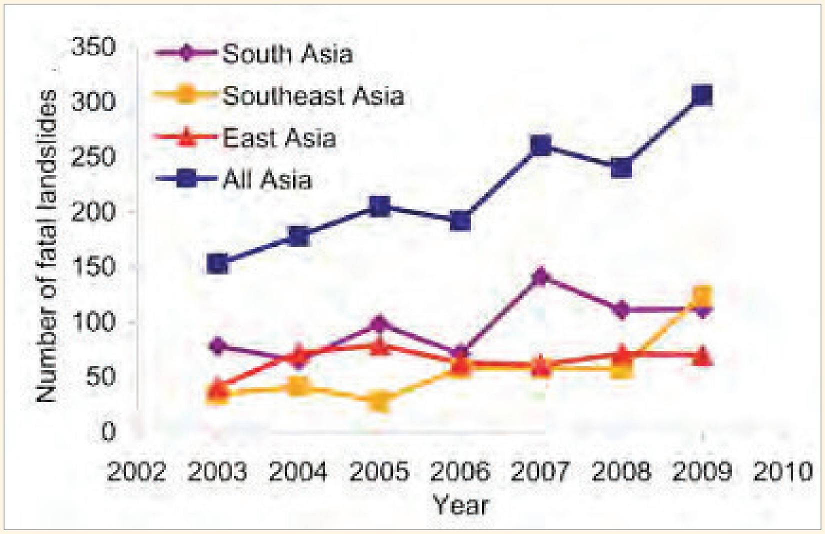

Figure 1.3. Number of fatal landslides in Asia by subregion 2003-2009 (excluding earthquake damage)
Source: Petley, 2010. (148)

The increasing incidence of fatal landslides in Asia is corroborated by data from the Durham Fatal Landslides Database (DFLD),[149] which independently shows rising numbers of fatal landslides over the past decade, particularly in Southeast Asia (Figure 1.3). Some of this increase is likely to be due to improvements in communications and reporting, but increasing precipitation frequency, intensity and/or duration; deforestation; population growth; urbanization; and infrastructure development are also likely to have played a role.[148]

With respect to the overall frequency and severity of landslides, the DFLD indicates an average of 219 fatal landslides per year between 2003 and 2009 (2 585 fatalities per year) – more than three times the number recorded in the International Disasters Database for the same period (68 landslides with 538 fatalities).[148,82] The difference results from the inclusion of landslides with fewer than ten fatalities in the DFLD and indicates the greater significance of smaller events.

1.2 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 quotas, conversion of sloping croplands to forest and reforestation activities in several provinces.[30] The logging ban is controversial, however, with authorities accused of making excessive claims in relation to the downstream impacts of deforestation in northwest Yunnan.[105] The drought and flooding periods also coincided with strong El Niño and subsequent La Niña events, the effects of which may not have been adequately taken into account.

In the Philippines, recurrent devastating floods and landslides were attributed to illegal logging and land conversion and led to the introduction of a series of logging bans, most recently in 2011.[98,123,13] The poor location of settlements and lack of flood adaptation, however, accounted for some of the most devastating effects. In relation to deep-seated landslides that occurred within the affected area, reforestation, although proposed as a major response, was probably inappropriate.

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 1.4). However, some reports suggested that landslides had tended to occur regardless of the type of vegetation cover and that rainfall intensity had overwhelmed the stabilizing properties of vegetation.[151] Forest clearance and replacement with vegetation less capable of securing the soil – rubber in particular – were also suggested to have been of greater significance than logging.[158,32]

In most cases where radical policy changes have been adopted in response to natural disasters the technical basis for change has been challenged. Knowledge on the nature of relationships between disasters and human activities – road building, deforestation, logging, agriculture, etc. – is still being refined.[66,93] 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 unnecessary costs it is important that future policy responses should be based on sound technical understanding.

Figure 1.4. Landslide scars in Southern Thailand following heavy rains in 1988
Courtesy: Masakazu Kashio.

2.Climate, landslides and the role of forests

2.1 Relevant landslide types

Landslides encompass a wide range of phenomena including slumps, rock falls, debris slides and earth-, debris- and mud-flows. Several common types of landslide can be influenced by forests or lack of them. A simplified landslide classification includes three broad categories:

1) Shallow;
2) Deep-seated wasting; and
3) Rock failures.[185]

Shallow slides occur within the zone penetrated by tree roots (or assumed rooting depth if trees are no longer present) while deep-seated movements occur below the depth of tree roots and above the bedrock. 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 – shallow landslides consist of soil or debris (rock and soil) moving down the slope. The velocity of shallow landslides is determined primarily by the slope gradient and the amount of water incorporated in the slide. People may be able to escape slow-moving slides (<3 metres/second), but more rapid onset and higher speeds of movement increase the potential hazard.

In the past it was believed that human activities had little influence on deep-seated slides, but it is now thought that timber harvesting, road building and changes in surface hydrology can have some effects.[41,77] Drying of soil, through transpiration by forests, slows the rate of creep and shortens the 'season' of movement – normally during the rainy season when soil water content is high.[184] Deep-seated slope movements 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, waterways and natural resources.

Finally, rock falls 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 freeze-thaw cycles are particularly at risk. Where infrastructure developments cannot avoid rock fall hazards, some form of protective barrier can reduce risks. In this respect, trees can act as a barricade or obstruction to smaller rock falls and limit run-out distance.[46] However, forests cannot protect against larger rock falls and where they are a potential hazard conventional engineering works or relocation of development activities are required.

2.2 Topography, geology and climate

Topography

Slope gradient and slope curvature are the main topographic factors that create susceptibility to landslides. Steeper gradients are generally more prone to landslides although other geologic and climatic factors may also make gentler slopes 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 pooling and soil saturation. Slopes with lower gradients that have been altered by road construction are also more susceptible to sliding.[81]

On natural slopes, shallow landslides commonly occur at gradients of 15-25° for earth flows and 20-45° for debris flows (Box 2).[111] 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 (5-25°), although they have been recorded on slopes as slight as 1.3° and greater than 25°.[24,68]

BOX 2 - Slope gradient and landslide susceptibility

In the Western Ghats of India, slopes greater than 20° are the most susceptible to shallow landslides,[117] but without woody vegetation, some models suggest that slopes as low as 15° can fail.[118] In a number of case studies from coastal British Columbia, the average slope for landslide initiation in recently harvested areas was about 10° lower than in forested areas. On slopes with relatively weak soils or weathered bedrock the threshold gradients for landslides to occur drop even further.

Adding weight to a slope, particularly at the top, or cutting into a slope, especially at or near the base also increases susceptibility to landslides.[101,222] Common examples include construction of buildings, adding earth fills, rocks or mine tailings, and also planting of trees on steep, upper slopes. By contrast, additional weight at the base of a slope adds shear strength and enhances stability. Consequently, the loss of trees at the bottom of slopes seriously affects slope stability by eliminating the fixing effect of trees' extra weight, the lateral support they provide and their buttressing effects. It also removes barricade protection against smaller slides and rock falls.

Geology and soils

Key geological factors affecting 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 and presence and thickness of surface materials. For example, volcanic ash and loess (sediment formed by the accumulation of wind-blown silt), which cover a large proportion of some parts of Asia such as Japan and China, are especially prone to slope failure. In relation, vegetation provides important protection to loess soils, but the role of trees in stabilizing volcanic ash is less clear.

Some types of underlying bedrock are prone to high rates of chemical weathering and fracturing, which weaken the substrate and create entry paths for 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[71] and the physical properties of slopes[208] 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 than cleared areas, even on steep slopes.[120]

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 the incidence of landslides. High winds can also increase loading on trees and play a role in slope failure. On the other hand, higher temperatures, increased wind speeds 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, but other less severe weather systems also cause landslides. Other important sources of variability in rainfall include the South Asian and East Asian monsoons and the El Niño-Southern Oscillation (ENSO).

The ENSO affects the tropical Pacific and occurs every two to seven years (three or four years on average), with each episode lasting nine to 12 months. The effect of the ENSO on precipitation is greatest in Southeast Asia and the western Pacific. ENSO effects are strongest between December and April.[122] Different effects are associated with the ENSO depending on the phase – El Niño or La Niña:

- **La Niña** increases the severity of storms and causes wetter than normal conditions in Indonesia, Malaysia and surrounding areas during December to February, and over the Philippines, eastern Indonesia, Papua New Guinea and South Asia in June to August.[167,92] Landslide frequency escalates in these countries during La Niña episodes.
- **El Niño** (March to May) produces drier conditions by June to August with increased risk of forest fires in insular Southeast Asia (especially Indonesia and the Philippines).[168,92] South Asia is drier in the June to August period, except southern India and Sri Lanka where it is wetter in September to November.[146] El Niño usually brings more rain in East Asia in December to February.

Strong El Niño years – when landslide frequency falls in most countries – are usually followed by several years of La Niña. 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.[124] Slopes made vulnerable may be quickly saturated with rainwater, overcoming the reduced resistance to failure. This is a growing concern in some parts of Asia such as Indonesia, India, the Philippines, Papua New Guinea and Australia, especially as El Niño has been more frequent than La Niña in the last few decades.[168, 3]

2.3 Role of forests and trees in landslide prevention

Overview

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.[93,182] In shallow soils, roots may penetrate the entire soil depth, providing anchors into more stable layers while dense lateral roots stabilize soil surface layers against landslides.[178] Transpiration via extensive root systems also reduces soil water content and landslide risk.[182,45] Additionally, forests can play a role in slowing and blocking smaller debris flows and rock falls by forming a physical barrier.[89]

Deep landslides resulting from continuous heavy rainfall or earthquakes are less likely to be prevented by vegetation.[93] Vegetation is also of little use on undeveloped and unstable soils that 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. Activities that increase erosion and slope instability include logging, road and trail construction and forest conversion. In undisturbed forest catchments, there are usually relatively few landslides.[200] 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.[182] Across much of rural Asia, upland roads are often built without adequate attention to proper engineering standards and as such are a frequent cause of landslides.

Figure 2.1. Old patterns of logging on 40-45^{o} slopes associated with high landslide density on Kamanshi River, Yamanashi Prefecture, Southern Japanese Alps. Logging took place five years before the photo was taken. Notice clogging of the river channel and overrun check dams
Courtesy: Yuichi Onda.

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.[182] Landslides begin to increase when roots decay – around three years after forest clearance – and susceptibility remains high for around 15 to 20 years until regenerating roots mature. Rates of root recovery are likely to be significantly higher in tropical areas where rates of growth are generally higher.

Land-use 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 root infiltration.[182,125,74] 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 are unstable, or cover bedrock or another impermeable layer.[126] The extent of forest cover in Asian countries and the proportion designated for protection is detailed in Box 3.

BOX 3 - Extent of protection forests in Asia

Forest cover and the area of forests designated for protection, including protection against erosion and protection of water resources, vary in countries across Asia as shown in Figure 2.2.[67] 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 account for a smaller proportion of the total forest area. In the Republic of Korea, Malaysia, Myanmar, Democratic People's Republic of Korea (DPRK) and Brunei, where landslide risk is also significant, protection forests are less extensive although 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]

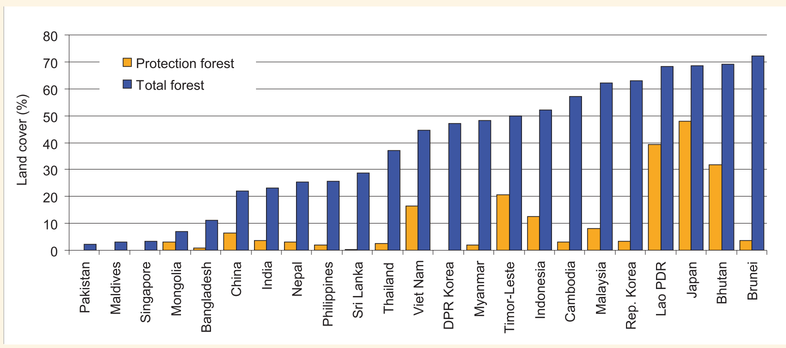

Figure 2.2. Total forest cover and cover of forest designated for protection in Asian countries, 2010[67]

In hilly and mountainous areas in Asia, forests, and in particular trees and shrubs, have a direct impact on the stability of slopes that is related to 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 these factors. 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.

General processes

The most important landslide protection services that forests provide are in relation to mechanical and hydrological properties and processes (see Figure 2.3). Mechanical properties associated with tree roots 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 lower 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 the soil surface from surface erosion and gullying.

Although the net effects of vegetation in preventing landslides are positive, there are a few negative effects that may reduce the protective functions of trees and forests. Mechanical factors and events 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.

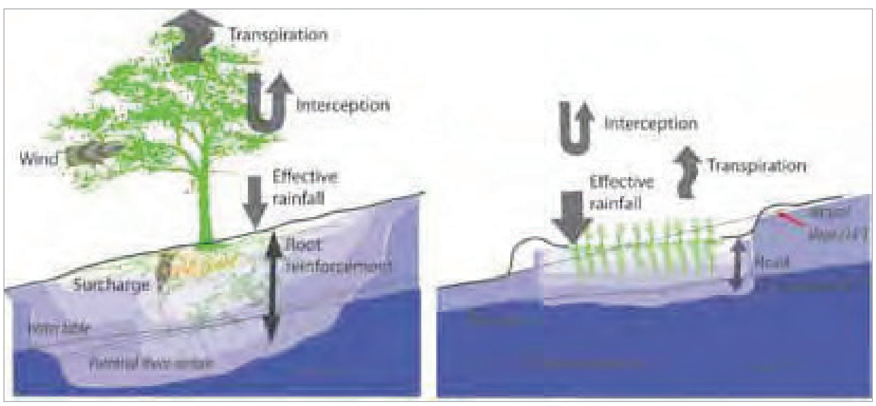

Figure 2.3. Relative influence of trees and upland rice on slope stability. The zones of root reinforcement and soil drying (lighter shade) will extend the length of the slope parallel to the surface with sufficient tree stocking. With shrubs, wind and surcharge forces are reduced, but soil reinforcement and drying remain comparable to trees

Mechanical effects

The stabilizing effect of roots in soil is supported by assessments that note an increase in landslide frequency following vegetation removal.173 Mechanical effects of vegetation on slope stability take place through a range of mechanisms as outlined in the following sections.

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 around a tree to a distance of at least 1.5 times the canopy radius.[85] Consequently, forests' effectiveness in protecting slopes depends on rooting depth relative to potential failure planes and the 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 the deeper that tree roots extend, the more planes of weakness they will pass through and bind.[27,198,136] Tropical species such as *Tectona grandis* and *Coffea arabica* have rooting depths up to 4 metres.[116] However, root biomass and consequently root reinforcement decreases rapidly with depth depending on species and climatic and soil conditions.[198,189] Nonetheless, forest vegetation can significantly increase soil strength at depths of greater than 1 metre, depending on the species.[15,152]

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.[75] 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.[205]

In shallower soils, tree and shrub roots may anchor the soil mantle to the slope and increase shear strength.[196] 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 20 to 30 centimetre depth. 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 (bridging of soil between points on a slope) are important functions of trees.[85] Particularly at the bottom or 'toe' of the slope, trees help to immobilize soil behind the tree.[209,84] The buttress effect also extends laterally, creating supporting arches to nearby trees. Furthermore, physical connections with adjacent ground at the outer edge of a potentially sliding raft of soil stabilize the slope over a broad area.[218] *In situ* tests showed a tremendous traction effect exerted by lateral roots of *Pinus yunnanensis* in the upper 60 centimetres of soil.[219]

Figure 2.4. Ponderosa pine tree buttressing a slope above a forest road. The unprotected portion of road cut to the left has failed. Mendocino National Forest, California, 1978
Courtesy: 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 (weight applied to the slope) combined with lowering of soil cohesion from heavy rainfall is believed to have contributed to slides on forested slopes near Santos, Brazil.[42,193]

In general, however, the effect of surcharge is small because the weight is usually distributed uniformly so that force per unit area is small. The effect can even be positive and enhance slope stability when soil cohesion is low, the groundwater table is high or when slope angles are low.[86] In this situation forces acting to pull soil down the slope are countered by the weight of the tree causing soil particles to lock together. Also, although tree removal on upper slopes may reduce stress and landslide probability, the effects of root reinforcement and soil moisture reduction are probably greater.

Wind loading

At times, the force of wind on trees can be significant, for example during tropical storms and cyclones.[193] Wind loading does not lead to landslides directly but the additional force placed on trees may tip the balance; for example, if wind and intense rainfall act in unison. Wind loading can increase shear stress and cause roots to be pulled out, reducing soil cohesion. Furthermore, wind may uproot trees and expose lower soil layers allowing large amounts of water to infiltrate which, by increasing soil water pressure, can trigger 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.

Hydrological effects

Beneficial hydrological effects relate to forests' ability to extract water from the soil and intercept rainfall and snow, allowing it to evaporate before reaching the soil. Modification of subsurface water flow through subsurface channelling along holes created by roots and enhancement of permeability may also improve slope stability. These effects reduce soil moisture content and delay the onset of soil saturation levels at which landslides are triggered. Forests are a particularly good land use with respect to landslide prevention because of their high rates of interception and transpiration. These may reduce saturation during a susceptible period, such as a monsoon season, and help to avoid a landslide incident.

Interception and evaporation

Intercepted rainfall is stored on leaves and stems and reduces the volume of rainfall reaching the ground. Water that does not reach the ground is lost to evaporation. The frequency of rainstorms is more important in determining the effective rainfall at ground level rather than the total amount, duration or intensity of precipitation.[25,108] In light rainfall most, if not all, of the rainfall may be stopped from reaching the soil. Even in high intensity storms, trees intercept about 15 to 25 percent of rainfall.[36] Over an annual cycle, and all else being equal, deciduous trees intercept smaller amounts of rain and snow than evergreen trees due to periods of leaflessness.

Aside from deciduousness, different species also have different interception capacity. The maximum amounts of rainfall intercepted in a single downpour by beech (*Fagus* spp.) and spruce (*Picea* spp.), for example, have been measured at 2.6 and 4.7 millimetres, respectively.[208] In the Pacific Northwest of the United States, interception in old-growth Douglas-fir (*Pseudotsuga menziesii*) ranges from 100 percent for light rain, to 15 percent for storms of around 75 millimetres (i.e. interception of 11.25 millimetres).[170] In broadleaf plantations in India, interception rates of 40 percent have been measured.[78] As a percentage of annual precipitation, typical interception rates are as follows:

- Cool-temperate hardwood forests, 10-15 percent;
- Temperate deciduous forests, 15-25 percent;
- Temperate coniferous forest and tropical rain forests 25-35 percent.[193]

In secondary or fallow vegetation in the tropics, interception rates range between 3.1 percent[174] and 21 percent[26] and even in drier, open forest ecosystems there can be significant interception by leaf litter.[21]

In comparison, grasses and crops typically intercept 20-48 percent of rainfall during the growing season[217] while interception rates of grazed grassland are about half and sparse crops like maize less than half again.[121] However, on an annual basis the percentage of rainfall intercepted is much smaller compared to forests as grasses or crops typically die, lose mass or are grazed or harvested.

Similarly, forests lose most of their rainfall interception capacity if harvested. One example from northwest California estimates that clear-cut logging of redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*) would increase effective annual rainfall (rainfall reaching the soil) by 20 to 30 percent with most of the increase during large storms, potentially influencing slope stability.[159]

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 at distances of up to three times the radius of their crown.[85] Although most roots are in the top metre 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 metres, and a maximum depth of 3.1 metres.[210] Feeder roots may also extend to great depths:

- Sclerophyllous brushland and forest − 5.2±0.8 metres;
- Temperate coniferous forest − 3.9±0.4 metres;
- Temperate deciduous forest − 2.9±0.2 metres;
- Tropical deciduous forest − 3.7±0.5 metres; and
- Tropical evergreen forest − 7.3±2.8 metres.[28]

The global average maximum root penetration depth for trees is around 7 metres, while for herbaceous vegetation it is only 2.6 metres. Most importantly, because trees are able to access water at depth and maintain transpiration for longer than other types of vegetation[99,217] the onset of soil saturation is delayed by forests, compared to other land cover, when rains recommence.

Where precipitation considerably exceeds potential transpiration, such as in cool temperate and subalpine regions, the reduction in soil moisture through transpiration and evaporation is small and soil drying is minimal. In these regions the transpiration effect of vegetation is minimal.[84]

Infiltration and subsurface flow

Forest lands generally have high infiltration rates, but soil moisture may be reduced through subsurface flow facilitated by pipes and channels formed by root decay and burrowing animals. Tree roots (both dead and alive) contribute to soil channel formation and form networks that can help slopes drain faster than if the channels were absent.[134,184] 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, caused by heavy machinery for example, reduces infiltration and can lead to surface water flow which, although removing water from the slope, also causes surface erosion and gully formation, the latter being a significant precursor to landsliding. Natural forests are generally not affected by soil compaction or surface and gully erosion. Shade and large amounts of organic matter associated with forests also limit soil cracking in clay-rich soils but if forests are cleared, cracking may lead to excessive infiltration rates.

Additional effects

Protective barriers

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.[46, 19] Forest barriers may mitigate some or all of the potential damage. For example, studies of debris flows in coastal British Columbia showed flows deposited much of their load when hitting a forest boundary and stopped entirely within 50 metres of that boundary in 72 percent of the 1 700 cases examined.[89]

The effect of tree buffers depends on width, spacing and tree diameter. Various species may show differences in protection against rock fall. 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*).[190]

Wildfire propensity

Relative to other land uses, some forest types are prone to destructive fires. Besides removing the protective functions of vegetation against surface erosion and landsliding, intense fires also weaken bedrock and increase landslide susceptibility.

Wildfires occur frequently in unmanaged coniferous forests in North, Central and East Asia, as well as submontane and montane forests and plantations elsewhere in Asia.[65] Fires also occur in deciduous forests in drier areas of Asia. With widespread forest degradation and shifts in climate the frequency of devastating fires may increase in coming years.

Net effects at critical levels of saturation

When soil moisture levels rise close to full saturation, the hydrological and mechanical effects of trees diminish. However, even under saturated conditions, soils reinforced with roots are stronger than those without. For example, three times more shear stress is required to cause failure in saturated colluvial soils[†] containing roots than in equivalent soils without roots.[50] The elasticity of the soil-root system also contributes to strength prior to failure.[133] During failure, fine roots act in tension and trees may provide the last available resistance in restraining material from sliding downhill.

2.4 Evidence of landslide prevention

Because landsliding is a natural process, most hillslopes eventually fail. Such events occur periodically when thresholds of resisting forces – including those provided by forests – are surpassed. During the most extreme events, factors such as heavy rainfall, cutting or excavation at the toe of the slope, weak underlying bedrock, seismic activity or other factors discussed above, are likely to override the effects of vegetation. In these situations, forest cover is unlikely to stop a landslide from occurring.

[†] Soils collected at the foot of a slope.

However, there are also many cases where landslides would have occurred were it 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. 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 are severe. Most of the reduction results from the lower 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 the first studies to evaluate the effects of clear-felling on landslide incidence reviewed data from southeast Alaska.[16] Both frequency and cumulative area of slides showed drastic increases after logging took place. Increases began two to three years after logging, coinciding with root decay and loss of root strength (Figure 2.5). Frequency of debris avalanches and debris flows increased substantially for nine years until forest vegetation re-established. The area affected by landslides during this period was five times greater than the estimated area disturbed by landslides during a 100-year period prior to logging. More than half the recorded landslides were initiated by a major storm six years after logging.

A more recent study in the Sanko catchment in central Japan,[100] which was periodically logged between 1964 and 2003, confirmed that changes in slope stability were correlated with root decay and recovery following harvest. The direct impact of forest removal on landslide occurrence was greatest in forest stands that were clear-cut one-to-ten years earlier, with diminishing impacts continuing up to 25 years. Sedimentation from landslides in forests clear-cut one-to-ten years earlier was about ten-fold higher than in control sites. The stabilizing effect of roots is supported by several other assessments that note an increase in landslide frequency following vegetation removal.[173, 72, 16,140,127, 213, 110]

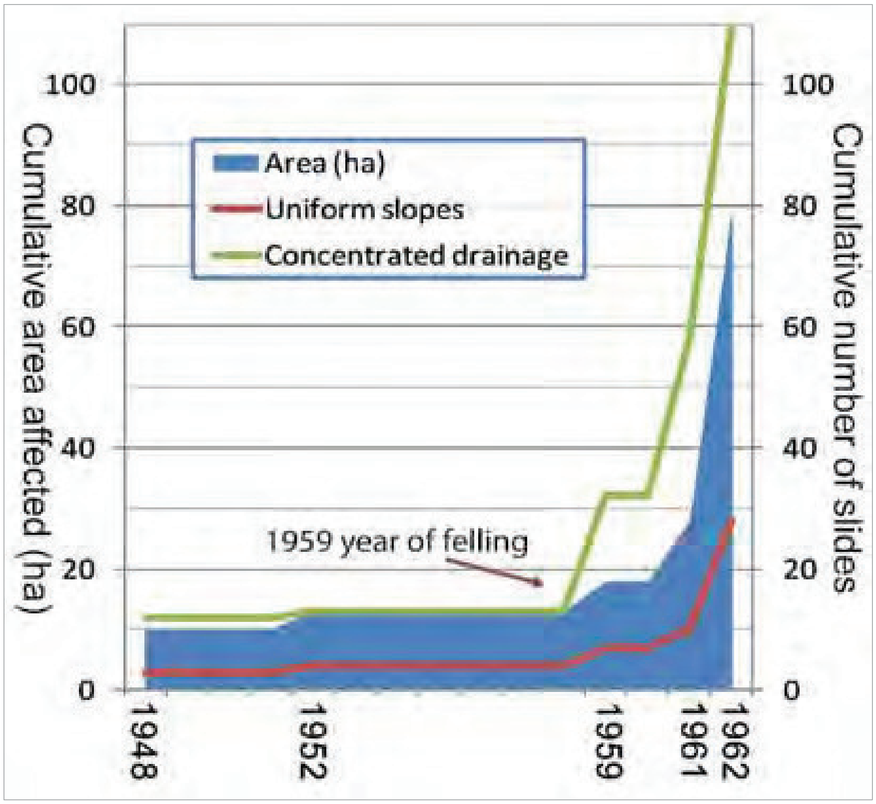

Figure 2.5 Clear-cut logging in Hollis, Alaska shows a link to substantial increases in landslide frequency and size of affected area for two different slope types. Authors suggested that root decay and consequent loss of stabilization by roots was the cause[16]

Further 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 during the three to 15 years after timber harvesting, [72, 16, 140, 213, 110] although on highly erodible soils rates may increase much more.[127] This increase in landslide frequency and volume is related to the period of minimum rooting strength after clear-cut harvesting and prior to substantial regeneration (Box 4).

Evidence from Nepal supports the view that factors other than just logging, namely grazing and agriculture, can 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 fuelwood. Most of them took place on steep (>33°) deforested slopes during an intense rain storm, whereas only a few landslides occurred in the thickly vegetated headwater area.[22] 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.[90]

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, the clearing of brushland for pasture led to five-fold increases in both area and numbers of soil slips after a series of major storms.[37] Elsewhere in California, on areas converted to perennial grass and annual grass, rates of soil mass movement are 1.5 and 2.5 times higher, respectively, than natural brush cover.[163]

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."[194]

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 pasturelands in the area are eight to 17 times higher than in indigenous forest.[143]

Furthermore, it has been observed that undisturbed forested slopes are often significantly steeper than the maximum angle at which a slope would otherwise be stable with the difference most likely attributable to the stabilizing influence of the vegetation.[155] Field tests on wooded slopes in Hong Kong S.A.R. showed that tree roots increased the slope stability threshold by 29 percent.[87]

Relative to other land uses, undisturbed forests exhibit the lowest levels of landsliding. For other upland land uses, such as coffee and tea plantations, grazing, cultivation and recently cleared shifting cultivation areas, surface erosion and landsliding rates are many times higher.[94,23,202]

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 closure of slopes to grazing.[95] If grazing can be controlled, higher rates of protection can be expected as forests grow. Natural forests and appropriately managed plantations and agroforests thereby provide the most effective ways of stabilizing soils in upland areas.

3.Why landslides are a growing hazard

There are many and often complex causes of landslides, acting over time scales of minutes to millennia. Landslides 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 that cause the slope to fail. Rainfall and earthquakes are the most common.

Throughout Asia, intense and/or prolonged storms and rainfall frequently trigger landslides while landslides also occur in drier regions as a result of earthquakes. Heavy rainfall, together with earthquakes, compounds the problem, such that even small tremors can initiate landslides. It is likely that changes in climate or weather will exacerbate many of these problems.

Other longer-term changes can also affect slope stability.[39] Frequently, changes in land use that involve soil excavation or loss of forest cover make slopes susceptible to failure. As human development has extended into hilly and mountainous areas in Asia, landslide incidence has risen above the natural 'background' level. For example, 80 percent of landslides in China result from human activities, with dam-building and road construction being the most significant causes.[192]

Activities most often associated with increases in landslide frequency include road and rail construction, hill-side construction, water pooling, agriculture and livestock rearing, logging and surface mining. The activities themselves 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.

3.1 Changing rainfall and snowmelt patterns

Large volumes of water entering the soil can destabilize hillslopes such that a large storm or cyclone can initiate hundreds of landslides. 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 events of much lower intensity can trigger landslides if forest removal has increased susceptibility to water saturation. Without reduction of soil moisture through forest transpiration, a period of rainfall causes soils to become saturated more rapidly 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 effect at the beginning of the rainy season.

Similar effects may occur during 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.

3.2 Earthquakes and seismic activity

The impacts of earthquake-induced landslides are escalating because of rising population densities and economic development in areas once thought too remote or too steep for development. Widespread landsliding due to earthquakes is restricted to rare large earthquakes. Earthquakes smaller than magnitude 6.0 contribute negligible amounts to total landslide volumes.[113] However, a single large earthquake can initiate thousands of landslides in an area up to 250 kilometres or more from the epicentre,[180] although the vast majority occur on or near the fault-line.[207] Additionally, slopes that do not fail may become predisposed to landsliding in the event of another tremor or moderate rainfall.[114]

In some areas, such as western New Guinea and to a lesser extent in Turkey, central Japan, the Islamic Republic of Iran and Tibet Autonomous Region of China, earthquake-induced landslides are the main agents of slope erosion.[113] They occur periodically in many other countries 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 when soil moisture content is high.[214]

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 3.1. Deep seated landslide resulting from the 2008 Sichuan earthquake. Trees had no mitigating effect
Courtesy: Patrick Durst.

3.3 Road and railway construction

Roads and railways are important contributors to increased landslide incidence.[187, 109] Road and railway construction frequently involves cutting slopes and removing soil from hillsides. Trees are invariably removed even when there is no soil excavation. Removal of soil and trees results in a significant reduction in lateral support to soil and landsliding often occurs subsequently. Roads built across mid-slopes and at the base of hills constitute the highest landslide risk due to subsurface water interception, undercutting and creation of additional load on slopes.[182]

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. Nonetheless, rapidly constructed roads often do not reach required standards of engineering.[192]

Trails and tracks associated with agricultural development and afforestation programmes, although associated with much less soil excavation, are also a significant cause of landslides.[13,202] Concentrated storm flows associated with trails and tracks often lead to gully erosion and landsliding.[202] 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 accelerated rates of infiltration.[161]

Figure 3.2. Landslide following road construction in Bhutan
Courtesy: Patrick Durst.

3.4 Deforestation and land-use conversion

Many activities associated with economic development – agriculture, logging, mining, residential development, tourism, etc. – bring land-use and land-cover change and loss of forests.[1] The loss of roots and the reinforcement they provide may significantly increase the likelihood of slope failure.[176,15,112]

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 (Box 4).[162,79,147,13,100,1] Although the replacement land-use type determines relative slope stability, most land uses are inferior to forests. Unlike weathering, groundwater content, rainfall or earthquakes, however, deforestation can be addressed and potentially controlled on relatively short time scales.

In Asia, deforestation is primarily 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 forested areas and their subsequent development is facilitated in particular by the opening of roads – often to support logging or plantation development.

BOX 4 - Tree removal and the window of landslide 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 three to five years small roots may lose over half their original tensile strength and significant increases in landslides can be expected after this.[142,141]

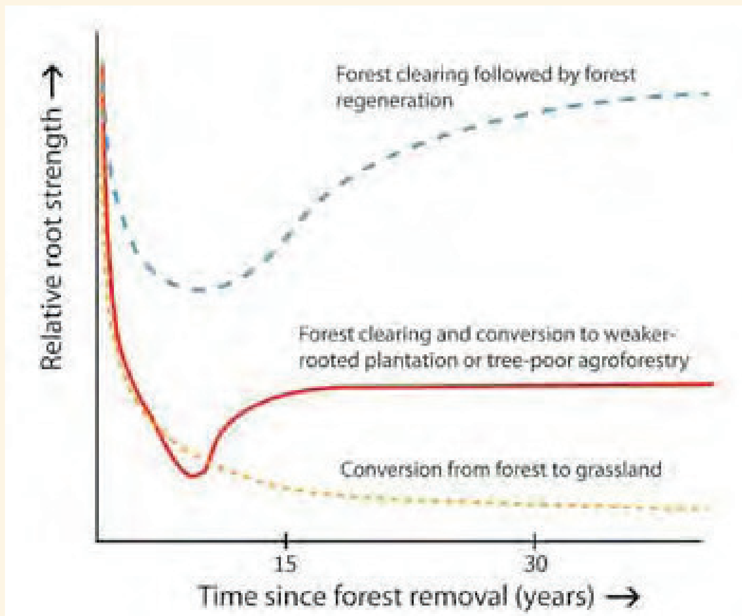

Figure 3.3. Forest clearing and the window of susceptibility

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.[118, 11] Where logging takes place, susceptibility is substantially reduced if selective silvicultural systems are employed instead of clear-cutting.[206]

The window of susceptibility (corresponding to the dip in Figure 3.3) may remain open for 15 to 20 years;[221,115,220] less in the humid tropics where regeneration is quicker (five to seven years)[211,118] and longer at high altitudes in temperate regions where it is slower.[4] Because shifting cultivation will temporally arrest natural succession and deplete soil nutrients, regeneration will be delayed and the window of susceptibility may become longer.

4. Implications of climate change

The close association between landslides, rainfall and other climatic variables make future changes in climate particularly important in determining the significance of landslides.

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 may be triggered. Rising temperature causes more extreme storms, speeds up soil and bedrock weathering, and elevates risk of wildfires that denude slopes and further hasten weathering.[34] On the other hand, higher summer temperatures accelerate transpiration rates and reduce soil moisture content, thereby reducing landslide risk providing drought does not damage vegetation and weaken root reinforcement.

Climate anomalies and changes in the frequency of extreme climatic events in Asia over past decades, although not necessarily evidence of climate change, have included increased occurrence of extreme rains causing, for example, 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 more intense rainfall events in many parts of Asia has increased, causing severe floods, landslides and debris/mud flows.[40] Other changes in past decades have included:

- In western and southern China, the frequency of extreme rains has 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, Bangladesh, Nepal and northeast 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 typhoons in the Philippines and stronger as well as more frequent typhoons in China have been recorded.
- Rapid thawing of permafrost and decrease in depths of frozen soils due to rising temperature have caused more frequent landslides and degeneration of some forest ecosystems in China and Mongolia.[40]

Looking to the future, precipitation is expected to increase over most of Asia in the period to 2039, 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.[106] In South Asia, increased rainfall during the northern summer is expected, while in Southeast Asia little change is foreseen until 2040.[40]

In combination with changes in precipitation, temperature increases are also expected across the region and an increase in occurrence of extreme weather including heat waves and precipitation events is predicted in South Asia, East Asia and Southeast Asia. In association, increases in tropical cyclone intensities by 10-20 percent are expected in Asia, while temperature is projected to increase by 0.7-1.8^{o}C in South, Southeast and East Asia and 1.5-2.9^{o}C in the Tibetan Plateau and North Asia.[40] In Japan, significant increases in both temperature and precipitation are predicted.

The predicted increases in extreme rainfall events are likely to increase the frequency of landslides in sloping areas, while cyclonic winds may induce landslides by toppling trees, exposing bare soil and increasing saturation failures.[169] Warmer weather and longer dry seasons are at the same time expected to affect tree physiology, forest growth and biodiversity while raising the incidence of fire, forest die-back and spread of pests, pathogens and invasive species.[186, 40]

Increased road development and rising levels of human activity in forest areas are also likely to increase the incidence of fire.[171] Root decay resulting from tree death by fire or disease is in turn likely to affect slope stability and fire is also likely to directly reduce soil stability and permeability.[179] Maintenance of forest health and vitality will therefore become increasingly important in slope protection as well as other climate change-related goals.[45,177]

All subregions of Asia are expected to see a significant acceleration of warming over that observed in the past century.[183] 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.

Based on the IPCC Fourth Assessment Report[102] the following predictions are made for seven subregions of Asia. Discussion focuses on the near-term period, 2010-2039.[195]

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,[107] and perhaps completely in the southern fringe of North Asia,[145] will result in extensive rock falls and slides, debris flows, thermal erosion as permafrost weakens, ground surface subsidence and impoundment of water. A greater frequency of extreme summers is likely to lead to significant increases in seasonal thaw depths.[96] Winter and spring precipitation is expected to increase between 10 and 16 percent and rise between 4 and 7 percent in summer and autumn. Increased snow and likelihood of rain-on-snow events during warmer springs will increase landslide incidence.

Predictions for summer are less clear. Although rainfall will be higher, temperatures and transpiration will also rise so 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.[204] Also, warmer winter temperatures will reduce winter insect kill and lead to explosions in insect populations that can kill forests over vast areas. Aside from 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 also experience similar impacts of permafrost loss and increased landslide incidence. Year-round temperatures may increase 1.5-2.1°C and cause progressive shrinkage of the permafrost area.[212] Glaciers are also melting at very high rates. Combined with significantly greater snow and rain (10-14 percent in winter and 4-7 percent during the rest of the year) landslide and debris flow incidence can be expected to increase, particularly during the spring-melt period and the Plateau's monsoon starting in May.

4.3 East Asia

China, Japan, Republic of Korea and DPRK are likely to 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 6.6 percent of the land area of China – are highly erodible and can disintegrate instantaneously when saturated, if vegetation is absent.[44] Japan has many areas with fragile geology that is easily weathered and susceptible to sliding, volcanic soils in particular.[34] East Asia is also subjected to typhoons of increasing frequency and intensity.[56] 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 annual precipitation falls during the monsoon, a small amount of additional rainfall, particularly at the end of the season, may lead to significant numbers of landslides if soils are near saturation. Additionally, the severity of South Asian tropical cyclones and storms is increasing although their frequency appears to be declining.[119]

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 subregion 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 typhoons 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

There are various complementary methods to manage landslide risk. Typically they are applied at two geographic scales: individual slopes within a subcatchment, and upland landscapes ranging in size from subcatchments to entire river basins.

For individual slopes, the options are the use of plants, including trees and shrubs, to reduce landslide hazards, or mitigating landslide impacts through site reclamation also using trees and shrubs.

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

5.1 Protection of landslide-prone landscapes

Control of landslides in upland areas requires an integrated approach. Tree planting alone will not meet the challenge of increasing incidence of landslides and erosion. 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 are also needed.[8]

Within agricultural and other areas, individual slopes with unstable soils or perched water tables‡ are best left as forest, or reforested if already cleared, due to the high risk of landsliding. Because landslide hazards are concentrated in critical areas of least stable topography, soil and land use, reforestation of highest risk areas results in disproportionately large reductions in landslide incidence and sediment yield.[12] For instance, it has been calculated that reforestation in the Waipaoa catchment, North Island, New Zealand of just 9.3 percent (159 square kilometres) could decrease the total sediment inputs from landslides by about 20 percent.[160]

‡ Water tables that occur above the regional water table.

A greater diversity of forest species improves slope stability through more complete coverage of available rooting zones. Inclusion of fruit trees or species that provide products without the need for felling can also support socio-economic needs. Protective forestation on severely degraded soils found in many parts of Asia will probably require soil fertility treatment. Planting will also be required in many areas to restore species composition, forest structure and the ecological functions typical of mature natural forests.[33]

Forestation options

At the landscape level, there are several forestation alternatives depending on local ecology and local socio-economic conditions. The options range from assisted natural regeneration and providing protection that allows forest recovery – as pursued in China under the 'mountain closure' scheme[192] – to intervening directly by planting indigenous and/or exotic species.[152]

Managing upland forests, including planning and implementation of protective forestation activities, is a complex task. Protective forestation is not a one-off 'plant and run' affair; regular tending during the initial stages is of critical importance. In relation, management structures that include local participation from the outset of the planting programme should be implemented.

The International Tropical Timber Organization's *Guidelines for the restoration, management and rehabilitation of degraded and secondary tropical forests* recommend a holistic approach taking into account other local landscape components.[104] The guidelines should help decision-makers to identify strategies that benefit local communities while preserving site-specific ecosystem integrity.[38]

BOX 5 - Species selection

On slopes susceptible to landsliding there is a need to select appropriate species for land stabilization. Species characteristics that are effective for erosion control are also desirable for the rehabilitation of landslide areas. In general order of importance, they are:[54,215]

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. Resistance to insects, disease, drought and animal browsing;
7. Good capacity for soil improvement, e.g. high rates 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; and
10. Low invasiveness.

Tolerance to soil infertility, acidic or toxic soils and exposure to desiccating wind and sun is critical. Erosion reduces soil fertility, while high rainfall causes leaching, acidity and sometimes aluminium toxicity. Species known to have exceptional physiological tolerances belong to the genera Acacia, Eucalyptus and Pinus.[55] In Malaysia, *Melastoma malabathricum* and *Leucaena leucocephala* are effective slope stabilizers and have superior resistance to acidity and aluminium toxicity.[135 166,165]

5.2 Slope protection and reclamation from landslides

Trees, shrubs and other plants may be used to stabilize landslide-prone slopes as preventative measures.[192,36,85] On slopes that have already failed there is generally a need to control ongoing 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 as forests or agricultural lands. In these cases, reclamation techniques may be appropriate.

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.[76] 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 often been implemented. Such innovations, although primarily developed to maintain soil fertility by controlling surface erosion and capturing nutrients and organic matter,[139] can also reduce landsliding in some cases.

Many production systems in the uplands of Asia are characterized by multiple land-use patterns in typically marginal, stressed agricultural ecosystems.[82] These systems range from pure agriculture to production from either planted or natural forests. In between are agroforestry systems, which mix herbaceous and woody plants and in some cases livestock.[132] In numerous and diverse forms, agroforestry includes most of the traditional systems practiced in Asia.[10]

In terms of landslide protection, agricultural systems with a high proportion of trees or shrubs may provide increased root density 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 landslide protection.

Shifting cultivation transitions

Shifting cultivation periodically opens a window of susceptibility to landslides when patches of forest are cleared for cropping. Depending on how quickly roots decay and new woody vegetation re-establishes, this period may last from three to more than 20 years. Forest regeneration after abandonment of shifting cultivation sites may be slower than after logging as a result of nutrient depletion resulting from burning and crop production.[183] In cases of severe surface erosion and nutrient depletion, vegetation more suited to drier and more fire-prone environments such as grassland may develop. In the case of Imperata (*Imperata cylidrica*) grasslands in Southeast Asia, frequent burning prevents re-establishment of forest.[53] While such grasslands may provide some protection from landslides, Imperata grasses are of little use to farmers and rehabilitation may be achieved through assisted natural regeneration of forests including fire suppression, restrictions on grazing or establishment of agroforestry.

Agroforestry

Much of the impetus behind current agroforestry development in tropical uplands has been to help stabilize shifting cultivation and related land degradation.[156,73,10] Attempts to provide alternative cultivation systems in the mountain areas of Yunnan[216], and rehabilitate abandoned fields colonized by Imperata grass in the Philippines and Indonesia through 'agroforestation[69,199] are two examples.

Surface erosion, gullying and landsliding can be mitigated by incorporation of rows of contour-planted trees, which help level the slope between rows over long periods of time.[203,215] Among the Ikalahan people of the northern Philippines, former shifting cultivators now plant rows of nitrogen-fixing trees 5-20 metres apart depending on the gradient.[9] On the steepest slopes, Sloping Agricultural Land Technology (SALT) guidelines suggest spacings of 3-5 metres.[144] While planting crops along the contour without alternating pasture or rows of woody vegetation can cut soil losses by half, incorporating trees can reduce losses by 90 percent.[14] SALT design also includes the use of diversion ditches to prevent water runoff from flowing onto the slope.[31]

Although conversion of forest to agroforest makes hill slopes more susceptible to landsliding,[182] the ultimate effect depends on the type of system established. If there is sufficient density of trees or shrubs, slope stability may not be significantly altered. Some systems such as home gardens, multilayer tree gardens[128] and some types of forest farming[47] will likely have levels of protection close to that of 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[188] and Tanzania.[91]

Forest farming

Within agricultural landscapes, 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 when land is not scarce. With increasing demand for land, these areas are increasingly being developed, leading to higher rates of landsliding and erosion.

One possible solution may be improved 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. A good example is the Kalahan Forest Reserve in Northern Luzon in the Philippines.[52] Newer management systems, termed 'closed-canopy high-diversity forest farming systems', are being employed in the Leyte Islands, Philippines as a means to replace environmentally destructive forms of land use between the lowland areas and the protected mountain forests.[129,80,175]

Gallery forests along inland valleys, where landslide susceptibility is greater and where forest farming would be most suited[47,83] are also favoured for irrigated rice production.[130] In these situations, terraced systems may have slope stability capacity comparable to forest but slope degradation can occur at a greatly accelerated rate if terraces are not maintained, as has been documented in Nepal.[29]

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. In this context, Barker (1984) made the following recommendations:

> "… 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."[9]

Land evaluation guidelines have been produced for different purposes including rainfed agriculture, irrigated agriculture, extensive grazing and forestry.[57,58,59,61,64] Because top-down approaches are not always successful, participatory approaches including farming systems analysis have also been introduced.[60,62] These have resulted in methods and applications for ecosystems and landscape analysis in agroforestry [164,157] and the Land Use Planning And Analysis Systems (LUPAS) methodology[98] which are suitable for resolving land-use conflicts in upland areas.

Reclamation of landslide scars

Following landslides, timely stabilization of affected sites can help reduce sedimentation of streams, prevent further landslides and mudflows, and re-establish livelihoods of local communities. In the Sanko catchment in Central Japan, sedimentation from some landslides has continued for 45 years.[100] Usually because of the expense and difficulty of reclaiming land only the most essential slopes are considered for reclamation.

Appropriate techniques depend on the soil and slopes must also be sufficiently stable if slope stabilization work is to be carried out. Soil biomass takes time to redevelop and different species may be more suited to new conditions than those previously present.[185]

Due to poor soil and exposure to desiccating sun and wind, plus the need 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 is developing in some countries.

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 single species and even age plantings.[74]

In addition to ecological factors, a range of other issues is 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.

Vegetation establishment

Because larger/older seedlings are best for successful establishment, reclamation may be expensive. Compared to conventional engineering solutions, however, planting of trees and shrubs is generally the most economical means to reclaim landslide scars. However, without additional erosion control measures, tree planting on eroding slopes stands a high chance of failure. Slopes where vegetation has been stripped are highly erodible, particularly during the rainy season. 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.

Tree planting usually requires site preparation 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.[8] Controlling soil movement is particularly important in mountain regions where torrents are frequent and cause both direct soil erosion and soil saturation, which increase landslide risk.

Natural regeneration versus planting

The choice between natural regeneration of vegetation or tree and shrub planting is likely to depend on the degree of disturbance, the total landslide-affected area, the proximity to potential colonizing 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 natural regrowth.[181,70,34] 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."[206]

If infertile subsoils are exposed or the distance to natural seed sources is great, or where the need to stabilize land is urgent, planting may be necessary. Tree and shrub species suitable for land stabilization will differ from those used for forest rehabilitation. Characteristics outlined in Box 5 also apply but species robustness is of greater importance. Because of the difficulty in establishing vegetation on inhospitable sites, proven exotic species are usually used. Testing of native species is, however, being carried out in countries including China, Thailand and India and new possibilities may become available.

In general, nitrogen-fixing species have been used successfully as many can tolerate the harsh environment and nutrient-deficient substrates that are typical of landslide scars. For example, a study of trees planted on mining waste in India found that acacias are superior to eucalypts in improving the soil.[154]

5.3 Identification and monitoring of landslide hazards

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 need to be based around scientific data collection including maintenance of an up-to-date landslide inventory, permanent monitoring of natural processes, research on natural phenomena and geomorphological mapping.[97] 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 geological 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.[7]

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 stability threshold estimates.[201] 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.

The ability to accurately predict landslides is of great importance if hazard assessments and zoning regulations are to prove useful. The 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 to 90 percent, depending on the type of model used and how well it represents a particular geological setting.[137,138,153,35]

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 landslide incidence by inhibiting surface erosion and the formation of gullies. Forests and trees have an additional role in providing a physical barrier to the movement of landslide material, as well as trapping material and gradually releasing it with reduced impact.

Continued development in upland areas will result in construction of roads and trails, forest clearance and expansion of land uses with shallow rooting depths. Logging roads and forest management in particular constitute a significant cause of landslides and careful road construction following available codes is therefore necessary.[63]

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

Climate change is also 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 the economics of natural hazards and disaster risk reduction is growing. While the economic costs of individual landslides are typically much lower than flood or earthquake events, they are likely to rise for the aforesaid reasons. Furthermore, although individual landslides are mostly small, the cumulative impact can be large and impacts often extend offsite and for long periods.

Consequently, mitigation of landslide hazard follows a two-pronged approach. Firstly, lives, property, natural resource assets and investments need to be protected. Secondly, there is often a need to re-establish production and livelihoods following landslides. Although 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

Understanding 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 zoning in upland areas;
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.

7.1 Land-use 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 precise estimates of hazards at each location.

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 below 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 areas.

7.2 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. Soil bioengineering that utilizes the root reinforcement and hydrologic drying properties of trees and shrubs is a 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 roles trees and shrubs play in stabilizing slopes and emphasize their retention where possible. This is especially important at the toe of slopes, where trees provide lateral support for the upper slope and protect infrastructure from damage by smaller rock falls and landslides. Consideration of the age (especially 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.[63] 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.

7.3 Vegetation management

Prevention of landslides requires management of vegetation at the landscape level. 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 potential landsliding impacts of such changes in land use.

Policies to control development in upland areas, and especially headwater areas, have relied on the creation of protection forests and should continue, particularly in headwater areas where sedimentation from gullying and landslides is a key problem. Similarly, treeless slopes with high landslide hazard ratings should be targeted for protective forestation programmes and appropriate vegetation management.

In addition to direct control of landslide risk, vegetation management should be extended to controlling surface erosion. In addition to trees, shrub species should be included as they provide comparable soil reinforcement but with reduced negative effects associated with weight and wind-loading forces.

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 non-wood forest products, such as fruits, with high local value, marketing of carbon sequestration capacity and water resources protection, ecotourism opportunities and so forth. Selection cutting of high-grade trees may be possible if large areas are not opened up and cable logging or other means to limit road and trail construction such as helicopter logging are employed.

7.4 Rehabilitation

Livelihoods, and associated natural resources, need to be quickly re-established after a landslide, while continuing offsite impacts also need to be managed. Landslide reclamation and rehabilitation of livelihoods requires financial resources and technologies to successfully re-establish vegetation. Although 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, landslide management and recognition of the role that forests and trees play should be integral parts of climate change adaptation and disaster risk reduction. Landslide incidence and associated impacts are expected to increase 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 key to minimizing the problem simply involves identification of hazardous slopes, management of vegetation and land use on these slopes, and implementation of best practices when altering slopes.

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In recent years, a number of devastating landslides in Asia have resulted in major tragedies and enormous destruction. Considerable economic losses have also been sustained due to the profusion of smaller landslide events throughout the region.

Current rural development trends and predictions of more extreme weather events will increase the probability of such disasters in the future if efforts to prevent landslides are not stepped up. Better understanding of the roles that trees and forests play in preventing landslides and rehabilitating landslide-affected areas will be critical for a safer, greener and more prosperous future.

This publication outlines the extent to which sound management of forests and tree planting can reduce the incidence of landslides and how forestation can assist in land rehabilitation and stabilization after landslides have occurred. It aims to bridge the gap between science and policy-making to improve management of sloping land both in Asia and elsewhere in the world.

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