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]

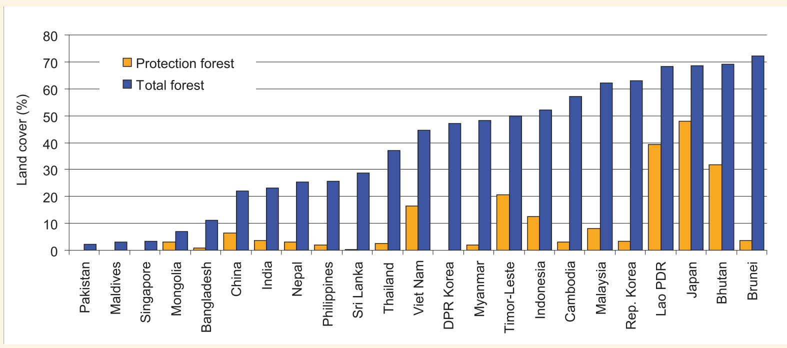

Figure 2.2. Total forest cover and cover of forest designated for protection in Asian countries, 2010[67]

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.

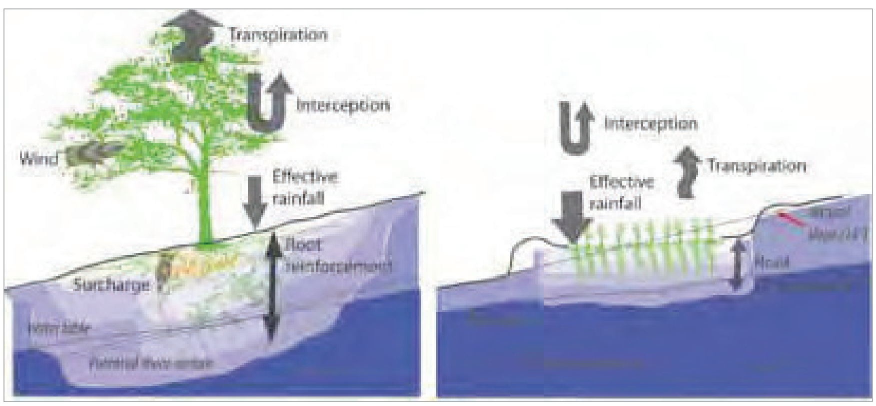

Figure 2.3. Relative influence of trees and upland rice on slope stability. The zones of root reinforcement and soil drying (lighter shade) will extend the length of the slope parallel to the surface with sufficient tree stocking. With shrubs, wind and surcharge forces are reduced, but soil reinforcement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

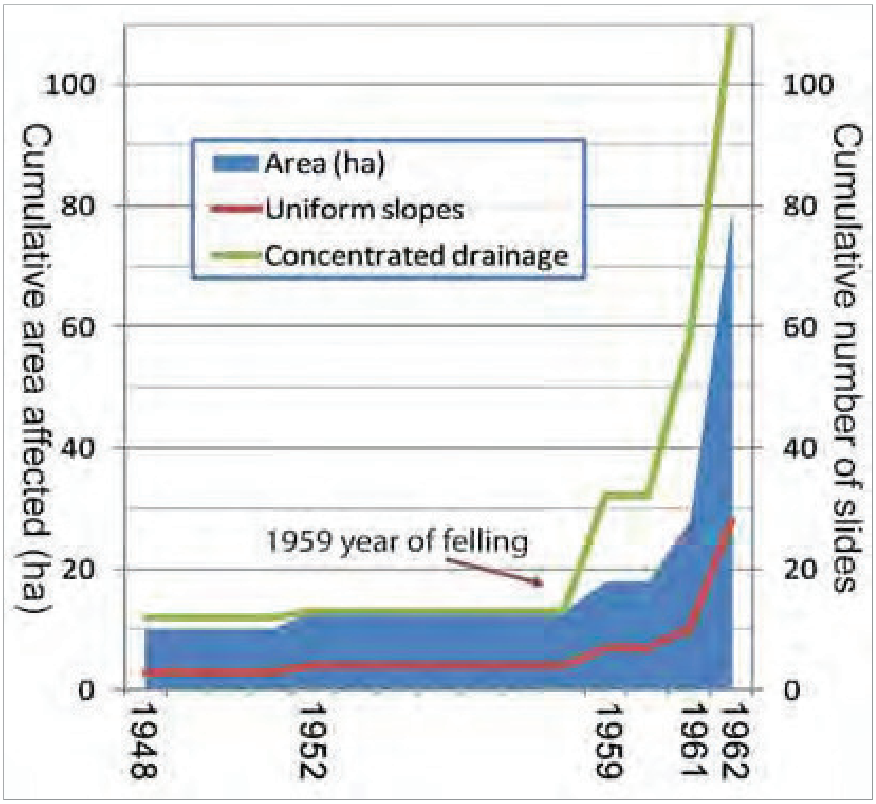

Figure 2.5 Clear-cut logging in Hollis, Alaska shows a link to substantial increases in landslide frequency and size of affected area for two different slope types. Authors suggested that root decay and consequent loss of stabilization by roots was the cause[16]

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.