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Introduction for Landslide Ecology

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1 · *Introduction*

Key points

1. The geological characteristics of landslides and their management as physical hazards are well documented. In contrast, the ecological processes that are initiated by landslides, and their relevance to efforts to restore stability to unstable slopes, have never been synthesized.
2. Landslides can cause intense human suffering and human activities can aggravate natural causes of landslides. However, we can ameliorate many of the worst effects of landslides through improved prediction and restoration of landslides and adjoining slopes.
3. Landslides initiate many ecological processes at landscape to local scales, including the process of ecological succession. Although landslides have negative effects on the survival of many terrestrial and aquatic organisms, they also recycle nutrients and provide habitats for colonizing species.
4. Landslides encompass many types of gravity-driven movements of mass. A typical landslide often has material that falls, slides, and flows, thereby creating geologically and ecologically heterogeneous substrates. Landslides cause and are caused by other disturbances, an interaction that creates a disturbance regime.

1.1 Relevance of landslides

A landslide is broadly defined as a sudden mass movement of substrate downhill and occurs on sloping terrain. Landslides can be localized slumps several square meters in size or so large that they are visible from space. Why are landslides important to you? Perhaps your property or farm has been damaged by landslides, or road access to your workplace or vacation site has been blocked. Maybe your telephone, water, or electrical power services were once disrupted. Or perhaps you follow reports of landslides because your home is on a steep slope and you wonder whether or

when your property will slide. Regardless of your personal experience with landslides, we demonstrate in this book that landslides are relevant at many levels, both personal and ecological. Landslides are geological events that have obvious immediate impacts on landscapes and humans, but they also provide such ecological services as nutrient enrichment of rivers and creation of new habitats for colonizing organisms unable to survive in the surrounding ecosystem. The geology of landslides and hazard management (e.g., how to minimize property losses through landslide prediction, prevention, and restoration) are well-studied, with several recent summaries of research progress (e.g., Sidle & Ochiai, 2006; Sassa *et al.*, 2007). However, the ecology of landslides (the interaction of organisms with the landslide environment) has received surprisingly little attention, given the dramatic influences that landslides have on the environment. Less than 1% of papers published on landslides between 1970 and 2010 address ecology (Web of Science, 2011). Landslides are a severe type of disturbance because they damage or remove plants, animals, and soil organisms. Landslide habitats are therefore of interest as examples of places where plant and animal communities assemble following disturbances that leave little or no biological legacy (primary succession). These ecological responses, when better understood, can be manipulated to augment restoration efforts that have, until recently, relied largely on modifications of the physical environment such as the construction of debris dams or re-contouring of slopes. Landslide ecology can thus be compared with other disturbances that initiate primary succession (e.g., volcanoes, retreating glaciers, and floods; Matthews, 1992; Reice, 2001; Walker & del Moral, 2003; Elias & Dias, 2009). This book attempts to fill the gap in our ecological understanding of landslides by presenting the first synthesis of the widely scattered literature on landslide ecology. In this opening chapter, we introduce the links among landslides and humans, landscapes, and ecological processes; then, we define the term landslide and describe it from multiple perspectives; finally, we present the central themes of each of the remaining chapters.

1.1.1 Humans

The term "landslide" has negative connotations for most people because of the often highly publicized destructive consequences of landslides. While many small landslides are only temporary inconveniences, some are more catastrophic, resulting in considerable loss of human lives. Perhaps the most lethal ever recorded was the 1920 earthquake-triggered landslide

in Gansu, China that killed 200 000 people (Close & McCormick, 1922). Landslides on the coast of Venezuela killed > 20 000 people in 1999. Landslides in the Peruvian Andes (1962, 1970) killed > 6000 people (see Chapter 6). In 1963, a landslide in Europe created a flood that killed 2600 people, while landslides (particularly in Japan, Hong Kong, the Philippines, Indonesia, Colombia, and the Caribbean Islands) have killed scores of people in recent decades (Hansen, 1984a; Petley, 2010). Prehistoric records indicate that large-scale landslides were common (Schuster, 2001), and they remain an important disturbance in today's landscapes, particularly because of human activities such as road building and urbanization.

Landslides can recur at a given site as long as the slope remains unstable. For some residents of unstable, mountainous regions, for example, landslides frequently disrupt their lives by repeatedly eroding pastures, blocking roads, and destroying houses (Haigh *et al.*, 1993; Singh & Pandey, 1996). Several dozen people die each year from landslides in the U.S., but mortality rates can be even higher in some developing countries. In contrast, costs of property damage are higher in developed countries, reaching about \$4 billion year^{-1} in the U.S. and Japan (Schuster, 1996b; Gori *et al.*, 2003). In either developing or developed countries, landslides can cause losses that become a significant percentage of a nation's budget (Hansen, 1984a). Costs include the direct losses of property and lives, but also the indirect costs of subsequent disturbances such as floods caused by blocked drainages. Other indirect costs include clean-up, lost productivity from agriculture and fisheries, and reduced revenues from tourists and real estate sales (Schuster, 1996b).

Humans have developed multiple ways to deal with the challenges that landslides present (see Chapter 6). Where population densities are low, landslide-prone areas are often avoided as building sites, unless those sites have desirable features such as views or access to water, fertile soil, or other resources which offset the dangers of building. Where population densities are higher, more people live or work in areas vulnerable to landslides because site selection is driven more by proximity to municipal services than by careful assessments of soil stability. Squatter communities of poor migrants from rural areas rim many large cities in developing countries and these communities are often located on steep, unstable slopes that were previously avoided, but have become the only areas left on which to build. Whether the newcomers build houses in the relatively wealthy suburbs of Los Angeles (U.S.) or grass mat shacks in the poor areas surrounding Lima (Peru), they are equally vulnerable

to the geological forces that produce landslides. Wealthier nations may have more to spend on prediction and prevention, but these defensive measures are not always effective. Sometimes, humans accommodate to the presence of landslides in their lives by using the new resources that landslides provide. Examples of such resources include drinking water (E. Velázquez, pers. comm.) and fast-growing trees that are harvested for firewood or fence posts in Nicaragua (Velázquez & Gómez-Sal, 2008); scrambling ferns collected for various medicinal purposes in southeast Asia (Robinson *et al.*, 2010); and tree fern trunks used for growing orchids in Hawaii (Fosberg, 1942) – until tree ferns were protected for conservation purposes (Mehltreter, 2010).

Humans cause landslides in a variety of ways (Sharpe, 1960; Bonuccelli *et al.*, 1996; Singh & Pandey, 1996; Sidle & Ochiai, 2006). Removal of soils or rocks from a slope can destabilize it; this occurs when roads, railroads, and canals are cut across slopes and interrupt surface and subsurface movement of water. Road embankments can slide due to inadequate compaction or heavy rainfall before adequate cover is established (Larsen & Parks, 1997), but also can slide where runoff from roads is not properly channeled. Such construction errors can be particularly dangerous when bridge abutments are destabilized (Alonso *et al.*, 1996). Urban construction involves not only cutting into slopes but adding the water from irrigation and the weight of buildings, vehicles, and fill material (Keller, 1996). Open-pit mines have unstable slopes at their cut edges, but piles of unusable or sorted rocks also can be unstable. Slope failures can occur on other anthropogenic piles such as municipal waste landfills (Towhata, 2007). Sometimes, recreational activities in mountainous regions (e.g., skiing, climbing, off-road driving) result in landslides. Finally, logging and grazing can reduce protective vegetative cover and accelerate erosion.

Rapid deforestation of tropical rainforests (13–16 million ha year^{-1} in the last two decades; Achard *et al.*, 2010) has increased the number of landslides, particularly where soils are shallow. When we alter slope hydrology by adding culverts or retaining walls, we sometimes concentrate previously diffuse drainages and increase erosion. On a larger scale, landslides can be purposefully caused by explosives to create dams for hydropower or protection from future landslides (Schuster, 1996b). Climate change (see Chapter 7) may also lead to more landslides in regions that receive increases in rainstorm intensity, increases in windstorm frequencies (less time for vegetative recovery), or increases in the irregularity of precipitation (and subsequent loss of a protective vegetative

cover). However, increased temperatures may also lead to increased evapotranspiration and therefore reduced water content on some slopes while increased vegetation cover in formerly arid regions could improve slope stability (Borgatti & Soldati, 2010).

The prediction of landslide occurrences has become an important aspect of hazard assessment that sometimes saves lives and provides guidance on where to build or live (Sidle & Ochiai, 2006). In some cases, there is an obvious correlation between rainfall duration and intensity and the occurrence of landslides (see Chapter 3; Caine, 1980; Larsen & Simon, 1993), but many other factors (e.g., soil type, slope, vegetative cover, successional stage, land use) usually complicate the prediction of landslides. For example, landslides associated with volcanoes (lahars, debris flows, mud flows) are generally unpredictable. When landslides are predictable, urban planners, architects, farmers, utility companies, and residents on sloped terrain can better adjust land management to reduce the chances of loss of lives and property. With an expanding human population that continues to exploit marginal lands with steep slopes, landslide hazard assessment will continue to be an important component of land management.

Prevention and restoration of landslides are other actions, which, like prediction, have only mixed success. Geological forces can overwhelm the best efforts to stabilize slopes, particularly wide or steep ones within high rainfall regions, but temporary and small-scale prevention can be successful, at least until unusually intense storms occur. In Japan, evacuation procedures have greatly reduced deaths from landslides in the last several decades through a combination of identifying potential hazards and improving preventive techniques (Takahashi, 2007). Many slopes re-slide, so restoring them to prevent further sliding is often attempted. Restoration efforts range in intensity from planting vegetation on the landslide to complete alterations of the local slope or hydrology. Drainage of surface and ground water is frequently successful (Schuster & Kockelman, 1996). Mechanical efforts include building earth buttresses at the base of the slope and various other restraining structures such as walls of wood, concrete, or rock-filled cages (gabions). Surfaces can be stabilized by metallic, plastic, or organic meshes placed over the soil. Metallic meshes are frequently seen covering roadside cliffs (see Chapter 6; Wyllie & Norrish, 1996). Finally, one can sometimes remove all material that could re-slide by reshaping the slope and leaving only exposed bedrock. Using biological tools such as plantings of grasses or trees can be initially straightforward and inexpensive, but learning how to properly restore

plant and soil communities that supply lost ecosystem services (e.g., clean water, biodiversity) and undergo natural successional changes takes a long time and it is a poorly understood process (Walker *et al.*, 2009).

1.1.2 Ecological processes within landslide-prone landscapes

Landslides cover about 4% of the earth's terrestrial surface each century (Restrepo & Alvarez, 2006; Hong *et al.*, 2007), but they are most common in earthquake-prone mountain regions and in landscapes heavily modified by human land use (Restrepo *et al.*, 2009). The effects of landslides expand beyond their actual physical limits because they influence downstream sediment loads (Fort *et al.*, 2010) as well as the regional biodiversity and movements of organisms. Landslides are usually discrete events that only last for mere seconds to several minutes. However, some types of mass movement (e.g., creeps) can have persistent consequences, including secondary erosion and alterations of regional hydrology. Gradual changes such as increases in soil water content can lead to the sudden sliding of a slope, while improving conditions for drainage can make a slope less likely to slide again (Keller, 1996).

Landslides help maintain such natural ecosystem processes as nutrient cycling and may promote biodiversity by the promotion of habitat diversity (Geertsema & Pojar, 2007). Landslides can be viewed as fluid systems, much like rivers, except that the medium that moves is soil and its contents, including nutrients and carbon as organic matter (Walker & Shiels, 2008). As part of the erosion of slopes, landslides move critical components down slope, including soil organisms, seeds, wood fragments, and rock-derived nutrients such as phosphorus and calcium, where they enrich down slope habitats. The sediments and nutrients from landslides fertilize aquatic ecosystems either directly (when the base of a landslide enters a river, lake, or ocean) or indirectly (through ground water or surface erosion). Landslides also create habitat gaps in a background matrix of a forest, shrub, or grassland community. These gaps provide refugia for colonizing organisms that, in turn, supply many other organisms with food or habitat (Wunderle *et al.*, 1987). Occasionally, landslides are so common that they become the background matrix for patches of mature vegetation.

Landslide habitats change through ecological succession. The rapidly growing plants that typically colonize landslides (Velázquez & Gómez-Sal, 2007, 2009; Restrepo *et al.*, 2009) serve various functions, including slope stabilization through rain interception and root growth,

maintenance of biodiversity, and sinks for carbon dioxide. Sometimes anthropogenic disturbances such as road embankments, clear cuts, and construction zones can provide habitats similar to landslides (e.g., bare soil combined with high light and warm soil conditions favorable to germination and growth). After the early colonists establish on the bare soil that typically characterizes a new landslide surface, they are gradually replaced by later arrivals. As the plant cover on landslides undergoes change, landslides become part of a shifting mosaic of patches in a landscape (Pickett & Cadenasso, 1995). Landslide successional processes often take decades before the landslide becomes indistinguishable from its background matrix (Ferreira *et al.*, 1996). Within landslides, there is also a mosaic of patches of vegetation at different stages of successional development, open areas of recent re-sliding, nutrient-rich and nutrient-poor patches, and patches of varying substrate stability. Animals respond to such habitat diversity by browsing on early successional growth, nesting in cliffs, perching on surviving trees, and using new ponds created in the deposition zone (Geertsema & Pojar, 2007). This spatial and temporal heterogeneity makes a landslide a complex but fascinating ecosystem to study. In this book, we discuss both the abrupt disturbance itself and the longer-term ecological processes that are triggered by the disturbance.

1.2 Terminology and types of landslides

A disturbance is a relatively abrupt event that causes a loss of biomass, ecosystem structure, or function. A disturbance has a cause or trigger (e.g., an earthquake or rainstorm), an event with physical characteristics (e.g., frequency, intensity, extent), and a consequence (e.g., damage caused, new habitat created; Walker, 2012). Landslides, as we use the term here, are both a disturbance event driven primarily by gravity that results from slope destabilization (Fig. 1.1) and the habitat created by the displaced debris. Landslides are a type of erosion but our use of the term erosion will generally imply the presence of landslides. Most studies of the ecological consequences of landslides focus on the post-erosion habitat. There is so much variation in how landslides occur that no standard classification system has emerged (Table 1.1; Hansen, 1984b). Strictly defined, a landslide is a sliding movement of a mass of rock, debris (loose rock or regolith), or earth (finer sediments with or without organic material) down a slope (Cruden, 1991). However, the term landslide is often used to include all types of slope failure or mass wasting (general terms for down slope movement of earth materials) that are

Table 1.1. *Classifications of landslides based on characteristics of hill slope movement*

Sorting variable	Name	Description
Type of movement	Slide	Translational (planar) or rotational (slumps)
	Fall	Outward and downward movement with exposed face (excludes slumps)
	Flow	Merges with creeps and spreads; called mass transport if sediments moved by water, air, or ice
	Complex	Mixture of slides, falls, and flows
Degree of movement	Active	Currently moving; can be advancing, retrogressing, widening, enlarging, or diminishing
	Inactive	Moved within past year
	Dormant	No movement in at least 1 year; cause remains
	Abandoned	No movement and no causes remain (e.g., river changes course)
	Relict	Rediscovered (e.g., due to new road cut); formed under different conditions
	Reactivated	By new or recurring disturbance
Rate of movement	Slow	Creeps (e.g., 0.06 m $year^{-1}$)
	Moderate	Initial and final moments of many slides
	Fast	Initial fall, movement through chute (e.g., 3 m sec^{-1})
Cause of movement	Geological	Weathering, shearing, fissuring; contrasting erosional surfaces
	Morphological	Slope changes due to 1) uplift from volcanoes, earthquakes, glacial rebound; 2) undercutting from waves, river currents, glaciers; 3) internal erosion through seepage; or 4) deposition of mass on the slope or its crest
	Physical	Earthquakes, volcanoes, rapid increase in water content, freeze–thaw weathering, rapid drawdown, vegetation removal by fire, drought, or wind
	Biotic	Plants increase water infiltration, add weight, transfer energy from windblown trees to soil; animals overgraze plants on a slope; humans remove or add rocks, soil, or vegetation and add water or induce vibrations

Sources include Coates, 1977; Varnes, 1978; Hansen, 1984b; Cruden, 1991; Cruden & Varnes, 1996; Cannon, 2001; Wondzell & King, 2003; Sidle & Ochiai, 2006; and Petley, 2010.

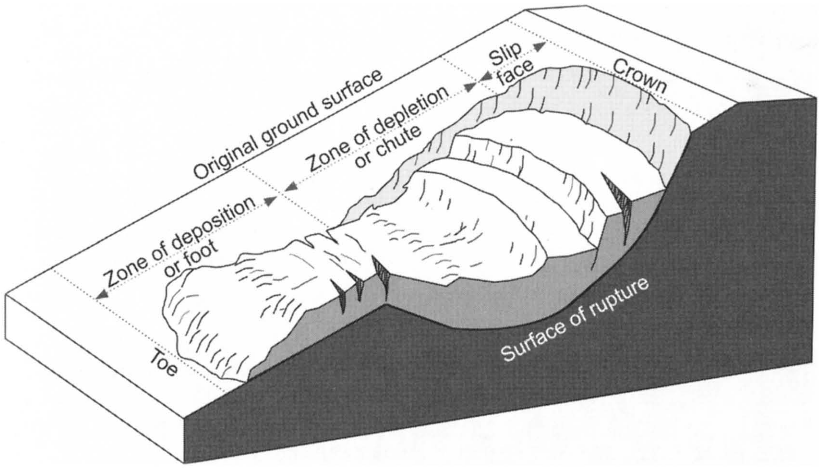

Fig. 1.1. Cross section of a typical landslide. Modified from Varnes (1958), Plate 1-t. Copyright, National Academy of Sciences, Washington, DC. Reproduced with permission of the Transportation Research Board.

Type of material	Type of movement (increasing speed) →				
	Slide		Flow	Fall	
	Rotational	Translational			
Bedrock	Rock slump	Rock slide	Rock avalanche	Rock fall	Increasing particle size ↑
Regolith	Debris slump	Debris slide	Debris avalanche Debris flow	Debris fall	
Sediments	Sediment slump	Slab slide	Earth flow Decreasing sediment size ↓ Sand flow Loess flow Liquefaction flow	Sediment fall	

Fig. 1.2. Terrestrial landslide classification. Modified from Coates (1977).

broadly defined as slides, flows, and falls (Fig. 1.2). Challenges in defining landslides start with the type of movement. True sliding can occur through rotational movements called slumps (Fig. 1.3) or along a plane (translational slides; Fig. 1.4; Coates, 1977). Flows (Fig. 1.5) consist of mass movement (movement influenced by gravity) and they are similar

Fig. 1.3. Rotational debris slump in Puerto Rico. Photograph by A.B. Shiels.

Fig. 1.4. Translational (planar) debris slide in Puerto Rico (foreground). Photograph by A.B. Shiels.

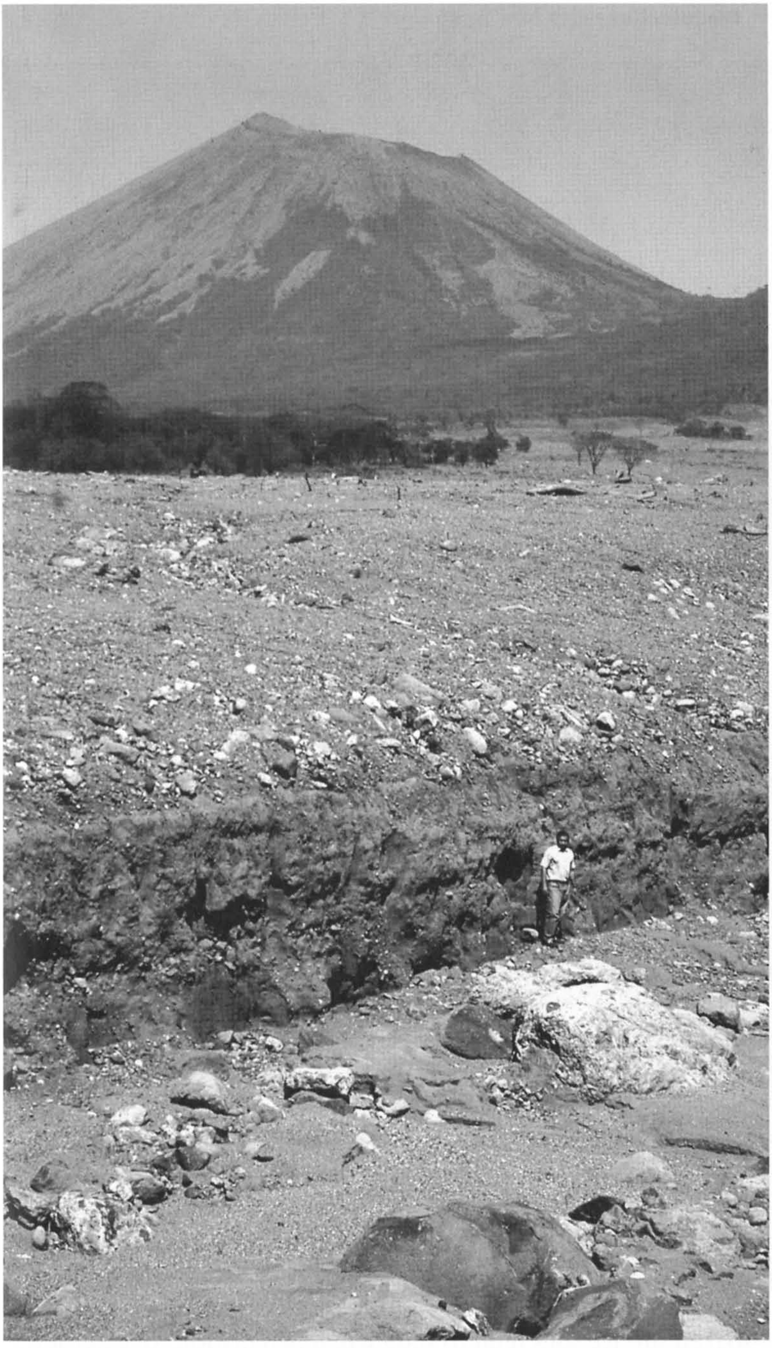

Fig. 1.5. The deposition zone of a large scale debris flow landslide on Casita Volcano, Nicaragua (top of photo). The debris flow extended 12 km from the volcano, was 1.4 km wide, and reached depths of > 4 m. Photograph by E. Velázquez.

to creeps and spreads (Varnes, 1978) and mass transport (when rock or soil is transported by a moving medium such as water, air, or ice). For example, rock avalanches and debris flows are types of landslides but a snow avalanche composed mostly of snow and ice is generally not classified as a landslide (Hansen, 1984b). Landslides also include falls (Plate 1; Fig. 1.6), which are outward and downward movements of rocks or debris with exposed faces (thereby excluding subsidence (sinking) as a type of landslide). Many landslides are complex mixtures of slides, falls, and flows (Fig. 1.7). The role of air in landslides cannot be discounted, because compressed air in front of a fast-moving landslide can be very destructive (see Chapter 6; Rouse, 1984). Further complications in defining landslides arise because landslides can be caused by a combination of slides, flows, and falls. For example, in a one-time survey of 215 landslides in an 89 km^2 basin in southern Spain, 40 landslides were combinations of slides, flows, and falls; these complex landslides accounted for 42% of the total area affected by landslides (Hamdouni *et al.*, 1996) while the remaining 58% fit into a single landslide category.

Other parameters used in defining landslides include the degree of movement of an erosive slope, the rate of movement, and the causes of movement (Table 1.1). The degree of movement categorizes various levels of landslide activity from active to inactive or dormant. The rate of movement varies both within one event and across types of landslides. Within a single landslide, the initial displacement at the slip face can be rapid, but mass movement (especially falls) down the chute can accelerate, and then, as the material spreads out in the deposition zone, it decelerates considerably. The steepness of the slope, the nature of the material, and the friction from the surface all modify the velocity. Velocity directly affects damage levels, because fast-moving landslides have a greater impact on buildings and leave people less time to escape.

Landslides have both ultimate causes such as weathering or steepness of slope and proximal triggers, such as a particularly intense rainstorm. These causes can be classified as geological, morphological, physical, or biotic (Table 1.1). Abiotic causes are variations of weathering (geological), slope changes (morphological), and changes due to recent disturbances (physical) (Cruden & Varnes, 1996; Petley, 2010) such as fire (Cannon 2001; Wondzell & King, 2003). Water movement in sediments is affected by both abiotic (e.g., fissuring) and biotic (e.g., plant root) factors. Water-soaked surface soils tend to slide when percolation to lower levels is slow or inhibited. Water can also liquify clay-rich soils, causing them to flow. Plants provide cover that generally has a stabilizing influence on

(a)

(b)

Fig. 1.6. (a) Rock fall at the slip face of a landslide on Casita Volcano, Nicaragua. Photograph by E. Velázquez. (b) Debris fall near Crater Lake, Oregon (U.S.). Photograph by A.B. Shiels.

Fig. 1.7. A complex landslide near San Carlos de Bariloche, Argentina with (from top to bottom) debris fall, debris slide, and debris flow. Photograph by L.R. Walker.

slopes because it reduces the impact of rain, facilitates water infiltration, decreases soil moisture through transpiration, and increases soil cohesion through root systems (Keller, 1996). The cohesive properties of roots vary by plant species, increasing with plant age and declining over time

as roots decay at species-specific rates when trees are cut (Sidle & Ochiai, 2006). Plants and animals can also destabilize slopes through a variety of mechanisms (Table 1.1). Anthropogenic causes, as noted in Section 1.1.1, include construction and mining activities that remove or add material to slopes, recreation activities, removal of vegetation through logging or agriculture, road construction, and additions of water (e.g., from irrigation or leaky pipes). Artificially induced vibrations from the use of explosives or heavy traffic can also trigger landslides.

Landslides often cause further disturbances, a feature that can also be used to categorize them. For example, landslides can cause small-scale deforestation by removing the above-ground biomass, damage roads and properties, modify slope hydrology, or (when under-water) cause tsunamis (Whelan & Kelletat, 2002; Bardet *et al.*, 2003). Large, submarine landslides can trigger earthquakes, and landslides can alter volcanic or glacial activity (Hewitt, 2009). When landslides partially or totally dam rivers they can divert or block water flow, leading to various secondary disturbances, including additional landslides. Partial landslide dams can trigger landslides on the opposite bank of the river; complete dams can cause landsliding along newly formed upstream lake shores (and create drought conditions downstream); the eventual collapse of a landslide dam can create many more landslides as flood waters rush downstream (see Chapter 2; Fort *et al.*, 2010). The sum of all interacting disturbances at a given site is considered the disturbance regime (Walker & Willig, 1999). Landslides are one of the more severe types of disturbance because of their removal of most organisms and soil.

Submarine landslides also can be categorized as rock falls, slides, or flows, but can occur on much shallower slopes than terrestrial landslides due to the presence of more unconsolidated material. Mass movements that begin as slides can become flows as the debris progressively deteriorates (Prior & Coleman, 1984). Submarine landslides are found throughout the world's oceans, but are particularly common in areas of high relief (e.g., submarine trenches, edges of continental shelves), tectonically active areas, and locations that receive large inputs of sediments (e.g., river deltas). Factors that promote them include volcanoes, earthquakes, water level changes, and sediment deposits from glaciers, deltas, tides, and underwater currents (see Chapter 2; Prior & Coleman, 1982).

In this book, we use a broad definition of landslides that follows Coates (1977) and considers all sudden mass movement from slides, falls, and flows as landslides. There are many related phenomena that we will mention in future chapters as they are relevant, such as solifluction in

areas of permafrost (soil creep due to freeze–thaw cycles; Matsuoka, 2001), movements of snow and ice (especially so-called dirty avalanches that transport rock and soil; Bründl *et al.*, 2010), and erosion of road, river, and canal embankments and unstable cliffs (Larson *et al.*, 2000).

1.3 Scope

This book addresses all aspects of landslide ecology and also covers the fundamental geological processes and consequences for human societies that are needed for a full appreciation of the ecological role of landslides. Chapter 2 discusses the spatial distributions of landslides and their ecological consequences. Landslides occur in marine, freshwater, and terrestrial environments. Terrestrial landslides are found mostly in wet, montane habitats and are the primary focus of this book. Groups of landslides in a landscape provide opportunities to examine gap dynamics and gradients across distinct habitat boundaries. Local features of landscapes that shape landslides include soil types, topography, climate, and vegetation. Spatial patterns within landslides are also helpful in examining recruitment, edge effects, and the role of microsites and repeat disturbances.

Chapter 3 considers the causes and physical consequences of landslides, including impacts on soils and post-landslide erosion. The ultimate cause of a landslide is slope instability, but a variety of natural and anthropogenic disturbances represent proximal causes or landslide triggers (see Section 1.2). We examine the various rock and soil types that are most susceptible to landslides. Persistent erosion commonly follows landslides, and it occurs until overall slope stability is achieved. Landslide effects on soil chemistry and soil development have many ecological consequences following a landslide.

Chapter 4 presents the biological consequences of landslides. Landslides can develop floristic and faunal assemblages that are distinct from the surrounding non-landslide areas, due to the altered microclimatic conditions. We examine whether such assemblages are unique to landslides or if generalist colonizer communities are found on other early successional sites. Many abiotic and biotic variables affect these colonists, including soil conditions, soil microbial populations, the presence or absence of seed banks, nitrogen fixing plants, and surviving pockets of residual soil and organisms.

Chapter 5 discusses how landslide ecosystems are dynamic in time as they undergo succession and interact with their immediate and broader surroundings. The process of succession results in species replacements

that are driven by species interactions (both positive or facilitative, and negative or competitive), herbivory, other on-going disturbances (e.g., drought, persistent erosion, fire, plant harvesting), and colonization by both later successional native species and non-natives. Non-native species can sometimes alter or arrest successional trajectories because they add a missing ecosystem function (e.g., nitrogen fixation) or rearrange trophic food webs or competitive hierarchies. Finally, successional dynamics alter local and regional biodiversity and landslide patches contribute to biogeographical dynamics including migration, dispersal corridors, and landscape connectivity.

Chapter 6 expands on the human relationship with landslides discussed at the beginning of this chapter. We include more examples of extremely large, damaging, or costly natural landslides, and infamous landslides of anthropogenic origin. We elaborate on the themes of how humans survive and learn to co-exist with landslides and how they cause them. Humans have colonized many landslide-prone habitats, so we also try to predict landslides and prevent them when we can. Finally, we discuss how successful co-existence of humans and landslides is best addressed through efforts to restore ecosystem function and biodiversity on landslide scars.

Chapter 7 places the details of previous chapters into a larger spatial context. We summarize land use changes in mountain societies and note how novel mixtures of native and non-native species will become increasingly common. We discuss how climate change will likely lead to more frequent landslides and how rehabilitation is best addressed at landscape rather than landslide scales. We suggest several lessons that landslide ecology provides and end with nine suggestions for how landslide ecology might develop in the next few decades, using technological, ecological, and cultural approaches.