The role of ecosystems in disaster risk reduction

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Edited by Fabrice G. Renaud, Karen Sudmeier-Rieux and Marisol Estrella

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Endorsements

"The application of disaster risk reduction has saved millions of lives and helped communities globally. But the ecosystems on which communities depend upon for their protection, economic well-being and recovery have, until now, been largely ignored in disaster risk reduction. Incorporating ecosystems into disaster risk reduction can save lives, aid recovery and help build a more resilient and secure planet for all. This timely book is an essential tool for policymakers, scientists, economists, sociologists, and practitioners on why and how to integrate ecosystems into disaster risk reduction. Scientific studies have repeatedly confirmed the role of healthy ecosystems in providing resilience against disasters; and they have demonstrated how environmental degradation contributes to more severe disasters including droughts, floods, and storm surges. A key challenge is how to integrate this knowledge into policy and planning. Multi-disciplinary approaches that combine ecology and engineering, science with sociology and economics have to be implemented. This book provides a sobering evaluation of the consequences of ignoring ecosystems in disaster risk reduction. But it also offers a range of well-considered and practical solutions which could be used in many existing regulations, policies and risk reduction activities."

Deborah Brosnan, Environment and Policy Scientist, University of California, Davis, One Health Institute

"In 2004, the earth shook, the waters rose, and the Indian Ocean tsunami changed the world. Almost a quarter of a million coastal dwellers died that day. Several years later, the earth shook again, this time in Haiti, and a disturbingly similar number of people lost their lives. In both cases, sustainable, healthy ecosystems could have substantially mitigated these disasters.

Recent disasters in Japan, the US East Coast, and several in SE Asia including Thailand and the Philippines, have led to a simple yet unsolvable question: How can the world's most vulnerable populations reduce the risk posed by natural hazards?

The Role of Ecosystems in Disaster Risk Reduction brings together the world's experts on how the natural environment has evolved tools to buffer against natural hazards in real, sustainable and cost effective ways. From coastal ecosystems that buffer large waves while providing valuable services to Indian Ocean communities to protective services that forests provide in the Swiss Alps, this book is a valuable contribution showing how environmentally and economically sustainable solutions can provide real benefits to exposed populations and resources."

Brian G. McAdoo, College Rector, Professor of Science, Yale-NUS College

"Why do ecosystems matter in disaster risk reduction? This book meets an urgent need. Intuitively we understand that working with and not against nature will help in protecting us from impacts of extreme natural events, but evidence has been lacking regarding the effectiveness and efficiency of such measures, particularly as alternatives to or in combination with engineered solutions. This rich collection of research findings and tested practices takes us around the globe, from coasts to forests, from agricultural landscapes to protected areas, from cities to mountains. It addresses conflicts between socio-economic development and environmental concerns, taken to its extreme in Cape Town where policymakers and planners have had to overcome the legacy of apartheid to find a sustainable trajectory. And it gives readers an array of methods and instruments to help overcome the sector and disciplinary stovepipes that often stand in the way of the holistic approaches needed to meet and reconcile multiple objectives: protecting vulnerable people and assets, halting the erosion of biodiversity and making sustainable use of our natural resource base. Those looking for the state of the art in ecosystem-based disaster risk reduction now know where to go."

Johan Schaar, Co-Director, Vulnerability and Adaptation Initiative, World Resources Institute

"With the human and economic losses of disaster events projected to grow, and with two-thirds of global disaster losses being caused by hydrometeorological events, this is a very timely compilation of the evidence needed to link up ecosystem management with disaster risk management as mutually reinforcing initiatives. It comes at a time when the post-2015 development paradigm and framework for disaster risk management are on the drawing boards. It will surely go a long way in informing the convergence of policies and benchmarks for ecosystem management as an integral aspect of climate and disaster risk management, to ensure near-term development gains and long-term climate and disaster resilience.

An extremely timely and comprehensive publication, a game-changer in the approach to natural resource management for sustainable development – and for climate and disaster resilience."

Prashant Singh, Team Leader, Partnerships and Governance, Global Facility for Disaster Reduction and Recovery (GFDRR) at The World Bank

"How do ecosystems relate to disasters? How do ecosystems contribute to disaster risk reduction (DRR)? This book gives us answers to these questions.

It is timely to address DRR-related coastal issues and water resources management, which are inevitable to countries being prone to water-related disasters such as storm surges and tsunamis as well as floods, droughts and erosion. Forestry and vegetation cover are also dealt with in relation to land management and landslides. These are serious problems which many parts of the world are facing in the twenty-first century under the pressure of sustainable development and survivable societies. Future perspectives are also given in concluding chapters.

This book will be of interest to disaster managers and policymakers, eco-hydrologists, coastal and water resources planners, engineers and managers, research scientists and students, international donor agencies, and many professionals from NGOs and the media."

Kaoru Takara, Disaster Prevention Research Institute, Kyoto University, Japan

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Foreword: Why do ecosystems matter in disaster reduction?

Margareta Wahlström, Special Representative of the Secretary-General for Disaster Risk Reduction and Head of the UN Office for Disaster Risk Reduction

The current global framework for disaster risk reduction, the Hyogo Framework for Action, was agreed in Kobe, Japan, in January 2005 as the world struggled to come to terms with the loss of life and devastation caused by the Asian tsunami of a few weeks earlier. Sustainable ecosystems and environmental management were placed top of the list under the Hyogo Framework's Priority for Action No. 4 on reducing underlying risk factors, and a few months later Hurricane Katrina engulfed New Orleans in a disaster that was both predictable and predicted. As is often the case following major disaster events, there was much focus on what should have been done to strengthen the city's physical infrastructure, such as improving the levee and drainage systems or building protection walls.

There is, of course, a very important but less appreciated "resilience gap" that faced New Orleans and the many small towns and villages that bore the brunt of the Asian tsunami, and that was the deterioration of their natural defences. In other words, there was a general failure to appreciate why ecosystems matter in disaster risk reduction and how they help to build a community's resilience to disaster events. In the case of New Orleans, economic development prior to Katrina had taken place at the expense of losing 4,800 km^2 of wetlands in the Mississippi Delta, which took thousands of years to accumulate and helped to dissipate the energy of storm surges in centuries past.

If one considers that floods disrupt the lives of over 100 million people every year, then it seems obvious that ecosystems have a role to play in limiting the impacts on our built environment and that we cannot simply pretend we can avoid harm by constructing more dykes, dams, spillways and other built structures. The proper use and preservation of natural and constructed wetlands not only help withstand storm surges but also reduce the volumes of rainwater runoff in urban areas. A key benefit of wetlands and environmental buffers is to act as flood retention basins and reduce flooding in built-up areas. One statistic worth pondering in relation to the value of well-managed ecosystems is that 1.3 million trees can catch 7 billion m^3 of rainwater per year, which amounts to a major reduction in stormwater drainage.

This is a welcome and timely publication that will make a major contribution towards shaping the successor to the Hyogo Framework for Action, which expires in 2015. It is also a forceful and eloquent reminder that environmental management is an essential part of best practice in disaster risk reduction.

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Abbreviations

ADV	Acoustic Doppler Velocity
AsgiSA	Accelerated and Shared Growth Initiative for South Africa
CAMP	coastal area management plan
CARICOM	Caribbean Community
CbA	community-based adaptation
CBA	cost–benefit analysis
CBD	Convention on Biological Diversity
CCA	climate change adaptation
CCSR	Center for Climate Systems Research
CCT	City of Cape Town
CDB	Caribbean Development Bank
CEA	country environmental analysis
CENOE	Centro Nacional Operativo de Emergência [National Emergency Operations Centre], Mozambique
CF	community forest
CFUG	Community Forest User Group
CRED	Centre for Research on the Epidemiology of Disasters
CRiSTAL	Community-based Risk Screening Tool – Adaptation and Livelihoods
Defra	Department for Environment, Food and Rural Affairs, UK
DIA	disaster impact assessment
DMP	Disaster Management Plan
DoF	Department of Forests, Nepal
DRM	disaster risk management
DRR	disaster risk reduction
EbA	ecosystem-based adaptation

Eco-DRR	ecosystem-based disaster risk reduction
EIA	environmental impact assessment
EM-DAT	Emergency Events Database
FECOFUN	Federation of Community Forest Users, Nepal
FEMA	Federal Emergency Management Agency, USA
GCM	Global Circulation Model
GDP	gross domestic product
GIS	Geographic Information System
GRRT	Green Recovery and Reconstruction Toolkit
HAZUS-MH	Hazards U.S. – Multi-Hazards tool
HFA	Hyogo Framework for Action
ICZM	integrated coastal zone management
INGC	Instituto Nacional de Gestão das Calamidades [National Disaster Management Institute], Mozambique
IPCC	Intergovernmental Panel on Climate Change
ISDR	International Strategy for Disaster Reduction
IUCN	International Union for Conservation of Nature
IWRM	integrated water resources management
LiDAR	Light Detection and Ranging
MEOW	Maximum Envelopes of Water
MERET	Managing Environmental Resources to Enable Transitions to More Sustainable Livelihoods
MESCAL	Mangrove Ecosystems for Climate Change Adaptation and Livelihoods
MSL	mean sea level
MSV	Many Strong Voices
NDMA	National Disaster Management Authority, Pakistan
NEP	National Estuary Program, USA
NGO	non-governmental organization
NOAA-CSC	National Oceanic and Atmospheric Administration's Coastal Services Center
NWP	Nairobi Work Programme
OECD	Organisation for Economic Co-operation and Development
PAARSS	Projecto de Abastecimento de Água Rural e Saneamento em Sofala [Programme for Rural Water Supply and Sanitation]
PARPA	Plano de Acção para a Redução da Pobreza Absoluta [National Poverty Reduction Strategy]
PEDRR	Partnership for Environment and Disaster Risk Reduction
PIOJ	Planning Institute of Jamaica
PROFOR	Programa de Repoblamiento Forestal
REA	rapid environmental impact assessment
RiVAMP	Risk and Vulnerability Assessment Methodology Development Project
SBSTA	Subsidiary Body for Scientific and Technological Advice
SEA	strategic environmental assessment
SIDS	Small Island Developing States
SLOSH	Sea, Lake and Overland Surges from Hurricanes

SLR	sea level rise
SLRTF	Sea Level Rise Task Force
SOVI	Social Vulnerability Index
SREX	Special Report on Managing the Risks of Extreme Events and Disasters
TEEB	The Economics of Ecosystems and Biodiversity
UDDT	urine-diverting dry toilet
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Reduction
UNU-EHS	United Nations University Institute for Environment and Human Security
UWI	University of the West Indies
VDC	Village Development Committee
WFP	World Food Programme
WSSD	World Summit on Sustainable Development

Part IV

Sustainable land management for disaster risk reduction

12

The role of vegetation cover change in landslide hazard and risk

Maria Papathoma-Koehle and Thomas Glade

Introduction

Landslides cause economic losses as well as considerable loss of life worldwide. They are commonly triggered either by hydro-meteorological events or by earthquakes. However, preconditioning factors such as topography, geology, soils, hydrological conditions, landslide history and vegetation cover determine the response of a landslide-prone catchment to a specific trigger. In this chapter, the focus is on the role of vegetation within the preconditioning factors and how a change might influence the consequent landslide risk. Also, aspects of climate change are addressed.

According to the Intergovernmental Panel on Climate Change (IPCC) Working Group I (2007), the type, frequency and intensity of extreme events such as heatwaves, droughts and floods are expected to change as a result of climate variations. Moreover, in a recent IPCC report (2012) it is suggested that there is high confidence that changes in heavy precipitation will affect landslides in some regions. Moreover, landslide occurrence in terms of magnitude, intensity, temporal pattern and spatial extent might be affected by this change. For example, increasing precipitation frequency and intensity as well as changes in soil temperature leading to a changed soil moisture regime can reduce slope stability (UNU, 2006). At large scales, higher temperature and mild winters will cause permafrost melting and saturation of soils, which might affect slope stability and eventually the occurrence of landslides (Bärring and Persson, 2006). Bo et al. (2008) also point out that climate change will affect

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the stability of slopes owing to changes in vegetation and in ground and surface water levels and they list the types of slopes that are most vulnerable to such change. Indeed, not all landslide types are expected to have the same reaction to these climatic changes. According to Geertsema et al. (2007), landslide types such as debris slides, debris flows and rock fall respond rapidly to these hydro-meteorological variations, whereas other types, such as earth slides and flows, have a delayed response. Responses are also heavily dependent on the magnitude of the triggering event.

Not only might climate change directly affect landslide occurrence but it can also influence the preconditioning factors of landslide initiation. For example, vegetation transformation driven by climate change might lead to changed slope stability and consequent landslide occurrence. However, such changes occur at different scales. Whereas direct interventions such as deforestation are occurring in rather smaller regions over short periods, climate change is affecting larger regions and principally at longer time scales. Thus, changes in vegetation cover as the result of climate change may be two-fold (see Figure 12.1): (1) climate change might slowly but constantly develop vegetation cover (for example, a slow shift in the tree line), and (2) extreme events might result in rapid changes (for example, fires remove forests or wind destroys forest cover). In addition to climatic stresses, anthropogenic forces often result in dramatic vegetation changes. Such forces might be related to (3) the logging of

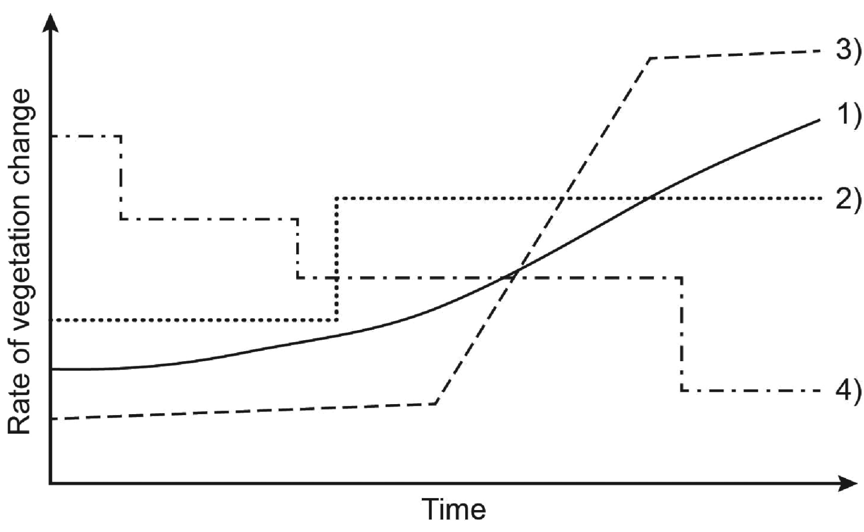

Figure 12.1 Schematic representation of various options for vegetation change in a given catchment/region with (1) continuous climate change; (2) extreme hydrometeorological events; (3) forest logging; and (4) changes in agricultural practices

forests in large areas or (4) changes in agricultural practices owing to policy decisions or farmers' economic motives.

Numerous studies have investigated the role of vegetation in relation to the occurrence of hazardous phenomena such as landslides, rock falls and debris flows (Alcántara-Ayala et al., 2006; Bathurst et al., 2009; Dorren et al., 2004, 2006; Gerrard and Gardner, 2002; Glade, 2003a; Greenway, 1987; Kuriakose et al., 2006; Masuya et al., 2009; Schmidt et al., 2001; Steinacher et al., 2009; Sudmeier-Rieux et al., 2011; Wasowski et al., 2007; Woltjer et al., 2008). They all regard vegetation as an important factor that influences slope stability.

Changes in vegetation as a result of climate change or anthropogenic factors may affect landslide occurrence but they may also play an important role in increasing or decreasing the physical vulnerability of individual elements at risk. Since vulnerability is of major importance to risk assessments and risk reduction strategies, as emphasized in the Hyogo Framework for Action 2005–2015, its role has to be closely examined and taken into consideration by decision-makers. Vulnerability is affected by people moving into previously forested areas with consequent impacts on landscapes because of the construction of critical infrastructure, the building of urban areas, a change in land use in regions cleared of forests, etc. Thus, the elements at risk and vulnerability are increasing concurrently with a reduction in vegetation cover. In addition, removal of "protection forests" in already developed regions might increase the vulnerability of existing critical infrastructure or houses (see below on protection forests).

Hence, the effects of climate change should not be overestimated. It is very difficult to assess the impact of climate change on slope stability owing to a lack of data on historical landslide activity and to other factors that also affect slope stability (Alcántara-Ayala et al., 2006). These other factors range from anthropogenic slope modifications, such as levelling, to a changed hydrological regime through drainage and also water supply to the slopes. According to Winter et al. (2010), these factors might have a positive or a negative influence on slope stability that even exceeds that of climatic changes. For example, Wasowski et al. (2007) concluded for their investigated catchment in Italy that changed slope stability is related not to climate change but to land-use change. Nevertheless, all authors dealing with the effects of climate change on natural hazards point out that it is urgent for decision-makers to consider climate change and put mitigation and adaptation strategies high on their agenda.

This chapter examines the ways in which changes in vegetation cover can affect the spatio-temporal pattern of landslide occurrences, its related consequences and the implications that these changes might have in decision-making and disaster management. We review the trends in vegetation change resulting from climate change and anthropogenic factors and the possible consequences for landslide occurrence and overall landslide risk. We present recent strategies of using land cover and vegetation for landslide risk reduction and emphasize the possible gaps and needs for future research.

Landslide hazard, vulnerability and risk

Landslides can be defined as the downslope movement of soil, rock or debris as the result of gravitational forces, which can be triggered by heavy rainfall, rapid snow melting, slope undercutting, etc. (see, for example, Crozier, 1999; Glade and Crozier, 2005b). The term “landslide” is used in this chapter for shallow landslides (defined by BRP, BWW and BUWAL, 1997, as less than 2 metres deep), debris flow (solid material with a high water content) and rock fall (loose stones and boulders) according to the internationally widely accepted definitions of Cruden and Varnes (1996) and Dikau et al. (1996). These types of landslides are mainly affected by vegetation cover and human activity, in contrast to deep-seated landslides, which are less likely to be stabilized by vegetation cover and are more affected by geological and hydrological conditions. The impact of landslides on buildings and infrastructure ranges from zero (if no buildings are exposed) or minimum (if landslide magnitude is minor and only negligible damage can be expected) to maximum (collapse or burial of buildings and infrastructure, loss of life and loss of agricultural land; refer to Glade and Crozier, 2005b, for more details). As far as debris flows and soil flows are concerned, not only do they influence the stability of buildings, but also, during low-magnitude events, material can enter buildings through doors or windows and damage building interiors (Holub and Fuchs, 2009). In contrast, large-magnitude events damage or even destroy the building structure such as walls (see Figure 12.2). On the other hand, rock falls usually affect individual buildings rather than large areas and they may also damage building interiors. Although, in Europe, large-magnitude landslides have a low probability of claiming lives, the concentration of assets on steep slopes, high standards of living and high population densities have rendered European households vulnerable to even small-magnitude landslide events (Blöchl and Braun, 2005).

The majority of studies concerning landslide hazards focus on hazard assessments (mapping and zoning), landslide modelling and landslide risk management. Although hazard assessments are very important for disaster risk reduction, understanding the vulnerability of the built environment, the natural environment and society is equally important.

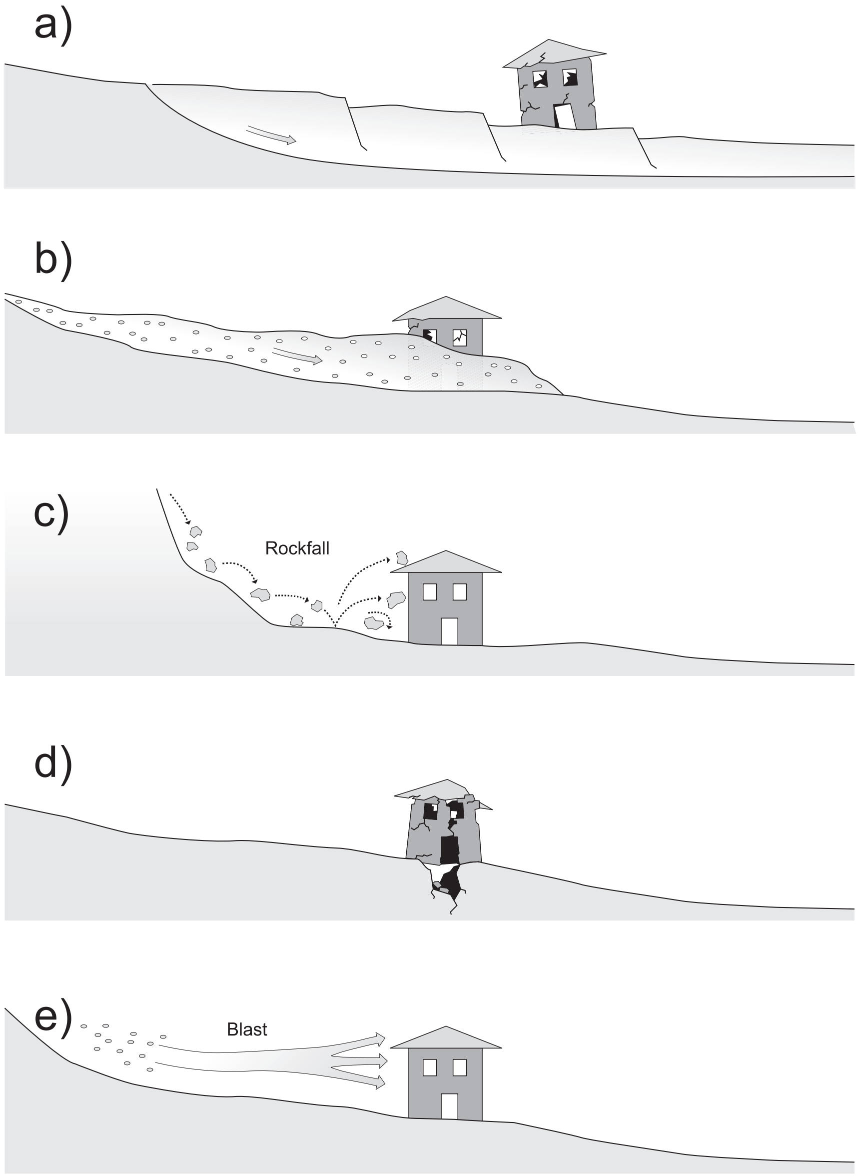

Figure 12.2 Examples of the consequences of landslide occurrence for different event magnitudes: (a) shallow translational or rotational landslide; (b) debris flow; (c) rock fall; (d) subsidence and (e) rock avalanche
Source: Based on Glade and Crozier (2005b).

Vulnerability assessment of elements at risk of landslide-related phenomena is a relatively new field of research (Glade, 2003b; Hufschmidt and Glade, 2010; Zhihong et al., 2010), which additionally brings together scientists from different disciplines (Fuchs, 2009). Because there is no common definition of vulnerability across all disciplines (the social sciences, the natural sciences, engineering), each group of scientists provides its own definition, clearly demonstrating the lack of common language and hindering vulnerability research from moving forwards (Brooks, 2003). In the social sciences, vulnerability is related only to the social context, whereas engineers and natural scientists try to define thresholds in order to determine acceptable risk and at what point risk reduction measures should be taken (Bohle and Glade, 2007).

As far as physical vulnerability is concerned, the most common definition used by natural scientists and engineers is the one proposed by the Office of the United Nations Disaster Relief Coordinator (UNDRO, 1984: 3): “Vulnerability is the degree of loss to a given element, or set of elements, within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss).” On this basis, the majority of vulnerability assessment methods for landslides either estimate the associated vulnerability (Glade, 2003b) or concentrate on creating vulnerability curves that connect the intensity of a process to the degree of economic loss of buildings (Bohle and Glade, 2007). In a review of methods for assessing vulnerability to alpine hazards, Papathoma-Köhle et al. (2011b) suggest that nearly half of the methods apply vulnerability curves. However, that means that in most cases only one characteristic of the element at risk (usually the building type) and of the phenomenon (intensity expressed as, for example, the thickness of the deposit in the case of debris flow) is taken into consideration. However, there are studies referring to other vulnerability indicators, such as demographics and vegetation cover near buildings (for example, Bell and Glade, 2004; Kappes et al., 2012; Papathoma-Köhle et al., 2007).

Papathoma-Köhle et al. (2007) introduced a framework to undertake an assessment of the vulnerability of buildings to landslides, based on the development of an “elements at risk database”. It takes into consideration the characteristics and use of buildings, their importance for the local economy and the demographic characteristics of the inhabitants (population density, age, etc.). In a modification of this methodology for multi-hazards, the type of vegetation surrounding a building is also taken into consideration (Papathoma-Köhle et al., 2011a; Kappes et al., 2012) in assessing its overall physical vulnerability. Four categories of vegetation surrounding buildings are presented: no trees, few trees, closed tree line and buildings located within the forest. However, the role of different vegetation types in protecting an element at risk has yet to be further explored.

The role of vegetation cover in landslide risk

Vegetation can reduce the probability of a landslide through the reduction of the soil pore-water pressure and can reduce the possibility of soil erosion through reinforcement of soil properties through the root system. In Figure 12.3, the destabilized slopes on the unforested part of the hills in East Cape, North Island, New Zealand, are shown. Alternatively, vegetation can increase the hazard by overloading the slope with weight and by weakening the regolith strength through movement of the roots, for example during strong wind storms (Popescu, 2002; Sidle et al., 1985; Steinacher et al., 2009). Another observed effect is that the vegetation cover indeed stabilizes the slope through root reinforcement; however, if the slope fails, the root weight could actually increase the size of the

Figure 12.3 Destabilized slopes on the unforested part of the hills, East Cape, North Island, New Zealand
Photo: Michael Crozier.

landslide. In the case of shallow landslides, rock fall or debris flows, vegetation can also reduce the vulnerability of elements at risk. Here, vegetation not only prevents the initiation of the landslide process but also acts as a protective barrier. In this section, the role of vegetation in landslide hazard, the vulnerability of the elements at risk and, finally, landslide risk are discussed through some examples for shallow landslides, debris flows and rock fall.

Different land uses and corresponding vegetation cover can have a significant influence on slope stability. During a rainstorm event in 2004 in the East Cape region of North Island, New Zealand, large areas were affected by landslides. As other studies have shown, the region has undergone significant land-use changes over the past century owing to the conversion of hillsides into farm pastures (for example, DeRose et al., 1995). Areas affected by landslides recover very slowly, often never returning to pre-landslide conditions (Smale et al., 1997). The landslide process often starts as shallow translational soil slides, which develop within the channels into mud and debris flows. As soon as the displacement of the regolith has been initiated, the transported materials turn into very liquefied matter. Once the drainage line or channel has been reached, these flow types can travel for very long distances, from tens to hundreds of metres downslope, causing damage to buildings and infrastructure that lie in their way. In contrast, forested slopes remain stable (Figure 12.3). Obviously, the magnitude of this triggering event was not large enough to destabilize the areas covered by forests to a similar extent. In the case of this specific event, the forest functioned as a protection against regolith destabilization and subsequent landsliding. However, this does not imply that the forested region and the exposed elements at risk located further downstream in the valleys are completely safe. It can be expected that, with an increasing triggering magnitude, even forested areas and elements at risk near the destabilized slopes will be affected. For events with a magnitude lower than or similar to that of 2004, forest cover can clearly be regarded as a protection against shallow landslides and consequent mud and debris flows.

Also in terms of landslide risk, the consequences are heavily dependent on the vegetation cover in the source areas of the catchment. In the case of 2004, regions below the forests were safe and did not experience any significant damage from landslides. In contrast, exposed elements at risk located in the non-forested regions experienced significant damage ranging from extensive mud cover (see Figure 12.4) to completely damaged houses and infrastructure. Therefore, management of vegetation cover can extensively influence landslide occurrence and consequent landslide risk.

In other regions outside New Zealand, a considerable number of studies have investigated the role of vegetation (in most cases forests) in

Figure 12.4 Extensive mud and debris deposits behind a fence following extensive landsliding in the catchment, East Cape, North Island, New Zealand
Photo: Michael Crozier.

slope stability and landslide occurrence. Peduzzi (2010) investigated the role of vegetation in slope stability in North Pakistan and concludes that the "presence of denser vegetation has a mitigation effect on landslide susceptibility" (Peduzzi, 2010: 633). He supports this argument with the results of landslide modelling with and without considering vegetation density, determined through the Normalized Difference Vegetation Index. The susceptibility of the area to landslides rose by 15.1 per cent when the presence of vegetation was not taken into consideration (Peduzzi, 2010). On the other hand, Popescu (2002) suggests that, although vegetation often reduces the occurrence of landslides through water content reduction and root anchoring, it may also have the opposite effect. He lists some negative effects of vegetation on slope stability, such as the fact that trees may destabilize slopes owing to their weight and their exposure to wind forces. Additionally, Popescu suggests that the roots of trees and plants can penetrate and expand the joints of rock, thus destabilizing the slope. However, he emphasizes that these effects are minor and that the positive effects of the vegetation on slope stability are the dominant ones.

Table 12.1 The influence of woody vegetation on slope stability

Mechanisms	Influences on types of landslides	
	Shallow, rapid	Deep-seated
Hydrological mechanisms		
Interception of rainfall and snow by canopies of vegetation, promoting evaporation and reducing water available for infiltration	B	B
Root systems extract water from the soil for physiological purposes (via transpiration), leading to lower soil moisture levels	B	B
Roots, stems and organic litter increase ground surface roughness and soil's infiltration capacity	MA	MA
Depletion of soil moisture may cause desiccation cracks, resulting in higher infiltration capacity of water to a deeper failure plane	MA	MA
Mechanical mechanisms		
Individual strong woody roots anchor the lower soil mantle into the more stable substrate	B	MB
Strong roots tie across planes of weakness along the flanks of potential landslides	B	B
Roots provide a membrane of reinforcement to the soil mantle, increasing soil shear strength	B	B
Roots of woody vegetation anchor into firm strata, providing support to the upslope soil mantle through buttressing and arching	B	MB
The weight of trees (surcharge) increases the normal and downhill force components	MA/MB	MA/MB
Wind transmits dynamic forces to the soil mantle via the tree bole	A	MA

Source: Marston (2010).
Note: A = mechanism adverse to stability; MA = marginally adverse mechanism; MB = marginally beneficial mechanism; B = beneficial mechanism.

The role of woody vegetation (trees and plants with hard stems) in slope stability is discussed extensively by Marston (2010). The mechanisms that influence slope stability are divided into two categories: hydrological and mechanical (see Table 12.1, which is modified from Greenway, 1987, and Sidle and Ochiai, 2006).

As far as rock fall is concerned, Corominas et al. (2005) suggest that falling rocks often lose their kinetic energy as the result of the presence of trees and never make it to the lowest part of the slope. However, Bigot et al. (2009) suggest that forests can offer protection to buildings only if the forest structure is adapted to this function. They also consider forests to be not only aesthetically more appealing in comparison with other protective measures such as nets and dams, but also cheaper to maintain. Numerous research studies have been carried out, and there is still ongoing investigation in order to determine the effect of protection forests on rock falls (Dorren et al., 2004, 2006; Masuya et al., 2009; Woltjer et al., 2008; see also below on protection forests).

The effect of vegetation on debris flow initiation and propagation has often been investigated in the past (Pabst and Spies, 2001). Kuriakose et al. (2006) quantify the effect of vegetation on the initiation of debris flow by using numerical simulation. The results revealed that, although during high-intensity rainfall the mitigating role of vegetation might be reduced, vegetation remains crucial to slope stability. Kuriakose et al. also point out that the mechanical effect (that is, root cohesion) rather than the hydrological effect of vegetation seems to play the most important role.

Rickli and Graf (2009) investigate the differences in shallow landslide occurrence between open land and areas covered with forests. By looking at six different landslide areas in Switzerland, they conclude that landslide density in open land is clearly higher than landslide density in forested areas. As far as landslide dimensions are concerned, there are no significant differences, with the exception that landslide depth is greater in forested terrain. Finally, Rickli and Graf (2009) suggest that shallow landslides in forested terrain are triggered in areas with steeper slope inclination.

Furthermore, the role of vegetation in maintaining slope stability has been investigated globally by numerous scientists in several case studies. Despite these efforts, there is still the need for more research on the role of vegetation in relation to the occurrence of rock fall. The vast majority of studies conclude that the role of vegetation in slope stability is positive but its significance varies depending on specific local characteristics such as topography, lithology and hydrology.

Change in vegetation cover and its effect on slope stability

Changes in vegetation cover can result from climate change and from anthropogenic activity (for example, deforestation, land-use change, logging, arson).

Climate change

With respect to climate change, plants may respond in three ways: persistence, migration and extinction (Theurillat and Guisan, 2001).

According to Theurillat and Guisan, possible changes in vegetation in the Alps owing to climate change may include altitudinal shifts of vegetation, changes in its composition and changes in the growth and productivity of grasslands. More specifically, as far as Switzerland is concerned, an increase of 3.3°C in mean air temperature would cause an upward altitudinal shift of 600 metres, which would reduce the area of alpine vegetation belt by 63 per cent (Theurillat and Guisan, 2001). However, the response of tree species in the Alps may vary. For example, a rise in temperature might increase the radial growth of the larch pine (*Larix decidua*), but at the same time it will reduce the radial growth of the Scots pine (*Pinus sylvestris*) because of the lack of water (Theurillat and Guisan, 2001).

In a wider study of the Euro-Mediterranean area, it is suggested that vegetation in Southern and Eastern Europe as well as in North Africa will be most affected by climate change. In more detail, in coastal northern Africa and Spain, grass will be replaced by temperate trees, whereas in non-coastal northern Africa there might be a transition to bare ground conditions as a result of severe drought (Anav and Mariotti, 2011). According to the same study, in Eastern Europe boreal vegetation and grass will be replaced by temperate deciduous trees owing to higher temperatures and increased rainfall.

In the United States, the impact of climate change on vegetation has already been observed, although it varies throughout the country. Modelling of vegetation change under different climatic scenarios for the United States has shown that, for moderate climate change scenarios, vegetation density will increase, but that, under more severe climate change scenarios, there will be a decrease in vegetation density. Especially in the eastern United States, catastrophic fires may cause a transition from forest to savanna (Bachelet et al., 2001). In addition, existing land-use practices (for example, timber harvesting, vegetation conversion, fire, road construction, residential development, mining activities) may accelerate or counteract the response of vegetation to climate change (Sidle et al., 1985; Wasowski et al., 2007). For this reason, land-use planning that takes into account climate change effects on vegetation is crucial (Theurillat and Guisan, 2001).

Deforestation

According to the Food and Agriculture Organization of the United Nations (FAO, 2010), deforestation is decreasing worldwide, although the rate of deforestation is still alarmingly high. Every year in the last decade, 13 million hectares of forest were converted to agriculture or were lost from natural causes. Furthermore, the deforestation rate varies significantly from country to country. For example, countries such as Brazil or Indonesia managed to reduce the rate of forest loss, whereas in Australia the rate increased as a result of forest fires (FAO, 2010). Moreover, forest areas managed for the protection of soil and water increased by 59 million hectares worldwide, mainly because of extensive forest planting in China (FAO, 2010).

Despite these general trends, deforestation is of major importance on hilly or mountainous slopes with regard to landslide occurrence. Although there are numerous, detailed studies on the effects of deforestation on slopes and adjacent landslide occurrence (for example, Gerrard and Gardner, 2002; Wang, 2004), no overall and global information is currently available on this topic.

Forest fires

Forest fires are often the result of a combination of factors, which may include ignition agents, fuel condition, topography, climate, wind velocity and direction, precipitation and humidity. Many studies suggest that an increase in forest fires should be expected as a result of climate change (for example, Flannigan et al., 2000). In particular, studies show that there has been an increase in forest fires in North America and Europe. Intensive forest fires strip slopes of vegetation, which could also have a significant impact on the occurrence of landslides (Cannon et al., 1998, 2001; Gabet, 2003). According to Rice (1977) the immediate effect of wild fires is similar to the effect of clear-cuts and may not immediately affect landslide occurrence. At a later stage, however, the remaining roots of the old vegetation will disappear, the macro-pores in the regolith will increase and the landslide hazard may increase. Moreover, Johansen et al. (2001) suggest that, following a fire, the amount of mineral soil exposed may increase by 60–70 per cent. By applying rainfall simulation and comparing the results with rainfall simulation on unburned plots, they conclude that burned plots produced 25 per cent more sediment yield than the unburned plots.

Cannon et al. (2003) suggest that burned plots of land are very susceptible to debris flow events. Following a fire, the soil is dry and incapable of absorbing rainwater. As a consequence there is increased overland flow. The increased runoff may lead not only to extensive soil erosion but also to the transport and deposition of this material in the lower areas of the catchment, for example by channelized debris flows (Cannon et al., 2003). The effect of vegetation change on slope stability may be greater from logging, which is short lived (5–20 years, the period between residual root decay and subsequent regeneration), compared with forest fires (Sidle et al., 1985).

Land-use change

In order to assess the impact of land-use change on landslide occurrence, many scientists have developed models that consider land-use scenarios in order to assess this impact. For example, Vanacker et al. (2003) modelled the impact of land-use change on landslide occurrence in the Andes, and Van Beek (2002) and Van Beek and Van Asch (2004) have developed several scenarios of land-use change in order to assess changes in landslide-susceptible areas in the Mediterranean.

In Mediterranean environments in Europe, the abandonment of cultivated agricultural land is increasing as a result of globalization, mechanization and intensification (Van Beek, 2002). Van Beek and Van Asch (2004) use a physically based model in order to assess the spatial and temporal landslide activity for two scenarios of land-use change involving land abandonment. The results demonstrate that landslide activity is likely to decrease and consequently the areal extent of landslides will hardly change. These results might have implications for perceived hazard levels and for the landslide hazard zonation of the area. Vanacker et al. (2003) modelled landslide susceptibility with a model that suggested that land-use change would continue in the same way that it had over the preceding 37 years in the Ecuadorian Andes. The modelling results clearly indicate that the conversion of secondary forest to grassland or cropland is likely to increase shallow landslide activity.

Meusburger and Alewell (2008) investigated the ways that land-use and climate changes are influencing the occurrence of landslides by investigating spatial landslide distributions in the Urseren Valley in Switzerland between 1959 and 2004. In this period, the area affected by landslides increased by 92 per cent. This can be explained only by the increase in extreme rainfall events and by land-use change. Specifically, goat pastures and spring pastures had disappeared and remote and less productive areas had been abandoned, being replaced by uncontrolled grazing within confined areas. Moreover, the abandonment of traditional farming practices, in combination with the mechanization of local agriculture, might have contributed to increased soil erosion and consequently to the occurrence of landslides. On the other hand, areas colonized by shrubs show low landslide density (Meusburger and Alewell, 2008).

Glade (2003a) focuses on geomorphic responses to anthropogenic land-use and land-cover changes in New Zealand. By analysing sedimentation rates in swamp, lake, coastal and marine environments, Glade

(2003a) concludes that the deforestation that took place after the arrival of the European settlers was connected with increased landslide activity, which was reflected in the sedimentation rates in these environments.

Common to all these studies is the strong interlinkage between landslide occurrence and changes in vegetation cover. Indeed, the link can work both ways. As argued above, forest cover can protect regions against landsliding for lower-magnitude triggering events but may also expand the landslide regions for large triggering events despite root reinforcement of the ground. Nevertheless, the focus of this chapter so far has been on the role of vegetation in preventing the initiation of landslides; the possible change in landslide risk and relevant disaster reduction strategies have yet to be addressed in detail.

Disaster reduction strategies

Vegetation has often been used by planners for hazard reduction and to protect exposed elements against various hazard types such as tsunamis (Forbes and Broadhead, 2007; Ohira et al., 2012; Tanaka et al., 2006) and snow avalanches (Brang et al., 2006; Clouet and Berger, 2010; Schönenberger et al., 2005). In many cases, restoration of vegetation coverage can serve as a cost-effective mitigation measure (Peduzzi, 2010). For example, in the case of tropical cyclones in Viet Nam, planting and protecting mangrove forests as a protection measure not only proved to be seven times cheaper than dyke maintenance but also offered secondary benefits to society such as exploitation of mangrove products by locals in order to increase their income (IFRC, 2002).

In the case of landslides, Popescu (2002) suggests that, although in the post-war period landslides were seen as "engineering problems" that would require "engineered solutions" such as the construction of walls and fences or the use of nets for rock fall, in recent decades there has been a clear shift towards non-structural solutions and environmental consideration. This shift is related to a number of reasons. Not only are civil engineering solutions such as slope flattening, tied-back retaining walls or sheet piles very expensive but they may not justify direct short-term economic investments (Bo et al., 2008). On the other hand, measures such as reforestation schemes to manage landslide hazards may have additional benefits to society, for example employment in forestry and the export of forest products (Phillips and Marden, 2005). As a side-effect, forests might also be used for recreational purposes. Most recently, the aesthetic aspect of landscapes, including forested landscapes, has been expressed as an important added value to society (Taboroff, 2003).

Within disaster reduction strategies, spatial landslide hazard analysis is of major importance for landslide risk assessments. The types of methods range from heuristic assessments to statistical and physically based modelling. Here, the type and spatial distribution of vegetation are some of the main factors determining, respectively, landslide distribution and hazards. Consequently, vegetation is commonly taken into account in spatial landslide hazard analysis and in the delimitation of landslide hazard zones (Van Beek and Van Ash, 2004; Wilkinson et al., 2002).

Besides its consideration within spatial analysis, vegetation is also used to assist risk reduction strategies worldwide (for example in France – Berger and Rey, 2004) in order to enhance slope stability (O'Loughlin, 1984). In particular, protection forests have regularly been used for slope stabilization in many countries in the world for many decades and even centuries (Stoffel et al., 2005). Here, the steep landslide-prone terrain is of particular importance. According to the FAO (2010), approximately 330 million hectares of forest (about 8 per cent of the world's forests) have as their objective the conservation of soil and water, avalanche control, sand dune stabilization, desertification control or coastal protection. The protective functions of the forest are summarized by Sakals et al. (2006) under the following two categories: retaining material in upslope conditions; containing, confining and resisting material during transport and deposition.

Of course, a forest's ability to protect an area from landslides depends also on its position in relation to the hazard. Clouet and Berger (2010) summarize the ability of forests to control different hazards in the departure and deposition zones (Table 12.2).

Berger and Rey (2004) recognize the role of forests in protecting against natural hazards in mountainous areas; however, they suggest that their role also depends on the position of the forest, the type of vegetation, its age and the spatial scale of the hazard. They stress that the protection of the forest can be active (when it is located in the hazard

Table 12.2 The ability of forests to control natural hazards

Natural hazard	Location	Forest control implemented
Avalanches	Departure zone	Yes
	Transit and stopping zone	No
Rock falls	Departure zone	Yes
	Transit and stopping zone	Yes
Landslides	Departure zone	No
	Transit and stopping zone	No

Source: Clouet and Berger (2010).

departure zone) or passive (when it is located in the departure and stopping zones). Yet the role of forests is rarely taken into account in risk mapping (Berger and Rey, 2004). Clouet and Berger (2010) suggest that the age of the forest can significantly decrease its protective efficiency. Although they recognize that forest management is very important, they suggest that silvicultural interventions may be very expensive. For this reason, Clouet and Berger (2010) have developed an analysis tool based on Geographic Information Systems that can assist in the prioritization and identification of areas within the forest where intervention is needed.

Berger and Rey (2004) stress that there is a need for a common guide as a tool for decision-making in the management of forests that offer protection against natural hazards in countries such as Austria, France and Switzerland. They present an example from France and make recommendations for better forest management for controlling natural hazards in mountainous areas. They discuss the methodological steps for protective forest delimitation. In France, the delimitation of protective forest areas is used in risk prevention plans. In 2006, a set of guidelines for protection forest maintenance was published (Wehrli et al., 2007).

In Austria, the role of the protective forests was understood as early as 1870 when the lack of forests in torrential catchments and the poor state of existing mountainous forests were considered to have contributed to the catastrophic consequences of floods (Austrian Federal Forests, 2009). Since then, protective forests have been used to mitigate the impact of natural hazards such as avalanches and landslides and, according to the Austrian Forest Act, are divided into three categories (FMAFEWM, 2009):

- site-protection forests: they protect themselves;
- protective forests: they provide protection from natural hazards or they enhance and maintain positive environmental effects such as climate or water balance;
- object-protection forests: they protect human settlements and agricultural areas.

Based on information provided by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft), at least 29 per cent of Austrian forests are protection forests and there are at least 83 current protection forest projects in the country. According to the Ministry, the ideal protection forest is a typical mixed forest with several types of old trees. As far as tree types are concerned, larch (*Larix decidua*) is ideal for use against rock fall, whereas spruce (*Picea*) forests are good against snow avalanches owing to their density. The Austrian authorities recognize that protection forests are a cheap alternative to structural protection measures but they also stress that sustainable forest management is required (Austrian Federal Forests, 2009). The necessary actions for the protection and management of protection forests in Austria are implemented through the "Protection Forest Platforms" of every federal state (FMAFEWM, 2009).

Finally, since the early 1980s there have been measures for the management of protection forests in Switzerland. A large amount of money is invested every year for their protection and management.

Phillips and Marden (2005) review the use of protection forests in New Zealand, where the importance of erosion control was already understood in the early 1940s. The first reforestation project using a variety of tree species started in 1948 and continued in 1953 with the purchase of eroded land by the government for the establishment of dual-purpose exotic forest, for protection against erosion and for timber production. In 1968 the East Coast Project (1968–1987) was approved so that unforested parts of the critical headwaters could be planted with protection forests. In 1988, the project was reviewed following Cyclone Bola, which caused widespread landslides in the country (Marden and Rowan, 1993). Following this event, it was obvious that mature native forest and pine forest offered significant protection (Hicks, 1991). In 1992, the East Coast Project was replaced by the East Coast Forestry Project, which aimed to plant 200,000 hectares in 28 years (Phillips and Marden, 2005).

In Australia, the Australian Geomechanics Society suggested that changes in vegetation can clearly increase the landslide risk and, for this reason, it includes retention of natural vegetation wherever practicable in the guidelines for hillside construction (AGS, 2000). In other countries, such as South Korea, Taiwan and Japan, forests are also used for erosion control and landslide risk reduction (Phillips and Marden, 2005). In South Korea, although erosion control projects started as early as 1907 and the forest area now occupies almost 65 per cent of the entire country, the majority of the forests consist of very young trees as a result of forest management (Phillips and Marden, 2005).

However, although vegetation can be, and often is, used as a non-structural protection measure against landslides, Peduzzi (2010) stresses that, depending on the slope, increasing vegetation density may not be the only solution since other factors contribute to landslide susceptibility, such as slope characteristics. For example, a common practice for slope stabilization is "bio-engineering", a combination of techniques to protect slopes against erosion, reduce the probability of planar sliding and improve surface drainage (Florineth et al., 2002). Bio-engineering uses vegetation in combination with other methods in order to stabilize a slope and reduce landslide hazard. According to Singh (2010: 385), bio-engineering is "the successful use of vegetation (both live and dead plants as well as use of raw materials derived from plants like jute and coir) together with engineering structures to increase slope stability. These include the use of vegetation and horticultural practices, coir and jute netting, asphalt mulch solution, retards, wattling etc. in combination with slope modification and improved agronomic practices." According to Singh, the most economical and simple method for slope stabilization is vegetation turfing. Florineth et al. (2002) suggest that the plants used in bio-engineering are selected on the basis of pioneer plant character, a dense and deep rooting system, potential and adventitious rooting system and fast and simple propagation.

In most cases, vegetation has been used mainly to enhance slope stabilization and avoid the occurrence of landslides rather than for mitigating the vulnerability of individual elements at risk. A review of studies concerning alpine hazards has shown that there are a limited number of vulnerability assessment methodologies dealing with the physical vulnerability of elements at risk of landslides (Papathoma-Köhle et al., 2011b). The review highlights that most methods do not take into account the presence of vegetation (for example forests, single trees, hedges) surrounding the exposed elements at risk (especially buildings). However, there are exceptions, such as the methods presented by Papathoma-Köhle et al. (2011a) and Kappes et al. (2012), who have included the presence of trees surrounding buildings in a database of physical vulnerability indicators for elements at risk.

It is evident that landslide occurrence and consequently landslide risk owing to climate change and anthropogenic factors will change significantly in the future. It is expected that vegetation change will have an effect on slope stability, contributing to an increase in landslide risk. The following recommendations might be beneficial for societies dealing with landslide hazard and risk in the face of climate and vegetation change:

1. Decision-making and planning for mitigation and adaptation should be based on an integrated observation and information system. Thus, systematic monitoring and robust modelling of landslide occurrence and also changes in the factors that affect slope stability (for example vegetation change) are very important (Watson and Haeberli, 2004). For this reason, a further refinement of models linking climate, slope hydrology, vegetation cover and stability is essential (as started by Brooks et al., 2004). Robust monitoring will contribute to determining the sensitivity of different landslide types to changing boundary conditions such as climate change (Glade and Crozier, 2005a).
2. Legislation should strengthen and expand existing restrictions on development in landslide-prone terrain, taking into consideration possible changes resulting from climate change (Bo et al., 2008). For example, in Seattle in the United States, municipal codes forbid the removal or clearing of vegetation or trees within landslide-prone areas

or any action detrimental to the habitat (Kazmierczak and Carter, 2010). In exceptional cases where vegetation removal has to take place, a reforestation plan should be ensured (Kazmierczak and Carter, 2010).

3. More research on the effects of vegetation on the different landslide types should be carried out. Currently, there is some research on the functions of different vegetation types in slope stability, but it is not commonly detailed by landslide type (for example, debris flows, shallow translational landslides, deep-seated rotational landslides).
4. The consequences of vegetation changes for landslide occurrence, and thus the landslide risk, have to be further explored. Here, the physical vulnerability of elements at risk, such as buildings and infrastructure, might be reduced by the presence of vegetation. Notwithstanding studies on rock fall, there is sparse research on how landslide risk reduction can be achieved and which characteristics of the vegetation could enhance its protective role. This could be done by extensive investigation of past event damage reports but also by establishing post-event damage recording protocols (Glade and Crozier, 2005a; Hübl et al., 2002).
5. There should be a shift from civil engineering measures to sustainable silvicultural actions that might also benefit the local economy and community, given that the maintenance costs are not as high as for engineering measures.
6. Climate change should be further taken into consideration in land-use planning, for example by allocating land susceptible to increased landslide activity because of climate change in a way that lowers hazard exposure. Examples of good practice are using land for open public space and sports fields rather than for housing development. In some cases, site abandonment may also be an option (Lee and Jones, 2004).
7. Climate change should be considered in the design of measures for slope stabilization and erosion control. For example, the specification of structural measures should allow for climate uncertainty or variability in the design parameters (Lee and Jones, 2004).
8. Finally, landslide risk assessments should take into account changes in climate and vegetation cover – in addition to socioeconomic changes (for example, the extension of urbanized regions or the development of new critical infrastructure such as transport networks and power lines).

Conclusions

The role of vegetation in landslide occurrence has been investigated for many decades. However, its influence on elements at risk (houses, critical infrastructure), their vulnerability and overall landslide risk is still an open question. This is even more so considering the short- and long-term effects of climate change. Climate and environmental change are expected to modify vegetation patterns, in particular in sensitive mountain areas. Land-cover changes in combination with increased precipitation may increase the probability of landslide occurrence. More research is needed in order to fully understand the relationship between vegetation and geomorphology (Marston, 2010), especially in landslide research. Although most studies suggest that the existence of vegetation increases slope stability and reduces the occurrence of landslides, many scientists point out that this is not always the case (Marston, 2010; Rickli and Graf, 2009). There are not sufficient studies quantifying the effects of vegetation change on landslide occurrence in both time and space and defining the thresholds of forests or other vegetation types for stabilizing and destabilizing slopes.

Moreover, the change in both landslide magnitude and intensity is still a challenging field of research. The use of protection forests is a common practice in many countries (for example in Austria, China, France, Japan, New Zealand and Switzerland). In most cases, vegetation cover and land use are taken into account in landslide hazard assessments and hazard zonations. However, the protective role of vegetation as far as reducing the physical vulnerability of buildings and infrastructure is concerned is usually not considered. More research is needed focusing on the role of the vegetation surrounding an element at risk and how this element reacts when it is affected by a particular landslide such as a rock fall or debris flow. Last but not least, vegetation and land-use changes caused by climate change should be taken into consideration in decision-making and planning processes.

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