Chapter 1

Environmental Change and Geomorphic Response in Humid Tropical Mountains

Wolfgang Römer

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/ 53395

1. Introduction

The tropics encompass a wide variety of environmental conditions sharing high radiation and high temperatures, whilst the timing and annual amount of the rainfall and the seasonal moisture pattern enable the distinction between humid tropical, seasonal wet tropical and arid tropical zones and of the savannah and rain forest environments [40]. As a result of its great areal extent, the tropical zone encompasses a wide range of tectonic regimes, structural and lithological settings and landscapes [38].

The understanding of environmental changes in the tropics appears to be of particular importance as this zone encompasses 35 to 40 per cent of the land surface of the earth and includes about 50 per cent of the world's population [67]. Tropical countries are characterized by a rapid growth in the population and a rapid development of urban areas [6, 45]. This has resulted in increasing demands on fresh water, food, arable land and energy and mineral resources, leading to an increase in per capita consumption and severe environmental degradation.

Tropical ecosystems have been subjected to human interference for thousands of years in the form of traditional land use of many and varied kinds [87, 38]. However, rapid growth in the population and the technical advances of the last 100 years have increased the human impact on physical environments to a much higher degree than the thousands of years of human activity before that. Human interference and environmental change have been rapidly increasing since the mid-twentieth century. Gupta quotes a mean annual loss of rain forest of 174,000 km^2 during the decade 1980 to 1990 [38]. Agriculture and urbanization have modified and transformed large parts of the physical environment and have altered the operation of the geomorphic process-response systems [36]. According to [2], the annual deforestation rate of rain forests ranges from 0.38 to 0.91 per cent in Latin America, Africa and

Southeast Asia with extraordinary high rates of 5.9 per cent in Sumatra and 4.9 per cent in Madagascar. More recent estimates of gross forest-cover loss in the first decade of the 21st century indicate no reversal of these trends [39]. Recent studies indicate an increase in hazards in many regions in the tropics. These appear to be linked to changes in global climate, an accelerated and disorderly process of urbanization, deforestation and the associated loss of hydrological storage capacity, particularly in mountainous domains and to the concentration of settlement activity in potential high-risk areas [44].

However, the severity of their impact varies spatially, and the intensity and course of the response to environment changes varies in the different physiographic domains depending on the nature and severity of the change and the sensitivity of the landscape. Landscapes can be viewed as systems consisting of various interconnected components or subsystems [15]. As the subsystems tend to interact on different spatial and temporal scales via different feedbacks, they may dampen or reinforce the effects of environmental changes depending on the coupling strength existing between the system components. The crossing of thresholds, on the other hand, causes a sudden change in the landscape or in the geomorphic processes, and the mutual operation of feedbacks and thresholds within the geomorphic system tends to induce a complex response to changes in environmental conditions. A consequence of these interactions is that the rate of change of landscapes as well as the severity of the geomorphic response to environmental changes is extremely variable.

1.2. Purpose and objectives

The understanding of developmental patterns in respect of the diverse and complex environmental controls and geomorphic responses in the tropics appears to be an essential prerequisite for the assessment and distinction of climatically-driven and humanly-induced environmental changes as well as for the planning of technological, social and political measures and a sustainable development. The objective of this paper is to demonstrate the role of the geomorphic response to environmental changes on a variety of temporal and spatial scales. However, a comprehensive and balanced view of the wide range of geomorphic process responses to environmental change, their causes and functional relationships is beyond the scope of this study. Instead, this study attempts to concentrate on the response of hillslope processes and their specific controls in the humid tropics, and, in particular, on the stability of hillslopes, on the role of surface wash processes in accelerating soil erosion, and on the role of weathering processes from the point of view of the availability of nutrients in the soils and the geotechnical properties of the weathered materials. A further objective of this study is to highlight some aspects of the role of the long-term development paths of the landscapes as this factor may provide some indication of susceptibility and of a potential response to environmental changes on the part of larger-scale landscape units.

The second chapter encompasses a discussion on the various factors which determine rapid mass movements in humid tropical mountains, and provides an overview of the role of extreme rainfall events in triggering landslides. As the responses of hillslopes are often predisposed by virtue of long-term evolutionary processes, the chapter also includes some case studies on the role of long-term hillslope development and of the effects of susceptibility on landslide hazards in rural and urban areas.

The third chapter is focussed on different aspects of soil erosion, land degradation and soil fertility. The fourth chapter highlights some factors which determine the intrinsic complexity of geomorphic response, interaction between human interferences, the role of changes in the frequency and magnitude of external events and the importance of interdisciplinary approaches.

2. Landsliding and environmental change in tropical mountains

2.1. Landslides in humid tropical environments

Rapid mass movements are important processes in mountainous landscapes and include a wide range of types and sizes of landslides and styles of movement (Table 1). Landslides have been documented in nearly all tectonic settings within the tropical area [80, 87]. However, large single landslides and landslide events encompassing hundreds to thousands of landslides tend to occur most frequently in tectonically active mountain belts and, although with a somewhat lower frequency, in highly elevated pericratonic areas, whilst landslide events appear to be relatively rare in cratonic areas. [14, 31, 38]. The frequent occurrence of landslides in tectonically active mountains and pericratonic areas can be attributed to a specific set of conditions, which include high escarpments, long steep hillslopes in ridge and ravine landscapes, copious rainfalls (high annual rainfall totals and high short-term intensity rainfalls), and highly weathered surface materials [59]. Earthquakes, volcanism and rapidly incising streams are further factors acting as trigger mechanisms for rapid mass movements, particularly in tectonically active mountain ranges [55, 80, 87, 12, 56, 38].

Type of movement	**Regolith**		***Rock***
Type of movement	**Fine-grained**	**Coarse grained**	
Falls	Earth fall	Debris fall	Rock fall
Translational slides	Earth slide	Debris slide	Rock slide
Rotational slides	Earth slump	Debris slump	Earth slump
Flows	Earth flow	Debris flow	Rock flow
Avalanche		Debris avalanche	Rock avalanche

Table 1. Modified after [84] and [75]A simplified classification of rapid mass movements

In many tropical mountains, landslides are part of a highly dynamic hillslope system, which is characterized by high temporal variability, cyclic changes in stability thresholds and temporal tendencies of recovery. This system is superimposed by climatic conditions, the effects exerted by the tectonic regime, lithology and structure, weathering processes and the rate of river incision. Where landsliding is the dominant formative process, changes in the environmental conditions are likely to influence the response of hillslopes by causing changes in the frequency, size and style of landsliding [58, 13, 56]. The off-site effects of large landslide events are the blocking of streams and valleys with landslide debris, and rapid sedimentation in the river channels promotes flooding in the downstream parts of the drainage basins. In a study on the impact of the hurricane Hugo in Puerto Rico it has been estimated that about 81per cent of the material transported out of the drainage basin had been supplied by landslides [47]. As events of a similar magnitude tend to occur once in 10 year the total rate of denudation due to landsliding has been suggested to range to about 164 mm/ka [47]. In Papua New Guinea, earthquakes provide an additional trigger mechanism, and estimates of denudation by landsliding indicate rates of 1000mm/ka [72, 34]. However, our understanding of the long-term contribution of landslides to the total denudation is fragmentary and the extrapolation of denudation rates to larger areas is subject to serious constraints.

Even in the case of shorter time scales, the triggering of slope failures depends on several interconnected and interacting factors. Site-specific factors such as slope, the relative relief, the degree of dissection of the landscape, the density of the vegetation cover, the geotechnical properties, the thickness of the material on the hillslopes and the intensity of land use determine the susceptibility of hillslopes to landsliding. Earthquakes and rainfall amounts are commonly the decisive triggers of landslides [76, 72, 38]. The incidence of landslides is closely associated with the timing, intensity and duration of the rainfall and the antecedent rainfall amounts [78, 1, 33]. These factors control the accumulation of moisture in the regolith and, hence, are associated with the likelihood of high pore water pressures. Hillslope steepness, on the other hand, controls the downslope directed forces and the rate of downslope subsurface water flow whilst the planform of the hillslopes determines the convergence and divergence of the surface and subsurface water flow lines and controls the size of the moisture-supplying area. The thickness of the weathering cover, its weathering degree, layering and textural characteristics, on the other hand, controls the hydrologic behaviour of the slopes and the type of movement. The accumulation of water by subsurface flow and infiltration in the regolith may also control the position of landslides on the hillslopes. In Puerto Rico most hillslopes failed at an elevation range of 600 to 800m because of the supply of water from higher elevated hillslope units [71]. Similar inferences concerning the position of landslides are indicated in studies of [48]. These indicate that slope failures resulting from extreme rainstorms are triggered on the middle or lower slope units of the hillslopes whilst landslides triggered by earthquakes tend to occur on the upper slopes.

Although landslide events are closely associated with high intensity rainfall events or periods of prolonged rainfall, there is no direct link between rainfall amount, rainfall intensity and the number and volume of landslides. Several studies have shown that rainfall events of similar order are capable of triggering different landslide volumes and of producing different landslide occurrences and landslide types [49, 37, 24]. This indicates that different thresholds are involved in the occurrence of landslide episodes. These thresholds are often interconnected by various feedbacks, resulting in complex relationships between the threshold of slope failure and the accumulation of moisture during the rainfall season and antecedent seasons, and the intensity of the rainfall event triggering the landslide [33, 62].

Instability thresholds of this type often depend on a number of site-specific factors. These may be associated with the impact of previous landslides on hillslope form, hillslope hydrology, regolith thickness, and with materials which are inherited from former landslide events.

However, even in tropical mountains with a high relief, steep hillslopes, high rainfalls and a high likelihood of high-pore water pressure, high-intensity landslide events may be rare [27]. Several factors have to work synergistically in order to trigger large-scale landslide events. Apart from bioclimatic conditions and specific structural and tectonic settings, the state of the landscape controls the response of hillslopes to environmental changes as the magnitude-frequency relationship of landslide events depends on the long-term association between overall denudation rates and the renewal of regolith by weathering. Studies on shallow landsliding in Borneo have demonstrated that under a given set of climatic, geological/structural conditions, landsliding is only possible where weathering processes are able to maintain a regolith thickness that is equal to or thicker than the threshold of critical sliding depth [27]. This indicates that on hillslopes where the regolith remains below the thickness necessary to trigger landslides, as the rate of regolith renewal is unable to keep pace with the gross denudation rate and the rate of river incision is too slow to steepen hillslopes towards a new threshold angle for landsliding, at a lower regolith thickness, large landslide events will be rare. However, this type of "regolith-supply limited" or "weathering limited" conditions appears to occur more often in tectonically active mountain belts or in terrains underlain by highly resistant rocks. As high weathering rates are characteristic features in many hot and humid tropical regions, the weathering processes and the geotechnical properties of the weathering mantles are of prime importance for an understanding of the landslide dynamics in tropical mountains.

FThe important role of chemical weathering in the development of impermeable layers in the regolith, and the importance of the highly variable geotechnical properties of the saprolite, soil and colluvium on hillslopes of the Serra do Mar (Brazil) has been emphasized by several authors [32, 46]. Another set of factors is associated with the coupling strength of hillslopes and rivers, the imprints of formerly different climatic conditions including hillslope deposits with variable geotechnical properties as well as the delayed response of hillslopes to the change from dry to humid conditions in the transitional periods from the Pleistocene to Holocene and their influence on the developmental paths of hillslopes [81, 82, 61]. The interaction of these different factors may result in hillslopes which are highly prone to landsliding, though the trigger mechanisms often depend on a site-specific combination of factors as different landscape components of the mountainous terrain are affected.

Human interference in the form of deforestation and urbanization and increased rural land use coupled with infrastructural measures and construction resulting in an oversteepening or undercutting of hillslopes and changes in hillslope hydrology frequently exacerbate the susceptibility of hillslopes to landsliding. The combined sum of the effects of human modifications and alterations in the mountainous domains has increased the socioeconomic impact of landsliding and also the risks in areas with a much lower natural susceptibility to landsliding [41]. Although the contemporary landscape setting, the geotechnical properties of the material, climate and the impact of human alterations determine to a large degree the incidence of mass movements, the triggering of slope failures may be also associated with processes that occurred in the past. The landscapes in which mass movements occur are often a composite of forms and deposits that are genetically linked with actual process dynamics on the hillslopes. The long-term component in studies of mass movements has often been neglected because of the underlying assumption that the current state of a hillslope or landscape is ascertainable from an analysis of the contemporary process-response system. In many cases, this assumption appears to be justified. However, the knowledge of the long-term developmental paths of landscapes may lead to predictions of the susceptibility or sensitivity to react to environmental changes or may lead to predictions on the consequences and impacts of past events which were caused by environmental change.

2.2. Form-process relationships and geomorphic response in south-eastern Brazil

2.2.1. Landsliding in the Serra do Mar

The Serra do Mar forms the elevated passive margin along the Brazilian Atlantic coast and extends from Rio de Janeiro to Santa Catarina with elevations ranging from 700 to about 2000 m. Most of the area consists of folded and faulted metamorphic and plutonic rocks from the Precambrian age and landscapes range from highly elevated plateaus with steep escarpments to dissected ridge and ravine terrains, and muliconvex hilly terrains [3]. The climate is humid tropical with maximum rainfalls in the summer and without marked dry seasons in the winter. The mean annual rainfall totals range from 1500 to 2500 mm, though annual rainfall may rise locally to 4000mm [68]. About 70 percent of the annual rainfall occurs in the summer, which is also characterized by high intensity rainfalls [68]. The potential vegetation along the Atlantic coast is pluvial rain forest, which formed a highly diverse assemblage of trees, shrubs, lianas, tree ferns and epiphytes [42, 89]. Settlement and forest clearance have destroyed much of the original rain forest and estimates indicate that the remaining forests merely constitute 5 per cent of the original coverage [20]. Some local measures have attempted in recent decades to reverse these trends by the afforestation of pines and other tree species [7]. However, the destruction of forests by increasing rural land use and urbanization remains a major problem [53].

Over the last fifty years, the rapid growth of urban areas has resulted in marked changes in hillslope hydrology and the stability of hillslopes. These changes are also associated with an increasing influence of social and economic factors on risks associated with flooding and landsliding [5, 53]. In several regions, hillslopes, villages and urban areas are affected nearly every year by disastrous landslides, and particularly highly dissected terrains with steep hillslopes and highly weathered, thick regolith mantles are prone to landsliding even under undisturbed conditions [22, 19]. Many important roads cross the Serra do Mar and villages, industrial complexes lying at the foot of mountain slopes and escarpments or in basins and valleys are exposed to serious hazards caused by landsliding [53].

However, in many areas of the Serra do Mar, landslides were presumably the most important formative processes since the Late Quaternary period. Landscape evolution was probably non-uniform because of base level changes and climatic changes in the Quaternary, and the intensity of landsliding is likely to have varied as a function of climatic conditions and periods of river incision [17, 18, 61]. The various controls are often genetically linked with the sensitivity to landsliding and concern several aspects of the long-term development of hillslopes.

2.2.2. Some aspects of the role of long-term process-response systems

Predictions about the way hillslopes tend to respond to changes in environmental conditions may be gained from studies of the long-term development of hillslopes. Of particular importance in this respect are the roles of inherited materials and the effects of a differing hillslope-channel coupling strength. Inherited materials may provide information on the processes that have acted during past environmental changes. This enables predictions on the vulnerability of hillslopes with respect to specific slope processes or supports regional surveys on hazards with respect to the geotechnical properties of soils, weathering layers or colluvial deposits. In the Serra do Mar, several lines of evidence suggest that mass movements have occurred alongside periods of intense colluvial accumulation in the Pleistocene and early Holocene [8, 83, 54].

The accumulation of the colluvium occurred as a result of relatively dry climatic conditions in the Pleistocene and the higher frequency in the magnitude of storm events in the early Holocene. The areal extent of land surfaces currently underlain by colluvial deposits in São Paulo is estimated to be in the range of 50 per cent [30]. Today, the knowledge of the complex stratigraphy, the geotechnical properties and of the distribution pattern of the colluvial deposits is important as these deposits are often associated with debris flow hazards which often occur after vegetation clearance [46, 19].

The tendency of landscapes to react to environmental changes by landsliding may be also indicated in the hillslope development paths. Many ridge and ravine landscapes in the Serra do Mar encompass steep hillslopes, which are covered by a moderately thick weathering mantle. In southern Sao Paulo, this terrain-type is underlain by mica schists and phyllites and often exhibits summit heights, which are dictated by the steepness of the valley-side slopes and by the spacing of the rivers [61]. These terrains are characterized by v-shaped valleys and straight valley side-slope profiles with a relative relief of 120 to 200m. The valley side slopes exhibit a narrow range of slope angles ranging from 26° to 34° for the mean slope angle and the mean maximum segment slope angle. A consequence of the geometric control of summit height by slope angle and valley spacing is that areas with similar drainage density and stream spacings are characterized by accordant summit heights [61, 60]. Such an adjustment is unlikely to result from short-term changes because the incision of the drainage net, the fixation of rivers in valleys and the development of steep valley side slopes with a mean relative relief of 120 to 200m are unlikely to have been accomplished within a period that is shorter than 10^5 years. Conversely, in order to maintain the geometrical expression, the hillslope processes and the hillslope-channel coupling have had to operate throughout the Holocene period.

Horizon	clay	silt	sand	cohesion	friction angle
units		weight- per cent		kPa	degree
B	54.3	26.4	19.3	10.5	31.5
B	47.2	23.8	29.0	6.6	30.2
B	67.8	15.3	16.9	13.7	29.9
T	28.8	19.1	44.9	1.9	30.4
S	20.7	28.5	50.8	0.9	38.0

Table 2. Geotechnical properties of the regolith on mica schistsB- textured B-HorizonT – transitional zone between B-Horizon and SaproliteS – SaproliteShear strength was determined by direct shear tests after consolidation to allow excess of pore pressures

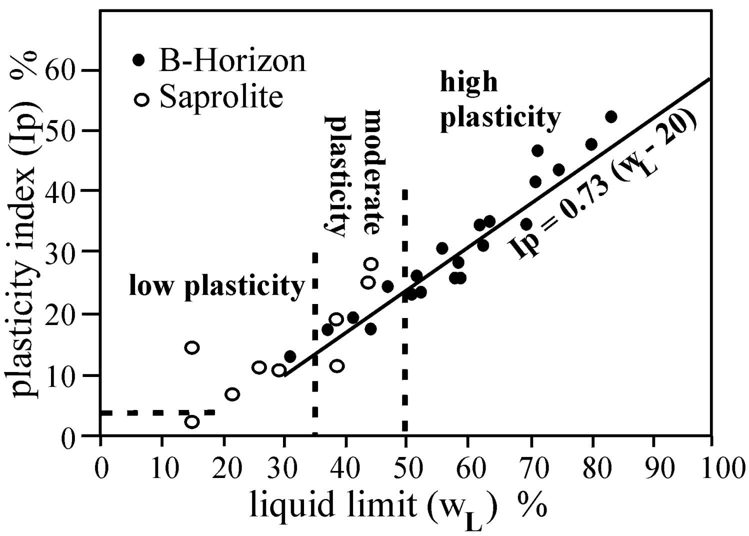

Figure 1. Range of plasticity index and liquid limits of B-Horizons and saprolitic weathering products of mica schists (modified after [61]).

Most valley side slopes in the area are covered by numerous landslide scars and landslide deposits of various ages indicating that the important formative hillslope process is shallow landsliding. The valley side slopes are covered by red-yellow podzolic soils, which show marked differences in the geotechnical properties of the soil horizons (Table 2, Figure 1, Figure 2). Particularly, at the contact of the B-Horizon to the transitional layer the decline of the cohesion tends to facilitate the development of a subsurface plane of failure. This is also indicated in the location of slip surfaces of relatively recent landslides, which occurred at a depth of 0.9 to 1.2m below the surface. This depth coincides roughly with the depth of the transitional layer.

Figure 2. Shallow translational landslide and earthflow which resulted from a single rainstorm and the high moisture content in the regolith. (Photo Römer).

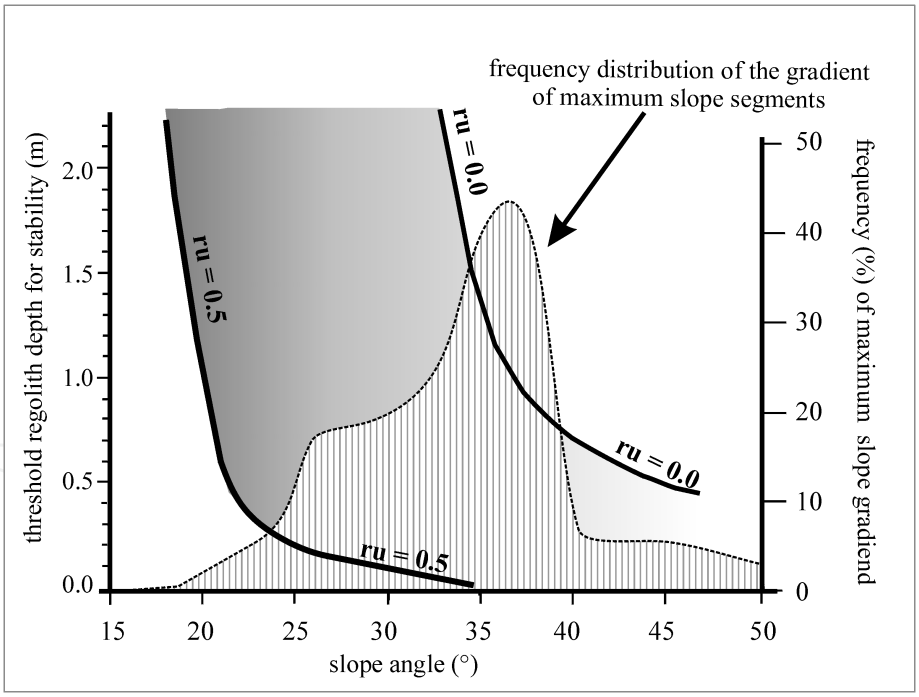

Figure 3. Limiting regolith thickness for a safety factor of slope stability (F =1.0) as a function of pore pressure ratio (ru) and the distribution of maximum segment slope angles on hillslopes underlain by mica schists. The bulk unit weight of the regolith ($\gamma = \rho$ g) = 17.4 kPa, the cohesion (c) = 1.9 kPa, and the friction angle (φ) = 30.4°. The limiting regolith thickness has been calculated by using the infinite model for translational landslides [11]. The factor of safety (F) has been calculated by $F = c + (\gamma d \cos^2\alpha - ru\ \gamma d) \tan\varphi / (\gamma d \sin\alpha \cos\alpha)$ with d = regolith depth (m), α = slope angle (°), $ru = \rho_w g\ d_w \cos^2\alpha / \gamma d$; ρ_w = density of the water (kg m^{-3}), g = gravitational acceleration (9.81 m s^{-2}), d_w = vertical height of the water table above the slide plane (modified after [61]).

A back calculation of the slope failures indicates that most valley side slopes are stable in a dry state, but tend to become instable at pore pressure ratios of 0.1 to 0.5 (Fig. 3). The close coincidences between the slope angle of the maximum segments, the threshold slope angle for failure and the threshold regolith depth indicates that the long-term formative process on the hillslopes is landsliding. This implies that as long as river incision enables the maintenance of steep slope angles, all hillslopes are likely to be affected by reoccurring landslides in the same places as long as weathering processes supply enough material to cross the threshold regolith thickness for slope failure with respect to the slope angle and the geotechnical properties again. However, the study also indicates that the form-process relationship is associated with events that are characterized by a low frequency and high magnitude reoccurring at temporal scales of several decades to centuries rather than being the result of continuously acting formative processes. It is easy to suppose that landscapes originating from such a process-response system where hillslope evolution resulted in the development of slopes close to the threshold of slope failure tend to respond violently to environmental changes and human interferences.

2.2.3. Extreme rainfall events and landsliding

Apart from human interferences, the high relative relief, steep hillslopes and the thick weathering layers, the most decisive factor contributing to landsliding is high rainfall. In the Serra do Mar landslide events are likely to occur independently of antecedent rainfalls and regardless of the vegetation cover and human interferences where rainfall exceeds 250 mm/24h [37]. Furthermore, the occurrence of landslides is promoted on most hillslopes which are steeper than 40% [32].

Since 1928, the Serra do Mar has been affected by about 25 to 30 extreme landslide disasters due to intense rainfall events, which have caused thousands of deaths and extensive damage to the infrastructure and various structures, though many smaller landslide events resulting in various degrees of damage tend to occur every year [23, 32, 19]. In the period from 1988 to 2000, the number of landslide fatalities in Santa Catarina, São Paulo, Rio de Janeiro, Minas Gerais, Bahia and Pernambuco averaged between 13 to 50 and locally, in coastal areas, between 51 to 364 [5]. About 85 percent of the landslide disasters occurred during the summer season, and most of the larger events that are documented in the scientific literature concentrate on the period between December and March [46, 53, 19, 68]. However, an extraordinary rainfall event was recorded in the winter of 2004. The event was caused by a cold frontal passage which became stationary in the coastal area of south-eastern Brazil [68]. Once the initially cold post-frontal anticyclone had acquired barotropic equivalent characteristics, a persistent southerly and south-easterly flow of winds became established which was impeded along the rise of the Serra do Mar causing advection and high rainfall. The event caused serious flooding and landslides along the coastal region of São Paulo [68].

Although any generalization of the functional relationships between the incidence, type and rate of movements may be overridden by local site-specific factors, the results of studies on landsliding in south-eastern Brazil suggest that most landslides occur in the late rainy season when the accumulation of moisture in the regolith has attained a temporal maximum [1, 19]. The increase in moisture in the regolith causes a rise of the pore water pressure and hence, results in a lowering of the threshold rainfall intensity necessary to trigger landslides. However, the triggering of landslides is also a function of slope angle, slope form and of the material on the hillslopes. On steep hillslopes with a relatively thin weathering cover, shallow landslides appear to occur mostly on the middle and upper hillslope segments. This landslide type is triggered during the wet season by rainfalls of long duration and moderate intensity or at the end of the wet season during heavy storms [25]. Failure may result from the increase in pore-water pressure or from the elimination of soil-suction and the reduction of the apparent cohesion [88, 46]. Debris flows, on the other hand, are triggered in the late rain season in hillslope hollows, on the lower slope segments and on steep hillslopes when the regolith is saturated with water. The incidence of debris flows is associated with high-intensity rainfall occurring in the late rain season and appears to be strongly associated with a destruction of the vegetation cover [19].

2.2.4. Urbanization, environmental change and landslide hazards

The rapidly growing population in the cities in south-eastern Brazil, the unplanned growth of urban areas and the inability to house the growing number of people have resulted in human occupation of geologically and topographically hazardous terrains, which are often characterized by an inappropriate infrastructure and precarious residences [5, 53]. The combined sum of these changes has also increased the risk of landsliding even in urban areas with a much lower natural susceptibility to landsliding.

The areal extent of the alterations in urban areas has often resulted in a reinforcement of the intensity of the hillslope processes as the affected subsystems tend to work synergistically. Urbanization is associated with a sealing of the surface, a lowering of the infiltration rate, a reduction of the water storage, and an increase in surface runoff. Soil erosion resulting from vegetation-clearing measures causes the development of gullies. Large gullies tend to affect the flow pattern of rivers by decreasing the baseflow whilst the stormflow is increased [21]. This leads to more intense floods and more events where hillslopes are undercut by rivers. Deforestation of hillslopes, on the other hand, tends to increase the likelihood of debris flows as a function of the decrease in root strength [19]. Road cuts or excavations destabilize hillslopes as the material supporting the regolith or rocks on the slopes is removed. Human settlement along streams and in valleys with houses perched on steep valley side slopes next to rivers increases the risk of disasters as hillslopes are undercut by rivers. The destruction caused during a landslide event also varies with the type, size and rate of movements. Disastrous effects are often associated with large debris flows which are induced in the late rainy season by heavy rainfalls once the material on the hillslopes has become saturated with water. During the 2011 landslide disaster in the vicinity of Rio de Janeiro, cascades of mudflows and debris flows destroyed houses and buildings. As the slipped debris moved downslope, water contribution from the surrounding areas resulted in an increased fluidization of the debris, which moved rapidly into the valleys and caused an increase in sediment load and in the flooding. Flooding and landsliding resulted from unusually persistent rain and an interspersed extreme storm rainfall event which had a devastating impact along the south-eastern Brazilian coast.

3. Soil erosion and land degradation

3.1. Soil erosion in humid tropical environments

Over the last four decades, deforestation and human interference with the environment have increased in nearly all tropical rain forest environments around the world [39]. The impact has caused increasing land degradation and is often accompanied by changes in the hydrologic regime, severe soil erosion and a declining productivity of cultivated areas [87, 36]. Recent developments in agricultural techniques, the increased use of agricultural machinery and the replacement of subsistence-orientated agriculture by export-orientated agriculture have resulted in a rapidly increasing and unfavourable change in environmental conditions.

Most studies on the role of soil erosion in rain-forest environments indicate that soil erosion in undisturbed rain forests rarely exceeds rates of 1t ha^{-1} a^{-1} as the canopy and understorey protect the soil from the impact of raindrops [59, 38]. In rainforests, much of the rainfall is intercepted and evaporated in the canopy and understorey, and permeable litter layers support high infiltration rates. Consequently, only a small fraction of the rain water remains available for overland flow [73]. The litter cover on the surface on the other hand, tends to dampen the forces of the impact of heavy raindrops. This cover is highly permeable. The permeability results from macro-pores provided by roots, which reduce the generation of erosive runoff [59]. Under natural conditions, with a continuous cover of litter layers, the water movement occurs as over litter-layer flow and as root litter flow in pores and in shallow subsurface pipes within the root-litter carpet [19]. This water flow is mostly highly discontinuous shallow unconcentrated overland flow with a low erosive power, except in hillslope hollows, where the convergence of surface water flow lines tends to promote a concentrated overland flow.

Disturbance of vegetation in rain forest environments appear to have serious effects on erosion rates as the spatial variation in the intensity and frequency of large rainfall events tends to be higher than in savannah environments [87]. The loss of ground vegetation and litter reduces the amount of soil organic matter, which diminishes the aggregate stability and increases the vulnerability of the soil to raindrop impact and the likelihood of soil crusting [29, 36]. The destruction of the soil aggregates by raindrop impact and the formation of a fine grained crust on the soil surface tend to impede infiltration. During rain bursts, this causes a rapid increase in overland flow and favours the development of rills and gullies. Soil erosion and changes in the physical characteristics of the upper soil horizon are not the only effects of vegetation disturbance. The nutrient cycle is markedly changed as nutrients are lost by soil erosion, by leaching of the soil and by the removal of nutrients which were formerly stored in the vegetation [59]. As tropical rainforests are unable to sustain their nutrient base without sufficient vegetation, the combined effects of vegetation destruction and soil erosion tend to result in a marked depletion of the soils and in a reduction in the biodiversity [86]. The complex relationships between vegetation destruction, agricultural use, soil erosion and loss in soil fertility has been documented from several areas in the tropics, and the interaction between socioeconomic and ecologic factors appears to be of major importance.

3.2. Land degradation and soil erosion in humid tropical mountains

Land degradation encompasses various processes ranging from disturbance of the vegetation to biodegradation of the humus and litter and the deterioration of soil quality. These changes are functionally associated with the productive capacity of the soils. Measurements of soil erosion rates in tropical environments are often highly variable. Calculated erosion rates range from 0.2 to 10 t ha^{-1} a^{-1} for rain forest environments in Guyana, Brazil and the Ivory Coast [34]. In the case of erosion in the Ivory Coast, rates increased on slopes with an inclination of 6% from 0.1 to 90 t ha^{-1} a^{-1} (crop cover) and 108 to 170t ha^{-1} a^{-1} (barren) [35, p. 113].

However, a quantitative assessment of the on-site and off-site impacts of soil erosion on the landscape remains a challenge because of the wide variety of environments and the relatively small data basis. Short-term soil erosion measurements from small test-plots do not always provide representative rates for hillslopes and the extrapolation of these erosion rates to larger areas is prone to errors as physical properties of the soils, the vegetation cover and parameters such as slope length, slope steepness tend to be highly variable. A further factor is the length of the measurement period. Extreme rainfall events are highly variable in terms of space and time and hence, are often not recorded. Rainfall erosivity modelling, on the other hand, provides information on the likelihood of soil erosion, whilst the calculation of erosion rates is complicated by the high number of interacting variables [74].

Although soil erosion rates imply a continuous loss of soil, the erosive processes are triggered by separate rainfall events, and the impact of singular rainfall events on soil losses may override all preceding soil erosion rates calculated. The important role of extreme rainfall events on soil losses and on sedimentation rates on the valley floors has been documented in the drainage basin of the Tubarão river (southern Brazil) [8]. In this area, a total amount of 400mm rainfall (three days) was recorded. This event caused serious soil erosion and resulted in the accumulation of a 30 to 60 cm thick pile of sediment on the valley floor. This implies that meaningful erosion rates can be only deduced when erosion measurements are supplemented by studies of the sediment balance in the drainage basins [8]. Studies on erosion/sedimentation events in drainage basins over a longer range of time (10^1 to 10^4 years). On the other hand, are rare and often confronted with the problem of distinguishing between human induced changes and natural environmental changes. The latter applies, in particular, to cases where landforms are polygenetic and are caused by rare, high magnitude events rather than by continuous processes. However, accelerated soil erosion as a result of the increased agriculture and the destruction of the vegetation cover has been recorded in the drainage basin of the Ribeira River [9]. The drainage area of the Ribeira river covers an area of 24,200 km^2. Since the 19th century, land use has increased from the equivalent of a few per cent to an area covering about 5000 km^2 in the year 1979 [9]. The Ribeira drainage basin is underlain by deeply weathered metamorphic and plutonic rocks. Most of the lower valley-side slope segments and small hillslope hollows are covered with pedogenetically transformed, clay-rich colluvial sediments of the late Pleistocene and early Holocene age, which have been deposited above the "in situ" formed saprolite [8, 63]. However, in areas where the original forest has been replaced by shrubs or agricultural land use, the colluvial soils exhibit truncated soil horizons whilst gully incision into the saprolite has given rise to the development of shallow hillslope hollows and deeply dissected hillslopes (Figure 4, 5). Most of the eroded fine-grained material has been transported to the rivers and on to the flat valley floors [9]. In the drainage basin of the Ribeira River, the high influx of sediment into the valleys and onto the flat valley floors has resulted in the accumulation of 5 to 6 m thick clayey sediments, which are rich in organic matter. In the area surrounding the village of Sete Baras, 5.8m thick sediments have been deposited above the river gravel of the Ribeira River [9]. Radiocarbon age determination of the organic matter of these deposits from a layer located just above the river gravel indicates that the material above the river gravel is younger than 300 years [9]. This provides an approximate age for the start of the increased erosion episode resulting from humanly induced disturbance of the vegetation. The geomorphic analysis of erosional forms, of the degradation of the colluvial soils, and of the start of the increased vegetation clearance indicates that soil erosion has contributed to a loss of soil $170 m^3 ha^{-1} a^{-1}$ or of $235 t ha^{-1} a^{-1}$ in the last 130 years [10, p. 65].

Figure 4. Accumulation of colluvium in a hillslope hollow in the drainage basin of the Jacupiranga River, which is a tributary of the Ribeira River. The colluvium has been deposited on the saprolite of the mica schists/phyllites. The colluvium was formed in the Pleistocene as a result of less dense vegetation cover and drier climatic conditions. (Photo Römer)

However, the amount of soil loss on the valley-side slopes appears to have varied in different geomorphic settings depending on the relative relief, the physical properties of the regolith cover and the process domains. Studies on ultramafic rocks in the Jacupiranga Alkaline Complex, which is part of the Ribeira drainage basin provided no evidence of an increase in soil erosion even on steep hillslopes although, mining and cultivation of tea and bananas resulted in extensive destruction of the original forest cover [57]. Hillslope development in this area is primarily controlled by chemical denudation in the highly permeable weathering mantles and, to a lesser degree, by slow mass movements, whilst surface wash is limited by the lack of a significant overland flow [60]. Nevertheless, the role of the destruction of the vegetation cover cannot be underestimated as leaching processes operate at high rates in the tropics and tend to remove nutrients from the upper soil horizon, possibly reducing the fertility of the soils.

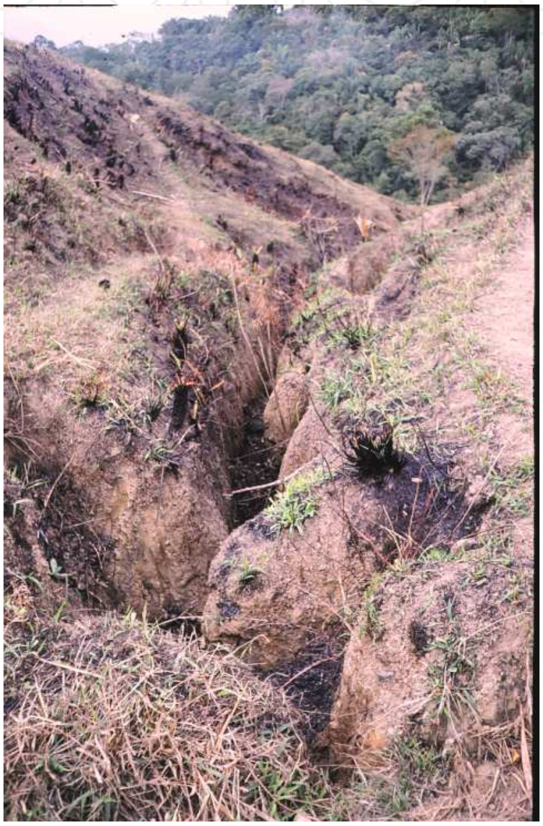

Figure 5. Piping and gully erosion in colluvium resulting from high rainfalls and vegetation disturbance in multiconvex hilly terrain in south-eastern Brazil at Jacupiranga. (Photo Römer)

3.3. Weathering and nutrient cycle

In tropical rainforests, the biomass above and below the ground contains most of the mineral nutrients. The maintenance of the nutrient level in the soil depends on the continuous cycling of the nutrients in the canopy and on the rate of decay of organic matter in the litter-layer. The latter is controlled by biological decomposition by invertebrates, and by the physico-chemical processes responsible for the release of nutrients in the upper soil horizons [59, 67]. However, the functional dependencies in the nutrient cycle appear to be stronger in soils with a low nutrient storage and low fertility and weaker in more fertile soils. Once the vegetation cover is destroyed, the supply of organic matter and the formation of the new litter on the soil surface is slowed down whilst the breakdown of the organic matter is accelerated by solar radiation [87, p. 277].

Although the physico-chemical processes controlling the productivity and fertility of the soils and the turnovers of the nutrients are not completely understood, several lines of evidence suggest that the degree of weathering and textural characteristics of the soil play an important role in the nutrient cycle. High weathering rates result in excessive base-leaching and a low pH, creating a decline in base saturation, loss of major cations and a decrease in the cation-exchange capacity [66]. This promotes the occurrence of free iron and aluminium either in the clay complexes or as amorphous iron and aluminium oxides or hydroxides in the weathering layers. As amorphous iron and aluminium oxides readily absorb, phosphorus tropical soils with a low pH are often characterized by a high phosphorus fixation capacity, resulting in a phosphorus deficiency [85, 59]. According to studies in the Amazon of Brazil the fixation of phosphorus rather than the overall nutrient decline appears in many cases to be the cause of the decline in pasture productivity [69].

Soil erosion and intense leaching in soils are responsible for several problems concerning productivity in agricultural land use. In a case study carried out in Rwanda several green farming methods applied to highly degraded soils failed to restore the fertility of the soils [77]. Improved fallow, mulching, green manure and the use of compost and cow dung were not sufficient to maintain the nutrient levels in the soil as the rapid decomposition of the organic matter at the start of the rain season resulted in a release and leaching of high amounts of nitrogen and a rapid reduction in the fertility of the soils [77]. From the point of view of the sustainability any agricultural strategies being considered, the materials used for fertilizing the soils have to be inexpensive and available from regional or local resources. The improvement of the physico-chemical properties of highly degraded soils, on the other hand, depends on several-site specific and soil-specific factors, and additional information is frequently required on the dynamics of the soil. Important improvements usually involve increasing the pH. This reduces phosphorus fixation, the disintegration of chlorite structures and reduces antagonistic effects in cation exchange.

However, any application of material has to maintain the slow dissolution of cations from dissolved minerals and has to inhibit silica dissolution which often involves an increase in pH and results in an increase in the disintegration rate of chlorite structures [77]. In relation to the requirements specified in Rwanda, several tests with calcium carbonate, travertine and volcanic tephra indicated that the combined application of cow dung and tephra represents a measure capable of improving the agricultural capacity of the degraded soils [77]. However, soil erosion, nutrient cycles and soil fertility are highly interrelated and depend often on specific local and regional factors. Although quantitative data of soil erosion rates and depletion rates are important for the implementation of effective soil conservation measures, socio-economic factors and the understanding of the traditional/cultural background appear to be of equal importance because many conservation strategies may be impractical or too expensive or are rejected as a result of limited access to the technologies required.

4. Conclusion

Over the period of the last fifty years, most tropical mountains have experienced marked changes in their environmental conditions due to the high rate of deforestation, rural land use and urban growth. These changes have often reinforced hillslope processes such as soil erosion and landsliding and have also resulted in an increase of geomorphic hazards, even in areas with a previously lower susceptibility to soil erosion or landsliding. Increased rates of soil erosion and landsliding have been documented from regions where large areas are affected by human intervention and hillslope processes are highly interdependent and tend to reinforce each other. The changes have not only affected the hillslope system but have also influenced other subsystems of the geomorphic/ecological system, which has resulted in the coupling of different responses similar to "chain reactions". Such "chain reactions" appear to occur frequently when the urban fringe expands into mountainous terrains [38]. Urbanisation and deforestation increase the runoff and hence induce soil erosion whilst the increase in storm runoff results in the undercutting of hillslopes and landsliding, thereby increasing the supply of material to the rivers, which in turn, increases the likelihood of flooding.

However, the geomorphic response displays a high degree of spatial and temporal variability. Under similar geologic and bioclimatic settings, some landscapes tend to react rapidly to ongoing environmental changes whilst others tend to absorb the effects of environmental change, as the reaction is delayed or dampened in the various interconnected geomorphic/ecological subsystems. Several factors contribute to the differences in the geomorphic response. The current state of the landscape, the degree of human modification of the landscape, the magnitude of climatically-driven events and the differing coupling strength between the long-term evolution of the hillslope system and the current hillslope processes. As geomorphic processes are triggered by separate events, the response to changes is a function of the magnitude and frequency of exogenous or endogenous events. With respect to rainfall-triggered events, the incidence of hillslope processes is often controlled by thresholds. However, these thresholds are continuously altered by human interference in the landscape, thereby increasing the risks of soil-erosion hazard and landsliding, though this interference is often necessary in that it benefits economic progress and advancement.

Disastrous landslide events are often closely associated with the expansion of the urban fringes into hilly and mountainous areas, and settlement activity in these areas has often resulted in the unsuitable modification of hillslopes, which, in turn, has increased susceptibility to mass movements [38, 53]. Although most of the recent landslide disasters are primarily controlled by geological, structural and environmental factors as well as by human interference, slope failure is often predisposed as a consequence of long-term evolutionary processes on the hillslopes. The dynamic coupling of existing controls and long-term evolutionary processes may result in the lowering of crucial thresholds. This includes the reduction of the shear strength by weathering processes, and the increase of shear stresses on the hillslopes caused by small subtle changes in slope angle and hydrology.

The intensity of human impact on tropical environments is documented in the large areas that have been subjected to deforestation. The impact has affected the geomorphic process-response system, the nutrient cycles, and biodiversity. Recent studies have shown that there is no reversal in the overall trend of tropical deforestation, though the rates of deforestation vary strongly from one decade to another and from one country to another, depending also on the methods used to assess deforestation [2, 28, 79, 39]. Estimates of the world-wide contribution of deforestation in the tropics to carbon emissions indicate a total emission of 810 $*10^6$ metric tonnes/year (period 2000 to 2005) excluding carbon emissions from logging, peatlands drainage and burning, and forest recovery [39]. However, the contribution of carbon emissions from tropical deforestation to global climatic change remains obscure as the turnover rates and recovery rates are related to various factors and the interaction between these factors is not completely understood [35, 38]. This applies also to the effects of global climatic change on the geomorphic process-response system as changes in magnitude and frequency of geomorphic processes depend also on all other environmental changes. Predictions on future climatic development trends in the tropics suggest an increase in summer monsoon and a decrease in summer rainfalls in Central America and Mexico and an increase in the number of cyclones, tropical storms and hurricanes [44]. However, human interference and climatic change often act simultaneously. This complicates predictions of crucial thresholds and the establishment of relationships between landsliding and large soil erosion events and the spatial distribution and the seasonal and annual variability of rainfall. The temporal clustering of landslide events in some regions, on the other hand, appears to indicate some associations. In Kenya landsliding was closely associated with the occurrence of El Niňo circulation [52]. In southern America, on the other hand, the temporal pattern of landslide events appears to coincide with the ENSO climatic cycle. However, hillslope processes are characterized by an intrinsic complexity. Many factors appear to be capable of causing changes in both frequency and magnitude on different spatial and temporal scales.

Studies on deforestation rates in several countries of humid tropical Africa have shown that the rate of forest destruction is not only a result of the growth in population but depends also on macro-economic changes. Apart from dependence on international market prices, the extent of the agricultural area appears to depend directly and indirectly on factors such as public investment, monetary policy and exchange-rate policy, urban income levels, fertilizer subsidies, and rural-to-urban and urban-to-rural migration [50, 64, 65]. With respect to the issue of sustainable development, socioeconomic factors must also be considered.

A significant statistical relationship has been determined between the decline of the cocoa and coffee prices and subsiding governmental input, which has forced farmers in Cameroon to expand their food and crop cultivation into forested areas [51]. International prices and demands on agricultural resources, on the other hand, often result in an expansion of agricultural areas at the expense of rain forests. An example is the expansion of agricultural areas for soybean production and the increase in cultivated pastures in Brazil, which resulted from the growing importance of cattle ranching. The expansion of soybean cultivation resulted in extensive clearance of savannah forests and of tropical forests and is noted to be the second most important driver of deforestation after ranching [43].

Socio-economic factors also play an important role in establishing new methods in agriculture to improve environmental quality. Financial aspects, work expenditure, the availability of resources necessary for carrying out improvements and the consideration of traditional agricultural techniques may determine the success of sustainable developments. Socio-economic aspects are also important in the mitigation of hazards in urban areas. Hillslopes prone to landsliding are often occupied as a result of the unplanned growth of cities and increases in rent and the declining availability of land for building in the cities to house the growing population [26, 4].

The complex interaction of socio-economic, biological, geological and geomorphic aspects indicates that sustainable development requires an interdisciplinary approach. With respect to environmental planning and sustainable development in the tropics, geomorphic studies of hillslope processes may contribute to unravelling the intrinsic complexity of various hillslope hazards. This takes in a multitude of objectives, which range from assessment of the severity of influences impacting on the environment, determination of the dominant processes and hazards, assessment of the vulnerability of specific sites, determination of external triggers and predictions of events which have no historically recorded precedent.

Author details

Wolfgang Römer*

Address all correspondence to: wroemer@geo.rwth-aachen.de

Department of Geography, RWTH (University) Aachen, Germany

References

[1] Ab´ Saber., A. N. (1988). A Serra do Mar na Região de Cabatão: avalanches de Janeiro de1985. *Ab´Saber, A.N. [Ed.]. A Ruptura do Equilibrio Ecologico na Serra de Paranapiacaba E.A. Polição Industrial, Brazil*, 74-116.

[2] Achard, F., Eva, H. D., Stibig, H., , J., Mayaux, P., Gallego, J., Richards, T., Malingreau, J., & , P. (2002). Determination of deforestation rates of the world´s humid tropical forests. *Science*, 297, 999-1002.

[3] Almeida, F. F. M., de Hasui, Y., de Brito, Neves. B. B., & Fuck, R. A. (1981). Brazilian structural provinces: an introduction. *Earth-Science Reviews*, 17, 1-30.

[4] Araki, R., & Nunes, L. H. (2008). Vulnerability associated with anthropogenic factors in Guarujá City [São Paulo, Brazil] from 1965 to 2001. *Terrae-Geoscience,Geography, Environment*, 3(1), 40-45.

[5] Augusto Filho, O. (2006). An approach to mitigation of landslide hazards in a slum area in São Paulo city, Brazil. *IAEG Paper*, 258, 1-7.

[6] Beckel, L. (2001). Megacities. *Geospace Verlag, Salzburg [Austria]*.

[7] Behling, H., & Pillar de Patta, V. (2007). Late Quaternary vegetation, biodiversity and fire dynamics on the southern Brazilian highland and their implication for conservation and management of modern Araucaria forest and grassland ecosystems. *Philos. Trans. Soc. London B, Biol. Science*, 362, 243-251.

[8] Bigarella, J. J., & Becker, R. D. (1975). International Symposium on the Quaternary. *Bol. Paran. Geoscienc. 33, Curitiba*, 1-307.

[9] Bork, H. R, & Rohdenburg, H. (1985). Studien zur jungquartären Geomorphodynamik in der subtropischen Höhenstufe Südbrasiliens. *Zentralblatt für Geologie und Paläontologie, Teil*, 1(11/12), 1455-1469.

[10] Bork, H. R., & Hensel, H. (2006). Blätter in der Tiefe am Rio Ribeira [Brasilien]. *Bork, H.-R.. Landschaften der Erde unter dem Einfluss des Menschen. Wissenschaftliche Buchgesellschaft [WBG] Darmstadt*, 63-65.

[11] Bromhead, E. N. (1992). The stability of slopes. *Blackie Academic & Professional, London*.

[12] Bull, W. B. (2007). Tectonic Geomorphology of Mountains. *Blackwell, Singapore*.

[13] Chatterjea, K. (1994). Dynamics of fluvial and slope processes in the changing geomorphic environment of Singapore. *Earth Surface Processes and Landforms*, 19, 585-607.

[14] Chen, H., & Lee, C. F. (2005). Geohazards of slope mass movement and its prevention in Hong Kong. *Engineering Geology*, 76, 3-25.

[15] Chorley, R., Schumm, S. A., & Sugden, D. E. (1984). Geomorphology. *Methuen & Co Ltd., London*.

[16] Coelho-Netto, A. L. (1987). Overlandflow production in a tropical rainforest catchment: The role of litter cover. *Catena*, 14, 213-231.

[17] Coelho-Netto, A. L. (1999). Catastrophic landscape evolution in a humid tropical region [SE-Brazil]: inheritances from tectonic, climatic and land use induced changes. *Geografia Fisica e Dinamica Quaternaria*, III(3), 21-48.

[18] Coelho-Netto, A. L., Avelar, A. S., Fernandes, M. C., & Lacerda, W. A. (2007). Landslide suceptibility in a mountainous geoecosystem, Tijuca Massif, Rio de Janeiro: The role of morphometric subdivision of the terrain. *Geomorpholgy*, 87, 120-131.

[19] Coelho-Netto, A. L., Avelar, A. S., & Lacerda, W. A. (2009). Landslides and Disasters in southeastern and southern Brazil. *Latrubesse, E.M. Natural Hazards and Human Exacerbated Disasters in Latin America. Development in Earth Surface Processes*, 13, 223 -243 .

[20] Consórció Mata Atlántica. The Mata Atlántica Biosphere Reserve Plan of Action [Reserva da Biosfera da Mata Atlántica Plano de Acão]. *São Paulo, Brazil*.

[21] Costa, F. M., Bacellar, L., & de , A. P. (2007). Analysis of the influence of gully erosion in the flow pattern of catchment streams, Southeastern Brazil. *Catena*, 69, 230-238.

[22] Cruz, O. (2000). Studies on the geomorphic processes of overland flow and mass movements in the Brazilian geomorphology. *Revista Brasileira de Geosciécias*, 30, 500-503.

[23] Da Costa Nunes, A. J., Costa Couto., A. M. M., Hunt, F., & Hunt, R. E. (1979). Landslides of Brazil. *Voight, B. [Ed.]. Rockslides and Avalanches, 2- Engineering sites. Developments in geotechnical engineering 14B, Elsevier, Amsterdam*, 419-446.

[24] Dai, F. C., & Lee, C. F. (2001). Frequency-volume relation and prediction of rainfall-induced landslides. *Engineering Geology*, 59, 155-166.

[25] De Ploey, J., & Cruz, O. (1979). Landslides in the Serra do Mar, Brazil. *Catena*, 6, 111-122.

[26] Dikau, R., & Weichselgartner, J. (2005). Der unruhige Planet. Der Mensch und die Naturgewalten. *Wissenschaftliche Buchgesellschaft [WBG] Darmstadt*.

[27] Dykes, A. P. (2002). Weathering-limited rainfall-triggered shallow mass movements in undisturbed steepland tropical rainforest. *Geomorphology*, 46, 73-93.

[28] FAO. (2006). GlobalForest Resources Assessment 2005- Progress towards sustainable forest management. *FAO Forestry Paper No. 147. Rome*.

[29] Farres, P. J. (1987). The dynamics of rainsplash erosion and the role of aggregate stability. *Catena*, 14, 119-130.

[30] Ferreira, R. C., & Monteiro, L. B. (1985). Identification and evaluation of collapsibility of colluvial soils that occur in the São Paulo State. *First International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils. Brasilia Vol.I Brasilia*, 269-280.

[31] Fort, M., Cossart, E., & Arnaud-Fassetta, G. (2010). Catastrophic landslides and sedimentary budgets. *Alcántara-Ayaly, I.; Goudie, A. [Eds.]. Geomorphological Hazards and Disaster Prevention. Cambridge University Press, Cambridge*, 75-85.

[32] Furian, S., Barbiéro, L., & Boulet, R. (1999). Organisation of the soil mantle in tropical southeastern Brazil [Serra di Mar] in relation to landslides processes. *Catena*, 38, 65-83.

[33] Gabet, E. J., Burbank, D. W., & Putkonen, J. K. (2004). Rainfall thresholds for landsliding in the Himalayas of Nepal. *Geomorphology*, 63, 131-143.

[34] Goudie, A. (1995). The changing earth. *Blackwell, Oxford*.

[35] Goudie, A. (2006). The human impact on the natural environment. *6th Ed., Blackwell Publ., Oxford*.

[36] Goudie, A. S., & Boardman, J. (2010). Soil erosion. *Alcántara-Ayaly, I.; Goudie, A. [Eds.]. Geomorphological Hazards and Disaster Prevention. Cambridge University Press, Cambridge*, 177-188.

[37] Guidicini, G., & Iwasa, O. Y. (1977). Tentative correlation between rainfall and landslides in a humid tropical environment. *Symp. on Landslides & Other Mass Movement, Praga, IAEG Bulletin*, 16, 13-20.

[38] Gupta, A. (2011). Tropical Geomorphology. *Cambridge Univ. Press, Cambridge*.

[39] Harris, N. L., Brown, S., Hagen, S. C., Saatchi, S. S., Petrova, S., Salas, W., Hansen, M. C. ., Potapov, P. V. ., & Lotsch, A. (2012). Baseline Map of Carbon Emissions from Deforestation in Tropical Regions. *Science 22*, 336(6088), 1573-1576, 10.1126/science. 1217962.

[40] Hidore, J. J., & Oliver, J. E. (1993). Climatology- an atmospheric science. *New York*.

[41] Higgit, D. (2010). Geomorphic hazards and sustainable development. *Alcántara-Ayaly, I.; Goudie, A. [Eds.]. Geomorphological Hazards and Disaster Prevention. Cambridge University Press,Cambridge*, 257-268.

[42] Hueck, K. (1966). Die Wälder Südamerikas. *Fischer Verl., Stuttgart [Germany]*.

[43] Huerta, A. I., & Marshall, A. M. Soybean production: competitive positions of the United States, Brazil, and Argentina. *Purdue Agricultural Economics Report*, 4-10.

[44] IPCC. (2007). Fourth Assessment Report: Climate Change 2007.

[45] Kraas, F. (2011). Megastädte. *Gebhardt, H.; Glaser, R.,; Radtke, U.; Reuber, P 2011.,. Geographie. Physische Geographie und Humangeographie. 2nd Ed. Spektrum Akadem. Verlag, Heidelberg*, 879-885.

[46] Lacerda, W. A. (2007). Landslide initiation in saprolite and colluvium in southern Brazil: Field and laboratory observations. *Geomorphology*, 87, 104-119.

[47] Larsen, M. C., & Torres, Sánchez. A. J. Landslide triggered by Hurricane Hugo in eastern Puerto Rico. *Caribbean Journal of Science*, 28, 113-125.

[48] Lin, G. W., Chen, H., Hovius, N., Horng, M. J., Dadson, S., Meunier, P., & Lines, M. (2008). Effects of earthquake and cyclone sequencing on landsliding and fluvial sediment transfer in a mountain catchment. *Earth Surface Processes and Landforms*, 33, 1354-1373.

[49] Lumb, P. (1975). Slope failures in Hong Kong. *Quarterly Journal of Engineering Geology*, 8, 31-65.

[50] Mamingi, N. (1997). The impact of prices and macroeconomic policies on agricultural supply: A synthesis of available results. *Agricultural Economics*, 16, 17-34.

[51] Mertens, B., Sunderlin, W. D. ., Ndoye, O., & Lambin, E. F. (2000). Impact of Macroeconomic Change on Deforestation in South Cameroon: Integration of Household Survey and Remotely-Sensed Data. *World Development*, 28(6), 983-999.

[52] Negecu, W. M., & Mathu, E. M. (1999). The El-Nino triggered landslides and their socioeconomic impact in Kenya. *Environmental Geology*, 38, 277-284.

[53] Nunes, L. H. (2011). Landslides in São Paulo, Brazil: An integrated historical perspective. *PAGES news*, 19.

[54] Oliveira, M. A. T., Behling, H., Pessenda, L. C. R., & Lima, G. L. (2008). Stratigraphy of near valley head deposits and evidence of climate-driven slope-channel processes in southern Brazilian highlands. *Catena* 75 . 77-92.

[55] Parra, E., & Cepeda, H. (1990). Volcanic hazard maps of the Nevado del Ruiz volcano, Colombia. *Journal Volcanol. Geotherm. Res*, 42, 117-127.

[56] Petley, D. (2010). Landslide hazards. *Alcántara-Ayaly, I.; Goudie, A. [Eds.]. Geomorphological Hazards and Disaster Prevention. Cambridge University Press, Cambridge*, 63-73.

[57] Pfisterer, U. (1991). Genese, Ökologie und Soziologie einer Bodengesellschaft aus Ultranasit und Bodenformen assoziierter Gesteine des süd-ost-brasilianischen Regenwaldes. *Schriftenreihe Institut für Pflanzenernährung und Bodenkunde. Universität Kiel, Kiel*.

[58] Rapp, A. Studies of mass wasting in the Arctic and in the Tropics. *Yatsu, E.; Ward, A.J.; Adams, F. [Eds.]. Mass Wasting. 4th Guelp Symposium on Geomorphology. Geo Abstracts LTD, Norwich, England*, 79-103.

[59] Reading, A. J., Thompson, R. D., & Millington, A. C. (1995). Humid tropical environments. *Blackwell, Oxford*.

[60] Römer, W., Kanig, M., & Pfisterer, U. (2002). The influence of lithology on hillslope development in the area of the Jacupiranga Alkaline Complex and its surrounding [São Paulo, Brazil]. *Catena*, 47, 151-171.

[61] Römer, W. (2008). Accordant summit heights, summit levels and the origin of the ″upper denudation level″ in the Serra do Mar [SE-Brazil, São Paulo]: A study of hillslope forms and processes. *Geomorphology*, 100, 312-327.

[62] Römer, W. (2012). Hillslope processes in tropical environments. *Shroder, J.Jr.; Marston, R.; Stoffel, M., [eds.]. Treatise on Geomorphology. Academic Press, San Diego, CA*, 7, [in press].

[63] Rohdenburg, H. (1982). Geomorphologisch-bodenstratigraphischer Vergleich zwischen dem nordostbrasilianischen Trockengebiet und immerfeucht-tropischen Gebieten Südbrasiliens. *Catena Suppl. Bd. 2, Braunschweig*, 72-122.

[64] Schiff, M., & Montenegro, C. E. (1997). Aggregate Agricultural Supply Response in Developing Countries: A Survey of Selected issues. *Economic Deelopment and Cultural Change*, 45(2), 393-410.

[65] Scholz, U. (2011). Strukturen und Probleme der ländlichen Räume in den Tropen. *Gebhardt, H.; Glaser, R.,; Radtke, U.; Reuber, P.,. Geographie. Physische Geographie und Humangeographie. 2nd Ed. Spektrum Akadem. Verlag, Heidelberg*, 837-852.

[66] Schultz, J. (2000). Handbuch der Ökozonen. *Ulmer, Stuttgart*.

[67] Schultz, J. (2005). The Ecozones of the World. *Springer, Berlin Heidelberg*.

[68] Seluchi, M. E., Chou, S. C., & Gramani, M. (2011). A case study of a winter heavy rainfall event over the Serra do Mar in Brazil. *Geofisica Interacional*, 50(1), 41-56.

[69] Serrão, E. A. S., Falesi, I. C., Bastos de, Veiga. J., & Teixeira, Neto. J. F. (1979). Productivity of cultivation on low fertility soils in the Amazon of Brazil. *Sanchez, P.A.; Tergas, L.E. [Eds.]. Pasture production and acid soils of the tropics. Crentro Internacional de Agricultura Tropica, Cali Colombia*, 195-225.

[70] Silva, A. M. (2004). Rainfall erosivity map for Brazil. *Catena*, 57, 251-259.

[71] Simon, A., Larson, M. C., & Hupp, C. R. (1990). The role of soil processes in determining mechanism of slope failure and hillslope development in a humid-tropical forest, eastern Puerto Rico. *Geomorphology*, 3, 263-286.

[72] Simonett, D. S. (1967). Landslide distribution and earthquakes in the Betwani and Trocelli Mountains, New Guinea. *Jennings, J.N.; Mabbutt, J.A. [Eds.]. Landform Studies from Australia and New Guinea. Canberra*, 64-86.

[73] Sinun, W., Wong, W. M., & Douglas, I. (1992). Throughfall, stemflow, overland flow and throughflow in the Ulu Segama rain forest, Sabah, Malaysia. *Phil. Transact. Royal Soc. London B*, 335, 389-395.

[74] Silva, A. M. (2004). Rainfall erosivity map for Brazil. *Catena*, 57, 251-259.

[75] Skinner, B. J., & Porter, S. C. (1987). Physical Geology. *John Wiley and Sons, New York*.

[76] So, C. L. (1971). Mass movements associated with the rainstorm of June1966 in Hong Kong. *Transactions Institute British Geographers*, 53, 55-66.

[77] Stache, N., & Wirthmann, A. (1998). Die Misere in der Landwirtschaft im tropischen Afrika am Beispiel einer geoökologischen Studie in Rwanda. *Petermanns Geographische Mitteilungen*, 142(5/6), 339-354.

[78] Starkel, L. (1972). The role of catastrophic rainfall in shaping the relief of the Lower Himalayas [Darjeeling Hills]. *Geographica Polonia*, 21, 103-147.

[79] Tavani, R., Saket, M., Piazza, M., Branthomme, A., & Altrell, D. (2009). Measuring and monitoring forest degradation through national forest monitoring assessment Case studies on measuring and assessing forest degradation. *Forest Resources Assessment Working Paper 172, Rome, Italy*.

[80] Thomas, M. F. (1994). Geomorphology in the Tropics. *Wiley, Chichester*.

[81] Thomas, M. F. (2004). Landscape sensitivity to rapid environmental change- Quaternary perspective with examples from humid tropical areas. *Catena*, 55, 107-1.

[82] Thomas, M. F. (2006). Lessons from the tropics for a global geomorphology. *Singapore Journal of Tropical Geography*, 27, 111-127.

[83] Thomas, M. F., & Thorp, M. B. (1995). Geomorphic response to rapid climatic and hydrologic change during the Late Pleistocene and Early Holocene in the humid and sub-humid tropics. *Quaternary Science Review*, 14, 193-207.

[84] Varnes, D. J. (1978). Slope movement types and processes. *Schuster, R.I.; Krizek, R.J. [Eds.]. Landslides, Analysis and Control. Transportation Research Board Sp. Rep176 Nat. Acad. Scie*, 11-33.

[85] White, L. D., Mottershead, D. N., & Harrison, S. J. (1984). Environmental Systems. *George Allen & Unwin, London*.

[86] Whitmore, T. C. (1990). An introduction to Tropical Rainforests. *Clarendon Press, Oxford*.

[87] Wirthmann, A. (2000). Geomorphology of the Tropics. *Springer, Berlin*.

[88] Wolle, C. M., & Hachich, W. (1989). Rain-induced landslides in Southeastern Brazil. *Proc. 12th Int. Conf. on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Brazil*, 3, 1639-1642.

[89] Ybert, J. P., Bissa, W. M. ., Catharino, E. L. M. ., & Kutner, M. (2003). Environmental and sea-level variations on the south-eastern Brazilian coast during the Late Holocene with comments on prehistoric human occupation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 189, 11-24.