13.1 Geomorphology of Human Disturbances, Climate Change, and Hazards

LA James, University of South Carolina, Columbia, SC, USA
CP Harden, University of Tennessee, Knoxville, TN, USA
JJ Clague, Simon Fraser University, Burnaby, BC, Canada

Glossary

Anthropogenic geomorphology A systematic subfield of geomorphology concerned with the study of landforms created or modified by human activity. Human-induced changes in geomorphic processes, process rates, and landscape sensitivity to change are also of concern (Szabó, 2010).

Climate change A statistically significant deviation from mean climate conditions persisting for a period of decades or longer. Climate parameters that may change include precipitation, air temperature, water temperature, humidity, and wind speed, direction, and duration of events. Changes in these parameters may be in the form of mean, maximum, or minimum values, or measures of variability such as standard deviation or seasonality, and may occur at spatial scales ranging from micro to global climates.

Landscape sensitivity The vulnerability of landscapes to change in response to environmental forces. Sensitivity may vary with the characteristics of geologic structures, soils, vegetation, or antecedent conditions (Brunsden and Thornes, 1979). Sensitivity to erosion varies spatially and may explain complex patterns of degradation to regionally uniform climate change or human alterations.

Natural hazards The threat of a naturally occurring event with adverse effects on society or the environment. They may be meteorologically, geologically, or geomorphically induced and include storms, floods, tsunamis, earthquakes, volcanic eruptions, sinkhole collapse, and debris flows.

Sustainability The ability of processes or activities to be maintained over extended periods of time "…without compromising the ability of future generations to meet their needs" (World Commission on Environment and Development (WECD), 1987). The concept may be applied to development, resource use, or environmental management and implies a commitment to the stewardship of natural systems. It began as a social and philosophical construct, but was later adopted by the scientific community as sustainability science (Kates et al., 2001).

Abstract

Anthropogenic geomorphology is an emerging systematic field that overlaps with climate change and natural hazards research. Collectively, these three topics form a human dimension of geomorphology that should gain increasing prominence in the twenty-first century with mounting concerns over the ability to reconcile population growth, dwindling

James, L.A., Harden, C.P., Clague, J.J., 2013. Geomorphology of human disturbances, climate change, and hazards. In: Shroder, J. (Editor in Chief), James, L.A., Harden, C.P., Clague, J.J. (Eds.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 13, Geomorphology of Human Disturbances, Climate Change, and Natural Hazards, pp. 1–13.

resources, global environmental change, climate warming, public safety, and sustainability with the stability of geomorphic systems. Humans create landforms directly and indirectly by altering geomorphic process rates and landscape sensitivities. Climate change may also alter process rates and sensitivities, or shifts to different climate regimes may result in complete changes in landform processes.

13.1.1 Introduction

In this day of increasing concern over global change and human impacts on the environment, it is fitting that a volume of the Treatise on Geomorphology is dedicated to disturbances, change, and vulnerability. Chapters or sections on the subjects of human agency, climate change, and hazards appear elsewhere in the Treatise within the context of a particular geomorphic system or set of methodologies, but this volume is focused on the human dimensions of geomorphology. For geomorphology to make a substantial contribution to the science of global environmental and climate change, and to be relevant to debates about the validity of those changes and policies to mitigate them, geomorphic research will need to reach beyond compartmentalized treatments of these critical topics and approach them in an integrated manner. The syntheses in this volume hopefully will help lead to recognition of general characteristics and theories that are common to multiple geomorphic systems.

This volume examines general concepts of anthropogenic geomorphology, climatic geomorphology, impacts of climate change, and geomorphic hazards. Human impacts on geomorphology and geomorphic effects on humans through natural hazards clearly involve interactions between humans and geomorphic systems. The human dimension of geomorphology is a vital area of research that has been largely neglected beyond the local and subregional scale. Global environmental change and climate change have become topics of great concern owing to recent realizations about the pervasive impacts of society at this scale. Much of the scholarship on environmental and climatic change, however, has been centered on interactions with ecosystems, agrosystems, and hydrologic systems (Slaymaker et al., 2009). Much less has been written about the effectiveness of humans as geomorphic agents or the impacts of climate change on geosystems.

Study is also needed of climate-change impacts on geomorphic systems to build upon early concepts of climatic geomorphology and improve knowledge of local-scale landscape sensitivity to global-scale changes. For example, it should be possible to anticipate responses of soil erosion and sediment yields at the hillslope scale to changes in precipitation regimes and vegetation cover at the scale of general circulation models. The effects of natural hazards on society also have not been adequately addressed from a geomorphic perspective. Geomorphic hazards are a human dimension of geomorphology in which physical systems drive change, and humans are the response variable. Humans influence natural hazards, however, and social vulnerability to hazards is clearly dependant on human behavior, so the relationship between independent and dependent variables can be reversed. Together, human impacts on geomorphic forms and processes, climate change, and geomorphic hazards form a trilogy of concerns that will need a great deal of study and a better understanding in the twenty-first century. The central goal of this volume is to pull together several syntheses and reviews from writings on these topics and show how geomorphology can benefit from an anthropogeomorphic viewpoint, and how global change and hazards research can benefit from a geomorphic perspective. Chapters in this volume are grouped into three primary sections: (1) human impacts on geomorphic systems; (2) impacts of climate change on geomorphic systems; and (3) natural hazards.

13.1.2 Background

Interrelationships among human activities, climate, and natural hazards may take many forms, of which direct responses of landforms to human activities are but one aspect (Figure 1). Human activities have indirect influences on landforms through cascades, biological systems, and natural hazards. Cascades in the movement and storage of mass or energy commonly link human activities to landform responses, so that geomorphic responses may be propagated indirectly and may be delayed, mitigated, or extended in time and space. Similarly, alterations to geomorphically relevant biological systems, such as vegetative cover that inhibits erosion, may result in indirect linkages between human activities and landform responses. For example, grazing animals may increase sensitivity of a landscape to erosion by reducing the protective cover of vegetation. Thus, the extirpation of wild herbivores may reduce erosion, or the introduction of domesticated grazing animals may increase erosion. Conversely, landform responses may have a positive or negative feedback on human activities. For instance, agriculturally induced

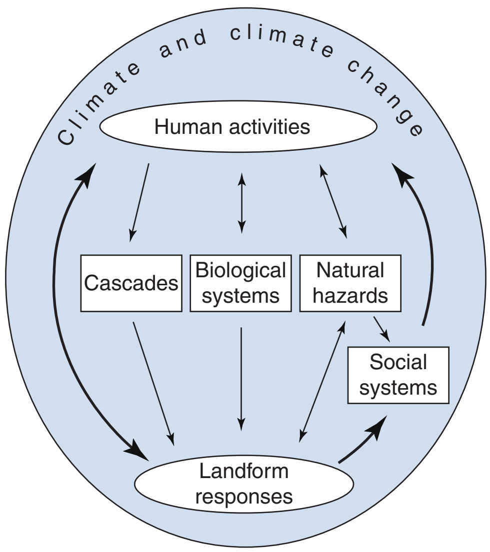


Figure 1 Systems diagram for interrelationships between human activities and landform responses. See text for explanation and discussion.

erosion that causes valley bottom aggradation and increased flooding may reduce human activity rates or may push agriculture up onto highly erosive hillslopes, causing accelerated erosion. Natural hazards may have a direct geomorphic impact on landforms through erosion and sedimentation. Natural hazards may also have an indirect effect on landforms by altering social systems, such as local economic or political stability and infrastructure that govern human rates of geomorphic activities. For example, the destruction of infrastructure such as irrigation works may result in decreased agricultural activity and reduced erosion and sedimentation, or the destruction may result in neglect of erosion-control measures and increased erosion and sedimentation. In addition, geomorphic events such as deflation, floods, and beach erosion may be influenced by human activities. Rates and intensities of human activities are influenced by cultural factors of the social system, especially the level of technology employed, and population dynamics, such as population growth and migrations. Social systems may respond to landform changes or natural hazards, resulting in complex interactions between physical and human systems. Agricultural destabilization of soils that leads to catastrophic deflation, regional economic decline, and out-migration is an example of this dynamic. Climate and climate changes may have a pervasive influence on human activities, landform responses to those activities, the sensitivity of cascading and biological systems to change, natural hazards, and social systems. In addition, climate change, itself, is a response to human activities, so the overarching effects of climate can be viewed as part of the system of anthropogenic geomorphology.

Geomorphic responses to climate change during the Holocene have commonly been difficult to distinguish from human impacts. Anthropogenic and climatic disturbances generally involve complex interactions and feedbacks between culturally and physically induced processes. Attempts to isolate anthropogenic from natural change is not always feasible or desirable. For example, natural climate change may increase landscape sensitivity and lower thresholds of response to disturbance (Knox, 2001). Thus, it is often preferable to study integrated systems as a whole.

Given the allied topics of hazards and anthropogenic change addressed in this volume, the focus is on late Holocene and historical time scales. Reconstructing past changes in Tertiary or Pleistocene climates is not an objective except insofar as early climates reflect processes that may be relevant to recent or future changes. Consideration of paleo-climates prior to the Holocene is provided in other volumes of the Treatise. Changes in climate and landscapes were much more rapid during the Quaternary than previously supposed, as evidenced by Greenland and Antarctic ice core data (Dansgaard et al., 1993; Petit et al., 1999). Modern effects of climate warming and anthropogenic change have increased these rates. Biodiversity has shown major variability through geologic time and is now decreasing at a rate that rivals major extinction events in Earth history (Wilson, 1992). Present rates of climate and anthropogenic change could challenge common assumptions of dynamic equilibria in geomorphic systems.

Global anthropogenic changes are not confined to the atmospheric and biologic spheres, but extend to geomorphic systems through strong system interconnectivity. Earth systems are closely interconnected through transfers of energy, water, sediment, and diverse chemical compounds. Tight coupling of systems implies that change in one system may be propagated to other systems and result in collective local-scale changes that have cumulative effects at the global scale. Growing awareness of this interconnectivity has been accompanied by increasing recognition that soils and biota influence climate systems, not simply the converse (Claussen, 2004; Steffen et al., 2004). For example, Avissar and Liu (1996) simulated spatial patterns of precipitation that strongly reflected patterns of vegetation and bare soil. Hydrologic systems also play a dual role as independent and dependent variables with climate in the Earth system. This realization is expanding the emphasis of hydrology from flood control, drought, erosion, sedimentation, and eutrophication to integrated water resources management and a global synthesis based on geospatial analyses (Meybeck and Vörösmarty, 2004). Aeolian processes also demonstrate high spatial connectivity across continents (**Figure 2**). For example, satellite remote sensing has documented sediment transport from the Sahara Desert in Africa to South America, where it provides a flux of nutrients to the Amazon rain forest (Koren et al., 2006), from Japan to North America (Uno et al., 2001), and between China and Japan (Iino et al., 2004). A map of global source areas for dust is presented by Lancaster (*see* Chapter 13.9, Figure 3). These aeolian events may also have feedbacks to large-scale atmospheric processes such as suppression of cyclogenesis (Evan et al., 2006). Glaciation propagates the effects of climate change through time and space. Downvalley changes are imposed by meltwater, outwash, and cold-air drainage, whereas large-scale changes to atmospheric circulation may be generated by ice sheets that induce cold-cored high-pressure conditions over large areas. Rapid changes in global ice volumes and the geomorphic effects of deglaciation are documented by Haeberli et al. (*see* Chapter 13.10).

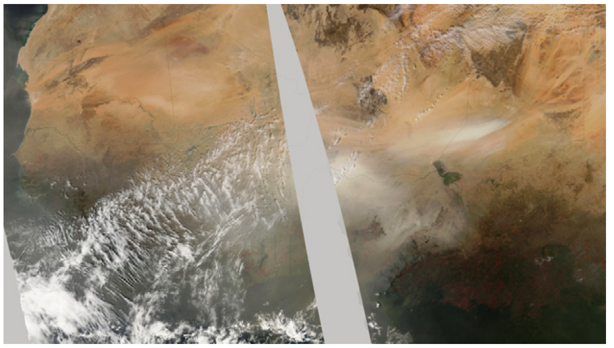


Figure 2 Dust storm emanating from the Bodele Depression toward Lake Chad in Saharan Africa. *Source*: NASA Earth Observatory Aqua satellite image, 2 January 2007. NASA Visible Earth: http://visibleearth.nasa.gov/

13.1.2.1 Early Concepts of Population, Technology, and Environmental Impacts

Exponential growth in the global human population is often cited as a factor influencing rapid rates of late Holocene environmental change. In addition to accelerating geomorphic change, the growing population also increases the vulnerability of society to natural hazards. Urbanization of lands that are susceptible to floods, tsunamis, volcanic eruptions, and the like put large numbers of people at risk and reduce the resiliency of society to catastrophic events. The relationship between population and environmental impacts has engaged philosophers from the time of Herodotus and Seneca, to Malthus and Darwin, to Commoner and Erhlich, and to the present. During the environmental movement of the 1970s, a scientific debate emerged over the theoretical causality of global environmental impacts. Although these ideas were concerned with broad environmental impacts, for example, toxicity, water quality, and ecological systems, they apply in a very general, qualitative sense to impacts on geomorphic systems. During these debates, the relative importance of technology and population emerged as a central focus. In contrast with Commoner, Ehrlich held that population was the primary driver of environmental impacts. A series of theorems presented by Ehrlich and Holdren (1971) ultimately led to a simple, iconic conceptual relationship, *IPAT*, that is commonly used to express environmental impacts in terms of population, affluence, and technology (Holdren and Ehrlich, 1974):

$$I = PAT \qquad [1]$$

where I is environmental impact, P is population, A is consumption or affluence, and T is technology. The loadings for T can be greater than or less than one so that technology can increase or decrease impacts. Although critiques of Malthusian pessimism evoked the positive aspects of technological innovations, Commoner (1972) concluded that most technological developments associated with growth of the US economy since 1946 created substantially greater environmental impacts than the technologies that they replaced. This viewpoint is supported by human-induced geomorphic changes in the form of earth movement by mining and road building that have proliferated in the past century (*see* Chapter 13.6). It is also corroborated by the potential use of thermonuclear technology for geomorphic change as described in the section on Project Plowshare at the end of this chapter. The *IPAT* approach to assessing environmental impacts has primarily been applied to global-scale problems and is difficult to apply to smaller scales of space and time (Steffen et al., 2004).

13.1.2.2 Structure of the Volume

The first section of this volume is concerned with the impacts of human activities on geomorphic systems, examined from both a physical and historical (stratigraphic) perspective. The first three chapters examine impacts of land use and vegetation clearance on watersheds and river channels at a variety of scales of space and time ranging from small watersheds to continents and from the Neolithic to present (*see* Chapters 13.2, 13.3, and 13.4). The next three chapters cover the effects of grazing, mining, and dams and reservoirs on geomorphic systems, respectively (*see* Chapters 13.5, 13.6, and 13.7). Four chapters in the second section of this volume examine the effects of climate and climate change on geomorphic systems. The first examines the long tradition of climatic geomorphology (*see* Chapter 13.8). It is followed by chapters on responses of aeolian, glacial, and periglacial systems to climate change, respectively (*see* Chapters 13.9, 13.10, and 13.11). The final section of this volume consists of six chapters that examine major catastrophes, tsunamis, volcanism, flooding, wild fires/debris flows, and effects of climate change on slope stability, respectively (*see* Chapters 13.12, 13.13, 13.14, 13.16, and 13.17). In addition, a few brief discussions are provided in this chapter to broaden the scope of human impacts covered elsewhere in the volume.

13.1.3 Human Impacts on Geomorphic Systems

Interest and focus on how humans change geomorphic systems accelerated in the late twentieth century as concerns mounted about global environmental change and growing population pressures. A new subdiscipline of geomorphology is emerging that operates on a variety of temporal and spatial scales. The nature, extent, and timing of human impacts on geomorphic systems are not merely academic questions, but may have serious physical and social implications. For example, soil loss is a geomorphic consequence of human activities that is highly relevant to feeding global populations. Most (99%) of the global food supply is derived from the land; less than 1% comes from oceans and aquatic habitats (Pimentel et al., 1994). Sustainability of terrestrial agriculture is of essential importance, therefore, as global populations increase from the present 6.9 billion to a projected 9.3 billion by the year 2050 (United Nations, 2011). Yet, soil erosion is reducing arable lands at an alarming rate when considered against the rate of pedogenesis. Pimentel et al. (1995) estimate that almost one-third of the global soil cropland was lost to erosion between 1950 and 1995.

13.1.3.1 Anthropogenic Geomorphology

Study of the effects of human activities on geomorphic systems is an emerging branch of geomorphology that focuses on humans as agents of change. Most systematic branches of geomorphology are named by the agents of change; that is studies of the action of rivers, glaciers, and wind are the realms of fluvial, glacial, and aeolian geomorphology, respectively. Anthropogenic geomorphology includes the study of surface landforms created by humans (Szabó, 2010), for example, open-pit mines, artificial levees, jetties, and groins. Anthropogenic geomorphology is a systematic branch of the discipline in which humans are the agents of change. Just as the processes and landforms of other systematic areas commonly overlap (e.g., coastal and aeolian), so human-induced influences overlap with other systematic processes and landforms. Several studies have been devoted to anthropogenic geomorphology for particular subdisciplines – fluvial geomorphology (Brierley and Stankoviansky, 2003; Batalla and Garcia, 2005; Syvitski et al., 2005; James and Marcus, 2006), coastal geomorphology (Walker, 1988; Nordstrom, 2000; Stutz and Pilkey, 2005), hillslope geomorphology (Walling and Probst, 1997), aeolian geomorphology (Gill, 1996), and climatic geomorphology (Wolman and Gerson, 1978;

Montgomery et al., 2001; Vandenberghe, 2003). Other studies have covered the broader topic of human impacts on geomorphic systems (Slaymaker et al., 2009; Szabó, 2010).

Anthropogenic geomorphology is also concerned with landforms and processes that result indirectly from human processes and alterations to natural rates of change (Szabó, 2010). Thus, where deforestation has accelerated erosion, rapid sedimentation downstream may result in the formation of alluvial fans and deltas that are, in part or wholly, anthropogenic landforms. As demonstrated in this volume, human activities have direct or indirect impacts on hillslope, fluvial, glacial, periglacial, aeolian, and coastal systems (**Table 1**). Human activities may result in global-scale changes that influence such a wide variety of landforms that the breadth of their impacts would be underestimated if their representation was confined to a single system (Szabó, 2010).

Human-induced geomorphic changes accelerated during the late Holocene. The current geologic time interval has been referred to as the Anthropocene, a distinct but informal time interval distinguished by major human impacts on geologic processes (Crutzen and Stoermer, 2000). Formal inclusion of the Anthropocene as an epoch of the geologic time scale has been considered by the Stratigraphy Commission of the Geological Society of London (Zalasiewicz et al., 2008). Potential criteria for defining the onset of the Anthropocene include the onset of increased CO_2 in ice cores, climate change, decreased biodiversity, the industrial revolution, and the presence of radionuclides from atomic bomb testing in the 1960s. Most of the early criteria were gradual and time-transgressive, which precludes a precise designation of the onset of the epoch. Some criteria, such as testing nuclear weapons, are based on events that occurred well after extensive anthropogenic changes had begun. Difficulties in identifying a specific time to characterize multiple changes that are time transgressive are not unique to the Anthropocene and are problematic to most existing geologic time divisions. It may suffice simply to identify a specific date, such as 1800, for the onset of the epoch (Zalasiewicz et al., 2008).

Table 1 Examples of anthropogeomorphic changes

System	*Anthropogenic changes*	*Geomorphic response*
Rivers	Damming; bank and bed armoring; river-bed mining	Sedimentation; deposition; flow frequencies; roughness changes
Coasts	Dredging; armoring; sea-level rise	Beach erosion; sediment redistribution
Hillslopes	Deforestation, plowing, road cuts	Rills, gullies
Groundwater	Mining	Subsidence
Glacial	Global warming	Ice margin retreat
Periglacial	Road embankments; global warming	Permafrost degradation
Arid & Aeolian	Vegetation change; vehicular traffic	Deflation and deposition

13.1.3.2 Scales of Space and Time

Human activities have long had an effect on environmental systems at a local scale, and many studies have documented human impacts on isolated landforms or spatially constrained systems such as individual hillslopes or river channels. Until the modern era, however, human impacts were considered relatively ineffective at the regional or global scale, and few geomorphic studies considered human impacts at a broad scale. Understanding global and climate change in the modern context, however, calls for consideration of anthropogenic changes to Earth systems at a larger geographic scale than has commonly been addressed by past geomorphic studies. Given scale-linkage problems in which larger systems require a longer time perspective, a shift toward global spatial scales may also require a longer temporal perspective (Schumm, 2005; Slaymaker et al., 2009; *see* Chapter 9.37).

A similar conclusion about the need for an historical perspective may be reached from a different logic based on questions of regional- or continental-scale impacts of human activities. The common need to identify undisturbed geomorphic conditions calls for recognition of early human changes and the geomorphic effectiveness of early human activities. These inquiries raise questions of what is a 'natural' geomorphic system. This question has been explored in some detail for fluvial systems because many regulatory and design procedures are predicated on the need to identify undisturbed reaches of rivers. Subsequent studies have concluded that anthropogenic changes to rivers have been so extensive that it may be difficult to locate an undisturbed river (Graf, 1996; Wohl, 2001; James and Marcus, 2006; Newson and Large, 2006; Wohl and Merritts, 2007; Fryirs and Brierley, 2009). In fact, many fundamental fluvial theories were based on river systems that have been substantially altered by deep historical sedimentation (Montgomery, 2008; Walter and Merritts, 2008). The question of what is natural should be raised in studies of other landform systems where sediment budgets governing landform processes may have been substantially altered by human activities and landforms are products of these activities.

13.1.4 Impacts of Climate and Climate Change on Geomorphic Systems

The second section of this volume has two main foci: a review of climatic geomorphology and syntheses of geomorphic impacts of climate change in three systematic areas of geomorphology that are defined largely by climate: aeolian, glacial, and periglacial systems.

13.1.4.1 Climatic Geomorphology

The first chapter in this section reviews the long history and diverse concepts of climatic geomorphology, which has deep roots in the discipline of geomorphology (*see* Chapter 13.8). The birth of the concept that specific morphogenetic features are associated with climatically driven processes can be traced to the glacial theory advanced by Louis Aggasiz (Derbyshire, 1973). During the mid-twentieth century, this approach largely focused on the identification of morphogenetic zones, morpho-climatic regions, and the reconstruction of paleoclimates from morphologic forms (Beckinsale and Chorley, 1991). Critiques of these methods arose from the lack of unique linkages between climatic processes and form (equifinality), poor-quality climate data, intervening factors such as geologic structure, and climate change. Climate change was generally not a primary concern of early climatic geomorphology, because the frequency and degree of Quaternary climate changes were not fully understood and because climate change introduces polygenetic landforms that pose substantial difficulties to the identification of morpho-climatic regions.

During the late twentieth century, climatic geomorphology tended to evolve into specialized subfields, in which climate is a defining element. The emergence of systematic subfields of tropical, glacial, periglacial, and aeolian geomorphology led to less emphasis on the recognition of global-scale regions or zones. Certain climates and processes were presumed as preconditions for membership to a given system (e.g., glacial geomorphology), which led to fewer comparisons between diverse climatic regions or process regimes. Nevertheless, identification and mapping of morphological evidence from paleo-landforms, combined with radiometric dating, continues to be a viable means of documenting the former extent and intensity of past climates. The emphasis has shifted from identifying morpho-climatic zones to recognizing climate change and reconstructing climate histories from landforms and stratigraphic evidence. Knowledge of climate change within the individual climatic subfields has progressed greatly as Quaternary geomorphologists developed detailed histories and concepts of evolving process regimes within certain regions. Examples of Quaternary change studies are provided in chapters in other volumes of this Treatise.

13.1.4.2 Impacts of Climate Change on Geomorphic Systems

Toward the end of the twentieth century, influences of climate change became a topic of great importance. Global warming due to increased atmospheric greenhouse gases is causing major geomorphic changes as sea levels rise, glaciers melt, and regional patterns in temperature and precipitation shift. Although debate continues about the relative importance of the role of humans in climate warming, there is no doubt that anthropogenic releases of CO_2 have increased, so the question is not whether humans have contributed to climate change, but how much that they have done so. Climatic warming, therefore, represents an indirect response to human activities that has extensive geomorphic implications. Within the field of geomorphology, interest in climate change took place largely within the framework of specific geomorphic systems, such as glacial, fluvial, or soils geomorphology. A systematic coverage of all geomorphic systems goes beyond the scope of this volume, but by considering climate change in a variety of regimes, this volume seeks to elucidate the implications of atmospheric processes that shift from one regime to another. From this broad perspective, climate can be seen as a geomorphic disturbance factor, not simply a static determinant of regional geographic patterns.

Three chapters in this volume examine the impacts of climate change on geomorphic systems associated with specific climate regions. The chapter on aeolian processes reviews the impacts of climate change in drylands, which cover $\sim$50% of the land surface of Earth (*see* Chapter 13.9). Dune reactivation, generation of dust, influxes of nutrients to oceans and distant lands, and human health implications are covered with an emphasis on decadal time scales. Haeberli et al. (*see* Chapter 13.10) describe the history and recent developments in global glacial monitoring that document glacial retreat and an acceleration of ice-mass loss over past decades. Implications include effects on sea-level rise, seasonality of runoff and water resources, creation of new lakes, destabilization of deglaciated slopes, and increased sediment delivery to streams. The increasing capabilities of Light Detection and Ranging (LiDAR) altimetry combined with the differencing of gridded digital elevation models (DEMs) (James et al., 2012) are producing a new generation of monitoring and morphometric analyses that will lead to detailed glacial monitoring at the scale of entire mountain ranges. The chapter on periglacial landscapes reviews the nature of climate-change impacts in an environment that is highly susceptible to regional warming and will likely experience the greatest degree of warming (*see* Chapter 13.11). These landscapes will likely experience thermokarst and ice-wedge degradation, hillslope instability, and substantial erosion. An estimated 25% of the Earth's surface is underlain by permafrost, so the release of CO_2 gases by thawing is a serious concern. In addition to these three chapters, chapters in other volumes of the Treatise are concerned with the effects of climate change; for example, the effects of climate change on rivers (*see* Chapter 9.40).

An impact of climate warming that has widespread geomorphic implications is the on-going rise in levels of the global oceans. Linking global sea-level budgets to energy budgets is an on-going area of research that is essential to calibrating simulations of climate change as scenarios of changes to atmospheric chemistry (Church et al., 2011). From 1961 to 2003, global mean sea levels rose $\sim$1.8 mm yr^{-1}, whereas after 1993 they rose at a higher rate of $\sim$3.1 mm yr^{-1} (IPCC, 2007). Most of the rise since 1993 (1 mm yr^{-1} or 57%) has been attributed to thermal expansion of sea water, whereas glacial and ice cap melting was credited for only 0.5 mm yr^{-1} (28%), and melting of polar ice 0.27 mm yr^{-1} (15%) (IPCC, 2007). Recent estimates of sea level rise from 1972 to 2008 indicate a total 1.8 mm yr^{-1} rate with contributions of thermal expansion only 0.8 ± 0.1 mm yr^{-1}, and melting of glaciers and ice caps contributing 0.7 mm yr^{-1} (Church et al., 2011). Mining of groundwater produced a surplus of water that offset all but 0.1 mm yr^{-1} of water stored in reservoirs and lost to oceanic recharge. If the ice masses of Greenland and Antarctica were to melt completely, sea levels would rise $\sim$64 m (Bamber et al., 2001; Lythe et al., 2001; IPCC, 2007). Glacier and ice cap melting rates increased in the late 1990s (Church et al., 2001, 2011) and this could increase rates of geomorphic change in coastal environments.

13.1.4.3 The Human Role in Early Climate Warming

It was long held that humans had little effect on global climate (Thornthwaite, 1956), but this changed rapidly with the realization that concentrations of greenhouse gases in Earth's atmosphere were rising (Plass, 1956). The effects of prehistoric and preindustrial anthropogenic land use and land cover on global climate are currently the subject of a lively debate. It has been argued that modern global warming can be traced back to prehistoric deforestation by burning and land clearance in the early Holocene that released enough CO_2 to initiate a global climate response (Ruddiman, 2003, 2007). Through numerous Quaternary glacial advances and retreats, interglacial warm periods tended to begin with high levels of atmospheric carbon dioxide and methane that declined after interglacial warming began, followed by cooling and a return to glacial climatic conditions. The Holocene, however, has been quite different. Greenhouse gases were initially high and then declined in the early Holocene in keeping with most interglacial periods, but CO_2 concentrations began to rise approximately 8000 years ago and methane concentrations began to rise around 5000 years ago (Ruddiman, 2007). A number of studies have demonstrated the sensitivity of global climate to Holocene trends in atmospheric CO_2 and CH_4 (methane) concentrations (Ruddiman, 2004; Vavrus et al., 2008). Deforestation may have led to CO_2 increases in the atmosphere, and the introduction of large populations of grazing animals and rice agriculture may have increased CH_4 emissions to the atmosphere (Ruddiman and Ellis, 2009). This sensitivity has been demonstrated by recent paleoecological data suggesting that reforestation after the collapse of indigenous populations in Neotropical Latin America following European contact was sufficient to perturb the global carbon cycle and climate system and to contribute to Little Ice Age cooling (Nevle and Bird, 2008; Dull et al., 2010).

Some modeling studies that have attempted to estimate prehistoric and preindustrial anthropogenic CO_2 and CH_4 emissions have concluded that the emissions were too small to have had a substantial effect on global climate (DeFries et al., 1999; Olofsson and Hickler, 2007; Pongratz et al., 2009), and attributed the observed trends in CO_2 and CH_4 concentrations to natural sources. Recent model runs based on updated greenhouse gas concentrations for a low (natural) scenario and a modern scenario simulate substantially lower temperatures for the low scenario than the anomalously high CO_2 and CH_4 concentrations since the industrial period (Kutzbach et al., 2010). The regional temperature differences range from 2 °C cooler in the tropics to 4–8 °C cooler in polar regions. Kutzbach et al. (2010) concluded that a state of incipient glaciation would be present if it was not for the current elevated greenhouse gas concentrations.

Several studies have documented changes to the global carbon balance. Although information about rates of land-use change and biomass densities has improved greatly over the past decades, the variability in estimates of carbon emissions from these changes has increased (Houghton, 2010). Several estimates of the relations between carbon sources and sinks from land use and land-use change have been made (House et al., 2003; Ramankutty et al., 2007; Ito et al., 2008; Houghton, 2010).

Climate change influences the sensitivity of landscapes to erosion and sedimentation. The relation between climate and soil erosion has long been shown by empirically derived erosion models. For example, a climatic aggressiveness index introduced by Fournier (1960) linked annual sediment production to climatic and topographic factors. This concept was later adapted and combined with annual precipitation variability for use with the Universal Soil Loss Equation (Arnoldus, 1978). A modeling approach based on geographic information system (GIS) analysis was used by Asselman et al. (2003) to simulate the combined effects of climate change and land use on fine sediment production, transport, and deposition on floodplains in the Rhine Basin. They concluded that sediment production will increase in the Alps and decrease downstream in Germany, producing an overall increase in erosion of ~12% basin-wide with negligible changes to sediment loads downstream in middle reaches, and an increase in erosion of ~13% in the Rhine Delta. Although the magnitude and frequency of floods is expected to increase, floodplain deposition is expected to decrease owing to reduced sediment loads during moderate floods with high floodplain trap efficiencies.

Carbon-balance studies should consider not only the contemporary cycling of carbon within the biomass but also the long-term cycling of soil organic carbon (SOC). Reductions in SOC are also relevant to geomorphology through relationships between organic matter and soil erodibility. Studies of relatively recent changes in SOC have concluded that substantial releases of SOC have accompanied deforestation and that much of this change is irreversible over decadal or centennial time scales. For example, Don et al. (2010) examined 385 studies of SOC in tropical forests and found that conversion of primary forest to cropland resulted in SOC losses on the order of −25% and conversions to grassland on the order of −12%. They also found that secondary (regrowth) forests contain typically 9% less SOC than primary forests, and that SOC losses are only partially reversible with reforestation. Even larger SOC decreases have been documented following deforestation in boreal forests. For example, Grünzweig et al. (2004) measured a reduction of 44% in SOC following deforestation in central Alaska.

Changes in land use also have substantial impacts on global climate through mechanisms other than greenhouse gases. By including land-cover changes in global climate models, the outcome of those models can be significantly changed (Kabat et al., 2002; Feddema et al., 2005). Although global climate changes are driven by carbon sequestration, microclimate changes are commonly driven by alterations in local water budgets.

13.1.5 Geomorphic Hazards

Geomorphic hazards warrant focus from a modern geomorphic perspective. Hazards arising from geomorphic processes can have large impacts on society. Humans are not only agents of change, but they are also vulnerable to geomorphic processes operating outside what might be considered the normal magnitude range. The human dimension of geomorphology is concerned, therefore, not only with human impacts on climate and land systems, but also with the reverse role, in which geomorphic systems impact humans. The effects that climate and environmental systems have on human societies is a central concern of natural hazards research. A broad view should consider not only the impacts of hazards on society, but also how human activities influence hazards.

For example, anthropogenic channel aggradation increases flood risks. Human activities also clearly influence vulnerability and resilience to disasters stemming from hazardous natural processes.

Not all natural hazards are susceptible to change by human activities. To make distinctions, it may be useful to separate endogenic and exogenic processes in the classification of geomorphic hazards. The forces applied by endogenic processes, such as earthquakes, tsunamis, and volcanism, are not appreciably altered by human action, although vulnerability and resilience clearly are affected by behavior. The forces applied by exogenic geomorphic processes, however, such as storms, floods, deflation, and fire, are commonly affected strongly by land use and engineering works. Alterations in the magnitude and frequency of these events may result in complex interactions between society, hazards, and geomorphic processes (**Figure 3**).

This volume includes several papers concerned with concepts, implications, and processes of natural hazards, including many of the individual geomorphic processes that underlie extreme events, such as large earthquakes, tsunamis, volcanic eruptions, landslides, and floods. Humans have suffered from hazardous natural processes as long as our species has existed (*see* Chapter 13.12). The situation today, however, differs at least in degree. Global population now exceeds 7 billion and people are increasingly choosing to live in urban areas located in high hazard areas, for example, in earthquake zones and areas where cyclones make landfall. Many of the worlds 'megacities' and much global wealth are located in areas subject to large earthquakes, tsunamis, floods, and severe storms. The potential for catastrophic loss of life or economic damage exceeding anything humans have experienced to date represents a real threat. Further, we live in an economically integrated world, such that a catastrophic earthquake or tsunami in, for example, Japan can impact all people.

In this light, an improved understanding of hazardous processes and of the relationship between hazard and risk is essential. Several papers in this volume explore these issues, as well as the frequency-magnitude concept that underpins many hazard studies. Goff and Dominey-Howes (*see* Chapter 13.13) provide a review of tsunamis, both as a geophysical process and as a profound threat to low-lying coastal communities. Hickson et al. (*see* Chapter 13.14) discuss volcanism both as a hazard and as a major shaper of landscapes near plate boundaries. Benito (*see* Chapter 13.15) focuses on rivers as a geomorphic agent. Streams and rivers are important agents of denudation and deposition; they produce new land in the form of deltas, and over geologic timescales, modulate isostasy in orogens. The chapter by Santi (*see* Chapter 13.16) deals with the geomorphic implications of wildfire, especially the impact of fire on sediment supply and delivery to fluvial systems. Finally, Huggel et al. (*see* Chapter 13.17) consider the impacts of recent climate change on the stability of slopes in mountains. They show that the frequency of landslides and ice avalanches may be increasing in many mountain areas due to glacier thinning and retreat and to thaw of alpine permafrost.

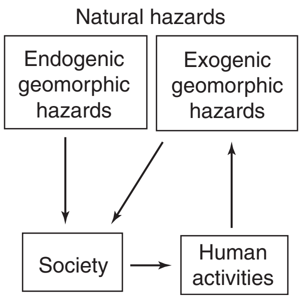


Figure 3 Systems diagram for interrelationships between natural hazards and human activities. Both endogenic and exogenic hazards have an effect on society and therefore on human activities. Human activities can only alter exogenic hazards such as storms, floods, and fire.

Linkages between hazards, climate, and vulnerability indicate the need to consider hazards in light of climate change and human activities. Some hazards are directly related to meteorological events such as relations between hurricane frequency and sea surface temperatures. Vulnerability to hazards, in turn, is affected by human activities, such as the location of human settlements in disaster-prone areas. Natural catastrophes also influence the nature of human activities. Clearly the trilogy of topics in this volume – human impacts on geomorphic systems, climate change, and natural hazards – should not be studied in isolation.

13.1.6 Nuclear Detonations as a Geomorphic Agent

Although natural hazards, such as hurricanes, volcanic eruptions, and earthquakes, can release more energy, the greatest potential for rapid, purely anthropogenic geomorphic change comes from thermonuclear explosions. This potential was demonstrated vividly during the post-World War II period by experiments conducted by the US government aimed at understanding the behavior of nuclear explosive devices both for warfare and peaceful uses. Project Plowshare was designed to explore the feasibility of peaceful uses of nuclear devices, specifically the use of underground nuclear explosions as geomorphic and resource-extraction agents. Although Project Plowshare never progressed beyond the experimental stage, the projects that were envisioned demonstrate the tremendous capability of humans for geomorphic change if the use of modern technology is unrestricted. The US government envisioned earth-moving operations on a large scale, including creation of canals and harbors, blasting road cuts, and mining by removing or fracturing earth. In particular, widening the Panama Canal, excavating a roadcut through the Bristol Mountains for a railroad line and Interstate 40 across the Mojave Desert, and cutting a 5 km divide to excavate a 400 km canal connecting the Tennessee and Tombigbee rivers were considered as applications of controlled nuclear detonations. A similar program for peaceful uses of nuclear detonations in the former Soviet Union was known as Nuclear Explosions for the National Economy (Nordyke, 2000).

Thirty-five Plowshare experimental nuclear detonations were conducted from December 1961 to May 1973, before the project was halted due to the dangers of radiation (US Department of Energy, 2000). Fifteen of the detonations each

Figure 4 Project Plowshare experimental blasts were conducted from 1961 to 1973 for peace-time tests of the feasibility of effecting geomorphic changes for construction. The Sedan crater was produced by a test nuclear detonation of 104 kilotons at the Nevada Test Site in 1962. The blast is 98 m deep and 390 m in diameter. *Source*: US Department of Energy, 2000. United States Nuclear Tests, July 1945 through September 1992. Nevada Operations Office, DOE/NV-209-REV15.

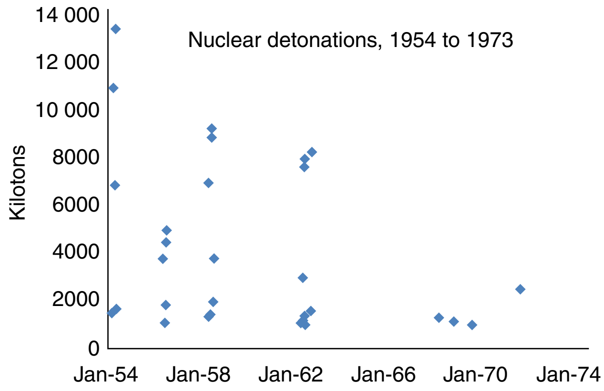


Figure 5 Energy released by experimental thermonuclear detonations conducted from 1954 to 1973. These detonations dwarf the 104 kilotons detonation that created the Sedan crater shown in **Figure 4**. Reproduced from US Department of Energy, 2000. United States Nuclear Tests, July 1945 through September 1992. Nevada Operations Office, DOE/NV-209-REV15.

released more energy than an equivalent mass of 10 kilotons (kt) of trinitrotoluene. One of the largest Plowshare experiments was conducted to test the feasibility of building an artificial harbor at Cape Thompson, Alaska, which was never constructed. A 104 kt blast was detonated at a depth of 194 m on the Nevada Test Site on 6 July 1962 as an experiment for the harbor project. The blast moved more than 11×10^6 tons of rock, alluvium, and soil and created the Sedan Crater (**Figure 4**). Other large detonations conducted to test the feasibility of using nuclear explosions for excavations were the Flask (105 kt), Kikitat (70 kt), Stoddard (31 kt), and Schooner (30 kt) tests.

Most nuclear detonations by the US Government were for weapons testing. More than a thousand nuclear devices were detonated between 1954 and 1973. The energy released by the largest blasts was two orders of magnitude larger than the largest detonations for Project Plowshare (**Figure 5**). More than 30 detonations greater than one megaton were conducted between 1952 and 1971 (US Department of Energy, 2000). Most large explosions were over islands in the tropical Pacific Ocean during the early period of testing, and the potential impact on geomorphic systems was not measured.

The potential for nuclear weapons to do instantaneous geomorphic work is tremendous and may exceed all other rates of human geomorphic change when considered over short time periods and restricted areas. A simple linear extrapolation of the energy released by the 104 kt Sedan detonation to larger 10 Mt events that could be used in thermonuclear warfare suggests that each device could move $\sim 10^8$ tons of material. The product of 100 such nuclear warheads and the geomorphic work done by each bomb yields a potential mass of 10^{10} tonnes of earth material that could be moved. The total movement of earth material by this process is roughly equivalent to the total combined movement of material by mining, agricultural, road building, and other human activities each year. An estimated 3.8×10^9 tons of material are moved by mining each year in the US alone (Hooke, 1994; *see* Chapter 13.6). However, many nuclear devices could disrupt geomorphic systems in ways that could initiate on-going geomorphic changes. For example, removal or closure of dams, lake sills, harbors, and river mouths, and destabilization of vegetation and ground cover, could initiate catastrophic geomorphic responses beyond the work of the initial explosions. Clearly, the capacity for instantaneous geomorphic change concentrated in specific places is a frightening aspect of human geomorphic potential and the proliferation of nuclear weapons should be avoided at all costs.

13.1.7 Restoration, Stabilization, Rehabilitation, and Management

The disruption of geomorphic systems by human activities or climate change may call for remediation to stabilize the system or to return part or all of it to a previous state. Remediation is likely to be an important area of growth in the future of anthropogenic geomorphology as the impacts of humans become better understood. Before remediation programs are undertaken, however, careful attention should be given to identifying alternatives, clearly defining the objectives, and reaching an agreement on the limitations to a project. Various approaches to treating disturbed geomorphic systems are available for consideration, and the costs and implications vary widely. Definitions of such terms as 'restoration' also vary widely, so a first step toward developing a program to treat a disturbed system should be to establish a common set of definitions, such as those presented in **Table 2**. Each of these approaches has different goals, yet the terminology is commonly used interchangeably, which can cause great confusion.

Table 2 Strategies for remediation of geomorphic change

Restoration	Reestablish structure and function of environmental systems to a predisturbance condition
Rehabilitation	Improve some structures and functions but not to predisturbance or stable conditions
Substitution or mitigation	Create or alter features to compensate for human changes, often in a different location
Reclamation	Alter a natural system to a different state; for example, wetland drainage or flood-protection projects
Stabilization	Reducing geomorphic change by protective engineering measures

Adapted from definitions used in aquatic restoration.
Source: FISRWG (1998), NRC (1992, 1999).

'Restoration' may imply many different strategies with entirely different goals, including stabilization, enhancement, or substitution projects. A common definition applied to aquatic restoration requires the return of a system to a predisturbance state:

> [R]estoration is defined as the return of an ecosystem to a close approximation of its condition prior to disturbance… Merely recreating the form without the functions, or the functions in an artificial configuration bearing little resemblance to a natural resource, does not constitute restoration. The goal is to emulate a natural, functioning self-regulating system that is integrated with the ecological landscape in which it occurs. Often, natural resource restoration requires one or more of the following processes: reconstruction of antecedent physical hydrologic and morphologic conditions; chemical cleanup or adjustment of the environment; and biological manipulation, including revegetation and the reintroduction of absent or currently nonviable native species. (NRC, 1992).

Restoration, therefore, may require identification of a reference system that is regarded as undisturbed or 'natural'. This calls for an understanding of geomorphic change and historical reconstructions.

Rehabilitation seeks to recover functionality of part a system without returning it to a previous condition is (FISRWG, 1998; NRC, 1999). For example, a beach may be rehabilitated by replenishing sand and protecting against erosion with groins, without restoring the natural sediment budget. Substitution or mitigation creates a new system, characteristically in a different location. For instance, a coastal dunefield may be created to replace one that has been developed. In contrast, reclamation projects that alter natural systems from their natural condition for practical purposes, such as wetland drainage, are commonly antithetical to restoration. Similarly, stabilization projects seek to reduce geomorphic change by protecting against erosion or sedimentation. These approaches tend to resist natural processes to enhance the human utility of systems, so they may be related to reclamation.

An important beginning in remediation of a disturbed system is to halt the disturbance processes to allow recovery. Once the disturbances are arrested, passive or natural restorati*o*n may be sufficient to repair the system (FISRWG, 1998; NRC, 1999). Passive restoration methods, such as the cessation of grazing animals, tend to be slow but can be an inexpensive method of restoration or rehabilitation. Active restoration involves direct methods that assist in the recovery process. In river restoration, for example, spawning gravels and large woody debris may be reintroduced.

13.1.8 Conclusion

This volume examines the human dimension of geomorphology, including anthropogenic geomorphology, climatic geomorphology, climate change impacts, and natural hazards. These diverse processes can be indirect and may involve lag times caused by storage and transfer of energy and mass, shifting thresholds of stability caused by changing landscape sensitivities, and feedbacks caused by changes in human activities prompted by geomorphic impacts. Rates of anthropogenic geomorphic change are accelerating in response to the increasing technological potential to do work and to the growing global population. The effects of climate warming are superimposed on the geomorphic potential of humans and also involve lag times, shifting thresholds, and feedbacks. Climate change is an anthropogenic phenomenon by itself, but it also has great relevance to human-induced geomorphic change because it has widespread impacts on landscape sensitivity and may alter the nature of impacts and response rates.

The effects of anthropogenic change can be traced back into the Neolithic, but they accelerated greatly in the industrial era. It is now commonly acknowledged that human activities can change the Earth surface system at a global scale. These changes are not confined to the atmospheric and biologic spheres, but extend to global geomorphic systems through a strong interconnectivity among systems. Natural hazards are an example of geomorphic processes affecting society, rather than the converse. Exogenic hazards may be intensified by human activities, and vulnerability to all natural hazards tends to increase greatly with population growth and dense settlement in hazardous areas. Nuclear detonations are both an effective geomorphic agent and a technological hazard that have the greatest instantaneous potential for anthropogenic geomorphic change. Environmental management will increasingly require and seek methods to stabilize and restore geomorphic systems and this will be an important growth area in geomorphology.

References

Arnoldus, H.M., 1978. An approximation of the rainfall factor in the Universal Soil Loss Equation. In: De Boodst, M., Gabriels, D. (Eds.), Assessment of Erosion. Wiley, Chichester, UK, pp. 127–132.

Asselman, N.E.M., Middelkoop, H., van Dijk, P.M., 2003. The impact of changes in climate and land use on soil erosion, transport and deposition of suspended sediment in the River Rhine. Hydrologic Processes 17, 3225–3244.

Avissar, R., Liu, Y., 1996. A three-dimensional numerical study of shallow convective clouds and precipitation induced by land-surface forcing. Journal of Geophysical Research 101, 7499–7518.

Bamber, J.L., Layberry, R.L., Gogineni, S.P., 2001. A new ice thickness and bed data set for the Greenland ice sheet. 1. Measurement, data reduction, and errors. Journal of Geophysical Research 106(D24), 33,773–33,780.

Batalla, R.J., Garcia, C. (Eds.), 2005. Geomorphological Processes and Human Impacts in River Basins. International Association of Hydrological Sciences, Publication 299, IAHS Press, Wallingford, UK, 245 pp.

Beckinsale, R.P., Chorley, R.J., 1991. The History of the Study of Landforms, vol. 3. Routledge, London.

Brierley, G., Stankoviansky, M., 2003. Geomorphic responses to land use change. Catena 51, 173–179.

Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. Transactions Institute of British Geographers NS4, 463–484.

Church, J.A., Gregory, J.M., Huybrechts, P., et al., 2001. Climate change. In: Houghton, J.T., Ding, Y., Griggs, D.J., et al., (Eds.), The Scientific Basis. Cambridge University Press, Cambridge, pp. 639–694.

Church, J.A., White, N.J., Konikow, L.F., et al., 2011. Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. Geophysical Research Letters 38, L18601. http://dx.doi.org/10.1029/2011GL048794

Claussen, M., 2004. Does land surface matter in weather and climate? Part A. In: Kabat, P., Claussen, M., Dirmeyer, P.A., et al., (Eds.), Vegetation, Water, Humans and Climate: A New Perspective on an Interactive System. Springer-Verlag, Berlin, 566 pp.

Commoner, B., 1972. The environmental cost of economic growth. In: Ridker, R.G. (Ed.), Population, Resources and the Environment. US Government Printing Office, Washington, DC, pp. 339–363.

Crutzen, P.J., Stoermer, E.F., 2000. The 'Anthropocene'. Global Change Newsletter 41, 17–18.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., et al., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature 364, 218–220.

DeFries, R., Field, C., Fung, I., Collatz, G., Bounoua, L., 1999. Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. Global Biogeochemical Cycles 13, 803–815.

Derbyshire, E., 1973. Introduction. In: Derbyshire, E. (Ed.), Climatic Geomorphology. Harper & Row Pub., Inc., New York, pp. 11–18.

Don, A., Schumacher, J., Freibauer, A., 2010. Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. Global Change Biology 17, 1658–1670.

Dull, R.A., Nevle, R.J., Woods, W.I., Bird, D.K., Avnery, S., Denevan, W.M., 2010. The Columbian encounter and the Little Ice Age: abrupt land use change, fire, and greenhouse forcing. Annals Association of American Geographers, 100(4), 755–771. doi:10.1080/00045608.2010.502432

Ehrlich, P.R., Holdren, J.P., 1971. Impact of population growth. Science 171(12), 12–17.

Evan, A.T., Dunion, J., Foley, J.A., Heidinger, A.K., Velden, C.S., 2006. New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks. Geophysical Research Letters 33. L19813.http://dx.doi.org/10.1029/2006GL026408 L19813.

Feddema, J.J., Oleson, K.W., Bonan, G.B., Mearns, L.O., Buja, L.E., Meehl, G.A., Washington, W.M., 2005. The importance of land-cover change in simulating future climates. Science 310, 1674–1678.

Federal Interagency Stream Restoration Working Group (FISRWG), 1998. Stream Corridor Restoration: Principles, Processes, and Practices. PB98-158348LUW. Federal Interagency Stream Restoration Working Group, Washington, DC.

Fournier, F., 1960. Climat et Erosion. Presses Universitaires de France, Paris.

Fryirs, K., Brierley, G.J., 2009. Naturalness and place in river rehabilitation. Ecology and Society 14(1), 20. http://www.ecologyandsociety.org/vol14/iss1/art20/ (accessed October 2010).

Gill, T.E., 1996. Eolian sediments generated by anthropogenic disturbance of playas: human impacts on the geomorphic system and geomorphic impacts on the human system. Geomorphology 17, 207–228.

Graf, W.L., 1996. Geomorphology and policy for restoration of impounded American rivers: what is 'natural'? In: Rhoads, B.L., Thorn, C.E. (Eds.), The Scientific Nature of Geomorphology. John Wiley & Sons Ltd., NY, pp. 443–473.

Grünzweig, J., Sparrow, S., Yakir, D., Chapin, S., 2004. Impact of agricultural land use change on carbon storage in Boreal Alaska. Global Change Biology 10, 452–472.

Holdren, J.P., Ehrlich, P.R., 1974. Human population and the global environment. American Scientist 62, 282–292.

Hooke, R., 1994. On the efficacy of humans as geomorphic agents. GSA Today 4, 224–225.

Houghton, R.A., 2010. How well do we know the flux of CO_2 from land-use change? Tellus B 62(5), 337–351. http://dx.doi.org/10.1111/j.1600-0889.2010.00473.x.

House, J.I., Prentice, I.C., Ramankutty, N., Houghton, R.A., Heimann, M., 2003. Reconciling apparent inconsistencies in estimates of terrestrial CO_2 sources and sinks. Tellus 55B, 345–363.

Iino, N., Kinoshita, K., Tupper, A.C., Yano, T., 2004. Detection of Asian dust aerosols using meteorological satellite data and suspended particulate matter concentrations. Atmospheric Environment 38, 6999–7008.

International Panel on Climate Change (IPCC), 2007. Summary for Policymakers. In: Solomon, S.Q.D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., (Eds.), pp. 1–18. Cambridge University Press, Cambridge, UK.

Ito, A., Penner, J.E., Prather, M.J., et al., 2008. Can we reconcile differences in estimates of carbon fluxes from land-use change and forestry for the 1990s? Atmosphere Chemistry and Physics 8, 3291–3310.

James, L.A., Hodgson, M.E., Ghoshal, S., Megison Latiolais, M., 2012. Geomorphic change detection using historic maps and DEM differencing: the temporal dimension of geospatial analysis. Geomorphology 137, 181–198.

James, L.A., Marcus, W.A., 2006. The human role in changing fluvial systems: retrospect, inventory and prospect. Geomorphology 79, 152–171.

Kabat, P., Claussen, M., Dirmeyer, P.A., et al., (Eds.), 2002. Vegetation, Water, Humans and the Climate: A New Perspective on an Interactive System. Springer, Heidelberg.

Kates, R.W., Clark, W.C., Corell, R., et al., 2001. Sustainability Science. Science 292(no.5517), 641–642. http://dx.doi.org/10.1126/science.1059386.

Knox, J.C., 2001. Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. Catena 42, 193–224.

Koren, I., Kaufman, Y.J., Washington, R., Todd, M.C., Rudich, Y., Martins, J.V., Rosenfeld, D., 2006. The Bodele depression: a single spot in the Sahara that provides most of the mineral dust to the Amazon forest. Environmental Research Letters 1(014005), 1–5.

Kutzbach, J.E., Ruddiman, W.F., Vavrus, S.J., Philippon, G., 2010. Climate model simulation of anthropogenic influence on greenhouse-induced climate change (early agriculture to modern): the role of ocean feedbacks. Climatic Change 99, 351–381.

Lythe, M., Vaughan, D.G. the BEDMAP Consortium, 2001. BEDMAP: a new ice thickness and subglacial topographic model of Antarctica. Journal of Geophysical Research 106(B6), 11335–11352. http://dx.doi.org/10.1029/2000JB900449.

Meybeck, M., Vörösmarty, C.J., 2004. The integrity of river and drainage basin systems: challenges from environmental change. In: Part D., Kabat, P., Claussen, M., Dirmeyer, P.A., Gash, J.H.C., Bravo de Guenni, L., Meybeck, M., Pielke, R., Vörösmarty, C.J., Hutjes, R.W.A., Lütkemeier, S. (Eds.), Vegetation, Water, Humans and Climate: A New Perspective on an Interactive System. Springer-Verlag, Berlin, pp. 297–463.

Montgomery, D.R., 2008. Dreams of natural streams. Science 319(5861), 291–292.

Montgomery, D.R., Balco, G., Willett, S.D., 2001. Climate, tectonics, and the morphology of the Andes. Geology 29(7), 579–582.

National Research Council (NRC), 1992. Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy. National Academy Press, Washington, DC.

National Research Council (NRC), 1999. New Strategies for America's Watersheds. National Academy Press, Washington, DC.

Nevle, R.J., Bird, D.K., 2008. Effects of syn-pandemic fire reduction and reforestation in the tropical Americas on atmospheric CO_2 during European conquest. Palaeogeography, Palaeoclimatology, Palaeoecology 264, 25–38.

Newson, M.D., Large, A.R.G., 2006. 'Natural' rivers, 'hydromorphological quality' and river restoration: a challenging new agenda for applied fluvial geomorphology. Earth Surface Processes and Landforms 31, 1606–1624.

Nordstrom, K.F., 2000. Beaches and Dunes of Developed Coasts. Cambridge University Press, NY.

Nordyke, M.D. 2000. The Soviet Program for Peaceful Uses of Nuclear Explosions. UCRL-ID-124410 Rev 2. Lawrence Livermore National Laboratory, Technology Information Department Digital Library.

Olofsson, J., Hickler, T.H., 2007. Human impact on the global carbon cycle during the last 6000 years. Vegetation History and Archeobotany 17, 605–615.

Petit, J.R., Jouzel, J., Rayaud, D., et al., 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399, 429–436.

Pimentel, D., Harman, R., Pacenza, M., Pecarsky, J., Pimentel, M., 1994. Natural resources and an optimum human population. Population and Environment 15, 347–369.

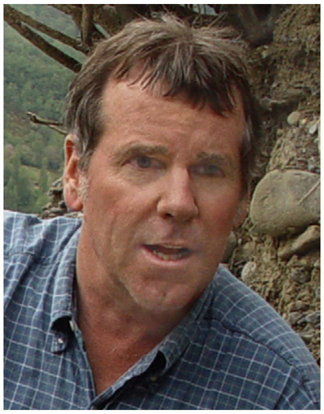
Pimentel, D., Harvey, C., Resosudarmo, P., et al., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267, 1117–1123.

Plass, G.N., 1956. Effect of carbon dioxide variations on climate. American Journal of Physics 24, 376–387.

Pongratz, J., Reick, C.H., Raddatz, T., Claussen, M., 2009. Effects of anthropogenic land cover change on the carbon cycle of the last millennium. Global Biogeochemical Cycles 23. GB4001. http://dx.doi.org/10.1029/2009GB003488.

Ramankutty, N., Gibbs, H.K., Achard, F., DeFries, R., Foley, J.A., Houghton, R.A., 2007. Challenges to estimating carbon emissions from tropical deforestation. Global Change Biology 13, 51–66.
Ruddiman, W.F., 2003. The anthropogenic greenhouse era began thousands of years ago. Climatic Change 61, 261–293.
Ruddiman, W.F., 2004. The role of greenhouse gases in orbital-scale climatic changes. EOS 85, 1–7.
Ruddiman, W.F., 2007. The early anthropogenic hypothesis: challenges and responses. Reviews of Geophysics 45, 1–37.
Ruddiman, W.F., Ellis, E.C., 2009. Effect of per-capita land use changes on Holocene forest clearance and CO_2 emissions. Quaternary Science Reviews 28, 3011–3015.
Schumm, S.A., 2005. River Variability and Complexity. Cambridge University Press, Cambridge, UK, 220 pp.
Slaymaker, O., Spencer, T., Dadson, S., 2009. Landscape and landscape-scale processes as the unfilled niche in the global environmental change debate: an introduction. In: Slaymaker, O., T. Spencer, Embleton-Hamann (Eds.), Geomorphology and Global Environmental Change. Cambridge University Press, Cambridge, UK, pp. 1–36.
Steffen, W., Sanderson, A., Typson, P.D., et al., 2004. Global Change and the Earth System: A Planet Under Pressure. Springer-Verlag, Berlin, 336 pp.
Stutz, M.L., Pilkey, O.H., 2005. The relative influence of humans on barrier islands: humans versus geomorphology. Reviews in Engineering Geology 16, 137–147.
Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impacts of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376–380.
Szabó, J., 2010. Anthropogenic geomorphology: subject and system. In: Szabó, J., Dávid, L., Lóczy, D. (Eds.), Anthropogenic Geomorphology: A Guide to Man-Made Landforms. Springer, Dordrecht, Translated from Antropogén Geomorfológia (2006), by Z. Baros, D. Lóczy, and P. Rózsa. University of Debrecen, Hungary.
Thornthwaite, C.W., 1956. Modification of rural microclimates. In: Thomas, Jr. W.L. (Ed.), Man's Role in Changing the Face of the Earth. University of Chicago Press, Chicago, pp. 567–583.
US Department of Energy, 2000. United States Nuclear Tests, July 1945 through September 1992. Nevada Operations Office, DOE/NV-209-REV15.
United Nations, 2011. World population to reach 10 billion by 2100 if fertility in all countries converges to replacement level. Press Release, 3 May 2011.
Uno, I., Amano, H., Emori, S., Kinoshita, K., Matsui, I., Sugimoto, N., 2001. Trans-Pacific yellow sand transport observed in April 1998: a numerical simulation. Journal of Geophysical Research 106(D16), 18,331–18,344.
Vandenberghe, J., 2003. Climate forcing of fluvial system development: an evolution of ideas. Quaternary Science Reviews 22, 2053–2060.
Vavrus, S., Ruddiman, W.F., Kutzbach, J.E., 2008. Climate model tests of the anthropogenic influence on greenhouse-induced climate change: the role of early human agriculture, industrialization, and vegetation feedbacks. Quaternary Science Reviews 27, 1410–1425.
Walker, H.J. (Ed.), 1988. Artificial Structures and Shorelines. Kluwer Academic Publications, Dordrecht.
Walling, D.E., Probst, J.-L. (Eds.), 1997. Human Impact on Erosion and Sedimentation. International Association of Hydrological Sciences Publication 245, IAHS Press, Wallingford, UK, 311 pp.
Walter, R.C., Merritts, D.J., 2008. Natural streams and the legacy of water-powered mills. Science 319, 299–304.
Wilson, E.O., 1992. The Diversity of Life. Harvard University Press, Cambridge, MA.
Wohl, E.E., 2001. Virtual Rivers: Lessons from the Mountain Rivers of the Colorado Front Range. Yale University Press, New Haven, CT.
Wohl, E.E., Merritts, D.J., 2007. What is a natural river? Geography Compass 1, 871–900.
Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes and Landforms 3(2), 189–208.
World Commission on Environment and Development (WCED), 1987. Our Common Future: Report of the World Commission on Environment and Development. University Press, Oxford, UK.
Zalasiewicz, J., Williams, M., 2008. Are we now living in the Anthropocene? GSA Today 18(2), 4–8.

Biographical Sketch



L. Allan James is a professor in the Department of Geography at the University of South Carolina, Columbia, South Carolina. He received an undergraduate degree in geography at the University of California, Berkeley, masters degrees in water resources management and geography at the University of Wisconsin, Madison, and a PhD in geography and geology at the University of Wisconsin, Madison. His primary research interests are in river and watershed science, fluvial geomorphology, and linking human impacts in river systems to historical sedimentation and flood hydrology. He is also engaged in research on human–environment interactions, water resources, and hydrogeomorphic applications of geographic information (GI) science. He has allied interests in geomorphometry and remote sensing applied to historical change detection, especially to fluvial systems and gullies, and mapping geomorphic evidence of former glaciations in the Sierra Nevada, California. He has served as chair of the Geomorphology Specialty Group of the Association of American Geographers, panelist to the Geomorphology and Quaternary Science Division of the Geological Society of America, founding editor of the GSG_AAG web page, and national councilor to the AAG.

Carol Harden is professor and interim head of the Department of Geography at the University of Tennessee, Knoxville, TN 37996-0925. Her research interests include human–environment interactions, watershed processes, and terrestrial land–water interfaces. She has active research projects in the Southern Appalachians and Andes mountains. Harden is editor-in-chief of *Physical Geography* and served as president of the Association of American Geographers in 2009–10.

John Clague is Shrum professor of science at Simon Fraser University. He was educated at Occidental College (BA, 1967), the University of California Berkeley (MA, 1969), and the University of British Columbia (PhD, 1973). Clague worked as a research scientist with the Geological Survey of Canada from 1975 until 1998. In 1998 he accepted a faculty position in Department of Earth Sciences at Simon Fraser University, where he is currently the Canada Research Chair in Natural Hazard Research. He is director of the Centre for Natural Hazard Research at SFU. Clague has published more than 200 papers in 45 different journals on a range of Earth science disciplines, including glacial geology, geomorphology, stratigraphy, sedimentology, and natural hazards, and has consulted for several private-sector firms and government agencies. His graduate students are currently conducting research on natural hazards and late Holocene climate change in western Canada. Clague's other principle professional interest is improving public awareness of Earth science by making relevant geoscience information available to students, teachers, and the general public. He gives frequent talks to school and community groups and is regularly called on by the media to comment on a range of Earth science issues. Clague has written two popular books on the geology and geologic hazards of southwest British Columbia, and a textbook on natural hazards. He is a fellow of the Royal Society of Canada, former President of the Geological Association of Canada, and Past-President of the International Union for Quaternary Research. He is recipient of the Geological Society of America Burwell Award, the Royal Society of Canada Bancroft Award, APEGBCs 2001 and 2005 *Innovation* Editorial Board Awards, the Geological Association of Canada's (GAC) 2006 E.R.W Neale Medal, and GACs 2007 Logan Medal. He was the 2007–08 Richard Jahns Distinguished Lecturer for the Geological Society of America and Association of Environmental and Engineering Geology.