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Résumé de l'article

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Article

Rapid Geological Change Challenges Concepts of Sustainability

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SUMMARY
Many landscapes are subject to biophysical change on the time scale of a normal human life. Despite a common belief that if the human footprint were absent, natural landscapes would be in benevolent stasis, such rapid changes have frequently affected human history; also, they have implications for environmental attitudes and policies. Now, when human influences on the environment are greater than ever and threaten to overwhelm natural systems, a re-examination of non-human change, and particularly those earth processes that cause harm, may be instructive. Scanning the voluminous literature on sustainable development, it is hard to find discussions of natural disasters and rapid geological change. There is an opportunity for earth scientists to contribute to the search for a clearer concept and its application. Looking at physical landscapes in terms of their potential for continuity and for providing natural resources can offer fresh perspectives on the complex idea of sustainability.

SOMMAIRE
Nombreux sont les paysages qui sont exposés à des changements biophysiques à l'échelle temporelle humaine normale. Contrairement à la croyance répandue selon laquelle en l'absence d'humains, les paysages naturels connaîtraient un état d'équilibre bienveillant, de tels changements ont fréquemment modulé l'histoire humaine; ces changements ont aussi des implications sur les attitudes et les politiques environnementales. Maintenant que les effets anthropiques sur l'environnement n'ont jamais été aussi importants, menaçant même l'existence de systèmes naturels, il serait instructif de réexaminer les changements autres qu'humains, en particulier les processus terrestres néfastes. L'étude de l'imposante documentation traitant de développement viable ne comprend que peu d'études traitant de désastres naturels et de changements géologiques rapides. Voilà l'occasion pour les géoscientifiques de contribuer à mieux circonscrire le concept de viabilité et à en développer des outils d'application efficaces. Considérer les paysages physiques en s'attachant à établir leur potentiel naturel respectif à subsister et comme source de ressources naturelles pourra dévoiler des perspectives nouvelles sur la notion de viabilité.

NATURE STRIKES
December 26, 2004. News spreads round the world of a massive tsunami that washes over coastal lowlands in the Indian Ocean. Over the following days, the magnitude of this natural disaster, with its horrifying loss of life, becomes clear (Fig. 1a). Nine months later, New Orleans is extensively flooded as Hurricane Katrina strikes and breaches the levees along the Mississippi, and towns and villages along the northern Gulf Coast are inundated. In both situations, coastlines undergo irreversible changes. Parts of NW Sumatra are uplifted by the fault movement that caused the tsunami, so that some coral reefs are now high and dry: in other places residential land is submerged. On the south and east coasts of Sri Lanka, blankets of sand cover nearshore soils, potable groundwater is contaminated by sea water, and coastal dune complexes are breached. Along the Gulf Coast of Mississippi, barrier islands disappear and estuaries are blocked or diverted to other courses.

Those who live in coastal areas of the five nations that border the Caspian Sea are used to somewhat slower changes. The largest inland water body on Earth, the Caspian Sea has a long history of fluctuating levels, but for reasons not entirely understood, the 20th century record was particularly strange (Rychagov 1997; Golubev 1998). In the 1930s, when the region was very dry and runoff into the Caspian Sea was low, water levels began to drop. The forecasts were that the sea level would decline further and never again rise, so many settlements and port facilities were moved closer to the new shoreline. Indeed, after a brief period of stability, the water level continued to drop. Russian authorities made plans to divert northern rivers so that they would flow south into the Caspian Sea. Then to general surprise, having reached 3 m below the 1930s level, the water began to rise again in

Figure 1. a) The tsunami of December 26, 2004 destroyed this urban landscape in Galle, Sri Lanka (I. Amerasinghe); b) Iranian mosque flooded by sea-level rise. Eastern end of Minakaleh spit, SE corner of Caspian Sea (S. Kroonenberg); c) To assist farmers in managing groundwater usage, a sign near Narromine, NSW, Australia, indicates changes in groundwater level (Colin Simpson); d) Stonehenge in southern England - little change over some 5000 years.

1977, and by 1992 it was 2 m higher. The scale of this change was comparable to the disastrous fall of the 1930s, although in the opposite direction. The shoreline of the sea in places moved 25-35 km inland, and ports, railroads, roads, oil wells, and even a nuclear waste dump were inundated (see Fig. 1b). These variations in sea levels forced many changes to coastal landscapes, habitats, vegetation and aquatic life. They also caused great difficulties for people living on the edges of the sea. In the latest flooding, some 25 000 people lost their homes. The financial costs, during the period of rising water levels, for Kazahkstan reached $2 billion, Azerbaijan nearly $4 billion and Russia $7 billion (Golubev 1998). The best attempts to plan ahead had been thwarted by nature's surprise.

NATURE IN FLUX NOT STASIS

The world around us - the outdoors, the physical landscape that is not overwhelmed by cultural overlays - frequently wreaks havoc on all forms of life. Hardly a day goes by without some new weather extreme, flood or earthquake featured in the media. There is growing concern among relief agencies, environmental authorities and insurance companies about the risks of natural hazards and the mitigation of disasters, and there is no shortage of books on the topic. Floods, earthquakes, volcanic eruptions, cyclones, tornados, tidal waves, are all common and repeated evidence of nature's harmful ("dark") side. Yet, it is common to blame such events on human actions, assuming that landscapes fare better in the absence of people. Underpinning this seems to be a deep-seated conviction that harkens back to the idea of a Garden of Eden, a place of perfection where nature was ever at peace and equilibrium until the first humans entered the scene.

A few years ago, Prince Charles was quoted as blaming the storms and floods then ravaging Britain on humanity's "arrogant disregard of the delicate balance of nature" (*Guardian Weekly* Nov 9-15, 2000, p. 9). In the Outer Hebrides, a plan to install a bank of giant windmills recently met opposition on the grounds that landscapes are "being hastily sacrificed in the name of clean energy". Given that no one in their right mind would advocate burning masterpieces of landscape art to generate energy, Robert Macfarlane in the *Guardian Weekly* (March 4-10, 2005) asks why would they sacrifice equally "irreplaceable" landscapes. He goes on to write that "language and even a people may go, but the land was immutable, a last and lasting bastion for human sanctity and belonging." A landscape painting may well not change with time, if kept in the right conditions, but far from being fixed and static, landscapes the world over are ever changing, at one temporal and spatial scale or another. Seeing landscapes as "immutable" denies nature its independence, its on-going autonomy.

THE ABIOTIC IN DEEP AND SHALLOW TIME

This is a time of unprecedented focus on environmental matters, from local pollution to global climate change. Much of the contemporary discussion and the search for a better environmental ethic are based on what we know about the living world, about individual organisms, species and their communities. Ideas from biology, ecology, forestry, and wildlife studies have greatly influenced the way we think about nature. The importance of the geological perspective has, perhaps, been less recognized, despite the fact that all life draws its energy and nutrients from the inorganic world: the sun, air, water, and rocks and soils. Geological processes tell us important things about the character of nature, and about environmental change, but for the general public it is only the short-term changes that are relevant.

To most, geology is about ancient fossils, rocks, and mineral deposits that formed millions of years ago. Indeed, geology is the source of one of the most important contributions to our thinking about the world - the concept of "deep" time. The idea of a thousand million years of time is hard to grasp, especially in today's world where television and the Internet have given us the capacity to see almost instantaneously what is happening all over the world. Events in politics, sports and the arts take place, hold one's attention briefly and pass from the media stage in days. Beyond the electoral and planning cycle of 5 to 10 years, change seems of little concern, or did, at least, before climate change entered the public discourse. So, by concentrating on the very long time span, earth scientists try the patience of decision-makers and others fixed firmly on events and issues that last only a few years or so. This is why it is so important to emphasize the many physical processes and events that take place on a much shorter time scale, and that can be readily seen within a normal human life, say 100 years at most.

For those who study geomorphology; the way the chemistry of soils, water and rocks interact and affect life; the behaviour of rivers, lakes and coasts and the sediment that move through them; and the formation, movement and disappearance of glaciers and ice sheets; the story told is one of continual change in the land and the water that flows through it. There are both the very rapid changes, such as floods and eruptions that overwhelm people and ecosystems, and slow, more pervasive transformations that may be perceptible only after many decades or centuries. Intermediate between these two extremes are processes such as glacier advance and melting, switches in river channels, ground subsidence where fluids beneath the surface are withdrawn, dissolution of limestone and gypsum bedrock in areas of active karst, and a wide range of near-surface changes when ground freezes or thaws. Snow avalanches can move at speeds of m/sec, debris and mudflows at cm to km/hour, groundwater and glaciers cm/day to km/year, and desert dunes mm to cm daily. A simple taxonomy of the most important short-term (<100 years) geological changes has been formulated by the International Union of Geological Sciences under the term "geoindicators" (Berger and Iams 1996; Berger 2006; see also Table 1 and [www.geoindicator.org]).

Table 1. Landscape processes and components that can change in less than 100 years

Landscape Feature	Processes & Components
Arid Lands	dune movement, dust transport, wind erosion, surface crusts and fissures
Cryosphere	glacier advance/retreat, frozen ground activity
Wetlands	areal extent, structure, hydrology
Soils and Sediments	quality, erosion, sequence and composition, gas content
Coasts	shoreline movement, relative sea level, coral chemistry
Lakes	levels and salinity
Rivers	streamflow, sediment transport and storage, channel location and morphology
Surface and Groundwater	quality, groundwater level, soil water chemistry, karst activity, springs and deposits
Hazards	earthquakes, eruptions, landslides, avalanches, floods, surface subsidence
Others	subsurface temperature, ground fire, submarine topography

TRACKING RAPID LANDSCAPE CHANGE

There is a problem in obtaining the information needed to model, understand and respond to many environmental challenges. The public demands and governments receive a constant flow of information on the weather and the economy, including the daily reporting of stock exchange indices and foreign exchange rates. Even though some economists increasingly warn that standard econometric indicators, such as GDP, ignore nature's "capital" and its environmental services, there is still widespread resistance when it comes to monitoring changes in the biophysical environment. Despite the wide range of instruments and techniques available to measure the pulse of the Earth and its surficial processes, parameters relating to rapid geological change rarely appear in national accounts. One exception is the annual State-of-the-Environment report for Lithuania, which includes rates of karstic denudation, the number of new sinkholes, and changes in groundwater level and chemistry (Satkunas, pers. comm. 2008, see also Fig. 1c).

Government agencies responsible for the environment commonly offer the excuse that to monitor landscape change is too time-consuming and expensive. Academic institutions and research funding agencies generally regard the tracking of natural systems as inferior to primary research. Yet, to be able to understand and assess the importance of landscape change, data are needed on what changes are taking place, their extent, past trends, and impending thresholds. Even if the instrumental record is still too short to enable us to fully characterize earlier changes, a picture of past variations in climate and landscape conditions is now available from ice cores, lake and river sediments, growth rings in corals and trees, temperatures in boreholes, and isotopes in groundwater (NRC 2006).

The evidence that human actions are now influencing global climate is overwhelming (Flannery 2005; IPCC 2007), and some argue that reducing the human imprint to zero would stabilize the global climate. However, climate changes have occurred throughout geological history, and not long before modern humans appeared, there were several very abrupt changes, at times on the order of 5 to 10°C within a decade or two (Weart 2007). So pervasive has the idea of climate change become that it is now commonplace to identify this as a cause of many environmental stresses, ignoring both other causes and the fact that weather and climate are different. Moreover, there are many landscape changes that can take place in a regime of steady climate, related for example to variations in precipitation and storm occurrences. Landslides, dust storms, and coastal erosion do not require climate changes, and seismic and volcanic events are triggered independently of climate and weather, although they may well influence meteorological processes. As serious a challenge as climate warming undoubtedly is, it cannot cancel out all other natural changes.

LANDSCAPE CHANGES ON A HUMAN TIME-SCALE

Looking back in history and pre-history, are there insights from past landscape change, whether climate-driven or not, of which ancient peoples would have been aware and to which they would have had to react in some way? Did they adapt and remain where they were? Did such changes force emigration, as people sought places more amenable to their way of life? Were their experiences remembered in story and tradition? Are there lessons from the past for circumpolar peoples now facing rapid environmental and climate change, as permafrost and glaciers melt, sea ice disappears and coastlines erode?

Many long-term processes are invisible over the short term. Where one observer looks for signs of recent change another sees only the long-term pattern. As Moseley (2002, p. 193) puts it, "a short drought is recognized as an unnatural condition, but one that endures for centuries becomes the natural state of things". The existence today of Pyrenean caves occupied by pre-historic peoples, of ancient ruins still standing on flood plains in Egypt, and of undisturbed campsites built four millennia ago along Arctic beaches demonstrates that some landscapes do indeed exhibit long-term stability (Fig. 1d). Elsewhere, landscapes change rapidly enough to disrupt people's lives, as in the sudden burial of Pompeii in 79 AD, the destruction of Lisbon in 1755, and the inundation of coastal settlements of the southern Indian Ocean in December 2004. There are innumerable examples where non-catastrophic landscape changes of the past must have been obvious to local inhabitants, and others where the human response may not show up for decades. In the Indian state of Orissa, there are many one-time coastal settlements that are now tens of kilometres inland as a result of shifting of river courses, sediment deposition along the shoreline, and falling sea levels (Patnaik 2003). Though contemporary accounts are lacking of how people adapted to these changes, it is hard to imagine that they would not have been aware that their coastal landscapes and their way of life were changing.

Fiji and other western Pacific islands were first populated by the Lapita people between 1260 and 550 BC. Most settled near the sea, where they depended on marine resources, especially coral reefs, and from horticulture in the coastal lowlands. Between 1200 and 1475 AD, sea level fell over 1.5 m, temperatures dropped about 1.5°C, and El Niño increased in frequency, yielding more rain. This "AD 1300 event" caused profound environmental and socio-cultural changes (Nunn 2000; Kumar et al. 2006). New islands appeared above sea level, and coral reefs along former coastlines became less productive. As sea level fell so did water tables, and people abandoned coastal settlements on many islands to move to hilltops and caves.

Did past waves of migration across the Arctic and sub-arctic take place during the good times of plenty, or were they driven by changes in land and ice distribution? One likely factor in the decline of the Tuniit peoples of the Arctic, the fore-runners of the Inuit, was the Medieval Warm Period, which brought open water near their coastal lands and prevented them from hunting on the ice, a scenario being repeated today (McGhee 2007). That the Arctic landscape did change markedly during times of human occupation is not in doubt. Some 8000 years ago, people were living on what was then the continental mainland, in wooden houses that can still be seen on what is now a remote island nearly 600 km north of the present margin of the East Siberian Sea (Bauch and Kassens 2005; McGhee 2007). The Arctic Human Development Report (Einarsson et al. 2004) sees many Northern cultures as continuing to be vigorous, despite what outsiders see as destructive changes. For other commentators, the current environmental changes may be starting to challenge the ability of Northern peoples to adapt (Krupnik and Jolly 2002).

Historians have traditionally described the rise and fall of societies and civilizations in terms of social clashes and struggles for power, and for many years it was an article of faith among many archaeologists that early societies were immune to natural change. The numerous examples of the societal effects of volcanic eruptions challenge this view (de Boer and Sanders 2001; Torrance and Grattan 2002). The debate is very much alive today, for although some writers still attribute the decline of many early civilizations, such as those of the Bronze Age from the Mediterranean to the Indus Valley, to climatic and related landscape changes (Wright 2004), others emphasize the complex interplay of environmental and social factors (Bawden and Reycraft 2000; Rowland 1999; Hoffman and Oliver-Smith 2002; Gunderson and Holling 2002; Diamond, 2005; Costanza et al. 2007). For example, it has long been thought that the eruption of Thera on Santorini in the

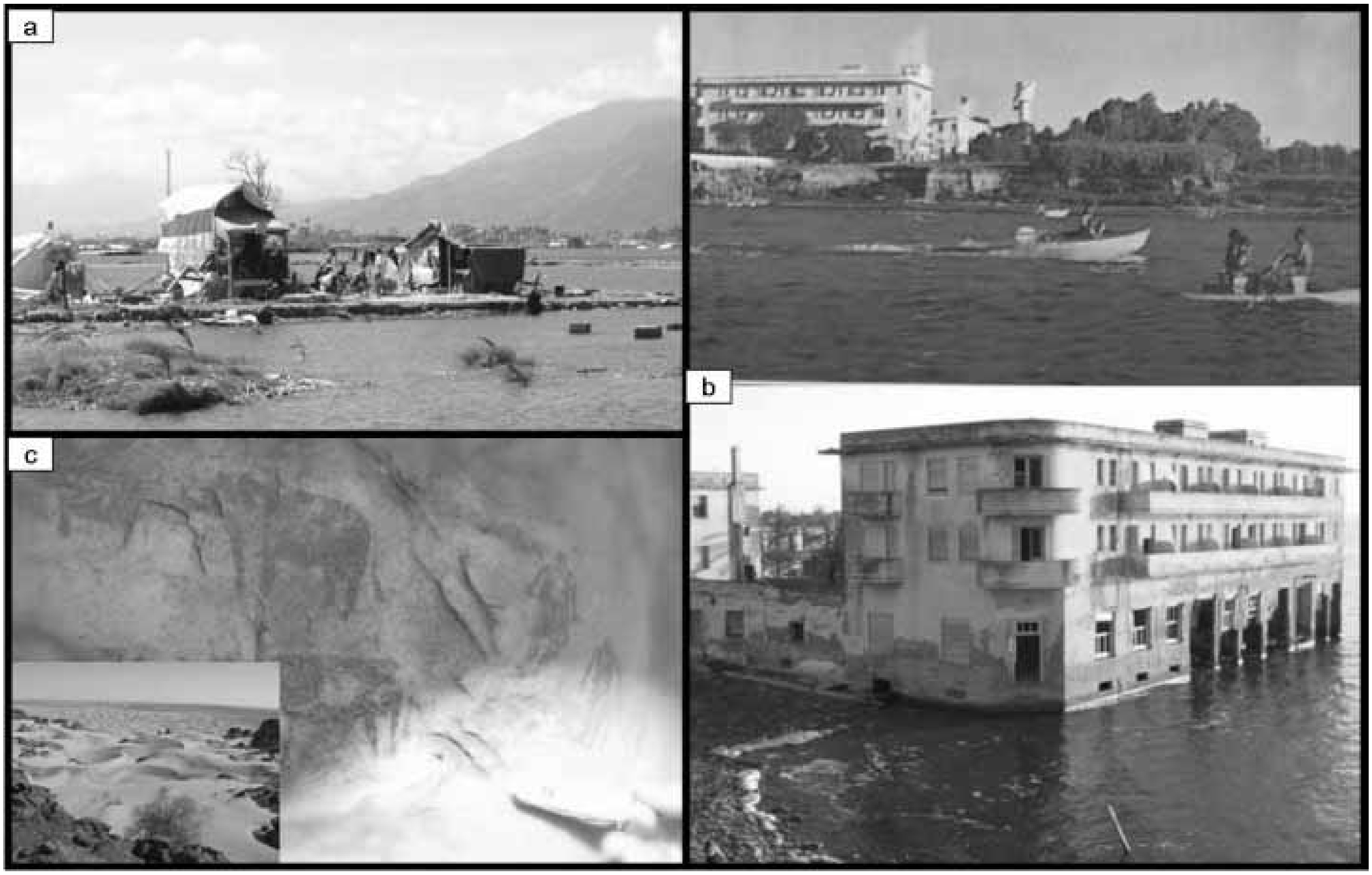

Figure 2. a) This family near Banda Aceh in Sumatra is trying to rebuild their home where it was before the land subsided during the earthquake (T. Babcock); b) Laguna Mar Chiquita, in Cordoba Province, Argentina, one of the largest saline lakes in the Southern Hemisphere, has varied markedly in level, mainly as a result of changes in rainfall. Today, this once proud lakeside hotel is abandoned, save for the occasional "mystery tour"; c) Dune field in western Mauritania (inset). Caves in foreground contain Neolithic rock paintings of people and animals.

Aegean Sea between 1628 and 1520 BC was responsible for the demise of the Minoan culture of Crete shortly afterwards. Current research, however, indicates that there were likely other social and economic factors involved, and that the huge eruption and collapse of Thera may have had only a marginal effect (Grattan 2006).

Diamond (2005) navigates the debate by discussing a wide range of causes, human and non-human, that influenced history and remain relevant today. Yet, all of those he lists as the most serious past and present environmental problems are firmly human-caused. Natural change, whether fast or slow, figures little in his summary discussion (see also Tainter 2006). This is in marked contrast to the neo-deterministic view of the climate-driven rise and fall of Middle Eastern civilizations presented by Issar and Zohar (2004). In the Negev Desert, for example, there are the ruins of six towns dating from 300 BC to 500 AD. The traditional view was that the collapse of these cities was brought about by invading Arab nomads who neglected the dams and terraces built to deliver water to the settlements and farmlands. However, as Issar and Zohar (2004) show, this was also a period of natural climatic change that led to the desertification of the region. Whatever the precise mix of societal and environmental effects, it seems clear that the collapse of the Mayan civilization in the Yucatan Peninsula of Mexico was induced by repeated drought, with the effects played out over several centuries (Haug et al. 2003). Rapid population expansion during favourable climatic conditions from 550 to 750 AD left the Mayans operating at the limits of the carrying-capacity of their environment, so that when repeated severe droughts occurred during the next 160 years, at 760, 810, 860 and 910 AD, millions died (Gill et al. 2007).

Responses to natural disasters and rapid landscape change vary according to local circumstances. Surprise is often expressed that those whose homes and livelihoods have been destroyed by disaster return to re-build what they have lost rather than moving out of dangerous locations (Leroy 2006). A return to home territory is evident today in the coastal zones of Sumatra (Fig. 2a), Sri Lanka, and Thailand, as fishermen and townspeople re-build on the coastal plains swept by the 2004 tsunami. There are several obvious reasons why this may be so. First, this is the land they own and to which they have a long attachment. Second, they may be unable to afford to live elsewhere. Third, beyond the margins of the flood plain or the slopes of the unstable mountain, the volcano or the fault zone, the suitable land may be already owned or occupied by others, as along part of the tsunami-damaged coast of Sri Lanka where there is nowhere else handy to move. Moreover, people may be adapted to a culture of disaster, so that they accept the risk of future catastrophes and prefer to live on land they know than to move elsewhere, as along the fault zones of California or the slopes of Italian volcanoes or Swiss mountains.

It is strange to find that the record of natural disasters of the historical past is sometimes missing or blurred. The destruction of Pompeii and its 20-30 000 inhabitants by the 79 AD eruption of Vesuvius was witnessed by many people at the time and described in detail by Pliny the Younger. Yet, for a long time afterwards, there was little memory of where Pompeii was actually located. Only in 1755, during the construction of a nearby canal, did workers first come across buried ruins that were identifiable as Pompeian. The classical sources were reticent on the subject, which "testifies to the depth of the shock that was felt at the time" (Butterworth and Laurence 2005, p. 3). Perhaps a similar sense of shock typifies other natural disasters of the past so that only vague memories survive. It is remarkable, for example, that the sagas of Iceland, which has one of the world's longest historical archives, extending for some 1000 years, contain so few references to volcanic eruptions and earthquakes, despite the scientific evidence that there were, in this period, a number of major events. Indeed, Iceland lost about 25% of its population after the 934 eruption of the Eldgja fissure and of Laki in 1783 (Grattan 2006)

There is an odd juxtaposition of attitudes here. Monuments to human-induced tragedies, such as war or the collapse of bridges and office towers are common, but similar markers for natural disasters are few and far between. Many in North America might well agree that 9/11, in which nearly 3000 people were killed, was "the great apocalyptic act of our time" (Pearson 2006, p. 38), rather than the Sumatran tsunami, in which as many as 300 000 lives were lost. Some may wish to forget when the power of nature strikes death and destruction, for these are terrible disappointments to the belief in an Arcadian environment, despite the contemporary fascination with catastrophe, as portrayed on the screen. As Davis (1999 p. 278) asks, "Who doesn't enjoy a slapstick apocalypse now and then?"

ARE WE BARKING UP THE WRONG TREE?

Many of the efforts to improve the way we live on this small planet place the entire blame for today's environmental ills on human actions. Take the example of the United Nations report on environmental sustainability (UN Millennium Project 2005). Here, the causes of environmental change are discussed in terms of "drivers", which refer to any direct or indirect cause, with human activities predominating over natural forces. The report lists five direct drivers: land cover change, over-use or inappropriate exploitation of natural resources, invasive alien species, pollution, and climate change. Missing are non-climatic environmental changes that affect people and ecosystems, including volcanic eruptions, earthquakes, river channel switching, and weather extremes. These and other non-human processes drove the development of landscapes and species throughout evolutionary time and have not ceased to operate today.

There can be no doubt that human activities are increasingly affecting natural systems, from climate to biodiversity, from water and air quality to forests and soils. We are obviously responsible for rapacious "development", and for gross neglect and carelessness toward the land and its plants and animals, whether through energy emissions that warm climate, industrial pollution of waters and air, or the myriad ways in which people in the richer countries waste natural resources. It would be foolish to deny that humans are transforming environments at an unprecedented rate: the evidence is simply overwhelming (e.g. Steffen et al. 2004; Diamond 2005; Zalasiewicz et al. 2008). Only the most ardent apologist for unbridled economic development would argue that our collective footprint does not threaten to crush the very values the land has always held for us.

Clearly, we need to reduce damage to biodiversity, climate, water quality, and the health of forests and soils. The search for a better environmental ethic and policy, however, requires that we consider not only "man" against nature but also the reverse. We need to incorporate in our thinking what science tells us about the behaviour of nature, that it is rarely at equilibrium for long and is full of surprises. If recognizing nature's autonomy leads to a sense of frustration because we are unable to forecast many natural changes and thus prepare ourselves, neither are actions based on the notion of a stable, benevolent nature likely to be useful. For example, laws and regulations that aim to control inland waterway navigation, such as through the Everglades, are meant to be stable referents for human behaviour. The challenge is to adjust them continually to the natural opening up of new channels through dynamic wetlands, and the closing of others. It may not be possible to relate all local changes to simple and identifiable causes. The difficulty of separating human-induced from natural environmental change does not make any easier the management of landscapes and urban areas, but neither does ignoring what earth science has revealed in the past few decades about natural change and its effects on people and societies.

Perhaps it is unhelpful to point a finger at nature. But when it comes to developing policies and practices, or strengthening the ethics that underlie them, it seems extraordinarily lop-sided to treat nature as though it has been ground so thoroughly beneath the human foot that it can no longer act on its own. The UN Millennium Project report (2005) states that more droughts and floods induced by changing climate will affect the availability of surface water. Throughout history, and long before humans evolved, natural hydrological systems have done much the same, at times transforming landscapes and coastlines. Rivers have always flooded and dried out, deserts have advanced then retreated, droughts have succeeded times of ecological abundance, and species have moved from place to place to take advantage of new opportunities, or when their original habitats were destroyed, say, by glaciation or volcanic eruption. In the Northern Hemisphere, plants, trees and animals moved northwards as the last of the Pleistocene ice melted, and when the North African savannah (Fig. 2c) was replaced by Saharan desert some 5000 to 6000 years ago, people were forced to move elsewhere (Brooks et al. 2005). There is an obvious need today for better warning systems and disaster responses, but when the natural background is ever shifting, what prospect is there of a more steady world? Perhaps the answers might throw light on what is a very modern problem – how to survive and prosper in a world of increasing climate change with its attendant natural hazards, where a dominant vision is that of environmental continuity, and of sustainability.

WHAT AND WHERE IS SUSTAINABILITY?

The idea of sustainability has now been before the public eye for about 20 years (World Commission on Environment and Development 1987). There are hundreds of definitions and a huge literature dealing with the concept, (see Kates et al. 2005, for a succinct summary) but one common element is of systems that continue in time, with conditions lasting generations. The other major requirement is for conditions that are equitable, fair to all, and characterized by social justice. As to sustainable development, for some like Martens (2006, p. 38), this is too complex an idea to be "unequivocally described or simply applied." A simple-minded interpretation is that it is not so much a goal that can be reached at a specific time, as a process whereby less sustainable conditions improve, bringing an on-going measure of social equitability to those now living in poor conditions.

The term sustainable is loosely used in a wide range of activities, including mining and farming, and in places such as cities and protected areas, so an attempt to apply it to landscapes might be in order. To those working in horticulture, the term sustainable can refer to "a healthy and resilient landscape that will endure over the long term without the need for high input of scarce resources such as water. The natural functions and processes of the landscape are able to maintain themselves into the future" [www.environment.sa.gov.au/botanic-gardens/sustainable]. Such a designation, like others in ecology, puts ecosystem requirements before human needs. Taking a broader view, a physical landscape might be regarded as sustainable when 1) it provides the basic resources, including soil and water, that local people (and, perhaps, ecosystems) need to survive and prosper, and 2) its physical and biological components are resilient in the face of change and likely to last. Inhabited places with little history or prospect of rapid biophysical change could, thus, become more sustainable as the quality of life for all is improved. But such a condition is much more difficult to achieve where people live under constant threat of rapid change – low-lying coasts and islands, mountain ranges, tundra, deltas, estuaries and alluvial rivers, lakes, deserts and karstic terrains, seismically and volcanically active regions, and where climate change is pronounced.

The rich agricultural lands of England and France have fed, sheltered and clothed many generations. Buildings, waterways and forests in some towns and villages have survived well, and still possess some of their ancient character. Though social inequalities remain, rural landscapes here have long sustained their residents, at least since that time when forests and land were cleared for agriculture and settlements. When the Dutch built dikes and polders to recover land from shallow marshes and coastal embayments, they changed the landscape dramatically. Since then, The Netherlands has become a remarkably stable society with a firm land base.

Scanning the voluminous literature on sustainable development, it is hard to find discussions of natural disasters and rapid geological change. To some this may be a non-issue, but it may be that there is here an opportunity for earth scientists to contribute to the search for a clearer concept and its practical application. For example, what does it mean to speak of sustainability along the coastal plains of northwestern Sumatra, where the earthquake that generated the 2004 tsunami resulted in land being submerged and tidal flats and coral reefs being uplifted above sea level? Or along the Louisiana and Mississippi coasts where Hurricane Katrina caused long-term inundation of many nearshore settlements and structures, as well as destroying offshore barrier islands (see also Fig. 2b)? In Bangladesh, some 600,000 landless people are forced by economic circumstance to live on ephemeral sand-silt bars (chars) in the river beds of the Ganges, Brahmaputra, Meghna and Jamuna (Howell 2003; Sarker et al. 2003). Frequent floods force them to move to new riverine islands until the next flood comes along. Along the Bangladesh coast, extraordinary measures are needed to protect people and property from the combined effect of contemporary land subsidence and sea-level rise. As long as there is neither social justice nor environmental continuity in the fluvial and coastal landscapes, it is hard to see how a vision of sustainability can be attained, despite the fact that people have been living there for many generations.

In terms of its temporal component, we could reset the clock of sustainability each time there is a substantial landscape change, and strive to convert a temporary and inequitable situation to one lasting and fair to all. Disasters are likely to be replaced at some scale by new economic and social conditions (Moseley 2002, p. 212), or as ecologists might put it, "new configurations will emerge because the resilience of the prior system was exceeded" (Gunderson et al. 2005; see also Costanza et al. 2007). Circumstances in a city destroyed by flood could be right for investing more resources into protection against future storm surges. However, on the social side it seems that after Katrina, New Orleans lost a large portion of its population, especially among the urban, largely black poor. A year later they showed little sign of returning to their homes, which were damaged or destroyed. By 2006, the population of the city had declined by nearly 50%, and there was a corresponding 14% increase in the proportion of white and a 17% decrease of black residents. The median household income had grown by 9%. If these trends continued New Orleans would have become smaller, richer and whiter (Globe and Mail, August 26, 2006, p. A11). In the long run, therefore, thanks to Katrina, New Orleans might even become temporally more sustainable, because some of its problems of poverty were exported elsewhere. Paradoxically then, despite physical destruction it may be that in the long run a place, by losing its poor, can move more easily towards a wealthier, more socially sustainable state, although this is probably not what most would consider sustainable development.

In former times, people could flee from areas undergoing rapid change because political, legal and security concerns about borders were not as great as they are today. Migration from disaster-prone areas is now more difficult. Modern cities may also find it hard to adapt to natural disasters and other abrupt landscape changes, for they have become so large, their infrastructure so fixed, and their residents so determined to stay. Again, the potential for sustainable development is doubtful.

CONCLUSION

So where does this get us? To what extent is it possible to achieve some kind of sustainability with climates warming, the social and economic effects of natural disasters increasing, and the human footprint becoming heavier? It may be helpful, as many think, to turn away from classic models of economic growth, which marginalize environmental realities. But as global change becomes more evident, the prospect for natural environments that are in a more-or-less steady state seems to be diminishing. If the importance of rapid changes in landscapes on which all life is based has not been fully acknowledged, the idea of sustainability may exaggerate the potential for continuity in the physical and biological base for all life.

Underlying much contemporary environmental thought and writing is the oft-quoted statement that "A thing is right when it tends to preserve the integrity, stability and beauty of the biotic community. It is wrong when it tends to do otherwise" (Leopold 1949, p. 224). To put it another way, as is common in the Green/Deep Ecology movement, "It is genuinely immoral to destroy . .. an ecosystem—a bounded, self-maintaining habitat" (Anderson 1996, p. 182). Is a hurricane that destroys sand bars that shelter flourishing ecosystems "wrong"? Is a landslide that blocks a fish-laden stream "wrong" or a wandering comet that smashes into the Earth causing mass extinctions? These and many other biophysical changes also raise questions about the idea of ecosystem health and sustainability, for a landscape being over-run by desert sands, or a coastal plain drowning by rising sea-levels may not be healthy in the sense of functioning well, or sustainable in the sense of lasting. It is all very well to state that the essence of sustainable development is "to provide for the fundamental needs of humankind without doing violence to the natural system of life on earth." (Martens 2006, p. 36), but squaring this with nature's proclivity for violence and destruction is not easy.

Setting the discussion on a landscape level may help to ferret out some of the many dimensions of the ideas of sustainability and sustainable development, even if these are found to have limited usefulness as clear and practical societal goals. The danger in this approach is that societal changes might be thought to be driven only by environmental stresses. Any simple deterministic argument is bound to miss the intricate interweaving of social, economic, environmental and even spiritual factors that influence the way societies and ecosystems function (Costanza et al. 2007).

Those working in the field of sustainability science and sustainability governance, both of which aim to set societal goals for development within the Earth's environmental limits over the long term (Clark and Dickson 2003), need to reconcile the human goal of continuity with the reality of changing landscapes and environments. It is not easy to see how rapid landscape change is reflected in the new measures of sustainability, including the Genuine Progress Index [www.gpiatlantic.org], the Human Development Index [www.hdr.undp.org/en/statistics], the Ecological Footprint [www.footprintnetwork.org] or the Environmental Performance Index [www.epi.yale.edu]. Where landscapes are less dynamic and geological stability greater, as in some continental interiors, this may seem a moot point, but not for those living in more changeable landscapes such as the Arctic, the Caspian region, or Indonesia. Should there, then, be a vision of different kinds of sustainability: one for landscapes with long-term stability where continuity can be meaningful, and another for dynamic terrains where change is frequent and systems that last are much less common?

There is also the question of how to deal conceptually with rapidly changing landscapes, and how to develop better environmental policies and actions against a natural background that is full of surprises. To do this will require careful exploration of the role of non-human environmental change on a landscape level. Despite the increasing human footprint, we need to read the earth and its archives more fully to develop a better picture of the importance of non-human change throughout the Holocene and, now, the Anthropocene (Zalasiewicz et al. 2008). This will require basic data on abiotic as well as biological change, and for tracking the ways that landscapes actually change so as to provide the basis for verifying sustainability models.

Finally, our current view of the natural environment is strongly influenced by our understanding of human stresses, which might potentially be managed by regulation, legislation or taxation. Nature cannot be sued, so the challenge may be to compensate for natural, non-human, stresses. How do we acknowledge natural change in the ways we conceptualize the world, in our belief systems? Do we come down on the side of Heraclites, who argued that all was change, or Parmenides for whom nature was fixed and orderly (Godlovitch 1998)? Distinguishing changes that are brought about by human actions from those that are part of the natural background is of paramount importance. In a world where human actions lead to unnatural disasters, climate warming, and even perhaps a mass extinction, it is well to remind ourselves that however much *natura naturans* – non-human nature doing what it has always done - may now be trumped by anthropocentric drivers, it has neither disappeared, nor weakened. To blame all environmental ills on human folly is folly itself.

Whatever the answers, it is hard to see how earth science can contribute more meaningfully to the search for a sustainable world as long as the perception persists that geology works too slowly to be of human concern, that natural processes are either "humanly short and rapid" or "geologically slow" (Robb 2008). A renewed emphasis on rapid landscape change should help to change this, and by concentrating on the short term, earth scientists may help to counter a sense of despair, especially in youth, that the Earth is changing dangerously - and very soon - in a way never before seen. We can do this by demonstrating that natural change has always been around – albeit on different temporal and spatial scales – and that the human species has always proved to be resilient.

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