The Geological Society of America
Special Paper 453
2009

Megascale processes: Natural disasters and human behavior

Susan Werner Kieffer*
Department of Geology, University of Illinois, Urbana, Illinois 61801, USA

Paul Barton
U.S. Geological Survey, M.S. 954, Reston, Virginia 20192, USA

Ward Chesworth
Land Resource Science, University of Guelph, Guelph, Ontario, N1G 2W1, Canada

Allison R. Palmer
4875 Sioux Drive, #206, Boulder, Colorado 80303, USA

Paul Reitan
Department of Geology, State University of New York at Buffalo, Buffalo, New York 14260, USA

E-an Zen
Reston, Virginia 20191, USA

ABSTRACT

Megascale geologic processes, such as earthquakes, tsunamis, volcanic eruptions, floods, and meteoritic impacts have occurred intermittently throughout geologic time, and perhaps on several planets. Unlike other catastrophes discussed in this volume, a unique process is unfolding on Earth, one in which humans may be the driving agent of megadisasters. Although local effects on population clusters may have been catastrophic in the past, human societies have never been interconnected globally at the scale that currently exists. We review some megascale processes and their effects in the past, and compare present conditions and possible outcomes. We then propose that human behavior itself is having effects on the planet that are comparable to, or greater than, these natural disasters. Yet, unlike geologic processes, human behavior is potentially under our control. Because the effects of our behavior threaten the stability, or perhaps even existence, of a civilized society, we call for the creation of a body to institute coherent global, credible, scientifically based action that is sensitive to political, economic, religious, and cultural values. The goal would be to institute aggressive monitoring, identify and understand trends, predict their consequences, and suggest and evaluate alternative actions to attempt to rescue ourselves and our ecosystems from catastrophe. We provide a template modeled after several existing national and international bodies.

*skieffer@uiuc.edu

Kieffer, S.W., Barton, P., Chesworth, W., Palmer, A.R., Reitan, P., and Zen, E., 2009, Megascale processes: Natural disasters and human behavior, *in* Chapman, M.G., and Keszthelyi, L.P., eds., Preservation of random megascale events on Mars and Earth: Influence on geologic history: Geological Society of America Special Paper 453, p. 77–86, doi: 10.1130/2009.453(06). For permission to copy, contact editing@geosociety.org.

INTRODUCTION: FROM EARTH ISLANDS TO PLANET EARTH TO ISLAND EARTH

Unlike the other planets discussed in this volume, Earth has human inhabitants, and in this paper we look at our own capacity to create a megadisaster comparable to exogenous and endogenous events discussed in other papers. We who have lived through the second half of the twentieth century have witnessed a profound transition in the relation between the physical planet and its human inhabitants. In the middle of the century, the planet still had real islands, both physical and sociological, beyond which were frontiers that held new lands, mysteries, adventures, cultures, and resources. Expanding population and technology merged these islands into a relatively seamless planet by the end of the century.

Astronauts in space took hauntingly beautiful photographs at a resolution that revealed a beautiful and pristine planet Earth, the "Pale Blue Dot" of Carl Sagan (1994) (Fig. 1). However, in the early years of the twenty-first century, we see higher resolution views of this planet that reveal global-scale changes caused by our species. On 4 August 2005 Commander Eileen Collins and her international crewmates aboard the shuttle Discovery said, in a video-conference from space with the Prime Minister and high officials from Japan, "Sometimes you can see how there is erosion, and you can see how there is deforestation. It's very widespread in some parts of the world. We would like to see, from the astronauts' point of view, people take good care of the Earth and replace the resources that have been used. The atmosphere almost looks like an eggshell on an egg, it's so very thin. We know that we don't have much air, we need to protect what we have."

Although life forms have affected the planet on a global scale throughout geologic time (e.g., causing the formation of the oxygen-rich atmosphere), never before has a species been able to observe its effect on its own environment at this scale. This planet is the home, the only home, of our species, and there are many indications that we are altering that home in ways that will undermine our survival and evolution into the civilized global society that we might become. "It has often been said that, if the human species fails to make a go of it here on Earth, some other species will take over the running. This is not correct. We have, or soon will have, exhausted the necessary physical prerequisites so far as this planet is concerned. With coal gone, oil gone, high-grade metallic ores gone, no species however competent can make the long climb from primitive conditions to that high-level technology. This is a one-shot affair. If we fail, this planetary system fails so far as intelligence is concerned" (Hoyle, 1964).

Figure 1. Our "Pale Blue Dot," the view of the rising Earth that greeted the Apollo 8 astronauts as they came from behind the Moon after the lunar orbit insertion burn. Earth is about 5° above the horizon in the photo. Photo from NASA.

As implied in Hoyle's quote, many of the value-laden comments in this paper have time scales associated with them. For example, if we simplify resources into two categories, renewable and nonrenewable, we need to ask "over what time scale?" All resources may be renewable on geologic time scales, but this is not relevant to the time scales of human needs. We are specifically looking at problems that are urgent on the time scale of collapse of civilized societies. This time scale is decades to centuries.

At the end of 2004, the Sumatran earthquake gave us a glimpse of the enormous megascale geologic processes that can happen on the Earth on human time scales—earthquakes and tsunamis in this case, and floods, hurricanes, landslides, avalanches, volcanic eruptions, and meteorite impacts as discussed elsewhere in this volume. Megascale geologic events are rare by human reckoning, and most occurred in the past when the total human population was small or nonexistent. Earlier human societies were relatively isolated, either on real islands or in local societies, on continents that were effectively isolated from one another by distance and primitive technologies. The effect of a geologic event on individuals could always have been catastrophic, but the catastrophe was not global in scale.

At present, however, societies of the whole planet are so interconnected that planet Earth is essentially a single island, perhaps more aptly, a spaceship. The only remaining islands for us are other planets. We do not have the technology to move from this island to another, and may not have it in the near-enough future. With the present daily net population increase on our planet exceeding 250,000 we will surely never have a means of mass migration for a significant fraction of Earth's population (Hardin, 1993, p. 9–11).

By geologic time scales, human population and the scale and rate of human exploitation of nonhuman resources are exploding so that even rare events may critically affect our survival. In other words, our civilization has become so globally connected that even relatively "small" megascale events on the geologic scale can have potential for immense consequences to our species.

Civilization is a fragile enterprise: we depend on a favorable global climate, abundance of natural resources, and geologic as well as social stability. This fragility is compounded by our propensity to take for granted our planetary resources—and each other—with our current political systems and a short-sighted view of the future.

What has been the effect of past natural megadisasters on humans? What might be the consequences of the same events with the current population distribution? What is the magnitude of the human endeavor compared to these natural events? What can be done to protect humans and the ecosystems on which they depend from disasters? This paper explores these questions.

THE EFFECTS OF NATURAL MEGASCALE EVENTS ON HUMANS: PAST, PRESENT, AND FUTURE

As discussed throughout this volume, earthquakes, volcanoes, tsunamis, and exogenous events such as meteorite impacts or solar activity have the potential to produce megascale catastrophes.

Earthquakes

The deadliest earthquakes in recorded history have occurred in China: in 1556, Shansi, with ~830,000 dead; and in 1976, Tangshan, Hebei, with 255,000 officially known dead and as many as 655,000 possibly dead. Earthquakes in Iran, Syria, Japan, Turkmenistan, Italy, Pakistan, Peru, and Portugal have killed 50,000–200,000 people repeatedly throughout recorded history. By comparison, the M 8.25 San Francisco earthquake in 1906 caused 700–3000 deaths out of the population of 400,000. The Sumatran earthquake was the greatest megascale event recorded by modern technology: the magnitude (M) 9.1–9.3, duration (>10 min), and recorded fault break (1200–1300 km) were the greatest in history (Lay et al., 2005). The tsunamis from the Samatran earthquake were not particularly large on a geologic scale, with a maximum height on the order of 10 m, but because of the density of population in vulnerable areas, 283,000 people died suddenly.[1] Images of the devastation of a megaevent were seen around the whole world, and this quake did not occur in the densely populated economic centers of Indonesia where the death toll could have been much higher. The Kashmir/Pakistan earthquake of 8 October 2005 killed nearly 100,000 people and left 3.3 million homeless to face dying in a brutal winter. However, in both cases, the consequences to humans may have been the most severe because of the secondary events, what we have called the "disasters within the disaster."

There is much current interest in clusters and long-distance connections of geologic processes such as earthquakes and volcanism. Earthquake "storms" pose large-scale and prolonged dangers. A storm is an unusual cluster of very strong earthquakes in a contiguous region spanning several decades, the clusters often separated by centuries of relative quiescence. Compelling evidence indicates that earthquake storms caused the demise of the Bronze Age civilizations in the eastern Mediterranean ~1225–1175 B.C. (Nur and Cline, 2000). The civilization failed by a system collapse—the destruction of buildings, massive migrations of people, loss of culture, famine, and uprisings. At this time, between 2000 and 1000 B.C., the world population is estimated to have been in the range of 25–50 million, and the population in the Middle East was possibly between 6 and 9 million.

In comparison, the combined population of the Middle East and North Africa was 300 million people in 2001, and is projected by the World Bank to approach 388 million by 2015. One population center at particular risk in modern times is Istanbul. More than 10 million people live in Istanbul alone today, more than in the whole Middle East 3000–4000 yr ago. The largest earthquakes in Turkey have occurred on the North Anatolian fault. An earthquake storm appears to have started in 1939 with a M 7.8 earthquake near Erzincan. Earthquake activity migrated westward through 1969, rupturing the fault zone in a series of earthquakes with M 7 and greater (Okumura et al., 1993). The fault geometry becomes complicated at the western end, but two M 7+ earthquakes occurred there in 1999, killing over 18,000 people and causing $25 billion in damage. U.S. Geological Survey scientists (Parsons et al., 2000) have estimated that there is a 60% chance that a large earthquake will hit Istanbul by 2030. Many other major cities around the world are subject to similar earthquake risks. Earthquakes (and potentially bolide impacts, see below) near or in bodies of water pose an even greater danger because of the potential for tsunamis.

Civilization in the Mediterranean areas has been affected more than once by megascale events such as earthquakes, volcanic eruptions, and tsunamis. Strong earthquakes in the seventeenth century B.C. destroyed many Minoan palaces on Crete. These were followed by the eruption of ~30 cubic km of magma from Santorini in ca. 1627–1628 B.C. (Grudd et al., 2000). The Minoan city of Akroteri was smothered under ~2 m of ash, and the ash deposits destroyed the agricultural fields. These events are believed to have contributed to, or caused, the end of the Minoan civilization centered on the island of Crete, again probably by system collapse. It has been suggested that tsunamis from the eruption 40 km away not only destroyed cities, but also destroyed the navy at Crete. Over the next few centuries, the navy lost crucial battles with the Mycenaean navy, so that a former colony took over the empire.[2]

Hurricanes

Hurricanes, also called typhoons or tropical cyclones, are events that have occurred throughout recorded history, but only in the past few decades has there been sophisticated instrumentation to allow us to describe them accurately. Because of this relatively short time of monitoring, the "biggest" events recorded to date are likely not to have been the biggest that have occurred.

The intensity of a hurricane is measured by either the low pressure in the center or the maximum sustained winds at ground

[1]Earthquake statistics used in this paper are from http://neic.usgs.gov/neis/eqlists/eqsmosde.html.

[2]An accessible encyclopedia article on this is http://www.nationmaster.com/encyclopedia/Bronze-age.

level. Hurricane Katrina's lowest pressure was 902 millibars (mb), and maximum sustained winds were ~150 miles per hour (mph). (By comparison, hurricanes in different meteorological settings can have different properties: the most intense hurricane recorded was Typhoon Tip in the Northwest Pacific Ocean, 12 October 1979, with a much lower central pressure of 870 mb, and maximum sustained winds of 190 mph.)

Katrina intensified over a period of four days after it entered the Gulf of Mexico in late August 2005, providing time for planning and evacuation. Lessons learned from Katrina were implemented when Hurricane Rita came into a nearby region in late September 2005. Other tropical storms in other oceanographic settings have been even more severe: Typhoon Forrest in September 1983 intensified in just under 24 h as the pressure dropped from 1000 mb to 876 mb. Estimated surface sustained winds increased 35 mph in just 6 h, and 99 mph in one day, reaching 190 mph. Katrina produced a storm surge on the order of 20 ft; the Bathurst Bay hurricane in Australia in 1899 produced a 42-ft storm surge. Tropical Cyclone Denise dropped 97 in. of rain on La Reunion Island in 1958; Cyclone Hyacinth dropped 128 in. of rain on the same island in just 3 days in 1980, and 223 in. in the 10 days of the storm duration.

Tsunamis

Earthquakes, and potentially bolide impacts (see below), near bodies of water often cause tsunamis. In ~900 A.D., an earthquake on the Seattle fault in the present state of Washington, USA, sent a tsunami throughout the waters of Puget Sound, burying Native American fire pits beneath sand that was swept ashore by the wave (Koshimura et al., 2002; Atwater and Moore, 1992). A recent interpretation of historical Japanese documents, and computer simulations, suggest that an ~M 9 earthquake occurred on the same fault between 1680 and 1720 A.D. (Atwater, 1992; Yamaguchi et al., 1997). The populations of Puget Sound in 900 or 1700 A.D. are unknown, but would have been nowhere near the 3 million people that live and work in this area today. If an earthquake of comparable magnitude should occur in the colliding tectonic plates of the northwestern United States or southern British Columbia, Canada, the shaking, especially of tall buildings, could extend from the heavily populated areas of Vancouver, British Columbia to northern California and could last for several minutes causing extensive destruction. An earthquake of M 9 could also send tidal waves as large as 11 m onto shore in the Northwestern United States within minutes, and send additional waves westward across the Pacific Ocean.[3] Such quakes occur on average once every 500 yr: the last big quake having occurred ~300 yr ago (the fault is currently locked, accumulating energy for a future destructive event). Intensive monitoring and warning efforts may minimize damage and loss of life, but there will inevitably be economic repercussions around the globe from the disruption of such a densely populated, high-technology area.

[3]An updated summary of Northwest tsunami hazards is available at http://www.pmel.noaa.gov/tsunami/time/or/resources.shtml.

Volcanoes

Seattle is not only in danger from tsunamis, but also from a future eruption of Mount Rainier, which is volcanically active. It has a magnificent and beautiful summit cap of ice. However, intrusion of magma into the edifice of the volcano could cause melting of the ice, resulting in the generation of enormous mudflows like those at Nevado del Ruiz, Colombia that killed 29,000 people within minutes in 1985. A mass of mud, ice, and water traveled a distance of 100 km down the White River valley 5600 yr ago into what is now the middle of Seattle and Tacoma (Valance and Scott, 1997). This event covered the land with a layer of mud 90 m thick in places. Large mudflows have traveled the same path on the average of 600 yr, and over 100,000 people live directly on the young mudflows.

Volcanoes also emit gases (primarily SO_2, H_2O, and CO_2) that alter the composition of the atmosphere. Approximately 73,000 yr ago, the volcano Toba in Indonesia erupted ~2800 km^3 of magma, a volume that only seven seas or lakes in the world surpass (Caspian, Baikal, Tanganyka, Superior, Nyasa [Malawi], Michigan, and Huron). The ash and gases from the eruption caused short-term global cooling of 3–5 °C, and perhaps as much as 15–20 °C in local regions (Rampino and Self, 1992, 1993). The eruption coincided with, and perhaps caused, a reduction of human population to fewer than 3000–10,000 individuals at that time (Ambrose, 1998). Historically, even smaller eruptions have produced temporary coolings that have had mild to severe impacts regionally. Examples include eruptions from: Laki (1883, 4.8 °C cooling in Europe, ~1 °C in the eastern United States); Tambora (1815, snow in all summer months in New England and Europe); and Pinatubo (1999, world temperature decrease of ~1 °C over 2 yr). The eruption of Laki was tiny compared to eruptions that we know have happened in the past and that have had similar chemistry—flood basalts. The significant impact of its sulfurous emissions on climate suggests possible catastrophic effects of eruptions on ecosystems and humans.

Exogenous Events

We have thus far considered events endogenous to the Earth, but we should be aware that there are also important exogenous events, viz., large solar outbursts of charged particles, supernova explosions, and meteorite impacts. The effects of an impact of a meteorite ~10 km in diam 65 Ma ago caused the extinction of a large number of animal and plant species, including the dinosaurs (Alvarez et al., 1980). We do not need meteorite impact events of this scale to cause major global disruptions at the present levels of population. Added to the direct-hit effects—including atmospheric shock waves and tsunamis—there would be secondary effects on the climate and ecological support systems, and tertiary effects on dependent humans and a functioning global civilization, another scenario for system collapse. Solar flares have caused significant economic disruption within the past decade by disrupting modern communications. Our economic systems and our survival depend on the resilience of our response to these uncontrollable processes.

The megascale processes described above generally cannot be prevented. Thus far, we cannot tell which of the numerous possible events will occur first, or when. We simply know from our geologic concept of "deep time" (Palmer, 2000) that these events will occur. In some instances, mitigation and remediation are possible—for example, human casualties of the tsunami in the Indian Ocean could have been mitigated by an effective warning system. A deep space warning system may give us advance notice of a meteorite heading toward us, just as volcanic monitoring systems may give us warning of new activity. However, mitigation costs money, and mitigation of rare events is traditionally given a lower priority than mitigation of frequent events. We live on a planet with constantly changing geological conditions: some are gradual, some are episodic, and both can be of a scale to be catastrophic.

HUMAN BEHAVIOR AS A MEGASCALE PROCESS

There is an on-going megascale process not yet considered. It is unique in the history of the Earth: the expansion of an animal species with a population and brain large enough to challenge all competition in the ecosystem—humans. Other so-called "terminator species" (Flannery, 1994) have existed in the past, but never at the global scale. We have been able to use our brains to bypass, or delay, the negative feedback of natural selection—the process that keeps other species from dominating the biosphere. Consequently, the size of the human population has increased along an exponential trend. For perspective, the deaths in World Wars I and II, and those from the Spanish flu epidemic during World War I, did not produce a noticeable dent in the population growth curve. At current birth rates, over 250,000 babies were born in slightly less than 1 day after the 26 December 2004 earthquake that took a similar number of lives. We are the only big fierce animals (Colinvaux, 1979) remaining whose population is growing.

Population

Exponential population growth means that our behavior en masse, particularly consumption of resources and generation of waste, has also been magnified along an exponential trend. Stripped to its fundamentals, human behavior is no different from the behavior of other animals: we eat, reproduce, and ignore our dependence on other components of the ecosystem at our own peril just as do rabbits, cockroaches, foxes, and lemmings.

The number of humans that the planet could support, the so-called "carrying capacity," is debatable. Extremes vary from 0.5 to 14 billion; medians of the low and high estimates yield a range from 2.1 to 5.0 billion (Cohen, 1995). This number depends strongly on assumptions about standards of living, technology, resources, and whether or not we live in a world of strongly recycled or vastly depleted natural resources. Our current population exceeds 6 billion and is projected to reach 9 billion by 2050. For this paper, we arbitrarily consider a future in which 3 billion people might live sustainably.

The major difference between "us" and "the rest" of the ecosystem is that we have been able to extend our lifetimes and avoid some of the obvious natural selection processes. The fact that we have probably overshot the carrying capacity of the planet with respect to our species means that this "natural" behavior has become problematic to our own survival. Collective human behavior is affecting the physical and biological state of the planet on a massive, and dramatically rapid, scale. Many tend to view the effects of human behavior on the planet as gradual because of the perception of time on a human, rather than geologic, time scale. However, all island societies have collapsed within geologically short time scales when the populations exceeded the carrying capacity. We are heading toward a megascale catastrophe on island Earth if we cannot change our behavior (Diamond, 2004; Wright, 2004).

Suppose, for example, that when the Earth population reaches 9 billion people in ~2050, a natural event of the type described above caused catastrophic system collapse. Suppose that conditions and resources after the collapse permitted only 3 billion people to ultimately survive. Suppose that this collapse lasts 60 yr. The result would be 250,000 more deaths per day than births per day for 60 yr, i.e., the magnitude of the deaths from the 26 December 2004 tsunami would be repeated daily for 60 yr!

However, this example treats the human conditions around the world as uniform. They are not. Both within and between countries, the rich are getting richer and the poor are getting poorer. The United States has less than 5% of the world's population, consumes one-quarter of its resources, and generates at least that fraction of the world's waste. It has been estimated that each child born in the United States will consume 10–15 times the resources of a child born in India (Wackernagel and Rees, 1996, p. 85, Table 3.4 using 1991 data; Zen, 2000, p. 389–390).

Thus the standard U.S. family with two children is equivalent to a family of 20–30 children in the Third World. Each American consumes more grain per year than 150 Bangladeshis or 500 Ethiopians. This disparity, on the other hand, exposes the high-technology, consuming nations to greater vulnerability to a megadisaster than, for example, subsistence farmers because of the dependence on a functional global economy.

Another aspect of the current population distribution is the vulnerability of food production and distribution networks. Consider the grain situation in the world. Much of the world's grain comes from prairies of the mid-continents of the United States and Canada. Upwind from the plains is the active volcano of Yellowstone, Wyoming, currently being monitored for potential large-scale volcanic activity. An eruption occurred at Yellowstone 2 Ma ago comparable to the Toba eruption mentioned before. Only 600,000 yr ago, the volcano erupted more than 1000 km^3 of ash. If Yellowstone had a volcanic event of these magnitudes today, roughly half of the grain-producing area of North America would be covered with more than 10 cm of volcanic ash (Fisher et al., 1998), and a system collapse would inevitably follow.

The development of human society has already led to a range of well-recognized man-made hazards, which, if they occurred, could be comparable in scale to some of the natural megaevents. Some are obvious: for example, nuclear warfare, bio- or technological terrorism, nanotechnology gone wild, a volcanic intrusion into a nuclear waste repository, or the strange scenario of a high-energy physics experiment gone awry (see Posner [2004] for a discussion of risk and response to rare, but high-consequence events such as these). As serious as these events may be, our integrated collective behavior on a much less obvious scale poses equal or perhaps even more dangerous threats. All but the most extreme of these man-made hazards will not impact the global environment on the scale of our collective behavior. There is clear evidence from observation of many components of the planet that our activities are changing the environment on which we depend, in ways that will preclude traditional future use: soils, rivers, climate, water, landscape, resource distribution, and ecosystems. A few examples illustrate the wide range of our impact.

Rivers

For over 7000 yr, the manipulation of the Nile River by humans has affected increasing areas of the river corridor, its delta, and now, the Mediterranean Sea (Stanley and Warne, 1998). During much of this history, the population of all of Egypt (concentrated mostly in Memphis on the northern part of the Nile, and Thebes in the southern highlands) was fewer than 1 million people; but even as early as 2200 B.C., limits of the resources on the Nile seem to have caused the decline of the Old Kingdom.

The alteration of the Nile has continued, accelerating dramatically in the nineteenth and twentieth centuries with the building of the Aswan Dams from 1889 to 1970. Today, ~60 million people live on the delta, with population densities of 1000 people/km^2, and much greater in places like Cairo. Nearly all 2500 km^2 of the delta have been affected by the manipulations of the Nile (Farvar and Milton, 1972). The river no longer cleanses its banks or deposits new soil. This change in the river has amplified the effects of humans, e.g., artificial fertilizer, now necessary because the soil is not replaced, leaves deposits of toxic minerals. Human-induced conditions of stagnant water have caused a resurgence of severe diseases. Loss of silt and algae from the Nile has caused the disappearance of a major sardine resource from the Mediterranean and its shrimp population has been adversely affected by the reduced discharge of the Nile. Loss of the fresh water cover is causing invasion of Red Sea fauna into the Mediterranean across the Suez Canal.

Hydrologic Cycle and Climate

On a larger scale, humans have transformed the global hydrologic cycle, partly caused by human-abetted global warming, and evidenced by retreat of glaciers and thinning of Arctic ice (see IPCC [2001,Table 3–2, p. 70] for predictions of events absent climate policy interventions). There is high confidence that by 2025 there will be further retreat of glaciers, decreased sea ice, thawing of some permafrost, and longer ice-free seasons on rivers and lakes, and medium confidence that there will be extensive sea-ice reduction (Kennedy and Hanson, 2006). Global warming will increase the severity of hurricanes, an indication perhaps being hurricanes Katrina and Rita in 2005.

We have changed the climate and even the solar input to the surface of the Earth through the formation of the ozone hole. The evidence that the climate is changing, and that human contributions now are overriding the natural variability, has become compelling to most scientists (Karl and Trenberth, 2003).

Carbon is cycled through the biosphere by both biological processes (dominant) and geologic processes, in the form of CO_2 and other gases, in solution in water, and bound in carbonate rocks. Time scales vary considerably, with volcanism and silicate weathering playing significant roles on geologic time scales, but small roles on human time scales. Photosynthesis accounts for 120 Gt/yr of carbon (metric gigatonnes, GtC), about half through respiration and half through net primary production.[4] On a global scale, humans, who represent roughly 0.5% of the total heterotroph biomass on Earth, appropriate ~32% of the net primary production (Imhoff et al., 2004). Total anthropogenic emissions from fossil fuel burning, cement production, and changes in tropical land use are ~7 GtC/yr (Schimel et al., p. 76–86 in IPCC, 2001). How much is 7 billion tonnes of carbon? An average human weighs ~0.075 tonne. So, this mass of carbon is equal in weight (not in carbon mass) to ~93 billion people, or 15 times the entire population of the planet. About 45% of the anthropogenic CO_2 stays aloft in the atmosphere. Even if we allow for controversy about the human contribution to this change by our behavior, these numbers suggest that we should act prudently.

Sulfur from natural sources (volcanoes, biogenic marine, and terrestrial biogenic) is still a significant fraction of the total sulfur balance in the tropical latitudes of the northern hemisphere and in all latitude belts of the southern hemisphere. However, between 35° and 50° N lat, only 8% of the sulfur emissions come from natural sources, and the human-produced emissions dominate the global sulfur budget (see Crutzen et al. [2003] for a general discussion of the effect of "parasols" on climate).

Other large human impacts include our creation of megacities where the paving of so much land surface has altered the albedo, the hydrology, and the pattern of heat from solar input. We have changed the definition of "dark night side of the Earth" by the artificial illumination of our cities. Within the continental United States, Mexico, Japan, and China, surface temperatures on weekends (Saturday–Monday) vary systematically from weekday weather (Wednesday–Friday) over large spatial scales

[4]Net primary production is the net amount of solar energy converted to plant organic matter through photosynthesis, usually measured in units of elemental carbon. This is the primary food energy source for the global ecosystems.

(Forster and Solomon, 2003). The effect can be as large as 0.5 °C, but whether this is an increase or a decrease of temperature is not the same in all locations. Aerosol-cloud interactions caused by accumulated man-made products are suspected as the cause.

Soils, Energy, and Minerals

We have altered soils through compaction and erosion with unsustainable agriculture practices. Human-caused soil erosion rates exceed those of steady geologic processes: we move earth at a rate of ~35 Gt/yr, ~3 times that of all other natural agents, mostly through plowing (Hooke, 1994). Plowing, overgrazing, compaction, acidification from acid rain, and the use of fertilizers and biocides are changing the physical, chemical, and biological nature of soil. Numerous studies show that worldwide, soil erosion is occurring much faster than renewal rates (Pimentel et al., 1995; Pimm et al., 1995). Soil cannot be viewed as a renewable resource on the time scale of humans. That it has been so regarded may account for the fact that our record in soil conservation is so abysmal. Soil is necessary not just for agriculture but also for the entire terrestrial ecosystem: no soil, no terrestrial plant life, no land-based photosynthesis, and little food for animals or humans. Unless we learn to use the soil sustainably, we will never be able to maintain the food supply that our complex society depends upon (Leopold, 1949).

We have extracted energy and minerals at such a rate that scarcities are likely to occur within decades, at worst, or centuries, at best. Current estimates are that peak production of liquid petroleum and natural gas will occur before 2050, possibly decades earlier. Even a new rare, 10 billion barrel supergiant field, if all could be extracted, would delay peaking by only a few months or very few years (Campbell, 1997; Duncan and Youngquist, 1999; Gluskoter, 1999). With population increasing toward 9 billion and increasing per capita energy demand, we could exhaust coal supplies within centuries. Because of high CO_2 levels and soot pollution from coal—the question is—"Should we want to burn this coal, even if we can?"

Referring back to our Introduction in which we emphasized that our concerns are about time scales that affect the stability of civilized societies, we argue that neither fossil fuel energy sources nor soils, or possibly some critical mineral resources, are renewable on relevant time scales. It could be argued that our waste dumps or even the wasted remains of our cities are essentially economic resources for a future civilization because we have done a huge amount of work concentrating minerals as we have used up our fossil fuels; or, perhaps some soils could be considered "enriched" for future ecologies rather than viewed as "poisoned" for our own ecologies. In our view, such arguments lie in the realm of science fiction or fantasy rather than science fact or rational philosophy.

The Rest of the Ecosystem

As the current terminator species, we are causing the extinction of other species on a massive scale. Estimates of extinction rates are extremely variable and difficult to make because the time scales for ecology are so short compared to those of geology. Background rates of extinction over 600 Ma are estimated to have been ~1–10 species/yr for every million species on the earth, or 0.0001% per yr. Estimated current rates of extinction by a variety of methods are ~1000 times prehuman levels (0.1% per yr) with the rate projected to rise, possibly very sharply (Pimm et al., 1995). Although the concept is qualitative, comparisons have been made of the present situation to the five times in Earth history that have been "mass extinctions" in which more than 50% of species went extinct in a geologically short period of time.

The impact of the extinctions is already being felt in the economies of the world, and in food shortages affecting human welfare. We have removed the top predators from a number of important systems resulting in cascading effects through ecosystems. Frank et al. (2005) have documented this effect in the decline of the large cod-dominated marine ecosystem of eastern Canada. The trophic system becomes completely restructured, at least on time scales significant to economics. It is possible that this is not just a situation of dwindling numbers that could recover, but of extinctions.

The examples given so far relate to the active role of humans in bringing about disaster by our collective behavior in consumption and waste production. The sheer size of the human population means that we may also be the passive cause of disaster. Returning to the Sumatran tsunami, one could cogently argue that the loss of 150,000–300,000 lives in southern Asia was caused by overpopulation that forced people to live in vulnerable areas, in combination with a blatant disregard for the preservation of a sustainable ecosystem.

There is one major, and potentially hopeful, difference between the random catastrophic event and the gradual build up to a potential human-induced catastrophe: namely, we do have advance warning of the approach of a disaster, as shown by the examples cited above. We ignore this warning at our peril. Encouragingly, the megascale process of the evolution of our species is unique in being within the grasp of human control—if we can muster the collective will to act on the evidence. Given that we humans have the ability to think, act, and organize, we have the potential to moderate our own behavior. Unfortunately, we are reluctant to fully acknowledge our abuse of our air, water, and soils, the consequences of our unfettered energy and mineral consumption, and our contempt for the rest of the ecosystem. Due to our own survival instincts, reinforced by both religious and political thought that we are the masters of the domain rather than merely part of it and an economic belief that we cannot sacrifice short-term gain, we maintain a state of denial about our effect on the planet. We seem curiously unwilling to take the actions needed to rescue ourselves from that self-induced megascale terminal event called "extinction of civilized society."

FUTURE OPTIONS IN A COMPLEX SYSTEM

Civilization is a complex system, in the strict sense in which that concept is emerging in modern mathematics (Bar-Yam, 2002). An inherent property of complex systems is that there is some parameter that is "tuned" until the unexpected happens. For a thought experiment, consider observing a pot of water over a fire and pretend that you had never seen water heated in this way before. The temperature of the water is being "tuned" by the heat from the fire. Nothing much happens as the temperature rises from ambient, except maybe the formation of a few bubbles as dissolved air comes out of solution. However, as the temperature approaches 100 °C, the "unexpected happens": the water begins to boil, it suddenly changes state from a single-phase liquid to a two-phase boiling mixture and, ultimately, to vapor.

A major tuning parameter for populations is the number of members—if the number is increased relative to critical resources, nothing dramatic happens for some time. Then the resource is rather suddenly depleted and the population declines or collapses. The system typically reverts back to a less complex structure, and indeed, the loss of complexity in structure has been used as a definition of the collapse of societies (Tainter, 1988).

A complex system can be organized in various ways. It can be chaotic (resembling a random system), or it can be in different stable states. To qualitatively follow the boiling water analogy above, water can be in the stable states that we call ice, liquid, or vapor; or it can be chaotic, i.e., on the phase boundaries between solid and liquid, or liquid and vapor. A challenge to our civilization is to find a stable state. Because we have depleted nonrenewable resources, we do not have the choice of going back to a previous stable state, but must search for a new relationship between the human population and the planet on which we live.

Organization can change the nature and operation of the system. Evidence from the past is that human civilizations have not been able to organize coherently to prevent overuse of resources (Tainter, 1988, 1995; Diamond, 2005). The current global impasse over acknowledging the magnitude of the problems and negotiating ways to intervene (viz., the Kyoto Treaty process) is an example of continuing lack of coherent organization. In complex systems, partial organization does not put the system into a stable state; the whole system must be "self-organized." The implication is that in this world of global interdependence, the next stable state must include the whole planet—both its peoples and its resources.

This same concept was stated more broadly by the environmental philosopher J. Baird Callicott (2005), in reviewing the seminal paper on environmental ethics by Lynn White, Jr. (1967). White's fundamental assumption was that "what we do collectively depends on what we collectively think," which leads to the conclusion that "if we are to change what we do to the environment, we must begin by changing what we think about the environment." Education and public awareness of the true state of the world is imperative, to be followed by action on that knowledge (Reitan, 2005).

Two options or courses of action appear to be open to us: (1) Do nothing or little, and wait for the catastrophe to occur, which is the current state and is deemed most likely by Milbrath (1989, p. 340). (2) Attempt remediation and conservation, as fast as is humanly possible, which we will call "adaptation." In either scenario, we need to prepare for adaptation to an inevitably rapidly changing world. Hence we come to the final point of this paper: We need to understand that we humans are a geologic force affecting the whole planet, and we need to break the collective denial about our effects on the planet and institute aggressive procedures to monitor, understand, evaluate, predict, and recommend actions for the health of the planet.

During the time we have been thinking about this problem the epidemic of sudden acute respiratory syndrome (SARS) and the potential epidemic of bird flu have dramatically illustrated the global interconnectedness and fragility of our species. Without rapid detection, acknowledgment of the problem, aggressive monitoring, and treatment through such organizations as the Centers for Disease Control (CDC) and the World Health Organization (WHO), catastrophic pandemics of SARS or flu might have occurred (and still may). Monitoring showed that in the absence of initial control measures, individual SARS spreaders infected 2.7 or 3 people on average in Hong Kong and Singapore, respectively (Riley et al., 2003; Lipsitch et al., 2003). As control measures were instituted, the transmission rate fell. With four key actions—detection, acknowledgment, aggressive monitoring, and treatment—the pandemic was at least temporarily halted in the societies that instituted these remedial measures.

By analogy, thoughtful people have already detected and defined many aspects of human behavior that are jeopardizing the planet. Regardless of which of the two paths we follow (do nothing, or remediate and adapt), a large body of wise leadership, and a huge database for research, education, and policy will be required at a global scale (Zen et al. [2002] proposed a global monitoring system as part of a prudent strategy for using Earth's resources wisely). For example, the very concept of "adaptation" of humans to the natural world in the midst of an ecological catastrophe is poorly defined, if defined at all. The resources for analyzing and thinking of the world on a global scale do not currently exist (Speth [2004], and in previous works, discusses this in detail; see also Ehrlich and Kennedy [2005]). We examined the charter of the United Nations and found aspects of its mandate to be appropriate, but because of its historical and current focus explicitly on war and war prevention, the focus is only obliquely on environmental sustainability (e.g., it is only one of eight of the Millennium Development Goals).

We realize that a number of different organizations will, in fact, be required to deal with such a massive problem, e.g., a scientific body to provide impartial facts and uncertainties, an engineering body to propose and implement technical solutions, a negotiating body to balance the realities of political, economic, religious, and cultural values (like the United Nations, and like the new initiative on human behavior advocated by Ehrlich and Kennedy [2005]), and an enforcement body that is responsive to all of the inputs (like the Canadian peace-keeping forces?). However, some entity must be seen as the best provider of scientific truth and reality, as free from bias as is humanly possible. Current efforts of global collaboration by the National Academies[5] represent a positive development. However, given the volunteer status of most members to the Academies, and the lack of policy that mandates that they be at the political and moral bargaining tables, much needs to be done.

Freedom from bias in the duties of a scientist does not imply lack of responsibility to provide the best estimates of consequences of actions and the uncertainties, nor opinions about what will and will not work for humankind. This kind of scientific assessment can be done independently of political, economic, religious, and cultural pressures, as long as the judgments about what to do about it include those who deal with human morality, economics, and politics.

To address our perceived global scientific needs, we have taken the mandates of the Centers for Disease Control and modified them to arrive at a concept of a mandate for a much-needed global body, a "CDC for Planet Earth" (CDCPE, perhaps standing for the "Center for Disaster Control for Planet Earth" in our thinking).

PROPOSAL FOR A CDCPE

The existing CDC mandate is

The Centers for Disease Control and Prevention (CDC) is recognized as the lead federal agency for protecting the health and safety of people - at home and abroad, providing credible information to enhance health decisions, and promoting health through strong partnerships. CDC serves as the national focus for developing and applying disease prevention and control, environmental health, and health promotion and education activities designed to improve the health of the people of the United States.

To paraphrase the CDC mandate and take it to a global scale, we propose that:

"The CDCPE should be recognized as the lead world body for protecting the long term health and safety of the planet and all of its inhabitants, providing credible information to enhance decisions relating to all resources of the planet, and promoting wisdom in resource use through strong international cooperation. The CDCPE serves as the international focus for developing and applying resource conservation, and promoting education activities designed to improve the conditions for continued human existence on the planet."

In carrying out its activities, the CDCPE might have the following five core functions for resource evaluation:

- *Manage information by assessing resource data and their uncertainties, and assessing trends; set the agenda for, and stimulate, research and development.*
- *Set, validate, monitor, and pursue the proper implementation of norms and standards.*
- *Catalyze change through technical and policy support that stimulates cooperation and action and helps to build sustainable global capacity.*
- *Negotiate and sustain national and global partnerships.*
- *Articulate consistent, ethical, and evidence-based policy and advocacy positions.*

This body needs at the least to be (1) global, (2) credible, (3) scientifically based, and (4) sensitive to political, economic, religious, and cultural values while avoiding direct bias. If we have the collective will to build a "CDC for Planet Earth" to institute aggressive monitoring, to identify and understand trends, to predict their consequences, and to suggest and evaluate alternative actions, we may be able to rescue ourselves and our ecosystems from catastrophe. Such actions would be prudent insurance and necessary if remediation were attempted.

CONCLUSION

We must do something, and we must be sure that the actions are real, and not delusions of action. We agree with the quote from Hoyle at the beginning of this paper, with one exception: perhaps civilization is not a one-shot kick at the can. Something majestic might arise from our rubble using renewable resources alone, and certainly the individuals that would create such a future civilization would have to be collectively wise in ways that we have not been. If we can envision such a future society, can we not envision a way to become that civilization ourselves? Planet Earth—that small blue dot—is now island Earth and it is time for action to ensure our survival on that island.

ACKNOWLEDGMENTS

We appreciate the thoughtful comments of Clark Bullard, Laszlo Keszthelyi, and Mary Chapman in review.

REFERENCES CITED

Atwater, B.F., 1992, Geologic evidence for earthquakes during the past 2000 years along the Copalis River, Southern Coastal Washington: Journal of Geophysical Research, v. 97, no. B2, p. 1901–1909, doi: 10.1029/91JB02346.

Atwater, B.F., and Moore, A.L., 1992, A tsunami about 1000 years ago in Puget Sound, Washington: Science, v. 258, no. 5088, p. 1614–1617, doi: 10.1126/science.258.5088.1614.

Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, H.V., 1980, Extraterrestrial cause for the Cretaceous Tertiary Extinction: Science, v. 208, p. 1095, doi: 10.1126/science.208.4448.1095.

Ambrose, S., 1998, Late Pleistocene human population bottlenecks, volcanic winter, and differentiation of modern humans: Journal of Human Evolution, v. 35, p. 115–118.

Bar-Yam, Y., 2002, Complexity rising: From human beings to human civilization, a complexity profile: Encyclopedia of Life Support Systems (EOLSS) developed under the Auspices of the UNESCO, EOLSS Publishers, Oxford, UK, http://www.eolss.net.

Callicot, J.B., 2005, http://environment.harvard.edu/religion/disciplines/ethics/index.html.

Campbell, C.J., 1997, The Coming Oil Crisis: Essex, England, Multi-science Publ. Co., 210 p.

Cohen, J., 1995, How Many People Can the Earth Support?: New York, W.W. Norton, 532 pp.

[5]The United States, National Academy of Sciences, the National Academy of Engineering, the Institute of Medicine, and their global counterparts in other countries.

Colinvaux, P., 1979, Why Big Fierce Animals are Rare: Princeton, Princeton University Press, 264 pp.

Crutzen, P.J., Ramanathan, V., Anderson, T.L., Charlson, R.J., Schwartz, S.E., Knutti, R., Boucher, O., Rodhe, H., and Heintzenbert, J., 2003, The parasol effect on climate: Science, v. 302, p. 1679–1681, doi: 10.1126/science.302.5651.1679.

Diamond, J., 2005, Collapse: How Societies Choose to Fail or Succeed: New York, Viking Press, 591 pp.

Duncan, R.C., and Youngquist, W., 1999, Enhancing the peak of world oil production: Natural Resources Research, v. 8, p. 219–232, doi: 10.1023/A:1021646131122.

Ehrlich, P.R., and Kennedy, D., 2005, Sustainability: Millennium assessment of human behavior: Science, v. 209, no. 5734, p. 562–536, doi: 10.1126/science.1113028.

Farvar, M.T., and Milton, J.P., eds., 1972, The Careless Technology, Ecology and International Development: Garden City, Natural History Press, 1030 p. (available online by chapter).

Fisher, R.V., Heiken, G., and Hulen, J.B., 1998, Volcanoes: Crucibles of Change: Princeton, Princeton University, 334 p.

Flannery, T., 2002, The Future eaters: An ecological history of the Australasian lands and people: New York, Grove Press, 432 p.

Forster, P., and Solomon, S., 2003, Observations of a "weekend effect" in diurnal temperature range: Proceedings of the National Academy of Sciences of the United States of America, v. 100, p. 11,225–11,230, doi: 10.1073/pnas.2034034100.

Frank, K., Petrie, B., Choi, J., and Leggett, W., 2005, Trophic cascades in a formerly cod-dominated ecosystem: Science, v. 308, p. 1621–1623, doi: 10.1126/science.1113075.

Gluskoter, H., 1999, Increase in fossil fuel utilization in the twenty-first century: Environmental impact and lower carbon alternatives: Division of Fuel Chemistry of the American Chemical Society, Preprints, v. 44, no. 1, p. 36.

Grudd, H., Briffa, K.R., Gunnarson, B.E., and Linderholm, H.W., 2000, Swedish tree rings provide new evidence in support of a major, widespread environmental disruption in 1628 BC: Geophysical Research Letters, v. 27, p. 2957–2960, doi: 10.1029/1999GL010852.

Hardin, G., 1993, Living within Limits: Ecology, Economics, and Population Taboos: New York, Oxford University Press, 339 p.

Hooke, R., 1994, On the efficacy of humans as geomorphic agents: GSA Today, v. 4, no. 9, p. 217, and 224–225.

Hooke, R., 1994, Spatial distribution of human geomorphic activity in the United States: Comparison with rivers: Earth Surface Processes and Landforms, v. 24, p. 687–692, doi: 10.1002/(SICI)1096-9837(199908)24:8<687::AID-ESP991>3.0.CO;2-#.

Hoyle, F., 1964, Of Men and Galaxies: Seattle, University of Washington Press, 73 p.

Imhoff, M.L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., and Lawrence, W., 2004, Global patterns in human consumption of net primary production: Nature, v. 429, p. 870–873, doi: 10.1038/nature02619.

IPCC, 2001, Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the third Assessment Report of the Intergovernmental Panel on Climate Change, Watson, R.T., and the Core Writing Team, eds.: Cambridge, UK, and New York, Cambridge University Press, 398 p.

Karl, T.R., and Trenberth, K.E., 2003, Modern global climate change: Science, v. 302, p. 1719–1723, doi: 10.1126/science.1090228.

Kennedy, D., and Hanson, B., 2006, Ice and history: Science, v. 311, p. 1673, doi: 10.1126/science.1127485.

Koshimura, S., Mofjeld, H.O., Gonzalez, F.I., and Moore, A.L., 2002, Modeling the 1010 bp tsunami in Puget Sound, Washington: Geophysical Research Letters, v. 29, no. 20, p. 1948, doi: 10.1029/2002GL015170.

Lay, T., Kanamori, H., Ammon, C., Nettles, M., Ward, S., Aster, R., Beck, S., Bilek, S., Brudzinski, M., Butler, R., DeShon, H., Ekstrom, G., Satake, K., and Sipkin, S., 2005, The great Sumatra-Andaman Earthquake of 26 December, 2004: Science, v. 308, p. 1127–1133, doi: 10.1126/science.1112250.

Leopold, A., 1949, Sand County Almanac, and Sketches Here and There: New York, Oxford, 226 p.

Lipsitch, M., Cohen, T., Cooper, B., Robins, J., Ma, S., James, L., Gopalakrishna, G., Chew, S., Tan, C., Samore, M., Fisman, D., and Murray, M., 2003, Transmission dynamics and control of severe acute respiratory syndrome: Science, v. 300, p. 1966–1970, doi: 10.1126/science.1086616.

Milbrath, L.W., 1989, Envisioning a Sustainable Society: Learning Our Way Out: Albany, NY, State University of New York Press, 403 p.

Nur, A., and Cline, E.H., 2000, Poseidon's horses: Plate tectonics and earthquakes storms in the Late Bronze Age Aegean and Eastern Mediterranean: Journal of Archaeological Science, v. 27, p. 43–63, doi: 10.1006/jasc.1999.0431.

Okumura, K., Yoshioka, T., and Kuscu, I., 1993, Surface faulting on the North Anatolian Fault in these two Millennia: U.S. Geological Survey Open-File Report 94–568, p. 143–144, http://home.hiroshima-u.ac.jp/kojiok/anatolia.htm.

Palmer, A.R., 2000, Engaging "my neighbor" in the issue of sustainability, Part II: The context of humanity: Understanding deep time: GSA Today, v. 10, no. 2, p. 10.

Parsons, T., Toda, S., Stein, R., Barka, A., and Dieterich, J., 2000, Heightened odds of large earthquakes near Istanbul: An interaction-based probability calculation: Science, v. 288, p. 661–665, doi: 10.1126/science.288.5466.661.

Pimentel, D., Harvey, C., Resosundarmo, R., Sinclair, K., Kurz, D., McNair, M., Cris, S., Shpritz, L., Fitton, L., Saffouri, R., and Blair, R., 1995, Environmental costs of soil erosion and conservation benefits: Science, v. 267, p. 1117–1123, doi: 10.1126/science.267.5201.1117.

Pimm, S.L., Russell, G.T., Gittelman, J.I., and Brooks, T.M., 1995, The future of biodiversity: Science, v. 269, p. 347–350, doi: 10.1126/science.269.5222.347.

Posner, R.A., 2004, Catastrophic risk and response: New York: Oxford University Press, 322 p.

Rampino, M.R., and Self, S., 1992, Volcanic winter and accelerated glaciation following the Toba super-eruption: Nature, v. 359, p. 50–52, doi: 10.1038/359050a0.

Rampino, M.R., and Self, S., 1993, Climate-volcanism feedback and the Toba eruption of ~74,000 years ago: Quaternary Research, v. 40, p. 269–280, doi: 10.1006/qres.1993.1081.

Reitan, P., 2005, http://ejournal.nbii.org/archives/vol1iss1/communityessay.reitan.html.

Riley, S., Fraser, C., Donnelly, C., Ghani, A., Laith, J., Abu-Raddad, L., Hedley, A., Leung, G., Ho, L., Lam, T., Thach, T., Chau, P., Chan, K., Lo, S., Leunt, P., Tsang, T., Ho, W., Lee, K., Lau, E., Ferguson, N., and Anderson, R., 2003, Transmission dynamics of the etiological agent of SARS in Hong Kong: Impact of public health interventions: Science, v. 300, p. 1961–1966, doi: 10.1126/science.1086478.

Sagan, C., 1994, Pale Blue Dot: A Vision of the Human Future in Space: New York, Random House, 429 p.

Speth, J.G., 2004, Red sky at morning: America and the crisis of the global environment: New Haven, Yale, 299 p.

Stanley, D.G., and Warne, A.G., 1998, Nile delta in its destruction phase: Journal of Coastal Research, v. 14, p. 794–825.

Tainter, J., 1988, The collapse of complex societies: Cambridge, UK, Cambridge Univ. Press, 250 pp.

Tainter, J., 1995, The sustainability of complex societies: Futures, v. 27, p. 397–404, doi: 10.1016/0016-3287(95)00016-P.

Vallance, J.W., and Scott, K.M., 1997, The Osceola mudflow from Mount Rainer: Sedimentology and hazard implications of a high clay-rich debris flow: Geological Society of America Bulletin, v. 109, p. 143–163.

Wackernagel, M., and William R., 1996, Our ecological footprint—Reducing human impact on Earth: Gabriola Island and Stony Creek, New Society Publ., 160 p., see p 85, Table 3.4 (for 1991 data).

White, L., Jr., 1967, The historical roots of our ecologic crisis: Science, v. 155, p. 1203–1207, doi: 10.1126/science.155.3767.1203.

Wright, R., 2004, A short history of progress: Toronto, Anasi Press, 211 pp.

Yamaguchi, D.K., Atwater, B.F., Bunker, D.E., Benson, B.E., and Reid, M.S., 1997, Tree-ring dating the 1700 Cascadia earthquake: Nature, v. 389, p. 922–923, doi: 10.1038/40048.

Zen, E., 2000, Stakes, options, and some natural limits to a sustainable world, *in* Schneiderman, J.S., ed., The Earth around us: Maintaining a livable planet: New York, W.H. Freeman, p. 386–397, 440–441.

Zen, E., Barton, P.B., Reitan, P.H., Kieffer, S.W., and Palmer, A.R., 2002, Earth resources: The little engine that could brake sustainability: published on the Boulder Community Network site, http://bcn.boulder.co.us/basin/local/sustain_update.html.

Manuscript Accepted by the Society 3 November 2008

Printed in the USA