IT'S TIME!—RENEW YOUR MEMBERSHIP & SAVE 15%

DECEMBER 2012 | VOL. 22, NO. 12

GSA TODAY

A PUBLICATION OF THE GEOLOGICAL SOCIETY OF AMERICA®

Land transformation by humans: A review

Inside:

Preliminary Announcement and Call for Papers: 2013 GSA Cordilleran Section Meeting, p. 22

Preliminary Announcement and Call for Papers: 2013 GSA Rocky Mountain Section Meeting, p. 24

Final Announcement and Call for Papers: 2013 GSA Northeastern Section Meeting, p. 26

GSA TODAY

GSA TODAY (ISSN 1052-5173 USPS 0456-530) prints news and information for more than 25,000 GSA member readers and subscribing libraries, with 11 monthly issues (April/May is a combined issue). *GSA TODAY* is published by The Geological Society of America® Inc. (GSA) with offices at 3300 Penrose Place, Boulder, Colorado, USA, and a mailing address of P.O. Box 9140, Boulder, CO 80301-9140, USA. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of race, citizenship, gender, sexual orientation, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Subscriptions: GSA members: Contact GSA Sales & Service, +1-888-443-4472; +1-303-357-1000 option 3; gsaservice@geosociety.org for information and/or to place a claim for non-receipt or damaged copies. **Nonmembers and institutions:** *GSA TODAY* is US$80/yr; to subscribe, or for claims for non-receipt and damaged copies, contact gsaservice@geosociety.org. Claims are honored for one year; please allow sufficient delivery time for overseas copies. Periodicals postage paid at Boulder, Colorado, USA, and at additional mailing offices. Postmaster: Send address changes to GSA Sales & Service, P.O. Box 9140, Boulder, CO 80301-9140.

***GSA TODAY* STAFF**

Executive Director and Publisher: John W. Hess

Science Editors: Bernie Housen, Western Washington Univ. Geology Dept. (ES 425) and Advanced Materials Science and Engineering Center (AMSEC), 516 High Street, Bellingham, WA 98225-9080, USA, bernieh@wwu.edu; R. Damian Nance, Ohio University Dept. of Geological Sciences, 316 Clippinger Laboratories, Athens, OH 45701, USA, nance@ohio.edu

Managing Editor: K.E.A. "Kea" Giles, kgiles@geosociety.org, gsatoday@geosociety.org

Graphics Production: Margo McGrew

Advertising (classifieds & display): Ann Crawford, +1-800-472-1988 ext. 1053; +1-303-357-1053; Fax: +1-303-357-1070; advertising@geosociety.org; acrawford@geosociety.org

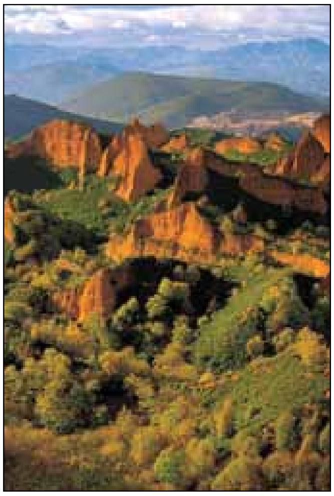
GSA Online: www.geosociety.org
GSA TODAY: www.geosociety.org/gsatoday/

Printed in the USA using pure soy inks.

THE GEOLOGICAL SOCIETY OF AMERICA®

VOLUME 22, NUMBER 12 | DECEMBER 2012

SCIENCE ARTICLE



Cover: Hydraulic gold mining by Romans nearly 2,000 years ago left this dramatic example of human modification of the landscape at Las Médulas, Spain, a UNESCO World Heritage Site. Water obtained from surrounding mountainous watersheds was used to undermine the >100-m-thick Miocene alluvial fan sediments here until they collapsed—a process called *ruina montium*, loosely translated as ruin the mountain—and then washed to separate the gold. Tailings total ~90 Mm^3. Photo by Justino Diez. See related article, p. 4–10.

Land transformation by humans: A review

Roger LeB. Hooke, *School of Earth and Climate Sciences and Climate Change Institute, University of Maine, Orono, Maine 04469-5790, USA, rogerhooke@gmail.com;* ***José F. Martín-Duque,*** *Dept. of Geodynamics and Geosciences Institute (CSIC-UCM), Complutense University, 28040 Madrid, Spain; and* ***Javier Pedraza,*** *Dept. of Geodynamics, Complutense University, 28040 Madrid, Spain*

ABSTRACT

In recent decades, changes that human activities have wrought in Earth's life support system have worried many people. The human population has doubled in the past 40 years and is projected to increase by the same amount again in the next 40. The expansion of infrastructure and agriculture necessitated by this population growth has quickened the pace of land transformation and degradation. We estimate that humans have modified >50% of Earth's land surface. The current rate of land transformation, particularly of agricultural land, is unsustainable. We need a lively public discussion of the problems resulting from population pressures and the resulting land degradation.

INTRODUCTION

"Global Change" refers to changes that alter the atmosphere and oceans, and hence are experienced globally. It also refers to local changes that are so common as to be, collectively, of global importance; these include changes in climate, in composition of air and water, in biodiversity, and in land use (Vitousek, 1992; Rockström et al., 2009). Herein, we focus on land use (Fig. 1). Vitousek (1992, p. 7) remarks that this may be the "most significant component of global change" for decades to come.

Many changes in land use are a consequence of the increase in human population and the resulting demand for more resources—among them, minerals, soil, and water. This demand now exceeds that which Earth can provide sustainably. The long-term sustainability issue is more serious than, but exacerbated by, climate change.

By the middle of the nineteenth century, the extent to which humans had already modified the landscape was recognized by George Perkins Marsh (1864). Marsh understood that Earth's ability to provide the many ecosystem services upon which we depend was exhaustible.

Over the last half century, numerous impacts of changes in land use have been identified (Lambin and Geist, 2006, p. 1). In the 1970s, it was recognized that changes in albedo and evapotranspiration due to clearing and overgrazing had led to local decreases in rainfall. In the 1980s, the role of land-use changes in the carbon cycle was highlighted. Many papers since the late 1990s have drawn attention to the effects of land use on biodiversity, ecosystem services, and soil degradation.

Humans are likely the premier geomorphic agent currently sculpting Earth's surface (Hooke, 1994). Earth is moved and the landscape modified, commonly degraded, by many of our activities. Mining, infrastructure expansion, and urban development are obvious ones. Plowing moves huge amounts of earth and leads to accelerated erosion. Grazing and logging also increase erosion. Much of the eroded sediment ends up as colluvium on hillslopes and as alluvium in floodplains (Trimble, 1999; Wilkinson and McElroy, 2007), thus subtly altering the shape of the land. The rest is carried away by streams and rivers.

We are land animals. The resources upon which we depend come largely from the land. The land and the other inhabitants it supports, its biodiversity, provide us with food, fiber, mineral resources, medicines, industrial products, and innumerable ecosystem services like cleansing our waste water, dampening flood peaks, breaking down rocks into productive soil, maintaining the supply of oxygen in the atmosphere, and supporting pollinators for many crops and predators that control many agricultural pests (MEA, 2003 [see esp. chapter 2, p. 49–70]; TEEB, 2010). The diversity of species contributes to the stability or resilience of this life support system, facilitating continuation of services despite disturbances (Rockström et al., 2009). Degrading the land degrades our life support system. The land is an essential resource for future generations.

LAND AREA MODIFIED BY HUMAN ACTION

Assessments of the percentage of ice-free land affected by human action vary from 20% to 100%. Humans appropriate 20% to 40% of Earth's potential net primary biological production (Haberl et al., 2007; Imhoff et al., 2004; Vitousek et al., 1986). Nearly 24% of Earth's surface area likely experienced decline in ecosystem function and productivity between 1981 and 2003 (Bai et al., 2008). As of 1995, ~43% of Earth's surface area had experienced human-induced degradation (Daily, 1995). Ellis and Ramankutty (2008) concluded that more than 75% of Earth's ice-free land area could no longer be considered wild. Of Earth's ice-free land area, 83% is likely directly influenced by human beings (Sanderson et al., 2002). Our pollutants affect plant and animal physiology worldwide (McKibben, 1989, e.g., p. 38, 58).

The amount of earth moved by humans and the history of human earth moving have been discussed previously (Hooke, 1994, 2000). Herein, we consider the *area* of the landscape we humans have reconfigured.

Changes through Time in Cropland, Pasture, Forest, and Urban Land

In pioneering studies, Ramankutty and Foley (1999) and Klein Goldewijk (2001, and pers. comm., March 2010) assessed the land area used as *cropland* or *pasture* (Klein Goldewijk, 2001, only) and that covered by *forest* (supplemental data[1]), during the past 300 years. Recently, they have updated some of their estimates (Ramankutty et al., 2008; Klein Goldewijk et al., 2011), and Pongratz et al. (2008, and pers. comm., Jan. 2012) have presented

---

GSA Today, v. 22, no. 12, doi: 10.1130/GSAT151A.1.

Figure 1. Land transformation: Before New York (top: reproduced from *National Geographic Magazine*, September 2009, with permission of the National Geographic Society; bottom: New York, USA, © Robert Clark/INSTITUTE for Artist Management).

new ones. All of these studies are based on data collected by the Food and Agriculture Organization of the United Nations since 1961 (http://faostat.fao.org). The authors then hindcast and sometimes forecast using satellite, ground-truth, and historical data (Fig. 2). Ramankutty et al. (2008) give values only for 2000. Thus, we adjusted the Ramankutty and Foley (1999) values for cropland in earlier years downward by the percent difference between the Ramankutty et al. (2008) and projected Ramankutty and Foley (1999) values for 2000 (see the supplemental data, Sec. C, for additional details [footnote 1]).

Noteworthy in Figure 2 are the increases in cropland and pasture over the past 300 years, the corresponding decrease in forest, and the recent decreases in the rate of change of all three.

Recent estimates of the global *urban* area range from 0.3 to 3.5 Mkm^2 (Potere and Schneider, 2007). The wide range is due to differences in the definition of "urban" and in the methodology for identifying areas that are urban. An urban area is one in which the population density exceeds a minimum value. Different countries, however, use different minima, ranging from <200 to 4000 people/km^2. Methodologically, the problem is the lack of a standard remote sensing technique for identifying urban areas. Common approaches use either the intensity of night lights or the extent of impervious ground. The former varies spatially, because more affluent countries use more power. The latter overlooks open space around houses that, nonetheless, has been modified by human action.

We think of "urban areas" as expanses of contiguous land, divided into parcels (≤~1 ha) with different owners, and modified for residential or commercial purposes. This includes land covered by structures or pavement as well as intervening land modified to form gardens or parks. The estimate of 3.5 Mkm^2 (CIESIN, 2010) best reflects this description. It is based on night lights, censuses, and a variety of supplementary data, and is as of 2005. We projected backward and forward using CIESIN's population density (796 people/km^2) and estimates of urban population from UNPD (2004, 2007a, 2007b) and Kelley and Williamson (1984).

---

[1] GSA supplemental data item 2012340, supplemental information, definitions, figures, tables, and references, is online at www.geosociety.org/pubs/ft2012.htm. You can also request a copy from *GSA Today*, P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

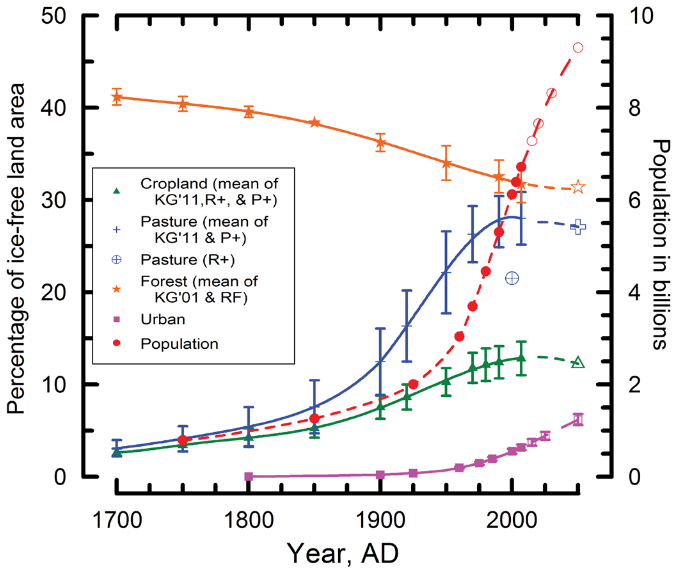


Figure 2. Changes in land use through time with extrapolations to 2050 AD. Population data and projections are from UNPD (1999). See text and supplemental data (Sec. C; see text footnote 1) for other sources and estimates. KG'01—Klein Goldewijk (2001); KG'11—Klein Goldewijk et al. (2011); P+—Pongratz et al. (2008); R+— Ramankutty et al. (2008); RF—Ramankutty and Foley (1999).

Land Modified by Human Action as of 2007

In Table 1, we present a more comprehensive estimate, as of 2007, of the land area modified either directly by human earth moving or indirectly by actions causing changes in sediment fluxes.

To obtain the areas of *cropland* and *pasture* in Table 1, 16.7 ± 2.4 Mkm^2 and 33.5 ± 5.7 Mkm^2, respectively, we first adjusted the Ramankutty et al. (2008) value for pasture in 2000 downward by the mean decrease between 2000 and 2007 in the FAO (2009) and Pongratz et al. (2008) estimates. We then fit a 4th order polynomial through the Klein Goldewijk et al. (2011) and Ramankutty et al. (2008) cropland data and extrapolated them to 2007. Finally, we then averaged these values with those of Pongratz et al. (2008).

Erosion rates are higher on agricultural land; typical estimates are 15 t ha^{-1}y^{-1} for cropland and 5 t ha^{-1}y^{-1} for pasture (e.g., USDA, 1989; Pimentel et al., 1995; Montgomery, 2007). Of this, ~70% is likely redeposited nearby on slopes and floodplains (Wilkinson and McElroy, 2007). Using population estimates, the per capita need for agricultural land, and a mean deposition of 1 ± 0.5 m, we estimate that the area thus reshaped in the past five millennia is ~5.3 ± 2.0 Mkm^2 (see supplemental data, Sec. D [footnote 1]).

Logging operations disturb forest soils and thus also increase erosion (Elliot et al., 1998). Unlike agricultural land that is reused annually, however, logged areas recover as regrowth occurs. Furthermore, part of the logged land may not be degraded. We estimate the global area logged annually by dividing the production (3.5 Mm^3 in 2007) by an estimate of the yield per hectare (15 ± 5 m^3 ha^{-1}). We assumed that 50% of the area would have been disturbed during the year in which it was cut and that due to regrowth half of the area remaining disturbed in any given year would have recovered by the next. This calculation yielded a disturbed area of 2.4 ± 1.2 Mkm^2 in 2007. The uncertainty is based on uncertainties of 50% in the regeneration rate, 25% in the area initially disturbed, and 33% in the yield per hectare (see supplemental data, Sec. E [footnote 1]).

For *forested* area, we extrapolated the Ramankutty and Foley (1999) time series using a 4th order polynomial and averaged it with the FAO (2009) estimates, yielding 41.3 ± 2.6 Mkm^2. This is identical to the Pongratz et al. (2008) estimate for forest plus shrubland. As this includes both natural and planted forests, we subtracted the latter, 2.7 Mkm^2 (FAO, 2009). We also subtracted the area disturbed by logging, yielding 36.2 ± 2.9 Mkm^2.

To estimate the area of *urban* development in 2007, 3.7 ± 1.0 Mkm^2, we extrapolated the CIESIN (2010) estimate of the area in 2005, using an annual growth rate of 2.1% (UNPD, 2007a).

The area occupied by *rural housing and businesses*, 4.2 ± 1.4 Mkm^2, is assessed from the rural population in 2007 (UNPD, 2007b), assuming that 8^{+4}_{-2} people would disturb a hectare of rural land.

To calculate the land area affected by *roads in rural areas*, we used data for 2002–2007 on the total lengths of roads of various classes in 188 countries (IRF-WRS, 2009). Other data suggest that 70% of these roads are rural. We assigned widths to these various road classes, based on standards in the United States (supplemental data, Sec. F [footnote 1]). Assuming an uncertainty of ±15% in road widths and in the percentage of rural roads, we obtained 0.5 ± 0.1 Mkm^2.

A comprehensive list of reservoir volumes has been compiled by the International Committee on Large Dams and updated by Chao et al. (2008). They sum to ~10,800 km^3. B.F. Chao (pers. comm., 2011) thinks the mean reservoir depth is ~50–100 m. Noting the large number of small reservoirs, we chose the lower number, yielding a total surface area of 0.2 ± 0.1 Mkm^2.

Table 1. Land area modified by human action (as of ca. 2007)

Activity	Area involved 10^6 km^2	% of Earth's land surface
Human-modified land		
Cropland (mostly cultivated or plowed land ≡ FAO's arable land and permanent crops)	16.7 ± 2.4	12.8 ± 1.8
Permanent meadows and pastures (mostly uncultivated)	33.5 ± 5.7	25.8 ± 4.3
Land area modified by deposition of eroded sediment	5.3 ± 2.0	4.1 ± 1.5
Land area modified by logging operations	2.4 ± 1.2	1.8 ± 0.9
Forest area (planted)	2.7	2.1
Subtotal agriculture and forestry	**60.6 ± 6.5***	**46.6 ± 5.0**
Urban areas (including urban roads)	3.7 ± 1.0	2.8 ± 0.8
Rural housing and businesses	4.2 ± 1.4	3.2 ± 1.1
Highways and roads in rural areas	0.5 ± 0.1	0.4 ± 0.1
Reservoirs	0.2 ± 0.1	0.2 ± 0.1
Railways	0.03	0.02
Mining and quarrying	0.4 +0.4/–0.1	0.3 +0.3/–0.1
Subtotal human infrastructure	**9.0 ± 1.7**	**6.9 ± 1.3**
Total land area modified by humans	**69.6 ± 6.7**	**53.5 ± 5.1**
Natural land (mostly)		
Forest area (natural but not necessarily virgin)	36.2 ± 2.9	27.8 ± 2.2
Other land (largely high mountains, tundra, and deserts, unsuitable for agriculture)	24.3	18.7
Total natural land	**60.5**	**46.5**
Total land area (exclusive of ice sheets)	130.1	100.0

Note: FAO—Food and Agriculture Organization of the United Nations.
*Apparent errors in some sums are due to accumulated round-off errors.

Data on the global length of *railways* are from IUR (2008). Widths are from ADIF (2005). The product is 0.03 Mkm^2. We have no basis for estimating an uncertainty.

We found summary data on the area disturbed by *mining* for 14 regions or countries representing 22% of Earth's ice-free land area, all continents except Africa, and the two principal economic powerhouses of today's economy, China and the United States (supplemental data, Sec. G [footnote 1]). The weighted mean is 0.3%. Assuming that this percentage applies globally, we obtain ~$\mathbf{0.4}^{+0.4}_{-0.1}$ Mkm^2. For comparison, Norse et al. (1992) suggest that the area is between 0.5 and 1.0 Mkm^2, but the basis for this estimate is unclear.

Our subtotal for land disturbed by human infrastructure (Table 1) is ~9.0 ± 1.7 Mkm^2. We believe this is a conservative estimate because we have not evaluated the land area modified by coastal or river engineering projects; by construction of infrastructure like levees, electric power grids or wind farms; or by infrastructure from the distant past (e.g., prehistoric archaeological sites).

DISCUSSION

The data in Table 1 suggest that ~70 Mkm^2, or >50% of Earth's ice-free land area, has been *directly* modified by human action involving moving earth or changing sediment fluxes. Many of these activities have *indirect* consequences well beyond the area directly affected. Converting land to agriculture leads to local extinctions of biota in adjacent areas, the insecticides and herbicides used diffuse into the surroundings, killing non-target species (Ehrlich and Ehrlich, 1981), and fertilizers foul our streams and rivers, leading to dead zones in the ocean (Halpern et al., 2008). Invasive species commonly find footholds on surfaces disturbed by agricultural activities, and can severely reduce the usefulness of large areas (e.g., Tobler, 2007). Toxic chemicals spewed into the air from urban centers rain out over vast areas downwind. Others, like CO_2, diffuse over the entire globe. Roads and railways fragment ecosystems, a key element of habitat destruction and a principal cause of loss of biodiversity (Vitousek et al., 1997; Sala et al., 2000), and runoff from them carries pollutants. The land area ecologically impacted by roads may be tens to hundreds of meters wider than the area physically disturbed (Forman, 2000). Runoff from mining areas is commonly contaminated and has a high sediment load, affecting hundreds of kilometers of riparian ecosystems. Dust raised by plowing and other human activities is deposited over distant surfaces. Dust commonly contains pathogens (Prospero et al., 2005) or heavy metals (Herut et al., 2001; Reynolds et al., 2010) that can have adverse effects on people and other organisms. Dust also accelerates melting of snow and ice on mountains, affecting water supplies downstream (Painter et al., 2010). Levees on rivers prevent natural water storage during floods, thus increasing damage downstream (e.g., Pinter et al., 2008). Deforestation and construction projects involving earth moving on steep slopes too commonly result in catastrophic failures and in human deaths (Kellerer-Pirklbauer, 2002). Thus, the impact of land transformation is much larger than suggested by the numbers in Table 1.

These impacts reduce the ecosystem services we receive, *seemingly for free*, from the plants, animals, insects, and microbes with whom we share the planet (MEA, 2005; TEEB, 2010). The global annual value of these services is roughly twice the global GNP (Costanza et al., 1997; Daily, 1997). They are essential for human survival. Some are likely irreplaceable.

Cropland

The data in Figure 2 suggest that the rate of change in area of cropland and pasture has decreased in the last few decades. Projected into the future, these trends suggest a peak and then a decline in the areas of both. Let's focus on cropland, because that is the land use for which data are most robust and the one of most concern, given our swelling population (Fig. 2).

At least three trends are contributing to the decline in the rate of increase in cropland:

1. **Urban area is increasing, commonly at the expense of agricultural land.** Between 2000 and 2030, worldwide, the loss of agricultural land to urbanization may be as much as ~15,000 km^2 *annually* (Döös, 2002).
2. **There is a dearth of additional land suitable for agriculture.** Of Earth's land area, 70% to 80% is unsuitable for agriculture owing to poor soils, steep topography, or adverse climate (Fischer et al., 2000, p. 49; Ramankutty et al., 2002). About half of the rest is already in crops (Table 1), and a large fraction of the other half is presently under tropical forests that beneficially take up CO_2. Tropical-forest soil loses fertility rapidly, once cleared.
3. **Some existing agricultural land has deteriorated so much that it is no longer worth cultivating.** As of ca. 1990, soils on nearly 20 Mkm^2 of land, or ~40% of the global agricultural land area, had been degraded (Oldeman et al., 1991, p. 28). Of this, over half was so degraded that local farmers lacked the means to restore it.

Partially offsetting these trends may be increases in efficiency of farming and food distribution. Rudel et al. (2009), however, could not find correlations that supported this hypothesis.

PROGNOSIS FOR THE FUTURE

Looking ahead a few decades, land suitable for agriculture will likely continue to diminish as urban areas expand, soil is degraded, fertile soil is washed down rivers and blown away ten times faster than it is replaced (Montgomery, 2007), and water tables decline in areas dependent on groundwater for irrigation (Gleick, 1993). Foreseeing a shortage of arable land, global investors are, in fact, buying huge tracts in Africa and South America (De Castro, 2011). In addition, despite foreseeable future technological developments, agricultural productivity is likely to decrease as (*i*) the supply of phosphate for fertilizer decreases (Rosmarin, 2004); (*ii*) petroleum (used to run farm machinery and as feedstock for fertilizer) becomes more expensive and less available; (*iii*) pollution adversely affects pollinators, plant growth, and predators that control agricultural pests (Peng et al., 2004; supplemental data, Sec. H [footnote 1]); and (*iv*) climate changes.

Will Earth be able to support the projected 2050 population of 8.9 billion? Fischer et al. (2000, p. 88) believe that it can. Döös and Shaw (1999), considering climate change, water availability, irrigation, salinization, pests, farm management, and access to fertilizers, think it likely that the demand for cereals could be met in the more developed countries, and *highly unlikely* that it would be met in less developed ones. Seto et al. (2010, p. 95) conclude that it is unlikely that Earth's land resources can support current and future populations sustainably without a "breathtaking" change in our way of life. Wackernagel et al. (2002) estimate that, as of ca. 1978, the land area needed to grow crops, graze animals, provide timber, accommodate infrastructure, and absorb waste, *all sustainably*, already exceeded Earth's available area, and that as of 2002, we needed 20% more land than is available. If this is the case, we are in a period of overshoot.

Overshoot

Overshoot occurs when populations exceed the local carrying capacity. An environment's carrying capacity for a given species is the number of individuals "living in a given manner, which the environment can support *indefinitely*" (Catton, 1980, p. 4). Only a population less than or equal to the carrying capacity is sustainable.

A sustainable population is one that (*i*) consumes renewable resources at a rate less than the rate at which they are renewed; (*ii*) consumes non-renewable resources at a rate less than the rate at which substitutes can be found; and (*iii*) emits pollution at a rate less than the capacity of the environment to absorb the pollutants (Daly, 1991, p. 256).

It is axiomatic that, on a finite planet, there *is* a limit to growth. The question is, "Are we now bumping up against that limit?"

Several observations suggest that, with *our present lifestyles*, we are, indeed, now living in a state of overshoot. We struggle to supply the food needed by the present population. Groundwater tables are declining. Our way of life is based on non-renewables like fossil fuels, phosphates, and ores, accumulated over millions of years, with no clear plan for adequate substitutes once natural sources are exhausted. We discard many chemicals (e.g., CO_2, N, plastics) faster than they can be absorbed by the environment.

When the number of individuals exceeds the carrying capacity, overuse of the environment sets up forces that, *after a delay*, first reduce the standard of living and then eventually the population (Catton, 1980, p. 4–5). Initiation of the correction may be manifested by stagnant or negative economic growth rates, by famine and/or water shortages, by increases in disease resulting from undernourishment (Pimentel et al., 2007), and by increases in conflict. Sound familiar? Fifty-four nations with 12% of the world's population experienced economic declines in per capita GDP from 1990 to 2001 (Meadows et al., 2004, p. xiv; World Bank, 2003, p. 64–65). Famine, disease, and conflict are frequently in the news.

SOLUTIONS

If we are in a state of overshoot, here are three ways to bring the human impact on Earth back to sustainability:

1. **Reduce demand.** Demand can be reduced by improving building insulation or mandating energy-efficient vehicles and appliances. Recycling reduces demand for primary materials. Tempering our impulse to buy things that we don't really need or of which we will soon tire also reduces demand.
2. **Develop technological solutions.** Existing technology can mitigate our impact. Adoption of efficient building and farming practices limits degradation, and ecological restoration can partially reverse it (Rey Benayas et al., 2009). Technological breakthroughs are also possible. Simon (1996) argued that a larger population increases the likelihood of spawning the brain power needed to achieve such breakthroughs. But without well-fed bodies, brains don't function well.

   Our technological skills have enabled us to support an ever increasing population. They have also exacerbated some problems. Use of oil as an energy source in agriculture has increased efficiency, but at the expense of leaving us presently dependent on a non-renewable resource. Mechanical well drilling and pumping facilitate irrigation, but now groundwater tables are dropping unsustainably (Gleick, 1993). Given present usage, more than half of the U.S. High Plains aquifer will likely last for 50 to 200 years, *but* significant parts will be exhausted in <~25 years while others are already effectively spent (Buchanan et al., 2009). Use of bioengineered wheat in Punjab, India, and rice in Bali, Indonesia, increased crop yields, but also led to a variety of economic, pest, and health problems (Tiwana et al., 2007, p. xxii–xxiii; Lansing, 1991, p. 110–117).
3. **Reduce the population.** Increasing the availability of health care, education, and microfinancing, particularly for women in developing countries, reduces fertility. Reduced fertility reduces poverty, because available resources are distributed among fewer people. Couples worldwide can be urged to have only two children and to delay having them so there will be fewer people on Earth at any one time. These steps would first slow population growth and then lead to a long-term decline.

Reducing demand is a critical component of the solution, but in itself is not sufficient, given the magnitude of the problem. Technological progress, particularly in the energy field, is essential, but we also think it unwise to bet too heavily on unspecified future breakthroughs. Reducing and eventually reversing population growth needs to be a large part of the solution. Eventually, difficult decisions will have to be made about the size of an optimum population and how to achieve it.

CLOSURE

We would like to leave the reader pondering three questions:

1. **Are natural resources (such as land, soil, water, ecosystem services, ores) the fundamental basis for a comfortable life?**
2. **Above a certain threshold regional population, is comfort inversely proportional to population?**
3. **How much of the unrest in the world is a consequence of insufficient natural resources to support local populations at a tolerable level?** Periods of inadequate food production during the past millennium have led to unrest, war, and migration (Zhang et al., 2007). The Arab Spring is, at least in part, a consequence of high food prices and unemployment (Roubini, 2011).

We have shown, herein, that many of the problems now facing humanity will be gravely exacerbated if the population continues to increase and the land continues to degrade; many would be vastly easier to solve with a reduced population. The transition to a truly sustainable society (sensu Daly, 1991) requires more than a population policy though. Unqualified growth can no longer be our mantra. Thus, drastic changes in our economic philosophy and, hence, in the controlling legal structure are required. The needed changes are, indeed, breathtaking.

ACKNOWLEDGMENTS

This study was supported by the University of Maine, School of Earth and Climate Sciences, and by the Spanish Research Project CGL2010-21754-CO2-01. We thank K. Klein Goldewijk for supplying unpublished data on the land area covered by forests in the past; J. Pongratz for data files on changes in landcover; B. Chao for reservoir data; D. Fastovsky, B. Housen, and especially R. Reynolds for critical comments leading to significant improvements; and J. Moore, L. Balaguer, F. Valladares, J. Oyarzun, L. Santos, J.L. Lalana, M. Tejedor, E. Serra, and L.F. Prado for help in tracking down references.

REFERENCES CITED

ADIF, 2005, Environmental Report 2005: Madrid, Administrador de Infraestructuras Ferroviarias (ADIF), 139 p.; see p. 65 at http://www.adif.es/es_ES/conoceradif/doc/environmental2005.pdf (last accessed 1 Oct. 2012).

Bai, Z.G., Dent, D.L. Olsson, L., and Schaepman, M.E., 2008, Proxy global assessment of land degradation: Soil Use and Management, v. 24, p. 223–234.

Buchanan, R.C., Buddemeier, R.R., and Wilson, B.B., 2009, The high plains aquifer: Kansas Geological Survey Public Information Circular 18, 6 p.

Catton, W.R., 1980, Overshoot: The Ecological Basis of Revolutionary Change: Urbana, University of Illinois Press, 298 p.

Chao, B.F., Wu, Y.H., and Li, Y.S., 2008, Impact of artificial reservoir water impoundment on global sea level: Science, v. 320, p. 212–214.

CIESIN, 2010, Center for International Earth Science Information Network (CIESIN), Columbia University, Gridded Population of the World (GPW), version 3 and Global Rural-Urban Mapping Project (GRUMP) Alpha Version: http://www.sedac.ciesin.columbia.edu/gpw (last accessed 1 Oct. 2012).

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., and van den Belt, M., 1997, The value of the world's ecosystem services and natural capital: Nature, v. 387, 6630, p. 253–260.

Daily, G.C., 1995, Restoring value to the world's degraded lands: Science, v. 269, p. 350–354.

Daily, G.C., editor, 1997, Nature's Services: Washington, D.C., Island Press, 392 p.

Daly, H.E., 1991, Steady-State Economics: Washington, D.C., Island Press, 302 p.

De Castro, P., 2011, Corsa alla terra: Cibo e agricoltura nell'era della nuova scarsità (Rush for land: food and agriculture in a new era of shortages): Roma, Donzelli, 160 p.

Döös, B.R., 2002, Population growth and loss of arable land: Global Environmental Change, v. 12, no. 4, p. 303–311.

Döös, B.R., and Shaw, R., 1999, Can we predict the future food production? A sensitivity analysis: Global Environmental Change, v. 9, p. 261–283.

Ehrlich, P.R., and Ehrlich, A.H., 1981, Extinction: New York, Random House, 305 p.

Elliot, W.J., Page-Dumroese, D., and Robichaud, P.R., 1998, The effects of forest management on erosion and soil productivity, *in* Lal, R., ed., Soil Quality and Erosion: Boca Raton, Florida, St. Lucie Press, p. 195–209.

Ellis, E.C., and Ramankutty, N., 2008, Putting people in the map: Anthropogenic biomes of the world: Frontiers in Ecology and the Environment, v. 6, no. 8, p. 439–447.

FAO, 2009, Rethinking the value of planted forests: Food and Agriculture Organization of the United Nations, http://www.fao.org/news/story/en/item/10324/icode/ (last accessed 1 Oct. 2012).

Fischer, G., van Velthuizen, H., and Nachtergaele, F.O., 2000, Global agro-ecological zones assessment: Methodology and results: International Institute for Applied Systems Analysis, Interim Report no. IR-00-064, 338 p.

Forman, R.T.T., 2000, Estimate of the area affected ecologically by the road system in the United States: Conservation Biology, v. 14, no. 1, p. 31–35.

Gleick, P.H., 1993, Water and conflict: Fresh water resources and international security: International Security, v. 18, p. 79–112.

Haberl, H., Erb, K.H., Karusmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., and Marina Fischer-Kowalski, M., 2007, Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems: Proceedings of the National Academy of Sciences, v. 104, no. 31, p. 12,942–12,947.

Halpern, B.S., Walbridge, S., Selkoel, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., and Watson, R., 2008, A global map of human impact on marine ecosystems: Science, v. 319, p. 948–952.

Herut, B., Nimmo, M., Medway, A., Chester, R., and Krom, M.D., 2001, Dray atmospheric inputs of trace metals at the Mediterranean coast of Israel (SE Mediterranean): Sources and fluxes: Atmospheric Environment, v. 35, p. 803–813.

Hooke, R.LeB., 1994, On the efficacy of humans as geomorphic agents: GSA Today, v. 4, p. 217, 224–225.

Hooke, R.LeB., 2000, On the history of humans as geomorphic agents: Geology, v. 28, no. 9, p. 843–846.

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

IRF-WRS, 2009, IRF World Road Statistics: International Road Federation: Geneva, IRF, 270 p.

IUR, 2008, Synopsis 2008: Statistics of the International Union of Railways: http://www.uic.org/spip.php?article1347 (last accessed 1 Oct. 2012).

Kellerer-Pirklbauer, V.O., 2002, The influence of land use on the stability of slopes with examples from the European Alps: Mitteilungen des Naturwissenschaftlichen Vereines für Steiermark, v. 132, p. 43–62.

Kelley, A., and Williamson, J., 1984, Population growth, industrial revolution, and the urban transition: Population Development Review, v. 10, p. 419–441.

Klein Goldewijk, K., 2001, Estimating global land use change over the past 300 years: The HYDE Database: Global Biogeochemical Cycles, v. 15, p. 417–433.

Klein Goldewijk, K., Beusen, A., and van Drecht, G., 2011, The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years: Global Ecology and Biogeography, v. 20, p. 73–86.

Lambin, E.F., and Geist, H.J., editors, 2006, Land-Use and Land-Cover Change: Local Processes and Global Impacts: Berlin, Springer-Verlag, 222 p.

Lansing, S.J., 1991, Priests and Programmers: Technologies of Power in the Engineered Landscape of Bali: Princeton, New Jersey, Princeton University Press, 183 p.

Marsh, G.P., 1864, Man and Nature (1965 ed.): Cambridge, Massachusetts, Harvard University, Belknap Press, 472 p.

McKibben, B., 1989, The End of Nature: New York, Random House, 226 p.

MEA, 2003, Ecosystems and human well-being: A framework for assessment: Washington, D.C., Island Press, 245 p.

MEA, 2005, Current State and Trends. Millennium Ecosystem Assessment: Washington, D.C., Island Press, 839 p.

Meadows, D., Randers, J., and Meadows, D., 2004, Limits to Growth: The 30-year Update: White River Junction, Vermont, Chelsea Green Publishing Co., 338 p.

Montgomery, D.R., 2007, Soil erosion and agricultural sustainability: Proceedings of the National Academy of Sciences, v. 104, p. 13,268–13,272.

Norse, D., James, C., Skinner, B.J., and Zhao, Q., 1992, Agriculture, land use and degradation, *in* Dooge, J.C.I., Goodman, G.T., Rivière, J.W.M., Marton-Lefèvre, J., and O'Riordan, T., eds., An Agenda of Science for Environment and Development into the 21st Century: Cambridge, UK, Cambridge University Press, p. 79–89.

Oldeman, L.R., Hakkeling, R.T.A., and Sombroek, W.G., 1991, World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note (2nd edition): Wageningen and Nairobi: International Soil Reference and Information Centre (ISRIC), 35 p.

Painter, T.H., Deems, J.S., Belnape, J., Hamlet, A.F., Landry, C.C., and Udall, B., 2010, Response of Colorado River runoff to dust radiative forcing in snow: Proceedings of the National Academy of Sciences, v. 107, no. 40, p. 17,125–17,130.

Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S., and Cassman, K.G., 2004, Rice yields decline with higher night temperature from global warming: Proceedings of the National Academy of Sciences, v. 101, no. 27, p. 9971–9975.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri R., and Blair, R., 1995, Environmental and economic costs of soil erosion and conservation benefits: Science, v. 267, p. 1117–1123.

Pimentel, D., Cooperstein, S., Randell, H., Filiberto, D., Sorrentino, S., Kaye, B., Nicklin, C., Yagi, J., Brian, J., O'Hern, J., Habas, A., and Weinstein, C., 2007, Ecology of increasing diseases: Population growth and environmental degradation: Human Ecology, v. 35, no. 6, p. 653–668.

Pinter, N., Jemberie, A.A., Remo, J.W.F., Heine, R.A., and Ickes, B.S., 2008, Flood trends and river engineering on the Mississippi River system: Geophysical Research Letters, v. 35, L23404, doi: 10.1029/2008GL035987.

Pongratz, J., Reick, C., Raddatz, T., and Claussen, M., 2008, A reconstruction of global agricultural areas and land cover for the last millennium: Global Biogeochemical Cycles, v. 22, p. 1–16.

Potere, D., and Schneider, A., 2007, A critical look at representations of urban areas in global maps: GeoJournal, v. 69, p. 55–80.

Prospero, J.M., Blades, E., Mathison, G., and Naidu, R., 2005, Interhemispheric transport of viable fungi and bacteria from Africa to the Caribbean with soil dust: Aerobiologia, v. 21, p. 1–19.

Ramankutty, N., and Foley, J.A., 1999, Estimating historical changes in global land cover: Croplands from 1700 to 1992: Global Biogeochemical Cycles, v. 13, p. 997–1027.

Ramankutty, N., Foley, J.A., Norman, J., and McSweeney, K., 2002, The global distribution of cultivable lands: Current patterns and sensitivity to possible climate change: Global Ecology & Biogeography, v. 11, p. 377–392.

Ramankutty, N., Evan, A.T., Monfreda, C., and Foley, J.A., 2008, 1. Geographic distribution of global agricultural lands in the year 2000: Global Biogeochemical Cycles, v. 22, p. 1–19.

Rey Benayas, J.M., Newton, A.C., Diaz, A., and Bullock, J.M., 2009, Enhancement of biodiversity and ecosystem services by ecological restoration: A meta-analysis: Science, v. 325, p. 1121–1124.

Reynolds, R.L., Mordecai, J.S., Rosenbaum, J.G., Ketterer, M.E., Walsh, M.K., and Moser, K.A., 2010, Compositional changes in sediments of subalpine lakes, Uinta Mountains (Utah): Evidence for the effects of human activity on atmospheric dust inputs: Journal of Paleolimnology, v. 44, no. 1, p. 161–175.

Rockström, J., and 28 others, 2009, Planetary boundaries: Exploring the safe operating space for humanity: Ecology and Society, v. 14, no. 2, art. 32: http://www.ecologyandsociety.org/vol14/iss2/art32/ (last accessed 1 Oct. 2012).

Rosmarin, A., 2004, The precarious geopolitics of phosphorous: Down to Earth, v. 13, p. 27–34.

Roubini, N., 2011, World Economic Forum: Davos, Switzerland, 26 Jan. 2011 (presentation).

Rudel, T.K., Schneider, L., Uriarte, M., Turner II, B.L., DeFries, R., Lawrence, D., Geoghegan, J., Hecht, S., Ickowitz, A., Lambin, E.F., Birkenholtz, T., Baptista, S., and Grau, R., 2009, Agricultural intensification and changes in cultivated areas, 1970–2005: Proceedings of the National Academy of Sciences, v. 106, no. 49, p. 20,675–20,680.

Sala, O.E., Chapin, F.S. III, Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., and Wall, D.H., 2000, Global biodiversity scenarios for the year 2100: Science, v. 287, p. 1770–1774.

Sanderson, E.W., Jaiteh, M., Levy, M.A., Redford, K.H., Wannebo, A.V., and Woolmfer, G., 2002, The human footprint and the last of the wild: BioScience, v. 52, no. 10, p. 891–904.

Seto, K.C., de Groot, R., Bringezu, S., Erb, K., Graedel, T.E., Ramankutty, N., Reenberg, A., Schmitz, O.J., and Skole, D.L., 2010, Stocks, flows, and prospects of land, *in* Graedel, T.E., and van der Voet, E., eds., Linkages of sustainability: Cambridge, Massachusetts, MIT Press, p. 71–98.

Simon, J.L., 1996, The Ultimate Resource 2: Princeton, New Jersey, Princeton University Press, 734 p.

TEEB, 2010, The Economics of Ecosystems and Biodiversity (TEEB): Ecological and Economic Foundations: London, Earthscan, 400 p.

Tiwana, N.S., Jerath, N., Ladhar, S.S., Singh, G., Paul, R., Dua, D.K., and Parwana, H.K., 2007, State of Environment Punjab – 2007: Chandigarh, Punjab State Council for Science and Technology, 243 p.

Tobler, S., 2007, Cheatgrass: A Weedy Annual on Great Basin Rangelands: Appendix C in Southwest Utah Regional Fire Protection Plan, St. George, Utah, Five County Association of Governments, 196 p.

Trimble, S.W., 1999, Decreased rates of alluvial sediment storage in the Coon Creek Basin, Wisconsin: Science, v. 285, p. 1244–1246.

UNPD, 1999, The World at Six Billion: New York, Department of Economic and Social Affairs, Population Division, United Nations: See Table 4, p. 11, http://www.un.org/esa/population/publications/sixbillion/sixbillion.htm (last accessed 1 Oct. 2012).

UNPD, 2004, World Urbanization Prospects: The 2003 Revision: New York, United Nations, Department of Economic and Social Affairs, Population Division: http://www.un.org/esa/population/publications/wup2003/2003WUPHighlights.pdf (last accessed 1 Oct. 2012).

UNPD, 2007a, Urban Population, Development and the Environment 2007: New York, United Nations, Department of Economic and Social Affairs, Population Division: http://www.un.org/esa/population/publications/2007_PopDevt/Urban_2007.pdf (last accessed 1 Oct. 2012).

UNPD, 2007b, Urban and rural areas, 2007: United Nations, Department of Economic and Social Affairs, Population Division, http://www.un.org/esa/population/publications/wup2007/2007_urban_rural_chart.pdf (last accessed 1 Oct. 2012).

USDA, 1989, The second RCA appraisal: Soil, water, and related resources on nonfederal land in the United States: Analysis of conditions and trends: Washington, D.C., U.S. Department of Agriculture, 280 p.

Vitousek, P.M., 1992, Global environmental change: An introduction: Annual Reviews of Ecological Systems, v. 23, p. 1–14.

Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H., and Matson, P.A., 1986, Human appropriation of the products of photosynthesis: BioScience, v. 36, p. 368–373.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., and Melillo, J.M., 1997, Human domination of Earth's ecosystems: Science, v. 277, p. 494–499.

Wackernagel, M., Schulz, N.B., Deumling, D., Callejas Linares, A., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., and Randers, J., 2002, Tracking the ecological overshoot of the human economy: Proceedings of the National Academy of Sciences, v. 99, no. 14, p. 9266–9271.

Wilkinson, B.H., and McElroy, B.J., 2007, The impact of humans on continental erosion and sedimentation: GSA Bulletin, v. 119, p. 140–156, doi: 10.1130/B25899.1.

World Bank, 2003, World Bank Atlas – 2003: Washington, D.C., World Bank, 82 p.

Zhang, D.D., Brecke, P., Lee, H.F., He, Q-Y., and Zhang, J., 2007, Global climate change, war, and population decline in recent human history: Proceedings of the National Academy of Sciences, v. 104, no. 49, p. 19,214–19,219.

Manuscript received 14 Feb. 2012; accepted 16 Aug. 2012.