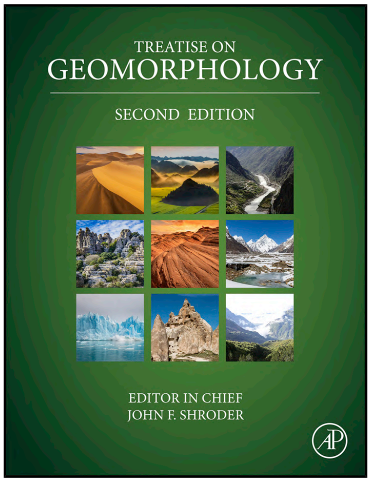

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9.08 Impact of the Great Acceleration on Our Life-Support Systems

Roger LeB. Hooke[a] **and José F. Martín Duque**[b], [a] School of Earth and Climate Sciences and Climate Change Institute, University of Maine, Orono, ME, United States; and [b] Faculty of Geological Sciences and Geosciences Institute IGEO (CSIC-UCM), Complutense University of Madrid, Madrid, Spain

9.08.1 Introduction

We face a daunting problem. Our life-support system consists of the air we breathe, the water we drink, the soils that provide the food we eat, and the climate that serendipitously is neither too hot nor too cold. This system is threatened. We are destroying soils and their indispensable microfauna, charging the atmosphere with greenhouse gases that are warming the climate, discarding potentially reusable waste, and in other ways polluting the air, soil and water. Owing to the warming climate, sea level is rising; heat waves and wildfires are killing people and wildlife and destroying infrastructure; and severe weather is becoming more common, modifying geomorphic processes and causing extensive damage to infrastructure. Particularly worrying is the alarming rate of species extinctions, which are irreversible.

In this essay, we first explore the increases in our impact on the environment during the past century, focusing on quantifying global changes in land use after World War II, and on human earth moving in the United States during this time. The geomorphic component of these changes is consequential, but it pales in comparison with the harmful impacts on our life-support system. Finally, we investigate some possible ways to mitigate these impacts, such as shifting to renewable energy sources, sequestering greenhouse gasses, restoring degraded landscapes and ecosystems, transitioning to a circular economy, and crucially, confronting the population challenge.

9.08.2 Background

Homo sapiens was born moving earth and in other ways modifying the environment to make life easier, and to improve his or her chances of survival. Nearly half a million years ago, our immediate ancestors, *H. erectus*, made seasonal dwellings with walls supported by small boulders and with foundations and floors built from stone rubble (Berreman et al., 1971; Leakey, 1981). They also undoubtedly picked up rocks to throw and dug holes to acquire tubers and other nourishing foods. In the mid-Paleolithic, ~100,000 years ago, Earth's human population likely numbered a few hundred thousand, and was confined to Africa (Sjödin et al., 2012). By ~12,000 years ago, however, Earth's population had increased to ~2.4 million (Klein Goldewijk et al., 2010) and people had reached western Europe. They had, by then, learned to make tools from particular rock types. In their search for one of these, flint, in the land we presently call England, they used digging tools made of bone and antler to excavate mine shafts over 10 m deep leading to galleries up to 10 m long (Bromehead, 1954). At this time the hunter-gatherer life style of Mesolithic *H. sapiens* was gradually transitioning to the agricultural routine of the Neolithic.

The clearing of forests and tilling of the soil associated with the transition to an agricultural life style had three important unintended detrimental effects: (i) soil erosion increased (Marsh, 1867, p. 33, 398), (ii) less CO_2 was sequestered in forests, and

(iii) CO_2 was released through burning. At ~7 ka, as a likely consequence of the latter two, CO_2 levels in the atmosphere began to rise [while this idea has been challenged (Joos et al., 2004; Broecker and Stocker, 2006; Elsig et al., 2009) Ruddiman (2011; 2014, p. 171ff) has responded effectively]. In contrast, during earlier interglacial periods CO_2 was still falling at this point in the glacial-interglacial cycle (**Fig. 1**A) (Ruddiman, 2003). Supporting this hypothesis is the observation that during periods of population decline due to disease or strife, when farms were abandoned and began to revert to forest, CO_2 levels actually *fell* (**Fig. 2**). At ~5 ka, atmospheric CH_4 also began to rise, whereas during earlier interglacials it was continuing to fall at this stage of the interglacial period (**Fig. 1**B). Ruddiman and Thomson (2001) convincingly attribute this rise to the advent of primitive rice farming. These increases in atmospheric CO_2 and CH_4 were likely sufficient to forestall initiation of a new episode of continental glaciation (Ruddiman, 2003).

Also at ~5 ka, when the global population was ~45 million, humans found that copper could be melted, and that when a small amount of tin was added to the molten copper, an alloy we call bronze was formed. This initiated the Bronze Age. Bronze was hard enough to be used for military weapons, but it was expensive. At ~3 ka, when the population had increased to ~115 million, higher furnace temperatures allowed the smelting of iron, initiating the Iron Age. Iron was more abundant and therefore less expensive, so it was used to make farm implements and other earth moving tools that commoners could afford. Exploitation of these metals led

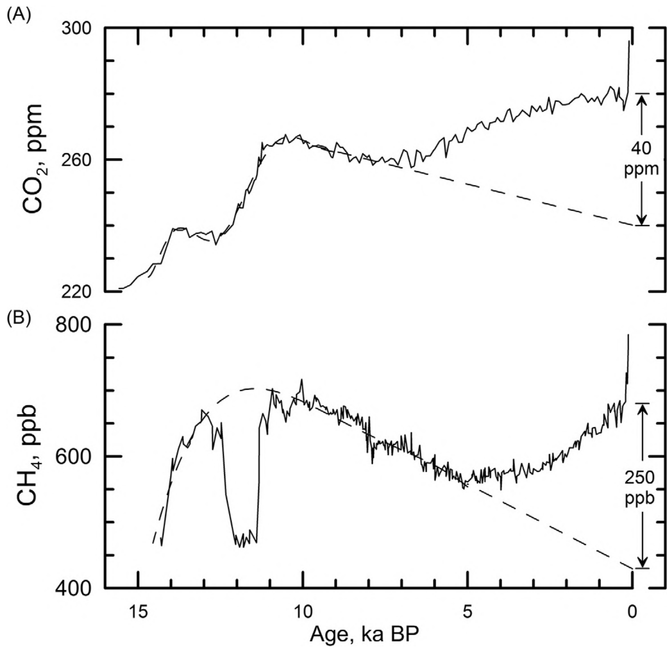


Fig. 1 Holocene record of atmospheric concentrations of (A) CO_2 and (B) CH_4. Dashed lines show typical trends during previous interglacials (from Ruddiman, 2003). Note deviation from these earlier interglacial patterns at ~7 ka in panel (A), and ~5 ka in panel (B). (CO_2 and CH_4 data are from the Dome C ice core: CO_2 from Lüthi et al., 2008 based on Monnin et al., 2001; CH_4 from Loulergue et al., 2008).

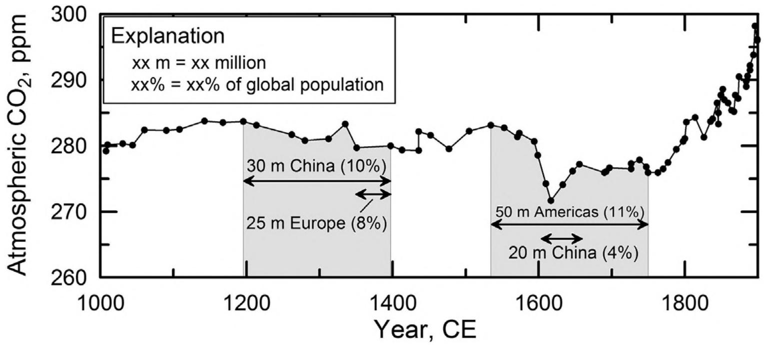


Fig. 2 Declines in atmospheric CO_2 coincide with declines in world population due to disease or strife. Double-headed arrows show duration of decline in population; labels indicate magnitude of decline in millions, region involved, and percentage of world population lost. After Ruddiman WF (2014) *Earth Transformed*. New York: W.H. Freeman and Company, Figure 20-1. CO_2 record from MacFarling Meure C, Etheridge D, and Trudinger C et al. (2006) Law Dome CO_2, CH_4, and N_2O records extended to 2000 years BP. *Geophysical Research Letters* 33: L14810.

to earth moving in mining operations. Invention of the wheel facilitated transport of the ore and other goods. Carts utilizing the wheel required roads, and constructing roads entailed additional earth moving.

Agriculture allowed people to settle in more permanent villages. As some of these villages morphed into cities, much of the construction was with stone. This required quarrying. Over time, new infrastructure was built on old, and the amount of earth material brought into cities raised them into hills, called "tells," some of which are over 40 m high and a kilometer in diameter (Hirst, 2019). Cities also needed water for both domestic use and transportation. Thus, canals were dug and aqueducts built (**Fig. 3**). Later, engineers harnessed steam, and then the internal combustion engine. This facilitated earth moving and construction. These engines of the Industrial Revolution required an energy source, resulting first in further deforestation to obtain wood for fuel, then in an increase in coal mining, and finally in exploitation of oil. Energy consumption expanded appreciably, in parallel with the population. Thus, emissions of CO_2 and CH_4 and of toxic trace metals like Cd, Cr, Mo, Ni, Sb, and Zn also increased; by ~1780 CE, these latter were being deposited as far away as Dasuopu glacier in the Himalayas (Gabrielli et al., 2020). Human earth moving increased dramatically (Hooke, 2000).

Human biogeomorphic work is not conceptually different from that of many other organisms that alter Earth's surface to suit their own convenience and comfort by digging holes, making mounds of various kinds, or damming and altering watercourses (Butler, 1995). However, the cumulative geomorphic effect of the human activity has produced a distinctive assemblage of landforms and landscapes. Thus, in many places, much of the small-scale topography that we see today is a consequence, either directly or indirectly, of human endeavor. An example is gullying and soil erosion initiated by land clearance, a problem that has been recognized since the time of Plato, some 2400 years ago (Dotterweich, 2013). In some cases this small-scale topography has been misinterpreted. Walter and Merritts (2008), for example, demonstrated that thousands of the fine-grained floodplains and terraces bordering mid-Atlantic streams of the United States are not pre-European natural landforms as previously thought, but are actually fills behind 17th- to 19th-century milldams. New in the decades following World War II, however, is the impressive rate and magnitude of our geomorphic activity (**Fig. 4**).

Marsh (1867), Gilbert (1917), and Sherlock (1922) were early pioneers in the analysis of humans as geomorphic agents. Numerous studies of anthrogeomorphic modification of the landscape followed (Thomas Jr., 1956; Jennings, 1965; Twidale, 1968; Friedman and Sanders, 1978; Alexandrowicz, 1983; Nir, 1983; Hooke, 1994, 2000; Haff, 2003; Szabó et al., 2010; Lóczy and Süto, 2011; Mossa and James, 2013; Tarolli and Sofia, 2016: Tarolli et al., 2018), as well as several chapters in this volume. However, only a few of these (e.g., Marsh, 1867; Gilbert, 1917; Montgomery, 2007; Hooke et al., 2012) have examined the threat that broad-scale human earth moving poses to our life-support system. This is our emphasis in this essay, focusing on the post-World War II period.

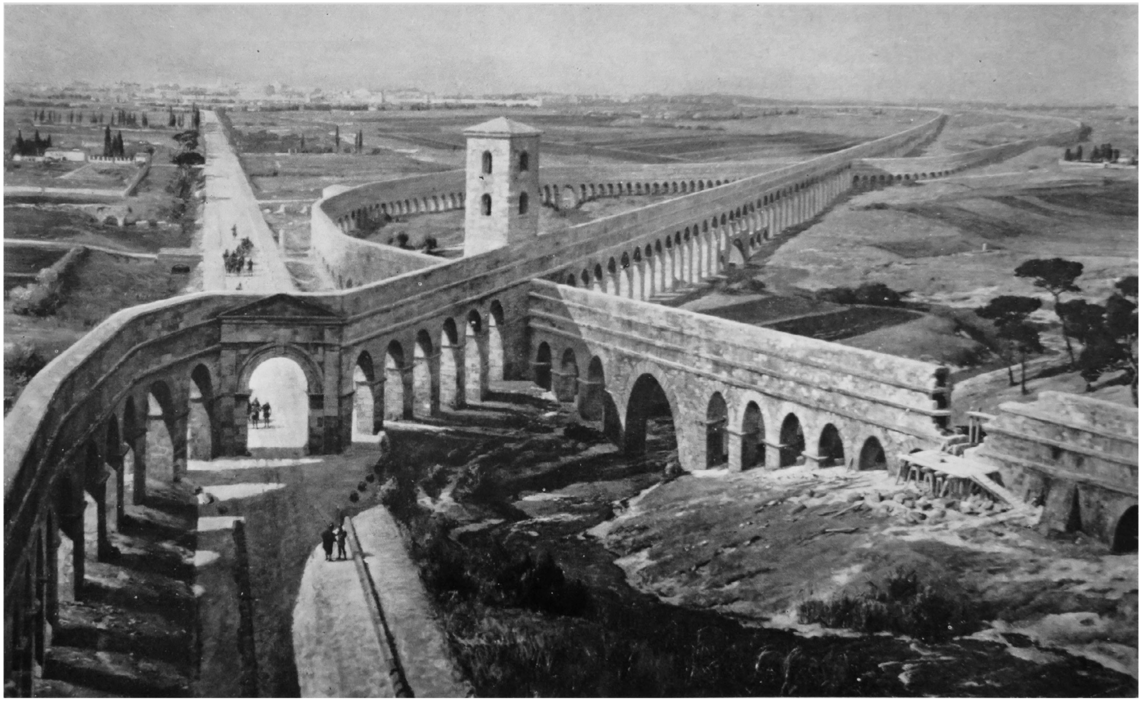


Fig. 3 Intersection of five Roman aqueducts southeast of Rome. There are three separate aqueducts (conduits) in the structure on the right (see cross section) and two in the structure on the left. The total length of Roman aqueducts was 350 km, of which 47 km were above ground. Modern pictorial reconstruction. The area, now the *Tor Fiscale Park*, is named for the tower above the intersection, parts of which still stand. From Forbes RJ (1956) Hydraulic engineering and sanitation. In: Singer C, Holmyard EJ, Hall AR, and Williams TI (Eds.), *A History of Technology*, vol. II. Oxford: Clarendon Press, pp. 663–694. Plate 29.

Fig. 4 Excavators working on a high-speed rail construction site in Saudi Arabia give the appearance of an army of ants eating the land. Photo: Courtesy of Vicente Mayordomo. INECO (February 2017).

9.08.3 The Great Acceleration

In the course of somewhat over a half-century, since the end of World War II, there has been a dramatic increase in the human impact on Earth's environment. During this period, the human population nearly tripled, the number of automobiles increased over 20 fold (McNeill and Engelke, 2014, p. 4), three-quarters of the human input of CO_2 to the atmosphere occurred, and global annual waste production more than tripled (**Table 1**). As McNeill and Engelke (2014, p. 2) write, "There is nothing in the demographic history of our species anything like the modern rise of population – nor will there be again." They continue (p. 41), "This bizarre interlude, with sustained population growth of more than 1 percent per annum, is … what almost everyone on Earth now regards as normal. *It is anything but normal*." (Our italics)

Other measures of the acceleration of our impact during these years are enumerated in **Table 1**. Note, in particular, the two columns labelled "Rate of increase." While all of these measures were increasing before World War II, the rates have multiplied several fold since the war. These alarming changes have provided the impetus for several international scientific programs including the United Nations Environment Programme, the World Climate Research Programme, and the International Panel on Climate Change (Hibbard et al., 2006, p. 350).

Hibbard et al. (2006) refer to this period in human history as *The Great Acceleration*. They observe that during World War II collaborations developed involving teams of scientists and engineers focused on specific problems, most notably development of nuclear weapons. In the post war decades, they argue, this teamwork continued in other enterprises, resulting in the remarkable growth of the energy, chemical, and agricultural industries (Hibbard et al., 2006, p. 344).

9.08.3.1 Changes in land use during the Great Acceleration

In terms of physical area, changes in land use during the Great Acceleration have been relatively modest (**Table 2**). This is, in part, because the land area of Earth is limited, and in part because much of the land is not suitable for the types of uses listed in **Table 2**. Thus, despite the three-fold surge in population, the area devoted to cropland and pasture has increased by a factor of only 1.3, and the rate of increase has declined. The latter reflects increased use of fertilizers, pesticides, and herbicides, boosting the yield per hectare and facilitating "rehabilitation" of degraded land, while at the same time greatly exacerbating pollution. These agrochemical applications, together with irrigation and increased mechanization, have intensified land use. They have also expanded the land area that a single farm family can manage with the consequence that young people from farm families have migrated to urban areas, seeking other jobs. This is, in part, responsible for a nearly five-fold increase in both urban area and in the rate of expansion of urban land.

Table 1 Changes in some global measures of human impact on Earth during the Great Acceleration.

	1885	*1945*	*2005*	*Increase[a] 1945–2005*	*Units*	*Rate of increase[b]* *Before The Great Acceleration*	*During The Great Acceleration*	*Units*
Area deforested[c]	11	14	18	1.3 ×	10^6 km^2	0.049	0.063	10^6 km^2 a^{-1}
Atmospheric CO$_2$[d]	13	30	99	3.3 ×	ppm above pre-industrial levels	0.4	1.5	ppm a^{-1}
Atmospheric CH$_4$[e]	150	410	1100	2.7 ×	ppb above pre-industrial levels	4	15	ppb a^{-1}
Energy use[f]	10	25	133	5.3 ×	10^{12} kwh a^{-1}	0.3	2.1	10^{12} kwh a^{-2}
Extinction rate[g]	2	19	88	4.6 ×	Ex a^{-1}	0.1	1.5	Ex a^{-2}
Fertilizer consumption[h]	0	14[i]	172	12 ×	10^6 tons a^{-1}	0.4	4.4	10^6 tons a^{-2}
Freshwater consumption[j]	430	1190	3880	3.3 ×	km^3 a^{-1}	9	62	km^3 a^{-2}
Gross Domestic Product[k]	2.7	8.5	76.1	8.9 ×	10^{12} \$ a^{-1}	0.1	1.2	10^{12} \$ a^{-2}
Irrigated area[l]	63[m]	108	305	2.8 ×	10^6 ha	1.0	3.8	10^6 ha a^{-1}
Long-distance migration	1.9[n]	3.1[n]	203[o]	68 ×	10^6 people a^{-1}	0.03	3.5	10^6 people a^{-2}
Marine fish catch[p]	0.1	8.5	135	16 ×	10^6 tons a^{-1}	0.24	2.1	10^6 tons a^{-2}
Population[q]	1.48	2.43	6.54	2.7 ×	10^9 people	16	69	10^6 people a^{-1}
Reservoir volume[r]	7	362	10,655	29 ×	km^3	6	221	km^3 a^{-1}
Waste production[s]	0.12[l]	0.36	1.24	3.4 ×	10^9 tons a^{-1}	0.005	0.014	10^9 tons a^{-2}

[a] Increases are calculated from original values before rounding off. Only two significant digits are warranted.

[b] Several of these values are based on linear fits to the original data over the central part of time span.

[c] Shaw (2012, Fig. 1, p. 9).

[d] https://data.giss.nasa.gov/modelforce/ghgases/Fig1A.ext.txt

[e] Ruddiman (2014, p. 169); https://www.methanelevels.org/

[f] https://ourworldindata.org/energy (accessed 24 February 2020).

[g] Scott (2008). Includes all species including plants and insects.

[h] https://ourworldindata.org/fertilizer-and-pesticides (accessed 18 March 2020).

[i] Estimated based on number of people supported by N fertilizer in 1945 and average number of people supported per tonne produced 1960–91.

[j] Interpolated and extrapolated from figures in McNeill and Engelke (2014, p. 53).

[k] https://ourworldindata.org/search?q=world+gdp+over+the+last+two+millennia%2C (accessed 3 October 2020).

[l] Siebert et al. (2015).

[m] Value is for 1900.

[n] 1880–90 and 1935–40 averages. From McKeown (2004, Fig. 1).

[o] From Betts and Kainz (2017, p. 1). Linear interpolation between values for 1970 and 2017.

[p] FAO (2012), and Watson and Tidd (2018). Totals include aquaculture.

[q] https://ourworldindata.org/world-population-growth (accessed 20 September 2008); see figure "Population growth by world region".

[r] Chao et al. (2008).

[s] Hoornweg et al. (2013).

Table 2 Changes in global land use during the Great Acceleration.

	1885	*1945*	*2005*	*Units*	*Increase 1945–2005*	*Rate of increase* *Before The Great Acceleration*	*During The Great Acceleration*	*Units*
Cropland[a]	8.90	13.18	16.84	10^6 km^2	1.3 ×	0.07	0.06	10^6 km^2 a^{-1}
Pasture[a]	14.31	27.51	36.42	10^6 km^2	1.3 ×	0.22	0.15	10^6 km^2 a^{-1}
Forest area[a]	47.96	44.57	41.49	10^6 km^2	0.9 ×	−0.06	−0.05	10^6 km^2 a^{-1}
Mining and quarrying[a]			0.40	10^6 km^2				
Mining and quarrying (US only)[b]		3.79	43.50	10^3 km^2	11 ×	0.15	0.70	10^3 km^2 a^{-1}
Railways[c]		1.25	1.00	10^6 km^1	0.8 ×		−0.004	10^6 km a^{-1}
Roads (paved and unpaved)[d]		12.80	30.58	10^6 km^1	2.4 ×	0.07	0.29	10^6 km a^{-1}
Urban area[a]	0.18	0.81	3.98	10^6 km^2	4.9 ×	0.01	0.05	10^6 km^2 a^{-1}
Wetlands[e]	4.13	2.34	1.02	10^6 km^2	0.4 ×	−0.03	−0.02	10^6 km^2 a^{-1}

[a] Hooke et al. (2012). Cropland, pasture, and forest are by interpolation of their Fig. 2.

[b] SCS (1977). Values for 1945 and 2005 are estimated using the mean ratio C/P for 1965, 1971, 1972, 1974, and 1977, where C and P are the cumulative km^2 disturbed and tons produced, respectively.

[c] World Bank (2019). From this database we compiled data for 2005 for the world (1 Mkm). For 1945 we compiled data for 121 countries from Mitchell (1998a,b,c). These 121 countries represent 98% of the 2005 total for the world. For some of the 121 countries, data for 1945 or 2005 were missing, so we used data for the year closest to 1945 or 2005.

[d] World Road Statistics (2019).

[e] Following Hu et al. (2017, Table 2), we define wetlands as marshes, shallow beaches, and estuarine deltas. Hu et al. estimate that the total area of these, prior to human intervention, was 18.42×10^6 km, or ~62% of the total included in the Ramsar convention definition. We then used the rates of change in Table 1 of Davidson (2014) to estimate the area in subsequent years.

Owing to continued draining and filling of wetlands and to deforestation, areas of these biomes have decreased (**Table 2**). Loss of wetlands results in loss of biodiversity and also loss of the services the wetlands provide by cleansing and replenishing groundwater and regulating water movement (Hu et al., 2017). Loss of forests decreases the uptake of CO_2, thus aggravating climate change. Deforestation decreases evapotranspiration, thus decreasing rainfall downwind (Ellison et al., 2017). In the Amazon, over 70% of the rainfall is derived from regional evapotranspiration, so deforestation reduces hydrocycling and endangers the remaining rainforest (Van der Ent et al., 2010). If deforestation there continues, a tipping point may be reached such that the rest of the Amazon reverts to savannah (Montaigne, 2019).

The length of our global road networks has increased ~2.4-fold (**Table 2**), increasing the connectivity among human settlements. This reflects the growth in both population and the global economy (GDP, **Table 1**). In contrast, the total length of railways in the world has decreased, as more traffic is handled by trucks, and rail lines are abandoned. This is unfortunate, as trucks produce three times as much pollution per ton-mile (Mullich, n.d.).

The area directly altered by mining and quarrying could be considered small compared with other land uses [$\sim 0.4 \times 10^6$ km^2, or 0.3% of Earth's land surface (Hooke et al., 2012)]. Data permitting a calculation of the global change in this area during the Great Acceleration were not found, but in the United States it increased by a factor of 11 (**Table 2**). Because runoff from these areas is commonly contaminated and has a high sediment load, off-site effects are often more detrimental than on-site effects. Water quality and stream biodiversity are degraded along hundreds of kilometers of downstream riparian ecosystems (Palmer et al., 2010). Thus, the land area affected by mining and quarrying is always larger than that directly transformed.

9.08.3.2 Changes in the rate of earth displacement in the United States owing to human activities during the Great Acceleration

One change that does not seem to have been quantitatively considered previously is that in the rate at which earth is displaced by human activities during the Great Acceleration. In evaluating this, we focused on those activities that we've discussed previously (Hooke, 1994; Hooke et al., 2012), and limited our analysis to the United States (**Table 3**) as comparable worldwide data were not readily available.

Erosion from cropland and overgrazed pasture has been recognized for centuries; Marsh (1867, p. 227) comments that, "The surface of a forest, in its natural condition, can never pour forth such deluges of water as flow from cultivated soil" and goes on (p. 231) to describe the erosion resulting from these torrents; Gilbert (1917, p. 43) estimated that $\sim 10^6$ t/ha had been eroded from cropland in the Yuba River basin, California, but does not provide a time frame for this erosion. To estimate rates prior to 1982 we started with assessments of total erosion from cropland in the United States for 1967 and 1977 by Magleby et al. (1995). We estimated separate values for wind and water using mean ratios of wind to water erosion and of pasture to cropland erosion in later years (**Fig. 5**), and then used linear interpolation to obtain approximate values for 1945, 1975, and 2005 (**Table 3**). With the caveat that the uncertainty in these estimates may be substantial, it is encouraging to see that improved tilling methods since 1975 seem to have reduced soil loss substantially. Nevertheless, global erosion rates from agricultural lands are still many times the rate of soil formation by natural geologic (weathering) processes (Montgomery, 2007). Erosion from cropland is also small compared with the total amount of earth displaced from furrows into ridges during plowing; following Haff (2003), we estimate this to be ~170 Gt a^{-1} in the United States.

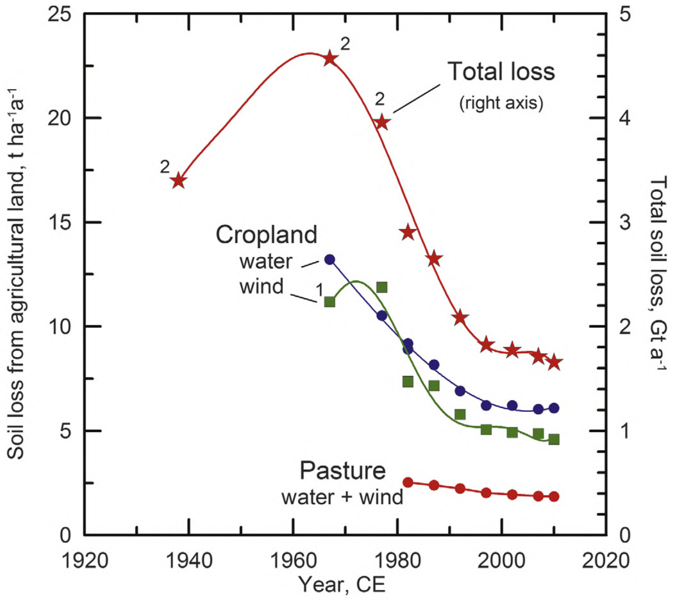
Annual data on housing starts (residential construction) from 1929 to the present are readily available (US Census Bureau, 1999, 2020a). Means for the 1940s, 1970s, and 2000s are 854,000, 1,724,000, and 1,450,000 per year, respectively. If we assume that houses measured 10 × 20 m in area, that a quarter of them had cellar holes 3 m deep (The Day, 2015), that the remainder, whether on a slab foundation or built with a crawlspace, involved moving earth to a depth of ½ m, and that the soil density was 2 t m^{-3}, the mean mass of earth moved per house was 450 t, not including landscaping. Although the number of starts varies substantially from year to year and has decreased slightly since 1975 (**Table 3**), there is a steady increase in the *cumulative* area of modified land.

To estimate the amount of earth moved in mining and quarrying we obtained the annual production of coal, stone, sand and gravel, iron, copper, and gold from 1932 to 2015. These products represent ~90% of the crystalline earth materials used by humans. We then used a multiplier (**Table 4**) to convert the annual production figures to an estimate of the total earth moved, including

Table 3 Changes in the rate of earth displacement in the United States owing to human activities during the Great Acceleration.

					Changes	
	1945	*1975*	*2005±*	*Units*	*1945–75*	*1945–2005*
Cropland erosion	3.5	3.9	1.6	Gt a^{-1}	1.1	0.5
Pasture erosion	0.19	0.22	0.10	Gt a^{-1}	1.2	0.5
Mining and quarrying[a]	4.3	6.4	9.6	Gt a^{-1}	1.5	2.2
Residential housing[a]	0.38	0.78	0.65	Gt a^{-1}	2.1	1.7
Road building[a]	0.28	0.49	0.30	Gt a^{-1}	1.8	1.1
Totals	8.7	11.8	12.3		1.4	1.4

[a] Decadal averages.



1. 1966 point is based on ratio of loss by wind to loss by water in subsequent years

2. Values for pasture prior to 1982 are based on ratio of loss from pasture to loss from cropland in 1982-2010

Fig. 5 Changes in soil loss from agricultural lands in the U.S. during the Great Acceleration. Total erosion data for 1938–1982 are from Magleby et al. (1995, Table 3) and those for 1982–2010 are from USDA (2013, p. 126 and 144).

Table 4 Multipliers used to estimate earth moved from data on production of various earth materials.

Material	*Multiplier*	*Reference*
Coal	4.87	Charbonnier (2001, p. 12)[a]
Copper	450	Charbonnier (2001, p. 12)[a]
Gold	950,000	Charbonnier (2001, p. 12)[a]
Iron	5.20	Charbonnier (2001, p. 12)[a]
Stone	1.40	Goodquarry (2011, Table 1)[b]
Sand and gravel	1.36	Goodquarry (2011, Table 1)[b]

[a] Multipliers were derived from figures published in standard textbooks and in other works on mineral production and materials use and then discussed with specialists to obtain maximum and minimum multipliers for individual commodities.

[b] Quarry waste is obtained by the website Goodquarry.com from data available from the UK Department for Environment, Food and Rural Affairs, and is for the United Kingdom.

overburden and gangue (Fig. 6). Finally we averaged the production over the decadal time periods in Table 3. Of interest in Fig. 6 are the increases in coal and iron production necessitated by World War II, and the steady reduction in coal production since 2008. The latter is being supplanted by less costly gas, wind, and solar energy sources, with clear environmental benefits.

To estimate the mass of earth moved in road building during various phases of the Great Acceleration we first obtained annual data (1941–2011) on the total length of US public roads, of unpaved roads, of freeways, and of interstates (USDT, 2019) (Fig. 7). The length of paved roads was obtained by subtracting the lengths of unpaved roads, freeways, and interstates from the total. Using linear fits to decadal segments of the curves in Fig. 7, we obtained the mean rates of change in length (dL/dt) for the decades of the 1940s, 1970s and 2000s. We then obtained the widths of roads of different classes and the mean thicknesses of pavement, base, and subbase (Table 5). This permitted a calculation of the earth moved (t km^{-1}) to construct the various classes of road. To account for earth moved in preparation for laying of the subbase and in regrading the shoulders and right-of-way, we doubled this. Then multiplying by dL/dt for the decade in question yielded an estimate of the mass of earth moved annually in road construction (Tables 3 and 5).

The length of unpaved roads decreased during the Great Acceleration, presumably because some of them were being paved. If these newly-paved roads were already constructed well, paving them would not have involved as much earth moving as would construction of a new paved road. Therefore, in Table 5 we subtracted the amount of earth moved in the initial construction of

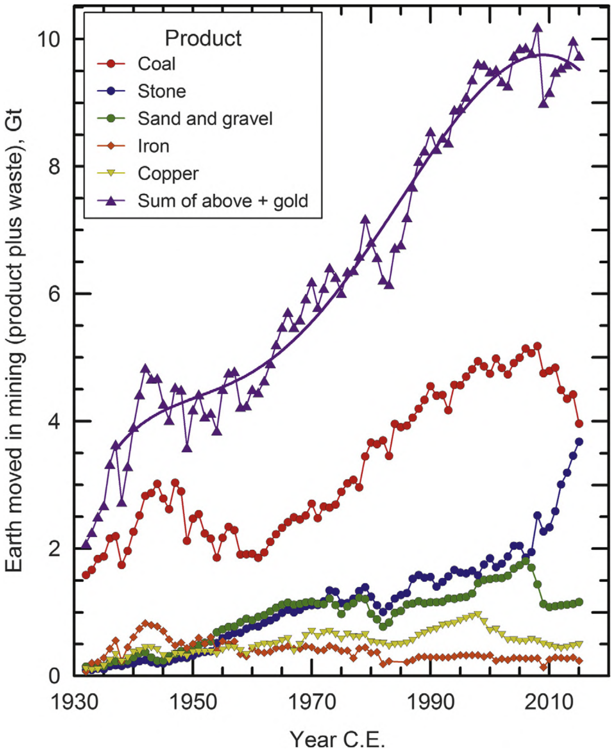


Fig. 6 Earth moved in mining and quarrying in the U.S. before and during the Great Acceleration. Data are from statistical summaries of mineral production published by the US Geological Survey (https://www.usgs.gov/centers/nmic/bureau-mines-minerals-yearbook-1932-1993) and (https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states).

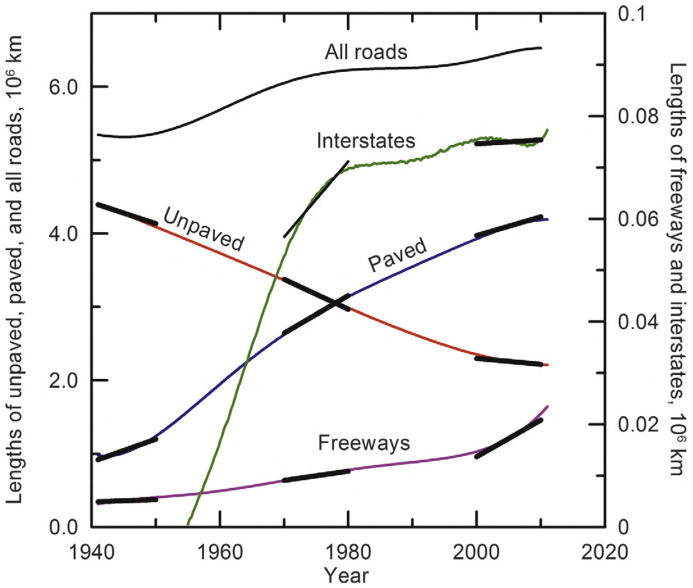


Fig. 7 Changes in length of the U.S. road network during the Great Acceleration. Curves are polynomial fits to the raw data. Short black lines are least-squares linear fits to decadal segments of the curves centered on 1945, 1975, and 2005. [Length data for unpaved roads and for all roads are from USDT (2019, Table hm212 for 1941–95, annual tables hm12 for 1996–2006 and 2011, and tables hm20 for 2010). Data for freeways in 1945 are from US Government (1947, Tables SM11, SM12, and SM13, pp. 83–85). Data for freeways since 1980 are from USDT (2018, Table hm220). Data for freeways from 1946 to 1980 are obtained by linear interpolation. Data for interstates in 1975 and 1976 are from USDT (1975, Table INT-2, p. IX-55) and USDT (1976, Table INT-2, p. 138), respectively. Construction of the interstate system began in 1955. Lengths of the interstate system in 1956–74 and 1977–80 were obtained by linear interpolation. To obtain the length of paved roads we subtracted the lengths of unpaved roads, freeways, and interstates from the total length of all roads.]

Table 5 Earth moved during road construction in the United States during the Great Acceleration.

				dL/dt, 10^6 km a^{-1}			*Earth moved, Gt a^{-1}*		
Road class	*Width,[a] m*	*Thickness,[b] m*	*Earth moved,[c] t km^{-1}*	*1945*	*1975*	*2005*	*1945*	*1975*	*2005*
Unpaved	3.1	0.14	1,736	–0.0289	–0.0408	–0.0081	–0.05	–0.07	–0.01
Paved	6.9	0.39	10,764	0.0310	0.0511	0.0256	0.33	0.55	0.28
Freeways (excluding interstates)	13.6	0.81	44,064	0.0000	0.0002	0.0007	0.00	0.01	0.03
Interstates	19.0	0.81	61,560	0.0000	0.0015	0.0001	0.00	0.09	0.00
						Totals	0.28	0.49	0.30

[a] Width data for paved roads and freeways are from US Government (1947, Tables SM8, SM9, SM11, and SM12) and are weighted means of widths of roads of various lengths. Widths of unpaved roads assume a single lane. Widths of Interstates are from Sullivan (2006).

[b] Thickness data for gravel roads are from USDT (2015, p. A4) and are for roads with medium subgrade support and low traffic volume. For paved roads data are from Clemen (2016, Table 2.2) and are pavement + base for medium truck traffic with medium subgrade support. Data for Interstates are from Sullivan (2006).

[c] Earth moved is obtained by multiplying width × thickness × 1000 m/km × 2 t/m^3 and then doubling this to allow for excavation prior to laying the subbase and for regrading of the shoulders and right-of-way.

these unpaved roads. Our final estimate of earth moved is almost certainly low, however, because we have not included earth moved in the course of resurfacing existing paved roads, nor have we any way to estimate the earth moved in making roadcuts or embankments in uneven terrain, as these vary with the topography. Compared with the 1940s, it appears that roughly twice as much earth was moved during road construction in the 1970s, and that the amount may have tapered off more recently (**Table 3**).

This decrease in the rate of earth moving during road construction in the United States (**Table 3**), and that globally in the length of railways (**Table 2**), are deceptive, however. While many railway lines have, indeed, been abandoned, many new ones have been constructed, and whereas the older roads and railways commonly followed the topography, new ones have sought to link destinations by the shortest possible distances in order to reduce travel time. Straightening these communication arteries necessitated construction of many embankments, cuts, and tunnels, involving much more earth moving per kilometer than in earlier times. Furthermore, the imprint of most abandoned roads and railways on the landscape persists.

Three earth-moving activities that we have not included in **Table 3**, owing to a dearth of data, are the construction of levees along rivers; of non-residential buildings; and of coastal structures such as seawalls, revetments, groins, breakwaters, ports, harbors, and marinas. We can, however, say something about the magnitude of their present contribution to human earth moving.

Levees have been constructed along rivers in the United States since at least 1718 when work was initiated on one around New Orleans (Rogers, 2008). It is estimated that there are now nearly 160,000 kilometers of levees in the United States [The estimate is given as an "editor's note" in Cabi and Weiner (2014) and is based on an unofficial estimate by the National Committee on Levee Safety several years ago (B. Vanbockern, written communication, 18.09.20)]. If we assume that the average levee was ~1.5 m high with 1:4 side slopes, the volume would have been ~9 m^3 per meter length. Had construction of the 160,000 km of levee proceeded at a constant pace over these 300 years, nearly 0.010 Gt of earth would have been moved annually. [For comparison a typical Mississippi River levee near New Orleans today is six times as high, and its volume per m length is ~460 m^3 (Rogers, 2008, Fig. 12), or 50 times as much as in our example.]

Nonresidential construction is somewhat more difficult to evaluate. Over the period 1993–2019, the annual dollar value of nonresidential construction, excluding the category "Highways and Streets," averaged 1.26 times the annual dollar value of residential construction (US Census Bureau, 2020a). However, there are 16 categories of nonresidential construction, such as Lodging, Commercial, Water Supply, and Communication, and we have no way of estimating the amount of earth moved per dollar spent in each of the various categories. It is probably safe to assume, however, that earth moving in nonresidential construction is of the same order as that moved in residential construction.

Finally, ~14% of the total US coastline had been armored as of 2015 (Gittman et al., 2015). This has resulted in significant beach erosion and a disproportionate loss of intertidal habitats affecting all trophic components (Griggs, 2005; Dugan et al., 2008).

9.08.3.3 Geomorphic consequences of the Great Acceleration

Compared with most of human history, anthropogenic earth moving since the Industrial Revolution, and especially during the Great Acceleration, has modified the physiography and functionality of a considerable fraction of Earth's land surface, producing readily-recognizable landforms and landscapes. Geomorphologists finally recognized this in the latter half of the 20th century and began to include anthropogenic landforms on geomorphological maps (CNRS, 1970; Demek, 1972). They also developed specific classifications of human-made landforms (Alexandrowicz, 1983). In due course of time they recognized that a new geologic epoch, the Anthropocene (Crutzen and Stoermer, 2000), had emerged, with humans acting as the premier agents of erosion, transport, and deposition. Currently LiDAR, aerial photogrammetry, satellite imagery, and other forms of high-resolution terrain data are being used to document these landforms (Tarolli and Sofia, 2016; Tarolli et al., 2017).

Open pit mining is a good example of the geomorphic changes in the landscape that have resulted from human activity since WWII. While open pit mining has always been practiced by humans, technology limited its scale. Advances in explosives during WWII and the subsequent development of large machinery permitting cost effective removal and transportation of the ore have resulted in the huge mines and quarries today (e.g., **Fig. 8**). Waste rock, or gangue, from these pits is either placed outside the pit, forming large monolithic waste dumps, or used to backfill it. In the latter case, depending on the ratio of product to waste, the resulting landform may be either a depression, commonly occupied by a lake, or an upland (Hancock et al., 2020). Underground mining (or groundwater extraction) can also cause subsidence, with attendant geomorphic effects (Bell et al., 2000). Land transformation by such activities has been dubbed the 'asteroid effect' (Bugosh, pers. com. to J.M.D.) owing to the similarity of the geomorphic consequences.

Subtler but more widespread are the effects of road construction in hilly or mountainous terrain. With their embankments and cuts, roads redirect runoff, disturbing topographic equilibria developed over millennia. This can result in gully development and even shallow landsliding (Montgomery, 1994; Nyssen et al., 2002). In some cases, the landslides develop into debris flows, affecting stream channels for substantial distances downstream (Jones et al., 2000). At a larger scale, construction of high capacity linear transport infrastructure for motor vehicles and high speed trains involves roadcuts and embankments on the scale of badland topography.

An overall impact of humans on geomorphic systems during the Great Acceleration is in the wholesale modification of continental erosion and sedimentation processes (Schumm and Rea, 1995; Dotterweich, 2013; Dotterweich et al., 2013; James, 2013), and hence in the global flux of sediment to the oceans (Syvitski et al., 2005; Reusser et al., 2014). Owing to human construction and agricultural activities, mean rates of denudation of ice-free continental surfaces currently lower Earth's surface by a few tenths of a millimeter per year, or roughly one order of magnitude higher than the mean over the past 500 My (Wilkinson, 2005). Furthermore, 83% of the sediment delivered to the oceans today comes from the lower 65% of Earth's land area, whereas in prehistoric times the same percentage was from the highest 10% of the land (Wilkinson and McElroy, 2007).

9.08.3.4 Implications of the Great Acceleration for our life-support system

There are some encouraging numbers in **Tables 1–3**. Although hunger has not been eliminated, we appear to be able to feed most of the nearly tripled population with only a modest increase in land area devoted to agriculture. Earth moved as a result of human activities, at least in the United States, appears to have stabilized since the central years of the Great Acceleration: erosion from agricultural fields and the amount of earth being moved in road construction have been dropping since the 1970s, compensating for the

Fig. 8 The "Super Pit," one of the Australia's largest open pit mines, is located in Western Australia. The pit is oblong in plan and is ~3.5 km long, 1.5 km wide and over 500 m deep (Mossa and James, 2013). Photo: J.F. Martín Duque, September 2019.

increase in mining (**Table 3**). The nine-fold growth in GDP while the population was growing only three fold (**Table 1**) presumably reflects an increasing standard of living.

For the most part, however, the numbers suggest increasing and cumulative damage to our life-support system. Almost all measures of our impact have increased during the Great Acceleration, some at double and even triple digit rates (**Table 1**). Associated with the growth in population and GDP are multi-fold increases in waste production, energy and fertilizer use, and CH_4 and CO_2 emissions, all of which contribute to pollution and to the surge in the rate of extinctions. Moreover, too much of the growth in population has been concentrated in poorer countries that lack resources to support this growth. This has forced a nearly 70-fold increase in long-distance migration, resulting in increased ethnic conflict and in a disastrous shift to nationalism in richer countries (Swain, 2019). Even in affluent countries, the increase in GDP is not shared equally—the gap between richer and poorer populations is increasing.

Global land-use changes during the Great Acceleration (**Table 2**) show multi-fold increases in land area devoted to roads; urban area, frequently at the expense of prime agricultural land (Döös, 2002); and, in the United States, in land area disturbed by mining and quarrying with similar increases likely in other parts of the world. In all three cases, the rate of increase was substantially higher during the Great Acceleration than in the preceding six decades. In addition, in the United States, the rate of earth moving in the course of residential construction doubled during the first three decades of the Great Acceleration, although it has stabilized more recently (**Table 3**). Finally, levee creation, non-residential construction, and coastline hardening, as discussed, are also significant geomorphologically, and all have serious consequences for ecosystems and pollution.

Several of the factors listed in **Table 1** have contributed to climate change. Deforestation has decreased the uptake of CO_2 by forests. Population growth has increased the demand for energy produced by combustion of fossil fuels, increasing emissions of CO_2 and CH_4. The increase in surface area of reservoirs has reduced CO_2 uptake by terrestrial plants, now submerged, and increased CH_4 production by bacteria that decompose the organic carbon stored in these submerged terrestrial plants and in the underlying soils (e.g., Beaulieu et al., 2014). As much as $\sim$20% of human CH_4 emissions may be from reservoirs (St. Louis et al., 2000, p. 772). Owing to these various impacts, atmospheric CH_4 has been increasing at an exponential rate and atmospheric CO_2 at a super-exponential rate (**Fig. 9** and **Table 1**). Earth's mean temperature is now $> 1 \pm 0.2\ ^\circ C$ above preindustrial levels, and we are on track to exceed 1.5 °C by 2052 (IPCC, 2019a). Nineteen of the warmest years on record have occurred in the past twenty. As a consequence of this global warming, violent storms are becoming more common; dry areas are becoming drier, leading to an increase in fire damage and deflation; wet areas are becoming wetter, resulting in extensive flood damage; and because the increase in atmospheric CO_2 is decreasing the need for trees to transpire, ground moisture is increasing so areas with relatively stable climate are experiencing more flooding (Retallack and Conde, 2020).

These changes in climate will have a significant effect on the landscape. Wetter climates will lead to more flow in rivers, particularly in winter and spring, and violent storms will increase the frequency of high discharges. At the same time, in drier climates, low flows will commonly become lower and some perennial streams will become intermittent (Döll and Schmied, 2012). The latter will have a major impact on water supply, navigation, hydropower generation, and freshwater ecosystems. Over time, in climates that become wetter, the higher flows are expected to increase the widths, depths and flow velocities of rivers (Leopold and Maddock Jr., 1953), and the rate of bank erosion and meander migration (e.g., Constantine et al., 2009). During the time it takes for these

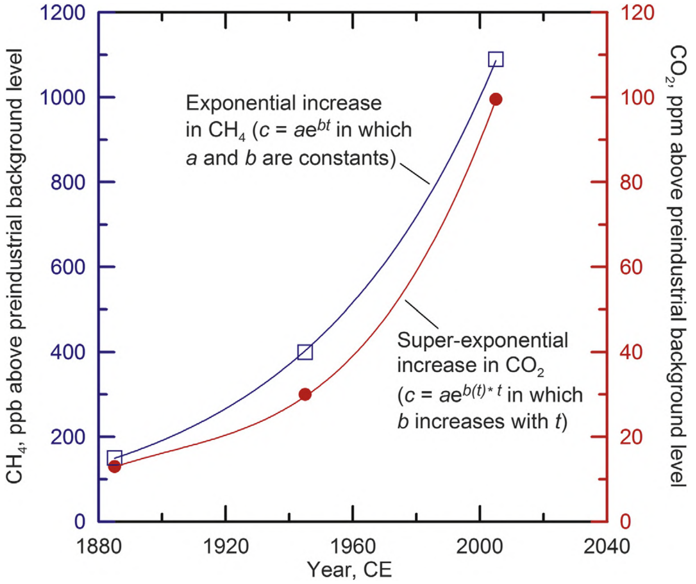


Fig. 9 Plot of the exponential increase CH_4 emissions and super-exponential increase in CO_2 emissions between 1945 and 2005 from **Table 1**. c = concentration; t = time.

adjustments to occur, flooding will be more frequent. Over longer time spans, meander wavelength will increase (Leopold and Wolman, 1957). In climates that become drier, the reverse may be anticipated.

Human transformation (and fragmentation) of the land is detrimental to biodiversity (Newbold et al., 2020) because surficial geology, topography, and biota are irreversibly changed (Nicolau, 2003). More than a million species are on the verge of extinction due to our activities (IPBES, 2019). Large endotherms, carnivores, fungivores, and insects are all disproportionately impacted; in comparison with areas with natural habitat, their populations have been reduced between 25% and 50%. Small ectotherms suffer from the substantially higher surface temperatures of lands modified by humans. The loss of some of these predators increases the risk of rodent-borne human diseases. The loss of habitat causes disproportionate declines in microbes and insects that form soil, pollinate plants, and remove toxic substances from water (e.g., Sánchez-Bayo and Wyckhuys, 2019). The loss of pollinators affects our food security. Each of these different functional groups makes a unique contribution to ecological processes, so the net effect on ecosystem functioning and on the many ecosystem goods and services on which we depend is significant and is compounded. Thus, human welfare and even survival are jeopardized.

These changes lead to a great paradox of our time. Winning the battle against many diseases and thus increasing our life expectancy is a magnificent human achievement. However, too little focus has been placed, so far, on the fact that the resulting burgeoning population and its associated consumption of land and resources and generation of waste, is severely degrading our environment. Healthy people are increasingly living in steadily-deteriorating ecosystems. This is not sustainable.

Let's turn now to some positive steps that can be taken to restore and sustain our life-support system.

9.08.4 Restoring sustainability

9.08.4.1 Restoring functional landscapes

The consequences of human earth-moving and modification of the vegetation cover are all too commonly soil erosion and degradation. Erosion carries soil moisture, nutrients, and seeds offsite, thus inhibiting soil-forming processes and plant re-colonization (Espigares et al., 2011). Ecosystems that once enhanced fertility are replaced with others that do not (Ehrlich and Ehrlich, 1992). In such degraded landscapes, healing is not possible without first rebuilding the hydrological functionality. The need for restoring these degraded lands is clear (e.g., UNEP, 2019). The goal is not to simply restore the physical elements of the ecosystem (e.g., trees), but primarily to restore the ecosystem functions.

Restoring ecosystem functions when the topography is highly disturbed is a complex process. The 'engineering approach' commonly fails because the new topography that is created tends to be linear, with slopes of constant gradient or with terraces and unnaturally rigid drainage structures. Such topographies don't restore natural functions, and they are not stable over the long term. Without constant costly maintenance, most of them gradually evolve to resemble natural ones with convex-concave slopes, and with streams that flow downhill rather than diagonally across hillslopes (Haigh, 1985; Sawatsky and Beersing, 2014).

Geomorphic Restoration is a partial solution to solving these problems. During geomorphic restoration, the landscape is designed to resemble a natural one as closely as possible, mimicking both the look and most importantly the functionality of nature (Toy and Chuse, 2005; OSMRE, 2019). This provides the foundation on which, after proper soil and vegetation restoration, the ecosystem goods and services of our life-support system can be re-established. On landforms mimicking natural ones, soil erosion is minimized, so conservation of nutrients released by decomposition, cycling of organic matter, and nitrogen fixing by microorganisms are maximized. These are key functions needed to restore the natural capital on derelict and degraded lands (Bradshaw and Chadwick, 1980).

There are several methods of geomorphic restoration (see Hancock et al., 2020). They all seek to replicate the relief and surficial architecture of natural landforms that are well-suited to the geologic and geomorphic conditions of the site, taking into consideration the future local climate and possible changes in land use. The goal is to re-establish a rough dynamic equilibrium between landforms and processes, leaving the "fine-tuning" to natural processes (Schumm and Rea, 1995; Toy and Black, 2000; Toy and Chuse, 2005).

Geomorphic restoration of mining sites in the United States is guided by the pioneering US 1977 Surface Mining Control and Reclamation Act (SMCRA, 1977) as further developed by Stiller et al. (1980), Toy and Hadley (1987), and Bugosh (2000, 2003). Backfilling and regrading is designed so that the mined area blends into, and complements, the drainage pattern of the surrounding terrain. One of the most successful examples is that of the La Plata open pit coal mine in New Mexico (**Fig. 10**) (Bugosh and Epp, 2019). This type of mine rehabilitation is also practiced in Canada (Sawatsky and Beckstead, 1996; Sawatsky and Beersing, 2014), Australia (Waygood, 2014; Kelder et al., 2016), and Spain (Martín Duque et al., 1998, 2010; Zapico et al., 2018; JRC, 2018).

Owing to the severity of degradation that earth movement commonly imposes, a paradigm shift in the way we approach land transformation is taking place. In a process called *Progressive Rehabilitation*, the land is restored during resource extraction, rather than in a large-scale effort at the end of the project. Thus, extraction and restoration, the latter following geomorphic principles, are part of the same process (**Fig. 11**), with the goal of integrating the waste materials into a landscape with the shape and functionality of the natural one. This avoids having to move the waste materials twice. A similar approach could be used in other civil engineering projects such as landfill construction, or urban development.

Restoring damaged landscapes is a positive step, but geomorphically-based ecological restoration can be only a partial solution to the impact of our earth moving on our life-support system. It needs to be complemented with measures like reducing the need for

Fig. 10 Geomorphic restoration at La Plata mine, New Mexico (USA). (A) July 2003: prior to geomorphic restoration; (B) August 2003: beginning of placement of leftover earth material in accordance with the restoration design; (C) October 2010: reconstructed landscape five years after completion of grading, topsoil placement, and seeding. The distance across the pit in (a) is $\sim$ 5 km. View is to the southwest; drainage is from right to left. Photo credits: Nicholas Bugosh.

resources, recycling, internalizing costs, transitioning to renewable energy sources, and especially dealing with the population problem.

9.08.4.2 Can we solve the greenhouse gas problem?

9.08.4.2.1 Renewable energy sources

Increased use of energy from renewable sources—solar, wind, biofuels, hydroelectric—are popular approaches to mitigating climate warming, but have their drawbacks. Reservoirs, commonly an integral part of a hydroelectric system, emit CH_4. Solar panels can't generate power at night, when electricity use increases, nor can wind turbines when it is calm. The fabrication of solar panels and turbines has a significant ecological and carbon footprint, and the metals and rare earths needed for these systems commonly lie in areas that overlap with protected areas and biodiversity hot spots (Sonter et al., 2020). Biofuels require land that might alternatively be used to grow crops. Finally, because standby fossil-fuel and nuclear plants can't start or stop instantaneously, they need to be kept running to provide power when solar or wind fail.

Fig. 11 Progressive geomorphic restoration at San Juan coal mine (New Mexico, United States). As extraction advances to the left in the upper left corner of the image, notice how a functional landscape, blending into, and complementing, the drainage pattern of the surrounding terrain, is being reconstructed with the waste (grey materials at the center of the image). Aerial image by James O'Hara, New Mexico Mining and Minerals Division, 2002.

Replacing the fossil fuel capacity likely to be retired in the United States over the next 25 years, would require solar panels covering an area roughly the size of New Jersey (22,600 km^2). A wind farm 100 km on a side would produce only ~1% of the energy capacity of the present US electrical system. Solar or wind farms on this scale in humid-temperate regions, where demand is likely to be highest, would destroy natural vegetation that already provides extremely effective decarbonisation by photosynthesis (Rubenstein, 2019). They would also disturb extensive areas of soil with its supply of essential microbes.

9.08.4.2.2 Geoengineering

Engineers are also exploring technological approaches to removal and sequestration of greenhouse gasses. Liquefied CO_2 can be injected into oil wells, saline aquifers, sedimentary rocks, or basalts; in some cases this CO_2 will, over time, react with minerals to form carbonates (Lal, 2008). Liquid CO_2 can also be injected at the bottom of the ocean; at depths in excess of 3000 m, it is denser than seawater and is expected to gradually sink into the sediment (Lal, 2008).

It would, however, take decades for such strategies to stabilize the climate. Furthermore, in view of the risks of leakage, CO_2 injection and storage require precise protocols for measurement, monitoring, and verification (Lal, 2009). Thus, also discussed are schemes to modify Earth's energy budget by seeding clouds to decrease the amount of heat they trap or increase the amount of radiation they reflect, or injecting aerosols in the lower stratosphere to increase the planetary albedo (Lawrence et al., 2018). While these approaches could potentially stabilize the climate on a time scale of years, they would be expensive and are still far from being developed to the industrial scale needed to solve the problem. They are also fraught with political problems, as neighboring countries may view the consequences as undesirable.

9.08.4.2.3 Reforestation and afforestation

While they are growing, trees combine atmospheric CO_2 and water in photosynthesis to make wood. The carbon is stored in the wood for the life of the tree, and for some years thereafter as the tree gradually decays. Thus, reforestation (planting of trees in logged areas) and afforestation (planting of trees in areas previously lacking them) are two popular approaches to reducing atmospheric CO_2.

Under the right circumstances, reforestation and afforestation: (i) reduce surface temperatures, (ii) increase atmospheric moisture, (iii) benefit wildlife by enhancing connectivity between forested areas, and (iv) improve ecosystem services (IPCC, 2019b, p. 590). Reforestation could potentially remove 5.8 ± 4.3 Gt $CO_2e\ a^{-1}$ (gigatons CO_2 equivalent per annum), and afforestation could sequester 4.7 ± 4.3 Gt $CO_2e\ a^{-1}$ (IPCC, 2019b, p. 585) [The large uncertainties reflect uncertainty in such factors as the amount of continued deforestation, the lifetime of wood products, and the efficiency of harvesting (Houghton and Nassikas, 2018)]. Total emissions of CO_2 from burning fossil fuels, however, are now $\sim$35 Gt a^{-1}, and agriculture and industrial processes add an additional $\sim$10 Gt a^{-1} making the total human emissions $\sim$45 Gt a^{-1} (Climate Watch, 2019), so reforestation and afforestation, while beneficial, will not, alone, solve our global warming problem.

There are also several problems with reforestation and afforestation. First, a healthy forest ecosystem includes animals that spread seeds, bacteria that fix N in soils, and fungi that digest decaying leaf litter, all of which are essential for healthy functioning of the system. However, an extended period of time is required to fully recreate this ecosystem (Irfan, 2019). Secondly, large-scale afforestation uses land that otherwise might be used to grow crops to feed our burgeoning population (IPCC, 2019b, p. 605); thus it could lead to higher food prices and undernourishment. Thirdly, all too often, afforestation results in land degradation and lower biodiversity, especially in arid and semi-arid (e.g., Mediterranean) landscapes. This is because, potential evaporation normally exceeds precipitation in these landscapes so soil moisture typically cannot sustain forest vegetation. Thus, afforestation efforts need to use a natural biodiverse steppe or scrubland vegetation that forms a sustainable ecosystem in equilibrium with the available water supply (Cao et al., 2010). Otherwise, degradation results. Afforestation in regions with extensive snow cover also decreases albedo, causing net warming (IPCC, 2019b, p. 572). Finally, both reforestation and afforestation normally involve earth-moving activities that degrade the soil and may release more CO_2 than is sequestered in the resulting trees (Linares et al., 2002; IPCC, 2019b, p. 582).

9.08.4.3 Reducing waste: The circular economy

In 2015, about two-thirds of the raw material we extracted from the planet, about 61 billion tons, were dispersed into the environment as unrecoverable waste (Kunzig, 2020). Examples of our profligate wasteful behaviors abound. Between 2000 and 2015, the explosion of "fast fashion" doubled clothing production, but the world population grew by only a fifth. Globally, roughly a third of all food is wasted, at an annual cost of nearly a trillion dollars. Plastics accumulate in giant gyres in the ocean. These and other examples are discussed by Kunzig (2020) who described our waste production as "the mother of all environmental problems."

Much of the waste ends up in landfills. "Landfill," however, is a bit of a misnomer; the waste is not put into a hole, thus "filling" the hole. Rather, it all too commonly accumulates in artificial hills of a very unnatural shape, as if one made an upside-down cake out of trash in an enormous baking dish, inverted it upon the landscape, covered it with soil, and seeded it with grass—a modern day tell. Geomorphic and ecologic restoration can improve the shape and functionality of the resulting landform, but once again, this is not a sustainable solution.

We, in fact, treat planet Earth as a huge waste dump. Air, soil, and water bodies (including groundwater) are receptors of our waste, degrading their capacity to support life. Indeed, waste is responsible for most of our environmental problems, including climate change (as both CO_2 and CH_4 are waste products). A worrying aspect of waste is its "bioaccumulation"—a process in which small organisms consume pollutants (e.g., trace metals attached to microscopic food particles) which are not excreted but rather further concentrated in ever larger organisms as they are passed up the food chain to higher trophic levels. This latter process—called "biomagnification"—causes declines in wildlife populations, negatively affecting ecosystems and potentially human health (Paasivirta, 2000).

Waste can be decreased by reducing our consumption, reusing items made from Earth materials, and recycling items that can no longer be reused—the well-known *Reduce, Reuse, Recycle* hierarchy. Recycling is the process of converting waste materials into new ones, whether for the original or other purposes. This process has obvious environmental benefits. It conserves finite natural resources; it prevents waste from going into landfills and into the environment; it significantly reduces the use of fossil fuels and the attendant CO_2 emissions entailed in making items from scratch; and it reduces air pollution from incineration or spontaneous combustion in landfills, and water pollution from landfill leakage (EP and CEU, 2008). Thus, by substituting recycled material for raw material as inputs to the economic system and by redirecting waste outputs from the system, recycling is a key element in achieving environmental sustainability.

Electronic waste, or e-waste, is a particular problem owing to the toxicity of many of the components. Rwanda has developed a progressive approach to this dilemma. Community members are paid well for every kilogram of e-waste delivered to a collection center. The material is then processed to recover precious metals such as gold, silver, platinum, palladium, copper, and tin. This novel business has created hundreds of new jobs (Mafaranga, 2020).

However, as is true of many partial solutions, recycling tackles only the symptoms of Global Change, not the causes (Barlt, 2014). Reuse and especially reduce are more beneficial, as they directly address the inputs to our waste stream. It is evident that complete avoidance of waste is impossible, at least in the short term, but it seems clear that waste reduction and reuse, in addition to recycling, are critical aspects of sustainability (Barlt, 2014).

The reduce, reuse, recycle approach has been condensed in the concept of a *Circular Economy*. In such an economy, all waste products are reused (Boulding, 1966; Pearce and Turner, 1989). This, in fact, has been the *de facto* common practice for most of human history. Human fecal material, rather than being flushed into local rivers, has been spread on agricultural fields as fertilizer; bronze and other metals have been melted down for reuse; large building stones (ashlars) have been reused by successive cultures; ash from fires has been used for brick making; and so forth. Indeed, the human economy was mostly circular until the Industrial Revolution inadvertently introduced the Linear Economy, in which natural resources have a single linear trajectory from mine to landfill. For decades after emergence of the Industrial Revolution, however, many materials were, in fact, reused; the linearity evolved gradually, but it is now dominant.

A Circular Economy is perhaps one of the most promising solutions to our waste problem. About 10% of natural resources are already recycled. Some countries, such as the Netherlands, have reduced food waste by nearly 30% since 2010 (Kunzig, 2020). Rwanda, as just described, has developed a profitable industry around recycling of e-waste. Thus, a move toward a Circular Economy is a step in the right direction, but it is not clear that it can occur fast enough to, as Daly (1991, p. 256) contends is required, reduce our waste stream to a level that matches the ability of the environment to absorb it.

9.08.5 The ultimate problem: Overpopulation

We have a problem. Humans are exploiting Earth in an unsustainable manner. The expansion of infrastructure and agriculture necessitated by population growth has accelerated the pace of land degradation, seriously impacting our life-support systems. This is most clearly illustrated by the over 40-fold increase in the rate of extinctions between 1885 and 2005 (**Table 1**). Presently, however, public focus is on the seven- or eight-fold increase, since 1885, in the amount by which atmospheric greenhouse gas concentrations now exceed preindustrial levels (**Table 1**), resulting in a $\sim 1\ ^\circ\mathrm{C}$ increase in global mean temperature. Numerous partial solutions to the global warming problem have been proposed. None is likely to solve the problem. Some would require vast land areas in humid-temperate regions that, with the present population explosion, are also needed for farms. Geoengineering solutions are not ready for implementation and have geopolitical consequences. And some attributes of our affluent society cannot be readily powered by renewable energy sources.

Human per capita use of natural resources (e.g., water, soil, fertilizer, energy, minerals: **Tables 1 and 2**) has increased as the population has increased, and this has fueled an increase in the average standard of living (= Global GDP per capita) that is clearly not coincidental. In a broad sense, once the population has exceeded some undefined minimum, prosperity (or our standard of living) is proportional to the abundance of natural resources per capita:

$$\text{Prosperity} \propto \frac{\text{Natural Resources}}{\text{Population}}$$

The island nation of Nauru provides a simple single-resource example. Nauru had large deposits of phosphate leached from guano. Up to 1989, when the supply ran out, export of the phosphate gave the people of Nauru one of the highest per capita incomes on earth. Subsequently, their standard of living has declined sharply (Anonymous, 2001).

It is likewise no coincidence that our emissions of CO_2 and CH_4, our solid waste stream (**Table 1**), our exploitation of the land (**Table 2**), and our earth-moving (**Table 3**) have increased along with the population. This suggests a third approach to reducing our impact on our home: embark on a crash program to reduce fertility below 2.1, the level needed to maintain a stable population. Over the long term, a fertility less than 2.1 will reduce the population to a sustainable level. Keys to this are: (i) helping the poorest regions of the world get out of poverty (not only because poverty is unbearable, but also because affluent couples tend to have fewer children), (ii) educating women in developing countries as, again, educated women have fewer children, (iii) delaying child bearing so there are fewer people on Earth at any one time, and (iv) making the two-child family the global, socially acceptable norm.

At this point it is worth repeating Herman Daly's (1991, p. 256) three requirements for a sustainable society:

(i) it must consume renewable resources at a rate less than the rate at which they are renewed;
(ii) it must consume non-renewable resources at a rate less than the rate at which substitutes can be found; and
(iii) its waste stream cannot be greater than the capacity of the environment to absorb the waste.

We are failing badly on all three counts. We can go some ways toward satisfying these requirements by simple measures like driving smaller, less polluting vehicles, recycling, or minimizing food waste. If we are to fully meet them without a drastic reduction in our standard of living, however, we need to embark on a sustained effort to reduce the population.

The present global population, as of October 14, 2020, is estimated to be 7.690 billion (US Census Bureau, 2020b), and counting. Several scientists have estimated Earth's carrying capacity for humans living moderately comfortable lives. Sverdrup and Ragnarsdottir (2011) believe that the supply of phosphate for fertilizer limits the sustainable population to ~3 billion. Wackernagel and Rees (1996) analyzed the surface area (ecological footprint) required to support an individual, and concluded that Earth can sustainably support a population of no more than 2–3 billion. Pimentel et al. (1999) studied the sustainable use of natural resources and reckoned that Earth's carrying capacity is ~2 billion. Grant (1997) considered agricultural production (as amplified by a limited supply of artificial fertilizers); climate change; and loss of biodiversity, especially among microbes; and concluded, again, that a sustainable population is in the range of 2–3 billion. As Grant (1996, p. 75) notes, "This suggestion is less radical than it sounds. It is where we were two generations ago [in the 1940s and 1950s]." Smail (2002) elaborates on these and other similar estimates of an optimum population. Employing a different measure, it is estimated that to *sustainably* provide the resources we now use and absorb the waste we generate, we would need 1.8 planet Earths (Anonymous, 2020).

Given our demonstrated ability to raise crops indoors in vertical farms, using less water and fertilizer than traditional farms while achieving triple-digit increases in productivity (Kunzig, 2020), some of these estimates may be outdated. However, the increasing number of visits to national parks and other natural areas in developed countries all over the world demonstrates that affluent societies also need open space, which an overcrowded planet cannot provide. Between the 1990s and 2020, there was a nearly six-fold increase in the number of people attempting to hike the full length of one of the three 2000+ km trails in the United States (Kristof, 2020). It is obvious that with a much-reduced population, our impact on the environment would be far less severe than it is today, and solving our environmental problems would be orders of magnitude easier. The senior author fondly remembers the freedom of the 1950s, when the global population was ∼2.7 billion and we needed far fewer rules and regulations than we do today.

9.08.6 Conclusions

The Great Acceleration has resulted in multiple impacts on our environmental, geomorphic, and life-support systems, most of them negative. Land suitable for agriculture has diminished due to soil degradation and to urban expansion. Earth moving has increased, resulting in damage to soils and their stockpile of microbes and entomofauna that are critical to our well-being, and degrading water resources of all types, including groundwater. Emissions of CO_2 and CH_4 have increased, resulting in climate warming, in increases in severe weather, in flooding in some areas and desertification in others, in sea level rise, and in other undesirable geomorphic changes. New toxic substances have been handled carelessly, polluting our air, water, and soil. Our pollution and population expansion have diminished habitat for other species, resulting in a more than 40-fold increase in the rate of extinctions compared with normal background rates.

Stop-gap measures may delay the impending crisis. Food waste can be reduced. Reforestation and afforestation can increase the uptake of CO_2 from the atmosphere by photosynthetically transferring it into the pools of biotic and soil carbon. Techniques are available to sequester carbon. Solar and wind energy can be substituted for that from hydrocarbons, thus reducing CO_2 and CH_4 emissions. We know how to discard our waste products in an environmentally benign way, to reuse resources, and to reduce resource consumption, but all too commonly do not do so. Ecosystem functions in land disturbed in the course of earth-moving activities can be largely re-established, and functional landscapes restored. However, these measures are insufficient. They will only delay, not avoid catastrophic collapse. A systematic effort to stem the population explosion and eventually reduce the global population is essential. Unqualified growth can no longer be sought. This transition requires more than a population policy, however. We need to make sweeping changes in our economic philosophy, and hence in the controlling legal structure. The changes in our way of life will need to occur soon, and, as Seto et al. (2010, p. 95) emphasize, will be breathtaking.

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