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Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch

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Growth in fundamental drivers—energy use, economic productivity and population—can provide quantitative indications of the proposed boundary between the Holocene Epoch and the Anthropocene. Human energy expenditure in the Anthropocene, ~22 zetajoules (ZJ), exceeds that across the prior 11,700 years of the Holocene (~14.6 ZJ), largely through combustion of fossil fuels. The global warming effect during the Anthropocene is more than an order of magnitude greater still. Global human population, their productivity and energy consumption, and most changes impacting the global environment, are highly correlated. This extraordinary outburst of consumption and productivity demonstrates how the Earth System has departed from its Holocene state since ~1950 CE, forcing abrupt physical, chemical and biological changes to the Earth's stratigraphic record that can be used to justify the proposal for naming a new epoch—the Anthropocene.

A stratigraphic case has been made for a planetary-scale Anthropocene time interval at epoch rank, one that would end the Holocene Epoch at ~1950 CE[1]. Conceptually, the transition reflects a change from human drivers of environmental change having gradually increasing significance and mostly regionally expressed, to becoming overwhelming and global in extent. But what quantifiable metrics enable direct comparison between the Anthropocene and the preceding Holocene? As a unit of the international Geological Time Scale, the Quaternary Period[2,3] formally partitions into Pleistocene (2.58 My to 11.7 ky) and Holocene (11.7 ky to present) epochs[4]. The Holocene, which follows the end of the last cold episode with the rapid northward movement of the oceanic polar front, is formally subdivided by the International Commission on Stratigraphy (ICS) into three ages:[5,6] Greenlandian (11.7 to 8.2

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ky), Northgrippian (8.2 to 4.3 ky), and Meghalayan (4.3 to 0 ky). Here, we trace the human footprint through each Holocene age, with focus on two historical and informal intervals: Pre-Industrial (1670–1850 CE) and Industrial (1850–1950 CE), within the Meghalayan Age. The Anthropocene as a potential epoch[7,8] is first compared to these earlier Holocene ages, using the human population and its energy consumption and economic productivity, and then assessed by evaluating how human action has disturbed the landscape, altered river discharge (water, particulate and dissolved constituents), and has shifted climate, biogeochemical cycles, biodiversity, and other parts of the Earth System. These changes have already resulted in a sharp distinction in the stratigraphic record between the Holocene and Anthropocene[1,7,8]. This study formulates a consistent quantitative approach evaluating key Earth-surface parameters and their human drivers to validate the contention that the Anthropocene is an epoch-level planetary interval in Earth's history, comparable to or exceeding in planetary impact the Holocene Epoch, and greatly exceeding component Holocene ages.

The Anthropocene Epoch is used here as a geological time unit for potential inclusion in the Geological Time Scale. A proposal to formalize the Anthropocene for this purpose is currently being developed by the Anthropocene Working Group (AWG), which includes many authors of this paper, and will require a defining Global Boundary Stratotype Section and Point (GSSP) to be selected and approved, consistent with ICS standard practice.

A Holocene history of the human footprint

The Greenlandian Age (11.7 to 8.2 ky) constitutes the first 3464-y of the Holocene, driven by Milankovitch warming of ~+0.5 °C[9], during which the Inter-Tropical Convergence Zone shifted northward[10] and Northern Hemisphere ice sheets ablated. Atmospheric CO_2 and CH_4 concentrations continued a trend of rapid rise initiated in the latest Pleistocene and peaking at ~10 ky[11]. Coastal human populations retreated inland from initial settlements[12], especially on deltas[13], as global mean sea level rose ~48.5 m, at a rate of ~15 mm/y between 11.4 ky and 8.2 ky[14]. Human population was sparse and grew from ~4 M to 8 M (Fig. 1a), at a rate of 0.01%/y (Table 1, Supplementary-Table 1).

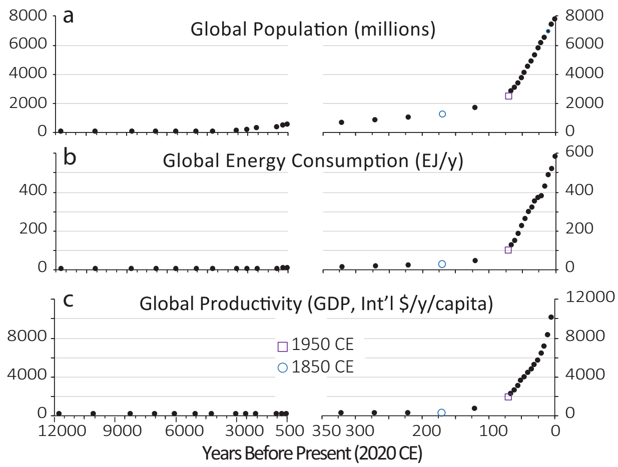

Fig. 1 Correlation of global human population, energy consumption and productivity during the Holocene and Anthropocene epochs. a Global human population (millions), **b** global energy consumption (EJ/y), and **c** global productivity ($/y/capita), across the Holocene and proposed Anthropocene epochs (in this paper starting in 1950 CE). All three parameters are highly correlated (Spearman's rank coefficient = 1.00). Larger circle = 1850 CE; large square = 1950 CE. Data references are listed in Supplementary Online Material.

Regional extinctions of large terrestrial mammals (e.g., ground sloths in North and South America) correlate with the arrival of humans[15]. Humans lived as foragers, fishers, or hunters, but in a few locations began to cultivate domesticated food crops[16]. Energy sources were wood-burning and human muscle, and more rarely, animal muscle, with an estimated per capita energy consumption of 6.2 GJ/y, ranging from 5.8 to 6.5 GJ/y (Fig. 1b, Table 1). The human population during the Greenlandian consumed 0.12 zetajoules of energy (with 1 ZJ = 10^{21} J). Global productivity is used here as a measure of output per unit of input, such as labor, capital or any other resource calculated for the global economy (GDP per capita per unit time), and if meaningful at all for the Greenlandian, was very low (Fig. 1c, Table 1).

During the Northgrippian Age (8.2 to 4.3 ky), global mean sea level rose another ~14.5 m, mostly in the first 1500-y, as the great Northern Hemisphere ice sheets largely had disappeared by 7000-y ago[14,17]. The Age-averaged rate of global mean sea-level rise was ~3.6 mm/y (Table 1). Global climate was relatively stable at a temperature plateau until 5.48 ky, when the planet cooled ~−0.2 °C, but with regional exceptions[9]. The trend in atmospheric CO_2 and CH_4 concentrations changed from slightly falling to slightly rising, at ~8 ky and ~5 ky respectively. Although some have argued that this increase reflected deforestation in response to expanding agriculture, in particular rice cultivation in the case of methane[10], others suggest that the rise reflects the gradual adjustment of ocean chemistry towards an equilibrium state following deglaciation[18]. Some humans, still a minority at the end of the Northgrippian Age, organized into structured agrarian societies. Once sea level stabilized, the human population grew to 27 M (0.03%/y), as urban centers and ports developed (Fig. 1a, Table 1) and the earliest state-level societies originated (Mesopotamia at 3700 BCE, Egypt at 3300 BCE, Peru 3000 BCE, Indus Valley at 2500 BCE, Mesoamerica 1900 BCE, and Yellow River 1700 BCE[19,20]). Energy sources included wood burning, human and animal muscle, with the per capita energy consumption at 7.1 GJ/y, ranging from 6.5 to 7.8 GJ/y (Fig. 1b, Table 1). Humans expended 0.34 ZJ across the Northgrippian Age, a 332% increase from the Greenlandian, reflecting an increased human population. Human productivity remained low (Fig. 1c, Table 1). The anthropogenic footprint included regional soil erosion from deforestation, a proliferation of pastureland, and some mining[21,22]. Extinction of large terrestrial mammals correlates with climate change[23], though some extinctions have been linked to human actions[15].

The Meghalayan Age, as represented here, is the recent ~4.2-ky interval (to ~1950 CE), when global mean sea level rose 1.0 to 1.5 m, or ~0.3 mm/y[14], as the global climate cooled ~−0.5 °C[9], in what is referred to as Neoglaciation[24]. Insolation decreased, and there were slight rises in atmospheric CO_2 and CH_4 concentrations[25]. Human populations increased by an average 0.2%/y, reaching a population of 2500 M by 1950 CE (Fig. 1a, Table 1). Apparently related to sea-level stabilization, biological productivity on the coastal margin increased dramatically and likely initiated the further movement to large empire level organization in human society facilitating greater demand for goods, increased trade and complex urbanization[19,20,26]. Large-scale water diversion schemes were built, and extensive farming practices increased[21,27]. Coal became a common energy supply in the 19th century[28]. Per capita energy consumption averaged 8.3 GJ/y, ranging from 7.8 to 40 GJ/y, with humans expending 14.2 ZJ across the Meghalayan Age, a 24-fold increase over the Northgrippian Age (Fig. 1b, Table 1). Per capita GDP averaged $144/y (Fig. 1c, Table 1). Humans transferred plant and animal species beyond their native ranges, exemplified by the spread of chickens[29], maize[30] and Pacific rats[31]. Human impacts produced extensive regional losses[32] and widespread

Table 1 Average values of key human and environmental drivers for each studied time interval.

Geological Unit	Greenlandian Age	Northgrippian Age	Meghalayan Age	Pre-industrial Interval (informal)	Industrial interval (informal)	Anthropocene (proposed Epoch)
Time Interval (y before 2020 CE)	11,720–8256	8256–4270	4270–70	350–170	170–70	70–present
Interval span (y)	3464	3986	4200	180	100	70
Global climate change (°C)	~ +0.5	~ 0.0	~ −0.5	~ 0.0	~ +0.2	~ +0.9
Sea Level Rise (mm/y)	15	3.6	0.3	0.15	0.75	2.4
Population growth rate (%/y)	0.01	0.03	0.2	0.4	0.8	1.6
Primary energy source	Wood & human muscle	Wood & increasingly animal muscle	Wood, muscle, coal in cities	Wood, muscle, whale oil, coal, streams	Coal, oil, hydroelectric	Coal, oil, gas, nuclear, renewables
Per capita energy consumption (GJ/y)	6.2	7.1	8.3	18.4	27.2	61
Total interval energy (ZJ)	0.12	0.34	14.2	2.9	4.9	22
Generalized human narrative	Primitive Agrarian Societies	Organized Agrarian Societies	Advanced Agrarian Societies	Empires, Nations, City States	Nations & Empires	UN
GDP (Int'l $/Capita/y)	96	109	144	170	679	5400

Human and environmental drivers across the IUGS/ICS-approved Holocene ages, along with values for two informal intervals occurring in the last 280 years of the ~11,700-y Holocene history, and the proposed Anthropocene Epoch starting in this paper at 1950 CE. All values shown are interval averages.

extinctions of land vertebrates[33], including the ancestors of domesticated cattle in Eurasia[34] and flightless birds in the Pacific[35]. Introductions and extinctions left a distinctive archeological and fossil signal[36–38].

Below we discuss two informal intervals, the Pre-industrial and the Industrial, that capture the end of the Meghalayan.

Pre-Industrial interval (1670–1850 CE). A 180 y-long interval when Holocene sea-level rise was at its slowest ~0.15 mm/y[14], with no discernible trend during the 18th century, and a slight fall from 1800 to 1850 CE[39], when Alpine glaciers were at their maximum Meghalayan extent[40] in response to extensive volcanism[41]. Earth had no discernible climate trend ~0.0 °C[9] during this interval, with cooling pulses varying regionally[42]. Human population expanded from ~600 M to 1247 M, a growth rate of 0.4%/y (Fig. 2a). The per-capita energy consumption was 18.4 GJ/y, ranging from 13.5 to 22 GJ/y (Fig. 2b, Table 1), with humans expending 2.9 ZJ or 20% of the human energy consumption during the 4,200-y Meghalayan Age (Table 1). Novel energy sources included whale oil[43] and stream energy; for example, there were >65,000 water-powered mills in the U.S.A. prior to 1840 CE[44,45]. Human-enabled species introductions expanded, and transfers happened rapidly, exemplified by the spread of accidentally introduced aquatic mollusks in Europe[46]. This informal interval represents the fundamental transformation from pre-industrial to full industrial energy use. Prior to 1670 CE, expenditures in England used to obtain basic energy resources (human food, fodder for animals, and wood fuel) amounted to 50–70% of GDP[47]. By 1850 CE, with the growing use of coal, less than 30% of GDP was allocated to obtaining energy, and <10% after 1950 CE, as fossil fuels dominated energy use[47]. Global per capita GDP increased by 1750 CE to $178/y in 1990 international dollars (Table 1, Fig. 2c).

Industrial interval (1850–1950 CE). This 100-y interval captures the change in human–nature interactions[48]. Atmospheric CO_2 increased from the spread of industrial activity and drove a planetary warming by ~+0.2 °C[49] (~ + 0.6 W/m^2)[49], on an otherwise essentially flat Milankovitch insolation signal[50,51]. Solar variability had very little effect, with the number of sunspots rising in 1950 CE to levels slightly lower than that in the 1860s and the 1780s[52,53], in contrast to the pre-industrial Maunder Minimum from 1645 to 1715 CE[54]. Thus, natural variability contributed little to warming, (<0.2 W/m^2)[49] during this interval, where the main natural changes were brief intervals of cooling related to large volcanic eruptions that ejected reflective material into the stratosphere (e.g. Krakatoa in 1883 CE)[55,56]. Sea-level rise accelerated to ~0.5 mm/y in the late 1800s, and to ~2.2 mm/y by 1940 CE, before beginning a temporary deceleration[57]. This pattern is consistent with the natural fluctuations in the warmth of the North Atlantic in responses to changes in the Atlantic Meridional Ocean Circulation that induces regional and slight global warming as it accelerates, reversing as it decelerates[58].

Human population grew at 0.8%/y, from 1250 M to 2500 M (Figs. 1a, 2b, Table 1). Energy consumption per capita averaged 27.2 GJ/y, ranging from 22 to 40 GJ/y (Fig. 2b), accounting for 4.9 ZJ or 35% of the energy consumption across just 2.4% of the 4200-y Meghalayan Age (Table 1). In addition to the growing use of coal, new energy sources included hydroelectric power, oil and natural gas, more than offsetting declines in whale oil and stream power (driven by gravity). Many large rivers were engineered, with levees, dams and water diversion schemes[59]. Some lake[60] and marine[61] ecosystems started to turn hypoxic. Biodiversity loss increased and introduced species, such as the giant African snail and naval shipworm[62,63], spread through terrestrial and aquatic environments[21,32,64]. Dispersals were facilitated by increasing global trade[65]. Per capita GDP had increased by 1900 CE to $679/y in 1990 international dollars (Table 1, Fig. 2c), underwriting new global transportation systems and power sources.

Although the European industrial interval began in the 1700s, we use 1850 CE as the start of the interval, given the remarkable change in both global energy use and global productivity (Fig. 2c). For most of the Holocene Epoch, human productivity (GDP per capita: see SOM Historical GDP Consumption Data) increased linearly with a growing population (Fig. 2c). From 1850 CE onwards, human productivity accelerated (Fig. 2c), which explains why that time period was originally suggested as the start of the Anthropocene[66,67]. For most of the Holocene, the ratio of human productivity to energy use decreased (Fig. 2d). After 1850 CE, human society became more productive per unit of energy use (Fig. 2d). During the 11.7 ky of the Holocene Epoch, including the Industrial interval, the global human population consumed 14.6 ZJ of energy of which 35% was consumed in the final 100 years.

An Anthropocene history of the human footprint

Proposed Anthropocene Epoch from 1950 CE:[1,68] Driven by the accelerated burning of hydrocarbon fuels, atmospheric temperatures increased by 0.9 °C in the last 70 years (and by 1.1 °C from 1900 to 2018 CE[69]), with much of the rise post-dating 1970 CE[70], during an interval of limited sunspot influence and a flat Milankovitch signal. Sunspot numbers rose slightly from their 1950 CE levels to peak levels in 1980 CE and 1990 CE that are more or less similar to those reached in the 1780s and the 1860s, and then began declining[52] even as warming continues (Box 1).

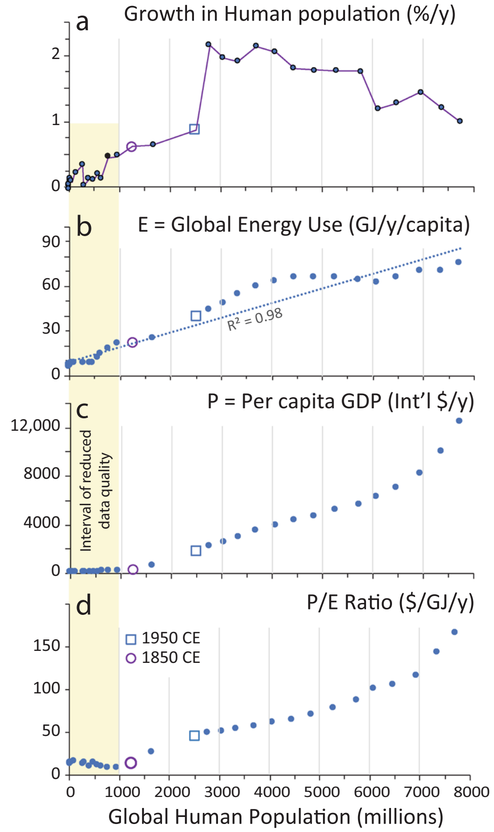

Fig. 2 Relationships between human population (millions) and key economic indicators. Relationships between human population (millions) and key economic indicators: **a** rate of population growth (%/y), **b** energy consumption per capita (**E** in GJ/y/capita), **c** per capita productivity (**P** as GDP in 1990 international dollars, $/y/capita), and **d P/E** ratio, each across Holocene and Anthropocene epochs. Purple circle = 1850 CE; blue square = 1950 CE. A marked change in GDP per capita after 1850 CE reflects the global spread of industrialization and technology. The rate of change in population sharply increases around 1950 CE. The **P/E** ratio fell for most of the Holocene, until 1850 CE, when human society became more productive per unit energy use. Data references are listed in Supplementary Online Material.

Atmospheric CO_2 levels reached 415 ppm in 2019[71], higher than at any time in the past 3 million years[71]. Planetary response to this atmospheric warming includes:

- **Sea-ice volume** shrinkage: 300 ± 100 km^3/y loss (~275 Gt/y) in the Arctic Ocean since 1980 CE[72]. Antarctic sea ice extent in October 2019 CE was less than for any previous October since satellite observations of sea-ice began in 1978 CE[73].
- **Glacial-ice mass** loss: from 113 ± 125 Gt/y during 1992–1996 CE to 665 ± 48 Gt/y during 2012–2016 CE[74], with ~5.6 Tt (=10^{12} tonnes) of land ice loss on Greenland[75] and ~5.0 Tt from Antarctica since 1980 CE[76].
- **Sea-level rise** acceleration: from 1.53 mm/y (0.96 to 2.11 mm/y) during 1901–1990 CE, to 2.06 mm/y (1.76 to 2.36 mm/y) during 1971–2015 CE, and to 3.07 mm/y (2.70 to 3.7 mm/y) during 1993–2015 CE[77–79].
- **Acidification of the global ocean:** through the absorption of atmospheric CO_2 with open-ocean surface pH declining by a range of 0.017–0.027 pH units per decade since the late 1980s[80–82], threatening the survival of particularly soluble organisms, such as aragonitic pteropods. Increasing acidity may raise the calcium carbonate compensation depth (CCD) in the deep ocean, causing the demise of carbonate-shelled deep-water benthic organisms.

Since 1950 CE, the human population has rapidly increased, with societal and medical advances extending lifespans. Industrial-scale agriculture, with its global distribution system, presently feeds a global population of 7800 M that grows at an average rate of 1.63%/y, presently 71 M/y. In absolute numbers, human migration within and between continents has reached its historical zenith during the Anthropocene, as many coastal cities have transformed into megacities (>10 M) in just decades[83] (Table 2).

1950 CE also marks an important upturn in the global spread of technological knowledge occurring when societies became more economically interdependent (the Great Acceleration[48,84]). Between 1650 and 1750 CE, the annual citations of scholarly references grew at ~0.15%/y[85], increasing by an order-of-magnitude to ~1.5%/y during 1750–1927 CE. After 1927 CE for all subjects, and after 1947 CE for the natural sciences, citation rates have jumped to ~8%/y[85] following compulsory education and widespread literacy.

Global per capita GDP has risen rapidly in the Anthropocene, to a current figure of $12,500/y (Fig. 2, Table 2). This inflation-adjusted global productivity is an order-of-magnitude greater than during the Industrial interval just 70 years earlier (Tables 1, 2, Fig. 2c). Since 1950 CE, energy consumption by humanity has averaged 61 GJ/y per capita (range 40 to 75 GJ/y; Fig. 2b, Table 1), enabled by a diversified portfolio of energy sources (coal, oil, gas, nuclear, and renewables). Fossil fuels power more than 80% of the economy[86]. In total, 60% of all human-produced energy has been consumed since 1950 CE, at 22 ZJ, more than in the entire previous Holocene (~14.6 ZJ: Table 1). Since 1871 CE, the Earth's oceans have stored ~436 ZJ of solar energy trapped through the

Box 1 | Slight oscillations within Earth's climate system do not disrupt underlying climate trends

Superimposed on the rises in both temperature and sea level are slight fluctuations caused by natural oscillations within the climate system. Warm El Niño events in the Pacific cause short-term spikes in global warming, with larger events responsible for brief global warmings of 0.2 °C above the underlying trend, while La Niña cold events, produce short-term global cooling. Longer term (circa 2 decade-long) events in the Pacific (Pacific Decadal Oscillation) and Atlantic (Atlantic Multidecadal Oscillation) also cause even smaller rises and falls in global temperature and sea level[56]. These oscillations help explain why global temperatures in the 1940s rose slightly above the overall trend of rising temperature and sea level fell slightly below the trend in the 1950s and 1960s, rose again in the 1980s, flattened slightly in the 2000s, and continued rising after 2013 CE[55]. These events do not disrupt the underlying trend.

Table 2 Selection of key global environmental parameter values spanning the Holocene-Anthropocene transition.

Environmental Parameter	1900 CE	1950 CE	2000 CE	2015 CE
Human Population (millions)	1643	2499	6076	7349
No. of megacities (>10 M)	0	2	39	45
Human Energy Consumption (EJ/y)	41	100	377	514
Fossil Fuel Consumption (TWh)	5973	20,139	94,462	132,891
CO_2 emissions (Gt/y)	2	5.8	25	35
Atmospheric CO_2 (ppm)	296	311	369	404
Atmospheric N_2O (ppb)	280	289	316	328.5
Atmospheric CH_4 (ppb)	890	1162	1774	1835
Sea level (mm)	−152	−87	0.0	49
Land-Ocean Temperature Index	−0.19	−0.08	0.39	0.83
GDP (billions 1990 Intl $/y)	1116	4656	38,267	73,902
Number of motor vehicles (M)	0.01	8	450	1200
Number of 15 m+ Dams (thousands)	1.6	7	47	50
Global Freshwater use (km^3)	671	1230	3790	4000
Global Shrimp Farming (Mt/y)	0	0.01	1.0	3.5
Plastic Production (Mt/y)	0	2	213	381
Cement Production (Mt/y)	5	130	1600	4180
Ammonia (NH_3) production (Mt/y)	0	2	126	175
Aluminum Production (Mt/y)	0	2	24	58
Copper Production (Mt/y)	0.5	2.4	13	19
Mineral Species (thousands)	5.3	8.3	85	170
Iron & Steel Production (Mt/y)	35	134	573	1160
Sulfur Production (Mt/y)	1	11	59	69
Salt Production (Mt/y)	12	48	195	271
Gypsum Production (Mt/y)	1	23	108	260
Helium Production (kt/y)	0.0	0.4	20	26

Global environmental parameter values for 1900 CE, 1950 CE, 2000 CE and 2015 CE. Almost all parameters see their largest increases after 1950 CE, with many parameters at or near zero near 1900 CE. Data references are listed within the Supplementary Online Material.

increases in anthropogenic greenhouse gases[87], and from warming-induced increases in water vapor[88], a reinforcing feedback. This is more energy by an order-of-magnitude than associated with direct human production and consumption (at 23.3 ZJ since 1871 CE). Approximately half of the Anthropocene sea-level rise stems directly from this steric effect on ocean volume, with the remainder largely derived from the melt of terrestrial snow and ice[49]. Since about 1950 CE, the global ocean has progressively warmed both at the surface and increasingly to depths exceeding 2000 m. Heat is transferred vertically by storms and eddies, and by the sinking of surface water made dense by cooling, especially in the Labrador and Norwegian-Greenland seas in the Atlantic and in the Southern Ocean around Antarctica.

Many anthropogenic impacts post-1950 CE are planetary, with greater than regional significance, and scale up with the population of humans and their energy consumption and economic productivity[48]. Below we offer 16 examples relevant to, and in support of, this Anthropocene Epoch thesis:

1. The magnitude of the anthropogenic N cycle is roughly equivalent to the global natural N cycle[89,90]. However, such a simplified numerical comparison underestimates the ecological consequences of such a perturbation which includes impacts on climate change, water and air quality, ozone depletion, and biodiversity loss[91–93]. Globally, reactive nitrogen (N_r) increased by ~50%, between 1600 and 1990 CE, with atmospheric emissions of N_r increasing by 250%, and N_r deposition into marine and terrestrial ecosystems increasing by more than 200%[94,95] (Table 2). More than half of human population is alive today because of the production and use of N_r in fertilizers[96] and half the nitrogen in our bodies now comes from artificial production. Rates of use of N_r in the U.S.A. have increased from 0.22 g N m^{-2} y^{-1}, in 1940 CE, to 9.04 g N m^{-2} y^{-1}, in 2015 CE[97]. One of many consequences of fertilizer overuse, along with contributions from increased livestock, human sewage and hydrocarbon combustion, is the spread of hypoxia in coastal waters as 'dead-zones' inimical to marine life[98]: world coastal zones now receive ~100 Mt/y of anthropogenic-sourced N_r[48]. Because industrially derived nitrogen is depleted in ^{15}N, its atmospheric deposition offers a strong and coherent far-field signal in the N isotope ratios of both lake sediments and ice cores, with the main inflection at ~1950 CE[99,100].
2. River systems have been largely replumbed during the Anthropocene, with the construction of dams, reservoirs and diversions, with channel-bed mining and levee hardening, and with discharge focusing[59,101,102]. Only 23% of rivers longer than 1000 km flow uninterrupted to the coastal ocean, and only 10.5% of large rivers in Europe and 18.7% in North America can be considered as free-flowing rivers[103]. Large dams (>15 m in elevation) are the main cause of fluvial sediment being sequestered upstream, leading to a global decline of 18% in sediment delivery to the coastal ocean compared with pre-human times[59,104]. Of the 58,519 large dams registered in 2017 CE[105], 1.4% were built before 1850 CE, having a combined reservoir capacity of 6.1 km^3; 10% were built during 1850–1950 CE, with a total reservoir capacity of 685 km^3. 95.7% of the world's total reservoir capacity was emplaced after 1950 CE, increasingly in Asia[106] (Fig. 3a, Table 2). Total reservoir capacity of these large dams today exceeds 15,000 km^3; together they trap >3100 Gt of sediment, equivalent to a 5 m-thick deposit covering all of California or Spain. During the Industrial interval, four rivers (Colorado, Nile, Indus, and Yellow) transported 1.5 Gt/y of sediment to the coastal ocean; today they deliver <0.2 Gt/y[107]. Similarly, smaller dams have greatly reduced discharges to the coastal ocean, a

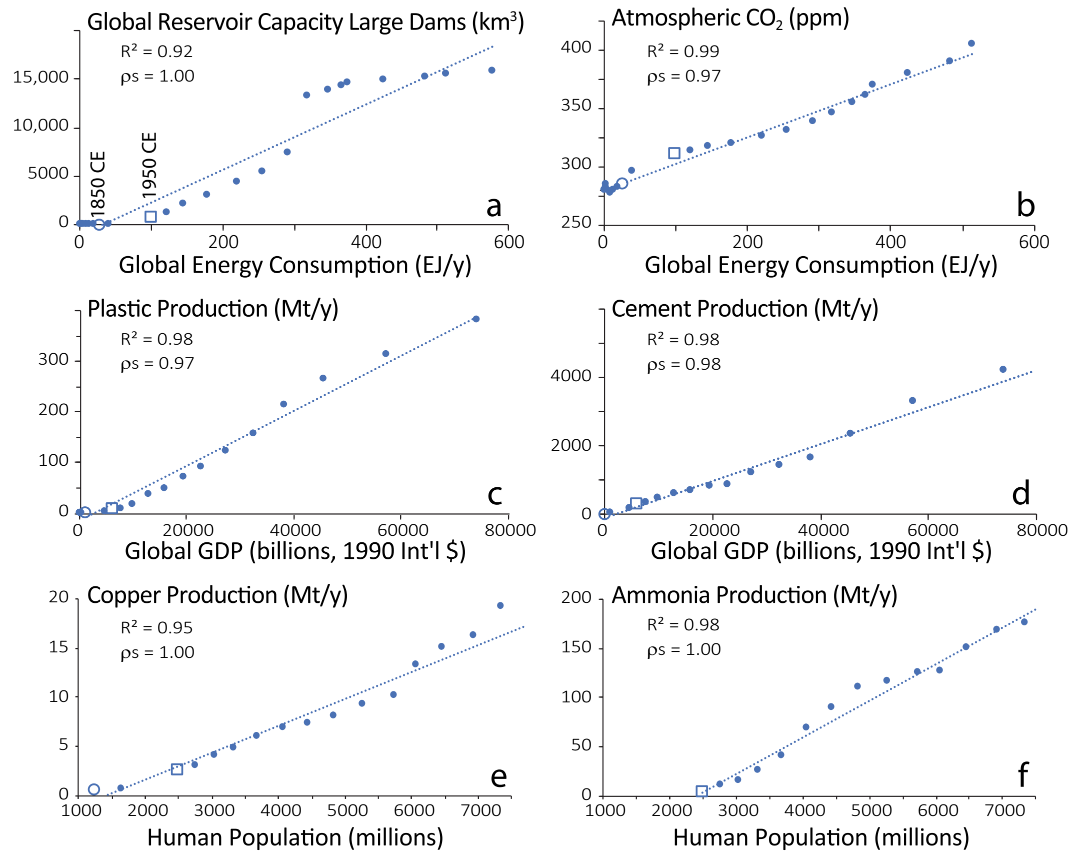

Fig. 3 Global relationships between population, productivity, and energy, the forces behind changes in the environment, and key environmental indicators. Example relationships between the global population (millions), global productivity, and global energy, the forces behind changes in the global environment, and key environmental indicators: **a** global reservoir capacity of large dams (km^3), **b** mixed atmospheric CO_2 (ppm), **c** global plastic production (Mt/y), **d** global cement production (Mt/y), **e** world copper production (Mt/y), and (**f**) world ammonia production (Mt/y) (see Supplementary-Table 2 for data, and Table 2 for other examples). 1850 CE (round) and 1950 CE (square) data points are highlighted. For data references see Supplementary Online Material. Correlation coefficients are provided for both dependent linear relationships (R^2) and Spearman's Rank (ρ_s).

consequence of upstream demands by human consumption and reservoir evaporation[107].

3. In 1904 CE, the U.S.A. had 225 km of paved highways outside of city streets[108]. Today 4.3 M km of U.S.A. roads are covered in asphalt or concrete; another 2.2 M km of roadway remain unpaved[109]. Since each road-km requires ~1250 metric tons of sand, and ~1875 metric tons of gravel, the U.S.A. highway system has consumed ~20.6 Gt of sand and gravel. By comparison the Great Wall of China contains only 0.4 Gt of stone[59]. The 64 M km of global roads and highways[110] have consumed ~200 Gt of sand and gravel to support the traffic of 1 billion motor vehicles (Table 2).
4. Industrial-scale mining has changed the global landscape; for example, the >500,000 abandoned mines and quarries in the U.S.A. alone[59], or the removal of mountain tops in West Virginia to access the coal underneath along with the concomitant dumping of spoils in nearby river valleys. Natural processes (ice, wind, water) transport 26 Gt/y of global sediment[59], a much smaller value than from modern mining activity. Estimates of global annual coal production (including underground, surface, hard and brown coals) and associated wastes totaled 74 Gt/y (35 km^3); other mining and mineral extraction, including overburden and waste removal accounted for another 27 Gt/y (13 km^3), as recorded in 2015 CE[111]. Coal mining in the U.S.A. increased from 0.9 Gt/y in 1905 CE[112] to 8.5 Gt/y during 2010–15 CE[113]. Bitumen (tar) sand-mining in Canada entered commercial production in 1967 CE; in 2012 CE, 1.5 Gt of bituminous sand were processed[59]. In 1970 CE, 944 Mt of sand and gravel were mined within the U.S.A., compared with 0.5 Mt in 1902 CE[108]. The Global Aggregate Information Network, representing 70% of global aggregate production (~50 Gt/y), operates 500,000 quarries and pits worldwide, employing 4 M people[114]. There is now concern that the increasing demand for sand for building megacities is outstripping supply. Offshore dredging for aggregates destroys marine habitats, as does bottom trawling for fish and shellfish, affecting marine biodiversity.

Since industrialization, human mining activities have impacted the global mobilization of naturally occurring elements, particularly the cycles of the chalcophile elements (e.g., As, Cd, Cu- Fig. 3e, Hg, Ni, Pb, Sb, Zn) associated with the smelting and refining of base metal ores, coal combustion and cement production[115,116]. In recent decades, platinum group elements that are required for advanced materials and technologies have been profoundly affected[117–119]. Increased extraction rates of ores (Table 2) have caused a transfer of metals from the lithosphere to these metal-in-use products and thence to wastes[120]. While negligible amounts of the industrial metals were extracted and put into use before 1900 CE[121], use of metals substantially increased after the 1950s[122] causing disturbances in natural biogeochemical cycles. Perturbations of

Pb, Hg, Se and Sn geochemical cycles now reach a global scale[123], with increasing perturbations for other metals[124].

5. Industrial-scale agriculture accounts for 50% of terrestrial soil loss[125,126], leaving nearby rivers with increased sediment and nutrient loads[126–128]. Forest clearing for the creation of agricultural lands has long increased soil erosion rates[27,129], but contemporary rates of soil loss from cropland exceed the natural rates of erosion 30-fold[130]. Cropland represents ~11% of the global land area, but accounts for ~50% of soil erosion[131]; soil erosion rates from forests are 77 times lower. From 2001 to 2012 CE, when 2.3 Mkm^2 of forest was lost, only 4% of this loss was converted to cropland, but was responsible for more than half of the increase in soil erosion[132]. Remaining soils are then progressively compacted by large agricultural machines and have their organic content gradually reduced, requiring replacement with artificial fertilizers (Fig. 3f). Soils have also become increasingly dry in response to atmospheric warming[133]. The industrial agricultural system consumes ~10 units of energy for each unit of food energy produced[134,135].
6. Many thousands of anthropogenic contaminants including persistent organic pollutants (e.g. organochlorine pesticides, brominated flame retardants) and pharmaceutical compounds have been deliberately or accidentally released into the environment. Following the discovery of its insecticidal properties in 1939 CE, the total usage of DDT during 1950–1993 CE was ~2.6 Mt[136]; 5-y emissions of DDT to the atmosphere from 1970 to 1975 CE were ~750 kt[137]. General use of pesticides in agriculture now reaches ~4 Mt/y[138]. Compounds such as DDT are highly persistent in the environment despite a 1970s ban in many countries and have left a clear signal in the sedimentary record[8]. Pesticides are widely released as legacy pollutants from melting glaciers[139]. Compounds such as PCBs find their way via the atmosphere to Arctic lands where they contaminate the wildlife (e.g. seals) used as food by indigenous peoples. Atmospheric emissions of the refrigerant chlorofluorocarbon CFC-12 (dichlorodifluoromethane, CF_2Cl_2) was zero in 1930 CE, rising to >460 kt in 1987 CE[140]. CFC releases have caused the Antarctic Ozone Hole, and their use is now banned under the Montreal Protocol. The combustion of coal, and historical gold and silver mining, has increased atmospheric mercury concentrations by ~450% over pre-industrial levels[141]. Global anthropogenic emissions of black carbon during 2000–2010 CE were ~6.6 to 7.2 Mt/y[142], compared with 0.6 Mt/y in 1875 CE[143]; the result has been a major increase in carbonaceous fly-ash in natural archives across the world since the 1950s[144].
7. Coastal engineering has globally added thousands of km of groins, jetties, seawalls, breakwaters and harbors to control the movement of coastal sediment, leading either to coastal erosion or to siltation[58,145]. Lacking the delivery of silt from the interior, along with the rise of coastal aquaculture and coastal megacities (Table 2), river deltas are subsiding at rates of tens to hundreds of mm/y[146–148]. Many coastlines now retreat at highly variable rates of tens to hundreds of m/y[145], except where substantial seawalls are emplaced, as in the Netherlands. The global extent of wetlands today is ~10 Mkm^2 [149]. Best estimates suggest that 54–57% of the total area of natural wetlands has already been lost, with the rate of loss accelerating during the 20th and 21st centuries[150]. In many tropical areas, natural and protective mangrove swamps have been replaced with shrimp and fish farms, further exposing coastlines to erosion[145]. Consequences of this wetland loss include the oxidation of extensive reserves of organic matter into CO_2, reduced water retention and storage, more groundwater infiltration by saltwater, and loss of wildlife habitat and biodiversity.
8. Plastic production has increased from ~2 Mt/y in the 1950s, to 359 Mt/y in 2018 CE[151–153], including 526 B/y of plastic beverage bottles and 3000 B/y of plastic cigarette filters[154] (Fig. 3c, Table 2). Plastic debris now enters into the ocean at rates between 4.8 and 12.7 Mt/y[155], and microplastics are increasingly being transported by aeolian vectors, permitting true global distribution, even to Arctic snowfields[156], forming a near-ubiquitous and unambiguous marker of Anthropocene strata[8].
9. Human-mediated mineral species and synthetic mineral-like compounds now exceed 180,000 in number, with most species created since 1950 CE[8,157] (Table 2). Earth's geological processes over the last 4.5 By have only supported the formation of 5,300 naturally occurring mineral species, including those mediated by biological processes[157,158].
10. Concrete production in modern times began in 1824 CE, with the patenting of the Portland Cement recipe. Production remained minor until 1950 CE when 0.13 Gt/y of cement produced ~1 Gt/y of concrete. Today, global cement and concrete production are 4 Gt/y and 27 Gt/y, respectively (Fig. 3d, Table 2), incorporating novel geochemical and mineralogical compositions, such as organic polymer fibers, silica fume, fly ash, nanotubes and nanospherules of silica, iron, graphene and titanium oxide[159]. Cement production requires the heating of $CaCO_3$ to release CO_2, leaving lime in the form of calcium oxide (CaO) or hydroxide.
11. As the planet heats up, water vapor evaporated from the oceans, lakes, reservoirs and soils has become the dominant greenhouse gas accounting for ~50% of the greenhouse effect, followed by clouds (~25%), CO_2 (~20%), then CH_4 and N_2O[88]. Atmospheric carbon dioxide is, however, the main driver of planetary warming. In 1750 CE, humans produced 0.009 Gt/y of atmospheric CO_2, increasing to 0.2 Gt/y by 1850 CE, 5.3 Gt/y by 1950 CE, then accelerating to 36.1 Gt/y by 2017 CE[160] (Fig. 3b, Table 2). Emission sources include combustion of coal, oil, and gas, and cement production. Similarly, atmospheric methane globally increased from 719 ppb in 1750 CE, to 1162 ppb in 1950 CE, and 1850 ppb in 2017 CE[160]; atmospheric nitrous oxide concentration shows a similarly increasing trend[160] (Table 2).
12. In 1950 CE, 1% of the high seas (non-territorial open ocean) were fished, with 0% of fishery species considered exploited, overexploited or collapsed, as defined by the UN's Food and Agriculture Organization. By 2006 CE, 63% of the high seas were fished and 87% of fish species were considered exploited, overexploited, or had collapsed[161], with overall marine fish declines of 38%. Certain baleen whale populations have declined by 80–90%[162].
13. Humans, together with their livestock including domesticated poultry, have a cumulative biomass of ~0.165 Gt C[163], 4-fold greater than the wild mammal and bird biomass (~0.04 Gt C) ~100 ky ago[164]. Fully 96% of today's mammalian biomass is represented by humans and their domesticated animals; the biomass of poultry birds amounts to 70% of all living birds[163]. Wild bird and mammal totals today have a much-reduced biomass ~0.009 Gt C[163]. For comparison, the total biomass of modern human-cultivated crops is ≈10 Gt C[163]. It is estimated that Earth's current total vegetation biomass is half of potential biomass stocks prior to human perturbation, mainly through forest loss[163,165].

14. Anthropogenic emissions of sulfur-containing gases exceed natural fluxes by 2 to 3 times[166]. Presently there is a peak in atmosphere emissions of SO_2 (~100 Mt/y), although emissions are expected to decline[167]. Emissions of SO_2 from nickel smelting in Sudbury, Ontario, reached their zenith in the 1960s (2.5 Mt/y), but technological innovations have since lowered these by ~95%[168]. Phosphorus mobilization by human activities currently exceeds the natural global cycle by a factor of 3[169]. Like N, P is commonly growth-limiting for biota with profound ecological consequences[170,171], with both nutrients contributing to surface water eutrophication.
15. The annual rate of species invasions has greatly increased since the late-20th century[172]. Species inventories of ecosystems record rapid or substantial changes in many seas[173], rivers[174], estuaries[175] and terrestrial settings[176,177], often leaving a biostratigraphical signature of change[46,178]. Many invasive species signal highly human-disturbed ecosystems[179].
16. The most widespread and globally synchronous human signal is the fallout from nuclear weapons testing commencing in 1945[180]. Liberation of radioactivity to the atmosphere via thermonuclear explosions from more than 500 tests between 1952 and 1980 CE, have left a clear signature of anthropogenic radionuclides on or near the surface of the entire planet[180]. Approximately 300 kg of ^{137}Cs and 120 kg of ^{90}Sr were released in those atmospheric explosions[181], along with 2900 kg of ^{239}Pu, corresponding to about 6.5 PBq of radioactivity[182]. ^{239}Pu occurs naturally in the Earth's crust but its pre-1950 CE concentration is extremely low, ~0.05 mBq/kg in typical soils[183]. Due to its long persistence (half-life 24,110 y), this naturally rare radionuclide will be detectable for ~100 ky into the future[184].

Human population has exceeded historical natural limits, with 1) the development of new energy sources, 2) technological developments in aid of productivity, education and health, and 3) an unchallenged position on top of food webs. Humans remain Earth's only species to employ technology so as to change the sources, uses, and distribution of energy forms, including the release of geologically trapped energy (i.e. coal, petroleum, uranium). In total, humans have altered nature at the planetary scale, given modern levels of human-contributed aerosols and gases[88,160], the global distribution of radionuclides, organic pollutants and mercury[123,139,141,144], and ecosystem disturbances of terrestrial[185,186] and marine environments[187]. Approximately 17,000 monitored populations of 4005 vertebrate species have suffered a 60% decline between 1970 and 2014 CE[188], and ~1 million species face extinction, many within decades[189]. Humans' extensive 'technosphere', now reaches ~30 Tt, including waste products from non-renewable resources[190].

Such vast alterations to Earth's natural atmospheric, hydrologic, pedologic, biologic, biogeochemical and sedimentary systems not only have changed the Earth System considerably[191–193] but have also created innumerable globally detectable and preservable signals. These changes are now being used to justify a new geochronologic epoch, the Anthropocene[1,194].

A thought experiment in measuring human impact

Humans, like all living organisms, inject a biological force into their environment. Individualized, this human force should collectively scale up with a growing population. With that logic and other things held constant, one billion humans would offer 1000 times the environment force of one million people. Early humans with their limited numbers (Fig. 1a), had a recognizable but minimal impact on the planet's terrestrial and marine environments through most of the Holocene (Table 1). Population grew slowly (Table 1, Supplementary-Table 1), and energy use remained low (Figs. 1b, 2b) even with the advances of tool-based hunting, use of fire, employment of animals in agriculture or travel, and the development of settlements. Earth's surface environment also has some ability to repair itself, such that 1000 humans across 1000 y would likely have a smaller lasting environmental impact than one million humans in just one year. The time-averaged human population in the Holocene is 97 M, compared with the Anthropocene's population of 4940 M (Supplementary-Table 1). Using a constant per capita energy consumption of say 1 GJ/y, human-derived energy use during the Holocene (to 1950 CE) would be 1.13 ZJ (97.2 M × 11,630 y × 1 GJ/y), and just 0.35 ZJ in the Anthropocene, a longer Holocene duration being more important than a larger Anthropocene population. However, per capita energy consumption increased by an order-of-magnitude across 11,700 years (Table 1, Fig. 1b). As a consequence, humans have already consumed more energy in the short space of the Anthropocene than in the entire Holocene (21.7 ZJ versus 14.6 ZJ).

Humans became a geological force over the last 300 y, particularly after the start of the global industrial revolution in 1850 CE when excess energy (fossil fuel) became widely available. There are strong relationships amongst three parameters: global population, global energy use, and global productivity (Table 2, Figs. 2 and 4). Increases in human productivity support larger populations that consume higher levels of energy and materials that in turn support increases in productivity. The harnessing of fossil fuels has allowed humans to apply this excess in available energy beyond simple food production and survival. As a result, the growth rate in human population increased rapidly, peaking during the mid-20th century (Fig. 2a), as did the associated rates of energy consumption and productivity (Figs. 1 and 2d, Tables 1 and 2). The result has been the mid-20th century 'Great Acceleration' when humanity began to dominate many of the planetary cycles as outlined above. Like the intertwining of global human population, energy consumption and productivity, major environmental tracers also appear tightly coupled to each other and to these three human forces (Table 2, Figs. 3 and 4). It should be of no surprise then that the global reservoir capacity of large dams, or atmospheric CO_2, each track closely with global energy use (Fig. 3a, b, Table 2), or that global plastic or cement production closely follows economic productivity (Fig. 3c, d, Table 2), or that the global production of ammonia (NH_3) and copper correlate highly with global human population (Fig. 3e, f, Table 2), as with many other human environmental signals outlined in Table 2: shrimp farming, production of gypsum, salt, iron, steel, sulfur, helium, aluminum, mineral species, atmospheric gases (CO_2, N_2O, CH_4), terrestrial freshwater budgets, surface temperatures, and sea levels. These major environmental parameters have been strongly altered by the mid-20th century (and beyond, Table 2).

The environmental parameters discussed above should be understood as the societal forcings that lead to stratigraphic markers that will characterize the Anthropocene, such as horizons identified by extinctions or invasive species, radioisotopes, elevated natural and novel chemical compounds, etc. In and of themselves, the societal metrics that we have identified here may not define the Anthropocene, but they can lead to the markers that do and, if present trends continue, will.

Proposed Anthropocene versus Holocene epochs

The Holocene Epoch, the most recent of the Quaternary interglacials, was a time of warm, relatively stable (±0.5 °C)

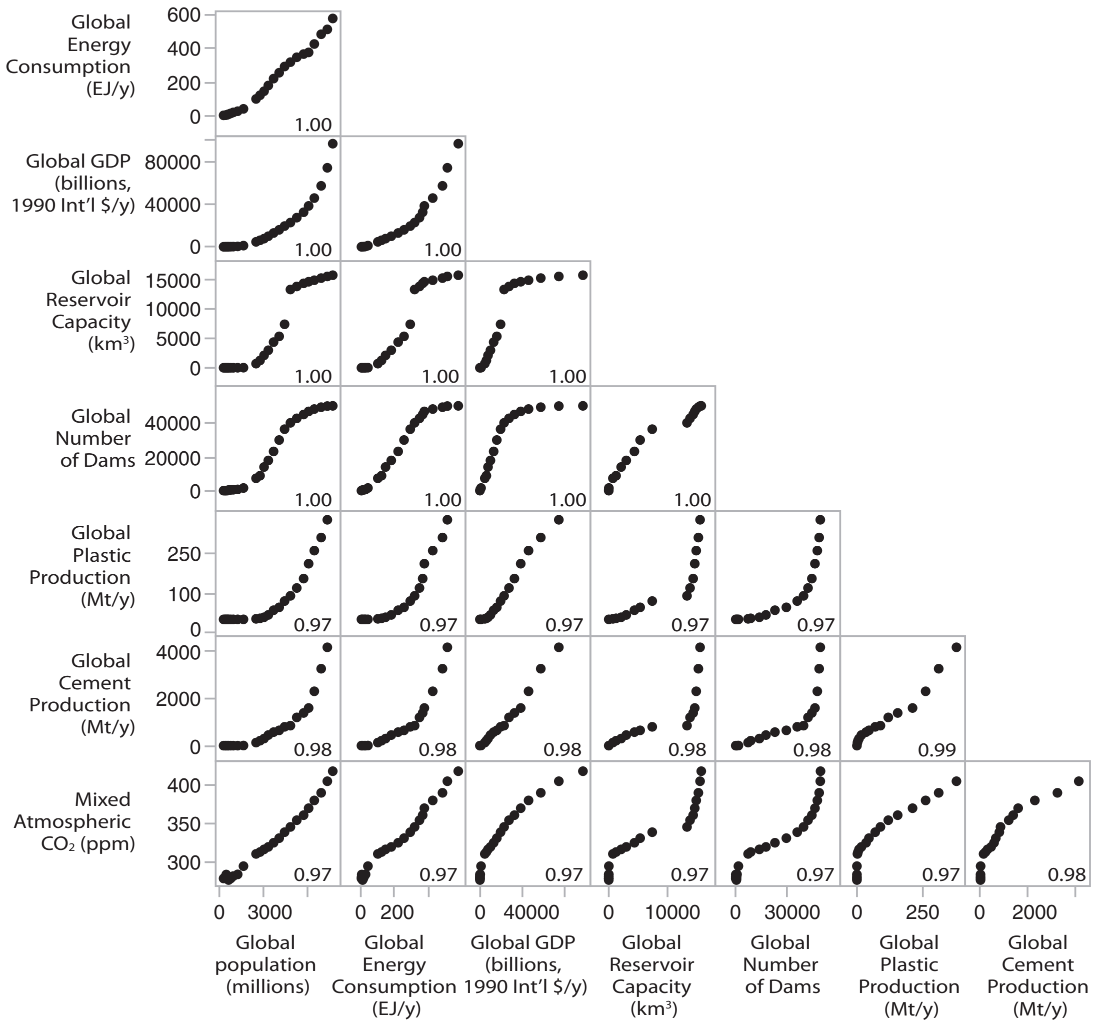

Fig. 4 Statistical relationships between human population, productivity, and energy, and key environmental indicators. Correlation-matrix displayed as cross plots for examples of Late Holocene and Anthropocene environmental factors, including ensemble estimates of global human population (millions), global human energy consumption (EJ/y), global GDP (billions, 1990 Int'l $/y), global reservoir capacity (km^3; year-end), global number of large dams (year-end), global plastic production (year-end), global cement production (year-end), mixed atmospheric CO_2 (mid-year). The value in the lower right corner of each plot identifies the Spearman's rank-order correlation coefficients. Data references are listed within Supplementary Online Material.

climate that fluctuated in response to variations in Earth's natural systems (e.g., Milankovitch): ice sheet volume decreased, and sea levels rose at an Epoch-averaged rate of 5.54 mm/y, larger than for the proposed Anthropocene Epoch (although if warming continues modern rates will quickly rise). The proposed Anthropocene Epoch sees many other key Earth-surface parameters change in response to human action (Table 2). Parameters with 200% to 300% variances or larger, compared to the Holocene Epoch, include atmospheric and ocean temperatures, atmospheric CO_2, CH_4, and N_2O levels, global reactive nitrogen, environmental mercury and many other metals, phosphorus release[194,195], sediment transport, terrestrial soil loss, and terrestrial and marine biomass losses. Parameters with order-of-magnitude increases, compared to the Holocene Epoch, include anthropogenic CO_2 emission rates, human-produced energy, upstream sequestration of sediment, number of "mineral" species, concrete production, rates of species extinction[32], declines in river runoff, and increased coastal hypoxia. There are also phenomenological changes without precedent in the Holocene, including a warmer and more acidic global ocean, global dispersal of new materials (plastics, ceramics, aluminum metal, radioisotopes, persistent organic pollutants, pharmaceutical compounds, fly-ash particles), and modern alterations to the biodiversity of marine and terrestrial ecosystems, with a globally distributed invasive species component[172] and a greatly raised rate of species extinction[33]. Even Earth's crustal process, such as earthquakes, can now have an anthropogenic imprint[196].

The Anthropocene Working Group (AWG) has voted to affirm a) the Anthropocene be treated as a formal chronostratigraphic unit defined by a GSSP, and b) the primary guide for the base of the Anthropocene be one of the stratigraphic signals around the mid-twentieth century of the Common Era[1,7,68]. Geological records characterizing the base of the Anthropocene are being assembled, and in due course the Group's recommendations will require approval by the International Commission on Stratigraphy. The narrative and quantitative data presented here strongly underpin the trajectory of the Earth System away from a Holocene state of the system, substantially and globally, around the mid-20th century, circa 1950 CE[192]. Establishing the proposed new epoch would formalize the use of the term Anthropocene, which already has been used widely in research describing changes induced by human actions and recorded in geological archives.

Data availability

The datasets analyzed during the current study are provided as tables within the main paper or within the accompanying online material file, along with the original data references to peer-reviewed sources including persistent government web links.

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Author contributions

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Competing interests

The authors declare no competing interest.

Additional information

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