Supplementary Online Material

Supplementary Tables

Supplementary Table 1 *Ensemble estimates of human population, global population change, global energy consumption (**E** in GJ/y/capita), global human energy consumption (EJ/y), global productivity (**P** in GDP normalized to 1990 international dollars, $/capita/y), **P:E** ratio ($/GJ/y). Data references are listed within Supplementary Online Material.*

Years before 2020 CE	Ensemble population estimate (millions)	Global population change (%/y)	**E** = Energy Consumption (GJ/y/capita)	Global Human Energy Consumption (EJ/y)	**P** = Ensemble GDP (in 1990 Int'l $/capita/y)	**P/E** ($/GJ/y)
11,720	4		5.8	0.02	93	16
10,020	5	0.01	6.2	0.03	96	15
8220	8	0.03	6.5	0.05	99	15
7020	11	0.03	6.8	0.07	103	15
6020	7	-0.04	7.1	0.05	109	15
5020	14	0.10	7.5	0.11	113	15
4220	27	0.12	7.8	0.2	112	14
3020	50	0.07	7.9	0.4	127	16
2520	100	0.20	8.0	0.8	137	17
2020	268	0.34	8.1	2.2	109	13
1020	289	0.01	8.2	2.4	133	16
720	397	0.12	8.3	3.3	89	11
520	471	0.09	8.7	4.1	138	16
420	561	0.19	11.5	6.5	141	12
320	629	0.12	14.8	9.3	164	11
270	772	0.45	18	14	178	10
220	951	0.46	21	20	195	9
170	1247	0.62	22	27	300	14
120	1643	0.64	25	41	679	27
70	2499	0.87	40	100	1863	47
65	2769	2.16	44	122	2213	50
60	3042	1.97	48	146	2517	52
55	3333	1.91	54	180	2977	55
50	3691	2.15	60	221	3504	58
45	4071	2.06	63	256	3900	62
40	4440	1.81	66	293	4371	66
35	4838	1.79	66	319	4691	71
30	5269	1.78	66	348	5177	78
25	5735	1.77	64	367	5642	88
20	6076	1.19	62	377	6298	102
15	6463	1.27	66	427	7052	107
10	6930	1.45	70	485	8229	118
5	7349	1.21	70	514	10,056	144
0	7717	1.00	75	579	12,500	167

Supplementary Table 2 *Data supporting correlation matrix (Fig 4) of Late Holocene and Anthropocene global human population (millions) based on ensemble estimates, global human energy consumption (EJ/y), global GDP (in billions of 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), and ammonia (NH_3) production (Mt/y) (year-end). Data references are listed within Supplementary Online Material reference section.*

Calendar Years (CE)	Population (millions)	Global Energy Consumption (EJ/y)	Global GDP (Billions 1990 Int'l $/y)	Global Reservoir Capacity (km^3)	Number of Dams	Plastic Production (Mt/y)	Cement Production (Mt/y)	Atmospheric CO_2 (ppm)	NH_3 production (Mt/y)	Copper Production (Mt/y)
1000	289	2.4	38	0.04	12	0	0	280	0	?
1300	397	3.3	35	0.04	14	0	0	282	0	?
1500	471	4.1	65	0.06	25	0	0	285	0	?
1600	561	6.5	79	0.29	54	0	0	280	0	?
1700	629	9.3	103	0.48	396	0	0	278	0	?
1750	772	14	137	1.1	453	0	0	280	0	0.03
1800	951	20	185	1.1	542	0	0	283	0	0.09
1850	1247	27	374	5.9	755	0	0	285.2	0	0.50
1900	1643	41	1116	19	1587	0	5	295.7	0	0.50
1950	2499	100	4656	705	7361	2	130	311.3	2	2.38
1955	2769	122	6128	1246	8895	4	217	313.7	10	2.90
1960	3042	146	7657	2111	14,075	8	300	317.1	15	3.94
1965	3333	180	9922	2980	17,978	17	413	320.2	25	4.66
1970	3691	221	12,933	4365	23,337	35	575	325.5	40	5.90
1975	4071	256	15,877	5340	30,126	46	650	331.4	68	6.74
1980	4440	293	19,407	7398	36,586	70	800	339.0	88	7.20
1985	4838	319	22,695	13,312	40,368	90	850	345.7	110	7.99
1990	5269	348	27,278	13,828	43,022	120	1200	354.3	115	9.20
1995	5735	367	32,357	14,360	45,322	156	1390	360.7	125	10.00
2000	6076	377	38,267	14,631	47,157	213	1600	369.6	126	13.20
2005	6463	427	45,577	14,886	48,569	263	2310	379.5	150	15.00
2010	6930	485	57,027	15,251	49,672	313	3270	389.2	168	16.10
2015	7349	514	73,902	15,534	50,346	381	4180	404.0	175	19.10
2020	7717	579	96,463	15,741	50,472	?	?	416.8	?	?

Supplementary Notes, Discussion, Methods

Methods

Interval average values, as depicted in Table 1, are calculated using the weighted average method: linear interpolation is used to calculate midpoint values for each time interval (row values in Supplementary Table 1); those values are multiplied by the time interval duration for that row, then summed for all rows pertaining to a particular geological age, interval or epoch, divided by the total duration of the age, interval or epoch, to arrive at the interval average.

Global population change (G_r, %/y), as depicted in Supplementary Table 1, is simply the increase in population in relation to the starting value P_1 compared to the end value P_2, divided by the time interval (T_1-T_2): $G_r = 100*((P_2-P_1)/P_1)/(T_1-T_2)$. Because time intervals in the table can be large (e.g. 1700 y between the first two value estimates), the associated G_r value (0.01%/y in that case) is a highly simplified approximation of much more variable population variability patterns (births-deaths). If the annual population growth rate is G_{rd} then the average of G_{rd} across 1700 years is not likely to be same as G_r. Therefore, G_r offers but crude approximations before the 19th century.

Historical Population Data

Historical human population data until 1950 CE (Table 1, SOM-Tables 1,2) are estimates and based on the ensemble average of eight datasets provided by the United States Census Bureau[1-8] and Maddison[9]. The ensemble average includes high and low population estimates, where available. The Earth's human population from 1950 to 2020 CE is from the UN's Department of Economic and Social Affairs, Population Division[10].

Historical Energy Consumption Data

Historical human energy consumption data (Table 1, SOM-Tables 1,2) are from the merging of two overlapping datasets: 1) values on the flow of energy into an industrial society between 11.7 ky and 0.15 ky[11]; and 2) modern energy production estimates for values between 1800 to 2017 CE[12], with updates from the UN's Department of Economic and Social Affairs[13]. The Cook estimates[A11] are updated using the constraints from Malanima[14] whose per capita energy consumption estimates are: 1) 3 GJ/y from food sources alone, 2) 7 GJ/y with the addition of fire, 3) 8 GJ/y with the addition of structured agriculture, and 4) 56.5 GJ/y with the addition of petroleum. Note that for the pre-industrial Holocene, values largely reflect energy from muscle power (human or via domesticated animals), whereas values for industrial societies tend to exclude this factor in favor of energy supplied by biomass and fossil fuel combustion[15].

Historical GDP Consumption Data

Historical inflation-adjusted global productivity values (Table, 1, SOM-Tables 1,2) are from: 1) DeLong[16], 2) the Maddison Project[9], and 3) UN data updates[10]. Values are normalized into 1990 international dollars, as defined by the World Bank.

Reservoir Capacity of Large Dams Data and Number of Large Dams Data

A large dam is defined by the dam industry as having a containing height of over 15 m. ICOLD is the International Commission on Large Dams and their data (SOM-Table 2) was procured in 2017 with later updates[17]. The database contains more than 50,000 individual dams that offer information on both completion dates and reservoir capacity and another nearly 8500 dams without the completion date, along with many other dam-related parameters.

Plastic Production Data

Annual global polymer resin and fiber production (plastic production) is measured in metric tonnes per year (SOM-Table 2), and values from 1950 to 2015 CE are from Our World in Data[18].

Cement Production Data

Early cement production data from 1880 to 1910 CE[19] are combined with United States Geological Survey-determined values capturing the period from 1932 CE to present[20] (SOM-Table 2).

Historical Atmospheric CO_2 Data

Atmospheric CO_2 data (SOM-Table 2) are based on 6 datasets: 1) data capturing the period 1000 to 1850 CE are from CO_2-trapped atmospheric gas measured from ice-cores and distributed by NOAA[21]; 2) data from 1850 to 1957 CE[22]; 3) data from 1958 to 1974 CE are continuous data at Mauna Loa and South Pole[23]; 4) data from 1975 to 1982 CE are NOAA/CMDL in-situ data at Mauna Loa and South Pole[24], 5) data from 1983 to 2003 CE are global means constructed using the 70 CMDL CCGG Sampling Network station data[25]; and 6) data from 2004 to 2020 CE are from global mean growth rates[26].

Ammonia Production Data

Ammonia (NH_3) production data[27] in Mt/y, are for the period 1946 to 2014 CE (SOM-Table 2).

Mineral species Data

Number of mineral species data (Table 2) are from Behrens and Luksch[28] and the Karlsruhe Inorganic Crystal Structure Database – ICSD[29]. Minerals referred to here are inorganic crystalline compounds as synthetic minerals are not minerals, by recent decision of the International Mineralogical Association.

Metal, Mineral and Element Production Data

World commodity production data (aluminum, copper, gypsum, salt, sulfur, and iron plus steel) in Mt/y, and helium (kt/y) are supplied by the United States Geological Survey's National Minerals Information Center[30] (Table 2, SOM-Table 2)

Historical Land-Ocean Temperature Index

The GISS Surface Temperature Analysis (GISTEMP v4) is an estimate of global surface temperature change in degrees centigrade (°C)[31,32] with data distribution by NASA's Goddard Institute for Space Studies (GISS) data portal (Table 2).

Historical Atmospheric N_2O and CH_4 Data

Atmospheric N_2O (ppb) and Atmospheric CH_4 (ppb) are from European Environmental Agency data portal[33] (Table 2).

Sea level Data

A global sea level datum in mm (Table 2) is derived from 3 month estimates of mean global sea level (1870 CE to present) and made available through the U.S.A. NOAA portal[34].

References for Supplementary Online Material

1. USCB (2019). https://www.census.gov/data/tables/time-series/demo/international-programs/historical-est-worldpop.html
2. UN, The Determinants and Consequences of Population Trends. *United Nations Population Studies*, No. 50, p 10 (1973).
3. Durand, J.D. Historical Estimates of World Population: An Evaluation. *U Pennsylvania, PSC Analytical and Technical Report Series*, No. 10 (1974).
4. Thomlinson, R. *Demographic problems, controversy over population control*. Dickenson Pub. Co; 2nd ed., 244 pp. (1975).
5. McEvedy, C., Jones, R. *Atlas of world population history*, Puffin Pub., New York, 342–351, 368 pp. (1978).
6. Biraben, J.N. An essay concerning mankind's demographic evolution. *J Human Evolution* **9**, 655–663 (1980).
7. Haub, C. How Many People Have Ever Lived on Earth? *Population Today* **23**, 4–5 (1995).
8. UN, The World at Six Billion, Table 1, World Population from year 0 to stabilization, p. 5, (United Nations Publ. New York, 1999).
9. Bolt J., Inklaar R., de Jong H. & van Zanden J.L. Maddison Project Database, version 2018. "Rebasing 'Maddison': new income comparisons and the shape of long-run economic development (2018).

https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2018
10. UN, *World Population Prospects. Total population (both sexes combined) by region, subregion and country, annually for 1950-2100*, File POP/DB/WPP/Rev.2019/POP/F01-1 (United Nations Publ., New York 2019).
11. Cook, E. The flow of energy in an industrial society. In: Piel G, et al. (Eds.) *Energy and Power*, (Freeman, San Francisco, 1971).
12. Roser, M. *Energy production and changing energy sources* (2016). https://ourworldindata.org/energy-production-and-changing-energy-sources/
13. UN, Energy Statistics, Department of Economic and Social Affairs (2019). https://unstats.un.org/unsd/energystats/data/
14. Malanima, P. Energy in World History. In: *The Basic Environmental History,* Eds. M. Agnoletti & S.N. Serneri, (Springer, New York, 2014).
15. Haberl, The Energetic Metabolism of Societies Part I: Accounting Concepts. *J. Industrial Ecology* **5(1)**, 11-33 (2001).
16. DeLong, B. *Estimates of World GDP, One Million B.C. – Present* 12 pp. (1998). http://delong.typepad.com/print/20061012_LRWGDP.pdf.
17. ICOLD (2019) http://www.icold-cigb.org/GB/world_register/general_synthesis.asp
18. OWID (2020) https://ourworldindata.org/plastic-pollution.
19. Cement production 1880–1910, *Ind. Eng. Chem.* **4(1)**, p. 67 (1912) [unstated author] https://pubs.acs.org/doi/pdf/10.1021/ie50037a027
20. USGS (2020) https://www.usgs.gov/centers/nmic/cement-statistics-and-information
21. NOAA (2020) https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/ice-core
22. Etheridge, D.M. et al. Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn. *J. Geophys. Res.* **101**, 4115–4128 (1996).
23. NOAA (2020) https://www.esrl.noaa.gov/gmd/obop/mlo/programs/coop/scripps/co2/co2.html
24. Tans, P. & K.W. Thoning (2020) ftp://ftp.cmdl.noaa.gov/ccg/co2/in-situ)
25. Tans, P. & T.J. Conway (2020) ftp://ftp.cmdl.noaa.gov/ccg/co2/flask
26. Conway, T.J. (2020) ftp://ftp.cmdl.noaa.gov/ccg/co2/trends)
27. Pattabathula, V. & Richardson, J. Introduction to Ammonia Production. *American Institute of Chemical Engineers* September 69–75 (2016).
28. Behrens, H. & Luksch, P. A bibliometric study in crystallography, *Acta Cryst.* **B62**, 993–1001 (2006) doi:10.1107/S0108768106030278 (Fig. 3)
29. Karlsruhe Inorganic Crystal Structure Database – ICSD https://www.fiz-karlsruhe.de/en/produkte-und-dienstleistungen/inorganic-crystal-structure-database-icsd
30. USGS-NMIC (2020) https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states
31. GISTEMP Team, GISS Surface Temperature Analysis (GISTEMP), version 4. NASA Goddard Institute for Space Studies. Dataset accessed 2020-06-01 at https://data.giss.nasa.gov/gistemp/ (2020).
32. Lenssen, N.G. et al., Improvements in the GISTEMP uncertainty model. *J. Geophys. Res. Atmos.*, 124(12), 6307-6326, doi:10.1029/2018JD029522 (2019).
33. European Environmental Agency data portal (2020) https://www.eea.europa.eu/data-and-maps/daviz/.
34. NOAA (2020) https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level