HUMAN IMPACTS by the numbers

Griffin Chure[1], Avi Flamholz[2], Nicholas S. Sarai[3], Tine Valencic[1], Yinon Bar-On[4], Ron Milo[4], Rob Phillips[2,5,*]

California Institute of Technology, Pasadena, CA, USA, 91125:
[1]Department of Applied Physics; [2]Division of Biology and Biological Engineering; [3]Division of Chemsitry and Chemical Enigineering; [5] Department of Physics
[4]Weizmann Institute of Science, Rehovot 7610001, Israel:
Department of Plant and Environmental Sciences

ABSTRACT

The greatest experiment of the last 10,000 years is the presence and action of modern human beings on planet Earth. At this point, the consequences of this experiment are being felt on many fronts. Yet, many people still hold the view that because the world is so "huge", humans cannot really make a substantial impact. One way to organize our thinking about what these impacts might be, with tongue in cheek, is to focus on Empedocles's classic elements, earth, air, water and fire, with the idea being to explore how humans have altered the land and its inhabitants, the atmosphere, the oceans and how our quest for cheaper and cheaper energy (fire) from the world around us has altered that world. This snapshot represents a small collection of numbers that summarize the broad reach of human action across the planet, presenting a view of the impact of human presence on Earth.

UNITS OF REFERENCE

human population = $\approx 7\times10^9$
mass of an elephant = ≈ 5 t
area of soccer pitch = ≈ 3000v m^2
power of a lightbulb = ≈ 100 W
volume of olympic pool = ≈ 2000 m^3

A MELT WATER

glacial melt volume $\approx 3\times10^{11}$ m^3/yr $\approx$ 150 million×/yr
ice-sheet melt volume $\approx 5\times10^{11}$ m^3/yr $\approx$ 250 million×/yr
total melt volume $\approx 10^{12}$ m^3/yr $\approx$ 5000 million×/yr

B RENEWABLE POWER GENERATION

wind $\approx$ 150 GW $\approx$ 1.5 billion×
solar $\approx$ 75 GW $\approx$ 750 million×
biofuels $\approx$ 150 GW $\approx$ 1.5 billion×
total $\approx$ 500 GW $\approx$ 5 billion×

C NITROGEN FIXATION

N_2 fixed via Haber-Bosch process $\approx 10^6$ t $\approx$ 200,000×

D RIVER FRAGMENTATION

global volume of dammed rivers $\approx 10^{12}$ m^3 $\approx$ 500 million ×
hydroelectric power production $\approx$ 500 GW $\approx$ 5 billion ×

E POPULATION OF LIVESTOCK

chicken population $\approx 2\times10^{10} \approx 3\times$
cattle population $\approx 2\times10^9 \approx 0.3\times$
pig population $\approx 1\times10^9 \approx 0.1\times$
total livestock population $\approx$ 30 billion $\approx 4\times$

F EXTENT OF TERRESTRIAL LAND USAGE

agriculture $\approx 5\times10^{13}$ m^2 $\approx$ 15 billion×
urban $\approx 4\times10^{12}$ m^2 $\approx$ 1 billion ×
total area $\approx$ 16 billion×

G OCEAN pH

% increase in H^+ concentration $\approx$ 0.5% / yr

H DEFORESTATION AND FOREST DISRUPTION

commodity driven /yr
agricultural /yr
urbanization /yr
fire /yr

I MATERIAL OF HUMAN ORIGIN

concrete production $\approx 3\times10^9$ t/yr $\approx$ 6 billion× /yr
steel production $\approx 2\times10^9$ t/yr $\approx$ 400 million× /yr
plastic production $\approx 4\times10^6$ t/yr $\approx$ 80 million× /yr
total anthropomass $\approx$?? t / yr

J HUMAN WATER USE

agriculture $\approx 1.5\times10^{12}$ m^3/yr $\approx$ 750 million× /yr
power generation $\approx 3\times10^{11}$ m^3/yr $\approx$ 150 million× /yr
domestic $\approx 6\times10^{10}$ m^3/yr $\approx$ 30 million× /yr
total water use $\approx 2\times10^{12}$ m^3 /yr $\approx$ 1 billion× /yr

K GLOBAL POWER CONSUMPTION

global power usage $\approx$ 20 TW $\approx$ 200 billion ×

L OCEAN WARMING

power deposited into world oceans $\approx$150 TW$\approx$1.5 trillion×
change in temperature $\approx$ 0.01 ° C / yr

M GREENHOUSE GAS PRODUCTION

CO_2 release $\approx$
CH_4 release $\approx$

N OIL & NATURAL GAS MINING

drilled volume of oil & natural gas $\approx$
oil & natural gas power production $\approx$

O HUMAN-CAUSED EXTINCTION

vertebrate species > 400
invertebrate species > 400
plant species > 150

P EROSION

soil moved by humans $\approx 4\times10^{10}$ t/yr $\approx$ 8 billion× / yr

Q SEA LEVEL RISE

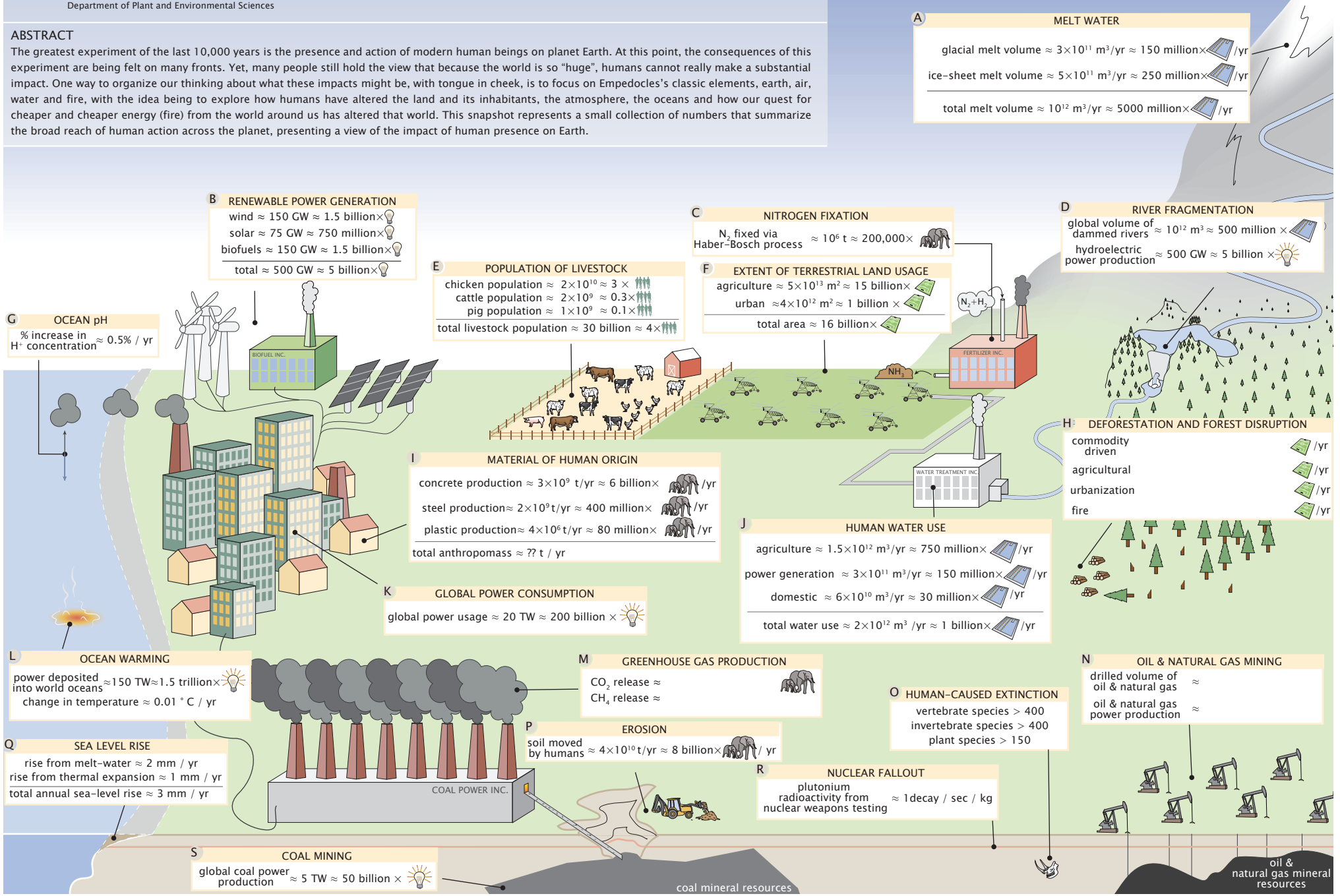
rise from melt-water $\approx$ 2 mm / yr
rise from thermal expansion $\approx$ 1 mm / yr
total annual sea-level rise $\approx$ 3 mm / yr

R NUCLEAR FALLOUT

plutonium radioactivity from nuclear weapons testing $\approx$ 1decay / sec / kg

S COAL MINING

global coal power production $\approx$ 5 TW $\approx$ 50 billion ×



HUMAN IMPACTS by the numbers

Griffin Chure[1], Avi Flamholz[2], Nicholas Sarai[3], Tine Valencic[1], Yinon Bar-On[4], Ron Milo[4], and Rob Phillips[2,5,*]

THE ANTHROPOCENE

A visit to any natural history museum will reveal that much about Earth's history can be learned by examining the geological and fossil record. As humans have made extensive changes to the Earth's chemistry and biology, in addition to the physical changes to the Earth's crust, the record of our existence will similarly be preserved in the geological record. The Anthropomass Number reveals that, as of 2020, the total mass of human-derived material (concrete, plastic, steel, etc.) is now approximately equal to the mass of the entire biosphere. The Terra Number illustrates that humans occupy or directly control ≈30% of the terrestrial surface area, meaning artifacts of human society is widespread across the planet. The Radionuclide Number describes a radioactive signature of nuclear weapons testing in a 20,000 fold enrichment in plutonium isotope radioactivity that will be detectable in stratified soil several hundred thousand years into the future. Finally, the Extinction Number shows that the current extinction rate is at least several hundred times above the background extinction rate for plant and animal species, dictating the future fossil record. While incomplete, these dimensionless numbers represent the magnitude to which human activity will be evident in Earth's geological record beyond the existence of our species as we currently know it.

ANTHROPOMASS NUMBER

$$Am = \frac{\text{total anthropomass}}{\text{total biomass}} \approx \frac{}{\text{550 Gt C}} \approx 1$$

TERRA NUMBER

$$Te = \frac{\text{land area used by humans}}{\text{land area of Earth}} \approx \frac{5\times10^{13}\ \text{m}^2}{1.5\times10^{14}\ \text{m}^2} \approx 0.3$$

RADIONUCLIDE NUMBER

$$Rn = \frac{\text{anthropogenic } {}^{239/240}\text{Pu in soil}}{\text{naturally occuring } {}^{239/240}\text{Pu in soil}} \approx \frac{1000\ \text{mBq / kg}}{0.05\ \text{mBq / kg}} \approx 2\times10^4$$

EXTINCTION NUMBER

$$Ex = \frac{\text{human-induced extinction rate}}{\text{background extinction rate}} \approx \frac{\text{dodo}}{\text{trilobite? non-mass ex}} > 200$$

THE MAGNITUDE OF HUMAN WATER USAGE

Humans use more water than any other substance on the planet. Our requirement for water, both for personal use and for industrial purposes, coupled with changes in our atmospheric chemistry have substantially altered the hydrosphere from many angles. The Niagara Number captures the magnitude of human water usage, revealing that on a daily basis, humans use approximately and order of magnitude more water than falls over Niagara falls in a single day. This use is dominated by power-plant usage (for cooling) and agriculture. The flow of water from high to low elevations can be used to generate hydroelectricity via river damming. The Hoover Number reveals that there is an approximately equal volume global river water used by hydroelectric dams as there are free-flowing rivers on Earth, which has strong implications on stability of watersheds and river ecosystems. Anthropogenic emission of CO_2 has lead to widespread warming of the climate, resulting in melting of glaciers and ice-caps. The Ice-Melt Number summarizes the extent as this melting as releasing ≈ 1 Grand Canyon's worth of water into the hydrosphere per year. Approximately 40% of CO_2 emissions are absorbed by Earth's oceans and seas, ultimately shifting the equilibrium of carbonic acid. The Acidic Ocean Number captures the extent of this effect, revealing a ≈30% increase in hydrogen ion concentration in the oceans over the 60 year period of 1960 - present.

NIAGARA NUMBER

$$Ni = \frac{\text{daily human water use}}{\text{Niagara Falls drainage rate}} \approx \frac{10^{10}\ \text{m}^3\text{/day}}{10^9\ \text{m}^3\text{/day}} \approx 10$$

HOOVER NUMBER

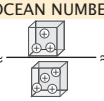
$$Hv = \frac{\text{fragmented river volume}}{\text{free-flowing river volume}} \approx \frac{\text{dam}}{\text{river}} \approx \frac{10^{12}\ \text{m}^3}{10^{12}\ \text{m}^3} \approx 1$$

ICE-MELT NUMBER

$$Ic = \frac{\text{annual melt volume from glaciers \& ice-caps}}{\text{volume of Grand Canyon}} \approx \frac{}{10^{12}\ \text{m}^3} \approx \frac{10^{12}\ \text{m}^3\text{/yr}}{10^{12}\ \text{m}^3} \approx 1\ \text{/yr}$$

ACIDIC OCEAN NUMBER

$$Ac = \frac{\text{ocean } [H^+] \text{ in 1960}}{\text{ocean } [H^+] \text{ today}} \approx \frac{1\text{M}\times10^{-8.2}}{1\text{M}\times10^{-8.1}} \approx 0.7$$



HUMANS AS THE EARTH'S GREATEST EVOLUTIONARY FORCE

Biology's greatest idea is evolution, the fact that over time, the living world has always and will continue to always change. Species come and species go. Natural forces, such as the closing of the Isthmus of Panama, result in profound changes to the living world. As humans have increased in population and technological prowess, so too has their impact on the evolutionary process. The Barnyard Number captures the magnitude of animal husbandry by humans by measuring the relative population sizes of the entirety of our domesticated animals relative to the size of the human population itself. Natural habitats across the globe have been altered significantly by human action. The Deforestation Number compares the loss of forest resulting from human activity to that which occurs naturally.

BARNYARD NUMBER

$$By = \frac{\text{livestock population}}{\text{human population}} \approx \frac{30\times10^9}{7\times10^9} \approx 4$$

DEFORESTATION NUMBER

$$Df = \frac{\text{human-caused forest area loss}}{\text{natural forest area loss}} \approx \frac{10^7\ \text{ha/year}}{3\times10^6\ \text{ha/year}} \approx 3$$

NUMBER RELEVANT TO ECOLOGY

NUBER RELEVANT TO MARINE LIFE

HUMAN IMPACTS ON ATMOSPHERIC AND BIOGEOCHEMICAL CYCLES

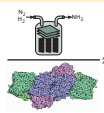
The Keeling curve has the same iconic status as the DNA double helix. Beginning in the 1950s, we have had a largely uninterrupted quantitative glimpse into the atmospheric concentration of CO_2. To get an impression of the human-induced increase in atmospheric CO_2, the Keeling Number compares the total anthropogenic CO_2 released in comparison with the CO_2 released from the eruption of Mt. St. Helens, revealing humans have released 200,000 times the amount of CO_2 as this infamous eruption. Perhaps even more dramatic than our impact on the CO_2 budget of the atmosphere is our role in nitrogen fixation. The Haber-Bosch Number measures the ratio of atmospheric nitrogen fixed through the Haber-Bosch process to that occurring naturally in the rhizosphere due to microbes. The Volta Number characterizes a less well-known example, namely, the volume of anthropogenic methane in comparison with the methane of XXXX. The Erosion number compares the volume of soil moved by humans to that moved by rivers.

KEELING NUMBER

$$Ke = \frac{\text{anthropogenic } CO_2 \text{ since 1880}}{CO_2 \text{ released from Mt. St. Helens}} \approx \frac{2\times10^{15}\ \text{kg } CO_2}{10^{10}\ \text{kg } CO_2} \approx 2\times10^5$$

HABER-BOSCH NUMBER

$$Ha = \frac{N_2 \text{ fixation through Haber-Bosch process}}{N_2 \text{ fixation through biological processes}} \approx \frac{200\ \text{Tg N}}{200\ \text{Tg N}} \approx 1$$



VOLTA NUMBER

$$V = \frac{\text{volume of anthropogenic } CH_4}{\text{volume of biological } CH_4} \approx \frac{???}{} \approx \frac{}{} \approx$$

EROSION NUMBER

$$Er = \frac{\text{soil moved by humans}}{\text{soil moved by rivers}} \approx \frac{\text{muddy river}}{} \approx \frac{40\ \text{Gt / yr}}{5\ \text{Gt / yr}} \approx 8$$

THE MAGNITUDE OF HUMAN ENERGY USAGE

Finding new ways to extract useful work from the world is one of the signature achievements of the human condition. And yet, this act of learning how to extract energy from the environment is a large part of the story of human impacts, whether in the burning of various fuels that change the atmosphere, or the damming of the world's rivers to produce electricity. The Solar Number is one of the most important human impacts numbers of all and compares the 20 TW per year energy use of humans to the 10,000 fold higher incident power from the sun. The Fossil Fuel Number

SOLAR NUMBER

$$Su = \frac{\text{annual human energy usage}}{\text{annual incident solar energy}} \approx \frac{20\ \text{TW}}{2\times10^5\ \text{TW}} \approx 0.0001$$

FOSSIL FUEL NUMBER

$$Fo = \frac{\text{volume of fossil fules mined annually}}{\text{volume of fossil fuels in proven resources}} \approx \frac{}{} \approx \frac{20\ \text{TW}}{2\times10^5\ \text{TW}} \approx 0.0001$$

NUMBER RELEVANT TO OTHER MINING

NUMBER RELEVANT TO RENEWABLE USE

HUMAN IMPACTS by the numbers

Griffin Chure[1], Avi Flamholz[2], Nicholas Sarai[3], Tine Valencic[1], Yinon Bar-On[4], Ron Milo[4,] and Rob Phillips[2,5,*]

SUPPORTING INFORMATION

A MELTWATER

glacial melt rate	HuID: 32459
ice-sheet melt rate	HuID: 000000
total melt rate	HuID: 000000

Data Source(s):
Notes:

B RENEWABLE POWER GENERATION

wind	HuID: 30581
solar	HuID: 99885
biofuels	HuID: 89570
total	HuID: 20246

Data Source(s): bp Statistical Review of World Energy, 2020.
Notes: Reported values correspond to estimates for the 2019 calendar year. Renewable resources are defined as wind, geothermal, solar, biomass and waste, and does not include hydroelectic power generation.

C NITROGEN FIXATION

N_2 flux through Haber-Bosch	HuID: 000000

Data Source(s):
Notes:

D RIVER FRAGMENTATION

dammed river volume	HuID: 000000

Data Source(s): Lorem ipsum dolor sit amet, consectetuer adipiscing elit, sed diam nonummy nibh euismod tincidunt ut laoreet dolore magna aliquam erat volutpat. Ut wisi enim ad minim veniam, quis nostrud exerci tation ullamcorper suscipit lobortis nisl ut

hydroelectric power	HuID: 27945

Data Source(s): bp Statistical Review of World Energy, 2020.
Notes: Value corresponds to the reported value of global hydroelectricity production for 2019.

E LIVESTOCK POPULATION

chicken	HuID: 94934
cattle	HuID: 92006
swine	HuID: 21368
total	HuID: 15765

Data Source(s): Food and Agriculture Organization of the United Nations Statistical Database (FAOSTAT).
Notes: Counts correspond to the approximate average of the standing populations reported between 2010 - 2018. Values are reported directly by countries, yet the FAO uses non-governmental statistical sources to address uncertainty and missing (non-reported) data.

F EXTENT OF TERRESTRIAL LAND USAGE

agriculture	HuID: 29582

Data Source(s): Food and Agriculture Organization of the United Nations Statistical Database (FAOSTAT)
Notes: "Agriculture" land is defined as all land that is under agricultural management including pastures, meadows, permant crops, temporary crops, land under fallow, and land under agricultural structures. Reported value corresponds to 2017 measurements by the FAO.

urban	HuID: 00000

Data Source(s): World Bank and Center for International Earth Science Information Network (CIESIN)/Columbia University. 2013
Notes: Urban land area is determined from satellite imagery. An area is determined to be "urban" if the total population is greater than 5,000. Rural land is defined as Urban and value correspons to the most recent estimate from 2010.

total	HuID: 15765

Data Source(s): Food and Agriculture Organization of the United Nations Statistical Database (FAOSTAT)
Notes: "Agriculture" land is defined as all land that is under agricultural management including pastures, meadows, permant crops, temporary crops, land under fallow, and land under agricultural structures.

G OCEAN pH

yearly change in $[H^+]$	HuID: 00000

Data Source(s):
Notes:

H DEFORESTATION

commodity-driven	HuID: 00000

Data Source(s):
Notes:

agricultural	HuID: 00000

Data Source(s):
Notes:

urbanization	HuID: 00000

Data Source(s):
Notes:

I MATERIAL OF HUMAN ORIGIN

concrete production	HuID: 25488
steel production	HuID: 51453

Data Source(s): USGS 2020, Mineral commodities. DOI:10.3133/mcs2020; Monteiro et al. 2017, DOI:10.138/nmat4930;
Notes: Concrete production value corresponds to approximate value from multiple sources. USGS 2020 Mineral Commodities Survey reports mass of cement produced in 2019. This is converted to concrete using a multiplicative conversion ofactor of ≈ 7 as described in Monteiro et al. 2017. Steel production correpsonds to the USGS estimated value for 2019.

plastic production	HuID: 97241

Data Source(s): Geyer et al. 2017. DOI:10.1126/sciadv.1700782, Table S2.
Notes: Value represents the sum total global production of plastic fibers and plastic resin during calendar year 2015. Original data set reports data from 1950 - 2015.

total anthropomass production	HuID: 00000

Data Source(s):
Notes:

J HUMAN WATER USE

agriculture	HuID: 43593
power generation	HuID: 78784
domestic	HuID: 69424
total	HuID: 27342

Data Source(s): Figure 1 of Qin et al. 2019. DOI:10.1038/s41893-019-0294-2.
Notes: "Agricultural use" is defined as water used for irrigation, maintenance of livestock, and water used in the management of irrigation via damming. "Power generation" is defined as water used for thermal power generation (coal, nuclear, gas, biomass, oil, and other/waste) and hydroelectric generation. "Domestic" is defined as water directly used by humans and water used in the maintencance of municipal water supply. "Total" water use includes the above categories as well as other uses of water in reservoir managment including flood control andd other unannotated uses. All values pertain to most recent estimates for 2016.

K GLOBAL POWER CONSUMPTION

global power consumption	HuID: 31373

Data Source(s): bp Statistical Review of World Energy, 2020.
Notes: Reported values correspond to estimates for the 2019 calendar year. Represents the sum total consumed energy from oil, natural gas, coal, nuclear energy, hydroelectric, and renewables.

L OCEAN WARMING

power deposition	HuID: 31373

Data Source(s): bp Statistical Review of World Energy, 2020.
Notes: Reported values correspond to estimates for the 2019 calendar year. Represents the sum total consumed energy from oil, natural gas, coal, nuclear energy, hydroelectric, and renewables.

M GREENHOUSE GAS EMISSIONS

yearly CO_2 released	HuID: 31373

Data Source(s):
Notes:

N OIL & NATURAL GAS MINING

oil & n.g. volume	HuID: 00000
oil & n.g. power production	HuID: 00000

Data Source(s): bp Statistical Review of World Energy, 2020.
Notes: Values pertain to 2019 estimates only. Oil volume includes crude oil, shale oil, oil sands, condensates, and natural gas liquids separate from specific natural gas mining. Natural gas value excludes gas flared or recycled and includes natural gas produced for gas-to-liquids transformation.

O HUMAN CAUSED EXTINCTION

animal species recently extinct	HuID: 0000
plant species recently extinct	HuID: 0000

Data Source(s): The IUCN Red List of Threatened Species. Version 2020-2. https://www.iucnredlist.org.
Notes:

P EROSION

soil moved by humans	HuID: 0000

Data Source(s):
Notes:

Q SEA LEVEL RISE

rise due to meltwater	HuID: 0000
rise due to thermal expansion	HuID: 0000

Data Source(s):
Notes:

R NUCLEAR FALLOUT

plutonium activity in soil	HuID: 0000

Data Source(s):
Notes:

S COAL POWER PRODUCTION

coal power produced	HuID: 0000

Data Source(s): bp Statistical Review of World Energy, 2020.
Notes: