The Anthropocene by the Numbers: A Quantitative Snapshot of Humanity's Influence on the Planet

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Abstract
The presence and action of humans on Earth has exerted a strong influence on the evolution of the planet over the past ≈ 10,000 years, the consequences of which are now becoming broadly evident. Despite a deluge of tightly-focused and necessarily technical studies exploring each facet of "human impacts" on the planet, their integration into a complete picture of the human-Earth system lags far behind. Here, we quantify twelve dimensionless ratios which put the magnitude of human impacts in context, comparing the magnitude of anthropogenic processes to their natural analogues. These ratios capture the extent to which humans alter the terrestrial surface, hydrosphere, biosphere, atmosphere, and biogeochemistry of Earth. In almost all twelve cases, the impact of human processes rivals or exceeds their natural counterparts. The values and corresponding uncertainties for these impacts at global and regional resolution are drawn from the primary scientific literature, governmental and international databases, and industry reports. We present this synthesis of the current "state of affairs" as a graphical snapshot designed to be used as a reference. Furthermore, we establish a searchable database termed the Human Impacts Database (www.anthroponumbers.org) which houses all quantities reported here and many others with extensive curation and annotation. While necessarily incomplete, this work collates and contextualizes a set of essential numbers summarizing the broad impacts of human activities on Earth's atmosphere, land, water, and biota.

Introduction
One of the most important scientific developments in modern history is the realization that the evolution of the Earth is deeply intertwined with the evolution of life. Perhaps the most famous example of this intimate relationship is the chemical transformation of Earths' atmosphere following the emergence of photosynthesis, an event so important to Earth's history that it has been colloquially termed the "Oxygen Holocaust" due to the massive extinction event that followed[1–3]. Over the past ≈ 10,000 years, humans have become a similarly influential force of nature, directly influencing the rise and fall of ecosystems[4–12], the temperature and volume of the oceans[13–19], the composition of terrestrial biomass[20], the planetary albedo and ice cover[21–28], and the chemistry of the atmosphere[29–34] to name just a few of many such examples. The breadth of human impacts on the planet is so diverse that it penetrates nearly every scientific discipline.

This penetration has resulted in a deluge of data, allowing us to describe the many facets of human impacts in quantitative terms often with remarkable precision and high resolution. However, these works are typically highly technical and tightly-focused, meaning that they paint a fragmented picture of the sweeping global changes wrought by human activities. Even seemingly simple questions such as "how much land or water do humans use?" can be difficult to answer when searching the scientific literature yields an array of complicated analyses with inconsistent definitions, methods, and assumptions, each reporting their findings in different units. This problem can lead to the perception that there is a disagreement on the facts when in reality there is broad scientific consensus.

We present a synthesis of these data, drawing heavily from scientific studies as well as industrial and governmental databases to assemble a broad, quantitative view of human action on Earth in a set of consistent and intuitive units. Paul Crutzen, who famously coined the term Anthropocene[35] in 2002, captured the essence of human impacts by pointing out that humans have transformed between 30-50% of the Earth's land area and increased the atmospheric concentration of CO_2 by 30% over the years 1800-2000. In this same spirit, we formulate and calculate an array of dimensionless quantities that compare the magnitude of the human impact (such as the biomass of livestock) to the natural analogue (such as the biomass of wild terrestrial animals). To make the data on this broad array of impacts transparent and their uncertainties clear, we have established a searchable online database which acts as a repository for the values presented here as well as many others. This manually curated and continuously updated database, termed the Human Impacts Database (www.anthroponumbers.org), contains a variety of quantities, each with a unique 5-digit identifier termed an HuID, which we reference throughout this work.

We consider the act of assembling the facts and making them easily accessible a prerequisite to discussing the actions that should be taken to manage the effects of human impacts. However, our work has led to a number of insights not obvious when the impacts are considered in isolation. First, as will be seen throughout the paper, though human activities impact a wide array of natural processes, these impacts are intimately intertwined in much the same way that the biosphere is intertwined with the atmosphere, geosphere and hydrosphere. Over and over, we find that the scale of human impacts is driven by a small number of crucial factors: the size of the human population and our demand for power, water and food. Second, by comparing the scale of human impacts (such as total biomass of livestock) to their corresponding natural counterparts (total biomass of wild animals) we see that human actions rival or exceed their natural analogues in nearly all cases.

Results

Global Magnitudes

In Figure 1, we present a gallery of critical human impacts at the global scale, categorized into five classes: land, water, flora and fauna, atmospheric and biogeochemical cycles, and energy, as indicated by the corresponding color of their banners. Though the impacts considered are necessarily incomplete, these values encompass many critically important numbers, such as the volume of liquid water resulting from ice melt (Figure 1 B), the extent of urban and agricultural land use (Figure 1 H), global power consumption (Figure 1 N), and the heat uptake and subsequent warming of the upper ocean (Figure 1 S). We direct the reader to the supplemental information for a detailed description and full referencing of each number reported in Figure 1.

Exploring these numbers reveals surprising quantities and relationships. For example, agriculture is a major contributor to many of these impacts, dominating both global land use (Figure 1 H, HuID: 29582) and human water use (Figure 1 L; HuIDs: 84545, 43593, 95345), as well as accounting for a third of global tree cover area loss (Figure 1 O; HuID: 24388). In addition, a vast amount of nitrogen is synthetically fixed through the Haber-Bosch process to produce fertilizer (Figure 1 F; HuID: 60580, 61614), which is a major source of N_2O emissions (Figure 1 K; HuID: 44575). Our collective agricultural practices also make us the stewards of a standing population of around 30 billion livestock (Figure 1 E; 15765). Along with rice paddies, ruminant livestock like cattle produce a majority of anthropogenic methane emissions (Figure 1 K; HuID: 96837, 30725). In contrast, urban land area accounts for a nearly negligible fraction of land use (Figure 1 H; HuID: 41339, 39341), and urbanization accounts for only ≈ 1% of global tree cover area loss (Figure 1 O; HuID: 19429). This is not to say, however, that urban centers are negligible in their global impacts. Urban areas now house more than half of the global human population (Figure 1 J; HuID: 93995) and the construction of urban structures, as well as the roads, tunnels, dams, and factories supporting them, is the dominant cause of earth-moving operations on an annual basis (Figure 1 W; HuID: 59640).

Collectively, the ≈ 8 billion humans on Earth (Figure 1 J; HuID: 85255) consume nearly 20 TW of power (Figure 1 N; HuID: 31373, 85317), with around 80% coming from the combustion of fossil fuels (Figure 1 P; HuID: 29470, 29109). This results in a tremendous mass of carbon dioxide emitted annually (Figure 1 K; HuID: 24789, 54608, 98043), which, along with other greenhouse gases, has increased the global surface temperature via the greenhouse effect by more than 1° C relative to the average temperature between 1850 and 1900 (Figure 1 A; HuID: 79598, 76539, 12147). A sizable portion of these emissions are absorbed by the oceans, leading to a steady increase in ocean acidity (Figure 1 G; HuID: 90472, 19394), threatening many marine ecosystems[36–41]. Furthermore, increasing average global temperatures contributes to sea level rise not only in the form of added water from ice melt and discharge from ice sheets (Figure 1 B and M; HuID: 32459, 95978, 93137, 81373, 70818) but also through the thermal expansion of water, which accounts for ≈ 30% of the observed global sea level rise (Figure 1 M; HuID: 97688). These are just a few ways in which one can traverse the impacts illustrated in Figure 1, revealing the remarkable extent to which human impacts are interconnected. In the supplemental information, we outline several other paths one could take through Figure 1 and encourage readers to explore this figure in a similar manner.

While Figure 1 presents the magnitude of human impacts at a global scale, it is important to recognize that both the origins and repercussions of human activities are highly variable across the globe. In the supplemental information and supplemental Figure S1, we present coarse-grained regional breakdowns of many of the numbers from Figure 1 for which regional distributions could be determined.

Dimensionless Representations

To quantitatively describe the Anthropocene, it is useful to compare the magnitude of human impacts to their natural analogues in a spirit similar to that initially presented nearly 20 years ago by Paul Crutzen[35]. In Figure 2, we outline a dozen "dimensionless ratios" which compare contemporary human impacts to natural processes closely related in scope or in value. We begin with one of the central questions pertaining to the anthropocene -- the extent of human land use. *The Terra Number,* diagrammed in Figure 2 A compares human terrestrial land use to total global terrestrial land area. This comparison reveals that humans have transformed 30% of terrestrial land for agricultural (≈ 5 × 10^7 km^2, HuID: 29582) and urban developments (≈ 7 × 10^5 km^2; HuID: 41339, 39341). In many cases, utilizing this land requires clearing it of its natural biota, such as trees and shrubs, in order to grow food or build structures.

*The Deforestation Number***,** shown in Figure 2 B, puts the extent of such land clearing in context. Through a combination of permanent deforestation (e.g. clear-cutting forest where there is no regrowth of natural tree cover) and temporary tree cover loss (such as tree cover lost through managed forestry and agriculture, where there is eventual regrowth), humans intentionally remove tree cover. Through these intentional and managed means, humans clear an area of ≈ 1.8 × 10^5 km^2 annually (HuID: 96098 , 24388, 38352, 19429), approximately twice as large as the area cleared through wildfires (≈ 7 × 10^4 km^2; HuID: 92221), some of which are human-caused (a subset of which are controlled burns). Agricultural activities alone lead to the clearing of an area comparable to that of wildfire. This cleared land is used not only to grow food but rear an impressive number of animals as livestock.

The enormity of the standing terrestrial livestock population is contextualized by *The Barnyard Number*, illustrated in Figure 2 C. The total biomass of global terrestrial livestock is ≈ 2 × 10^{12} kg and currently outweighs all terrestrial wild mammals and wild birds (≈ 7 × 10^{10} kg)[20] by approximately 30 fold. On a mass basis, therefore, it is more realistic to picture dominant land animals as cows and chickens rather than elephants and zebras. Together, the ≈ 30 billion terrestrial livestock animals (HuID: 43599) who make up this reservoir of biomass are dependent on humans to grow their food, culminating in an enormous demand for nitrogenous fertilizer and water.

The production of synthetic fertilizer requires chemical fixation of nitrogen to make reactive species like ammonia (NH_3), which plants can utilize, from the inert dinitrogen gas (N_2) that makes up nearly 80% of our atmosphere. Natural NH_3 production is catalyzed by various species of bacteria that often form symbioses with plants[42], however natural formation of NH_3 is not sufficient to sustain a human population beyond ≈ 3 billion individuals[43]. To meet this demand for NH_3, humans synthesize ≈ 1.5×10^{11} kg of reactive nitrogen annually via the energy-intensive Haber-Bosch process (HuID: 60580, 61614), a mass equal to that of all biological nitrogen fixation on Earth. The observation that humanity now matches nature in terms of production of reactive nitrogen is reflected in *The Nitrogen Number* calculated in Figure 2 (D). Since humanity now applies ≈ 10^{11} kg of nitrogenous fertilizer globally each year, it is crucial to ensure that the fertilized crops also receive enough water.

The Water Number (Figure 2 E) reflects the total amount of water withdrawn by humans, which is dominated by irrigation of cropland (≈ 1.5×10^{12} m^3 / yr; HuID: 43593), and closely followed by industrial use (≈ 6×10^{11} m^3 / yr; HuID: 27142), namely in the form of electricity production. Together, these two cases account for ≈ 95% of total human water use per year (HuID: 84545, 43593, 95345, 27142, 27342, 68004).Total human water withdrawals are about 5% of global river discharge volume, the major source of renewable freshwater[44]. While this is a small fraction of available freshwater, freshwater is highly variable across the globe and about a third of the human population lives in water stressed areas, where water withdrawal is greater than 40% of available freshwater[44].

The River Number, shown in Figure 2 F, summarizes the extent to which humans have shaped the flow of freshwater, harnessing it for irrigation and hydropower, and changing the flow to prevent floods. Currently, the total volume of rivers under human control (≈ 6×10^{11} m^3; HuID: 61661) , by dams and myriad smaller barriers, equals the total volume of free flowing rivers (≈ 6×10^{11} m^3; HuID: 55718). This massive repurposing of water flow has a huge impact on not only the water cycle but also the movement of aquatic organisms and sediment. Previous to human action, rivers were the major force moving sediment, but humans have now taken over that role.

The vast amount of sediment moved by humans is encompassed by *The Earth Mover Number* (Figure 2 G). Currently, humans move at least 2.5×10^{14} kg / year (HuID: 19415, 59640, 72899) over 15 times the amount of sediment that is moved by rivers (≈ 1.3×10^{13} kg / year, HuID: 51481). Urbanization alone accounts for over half of this, driving the movement of over 1.4×10^{14} kg of sediment a year (HuID: 59640). Waste and overburden from coal mining and erosion due to agriculture make up the remaining ≈ 0.9×10^{14} kg / year (HuID: 19415, 41496, 72899). In addition to a massive amount of earth moved, urbanization also requires an astounding amount of human-made materials such as steel and concrete.

Our calculation of *The Anthropomass Number* (Figure 2 H) shows that the mass of human-made materials now equals the dry weight of all living matter on the planet[45]. Material of human origin, termed *anthropomass* is dominated by construction materials, especially concrete (≈ 3×10^{13} kg / yr; HuID: 16995, 25488, 81346) and other aggregates (asphalt, sand, gravel, and bricks), with steel coming next (≈ 1.9×10^{12} kg / yr; HuID: 44894, 51453, 85891). In addition to the raw mineral resources, producing these materials requires an enormous amount of energy.

CO_2 is the most famous greenhouse gas and also the one that human activities produce in the largest quantity. *The CO_2 Number* (Figure 2 J) quantifies the amount of CO_2 produced by human processes relative to the natural sinks, namely absorption by Earth's oceans and photosynthesis by plants and algae[29]. About 85% of anthropogenic CO_2 emissions (≈ 4×10^{13} kg / yr; HuID: 60670, 24789, 54608) are due to burning fossil fuels like coal, oil, and natural gas, with the remainder due to land-use changes like the removal of forests for agriculture. Annual anthropogenic CO_2 emissions are roughly double the amount removed by natural sinks (≈ 2×10^{13} kg / yr; HuID: 52670). The remainder remains in the atmosphere, growing in concentration year after year. The excess CO_2 in the atmosphere contributes to warming the planet, while CO_2 absorbed by oceans changes the pH, increasing its acidity and disrupting oceanic ecosystems[21]. CO_2 is not, however, the only greenhouse gas humans produce in significant quantities.

Methane is an extremely potent greenhouse gas, having a global warming potential about 25 times that of CO_2 over 100 years[46]. Anthropogenic CH_4 emissions are mainly due to cattle, rice paddies, and burning fossil fuels[34] . As shown by *The CH_4 Number* (Figure 2 K) natural (≈ 3×10^{11} kg / yr; HuID: 56405) and anthropogenic methane emissions (≈ 4×10^{11} kg / yr; HuID: 96837) are currently roughly equal, indicating that humanity matches nature in the production of this critical gas.

The mining and burning of fossil fuels for electrical and mechanical power is a major driver of both CO_2 and CH_4 emissions. Despite using an enormous 18 TW of power globally (HuID: 31373, 85317), humanity only consumes a miniscule fraction of the power incident on the planet from the sun. This fraction is calculated as *The Solar Number* (Figure 2 I), which shows that current human power consumption is roughly 0.01% of annual incident solar energy. Today, most of our power derives from burning fossil fuels and only about 1% is solar. Solar power is therefore an enormous and mostly-untapped resource.

The 12 dimensionless numbers presented in Figure 2 quantify diverse yet specific ways in which humans are influencing the evolution of the Earth. The processes described by these 12 ratios are distinct, but interrelated, sharing many common themes. Intensification of agriculture leads us to convert forest to cropland, divert rivers and burn fossil fuels to power the synthesis of nitrogenous fertilizer. Building roads, tunnels, dams, homes and offices leads to massive earth-moving operations that similarly demand water, power, and land area. These myriad interconnected human activities have complex effects on natural ecosystems, many of which are smaller and more fragmented than they were 200 years ago. Our final dimensionless ratio, *The Extinction Number* (Figure 2 L), attempts to understand the scale of these effects on ecosystems. Over the past 500 years, at least ten times more animal species have gone extinct (≈ 760 species; HuID: 44641) than would be expected given the most conservative estimate for the background extinction rate[8,47]. The causes of this increased extinction rate are varied and remain poorly understood, and this quantity is necessarily a lower bound as only a small fraction of species have been studied. It is very likely that extinction is far more prevalent than we know, especially among arthropods and marine biota more generally.

Discussion

In this work we canvassed the scientific literature as well as governmental and international reports to assemble a broad, quantitative picture of how human activities have impacted Earth's atmosphere, oceans, rives, lands, biota and geology. We assembled these data into a comprehensive snapshot, released alongside this writing as a standalone graphical document (Supplemental Material 1) , with all underlying data, associated uncertainties and referencing housed in the Human Impacts Database. As illustrated by the dimensionless ratios presented in Figure 2, the scale of these impacts is not small. Rather, in nearly all cases, human activities impact the planet to a degree rivalling or even exceeding counterpart natural processes. Perhaps even more so than any other ratio we present, *The Anthropomass Number* (Figure 2 H) conveys this point by showing that the total mass of human-made "stuff" roughly equals the total mass of all living matter on Earth[45].

One insight that emerges from considering these diverse human activities together is that they are deeply intertwined and driven by a small number of pivotal factors: the size of the human population, the composition of our diets, and our demand for materials and energy to build and power our increasingly complex and mechanized societies. Understanding the scale of human agriculture, water and power usage provides a framework for understanding nearly the entirety of the numerical gallery presented in Figure 1. Indeed, agriculture alone is the dominant cause of human land and water use and a major driver of deforestation as well as methane and nitrous oxide emissions.

It is common in this setting to argue that the bewildering breadth and scale of human impacts should motivate some specific remediation at the global or local scale. We prefer a more modest "just the facts" approach. The numbers presented here show that human activities affect our planet to a large degree in many different and incommensurate ways, but they do not provide a roadmap for the future. Rather, we contend that any plans for the future should be made in the light of a comprehensive and quantitative understanding of the interconnected ways in which human activities impact the Earth system globally (Figures 1 and 2) and locally (Figure S1). Achieving such an understanding will require synthesis of broad literature across many disciplines, work that we have only just begun. While the quantities we have chosen to explore are certainly not exhaustive, they represent some of the key axes which frequently drive scientific and public discourse and shape policy across the globe.

The quantitative picture presented here summarizes the “state of affairs” as of 2020. Earth is the only habitable planet we know of, so it is crucial to understand how we got here and where we are going. That is, how have human impacts changed over time? How are they expected to change in the future? For every aspect of human entanglement with the Earth environment – from water use to land use, greenhouse gas emissions, mining of precious minerals, and so on – there are excellent studies measuring impacts and predicting their future trajectories. The time has come to integrate these disparate works and synthesize a complete picture of the human-Earth system, one that helps humanity coexist stably with the only planet we have.

Materials & Methods

All values reported in this work come from myriad sources in the scientific, industrial, governmental, and organizational reports and articles. Every value reported in Figure 1 as well as Supplemental Figure S1 are extensively documented in the supplemental information. In brief, each value reported was manually curated with one or more of the authors closely reading the original report/article/document, downloading (or in some cases requesting) the original datasets, and annotating and cleaning the data to follow the principles of “tidy data" formatting[48]. For each reported quantity, we identified the method of determination (e.g. direct measurement, statistical inference, or aggregated estimate) and provided an assessment of uncertainty. In cases where the uncertainty was undetermined or not reported, we sought additional sources to provide a range of reasonable values. Thus, as is reported in the supplemental information, we use equality symbols (=) to indicate values with an estimate of the uncertainty or values that are tightly constrained in range, and approximation symbols (≈) to indicate estimates likely accurate to within a factor of a few, and an inequality symbol (>) to indicate a lower-bound estimate for the value in question. Every dataset and source we considered in this work has been stored in a GitHub Repository (DOI: 10.5281/zenodo.4453277; https://github.io/rpgroup-pboc/human_impacts) with extensive documentation. We invite the scientific community to engage with this repository by submitting pull requests and opening issues for corrections, updating of values, or suggestions of new data that are relevant to the scope of this work.

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