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Supplementary information

Global human-made mass exceeds all living biomass

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Global human-made mass exceeds all living biomass

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Supplementary Discussion 1: Sensitivity analysis of the anthropogenic mass definition

In this study, anthropogenic mass is defined as the mass embedded in inanimate solid objects made by humans (that were not yet demolished or taken out of service). This definition is supported by the scientific field of industrial ecology and used by bureaus of statistics. As other definitions can be suggested, we here present their approximated influence on the intersection time between the anthropogenic mass and global living biomass, as illustrated in Extended Data Fig. 1. All the steps from raw data to end results are documented in the Jupyter notebook available at: https://github.com/milo-lab/anthropogenic_mass/tree/master/sensitivity_analysis/sensitivity_analysis.ipynb

1.1 Include humans under anthropogenic mass instead of under biomass

As a living species, the mass of the human population is naturally included in the global biomass. In terms of mass, humanity represents a tiny fraction of the current global biomass — only 0.01%. This means that opting to classify humans under anthropogenic mass rather than under biomass will have a minimal effect on both the biomass and anthropogenic mass trajectories, and will not shift the intersection year. The insignificant effect of the mass of humanity can be gleaned from Extended Data Fig. 1a, where the mass of the human population was subtracted from the biomass estimate and added to the anthropogenic mass estimate. The mass of the human population since 1900 was obtained from (Krausmann et al., 2018)[22] and was converted to a dry-weight basis by multiplying the mass by 0.3 (assuming water comprises 70% of the human body's mass).

1.2 Include livestock under anthropogenic mass instead of under biomass

The mass of livestock comprises a small fraction of the current global biomass. Thus, as can be gathered from Extended Data Fig. 1b, including livestock under anthropogenic mass rather than under the biomass will have a negligible impact on both the biomass and anthropogenic mass estimates, and will not affect the year of intersection. The mass of livestock since 1900 was obtained from (Krausmann et al., 2018)[22] and was converted to a dry-weight basis by multiplying the mass by 0.3 (assuming water comprises 70% of the mass of livestock).

1.3 Include mass of crops and agroforestry under anthropogenic mass instead of under biomass

To calculate the mass of crops and agroforestry (i.e., trees integrated in agricultural settings/landscapes), we mostly relied on the work by (Zomer et al., 2016)[72]. We first estimated the area of the agricultural land, and then multiplied it by the corresponding biomass density. To derive the agriculture area since 1900, we used the 2000 area estimate by Zomer et al.[72], and as an approximation, we assumed it behaves similarly to the cropland area, which we obtained from (Goldewijk et al., 2017; HYDE3.2)[73]. We then multiplied the cropland area by the corresponding mass density, derived from Zomer et al.[72], and assumed the observed trend in density remains constant. The outcome was subtracted from the biomass estimate and added to the anthropogenic mass estimate. As shown in Extended Data Fig. 1c, this adjustment slightly moves back the crossover point to 2014.

1.4 Add civil engineering earthworks, dredging and waste/overburden from metal and mineral production to the anthropogenic mass

The anthropogenic mass definition is composed only of the current in-use human-made mass. In addition to this mass, humanity moves and extracts material not intended for usage, for example, waste or overburden from mineral extraction, civil engineering excavations and dredging. Adding the accumulated mass of such material flows to the total anthropogenic mass increases the anthropogenic mass several fold and moves back the crossover point to 1975.

Our estimation of the yearly addition to the anthropogenic mass, presented in Extended Data Fig. 1d, is mostly based on a recent study by Cooper et al. (2018)[35], with updates to complement our anthropogenic mass estimation and avoid double counting. We included four groups: dredging, civil engineering earthworks, waste/overburden from mineral/metal or coal production, and considered their accumulated flows since 1900.

The estimates for dredging and waste/overburden from coal production since 1925 were adopted from Cooper et al.[35]. The estimates were extrapolated for years 1900-1925, assuming exponential growth.

To evaluate the mass of civil engineering earthworks, we followed the same approach as Cooper et al.[35] and multiplied the mass of cement and aggregates used by a factor of 2. We updated their aggregates and cement annual evaluations according to our anthropogenic mass estimate, as follows: For each year, we took the net addition to stocks for the aggregates, concrete and asphalt categories, plus their waste (obtained from Wiedenhofer et al., 2019[71]). The waste here includes the end-of-life, construction and re-manufacturing wastes. Thus, the estimate might be slightly high. Asphalt values were multiplied by 0.95 to represent the fraction of aggregates.

To estimate the amount of waste/overburden from mineral/metal production, we used Cooper et al.[35] values, which integrated waste/overburden with the mineral/metal production. To avoid double counting, we interpolated their mineral/metal production for all the surveyed years (using their production estimates for selected years), based on an exponential fit, and subtracted it from the overall integrated estimate, which yielded the waste/overburden component. We then extrapolated for the time period of 1900-1925, assuming exponential growth.

All four contributions were then summed and added in an accumulated fashion to the annual anthropogenic mass estimate; the sum is shown in Extended Data Fig. 1d.

1.5 Exclude industrial roundwood mass from the anthropogenic mass

Industrial roundwood, which includes solidwood products and paper, falls under the definition of anthropogenic mass and is accounted for in our estimate. As the overall mass of industrial roundwood in 2014 was less than 2% of the total anthropogenic mass, its exclusion does not affect the intersection year, as shown in Extended Data Fig. 1e. The mass of industrial roundwood over the studied period was obtained from (Wiedenhofer et al., 2019)[71].

1.6 Add anthropogenic atmospheric CO_2 stocks to the anthropogenic mass

We estimated the stock of anthropogenic CO_2 mass over the studied period by subtracting the pre-industrial CO_2 mass from the annual mean CO_2 stocks since 1900. The annual atmospheric CO_2 concentrations from 1959-2019 were obtained from NOAA/ESRL (available at: www.esrl.noaa.gov/gmd/ccgg/trends/; Dr. Pieter Tans; Mauna Loa Observatory, Hawaii) and the Scripps Institution of Oceanography (available at: scrippsco2.ucsd.edu; Dr. Ralph Keeling). Prior estimates, based on ice cores, were obtained from (MacFarling Meure et al., 2006)[74]; multiple records for the same year were averaged.

We then converted the concentration estimates to mass stocks of Gigatonnes CO_2, using factors obtained from (Friedlingstein et al., 2019)[39]. Next, we subtracted the pre-industrial CO_2 stocks, which were derived based on the IPCC estimate[75]. Adding the results to the anthropogenic mass estimations moves back the crossover year to 1996, as shown in Extended Data Fig. 1f.

Supplementary Discussion 2: Biomass trend in recent years

The overall biomass values in recent years have been found to be close to stable. Some studies discuss a net global carbon sink. A potential reason for these differing conclusions could be that the sink of carbon observed on land is not due to the accumulation of carbon in living biomass but because of its accumulation in the soil. For example, Pan et al.[12] reports a net sink of about 1 GtC yr^-1 in global forests. Looking at the data (Table S3 in their SI), one can see a decrease in the global stocks of living biomass in forests (from 367 GtC in 1990 down to 363 GtC in 2007). The main reason for this seeming contradiction is that the total land areas considered in 1990 and 2007 are not the same. In the tropics, deforestation has reduced the total forest area, but this now-deforested area, while no longer considered a forest, still contains remaining carbon mostly stored in the soil. If we add this extra remaining carbon to the 2007 estimate, we indeed see that the total carbon pool on the same surface area has increased by about 1 GtC yr^-1, even though the living biomass has decreased.

Supplementary References

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