From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900-2015

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Supporting Information

S1 Methods and data

S1.1 Material Extraction

We closely followed the procedure described in Krausmann et al. (2009) to update the time series of global extraction of materials from 2005 to 2015. Table S1 provides a concise overview of the main data sources and estimation procedures used for the different material flows in the update. For a detailed description of data and estimation procedures we refer to data and method section of the original study (Krausmann et al., 2009) and the handbook of material flow accounting (Krausmann et al., 2015). Here we only describe the accounting methods applied for a few materials which were not included in the original study because they are not or only fragmentary covered in statistical sources:

Additional sand and gravel: Additional sand and gravel used as subbase or base-course layers in construction is calculated in the Material Input Stocks and Output (MISO) model (see section S1.2) and based on assumptions and coefficients derived from Miatto et al. (2016). The estimate of aggregate demand for base-course layers of roads is derived from technical construction standards for roadways, where a multiplier is calculated to extrapolate aggregate demand from asphalt use. The value of the multiplier takes into account that with the expansion of road networks in the 20th century, an increasing share of asphalt is used in the refurbishment of existing roads, requiring less aggregate. It was assumed that aggregate requirement per t of asphalt remained constant at 5 t until 1940 and then declined to 2.56 t in 1980, remaining at this level afterwards. The estimate of aggregates required for sub-base layers of buildings is estimated on the basis of the used amount of concrete and bricks and a sub-base multiplier of 70 kg of aggregate per t of concrete and 45 kg per t of bricks used in construction. The amount of primary resource extraction is then calculated as the difference between calculated demand for sand and gravel and the available amount of recycled aggregates and down-cycled concrete, asphalt and bricks from the model results. A detailed description of the procedure can be found in Krausmann et al. (2017).

Clay for the production of bricks: Clay extracted for the production of bricks is not covered in statistical sources and was estimated. We used data on global brick production derived from the United Nations Industrial Commodity Production Statistics (UNSD, 2010) and assumed that 1.39 kg of clay is used per kg of brick (Krausmann et al., 2015).

Silica sand for glass production: Raw material demand for glass production was estimated on the basis of data for the global production of flat and container glass (see section S2 for details) and an assumed demand of 730 kg of silica sand per t of glass (Ruth and Dell’Anno, 1997). Other raw materials used in glass production (e.g., soda ash, limestone) were not added to DE since these materials are already accounted for in the statistical data on non-metallic mineral extraction. Recycling of glass as a substitute for primary material input in glass production was taken into account in the estimate. See section S1.2 for details.
Table S1: Sources and estimation procedures used to update domestic extraction (DE) by material groups. See Krausmann et al. (2009) for details on accounting procedures.

| Material group                        | Main source or estimation procedure used for update                                                                 |
|---------------------------------------|---------------------------------------------------------------------------------------------------------------------|
| Crops                                 | FAO (2017)                                                                                                         |
| Crop residues                         | Extrapolated from crop harvest using harvest indices and recovery rates documented in Krausmann et al. (2015, 2013). |
| Grazed biomass                        | Grazing gap calculation based on a detailed feed balance approach documented in Krausmann et al. (2009) and Krausmann et al. (2013). |
| Wood                                  | FAO (2017)                                                                                                         |
| Coal, petroleum, natural gas          | IEA (2016), UNSD (2013)                                                                                            |
| Ores and metals                       | United States Geological Survey USGS (Kelly and Matos, 2017); gross ore extrapolated from metal ore grades (Krausmann et al., 2009). |
| Sand and gravel                       | Demand of sand and gravel for the production of concrete and asphalt based on the consumption of cement and bitumen and appropriate coefficients (Krausmann et al., 2015, 2009). Global production of cement sourced from USGS (Kelly and Matos, 2017) and of bitumen sourced from IEA (2016). |
| Clay                                  | Based on brick production assuming a demand of 1.39 kg of clay per kg brick (Krausmann et al., 2015). Brick production estimated on the basis of data provided in UNSD (2010). |
| Limestone for cement                  | Extrapolated from cement production. Data sourced from Kelly and Matos (2017).                                      |
| Additional sand and gravel (used in subbase and base course layers) | Extrapolated from the consumption of concrete, asphalt and bricks using the MISO model (Krausmann et al., 2017; Miatto et al., 2016). |
| All other non-metallic minerals       | USGS (Kelly and Matos, 2017)                                                                                         |

S1.2 Stocks and net additions to stock

Livestock: The estimate of the mass of livestock was based on global livestock numbers sourced from FAO (e.g., FAO (2017)) and its precursor organizations (e.g., IIA (1922)) and region specific assumptions on the average live weight for different livestock species (Table S2). To estimate the average live weight of livestock, we differentiate between the population of growing and mature livestock for each species, based on an assumed ratio of lifetime until maturity and lifetime until slaughtering. Average lifetime until slaughtering is calculated as the inverse value of take-off rates and based on FAO data on livestock population and slaughtering. Lifetime until maturity has been estimated on the basis of a literature review. For the population of growing animals we assume that average live weight is 50% of live weight at slaughter. For the population of mature animals, we assume that average live weight equals live weight at slaughter. We calculated live weight at slaughter by combining data on carcass weight sourced from FAO (2017) with ratios between carcass and live weight at slaughter from FAO technical information (FAO, 1994). Prior to 1961 average livestock weights were held constant at the level of 1961.

Table S2: Overview on parameters used to calculate mass of livestock and output of carcasses. Ranges show the variation of parameters over time between 1961 and 2015. For lifetime until maturity, we assumed constant values over time. See text for details.

|                       | Take-off rate | Time until maturity | Live weight at slaughter | Average live weight (total lifetime) |
|-----------------------|---------------|---------------------|--------------------------|-------------------------------------|
|                       | [1]           | [years]             | [kg]                     | [kg]                                |
| Cattle                | 0.18 – 0.20   | 2.0                 | 302 – 414                | 217 – 291                           |
| Buffaloes             | 0.09 – 0.13   | 2.0                 | 299 – 312                | 275 – 266                           |
| Chickens              | 1.68 – 2.81   | 0.5                 | 1.5 – 2.0                | 0.9 – 1.0                           |
| Ducks                 | 1.17 – 2.16   | 0.2                 | 1.9 – 1.9                | 1.0 – 1.1                           |
| Turkeys               | 0.69 – 1.36   | 0.5                 | 16 – 22                  | 8.7 – 15.4                          |
| Sheep                 | 0.33 – 0.46   | 1.5                 | 31 – 32                  | 23 – 21                             |
| Goats                 | 0.30 – 0.57   | 1.5                 | 22 – 24                  | 17 – 16                             |
| Camels                | 0.05 – 0.09   | 1.5                 | 424 – 457                | 342 – 370                           |
| Horses                | 0.05 – 0.08   | 2.0                 | 355 – 311                | 230 – 272                           |
| Pigs                  | 0.93 – 1.42   | 0.6                 | 89 – 104                 | 54 – 55                             |
Humans: The estimate of the mass of the human population was based on global population data sourced from UN-DESA (2017) and Maddison (2013) and assumptions on average weight per capita for different age groups. Starting point was a study by Walpole et al. (2012) who estimated the human body mass for adults (15+) for 2005. To derive a rough estimate of changes in average weight per capita over time we used information on changes in the Body Mass Index (BMI) from Finuncane et al. (2008) and global height trends from Baten and Blum (2012) and Blum and Baten (2010). According to our estimate, average weight of the age groups 0-14 increased from 27 kg/cap in 1950 to 32 kg/cap in 2015 and for the population group 15+ from 55 kg/cap to 63 kg/cap. Prior to 1950 values for 1950 were held constant.

Manufactured capital (in-use artifacts): We used the Material Input Stocks and Output (MISO) model to calculate in-use stocks of manufactured capital, net additions to stock, processing and manufacturing wastes and end of life waste from discarded stocks. We updated the stock calculation of the original study, which covered the period 1900-2010, to 2015 using the data for global material extraction (see section S1.1). The model and the used parameters and assumption are described in detail in Krausmann et al. (2017). In the update, we also expanded the stock estimate and included two new stock types: container glass and flat glass. Global glass production was estimated on the basis of data provided in UNSD (2010) and industry statistics (e.g. Glass Alliance Europe, 2017; Mahrenholtz and Ommer, 2011; NSG Group and others, 2011). We assumed that the average lifetime of container glass declined from 5 to 4 years between 1900 and 2015 and that of flat glass from 50 to 39 years. Flat glass is not recycled; for container glass we assumed that global average recycling rate increased to 38% in 2015 based on data reported in Buttler and Hooper (2011), EPA (2016), Eurostat (2016) and OECD (2001).

Net additions to stock: NAS of humans, livestock and manufactured capital were calculated as the difference between stocks in year t and in year t-1.

S1.3 Domestic processed output (DPO, DPO*)

Livestock: We used existing data on the intake of feed, the output of animal products and methane emissions from livestock and combined it with information on the digestibility of feed materials and the stoichiometry of basic metabolic processes to arrive at a mass balanced account of inputs, stocks and outputs of the livestock system. The feed balance used to calculate grazed biomass for the material flow account (see Table S1) provides detailed data of feed intake by species and feed materials (forage crops, crop residues used as feed, grazed biomass and 65 types of market feed). Feed composition tables were used to quantify the composition of feedstuffs and the digestibility of main components, i.e. carbohydrates, proteins, lipids and minerals. Outputs of animal products (live weight of slaughtered animals, milk and eggs) were quantified on the basis of data sourced from FAOSTAT commodity balances (FAO, 2017) and extrapolated for the years before 1961 on the basis of livestock numbers.

DPO from livestock comprises CO₂, CH₄ and H₂O (vapor) from (aerobic) respiration and methanogenesis as well as solid and liquid excrements. CH₄ outputs were sourced from FAOSTAT emissions database (FAO, 2017) for the period from 1961 to 2015 and extrapolated on the basis of a constant ratio between livestock and CH₄ emissions for years prior to that date. The output of solid and liquid excrements was estimated by combining feed supply data with information in feed digestibility, mineral content and retention rates derived from the literature (e.g., Sauvant et al. (2002), Heuze et al. (2017) and NRC (2001)). The output of CO₂, CH₄ and H₂O from respiration and methanogenesis and the corresponding input of balancing O₂ was calculated using mass ratios derived from the stoichiometry of the according metabolic processes, following the basic approach outlined in Muñoz et al. (2008). The processes include the catabolism of carbohydrates, lipids and proteins via aerobic respiration, and the catabolism of carbohydrates via methanogenesis. For the years prior to 1961, we
used livestock numbers and extrapolated outputs of animal products from the ratio between animal stocks and outputs in 1961.

Table S3 shows the resulting percentage values for the allocation of dry matter feed intake to the outflow of animal products, solid and liquid wastes and the inputs into respiration and methanogenesis. Table S4 provides the multipliers applied to calculate the outflow of CO₂, CH₄ and H₂O from (aerobic) respiration and methanogenesis and the corresponding input of balancing O₂ from the dry matter input into these processes.

Table S3: Allocation of feed input to outputs of animal products and excrements and inputs to methanogenesis and respiration for non-grazing (pigs and poultry) and grazing animals (all other). The percentage values refer to the share of the respective flow in feed input on a dry matter basis. Differences from 1961 to 2015 mainly reflect changes in feed composition. For the coefficients used to convert feed input through respiration and methanogenesis into CO₂, CH₄ and H₂O see Table S4.

| Flow dry matter | Grazers | Non-grazers | Note |
|-----------------|---------|-------------|------|
| % of dry matter feed intake | 1961 | 2015 | 1961 | 2015 |
| Solid excrements | 34.6 | 37.1 | 17.3 | 15.6 |
| Organic components which are not metabolized though respiration but excreted. Based on feed digestibility tables from Sauvant et al. (2002) Heuze et al. (2017) and NRC (2001). |
| Liquid excrements | 3.6 | 3.9 | 0.9 | 0.8 |
| Mineral components which are not retained in body mass increase but excreted in urine. Based on Sauvant et al. (2002), Heuze et al. (2017) and NRC (2001). |
| Animal bodies and products | 2.5 | 2.8 | 8.4 | 20.1 |
| Feed components used to build up animal bodies and products. Calculated from FAO data on animal products, number of slaughtered animals and live weight at slaughter (see Table S2). |
| Methanogenesis | 6.7 | 5.3 | 1.9 | 0.9 |
| Feed components (carbohydrates) metabolized through methanogenesis. Calculated from methane emissions and mass ratios for the metabolic reaction of methanogenesis. |
| Respiration | 52.6 | 50.9 | 71.4 | 62.6 |
| Organic components metabolized through (aerobic) respiration. Comprises mainly carbohydrates and lipids, but also proteins not used to build up body mass. It was assumed that all feed components not going into solid/liquid excrements, methanogenesis and bodies/products are metabolized through respiration. |
| Total | 100 | 100 | 100 | 100 |

Table S4: Methanogenesis and respiration yield outputs of CH₄, CO₂ and H₂O; respiration requires additional inputs of O₂ (balancing flow). The table presents multipliers (derived from stoichiometric ratios) used to convert grams of input of feed and food components (dry matter) into grams of DPO flows related to respiration and methanogenesis for livestock and humans.

| Metabolic process | DPO flow | Multiplier to convert feed or food component input into DPO flow g DPO flow per g food input (dry matter) |
|-------------------|----------|---------------------------------------------------------------|
|                   |          | Livestock | Humans |
| Conversion of carbohydrates through methanogenesis | CO₂ output | 0.73 | Not applicable |
| CH₄ output | 0.27 | Not applicable |
| Conversion of carbohydrates, lipids and proteins through aerobic respiration | O₂ input (balancing flow) | 1.08 | 1.27 |
| CO₂ output | 1.45 | 1.58 |
| H₂O output | 0.59 | 0.59 |
| Urea output | 0.05 | 0.05 |

**Humans:** We combined data on food intake with information on the digestibility of food materials and the stoichiometry of human metabolism to provide a mass balanced account of inputs, stocks and outputs from humans following the approach suggested by (Munoz et al., 2008). We used information from the material flow database (food use), FAOSTAT commodity balance, and the calculated output of animal products to quantify the gross supply of food. To calculate actual food intake, we subtracted food losses from gross food supply derived from the material flow account and the calculated output of animal products from the livestock model. Food losses were calculated on the basis of information
about processing losses reported in FAOSTAT commodity balances and about food waste in households estimated on the basis of Alexander et al. (2017). The digestibility for different food items was derived from data in Wong and Jenkins (2007), Shakhalili et al. (2001), Sunvold et al. (1995) and FAO (FAO, 2013). Methanogenesis is negligible for humans.

Table S5 shows the resulting percentage values for the allocation of dry matter food intake to gross body mass increase (NAS and outflows of dead bodies), the outflow of solid and liquid wastes and the inputs into respiration. The multipliers applied to calculate the outflow of CO\textsubscript{2} and H\textsubscript{2}O from respiration and the corresponding input of balancing O\textsubscript{2} from the dry matter input into these processes are shown in Table S4.

Moisture content: The mass balance for input and output flows related to humans and livestock was established on a dry matter basis. Conversion to dry matter and back to fresh weight was done on the basis of information on average moisture content of input and output flows. Actual outflows of excrements of humans and livestock as reported in DPO was calculated assuming a moisture content of human excrements of 75% and of animal excrements of 85% (Lorimor et al., 2004; Rose et al., 2015; Vetter and Steffens, 1986). The input of balancing H\textsubscript{2}O was calculated as the difference between available water from crop moisture and moisture contained in excrements at fresh weight. DPO* reports solid and liquid excrements at the moisture content of food and feed input (excluding balancing H\textsubscript{2}O); the resulting average moisture content of solid and liquid excrements of humans and livestock reported in DPO* ranges between 49% and 54%.

Table S5: Allocation of food intake to body mass increase, excrements and inputs to respiration. The percentage values refer to the share of the respective flow in food intake on a dry matter basis. Differences from 1961 to 2015 mainly reflect changes in dietary patterns (food composition). For the coefficients used to convert food input through respiration into CO\textsubscript{2} and H\textsubscript{2}O see Table S4.

| Flow dry matter                     | 1961 | 2015 | Note                                                                 |
|-------------------------------------|------|------|----------------------------------------------------------------------|
| Solid excrements                    | 6%   | 6%   | Organic components which are not metabolized though respiration but excreted. Based on information from Wong and Jenkins (2007) for carbohydrates, FAO/WHO (1991) for proteins, Shakhalili et al. (2001) for lipids and Sunvold et al. (1995) for minerals. |
| Liquid excrements                   | 1.5% | 1.7% | Mineral components which are not retained in body mass increase and excreted in urine, based on mineral digestibility according to Sunvold et al. (1995) and the share of minerals in human bodies. |
| Human bodies (NAS+dead bodies)     | 0.4% | 0.2% | Food components used to build up body mass. Calculated from output flows and net additions to stocks for humans (see text for details). |
| Respiration                         | 91.7%| 91.8%| Organic components metabolized through respiration. Comprises mainly carbohydrates and lipids, but also proteins not used to build up body mass. |

Technical energy: Technical energy carriers (hard coal, brown coal, petroleum, natural gas, fuel wood and biofuels) for energetic use are converted into emissions, solid outputs (e.g., ashes, soot) and water vapor by thermal combustion. Mass balanced DPO and DPO* were calculated on the basis of information on the input of energy carriers from the MFA database (energy use), the average composition of energy carriers, stoichiometry and assumptions on the completeness of combustion. Table S6 shows the allocation on the composition of energy carriers, derived from the literature (EPA, 1993; IPCC, 1997; Pandey et al., 2005; Sass et al., 1974).

Emissions: We considered three types of gaseous emissions from thermal conversion of energy carriers: CO\textsubscript{2}, SO\textsubscript{2}, N\textsubscript{2}O. Calculated N\textsubscript{2}O emissions only include N contained in the energy carriers, oxidation of atmospheric N during the combustion process is not considered DPO. DPO comprises emissions as CO\textsubscript{2}, SO\textsubscript{2}, N\textsubscript{2}O, i.e., including balancing O\textsubscript{2}; Emissions in DPO* comprise the components contained in fossil energy carrier material (C, S, N) only and exclude balancing O\textsubscript{2}. For N contained in
energy carriers we assumed complete combustions; for C and S we assumed that only a part of the actual content is oxidized; the remainder was allocated to solid outputs. For C in coal we assumed that combustion technology improved in the observed period and that the share of total carbon in emissions increased from 90% in 1900 to 97% in 2015 (Bartonova, 2015; Bartonova et al., 2011; Dindarloo and Hower, 2015; Liu et al., 2014; Namazirad, 2012). For C in petroleum, natural gas and biomass we assumed a constant share of 99%, 100% and 97%, respectively (EPA, 1993). For S we assumed that until 1952 all S contained in the extracted energy carrier was oxidized; starting from 1952 and accelerating after 1979 (petroleum) and after 1988 (coal) we assumed that desulphurization of energy carriers and emissions increased, resulting in a declining fraction of total S contained in emissions. In 2015 the fraction of Sulphur allocated to emissions was 30% for coal and 10% for petroleum. These assumptions are based on the literature (Berdowski et al., 2001; Javadli and de Klerk, 2012; Lefohn et al., 1999; OECD and IEA, 2016 and Srivastava, 2012 for petroleum and Lefohn et al., 1999; OECD and IEA, 2016; Pandey et al., 2005; Smith et al., 2011 for coal). Table S6 shows the shares for 1900 to 2015 for the different energy carriers.

We crosschecked calculated CO₂ emissions with data from the Carbon Dioxide Information Analysis Center (Boden et al., 2009). Our estimates of carbon emissions from fossil fuels are very similar to the existing estimate, both concerning the trend over time and the absolute amount. Compared to Boden et al. (2016) we arrive at 1.7% higher cumulative carbon emissions in the period 1900-2014. This difference can largely be attributed to differences in the accounting of fossil energy carriers used for non-energy applications (e.g., bitumen, plastics, and lubricants). Boden et al. (2016) assumed that a fraction of the fossil energy carriers used for non-energy applications ultimately is also oxidized and therefore also included these flows in their account of C emissions. In this study we allocated all end of life outflow of non-energy use of fossil energy carriers to solid waste. We crosschecked calculated emissions of SO₂ with data reported in Smith et al. (2011). We found that both the size of the calculated emission flow and the trend over time are very similar. Overall, our estimate yields 1.4% higher cumulative emissions of Sulphur in the period 1900-2005 compared to those reported in Smith et al. (2011). The difference can probably be attributed to different assumptions on the Sulphur contained in fuels and the efficiency and temporal dynamics of desulphurization of energy carriers and emissions.

Water vapor (H₂O): Water vapor originates both from the moisture contained in energy carriers and from the oxidation of hydrogen contained in the energy carriers. We assumed that the oxygen required for the oxidation of hydrogen is first covered from oxygen contained in in energy carriers (Table S6); the remainder was considered balancing O₂ (and excluded in DPO*).

Solid outputs: Solid outputs from the combustion of energy carriers comprises the ashes contained in the raw fuel and the fraction of C and S¹ that are not oxidized, i.e. not allocated to emissions (Table S6). Solid outputs were allocated to the DPO flow processing waste.

¹ Sulphur not allocated to emissions due to desulphurization of energy carriers and flue gas was allocated to solid waste output from energy use; it has to be noted that part of this S is actually used in industrial processes (as elementary Sulphur or gypsum), the overall volume of this flow is, however, small compared to overall DPO flows. In 2015 only 0.08 Gt/yr of Sulphur were allocated to solid wastes from energy production.
Table S6: Composition of energy carriers and share of carbon, Sulphur and nitrogen contained in energy carriers that is oxidized i.e., allocated to emissions) in 1900 and 2015.

| Chemical composition of extracted energy carrier | Hard coal | Brown coal | Petroleum | Natural gas | Fuel wood | Other biomass |
|------------------------------------------------|-----------|------------|-----------|-------------|-----------|---------------|
| Carbon                                          | 57.8%     | 42.9%      | 85.1%     | 71.0%       | 40.1%     | 40.3%         |
| Oxygen                                          | 7.1%      | 13.5%      | 0.5%      | 0.0%        | 35.1%     | 35.1%         |
| Hydrogen                                        | 4.3%      | 5.1%       | 11.9%     | 27.5%       | 4.8%      | 4.8%          |
| Sulphur                                         | 0.8%      | 0.7%       | 1.2%      | 0.0%        | 0.2%      | 0.02%         |
| Nitrogen                                        | 1.4%      | 1.9%       | 0.5%      | 1.5%        | 0.0%      | 0.0%          |
| Moisture                                        | 21.4%     | 32.1%      | 0.0%      | 0.0%        | 15.0%     | 15.0%         |
| Ashes (in fuel)                                 | 7.1%      | 3.8%       | 0.5%      | 0.0%        | 4.8%      | 4.8%          |
| **Share of total C, S and N content oxidized**  | 100.0%    | 100.0%     | 100.0%    | 100.0%      | 100.0%    | 100.0%        |

*) continuous increases in combustion efficiency is assumed throughout the period
**) continuous increases in flue gas cleaning sets in from 1989 onwards
***) desulphurization in refineries begins in 1952 at a low level and accelerates from 1979 onwards

S2 Sensitivity analysis

Although the database for economy-wide material flows is growing and MFA derived indicators are widely used in science and policy, attempts to quantify uncertainties of aggregate MFA indicators are still rare. In their review of international global MFA data (Fischer-Kowalski et al., 2011) have analyzed differences across available MFA datasets and found that estimates for global material extraction and use deviate by about ±10%, somewhat less for biomass and fossil energy carriers and somewhat higher for minerals. They conclude that, because of the high level of methodological standardization and the good quality of statistical data for extraction and trade, estimates of global DE and the other metabolic flows are robust and the observed trends over time reliable. In a comparison of all available series of global DE shown in Fig. S1a we find differences between this estimate (excl. additional sand and gravel) and other estimates of global material extraction in the period 1980 and 2010 to range between −7% and +6%. The inclusion of sand and gravel used as subbase and base-course layer in this study increases global DE by 7-12% above previous estimates for 2010 (Fig. S1b), which have so far underestimated extraction of these materials (Miatto et al., 2016). Beyond that, differences in the trend, size and composition of domestic extraction are small and of minor significance. They are mainly due to differences in estimation procedures applied for sand and gravel, grazed biomass and gross ore extraction and to a minor extent due to differences in the statistical data sources that have been used (Fischer-Kowalski et al., 2011).
Material extraction: To provide a rough assessment of overall uncertainty of our results for material extraction (DE), we utilize and combine information from previous studies investigating specific materials to derive maximum upper and lower bounds for primary data and coefficients applied in estimation procedures. Uncertainty of global biomass harvest has been assessed for the period 1910-2005 in Krausmann et al. (2013). Uncertainty about the global extraction of non-metallic (construction) minerals has been reported for 1970 to 2012, however, it were derived only from different assumptions made in estimation procedures, not from the primary data itself (Miatto et al., 2016). Uncertainty about metal production has been deemed very low in previous studies, however excluding the quantities and uncertainties for ores and waste rocks (Pauliuk et al., 2013; Liu and Müller, 2013). Cao et al. (2017) derived uncertainties about cement consumption from the differences in reported trade volumes, but not for production volumes themselves. Recently, Wang et al. (2018) assessed global socioeconomic metal cycles and semi-quantitatively assessed uncertainty of mining and all other production and consumption stages. In summary, these studies found that extraction and consumption trends over time are robust for all materials and that uncertainty ranges between ±15% and ±28% for biomass materials, ±6% and ±8.5% for non-metallic minerals, ±2% to ±10% for metal production and mining and ±10% for cement consumption in developed countries and ±20% in developing countries.

In this study we performed a sensitivity analysis for global material extraction at a medium level of aggregation taking both uncertainties in primary data from statistical sources and in key assumptions made in estimation procedures into account. In general, there is little systematic information on the uncertainty of data reported in international statistical databases available. We derived plausible uncertainty ranges of data and coefficients from the literature, from assumptions made in previous studies or based them on our own assessment, drawing on extensive experience in working with statistical data. Uncertainties for crop and wood harvest were based on assumptions made in Krausmann et al. (2013) and in Lauk et al. (2012); uncertainties for grazed biomass were estimated based on differences in the results from studies using different estimation procedures (Herrero et al.,
2013; Krausmann et al., 2013; Wirsenius, 2000), own estimates and information on uncertainties in land use and livestock data from IPCC guidelines (Eggleston et al., 2006); uncertainties for fossil energy carriers were derived from considerations in Marland and Rotty (1984) and Marland et al. (2009). For metals previous studies mainly provide assumptions about the production of metals, usually ignoring gross ore production (Glöser et al., 2013; Liu and Müller, 2013; Pauliuk et al., 2013; Wang et al., 2018). Only Wang et al. (2018) considered extracted ores. In general, uncertainty for metal production is considered to be very low; here we assumed higher uncertainties for the extraction of ores. For the uncertainty in global cement data and various assumptions made to estimate DE of sand and gravel we used information in Miatto et al. (2016) and Cao et al. (2017).

As a general rule, we assumed that uncertainties in statistical data were higher in the beginning of the observed period and declined with the advancement and standardization of international statistical accounting after World War II. We further assumed that uncertainties are lower for materials of high economic or strategic significance for which elaborate statistical reporting is established (e.g., crops, fossil energy carriers, metals) than for materials of low economic significance and for estimated flows (e.g. non-metallic minerals for construction). Table S7 provides an overview of the assumed uncertainties in 1900 and in 2015. Asymmetric assumptions for uncertainties reflect that for some materials we assume that reported data or estimates are closer to the lower than to the upper bound of uncertainty (or vice versa).

**Table S7: Assumptions for uncertainties of primary data and applied coefficients used in the sensitivity analysis of material extraction**

| MFA parameter                      | 1900  | 2015  | Sources                                      |
|-----------------------------------|-------|-------|----------------------------------------------|
| Crop harvest                      | ±20   | ±10   | Krausmann et al. (2013)                      |
| Crop residues factor              | ±20   | ±20   | Own estimate                                 |
| Grazed biomass (incl. forage)     | +15/-25 | +10/-15 | Herrero et al. (2013), Wirsenius (2000), Krausmann et al. (2013), own calculations |
| Wood                              | +40/-20 | +20/-10 | Lauk et al. (2012), Eggleston et al. (2006), Krausmann et al. (2013) |
| Fossil energy carriers            | ±10   | ±5    | Marland et al. 2009                         |
| Iron ore                          | ±15   | ±10   | Own estimate based on Wang et al. (2018).    |
| Bauxite                           | ±15   | ±10   | Own estimate based on Wang et al. (2018).    |
| All other metals (content)        | ±15   | ±10   | Own estimate, based on Wang et al. (2018).  |
| All other metals gross ore factor | ±25   | ±15   | Own estimate                                 |
| Bitumen                           | ±10   | ±5    | As for fossil energy carriers                |
| Bitumen factor                    | ±20   | ±20   | Miatto et al. (2016)                         |
| Cement                            | ±15   | ±10   | Cao et al. (2017)                            |
| Limestone factor                  | ±5    | ±5    | Miatto et al. (2016)                         |
| Concrete factor                   | ±5    | ±5    | Miatto et al. (2016)                         |
| Additional aggregates             | ±30   | ±30   | Own estimate based on Miatto et al. (2016).  |
| All other non-metallic minerals   | ±25   | ±25   | Own estimate based                            |

Figure S2 shows the results for global DE and displays the maximum upper and lower bounds of the uncertainty estimates based on the assumptions presented in Table S7. We find that in 1900 overall uncertainty about global extraction was at ±23% and declined to ±16% in 2015 (Fig. S2a and Fig. S2b). In 2015 uncertainty was highest for non-metallic minerals (±20%) and lowest for fossil energy carriers (±5%) (Fig. S2c).
Figure S2: Uncertainty of results for global material extraction (DE). Maximum upper and lower bounds in absolute values (S2a), relative to the main result (S2b) and for main material groups in 2015 (S2c).

Stocks of manufactured capital and domestic processed outputs (DPO*) from stocks: For in-use stocks of manufactured capital and DPO* from discarded stocks, which are both calculated using the MISO model, we followed the approach outlined in Krausmann et al. (2017) and used Monte Carlo simulation to propagate errors for all parameters throughout the modeling, that is, for material input data, lifetime distribution and recycling rates of material from discarded stocks. The assumed uncertainties of model input data and the applied coefficients are documented in detail in the Supporting Information (Table S4) to Krausmann et al. (2017). Uncertainties of results are shown as ±3 standard deviations (99.7% confidence interval) over $10^3$ Monte Carlo simulations (MCS) in Fig. S3a (stocks) and Fig. S4 (DPO*). For stocks we also tested for systematic errors in the assumed values for mean lifetimes using a sensitivity analysis (Fig. S3b). Three different sensitivity tests for the parameter mean lifetimes were modeled: All mean lifetimes as used for the main result were decreased by $-30\%$ (LT-1/3), increased by $+30\%$ (LT+1/3) and increased by $+50\%$ (LT+50%). A decrease of $-50\%$ was not included as it did not seem plausible.

Figure S3 shows the results of the MCS and sensitivity analysis for stocks of manufactured capital in absolute values (Fig. S3a) and relative to the main result (Fig. S3b). We find that overall uncertainty ranges from $\pm18\%$ to $\pm5\%$ for total stocks between 1900 and 2015 and that trends over time are very robust. In 2015 uncertainties were highest for stocks of fossil materials ($\pm7\%$) and lowest for stocks of metals ($\pm3\%$) (Fig S3c)
Figure S3: Uncertainty of results for global in-use stocks of manufactured capital. Results for error propagation using Monte Carlo Simulations in absolute values (S3a); sensitivity of results for variations in mean lifetime (LT) of stocks (LT -1/3, LT +1/3, LT +50%) relative to main result (including the error band of Monte Carlo uncertainty, shaded area) (S3b); Monte Carlo uncertainties of in-use stocks of main material groups in 2015 (S3c).

Figure S4 shows the results of the MCS for DPO* from stocks (after recycling). The robustness of DPO* from stocks of manufactured capital is strongly influenced by the assumptions on lifetime distribution of stocks and recycling rates; the uncertainty of waste output from discarded stock is therefore higher than that of stocks and ranges between ±20% and ±11 in the observed period. In 2015 uncertainty was highest for fossil materials (±78%) and lowest for metals (±17%).

Figure S4: Uncertainty of results for domestic processed outputs (DPO*) from stocks of manufactured capital. Results for error propagation using Monte Carlo simulations in absolute values (S4a) and relative to main result (S4b); Monte Carlo uncertainties of DPO* for main material groups in 2015 (S4c).

Other DPO flows: DPO flows which are directly derived from input flows using process information and stoichiometry (e.g. wastes and emissions from energy use and food and feed use, other dissipative use) are assumed to be of a similar robustness as DE. This is corroborated by crosschecks with results from established emission series, which have shown that differences between our calculations and these series are small and range between 1% and 2% for cumulative emissions of CO\textsubscript{2}, SO\textsubscript{2} over the observed period.
### S3 Global stock convergence scenario

#### Table S8: Overview of main scenario assumptions: global or global average values

| Parameter                                                                 | 2014 | 2050 | Change 2014-2050 | Note                                                                                       |
|---------------------------------------------------------------------------|------|------|------------------|--------------------------------------------------------------------------------------------|
| Population (bn. head)                                                     | 7.2  | 9.1  | +27%             | UN population prospect, medium variant                                                    |
| Supply of animal based food (GJ/cap/yr)                                   | 0.78 | 1.5  | +81%             | Convergence at per capita level of industrial countries                                  |
| Supply of plant based food (GJ/cap/yr)                                    | 3.62 | 3.9  | +8%              | Convergence at per capita level of industrial countries                                  |
| Feed conversion efficiency: Market feed (kg dm/GJ animal based food)      | 255  | 178  | -30%             | Continuation of average annual efficiency gain 1970-2014                                |
| Feed conversion efficiency: Roughage (kg dm/GJ animal based food)         | 1199 | 1021 | -17%             | Continuation of average annual efficiency gain 1970-2014                                |
| Food conversion efficiency: Crops (kg dm/GJ plant based food)             | 85   | 75   | -12%             | Continuation of linear trend 1961-2013                                                   |
| Per capita stocks of manufactured capital (t/cap)                        |       |      |                  |                                                                                           |
| Stocks of manufactured capital (Gt)                                      | 131  | 323  | +146%            | Convergence at per capita level of industrial countries                                  |
|                                                            | 928  | 3137 | +238%            | Assuming exponential growth                                                               |
| Share of secondary materials in inputs to stock                         | 89%  | 80%  | -10%             | Continuation of trend 1970-2014                                                          |
| Conversion efficiency of primary materials to inputs to stock            | 82%  | 82%  | 0%               | Continuation of historic trend                                                           |
| Input intensity: Energy carriers used to build up and renew stock (kg energy materials / t material input) | 88   | 55   | -37%             | Extrapolation growth rate 1971-2014 (power function), comprises improvements in final energy use per unit of material input to stock and material intensity of final energy provision |
| Service intensity: Energy carriers used to provide services from stock (kg energy materials / t stock) | 11   | 6    | -47%             | Extrapolation growth rate 1971-2014 (power function), comprises improvements in final energy use per unit of stock and material intensity of final energy provision |
| Other dissipative use (kg/cap/yr)                                        | 0.84 | 1.0  | +19%             | Extrapolation from long term historic trend                                               |
S4 Material intensity

Figure S5: Comparison of the development of material intensity (DE per unit of GDP) from 2002 to 2015 using real GDP and GDP in purchasing power parities (PPP). GDP in international $ at constant prices of 1990 from Maddison (2013) and GDP in PPP in constant prices of 2011 from The World Bank (2017). Normalized to 1 in 2001.
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