Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use

Supporting Information (SI)

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Contents

1 Model documentation

1.1 System boundaries, stocks, flows and derived indicators

The MISO (Material Inputs, Stocks and Outputs) model is a mass-balanced, dynamic top-down inflow driven model (1–3). It is fully consistent with the principles of economy-wide material flow accounting (4–6) with respect to the definition of material stocks and flows and the applied system boundaries. This is an important feature of the MISO model, which has been built to complement and expand material flow accounting tools and to provide information consistent with MFA headline indicators as they are now widely used in science and policy (7). Figure S1 depicts the system boundaries of the MISO model and how it is linked to economy-wide Material Flow Accounting (MFA).

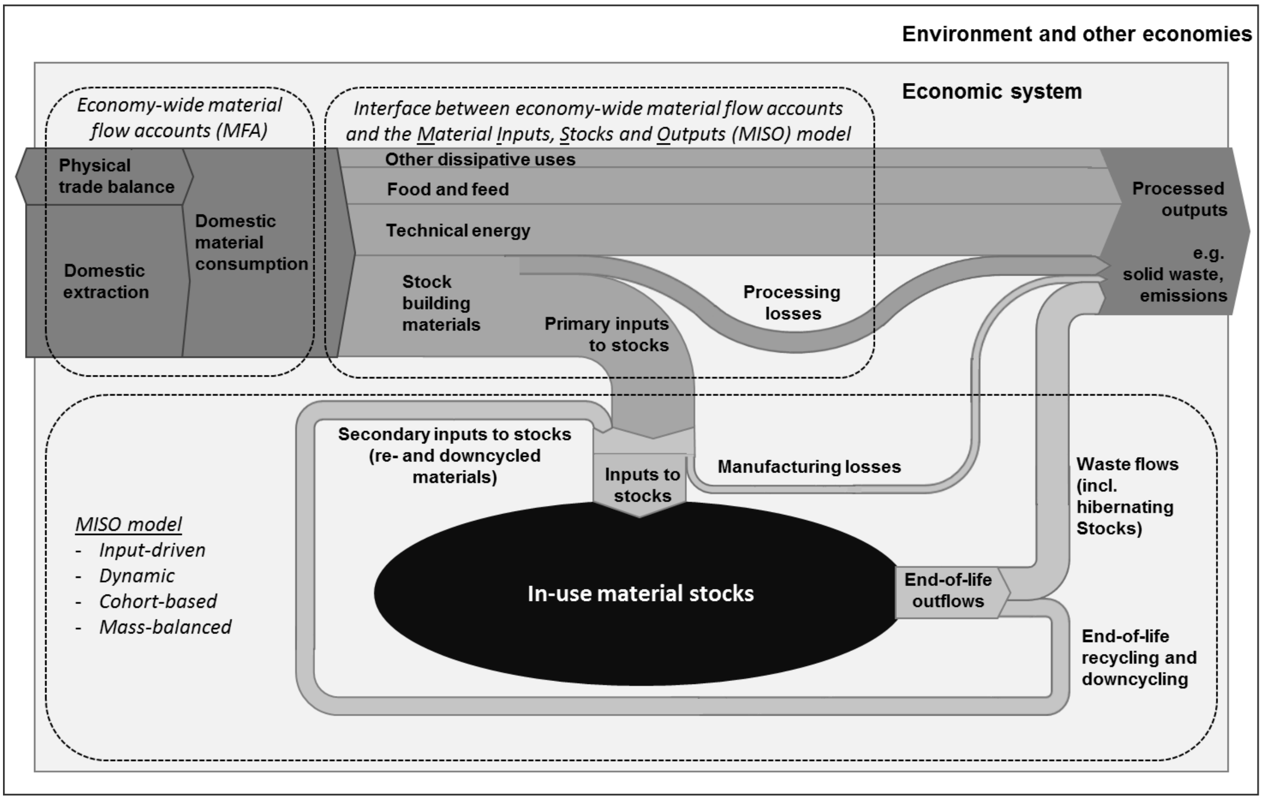


Figure S1: MISO model: System boundaries and material flows. Data from a global material flow database are converted into primary material inputs to stocks (Material Flow Accounting (MFA)-MISO interface) which serve as main input data for the dynamic MISO model The MISO model quantifies in-use material stocks as well as end-of-life outflows from discarded stocks, recycled materials and waste flows.

MFA provides detailed information on the extraction (**domestic extraction, DE**) of all materials (biomass, fossil energy carriers, metal ores and mineral materials) and, at the sub-global level, also on trade with raw materials and products. The **physical trade balance (PTB)** measures net trade (imports minus exports). Material use (**domestic material consumption, DMC**) is defined as the sum of DE and PTB (7).

The interface module links data from the global MFA database (see section 2.2) and the MISO model. It distinguishes between throughput materials that are consumed within a year and leave the economy as wastes and emissions, and stock-building materials. The former comprise all materials used to provide technical energy (fossil fuels, fuel wood), food and feed and other materials used in a dissipative way such as salt or fertilizer minerals. **Stock-building materials** comprise the raw materials used to produce the actual **primary inputs in stocks**. Initial processing of stock-building materials results in a considerable loss of mass comprising, for example, waste rock from ore processing, CO_2 from the calcination of limestone for cement production or changes in moisture content (e.g. in brick production). These losses are termed **processing losses** in Figure S1 and are considered wastes and emissions. **Primary inputs to stocks** are then defined as stock-building materials less processing losses and are a data input for the MISO model.

In the MISO model actual **inputs to stocks** are calculated by subtracting manufacturing losses from primary and secondary inputs to stocks. The flow **manufacturing losses** in Figure S1 comprises waste flows that occur during manufacturing of primary and secondary (i.e., recycled or down-cycled materials from end-of-life outflows from stocks) inputs. Note that recycled manufacturing scrap (pre-consumer scrap) is considered an internal flow as it remains within the manufacturing process; it is therefore not explicitly dealt with in the model. The material inputs to stocks remain in the system as **in-use material stocks** (short: material stocks) until the end of their service lifetime is reached (see section 1.4) and then turn into **end-of-life outflows**. A fraction of end-of-life outflows is recycled or down-cycled and used as **secondary inputs into stocks**. Note that recycled or down-cycled pre-consumer scrap is not included in secondary inputs into stocks. Recycling denotes the use of the material in the same stock type (e.g. metals), down-cycling denotes the use in a different stock type (e.g. crushed concrete used as base-course or sub-base layers in construction). The remainder of end-of-life outflows is considered waste and comprises both actual landfilled or uncontrolled waste and hibernating stocks. These unused or hibernating stocks remain in place without function and maintenance, but due to lack of data currently cannot be separated from waste flows (8, 9).

In the MISO model annual gross additions to stocks from primary and secondary inputs to stocks are handled as explicit cohorts and tracked throughout the entire time period, similar to a vintage, demographic or biological population model (Figure S2). End-of-life outflows are modeled from information on lifetime distributions and recycling or down-cycling based on rates compiled from the literature (see section 2 for details). Monte-Carlo Simulations are used to comprehensively propagate stochastic parameter uncertainty.

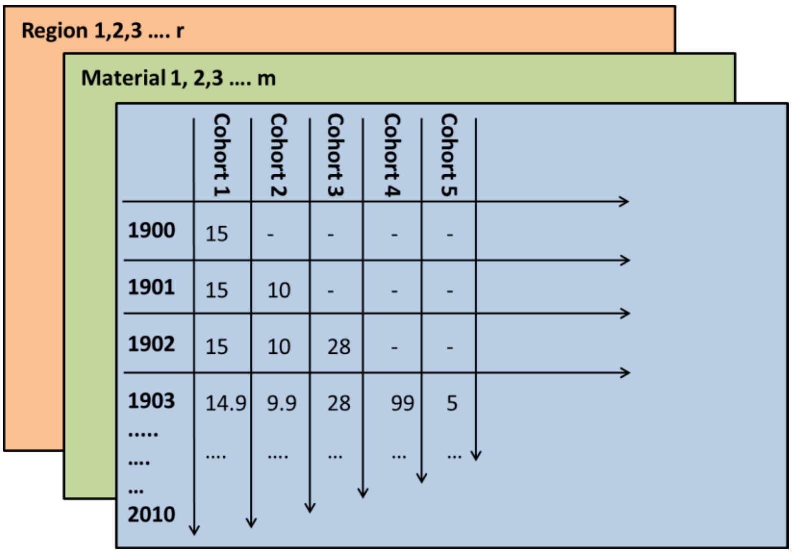


Figure S2: Structure and organization of the data in the MISO model

Based on the material flows calculated in the MISO model, we define two types of recycling rates:

$$\text{End}-\text{of}-\text{life recycling rate} = \frac{Secondary\ inputs\ to\ stocks}{End-of-life\ outflows}$$

$$\text{Recycling input rate} = \frac{Secondary\ inputs\ to\ stocks}{Primary\ inputs\ into\ stocks + Secondary\ inputs\ into\ stocks}$$

1.2 The generalized MISO model

The total stock of any material at a certain time *t* is calculated from the balance between annual inflows (inputs to stocks in Figure S1; data and model driven) and outflows (end-of-life outflows in Figure S1; model driven) plus the remaining stock from *t-1* (model driven). The annual inflow at the time *t* of material *m* in region *r* and Monte-Carlo Simulation *mc* is handled as its own cohort *c* = *t* of in-use stock $S^{mc}_{c,m,r}(t)$ (Eq. 1).

$$S^{mc}_{c,m,r}(t) = S^{mc}_{c,m,r}(t-1) + Inflow^{mc}_{c=t,m,r}(t) - Outflow^{mc}_{c,m,r}(t) \qquad \text{Equation 1}$$

The average cohort $\bar{C}$ of in-use stock $\bar{S}$ at the time *t* is then defined as the mean over all cohorts *c* of material *m* and region *r* in the Monte-Carlo Simulations *mc* at the time *t* (Eq. 2).

$$\bar{S}_{\bar{c},m,r}(t) = \frac{1}{n}\sum_{i=mc}^{n} S^{mc}_{c,m,r}(t) \qquad \text{Equation 2}$$

The total in-use stock of material *m* is then calculated as the sum over the average cohorts $\bar{c}$ of material *m* in region *r* at the time *t.* Uncertainty ranges are calculated similarly, where the standard deviations are calculated via error propagation for independent means (10), as well as minima and maxima of each Monte-Carlo run *mc* (Eq. 3).

$$\bar{S}_{m,r}(t) = \sum_{\bar{c}} \bar{S}_{\bar{c},m,r}(t) \qquad \text{Equation 3}$$

The annual inflow of material *m* at the time *t* in region *r* of Monte-Carlo Simulation *mc* is handled as its own cohort *c (c* = *t,* Figure S2*)*. The inflow is a combination of primary materials *Inflow_virgin* (data driven) and secondary materials (recycled *Recyl* as well as down-cycled materials D*cycl;* model driven) (Eq. 4). The parameter *manufacturing_losses* is used to correct for the share of materials that become waste during manufacturing processes and do not enter in-use stocks.

$$S^{mc}_{c=t,m,r}(t) = Inflow^{mc}_{m,r}(t) = [Inflow\_virgin^{mc}_{m,r}(t) + Recycl^{mc}_{m,r}(t) + Dcycl^{mc}_{m,r}(t)] * (1 - manufacturing\_losses^{mc}_{m,r}(t))$$

Equation 4

The material outflow from stocks at the time *t* is defined as the end-of-life outflows from all cohorts *c,* of material *m,* in region *r* and Monte-Carlo Simulation *mc*, determined via cohort, material, region and time specific lifetime distributions $L^{mc}_{c,m,r}\,(t,t')$. The lifetime distribution expresses the probability of each cohort *c* to reach the end of its useful service lifetime at the time *t* (Eq. 5).

$$Outflow^{mc}_{c,m,r}\,(t) = S^{mc}_{c,m,r}\,(t)\ *\ L^{mc}_{c,m,r}\,(t,t') \qquad \text{Equation 5}$$

Here the term L(t,t') then represents the probability that a stock cohort *c* of material *m* in region *r* and Monte-Carlo Simulation *mc* from time *t' < t* reaches its useful service lifetime at time *t*, assuming that these lifetimes follow a normal distribution with a mean lifetime τ and a standard deviation ∂ (shape of lifetime distribution) (see section 1.4) (Eq. 6).

$$L^{mc}_{c,m,r}\,(t,t')\ =\ \frac{1}{\sqrt{2\pi *\, \partial^{mc}_{c,m,r}}} * exp^{\frac{-\,(t-t'-\,\tau^{mc}_{c,m,r})^2}{2*\,\partial^{mc}_{c,m,r}{}^2}} \qquad \text{Equation 6}$$

This function is then normalized so that the integral over time equals 1 for any combinations of τ and ∂. But, as the lifetime cannot be negative (*t > t'*), a fraction of the curve is effectively cut-off, which can result in integrals smaller than 1 in this predefined positive area. This opens up the possibility that some cohorts are never entirely turned into outflows. However, this cut-off remains marginal when $2\partial \leq \tau$ (11).

The modeled end-of-life outflows from stocks can be recycled *Recycl*, i.e. material that reenters the original input flow (e.g. metals) or down-cyced *Dcycl*, i.e. material that enters a different input flow (e.g. if concrete or bricks are crushed and used as aggregates in sub-base layers), the reminder becomes waste.

Recycling is calculated on the basis of material-, time- and region- specific recycling rates $recy\_rate$, for each Monte-Carlo Simulation *mc* (Eq. 7).

$$Recycl^{mc}_{m,r}(t) =\ \left[\textstyle\sum_c outflow^{mc}_{c,m,r}\,(t)\,\right]\ *\ recy_{rate}{}^{mc}_{m,r}(t) \qquad \text{Equation 7}$$

A certain share of the remaining quantities is then assumed to be down-cycled. We apply material-, time- and region- specific down-cycling rate *dcycl_r* in each Monte-Carlo Simulation *mc* to quantify these amounts based on the on the remaining sum of outflows from stocks after recycling, of material *m* in region *r* and Monte-Carlo Simulation *mc* of recycled materials *recycl* (Eq 8).

$$Dcycl^{mc}_{m,r}(t) =\ \left[\textstyle\sum_c outflow^{mc}_{c,m,r}\,(t)\ - Recycl^{mc}_{m,r}(t)\right] * dcycl\_r^{mc}_{m,r}\,(t) \qquad \text{Equation 8}$$

Waste, in our approach, is then defined as the amount of outflows from stocks after recycling and down-cycling have been deducted. A distinction between actual waste flows (that enter waste treatment) or stocks that are abandoned but remain in place (so-called hibernating stocks) is not possible.

1.3 Quantifying uncertainty: the Monte-Carlo Simulations module

We incorporate a systematic quantification of stochastic uncertainty for our modeling results, using Monte-Carlo Simulations (MCS) (12, 13). The dynamic MISO model can be seen as a stochastic system, where each parameter is understood to be the mean μ of a normal (Gaussian) distribution with an uncertainty parameter σ. The simple but powerful idea behind Monte-Carlo Simulations is then that the entire model is run repeatedly (10^3 times) and for each of these independent iterations all parameters are stochastically defined anew within their respective normal distributions defined by µ and σ. When running a large number of iterations one can then treat all these simulations as a sample and calculate mean estimates and confidence intervals for all results, for example in-use stocks, end-of-life waste and recycling flows by material and region over the entire time series. For all of the following parameters errors are propagated through the modeling runs in each Monte-Carlo Simulation (Table S1). Given enough information, the uncertainty ranges for the parameters could be differentiated by cohort *c*, material *m*, region *r* and point in time *t,* but due to data constraints only for materials *m* different assumptions could be made (see SI section 2.4).

Table S1: Data for the MISO model parameters and coverage of the Monte-Carlo Simulations

MISO model parameter	**Data differentiated for each model parameter by …**				**Differentiated uncertainty ranges by material *m***
	Cohort *c*	**Material *m***	**Region *r***	**Time *t***	
Primary inputs into stocks	c = t	Yes	Yes	Yes	Yes
Manufacturing losses	c = t	Yes	No	All metals	Yes
Lifetimes μ	Yes	Yes	No	All metals	Yes
Shape of lifetime distribution σ	Yes	Yes	No	No	Yes
Base-course multiplier for roads	c = t	Only asphalt	No	Yes	Only applicable for asphalt
Sub-base layer multiplier for buildings	c = t	Only concrete and bricks	No	No	Same for concrete and bricks
Recycling rates *r*	c = t	Yes	Yes	Yes	Yes
Down-cycling rates *dcycl_r*	c = t	Only concrete, asphalt, bricks	Yes	Yes	Same for concrete, asphalt, bricks

For most parameters generalized assumptions on the underlying reliability of different types of data and sources had to be used. These assumptions were made on the basis of in-depth knowledge of data sources, information about data compilation methods available from technical documentation and from expert judgements. For example, data in material flow accounts has been subject to quality control and cross checks and is generally deemed to be reliable; it has been shown that different estimates of aggregate material use for countries and regions differ by 10–20% (7). Assumptions for model parameters such as lifetime distributions or recycling and down-cycling rates are derived from scattered evidence from the literature and are considered less reliable and therefore assigned higher uncertainty ranges. From the Monte-Carlo simulations we can then derive confidence intervals for all modeled results on material stocks and flows.

In addition to the Monte-Carlo Simulations we also performed sensitivity analysis for systematic errors from potential under- or overestimation of the assumed mean lifetimes. This is discussed in section 2.3.

1.4 Choosing the appropriate functional form for the lifetime distributions

Dynamic models of in-use material stocks apply different functional forms for the lifetime distributions of stocks (see e.g. (14) for metal stocks). The effect of using different functional forms of lifetime distributions L(t,t') has been investigated previously (15, 20). This includes the so-called delayed or leaching model using fixed lifetimes (16), Gaussian normal distributions (symmetrical), Gompertz (left-skewed), log-normal, gamma, and Weibull functions (right-skewed), just to cite the most common ones. Using a leaching model transmits any fluctuations in inflow data directly to outflows, which is rather unrealistic, because it assumes that the in-use stocks from a certain year all reach their end-of-life at exactly the same time. The other distributions have been shown to yield similar results for stocks, but can have a considerable influence on the dynamics of outflows from stocks (15, 17, 20). The appropriate function depends on the stock type (the lifetime distribution of transport equipment may have a different behavior than that of residential buildings or highways) (3, 18, 19), but also for the same stock type the most appropriate functional form of lifetime distribution may vary across time and space (20). The choice of function also depends on the availability of statistical data to calibrate specific functions to different types of stocks, because it requires empirical data on the specific end-of-life dynamics (18, 19).

Here we distinguish 11 types of in-use stock mainly by their material characteristics. Each of these stock types comprises stocks with different lifetime characteristics (e.g. the stock type concrete comprises concrete used in urban and rural regions, in family homes, industrial facilities, highways, tunnels, etc.). Because of this heterogeneity within stock types, in absence of detailed information on lifetime distribution and which side of "skewness" (e.g. a left-skewed Gompertz or a right-skewed log-normal distribution) best fits the global reality, we consider symmetrical distribution as the best compromise,. This is in line with the Central Limit Theorem, which postulates that the sum of independent variables tends towards a normal distribution, even if the original variables themselves are not normally distributed. The normal distribution is widely used in dynamic stock-flow models of materials and substances and it has the advantage that its descriptive parameters (the location parameter μ and the scale parameter σ) can be directly translated (μ is equal to the mean, median, and mode, and σ is equal to the standard deviation of the function) without any additional calculations in contrast to all the other functional forms which require calibration (14).

Based on the available literature we conclude that our stock estimate shows little sensitivity for the choice of lifetime distribution, which is corroborated by the good agreement with existing estimates of stocks, as shown in section 4.1 of the SI. However, the sensitivity of estimates of wastes and recycling flows to the choice of lifetime distribution is higher, because small differences in stocks can lead to much larger differences in outflows. This is especially relevant for future scenarios of waste flows without possible calibration.

1.5 Spin-up module: Approximating in-use stocks dynamics from 1820–1900

To estimate stocks beginning from the year 1900 it has to be taken into account that stocks do not develop from zero. In-use stocks accumulated prior to 1900, as well as resulting end-of-life outflows and recycling flows, must be considered. An approximation of these initial stocks and flows is required to properly estimate the dynamics for the period under investigation (1900–2010). Therefore a spin-up period has been implemented which provides an appropriate initial value of material stock by age group as well as for end-of-life waste and recycling for the year 1900. The length of this spin-up period is determined by the longest lifetime used in the modeling (80 years) and begins in 1820.

1.6 Primary (natural) and down-cycled aggregates – a gap calculation

Aggregates (sand, gravel, crushed stone) used in base-course layers of roads and sub-base layers in buildings are underreported in MFA databases (21). But these materials constitute a significant inflow of materials into stocks and natural aggregates can be substituted by re- or down-cycled construction and demolition wastes from bricks, asphalt and concrete. To properly capture the flow of primary (natural) and secondary (recycled or down-cycled) aggregates for these applications we developed a submodule which estimates the demand for primary aggregates taking available secondary aggregates into account. The estimation of the required total amount of aggregates is based on a procedure and coefficients provided in ref. (21): 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 (21) (Eq. 9). The value of the *base_course_multiplier* in time *t* takes into account that with the expansion of road networks over the observed time period an increasing share of asphalt is used in the refurbishment of existing roads, requiring much less aggregate. We assume that aggregate requirement per Mg of asphalt remained constant at 100 Mg until 1940 and then declined to 50 Mg in 1980 and then remained at this level. Based on the variability reported in ref. (21), we derived an uncertainty range (one standard deviation) of ± 30% of the aggregate intensity for the Monte-Carlo Simulation.

$$Aggregate\_base\_course_{\,r}(t) = Asphalt\ (t) * base\_course\_multiplier_{mc}(t) \qquad \text{Equation 9}$$

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 (Eq. 10). Miatto and colleagues (21) analyzed Japanese government data on construction activities for various types of structures ranging from single family houses to skyscrapers and factories (22) and estimated an average of 70 kg of aggregate in sub-base layers per Mg of concrete and 45 kg per Mg of bricks used in construction (Concrete_*sub-base_mult* & *Bricks_sub-base_mult*). For concrete this can vary from 0–140 kg and for bricks from 0–70 kg; from this we derive an uncertainty range of ± 33% (one standard deviation).

$$Aggregate\_sub\_base\_layer_r\ (t) = Concrete_{\,r}\ (t) *\ Concrete\_sub\_base\_mult_{mc}\ + Bricks_{\,r}\ (t) * Bricks\_sub\_base\_mult_{mc} \qquad \text{Equation 10}$$

The demand for aggregates for base-courses and sub-base layers can be met either by using primary natural aggregates (sand and gravel) or by using secondary resources (e.g. crushed concrete or asphalt). To estimate the amount of required primary resource extraction we implemented a gap calculation into the model. This module compares the estimated total requirements for aggregate in base-courses and sub-base layers with the available amount of recycled aggregates and down-cycled concrete, asphalt and bricks from the model estimate. The gap between estimated demand and available re- and down-cycled material is considered demand for primary aggregate extraction (Eq. 11).

$$Virgin\_aggregate_{\,r}\ (t) = Aggregate\_sub\_base\_layer_{r,mc}\ (t) +\ Aggregate\_base\_course_{\,r,mc}\ (t) - Recycl_{\,m,r,mc}(t) -\ Dcycl_{\,m,r,mc}\ (t) \qquad \text{Equation 11}$$

2 Data and Sources

2.1 Overview

In its current resolution the MISO model distinguishes 11 types of in-use stocks of materials characterized by their material properties rather than final use or functional characteristics:

- Biomass: solidwood, paper and paperboard
- Fossil materials: plastics, bitumen/asphalt
- Metals: iron and steel, copper, aluminum, other metals and minerals
- Non-metallic minerals: concrete, bricks, sand and gravel (primary natural aggregates and down-cycled construction and demolition waste).

Stocks and flows of materials are modeled for the period 1900 to 2010. Due to the spin-up period required to estimate the initial stocks and flows in 1900, input data are required for the time period 1820 to 2010. In addition to data on inputs of stock-building materials also information on lifetimes of the different stock types, end-of-life recycling rates and uncertainty ranges for these parameters are required. We focus on modeling global stocks, but additionally distinguish one country (China) and two country groups (Industrial Countries, Rest of the World (RoW)). At the sub-global level we only report aggregate stocks and flows, as region and time specific information on lifetimes and recycling rates for specific materials is fragmentary.

2.2 Material flow data

The main reference source for material input data is a comprehensive global material flow (MFA) database that provides long term data on global material extraction, trade with materials and apparent consumption of materials, which were compiled following agreed upon accounting principles and methodological guidelines (23, 24). The database provides global annual time series for the period 1850–2010 and national level data for the period 1950–2010 (25–27). Due to the spin-up period input data are required for the time period 1820 to 2010. To derive material input data for the years not covered by the MFA database (1820–1850 and for some materials (e.g. wood, bricks) also for the period 1820–1900), we assumed constant per capita material use before 1850 or 1900, respectively and extrapolated total inflows by multiplying per capita flows with population data sourced from the Maddison Project (28).

The MFA database distinguishes between 40–65 material groups and enables the identification of all important stock-building materials, i.e. materials which accumulate in in-use stocks with a lifetime typically longer than one year (see Figure S1). Table S2 provides an overview of the materials considered as stock-building materials in the MFA database. Data on sand and gravel used as sub-base and base-course layers in the construction of roads and buildings are initially not covered in the MFA database and are estimated in the MISO model on the basis of concrete, brick and asphalt use and specific multipliers (21) (SI section 1.5). Primary materials extracted to cover the estimated demand amount to roughly 6.8 Pg/yr in 2010 and increase the value for global material extraction reported in ref. (27) to 78 Pg/yr. Overall, we consider the coverage of stock-building materials as high (above 98% in terms of mass), although for a few material flows (e.g. building stone, slate) no data are available or could be estimated.

Table S2: Correspondence of stock-building materials as reported in the material flow database (26, 27) and primary material inputs to stocks used as input data in the MISO model. The column “uncertainty range” refers to uncertainties assumed for primary inputs to stock. The column “additional sources” lists the main sources used to obtain data on primary inputs to stocks or information used to convert MFA data into input data and to derive coefficients for losses during primary material processing (processing losses) and during manufacturing

(manufacturing losses) (see Figure S1). The percentage ranges of processing losses for metals are due to changes in ore grades over time derived from information in the MFA database. n.d. … no data.

Stock-building materials (MFA)	**Primary material inputs to stock**	**Uncertainty range** (± three StdDevs)	**Processing losses**	**Manufacturing losses**	**Additional sources**
Industrial roundwood	Solidwood	15%	10%	27%	(29)
Industrial roundwood	Paper and paperboard	15%			(29)
Iron ore	Iron and steel	15%	42–58%	17.5%	(30–34)
Copper ore	Copper	15%	96–99%	2.7%	(2, 31, 33)
Bauxite	Aluminum	15%	80–86%	7.6%	(31, 33, 35)
Other ores and minerals	Other metals and minerals	15%	91–97%	9.2%	(26, 33)
Crude oil/natural gas	Plastics	15%	n.d.	10%	(36)
Crude oil	Bitumen/asphalt	15%	n.d.	4%	(37–39)
Limestone, gypsum, clay	Cement/concrete	15%	44%	4%	(40, 41)
Clay	Bricks	45%	26%	4%	(42)
Sand and gravel	Split into sand and gravel used in concrete and asphalt	60%	0%	4%	(21, 24)
Not in database (see SI section 1.5)	Sand and gravel required as sub-base and base-course layer for road and building construction	60%	0%	0%	Calculated on the basis of concrete and asphalt use and coefficients from ref. (21)

The interface module (Figure S1) links data from the global MFA database with the MISO model. The primary raw materials reported in the MFA database that were identified as stock-building materials are converted into primary inputs to stocks (input data for the MISO model) using additional information from industry and production statistics and specific literature. Table S2 provides an overview of the stock-building materials reported in the MFA database, the corresponding model input data and the additional sources used. Primary inputs to stocks comprise raw materials and semi-manufactures such as metal contained in ores, concrete, asphalt or solidwood and paper. The difference between the mass of stock-building materials reported in the MFA database and primary inputs to stocks is considered a processing loss (Figure S1). Processing losses comprise, for example, tailings from gross ore processing, CO_2 from the calcination of limestone, bark from the processing of roundwood, or water vapor from changes in moisture content (wood, clay). These losses are either estimated by applying specific coefficients (e.g., average ore grades, stoichiometric relations) derived from the MFA database and literature or they are calculated as the difference between the stock-building material reported in MFA and data on primary inputs to stocks from additional data sources. In the latter case plausibility checks were made to assure consistency across the different data sources. Table S2 shows the average share of processing losses in stock-building materials and provides references to the data sources used (see section 2.4 for details).

In addition to the processing losses that occur during the conversion of extracted raw materials into primary inputs to stocks, losses may also occur during manufacturing of in-use stocks of materials. The MISO model takes losses from the manufacturing of primary and secondary inputs to stocks into account (Figure S1). Table S2 shows the average share of manufacturing losses in inputs to stocks, for details including sources see section 2.4. Note that manufacturing scrap (pre-consumer scrap) that is recycled or down-cycled is considered an internal flow and therefore not included in secondary inputs into stocks and recycling rates.

According to our calculation, the difference between the extracted stock-building materials and the actual primary inputs to stocks ranges between 13% and 30% in the observed period (Fig. S3). Figure S4 shows that inflows of stock-building materials by groups of stock-building materials increased from 1 to 36 Pg/yr, concrete being the largest fraction of inflow. The quality of material inflow data is regarded to be good (7) and we used uncertainty ranges of ± 15%. For clay and natural aggregates used in concrete, asphalt and base layers we assumed higher uncertainties of ± 40% (see Table S2).

Figure S3: Share of processing losses and primary inputs to stock (by material group) in stock-building materials (see Figure S1 for definition of flows).

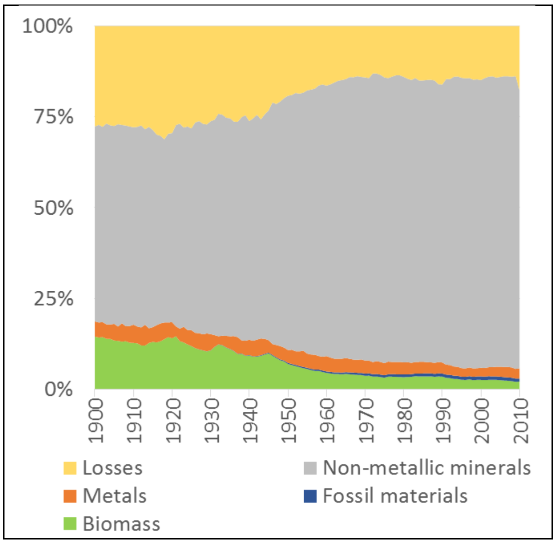
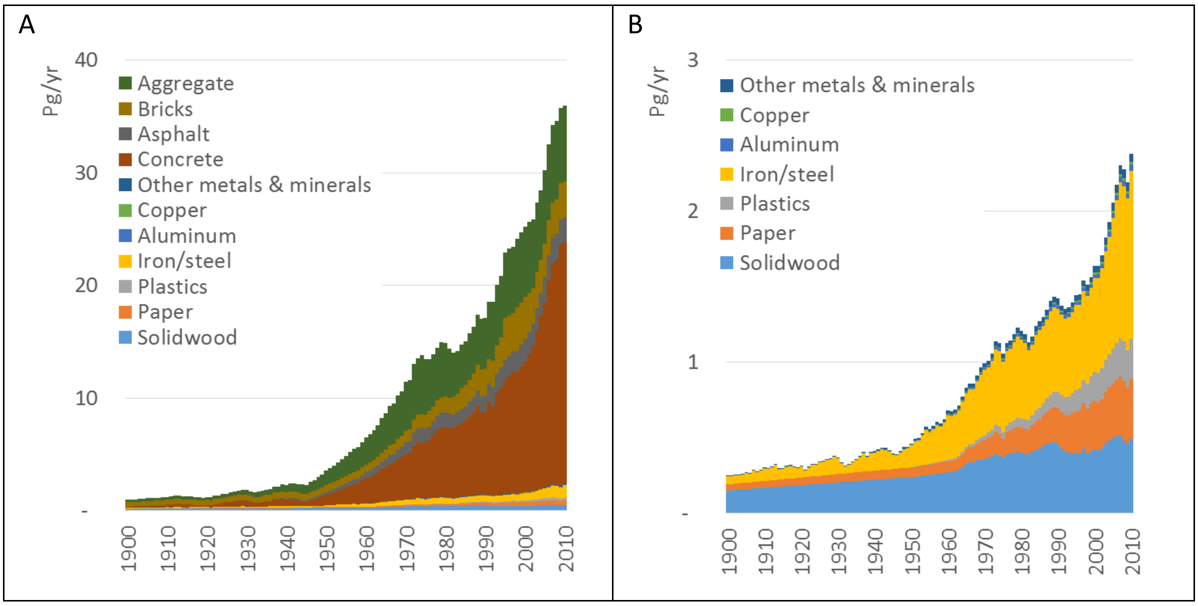


Figure S4: Development of primary inputs to stocks 1900 to 2010. S4A: Total primary inputs by 11 material groups; S4B: Primary inputs of biomass, metal and fossil materials. Note the different scale between S4A and S4B.



2.3 Regionalization of material flow data

In the current version of the MISO model we distinguish one country (China) and two country groups (Industrial Countries, Rest of the World (RoW)). Table S3 lists the countries included in each grouping.

For the period 1950/60 to 2010 country level data on material extraction, trade and use are available from the global material flow database (27) and also from most additional industry and production statistics databases (Table S2). This allows for the compilation of data on the apparent consumption of stock-building materials/inputs to stock for countries and country groups, consistent with global MFA results. Prior to 1950/60 no or limited country specific information was available. To obtain flows at the level of country groups we held the shares of the groups in the global flow in the last year for which country specific data were available (typically 1950 or 1960) constant and applied the share to the global total of the respective year.

Trade: At the sub-global level trade flows need to be taken into account in the calculation of inputs to stocks. Data on net trade for individual countries and country groups is available from the global material flow database (physical trade balance) or from additional material specific sources (see Table S2). In the MFA database trade flows at the three digit level of the Standard International Trade Classification, revision 1 (SITC rev.1) are allocated to material groups. Additional sources report production, trade and often also apparent consumption of specific materials or substances. Based on trade data from these sources it is possible to take trade with raw materials (e.g. metal contained in concentrates, metal ingots, scrap) and semi-manufactures (e.g. plates, rods, wires) into account. Trade with raw materials and semi-manufactures accounts for the largest part of trade flows. Trade with finished products consisting of a mix of materials which cannot be allocated in a straight forward way to one specific material (e.g. transport equipment, machinery, electric appliances, furniture) was not taken into account. This may lead to an underestimation of trade flows of metals and to a lesser extent also of plastics and wood for China and to a lesser extent also for the two country groups: A rough estimate based on PTB data (27) indicates that net trade of country groups with finished products is very small for most of the observed period and only reaches a relevant size after 1990. Data from the World Steel Institute (34) show that the impact of neglecting trade with finished products may lead to an overestimation of apparent consumption of iron and steel in China by 8% in 2010, but is much lower in 2003 and also for the two country groups. As the size of net trade of manufactures becomes a significant flow only in the last decade, the impact on the stock estimate is very low. Given the small share of metals and plastics in global material stocks the impact of the underestimation of net trade on total stocks is negligible.

Table S3: Country groups

	Industrial countries	China	Rest of the World (RoW)
Population 2010 [millions]	1,461	1,336	3,938
GDP/cap/yr 2010 [1990 intern. Geary Khamis $]	18,979	6,714	3,737
Definition of world regions	Europe, Soviet Union/ Former Soviet Union countries (USSR/FSU), USA, Canada, Australia, New Zealand, Japan	China	All other countries: Asia excluding Japan and China, Africa, Latin America and the Caribbean, Oceania excluding Australia and New Zealand
List of considered countries	Austria, Belgium, Luxembourg Denmark, Finland, France, Germany,	China	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo (Dem Republic of), Congo

	Greece, Iceland, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, Belarus, Kazakhstan, Kyrgyzstan, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Albania, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, T.F.Yug.Rep. Macedonia, Republic of Moldova, Poland, Romania, Yugoslavia, Slovakia, Slovenia, Ukraine, Canada, United States, Australia, New Zealand, Japan		(Republic of), Côte d'Ivoire, Djibouti, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Réunion, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania (United Rep of), Togo, Uganda, Zambia, Zimbabwe, Ethiopia (Territory of), Eritrea, Ethiopia, Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Fiji Islands, French Polynesia, India, Indonesia, Korea (Dem People's Rep), Korea (Republic of), Laos, Malaysia, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Samoa, Solomon Islands, Sri Lanka, Thailand, Timor-Leste, Vanuatu, Viet Nam, Argentina, Bahamas, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela (Boliv Rep of), Algeria, Bahrain, Egypt, Iran 8Islamic Rep of), Iraq, Israel, Jordan, Kuwait, Lebanon, Libyan Arab Jamahiriya, Morocco, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, Yemen

2.4 Parameters for losses, lifetime distributions, recycling and down-cycling and uncertainties

The MISO model requires information on production and manufacturing losses, lifetime distributions of stocks and end-of-life recycling rates for the different material or stock types. We have made an extensive literature research to gather time and region specific data for lifetimes and recycling rates for all material types, but reliable information on regional differences and development over time is scarce and could only be found for some parameters. Wherever we could not identify time and region specific parameters, we used global averages held constant over time.

In this section we briefly summarize the findings of the literature survey, the assumptions we made for global average values (and, if available, also for region specific values). We describe the parameters for the lifetimes and the respective normal distribution in terms of mean lifetime ± years (expressed as 99.7% range or three standard deviations for the probability that the stock comes to the end of its lifetime in these years). For the uncertainty ranges used in the Monte-Carlo Simulations we express the error range as a percentage of the respective parameter value, containing 99.7% (or three standard deviations) of the stochastic realizations of these variables throughout the 10^3 Monte-Carlo Simulations (MCS). Table S4 provides an overview of the assumptions we made for normal lifetime distributions and global average recycling/down-cycling rates as well as assumed uncertainty ranges for the years 1900 and 2010. An overview on the values assumed for processing and manufacturing losses is provided in Table S2.

We distinguish 11 stock types based on material characteristics. Each stock type may comprise stocks with rather different lifetimes (e.g. steel is used in cars, machinery, reinforced concrete, transport infrastructure) and in some cases physical interrelations between stock types exist (e.g. reinforced concrete is a combination of concrete and steel). As far as detailed enough information was available we have calculated average lifetimes for stock types as weighted averages of the different stocks and applications included in the stock type, taking interdependencies between stock types (e.g. steel and concrete) into account.

Solidwood, paper and paperboard: For industrial roundwood we assume processing losses (bark) of 10% (23). Based on data reported in FAO forestry statistics we estimate that losses during manufacturing of solidwood products and paper amount to 27% (incl. changes in moisture content) (29). Average lifetimes for solidwood products and paper/paperboard are based on the tier 1 approach of the IPCC guidelines for harvested wood products (43). These parameters have been confirmed by a review of case studies in previous work of the authors (44). The recycled amount of paper and paperboard is based on data from FAOSTAT (29) for 1961 to 2010; recycling rates were calculated from modeled end-of-life outflows from stocks and the reported amount of recycled paper products. Prior to 1961, we keep recycling rates constant at the level of 1961. For solidwood products, we assume material recycling to be negligible and therefore set recycling rates to zero. Thermal energy generation from end-of-life waste of wood and paper has not been considered as re- or down-cycling and is not taken into account.

Iron and steel: According to the MFA database (26) the global average ore grade of iron ore fluctuates between 58% and 42%; manufacturing losses were estimated at 17.5% (30). A study on global iron flows (45) reports a sectoral split of global iron and steel use and corresponding lifetimes for different iron and steel products: 40% construction (lifetime 75 years), 25% transport (lifetime 20 years), 25% machinery and appliances (lifetime 30 years), 10% others (lifetime 15 years). From this we calculate a weighted mean lifetime of 44 ± 22 years. Average lifetime for iron and steel was held constant for the whole period. A significant fraction of steel is used in combination with concrete (reinforced concrete). This is reflected in the overlap of the average lifetime of the two stock groups. For the MCS we used ± 15% on the mean lifetimes, similar to previous studies (45, 46). Our assumptions on the development of recycling rates of iron and steel is based on information for two data points: For 2010, we assume a recycling rate of 83% (75–91% for the MCS) for iron and steel (46), and a recycling rate of 74% in 1955 (47). We linearly interpolate recycling rates from these two data points for the whole time period, which means that recycling rates for iron and steel increase from 65% in 1900 to 83% in 2010.

Copper: According to the MFA database (26) the global average ore grade of copper ores declined from 4% in 1900 to 1.1% in 2010; manufacturing losses were estimated at 2.7% (2) Based on a study on global copper stocks and flows (2), we derived average lifetimes of copper products of 19 years in 1989 and 23 years in 2010. We held lifetimes constant at the level of 1989 prior to 1989. For the MCS we used ± 15% on the mean lifetimes. End-of-life recycling rates for copper for the period 1910 to 2010 are derived from the same study. We assume an increase from 10% in 1900–1910 to around 43% (39–47% for the MCS) in 2010, with most of this increase occurring between 1940 and 1950 (2).

Aluminum: According to the MFA database (26) the global average aluminum content of Bauxite fluctuates between 20% and 16%; manufacturing losses were estimated at 9.6% (48). Based on the average of sector specific lifetimes of aluminum products provided in a study on the development of global in-use aluminum stocks (49), we calculated the average lifetimes of aluminum to increase from 19 to 23 years during the time period 1950 to 2010. For the MCS we used ± 15% on the mean lifetimes. For the period 1900 to 1949, average lifetime was held constant at the level of 1950 (22 years). Recycling rates for 1950 to 2010 were calculated from data of the World Aluminium Institute on total available scrap and recovered scrap (35), resulting in recycling rates increasing from 2% to 62% (57–67% for the MCS) during this time period. Prior to 1950 aluminum was used in small quantities only and recycling was assumed to be negligible and therefore set to zero. No region or country specific information was derived.

Other metals and minerals: According to the MFA database (26) the global average grade of other metal ores and minerals fluctuated between 9% and 3%; for manufacturing losses we used the average of iron, copper and aluminum (9.2%). This heterogeneous group of mostly metals and some industrial minerals is a small flow (roughly 5% of all metal and industrial mineral inflows). The largest amount of the metals in this group (e.g. manganese, molybdenum, titanium, nickel) is used in alloys with iron, copper and other metals. We therefore applied the average of the lifetimes assumed for iron and steel, aluminum and copper, which is 30 years. For the MCS we used ± 15% on the mean lifetimes. Recycling rates for this material group was estimated to lie at 30% (50). For the MCS we used ± 30% on the recycling rate, yielding a range of 29 – 35%. These global averages were also used for the regions.

Plastics: Manufacturing losses were assumed at 10%, based on a substance flow analysis study for Austria (51). From studies on the use of plastic materials in Europe and the USA (52–55), India (56) and China (57, 58) we conclude that a third of annual plastics use is packaging and other short-lived applications which are discarded mostly within a year. Approximately a quarter of global production enters long-lived products such as cable coatings, pipes and tubes or insulations, while the remainder are medium-lived applications such as consumer electronics or furniture. Based on this information we assume a weighted lifetime distribution of 6 ± 2 years globally and for all regions. For the MCS we used ± 30% on the mean lifetimes.

Based on several studies on plastic flows (36, 54–56, 56, 58, 59) we assume that re- and down-cycling of plastic waste (excluding incineration and energy recovery) began in the 1970s and linearly increased to today's levels of approximately 20% of end-of-life outflows. For the industrial countries, where most plastics are incinerated, we arrive at a recycling rate of 20% for 2010 (53, 55) and for China of 21% (58). With the exception of India, where some authors report recycling rates of up to 60% (56, 59), no further information for other countries was found. We generally assumed ± 30% uncertainty of the recycling rates in the MCS, yielding a range of 14 – 26%.

Asphalt (road pavement): Manufacturing losses (wastage) were assumed at 4%, based on construction manuals and construction waste studies (60–64). Most bitumen is used in asphalt pavements, only a very small fraction is utilized for roofing or water insulation. Asphalt layers are usually replaced approximately every 15–30 years (21, 55, 60, 65–67), depending on technical standards and physical wear of the specific road section, the priority of the road and the economic situation of the country. In particular low priority rural roads with little heavy traffic might be in use considerably longer before maintenance is required. We assume a global average lifetime distribution for the asphalt layers of roads of 25 (18-33) years. For the MCS we used ± 15% on the mean lifetimes.

Recycling of asphalt pavements is feasible and widely practiced; the remaining outflows are often down-cycled (68–70). For 1996 the Environmental Protection Agency of the USA reports that of 91 million tons of asphalt pavement debris generated, 72% were recycled into pavements, 8% were down-cycled into base-courses and the remainder, 20%, were landfilled (as reported in ref. 62, 63). Based on this information and data for Europe (73), we assume that in the industrial countries recycling of end-of-life asphalt outputs began in 1960, with a linear increase of the recycling rate up to 80% in 2010. For non-industrial countries no information on asphalt recycling could be found. We assumed a global average recycling rate for asphalt of 27% in 2010 (14–39% for the MCS). For assumptions on down-cycling see below.

Concrete (buildings and infrastructures): Processing losses for limestone (CO_2 emissions due to the calcination of limestone for cement production) were assumed at 44%; manufacturing losses (wastage) were assumed at 4%, based on construction manuals (60–63, 74). Estimates of the lifetimes of different types of buildings and infrastructures in industrial countries range from 20 to 90 years with a clustering around 50 years (15, 19, 75, 76). Lifetimes of buildings in China are reported to be shorter at 20 to 40 years (77–80). Based on this literature we assume a lifetime of concrete stocks of 50 ± 45 years for the Industrial group and the Rest of the World. For China we assume that concrete stocks are in use for 40 ± 24 years. For the MCS we used ± 30% on the mean lifetimes.

While recycling of concrete is technically feasible, in industrial countries most of the concrete which is recovered from construction and demolition waste is down-cycled. In industrial countries approximately 40% of concrete is recovered after demolition (15, 55, 70, 81). In China the overwhelming majority of all construction and demolition waste is being landfilled or often dumped in uncontrolled sites, but recycling into concrete is increasing (77, 79, 82). For other parts of the world qualitative information suggests that there is hardly any recycling and very little technical down-cycling, therefore most construction and demolition waste is landfilled or, more realistically, left in place or dumped into uncontrolled sites (83, 84). Based on this literature review we assume a global average recycling rate for concrete of 7% in 2010, with a linear increase from 0% in 1970. For the industrial group we assume recycling of 7% in 2010, with a linear increase from zero in 1970. For China, based on recent studies (77, 79, 82), we assume recycling of 15% in 2010, which linearly increased from 0% in 1980. For the Rest of the World we assume 4% in 2010 and a linear increase from 0% in 1980. For the MCS we used ± 45% of the recycling rates, yielding a range of 3-9%. For the assumptions on down-cycling see below.

Down-cycling of asphalt and concrete: A large fraction of construction and demolition waste is crushed and used to substitute for natural aggregates (mostly in sub-base layers of built structures or base-course layers of roads), which we define as down-cycling. Down-cycling rates refer to the amount of waste material remaining after recycling has been deducted. We assume that down-cycling rates of asphalt and concrete are similar. For the industrial countries we assume down-cycling rates of 10% for the period 1900–1970. We assume that after 1970, with growing amounts of construction and demolition wastes accruing and land-filling becoming more expensive, down-cycling gained significance and linearly increases to 30% in 2010. For China we assume a linear increase of the down-cycling rate from 0% in 1980 to 30% in 2010. For the RoW we assume a linear increase from 1980 onwards to 10% in 2010. For the global average we arrive at 3% until 1980 and a linear increase to 23% in 2010. For the MCS a ± 45% uncertainty range for all down-cycling rates across time is assumed.

Bricks (buildings): Processing losses (mainly due to changes in moisture content of clay in brick production) were assumed at 26% (26); manufacturing losses (wastage) were assumed at 4%, based on construction manuals and construction waste studies (60–63). Bricks are mainly used in buildings. Based on the average lifetimes of buildings (see concrete) we assume a global mean lifetime of bricks of 40 (4-76) years. For China studies (77, 79) suggest a shorter lifetime of only 30 years. For the MCS we used ± 30% of the mean lifetimes.

Recycling of bricks is usually only possible via direct re-use, which is labor-intensive and requires careful deconstruction. We assume that the beginning of the period (1900 to 1930) 15% of discarded bricks were recycled and that this rate linearly decreased to zero from 1930 to 1960 where it remained until 2010. Down-cycling of bricks is more significant. We assume a rate of 35% for 1900 to 1930 and a linear decrease to zero in 1970, when it began to increase again to 23% in 2010. For the MCS we assumed a ± 60% uncertainty range of the respective parameter until 1970, after which the assumed uncertainty range decreases to ± 45% in 1980, from which it remains constant.

Sand and gravel used as sub-base layer for buildings and in base-course layers of roads: A considerable amount of sand and gravel is used to build sub-base layers for buildings and base-courses for roads and other infrastructures. Often these materials remain in place and are not recovered when a new building is constructed and roads are refurbished. We therefore assume that the lifetime of these material stocks is considerably longer than that of roads and buildings. For aggregates used in base-course and sub-base layers of roads and buildings (see section 1.5) we assume a lifetime of 80 (8-152) years for all regions and the global average. For the MCS we assumed ± 30% uncertainty of the mean lifetime. Most of these materials are directly re-used or recycled on site and we assume a constant recycling rate of 60% for all regions and globally. For the MCS we assumed ± 60% of the recycling rate.

Table S4: Summary of the applied global average values of MISO model parameters for 1900 and 2010: material input uncertainties, lifetime distributions and uncertainties as well as end-of-life (EoL) recycling and down-cycling rates and their uncertainty ranges. All uncertainty ranges are expressed as relative variation of the respective parameter (in %) and contain three standard deviations. The ranges shown for the normal (Gaussian) lifetime distributions contain three standard deviations, which means that 99.7% of the stock reaches the end of its service lifetime between these two values, with the shown mean lifetime. For detailed documentation, sources and regional parameterization see section 2.4.

Stock type	Material input uncertainty (±)	Lifetime distribution parameters					Recycling parameters			Down-cycling parameters		
		Lifetimes, mean (years)		Normal distribution (years, rounded, 99.7% of cases)		Mean lifetime uncertainty (±)	Recycling rates (% of EoL outflow)		Uncertainty (±)	Down-cycling rates (% of EoL outflow after recycling)		Uncertainty (±)
		1900	2010	1900	2010		1900	2010		1900	2010	
Solidwood	15%	30	30	8 - 53	8 – 53	30%	-	-	-	-	-	-
Paper	15%	2	2	1 – 4	1 – 4	30%	15%	32%	15%	-	-	-
Iron and steel	15%	44	44	22 - 66	22 – 66	15%	65%	83%	15%	-	-	-
Copper	15%	19	23	9 – 29	11 – 35	15%	10%	43%	45%	-	-	-
Aluminum	15%	22	23	11 – 33	11 – 34	15%	-	58%	15%	-	-	-
Other metals and minerals	15%	28	30	14 - 43	15 - 45	15%	30%	30%	45%	-	-	-
Plastics	15%	-	6	-	4–8	30%	-	15%	45%	-	-	-
Asphalts (roads)	15%	25	25	18–33	18 – 33	15%	-	27%	45%	-	23%	45%
Concrete (buildings, infrastructure)	15%	50	50	5–95	5–95	30%	-	6%	45%	3%	23%	45%
Bricks (buildings)	45%	40	40	4–76	4 – 76	30%	15%	0%	45%	35%	23%	45%
Aggregate (primary)	60%	80	80	8–152	8 – 152	30%	60%	60%	45%	-	-	-
Aggregate (down-cycled)	60%	80	80	8–152	8 – 152	30%	60%	60%	45%	-	-	-

3 Scenarios for the development of global stocks and related CO_2 emissions for 2010–2050

3.1 Stock development

We calculated three scenarios for the development of in-use stocks of materials until 2050.

A. In the **Business as Usual Scenario (BAU)** we assume that annual net additions to stock (NAS) remain constant at the level of the year 2010 (26 Pg/yr); in the period 2005–2010 NAS fluctuated between 24 and 26 Pg/yr.

B. In the global **Convergence 2010 Scenario (Conv. 2010)** we assume that until 2050 China and the Rest of the World develop the same per capita stock as the Industrial group (assuming an exponential trend), where stocks remain at their current level (335 Mg/cap). To calculate total global stocks in 2050 from per capita stocks we used population data from the medium variant of the 2015 Revision of the United Nation's World Population Prospect (85) which predicts a global population of 9.7 billion in 2050, i.e. a 40% increase between 2010 and 2050.

C. In the **Contraction and Convergence 1970 Scenario (Contr.&conv. 1970)** we assume that the level of per capita stocks that had been achieved in the industrial countries in 1970 (132 Mg/cap) is sufficient to provide a high quality of life. We assume that by 2050 all countries converge at this per capita level of stocks (assuming an exponential trend). This implies considerable stock growth in the Rest of the World, little growth in China and a reduction of stocks in the Industrial group. We used UN population projections (85) to extrapolate total stocks from per capita stocks in 2050. While total global stocks in this scenario are only 30% lower than in the BAU scenario, it reduces global inequality in the distribution of stocks between the three country groups.

Yearly material inputs required to renew existing stocks were estimated in all three scenarios by assuming a stock renewal rate (i.e. the fraction of existing stock that is renewed in the respective year). The stock renewal rate was derived from historic renewal rates which declined from 2.3% to 1.8% between 1900 and 2010 with lowest values of 1.6% in the 1970s. We assumed a renewal rate of 1.8% for the trend and conv. 2010 scenarios. For the contr.&conv. 1970 scenario we assumed a somewhat lower renewal rate of 1.5%, because in this scenario a considerable amount of stock in the industrial group that reaches the end of its lifetime is not renewed. The contribution of stock renewal to cumulative C emissions is small (around 10%) in all three scenarios.

3.2 Carbon emission intensity of stocks and of net additions to stock

We defined two trajectories for the development of emission intensities (EI) of stocks in order to estimate future CO_2 emissions based on stock development. We assume that all technical energy is either used to build up and renew stocks or to provide services from stocks.

We used long term data on global CO_2 emissions from fossil fuel use and cement production from the Carbon Dioxide Information Analysis Center (CDIAC) (86) to calculate EI of stocks (see Figure 2B in the main text). We distinguish two types of emission intensities: annual CO_2 emissions per Mg of material inputs to stock (i.e. emissions related to building and renewal of stock) and annual CO_2 emissions per Mg of stock (i.e. emissions related to providing services from stock). The CDIAC database provides data on CO_2 emissions from the combustion of fossil energy carriers and from the production of cement. To estimate the share of CO_2 emissions related to building and renewing stocks in total CO_2 emissions we used information on final energy use from the International Energy Agency (IEA) (38). IEA provides data on final energy consumption by economic sectors and end use type for the period 1971 to 2010.

We define energy use in industries, manufacturing and construction as energy used to build and renew stocks and all other energy use (e.g., in the sectors transport, government, commerce or in households) to be used to provide services from stocks. We assumed that the share of final energy used to build up and maintain stocks, which declines from 33% to 24% between 1971 and 2010 equals the share of emissions from fossil fuel combustion related to building and renewing stocks. To this we added the amount of CO_2 emissions from cement production. The ratio of CO_2 emissions to build up and renew stocks and material inputs to stock is the EI of inputs to stock (input EI) in a given year. Input EI declined from 119 kg/Mg to 62 kg/Mg between 1971 and 2010. The intensity of emissions related to providing services from stocks (stock EI) was calculated as the ratio of all other CO_2 emissions from fossil fuel combustion to the in-use stock of material in a given year. Stock EI declined from 14.2 kg/Mg/yr to 8.4 kg/Mg/yr between 1971 and 2010. GHG emissions from land use change and emissions other than from the combustion of fossil fuels are not considered.

For the scenarios on CO_2 emissions related to global stock development we defined two trajectories of the development of both stock EI and input EI:

1 Trend: Based on the development of emission intensities between 1971 and 2010 and an exponential function ($R^2 = 0.949$) we extrapolated stock emission intensity to decline by 52% from 8.4 kg C/Mg/yr to 4.0 kg C/Mg/yr of stock until 2050. The same relative improvement (–52% to 30 kg C/Mg inputs to stocks) was applied to input EI, which did not show a clear trend over time (reduction of 41% between 1980 and 1995, since then fluctuation between 60 and 68 kg C/Mg inputs).

2 Decarbonization: To contrast the trend scenario we have chosen a very optimistic scenario. We assume a full decarbonization of the energy system by 2050 in which both emission intensities linearly decrease to 0 in 2050. Note that full decarbonization by 2050 is considered very unlikely by energy experts, as, for example, the optimistic “Efficient World Scenario” of the International Energy Agency (IEA) indicates (87). The most recent “New Policy Scenario” of the IEA, which assumes the adoption of low-carbon technologies and improved energy efficiency, estimates that energy related CO_2 emissions will actually increase by 13% between 2013 and 2040 (88).

3.3 CO_2 emission scenarios 2010–2050

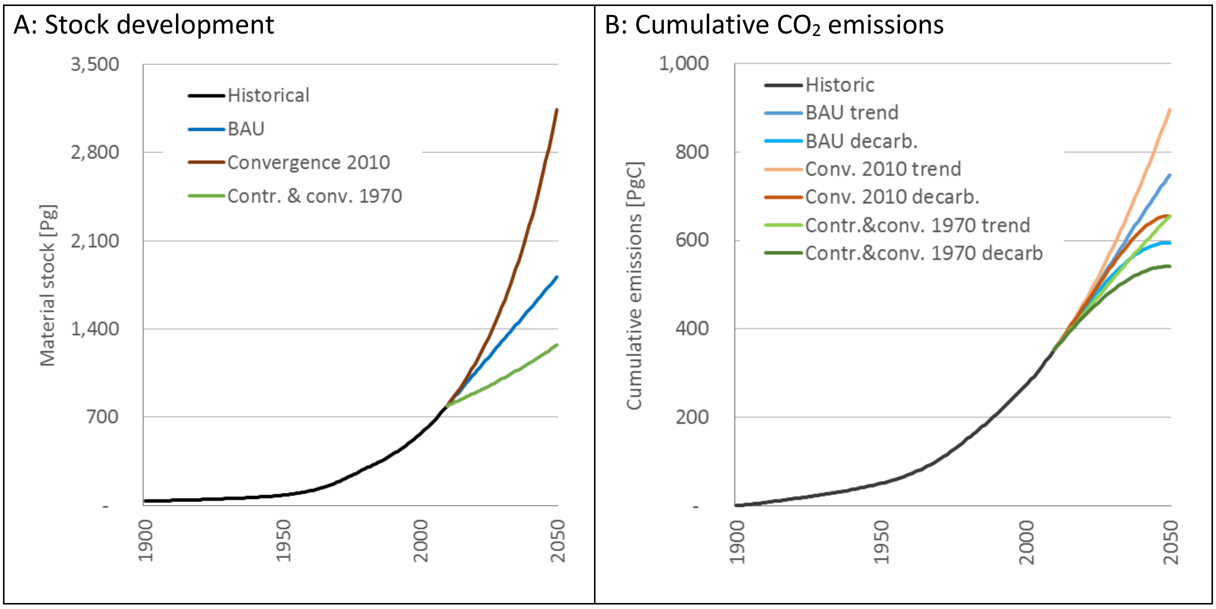
Based on the three stock-development scenarios and the two trajectories of emission intensities we calculated six scenarios for future CO_2 emissions on the basis of stock development. We calculated emissions from building up and renewing stocks by multiplying estimated global annual net additions to stock and material inputs required to renew existing stocks with the corresponding input EI. For the contraction and convergence 1970 scenarios we used gross NAS to take into account that stocks show negative growth in the Industrial group. We calculated emissions from providing services from stocks by multiplying total stock with the estimated stock EI. Both values were added to calculate total global annual emissions. Annual emissions in the period 2010 to 2050 were summated to calculate cumulative emissions. The share of emissions from providing services from stocks in total cumulative emissions ranges between 80% in the contraction and convergence 1970 scenarios and 72% in the convergence 2010 scenarios, where more emissions are related to building up the much larger material stock (18% compared to 10% in the contr.conv. 1970 scenarios). We calculated average annual CO_2 emissions and cumulative emissions for the period 2010–2050 measured in Petagram (Pg) of carbon (C). We compare these results to cumulative emission budgets from IPCC (89). We refer to the range given for the remaining emission budget that would be consistent with a 50% or higher chance of reaching the 2°C target without overshoot (860–1118 Pg CO_2, equal to 234–322 Pg C) or with overshoot and negative emissions after 2050 (1130–1530 Pg CO_2, equal to 308–417 Pg C), resulting in a total range of 234–417 Pg C. Table S5 provides an overview of the results for the six scenarios and shows the percentage by which they fall below or exceed the remaining emission budget. Figure S4 shows the trajectories in the three stock scenarios (S4A) and the six emission scenarios (S4B) in relation to the historic development.

Table S5: Scenarios for the development of stocks, net additions to stock (NAS), CO_2 emissions 2010–2050 (average annual emissions, cumulative emissions) and cumulative emissions as % of the remaining emission budget that would be consistent with a 50% or higher chance of reaching the 2°C target (see text).

Scenario type		**Average yearly NAS and stock**		**CO_2 emissions**		**Remaining budget 2050**	
		Mg/yr	Pg	PgC/yr	PgC	Lower	Upper
						% difference to	
						234 PgC	**417 PgC**
Stock	**Emission intensity**	**NAS**	**Stock 2050**	**average CO_2/yr**	**cumulative CO_2 2010–2050**		
2010 Basis		26	792	9	353		
BAU	Trend	26	1,812	10	395	+69%	-5%
	Decarbonization	26	1,812	6	242	+3%	-42%
Convergence 2010	Trend	59	3,137	14	542	+132%	30%
	Decarbonization	59	3,137	8	303	+29%	-27%
Contr&conv 1970	Trend	12*	1,274	8	302	+29%	-28%
	Decarbonization	12*	1,274	5	188	-19%	-55%

* Note that negative stock growth in the Industrial group reduces global net additions to stock (NAS) to 12 Pg/yr in the contr-&conv. 1970 scenarios. To calculate CO_2 emissions related to stock growth we used average global gross NAS which amount to 19 Pg/yr.

Figure S4: S4A: Stock development in the period 1900–2010 and in the three scenarios 2010 to 2050; S4B: Cumulative CO_2 emissions in Pg C from 1900 to 2010 (historical) and 6 scenario variations for the development to 2050.


A: Stock development

B: Cumulative CO_2 emissions

4 Additional Figures

4.1 Comparison with results from other studies

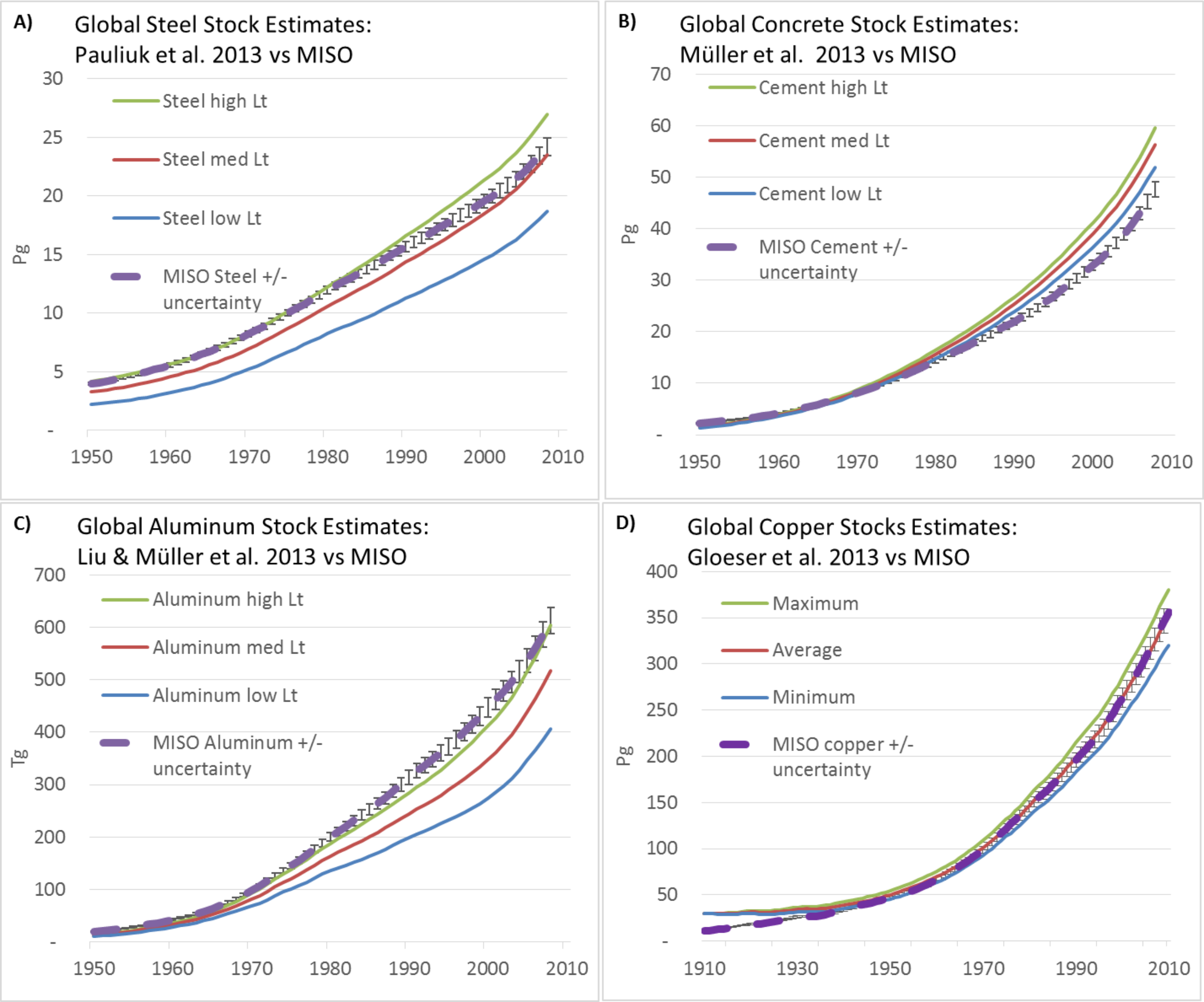


Figure S5: Comparison of MISO stock estimates with results from studies on specific substances and materials for A) steel (46), B) concrete (90) C) aluminum (49) and D) copper (2). Each study includes stock results based on high, median and low lifetime assumptions. Uncertainty ranges for MISO results are shown in the same way as in the main text (with 3 standard deviations which cover 99.7% of the 10^3 Monte-Carlo Simulations).

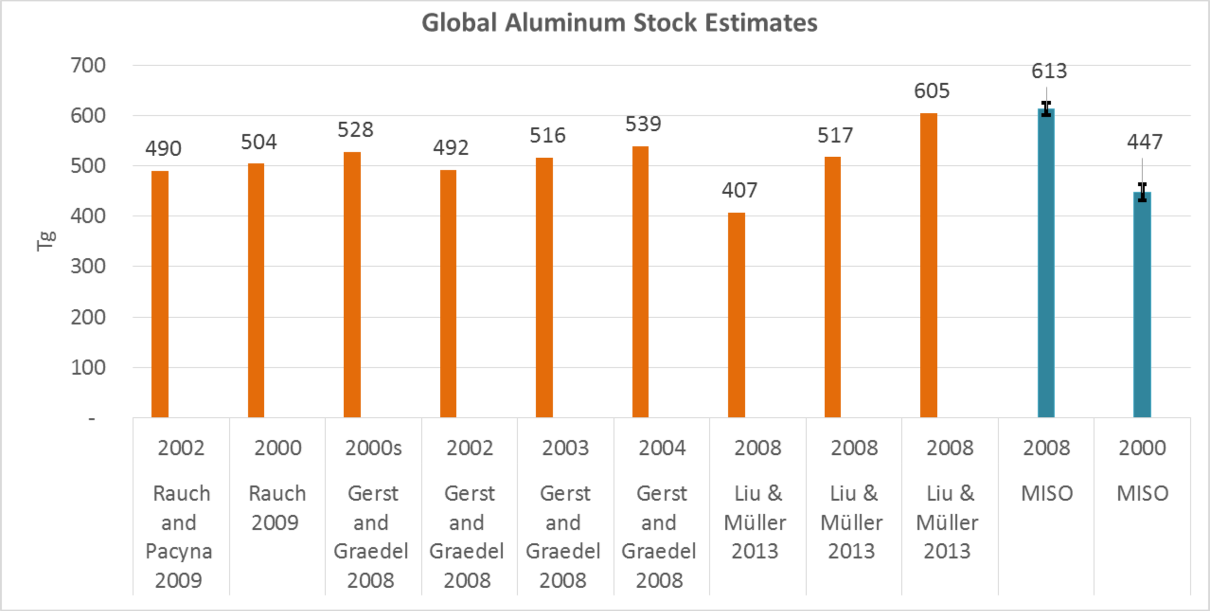


Figure S6: MISO stock estimates for aluminum in comparison with results from other studies (49, 91–93). Uncertainty ranges for the MISO results are shown in the same way as in the main text, with 3 standard deviations which cover 99.7% of the 10^3 Monte-Carlo Simulations.

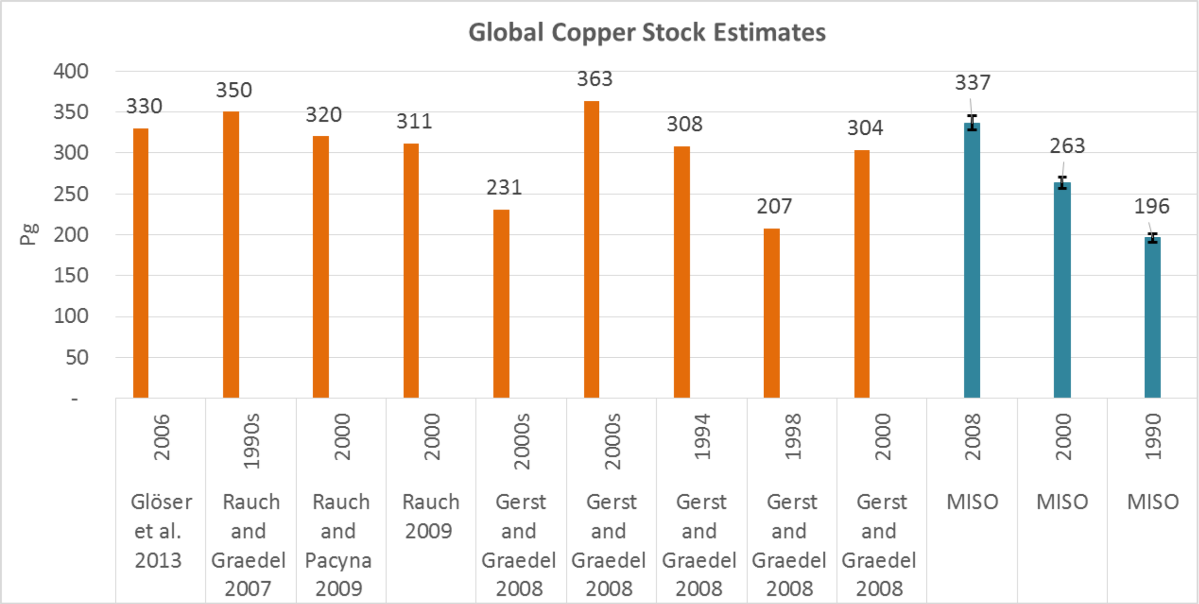


Figure S7: Comparison of MISO copper stock estimates with results from other studies(2, 91–94). Uncertainty ranges for the MISO results are shown in the same way as in the main text, with 3 standard deviations which cover 99.7% of the 10^3 Monte-Carlo Simulations.

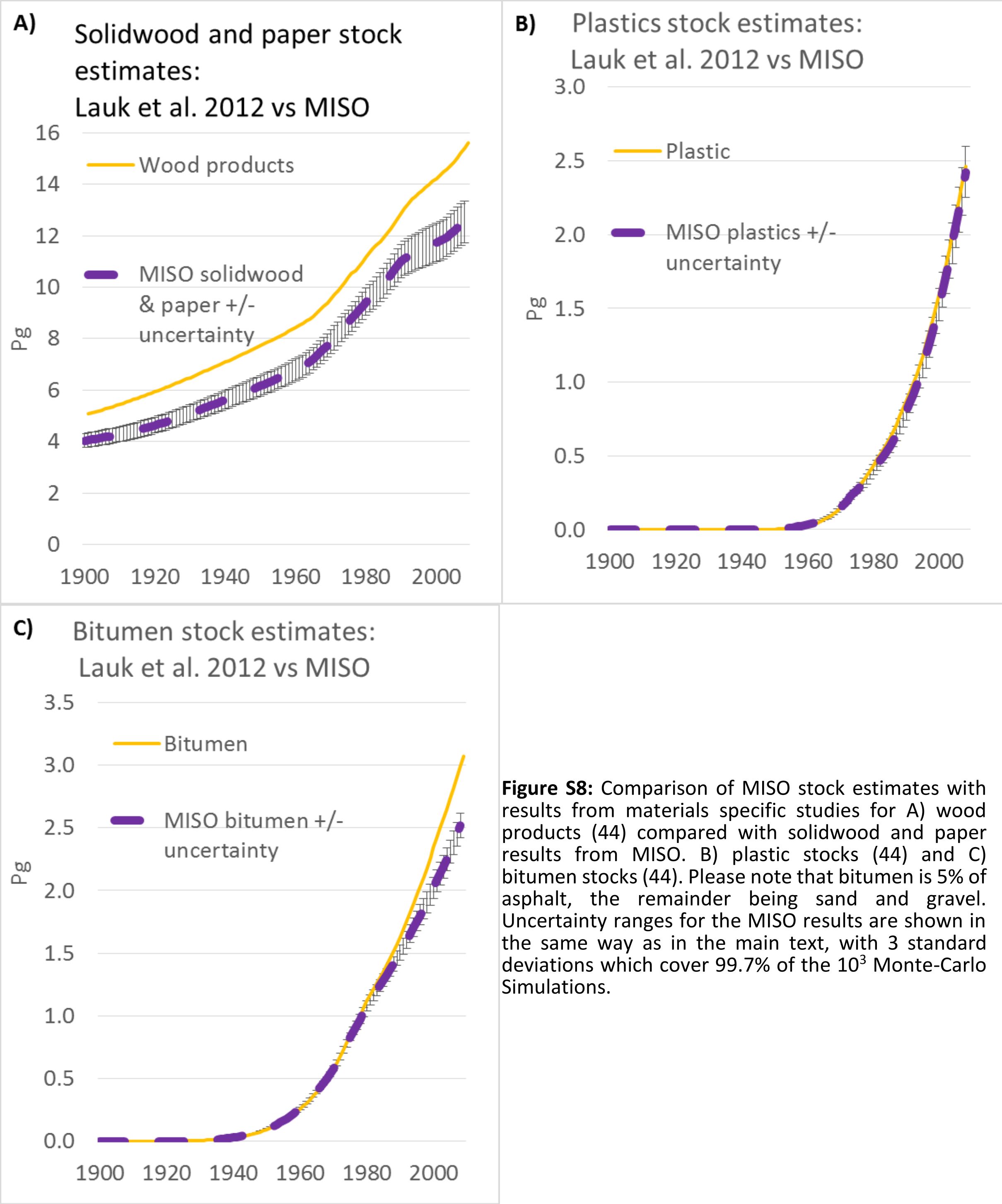


Figure S8: Comparison of MISO stock estimates with results from materials specific studies for A) wood products (44) compared with solidwood and paper results from MISO. B) plastic stocks (44) and C) bitumen stocks (44). Please note that bitumen is 5% of asphalt, the remainder being sand and gravel. Uncertainty ranges for the MISO results are shown in the same way as in the main text, with 3 standard deviations which cover 99.7% of the 10^3 Monte-Carlo Simulations.

4.2 Material inputs to stocks and the age composition of in-use stocks

The dynamic of stock accumulation over time is a result of the combination of the dynamic of inputs to stocks and of the lifetime of stocks. Figure S9 compares the cumulative inputs to stocks in the period 1900 to 2010 with the actual stock in 2010 by age cohorts (10 year intervals). Globally between 1900 and 2010 a total of 1163 Pg of primary and secondary materials have entered the in-use stock of materials of which roughly two thirds or 792 Pg were still present in in-use stock by the year 2010 (Fig. S9a). The remainder has turned into end-of-life waste, either in controlled landfills or in uncontrolled dump-sites, or remains in place as unused or hibernating stock. The results by age groups indicate that most of the global material inputs to stocks occurred only in the last three decades (63% of global cumulative inputs). Even in the Industrial group with a long history of urbanization and industrial development, 55% of the total inputs into stocks in the period 1900 to 2010 happened between 1981 and 2010 (Fig. S9b). The material inputs of these years form 76% of the total stock in-use in the industrial countries in 2010. This indicates that the surprisingly large share of relatively “young” stock is mainly due to the growth dynamics of inputs to stocks and that the last three to four decades of stock growth are highly important for the total composition and scale of the current in-use stock globally and in industrial economies.

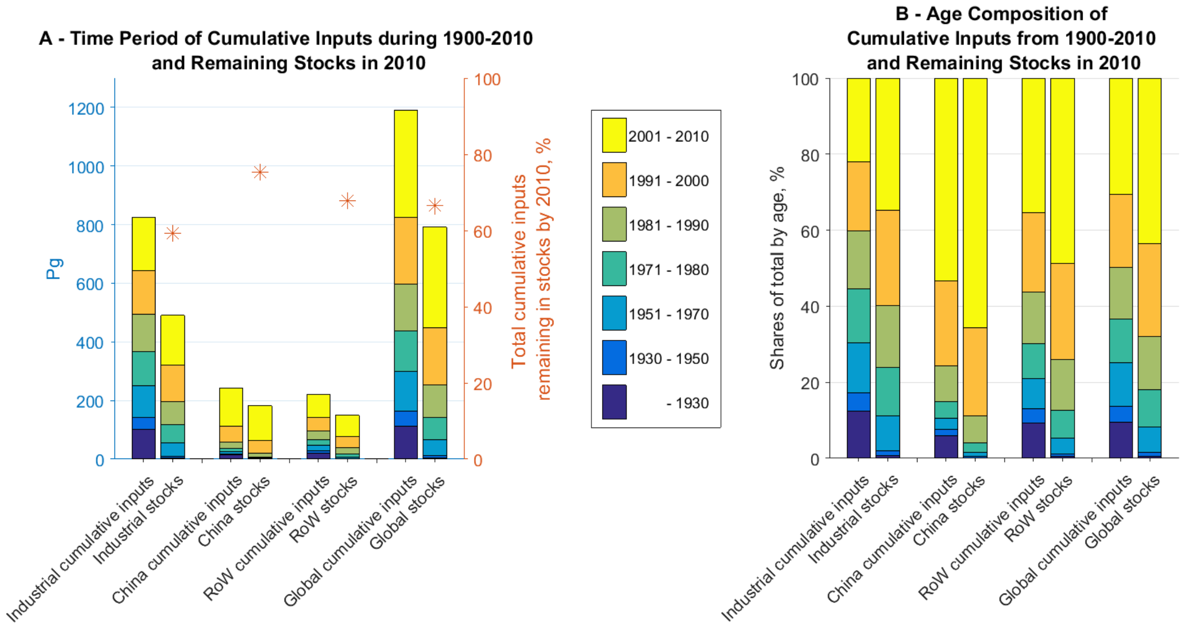


Figure S9: Cumulative inputs to stocks from 1900–2010 and in-use stocks in the year 2010 by age groups for the Industrial group, China, Rest of the World (RoW) and the global total. S9A: Cumulative inputs and stocks in Pg, Share of cumulative inputs remaining in stocks in 2010 in % (orange cross, right axis). S9B: Share of age groups in cumulative inputs and stocks in 2010. Year ranges are age cohorts and refer to the period of material inflow to stocks.

4.3 Sensitivity analysis of changes in mean lifetimes

The Monte-Carlo Simulations (MCS) used to propagate errors throughout the modeling cover stochastic uncertainty around each parameter value. MCS yields a +/- 5% uncertainty on the global stock estimate for 2010. To test for systematic errors in the assumed values for mean lifetimes, a sensitivity analysis was conducted. Three different sensitivity tests for the parameter mean lifetimes were modeled: All mean lifetimes as used for the main results (Table S2) were decreased by –30%, increased by +30% and increased by +50%. A decrease of –50% was not included as it did not seem plausible. The results shown in Figure S10a and S10b indicate that the results of the global stock estimate are robust against systematic under/overestimation of mean lifetimes. Assuming 50% longer lifetimes yields a 15% larger stock in 1950 and a 9% larger stock in 2010. The sensitivity test with significantly shorter lifetimes (–30%) yields –10% lower global stocks for 2010. Note that the low and asymmetric impact of changes in lifetime is strongly influenced by the dynamics of inputs to stocks over time. Inputs to stocks rapidly increased after World War II and a large fraction of all inputs occurred only after 1980, resulting in non-linear and asymmetric impacts of changes to the lifetimes (see section 4.2). This implies that in all lifetime variants a large fraction of these materials were still in-use by 2010.

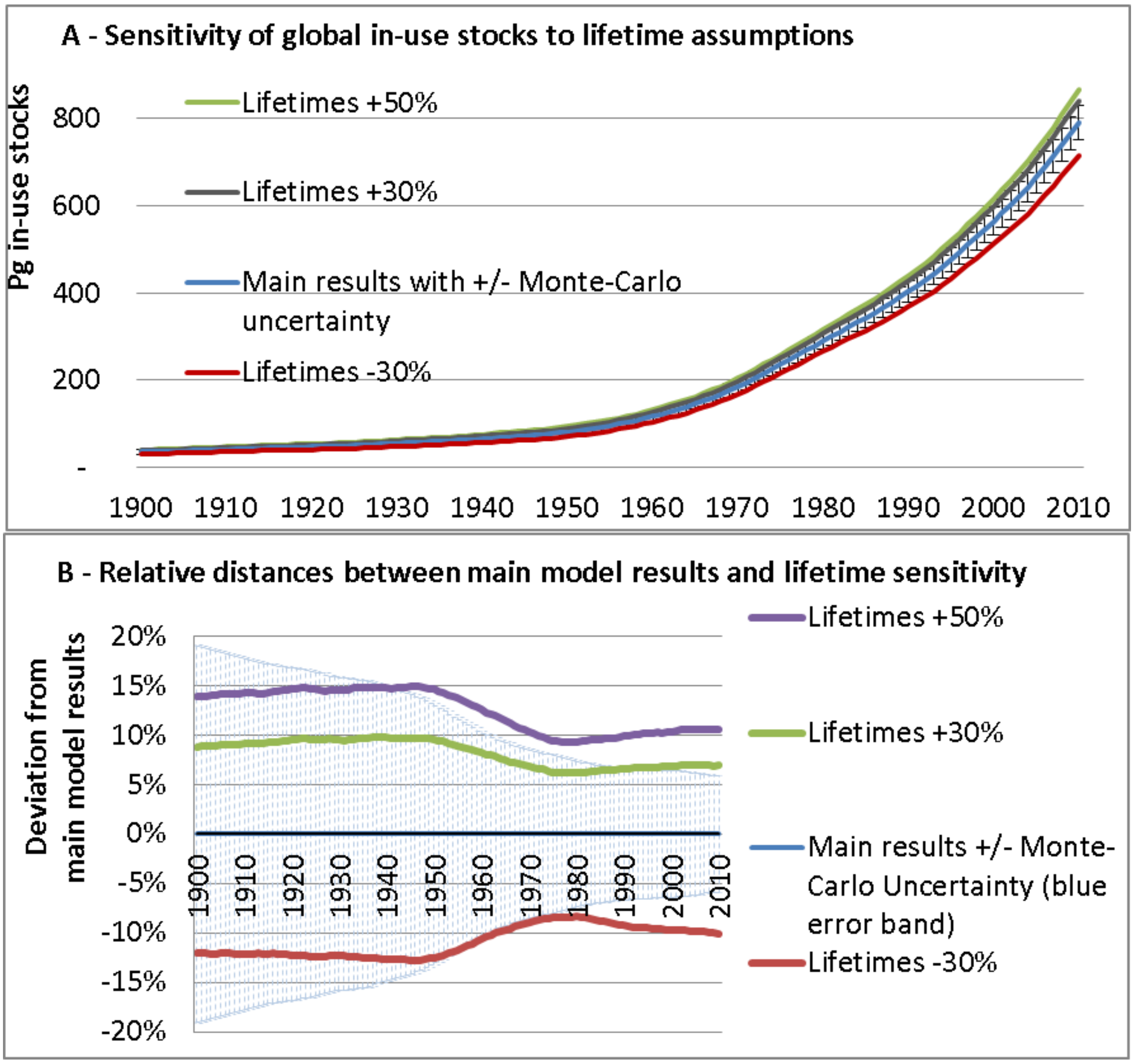


Figure S10: Sensitivity analysis. Comparison of global stock estimates resulting from the standard MISO model run with uncertainty ranges derived from Monte-Carlo Simulations and three different sensitivity tests with different assumptions on average lifetimes (Average lifetimes –30%, +30% and +50%). Global in-use stocks in Pg (S10a) and relative deviation of sensitivity test from standard model run in % (S10b).

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