Exploring the engine of anthropogenic iron cycles

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Stocks of products in use are the pivotal engines that drive anthropogenic metal cycles: They support the lives of people by providing services to them; they are sources for future secondary resources (scrap); and demand for in-use stocks generates demand for metals. Despite their great importance and their impacts on other parts of the metal cycles and the environment, the study of in-use stocks has heretofore been widely neglected. Here we investigate anthropogenic and geogenic iron stocks in the United States (U.S.) by analyzing the iron cycle over the period 1900–2004. Our results show the following. (*i*) Over the last century, the U.S. iron stock in use increased to 3,200 Tg (million metric tons), which is the same order of magnitude as the remaining U.S. iron stock in identified ores. On a global scale, anthropogenic iron stocks are less significant compared with natural ores, but their relative importance is increasing. (*ii*) With a perfect recycling system, the U.S. could substitute scrap utilization for domestic mining. (*iii*) The per-capita in-use iron stock reached saturation at 11–12 metric tons in ≈1980. This last finding, if applicable to other economies as well, could allow a significant improvement of long-term forecasting of steel demand and scrap availability in emerging market economies and therefore has major implications for resource sustainability, recycling technology, and industrial and governmental policy.

dematerialization | material flow analysis | resource management | secondary resource exploration | ferrous scrap recycling

In 1969, the urbanist Jane Jacobs referred to cities as "the mines of the future" (1). Her perspective was that resources that have been mined, processed, and fabricated into products constituted a material stock that could eventually supplant in-ground ore. Almost 4 decades later, and with still limited knowledge of these urban mines, we recognize significant differences between urban and traditional mines. First, whereas mineral ores change very slowly over time, anthropogenic stocks change rapidly and therefore require better monitoring. Second, mining production of mineral ores can readily be adjusted to changes in demand, provided that necessary reserves, capital, and labor are available, whereas urban mining faces physical limitations because it is restricted to products in use becoming obsolete. Third, the material in urban mines is generally of higher quality than mineral ores (2), because already processed and purified material often requires less energy and technology to re-employ. Fourth, there is extensive knowledge about the size and chemical and physical properties of geological ores, but there is very little understanding of anthropogenic material stocks and their dynamics.

The lack of knowledge about in-use stocks not only limits our insights into future resources, but it also confines our understanding of entire mineral cycles. Comprehending in-use stocks is therefore essential for measuring and improving overall resource utilization.

The study of anthropogenic material reservoirs as potential future resource providers, which has been termed as secondary resource exploration, has only recently begun to attract academic interest (3–7). Two methods are used to quantify anthropogenic material stocks: the "bottom-up approach," in which inventories of the most relevant products in use and their metal concentrations are quantified to calculate the overall metals stock, and the "top-down approach," in which the stocks are computed by using historic production and trade data and estimates for product lifetime distributions. Although bottom-up studies offer more detail about the different reservoirs, the top-down approach, which we use here, provides information on the historic development of stocks and flows.

Table 1. Mine production in 2005, reserves, reserve base, and theoretical depletion times for selected countries and the world

Country	MP, Tg/a	R, Tg	RB, Tg	DT (R), a	DT (RB), a
United States	35	2,100	4,600	61	133
Australia	174	8,900	25,000	51	144
Brazil	199	16,000	41,000	80	206
Canada	19	1,100	2,500	58	132
China	122	7,000	15,000	57	123
India	90	4,200	6,200	47	69
Kazakhstan	11	3,300	7,400	307	688
Mexico	7	400	900	56	125
Russia	55	14,000	31,000	254	563
South Africa	25	650	1,500	26	59
Sweden	15	2,200	5,000	145	330
Ukraine	38	9,000	20,000	238	528
Venezuela	14	2,400	3,600	166	249
Others	35	7,600	19,500	217	557
World	**839**	**78,850**	**183,200**	**94**	**218**

See ref. 13. Mine production in 2005 (MP), reserves (R), and reserve base (RB) in iron content. DT, depletion times.

Top-down approaches have been used to roughly quantify historic in-use stocks of copper in the United States (U.S.), North America, and Switzerland (4, 6, 8, 9); timber in Switzerland (3); and minerals in The Netherlands (5). Zeltner *et al.* (8) were the first to quantify resource stocks in all relevant compartments and thereby put primary- and secondary-resource reservoirs on equal footing; however, they neglected trade flows, which severely restricts accuracy. In general, little attention has been paid so far to the analysis and interpretation of temporal patterns of resource stocks in use.

Patterns of in-use stocks reflect the changing material requirements needed to sustain the lives of people in different cultural, socioeconomic, and geographical areas. Of particular interest in this context is the study of iron, because it is by far the most widely used metal, comprising >90% of the metal tonnage produced worldwide (10), and thereby constituting the technological fabric around which we have built our modern societies.

With ≈5% of the earth's crust consisting of iron, global iron shortages are not an issue. Given the current rate of extraction, identified global iron reserves would last almost 100 years, and the identified global reserve base† would last >200 years (Table 1).

SUSTAINABILITY SCIENCE

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Abbreviations: a, annum; Tg, million metric tons; Con, Construction; Tra, Transportation; M&A, Machinery and Appliances; Oth, Others; U.S., United States.

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†The reserve base is the identified and demonstrated ore and includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources).

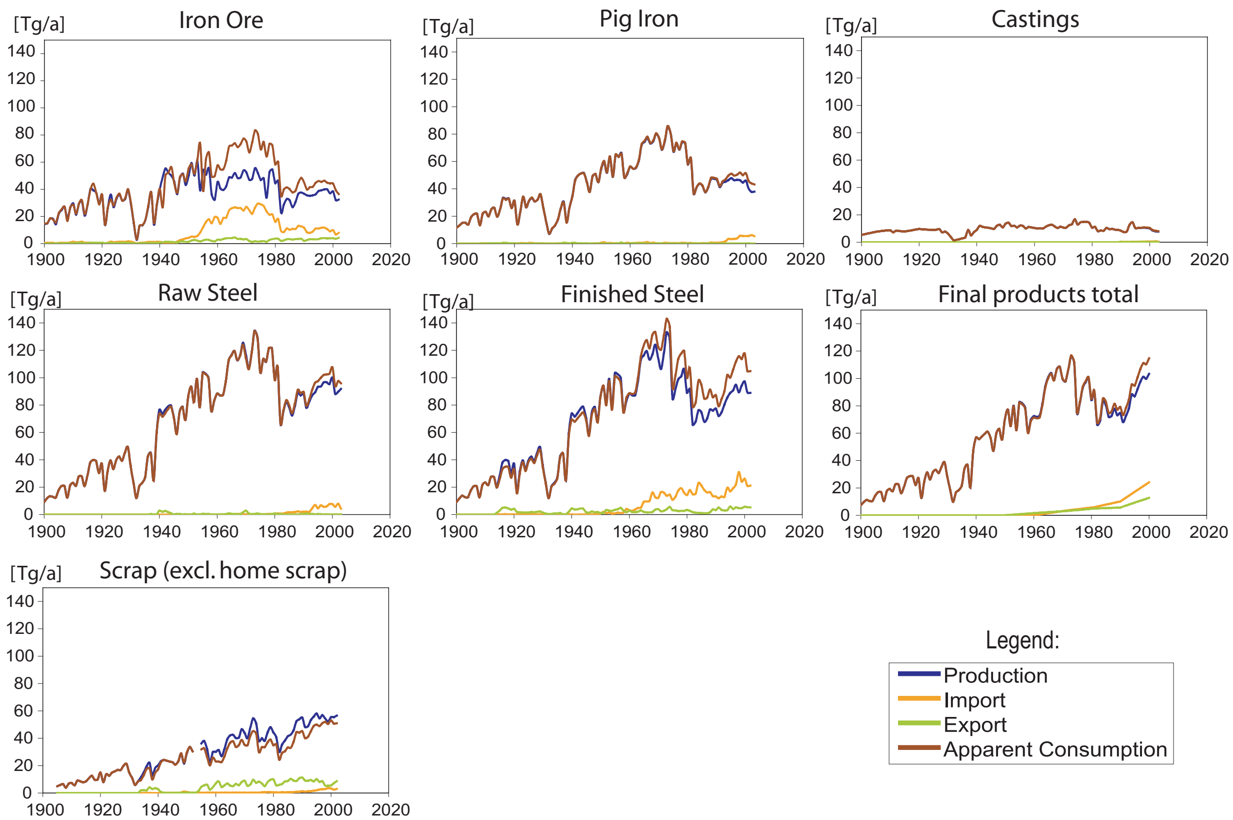

Fig. 1. Historic iron flows in the U.S. assembled by markets, 1900–2004.

Nevertheless, there are many incentives to use iron resources more effectively: U.S. iron ore grades have decreased since World War II from 50–60% to ≈25–30%, leading to significantly increased water and energy use and mining waste (tailings) production (10). Despite significant improvements in energy efficiency, the iron and steel industry is still very energy intensive, consuming ≈9% of all U.S. manufacturing energy use (11). Steel recycling eliminates the most energy-intensive step of steel making, the conversion of iron ore to iron in the blast furnace, thus reducing primary energy consumption by ≈75% (12), and, in turn, significantly reducing energy costs and CO_2 emissions.

For these reasons, the iron and steel industry has slowly shifted from primary (ore) to secondary (scrap) resources. Today, ≈50% of U.S. steel is produced in electric arc furnaces, which use scrap almost exclusively as an iron source. Such shifts involve large capital investments, and industry therefore has a vital interest in understanding the long-term availability and quality of scrap supply.

In the present work, we propose a framework for resource cycles that includes all relevant stocks and flows of metallic iron to assess present and future iron sources, and we apply this method to the U.S. iron cycle in the period of 1900–2004. Anthropogenic iron stocks are calculated by using a material flow analysis model.

The model features a previously undescribed system definition for material flow analysis that differentiates transformation and market processes. Transformation processes balance inputs and outputs of industrial facilities, whereas market processes balance domestic and foreign supply and demand in physical terms. Because the mass balance principle applies to both types of processes, this approach not only integrates engineering and economic perspectives of material cycles in physical terms, but it also significantly improves consistency and data quality.

Results

The historic iron flows, assembled in Fig. 1 by product markets, show the following.

- Most markets in the iron cycle (pig iron, raw steel, finished steel, and final products) show a similar pattern of increase, a

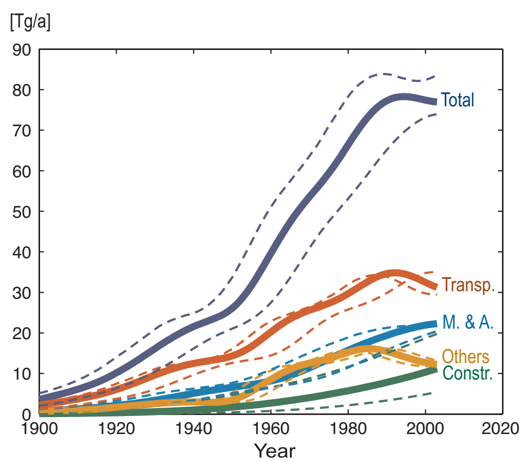

Fig. 2. Historic iron flows in obsolete products generated in the U.S., 1900–2004, for different assumptions of average product lifetime τ and standard deviation σ. Con: $\tau = 50, 75, 100$ years; $\sigma = 20$ years. Tra: $\tau = 15, 20, 30$ years; $\sigma = 7.5$ years. M&A: $\tau = 20, 30, 40$ years; $\sigma = 10$ years. Oth: $\tau = 10, 15, 20$ years; $\sigma = 5$ years. The thick lines indicate the medium lifetime assumptions for τ, and the bottom and top bands are the longer and shorter lifetimes, respectively.

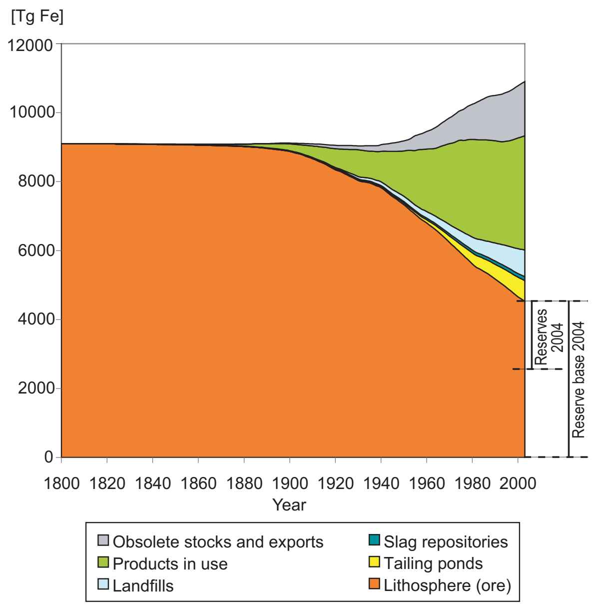

Fig. 3. Historic U.S. iron stocks in principal repositories, 1800–2004. Lithospheric ore calculations assume the current reserve base (13) and compute historic ore quantities from annual extraction data.

sharp drop after 1973, and partial recovery. Exceptions are the markets for iron ore, which peaked in 1953 and has since declined by ≈50%; the castings market, which was fairly constant throughout the entire 20th century; and the scrap market, which has continuously increased.

- The rates of flow in the iron cycle show a progressive decoupling, i.e., the production curves in different markets in the iron chain were more similar in the first half of the 20th century than in the second half.
- The reasons for the decoupling lie in the growing trade in iron-containing goods of most markets and the increasing use of scrap, which substitutes for iron ore and pig iron. Imports consistently exceed exports for all upstream markets (iron ore, pig iron, raw steel, finished steel, parts, and final products), whereas exports exceed imports for all downstream markets (used products and scrap).

Of particular interest for the recovery of scrap is the market for obsolete products (products that have reached the end of their service lifetime); however, obsolete product flows are not covered by any statistics. The generation of obsolete products therefore was determined by using model simulations (Fig. 2), which demonstrate that the dominant secondary iron source can be found in the category Transportation [Tra; currently 32 million metric tons per acre (Tg/a) for medium lifetime assumption], followed by Machinery and Appliances (M&A; 22 Tg/a), and Others (Oth; 12 Tg/a). Demolition waste from Construction (Con; 11 Tg/a) constitutes the smallest iron source for recycling, but this flow can be expected to increase when more steel structures reach the end of their service lifetimes. A sensitivity analysis (bottom and top bands in Fig. 2) shows that Con is the process that is most sensitive to the magnitude of the lifetimes assumed in the model. For all other product categories, the impact of the assumed lifetimes is low, because the amount of iron entering use has not changed substantially for the last 30–40 years, which is more than an average lifetime for all product categories except Con.

The magnitude of the iron flow in obsolete products indicates the potential current old scrap availability. The potential future scrap availability is indicated by the size of the different iron reservoirs. The overall iron stock in the U.S. has slightly increased over the last 200 years, whereas its distribution among different repositories has changed significantly (Fig. 3). Until the end of the 19th century, the anthropogenic iron stock was negligible compared with the iron in ores. Industrialization has moved iron out of the ground and incorporated it into products in use but also into tailings, slag, and landfills. The current in-use iron stock is ≈3,200 Tg, which is only ≈30% less than the domestic reserve base (4,600 Tg) and 50% more than the reserves (2,100 Tg) (13).

Landfills are the third largest iron reservoir (700 Tg), followed by tailings ponds (600 Tg) and blast furnace and steel slag repositories (100 Tg). The error margins for landfills and tailings ponds are estimated to be significantly higher (30–50%) than those for the other iron stocks (20%). The gray area in Fig. 3 is the cumulative difference between obsolete products leaving use and obsolete products entering "scrap processing and waste management" and includes accumulations in

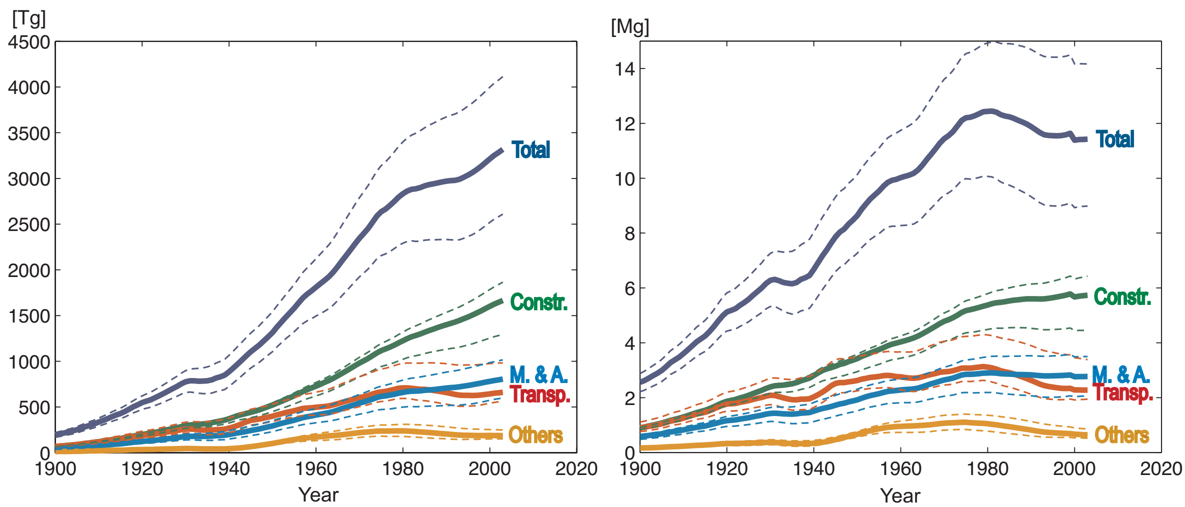

Fig. 4. Historic U.S. iron stocks in products in use, 1900–2004, absolute (*Left*) and per capita (*Right*). The assumed lifetime distributions are equal to those in Fig. 2.

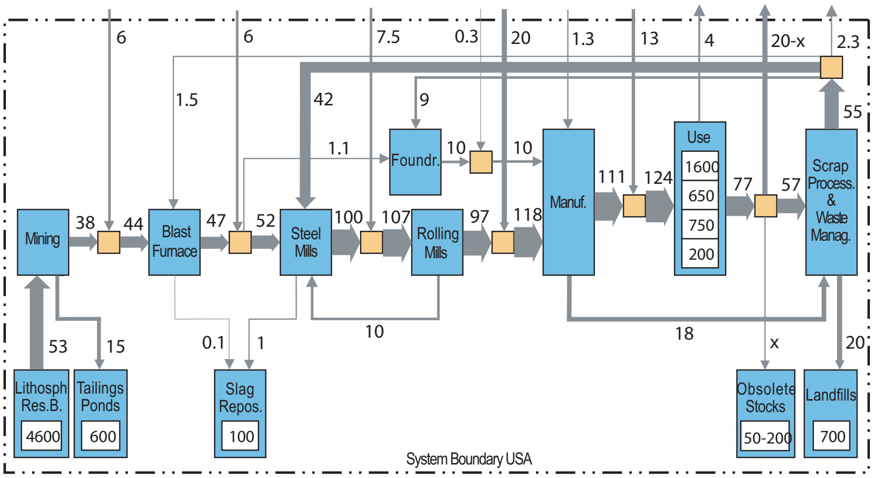

Fig. 5. The U.S. iron cycle, 2000. Flows are in Tg/a, stocks (values in boxes) are in Tg. Compare with system definition (Fig. 6). Imports and exports (flows crossing the system boundary) are aggregated to net trade flows.

stocks of obsolete products[‡] as well as net exports of obsolete products, two flows that cannot be distinguished on the basis of the available data. Independent of the assumption for stock accumulation and export of obsolete products, we observe an increase in total iron stock from 1800 to present, which reflects the cumulative effect of net imports of iron in traded goods.

Fig. 4 shows that approximately half of the total in-use iron stock can be found in Con (1,600 Tg), followed by M&A (750 Tg), Tra (650 Tg), and Oth (200 Tg). The total absolute in-use iron stocks have grown throughout the 20th century. On a per-capita basis, however, iron stocks increased until ≈1980, when they reached a peak of ≈12 metric tons (Mg) (for the medium duration lifetime assumptions), and have since leveled off to ≈11–12 Mg. The iron stock in Tra has saturated in absolute terms and has decreased in per-capita terms since 1980.

This decrease reflects the trend of the automotive industry to produce cars with less but higher strength steel, and the substitution of iron engine blocks, steel frames, and steel bodies by aluminum. Furthermore, the stock of ships sailing under the U.S. flag has significantly declined over the past decades. A sensitivity analysis shows that the per-capita saturation is robust with respect to the assumed lifetime distributions used to calculate the in-use stocks: Whereas the saturation levels strongly depend on the assumed lifetimes, the saturation phenomenon is independent of the lifetime assumptions because of the modest changes in inputs during the past decades.

The data presented above are assembled to generate our best estimate of the U.S. iron cycle in 2000. Fig. 5 illustrates the significance of international trade, represented as net import/export flows crossing the system boundary, for U.S. iron management: Of the 124 Tg/a entering use, most iron units stem from the *aggregate* net imports of iron ore, pig iron, raw steel, finished steel, parts, and new final products (54.1 Tg/a). The second most important iron source is scrap (52.5 Tg/a), while domestic iron ore contributes 38 Tg/a.

The largest losses result from discards of obsolete products to landfills (20 Tg/a), followed by tailings (15 Tg/a). Blast furnace and steel slag (total 1.1 Tg/a) is an order of magnitude smaller. A significant portion of the obsolete products leaving use does not reach scrap processing and waste management. The former (77 Tg/a) is calculated by using the lifetime distribution model, whereas the latter (57 Tg/a) is computed based on the mass balances of "scrap market" and scrap processing and waste management, leaving a gap of 20 Tg/a.

Discussion

This study quantifies the historic development of all major iron flows and reservoirs, an approach essential to evaluate the sustainability of resource management. The iron reservoirs in the U.S. were computed by using available government and industry statistics for flows of iron-containing goods. These statistics are incomplete and have highly variable uncertainties. The uncertainties of the calculated stocks are high for tailings ponds and landfills, because iron concentrations in tailings and discards are not monitored regularly and are known to have a large spatial and temporal variability. The stock of obsolete products could not be determined at all, because its annual net accumulation cannot be distinguished from trade in obsolete products. Despite the large uncertainties regarding some reservoirs, we can nevertheless conclude that the iron reservoir in use (3,200 Tg) has reached approximately the same size as the economically recoverable natural ores (reserves: 2,100 Tg; reserve base: 4,600 Tg) and that its relative significance as a potential iron source is increasing, whereas ores are shrinking in size and grade.

A rough estimation[§] shows that on a global scale, anthropogenic iron stocks are ≈25,000–30,000 Tg, which is approximately one-third of the global reserves (79,000 Tg) and approximately one-sixth or one-seventh of the reserve base (180,000 Tg) (13). However, if a midcentury global population of 10 billion would adopt per-capita in-use stocks at current U.S. levels, ≈120,000 Tg of iron would need to be incorporated into products. This would represent a quadrupling or quintupling of current anthropogenic iron stocks. Although such a scenario would not lead to a global iron shortage (even though regional shortages are very likely to be reinforced), it would require mining ores currently considered marginally or subeconomic, making urban mines even more attractive.

Total potential scrap availability in the U.S. is determined by the poorly understood market for obsolete products. Model simulations indicate a gap of 20 Tg/a between generation and use

[‡]Obsolete products are those domestic goods that have permanently exited Use but that have not entered Scrap Processing and Waste Management, such as abandoned structures, illegal dumps, temporary storage sites for containers around harbors, or airplane graveyards.

[§]Assumptions are as follows. The per-capita iron stock of 1.2 billion people (Organization for Economic Cooperation and Development countries) is on average 80% of the U.S. stock (10 tons), and the per-capita iron stock of the remaining 5.3 billion people is on average one-quarter of the U.S. stock (3 tons).

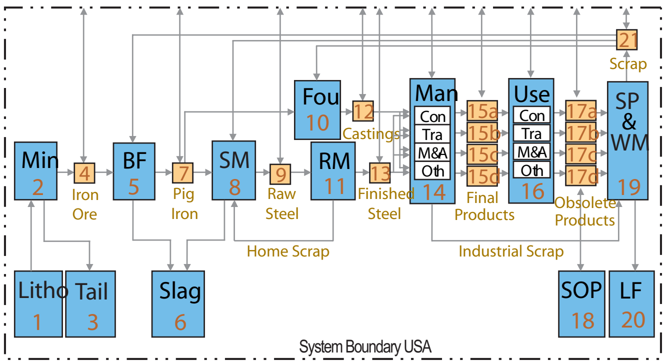

Fig. 6. System of the U.S. iron cycle. Blue boxes, transformation processes; yellow boxes, market processes.

of obsolete products in scrap processing and waste management. The following reasons can be advanced in possible explanation.

- Exports of shipments with a value below $2,500 (low-value shipments) have no filing requirement. Because of their low value and large mass, it is likely that large amounts of used and obsolete products fall into this category. Exporting obsolete cars and machinery might be more profitable than processing them in the U.S., where labor costs are high.
- Accounting aberrations are known for ships built in the U.S. that are then immediately registered in a foreign country; these are not reported in trade statistics. Additionally, U.S. military equipment used in foreign countries is officially never exported but often becomes obsolete and is scrapped outside the U.S.
- Exports of scrap are likely to be larger than reported, because inventory manipulation, speculation, and black market trading are common practices.
- The shape of the lifetime distribution functions could be highly skewed with long tails. In this case, obsolete product generation would be overestimated and a larger fraction of very old products is still in use.
- An increase in obsolete stocks is possible but is unlikely given the high scrap prices and the relatively small magnitude of the obsolete stock.

Corrosion of uncoated and unprotected steel products also results in unrecovered losses, but the rates of loss are much too low to account for a significant fraction of the gap (14).

If all iron in obsolete products were recovered for domestic recycling, mining of primary ores could theoretically be eliminated, provided that the necessary technology for doing so is available and financially profitable. This is possible as long as the U.S. iron cycle is sustained to a substantial degree by net imports of iron-containing goods [raw materials, intermediate (semi) products, parts, and final products], which together form the largest iron source in the U.S. and which substitute for domestic iron sources.

Another factor that keeps iron ore demand low is found in the observation that the per-capita in-use iron stocks in the U.S. leveled off ≈1980. This saturation coincided with the peak of U.S. iron and steel production. Because the demand for in-use stocks drives iron and steel production, the saturation of per-capita in-use stocks can begin to explain the decrease in steel demand in the late 1970s and 1980s. Other factors are the increasing imports of iron-containing products and the decreasing iron content of final products.

The observed saturation raises an additional question: Is this a transient phenomenon limited to the U.S., or does it also apply to other countries? If further research supports a general saturation hypothesis, saturation patterns observed in industrialized countries could be used to forecast long-term steel demand and scrap availability in emerging market economies and also to study the implications of saturation for resource sustainability, recycling technology, international trade, and industrial and governmental policy. Such an approach would be grounded in observable patterns of presumably robust physical variables (stocks) that connect resource demand (input) and secondary resource supply (output) and therefore has a potential to significantly improve economic long-term forecasting.

Table 2. Data sources and model approaches used to calculate variables in Figs. 1 and 5, using the system definition of Fig. 6

Variable	Total mass	Fe conc.	Fe mass	Notes
S_1	Ref. 13	Ref. 13, *I*	*I*	Ref. Reserve base 2004
$X_{1–2}$	Ref. 19		*B* 2	
$X_{2–3}$	*B* 2	Ref. 20	*M*	Crude iron ore
S_3			*I*	
$X_{2–4}$	Refs. 19, 21, 22	Ref. 19	*M*	Usable iron ore
$X_{0–4}$, $X_{4–0}$	Refs. 19, 21, 22		*M*	Grade like $X_{2–4}$
$X_{4–5}$	Refs. 19, 21		*M*	Grade like $X_{2–4}$
$X_{5–6}$	Ref. 19	Ref. 23	*M*	Slag sales
$X_{5–7}$	Refs. 19, 21, 22	Ref. 24	*M*	Includes direct reduced iron
$X_{0–7}$, $X_{7–0}$	Refs. 19, 22	Ref. 24	*M*	Includes DRI
$X_{7–8}$	Refs. 19, 22	Ref. 24	*M*	Includes DRI
$X_{7–10}$	Ref. 19	Ref. 24	*M*	
$X_{8–6}$	Ref. 19	Ref. 23	*M*	Slag sales
$X_{8–9}$	Refs. 19, 22, 25	Ref. 24	*M*	
$X_{0–9}$, $X_{9–0}$	Ref. 19	Ref. 24	*M*	
$X_{9–11}$			*B* 9	
$X_{10–12}$	Ref. 19	Ref. 24	*M*	
$X_{11–8}$			*B* 11	
$X_{11–13}$			*B* 13	
$X_{0–12}$, $X_{12–0}$	Ref. 19	Ref. 24	*M*	
$X_{12–14}$			*B* 12	Sum of flows
$X_{12–14.s}$			$=k_1*X_{12–14}$	k_1 equal to k_2
$X_{0–13}$, $X_{13–0}$	Refs. 19, 26	Ref. 24	*M*	
$X_{13–14}$	Refs. 19, 26	Ref. 24	*M*	Sum of flows
$X_{13–14.s}$			$=k_2*X_{12–14}$	k_2 from (15)
$X_{0–14.s}$, $X_{14.s–0}$	Ref. 16	*E*	*M*	
$X_{14.s–19}$			$=k_3*X_{12–14.s} + k_4*X_{13–14.s}$	k_3, k_4: industry yield factors
$X_{14.s–15.s}$			*B* 14.*s*	
$X_{0–15.s}$, $X_{15.s–0}$	Ref. 16	*E*	*M*	
$X_{15.s–16.s}$			*B* 15.*s*	
$S_{16.s}$			*I*	
$X_{0–16.s}$, $X_{16.s–0}$	Ref. 17	*E*	*M*	
$X_{16.s–17.s}$			Model	See text
$X_{0–17.s}$, $X_{17.s–0}$				No data
$X_{17.s–18}$, $X_{18–17.s}$				No data
S_{18}			Ref. 27	
$X_{17.s–19}$			*B* 19	
$X_{19–20}$			$=k_5*X_{17–19}$	k_5 from refs. 18 and 19
S_{20}			*I*	
$X_{19–21}$			*B* 21	
$X_{0–21}$, $X_{21–0}$	Ref. 26	Ref. 24	*M*	
$X_{21–5}$	Ref. 19	Ref. 24	*M*	
$X_{21–8}$	Ref. 19	Ref. 24	*M*	
$X_{21–10}$	Ref. 19	Ref. 24	*M*	

S_p, stock in process *p*; $X_{p–q}$, flow between processes *p* and *q*; *M*, values derived by multiplication of mass flows of goods and their iron concentration; *B p*, values calculated by mass balance of process *p*; *I*, stocks calculated by integrating net inputs over time; *E*, informed estimates.

Materials and Methods

The U.S. iron cycle was analyzed by using a system shown in aggregated form in Fig. 6. It consists of transformation (blue boxes) and market processes (yellow boxes), connected by flows of iron-containing goods (arrows).

The processes Manufacturing and Use are divided into four product categories: Con (buildings and infrastructures), Tra (automobiles, railways, ships, and airplanes), M&A (industrial and domestic), and Oth (e.g., containers, furniture, cans). Industry stocks are neglected because of their small size. The system excludes iron incorporated in minerals not destined for metallurgical iron uses, such as rocks or concrete.

The iron cycle was quantified for the period 1900–2004. In addition, rough estimates were made for the period 1800–1900 to obtain reasonable initial conditions for stocks. Data sources and model assumptions are shown in Table 2. Where data were available, iron flows were calculated based on mass flows of goods and their iron concentrations. Where no statistics could be obtained, data were derived from mass balances and model assumptions.

Data on steel used in different manufacturing sectors are incomplete. The American Iron and Steel Institute (AISI) records since 1941 divide domestic shipments of finished steel into 22 sectors (15). Similar data for imported steel and castings are lacking, so we assume the same sector split as for domestic steel shipments and that the U.S. sector split was constant before 1941. Because steel production was lower at the beginning of the century, and overall imports of finished steel historically have been <20%, the error resulting from this uncertainty is moderate. Furthermore, a rapidly increasing amount of steel, currently ≈40%, is shipped to wholesalers who do not report data for their sector split, which was assumed to be equal to that of steel mills.

Import and export flows of parts and final products were determined for the years 1962, 1971, 1981, 1990, 2000, and 2004, by using Standard International Trade Classification revision 1 data from United Nations trade statistics (16) and informed estimates of product iron concentrations. Data between these years were interpolated, and trade data before 1950 were assumed to be negligible. United Nations trade statistics do not distinguish between new and used products. Trade of used products was therefore calculated by using detailed trade statistics of the U.S. Department of Commerce (17), which differentiates used products for ≈5% of all iron-containing product categories. Because the resulting uncertainty is considerable, we used the conservative assumption that the determined fraction of used products also applies for the remaining 95%. Trade in new products was subsequently adjusted by subtracting used products from overall final products trade. The resulting trade in used products turned out to be very small for imports (3%) but substantial for exports (40%). Because overall imports of final products are approximately three times larger than of exports, the impact of errors in used product trade data on overall trade data remains moderate, but it can be substantial for export data.

The stock of products in use was divided into products that remain in the country, that are exported during the use phase, and that are imported during the use phase. For the latter two groups, it was assumed that products stay in domestic use for half of their lifetime. For products that remain in the country, obsolete products generation is calculated for all product categories s as follows:

$$X_{\mathrm{Obs}D,s}(t) = \int_{t_0}^{t} L_s(t, t') \cdot X_{\mathrm{New}D,s}(t')\, dt', \qquad [1]$$

where $L_s(t, t')$ is the lifetime distribution of product category s, which is the probability that a product that entered use at time t' exits use at time t. For all product categories, the lifetime distribution is assumed to be normal:

$$L_s(t, t') = \frac{1}{\sigma_s \sqrt{2\pi}} \cdot e^{\frac{t - t' - \tau_s}{2\sigma_s^2}}, \qquad [2]$$

where τ_s is the average lifetime and σ_s is the standard deviation. There is little firm data about the lifetime distribution of different product categories. For this reason, a sensitivity analysis was conducted to show the effect of different average lifetime assumptions. Because this sensitivity analysis did not show a significant impact on our overall conclusions, the impacts of different shapes of lifetime distribution functions (e.g., skewed curves or curves with multiple peaks) were not tested here. However, the precision of the data might be improved in further studies that differentiate various shapes.

Data on iron entering landfills are available only for municipal solid waste (18) and not for other waste categories. Recovery rates of iron in obsolete products were therefore estimated for different product categories by using data on municipal solid waste, recycling rates (19), and expert interviews.

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1. Jacobs J (1969) *The Economy of Cities* (Random House, New York).
2. Harper EM, Johnson J, Graedel TE (2006) *Environ Eng Sci* 23:493–506.
3. Müller DB, Bader H-P, Baccini P (2004) *J Ind Ecol* 8:65–87.
4. Gordon RB, Bertram M, Graedel TE (2006) *Proc Natl Acad Sci USA* 103:1209–1214.
5. Müller DB (2006) *Ecol Econ* 59:142–156.
6. Lichtensteiger T (2006) *Bauwerke als Ressourcennutzer und Ressourcenspender in der Langfristigen Entwicklung Urbaner Systeme* (VDF, Zurich).
7. Wittmer D (2006) *Kupfer im Regionalen Ressourcenhaushalt - Ein Methodischer Beitrag zur Exploration Urbaner Lagerstätten* (VDF, Zurich).
8. Zeltner C, Bader H-P, Scheidegger R, Baccini P (1999) *Reg Environ Change J* 1:31–46.
9. Spatari S, Bertram M, Gordon RB, Henderson K, Graedel TE (2005) *Ecol Econ* 54:37–51.
10. Kesler S (1994) *Mineral Resources, Economics, and the Environment* (McMillan College, New York).
11. US Department of Energy (2000) *Energetics* (US Dept of Energy, Washington, DC), DOE Publ DOE/EE-0229.
12. Fenton MD (2002) in *Minerals Yearbook 2000* (US Govt Print Office, Washington, DC), Vol 1.
13. US Geological Survey (2006) *Mineral Commodity Summaries 2006* (US Govt Print Office, Washington, DC).
14. Leygraf C, Graedel T (2000) *Atmospheric Corrosion* (Wiley Interscience, New York).
15. American Iron and Steel Institute (1941–1999) *Annual Statistical Report of the American Iron and Steel Institute* (AISI, New York).
16. UN Statistics Division (2005) *UN Commodity Trade Statistics Database* (UN Stat Division, New York), Vol 2005.
17. US Department of Commerce (2005) in *USA Trade Online*, ed STAT-USA (US Dept of Commerce, Washington, DC), Vol 2005.
18. US Environmental Protection Agency (1995–2003) in *Municipal Solid Waste Generation, Recycling and Disposal in the United States: Facts and Figures* (Solid Waste and Emergency Response, Washington, DC), Vol 2005, Publ 5305W.
19. US Geological Survey (1932–2005) *Minerals Yearbook* (US Govt Print Office, Washington, DC).
20. US Environmental Protection Agency (1994) *Technical Resource Document, Extraction and Beneficiation of Ores and Minerals* (Office of Solid Waste, Washington, DC), p 122.
21. US Bureau of the Census (1976) *Historical Statistics of the United States, Colonial Times to 1970* (US Govt Print Office, Washington, DC).
22. US Geological Survey (2001) in *Historical Statistics for Mineral and Material Commodities in the United States*, ed Kelly T (US Geol Surv, Reston, VA).
23. International Iron and Steel Institute (1987) *The Management of Steel Industry By-Products and Waste* (IISI, Brussels).
24. Shackelford JF, Alexander W (2001) *CRC Materials Science and Engineering Handbook* (CRC, Boca Raton, FL).
25. American Metal Market (1942) *Metal Statistics 1942* (Am Metal Market, New York).
26. US Geological Survey (2006) in *Historical Statistics for Mineral and Material Commodities in the United States*, eds Kelly T, Matos G (US Geol Surv, Reston, VA), Vol 2006.
27. Drakonakis K, Rostowski K, Rauch J, Graedel T, Gordon R (2006) *Resources Conservation Recycling*, 10.1016/j.resconrec.2006.05.005.