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Losses and lifetimes of metals in the economy

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The consumption of most metals continues to rise following ever-increasing population growth, affluence and technological development. Sustainability considerations urge greater resource efficiency and retention of metals in the economy. We model the fate of a yearly cohort of 61 extracted metals over time and identify where losses are expected to occur through a life-cycle lens. We find that ferrous metals have the longest lifetimes, with 150 years on average, followed by precious, non-ferrous and specialty metals with 61, 50 and 12 years on average, respectively. Production losses are the largest for 15 of the studied metals whereas use losses are the largest for barium, mercury and strontium. Losses to waste management and recycling are the largest for 43 metals, suggesting the need to improve design for better sorting and recycling and to ensure longer-lasting products, in combination with improving waste-management practices. Compared with the United Nations Environmental Programme's recycling statistics, our results show the importance of taking a life-cycle perspective to estimate losses of metals to develop effective circular economy strategies. We provide the dataset and model used in a machine-readable format to allow further research on metal cycles.

Modern societies need vast amounts of metals to thrive and to pursue Sustainable Development Goals (SDGs)[1,2]. Nevertheless, similar to other natural resources[3], metal stocks are under the pressure of an ever-increasing demand[1,4]. Consequently, many nations have started to identify commodities for which supply risks pose a particular threat to their economies. The European Union and United States consider approximately 30 metals and minerals as so-called critical raw materials as part of a crucial prioritization approach to secure regional supply strategies[5,6].

Circular economy strategies can be proposed as a response to this increasing stress. Minimizing metal losses along supply chains and increasing the lifespans of products help prolong the lifetimes of metals in the economy and increase the value they generate for humans while reducing possible environmental impacts and mitigating potential supply risks for future generations[7–9]. These strategies may also help reduce greenhouse gas (GHG) emissions from the metal-production sector[9–12], which is responsible for 7.9% of global emissions[13].

Losses of metals may be considered to negate circularity since they become inaccessible for future use[14]. Material flow analyses (MFAs) allow for tracing losses of metals from a life-cycle perspective. The fate of metals can be dynamically evaluated over time by considering the lifetime of products put on the market and identifying where these losses occur. However, for many metals, no comprehensive global MFA is available so far[15,16]. In this context, we seek to improve knowledge with an up-to-date evaluation of the losses of metals. Relying on a wide-ranging data collection stage and the so-called MaTrace dissipation model[17], we evaluate the lifetimes of 61 metals in the economy and attribute cumulative losses to different life-cycle phases over time. Our results are compared with the United Nations Environmental Programme's (UNEP's) global recycling indicators available for multiple commodities[18], revealing the importance of taking a life-cycle perspective when setting up circular economy strategies or, more generally, aiming for a more sustainable management of metals.

Global cycle of metals

We study the global trends of metal flows and use stocks over their life cycle (Fig. 1). 'Metals' here include most metals and metalloids; radioactive elements are not studied. The MaTrace model allows for tracing the fate of a specific cohort of extracted metals over time (Methods). We define losses as flows of metals emitted into the environment, stored in waste disposal facilities or diluted in a material flow where the specific characteristics of metals are no longer made use of, that is, through non-functional recycling[19]. The lifetimes of metals represent the average duration of their use in the economy, from mining until they have been entirely lost through different applications.

Metals are classified into four categories defined by the UNEP[18] (Fig. 2). Ferrous metals comprise iron and its main alloying elements, primarily used in the construction, mechanical equipment and transport sectors. Non-ferrous metals include most other widely produced metals that are typically used in sectors similar to ferrous metals and in electronics and various miscellaneous applications. Unlike the UNEP report, we also consider magnesia (magnesium) used as refractory materials for the steel industry and titanium oxides used in paint products, accounting for over 50% of their respective markets[20]. Specialty metals englobe many technology metals used in, for example, permanent magnets, batteries and electronics and a wide range of miscellaneous applications. Precious metals include platinum-group metals, most of which are used as catalysts for the automotive industry and industrial processes, and silver and gold, which are used mainly in electronics, jewellery and investment products.

The fate of metals and the evaluation of losses over time are derived from the estimated yields of processes among the main life-cycle phases and the distribution of metal applications per end-use sector and their corresponding lifetimes. They are not a forecast and do not include scenarios of technology development[19]. The year-by-year remaining in-use stocks for a single cohort of
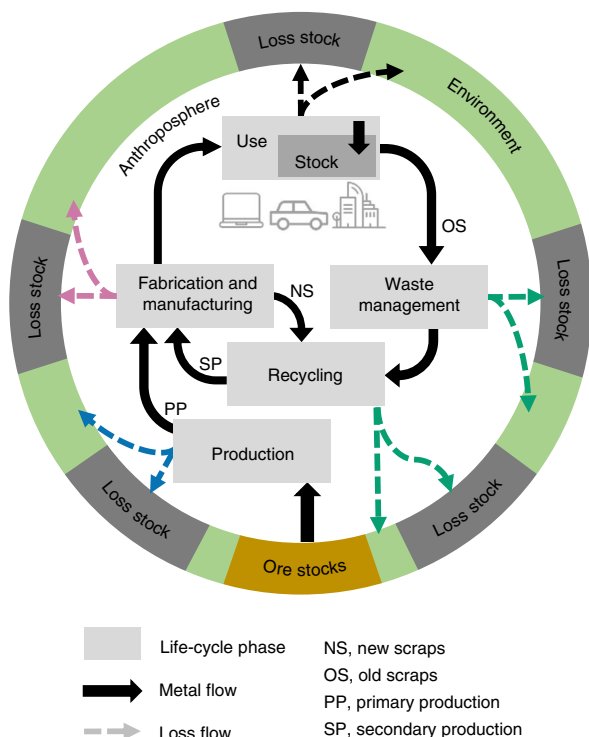
Fig. 1 | Global cycle of metals. Loss flows include emissions to the environment, non-functionally recycled metals ending up in other material flows and flows to waste disposal facilities (landfills, slags and tailings storage facilities). Figure adapted with permission from ref. [16], American Chemical Society.

each metal detailed per end-use sector, as well as the corresponding losses per life-cycle phase over the next 1,000 years, are provided in the Supplementary Data. The dataset and model are provided as separate machine-readable files (Data availability).

Losses per life-cycle phase

Figure 2 presents the share of losses attributed to different life-cycle phases: production, fabrication and manufacturing, use, waste management and recycling. The latter two are grouped together. The figure also presents the average lifetimes of metals in the economy, from extraction until they are completely lost.

Production. Production processes often target only one or two metals in sufficient concentrations in the extracted ores, leaving aside other metals because they are not economically extractable[21,22]. Nontargeted metals may be directly diverted to waste disposal facilities, dissolve in the carrier metal (that is, the main targeted metal for production) with no specific functionality or end up in low-value building materials[9]. Production losses are generally lower among widely produced ferrous and non-ferrous metals, which are also carrier metals in most cases. These losses are most important for 13 specialty metals, as well as for vanadium and osmium. Production losses account for over 30% of the total losses for rare earth elements (lanthanide series) and precious metals, 50% for cobalt, 70% for indium and greater than 95% for arsenic, gallium, germanium, hafnium, scandium, selenium and tellurium.

We herein evaluate global losses of metals by looking at a yearly cohort of extracted metals representative of average production statistics for between 2015 and 2019, as shown in Fig. 3. Approximately 25% of the extracted specialty metals are directly lost during production (4 Mt lost out of 16 Mt extracted). These losses

are proportionally lower for precious metals, with approximately 17% (6.6 kt lost out of 38 kt extracted); non-ferrous metals, with approximately 15% (21 Mt lost out of 140 Mt extracted); and ferrous metals, with approximately 13% (0.23 Gt lost out of 1.8 Gt extracted). Of the ferrous metals, iron alone accounts for about 1.7 Gt extracted, of which 0.22 Gt is lost to production.

Fabrication and manufacturing. Cumulative losses to the fabrication and manufacturing processes are the lowest for 34 out of 61 metals. They are negligible for iron and represent less than 1% of the cumulative losses of precious metals (0.35 kt). These losses become proportionally larger among specialty and ferrous metals other than iron, with 4% of cumulative losses (0.6 Mt and 3 Mt, respectively), and non-ferrous metals (6% of losses with 9 Mt). Most specialty metals undergo a single life cycle, explaining their lower cumulative losses to fabrication and manufacturing than those of other metals.

Use phase. Losses to the use phase are negligible for most metals. They represent approximately 2% of total losses by weight for ferrous metals (with 30 Mt; and 10% when disregarding iron, with 7 Mt). Likewise, around 2% of precious metals are lost during use (700 tons). Use losses are greater among non-ferrous metals (7% of losses, with 10 Mt) and represent as much as 31% of all losses for specialty metals (5 Mt, most of which is barium). These losses are most prominent for a few metals voluntarily used in dissipative applications. Notable examples include oil and gas well-drilling muds, representing about 80% of the demand for barium[18] and 30% of that for strontium[23], and artisanal gold mining, accounting for over one-third of the global use of mercury[24]. Other dissipative applications include agricultural products, accounting for approximately 5% and 10% of the total use of bismuth[25] and magnesium[26], respectively; fluid cracking catalysts used in the petroleum industry (approximately 5% and 45% of the demand for cerium and lanthanum oxides, respectively[27,28]); and deoxidization and desulfurization agents for steel production (approximately 3% and 26% of the demand for aluminium[29] and manganese[30], respectively).

Moreover, involuntary losses may also occur during the use phase, but they contribute minimally to total metal losses. For example, zinc-containing car tires and tungsten carbides used in cutting tools wear off during use, and some metals exposed to the outdoor environment corrode[31] (mainly ferrous and non-ferrous metals used in the construction and automotive sectors, for example, galvanized steel). Such losses are expected to remain mostly in the environment, unlike landfilled materials that are to some extent under human supervision[32].

Waste management and recycling. The largest share of cumulative losses over time is due to waste management and recycling for 43 metals. These two life-cycle phases account for approximately 85% of the losses of ferrous metals (1.5 Gt, 1.47 Gt of which is iron), 80% for precious metals (30 kt), 71% for non-ferrous metals (98 Mt) and 40% for specialty metals (6 Mt). Metals undergoing multiple life cycles due to relatively efficient collection and recycling channels are still mostly lost to waste management over time, albeit over longer periods (for example, aluminium, copper, gold, iron and platinum). Aside from the closed-loop recycling of a few valuable metals used in industrial applications (for example, platinum alloys used in the glass industry[33]) and jewellery and investment products, the recovery of metals from collection and sorting seldom reaches 90% and compares rather unfavourably with fabrication and manufacturing yields.

Moreover, recycling losses may occur during the remelting of alloys as different metals tend to accumulate in dusts (for example, zinc) and slags (for example, chromium and vanadium) or end up as contaminants in large-magnitude streams (for example, copper
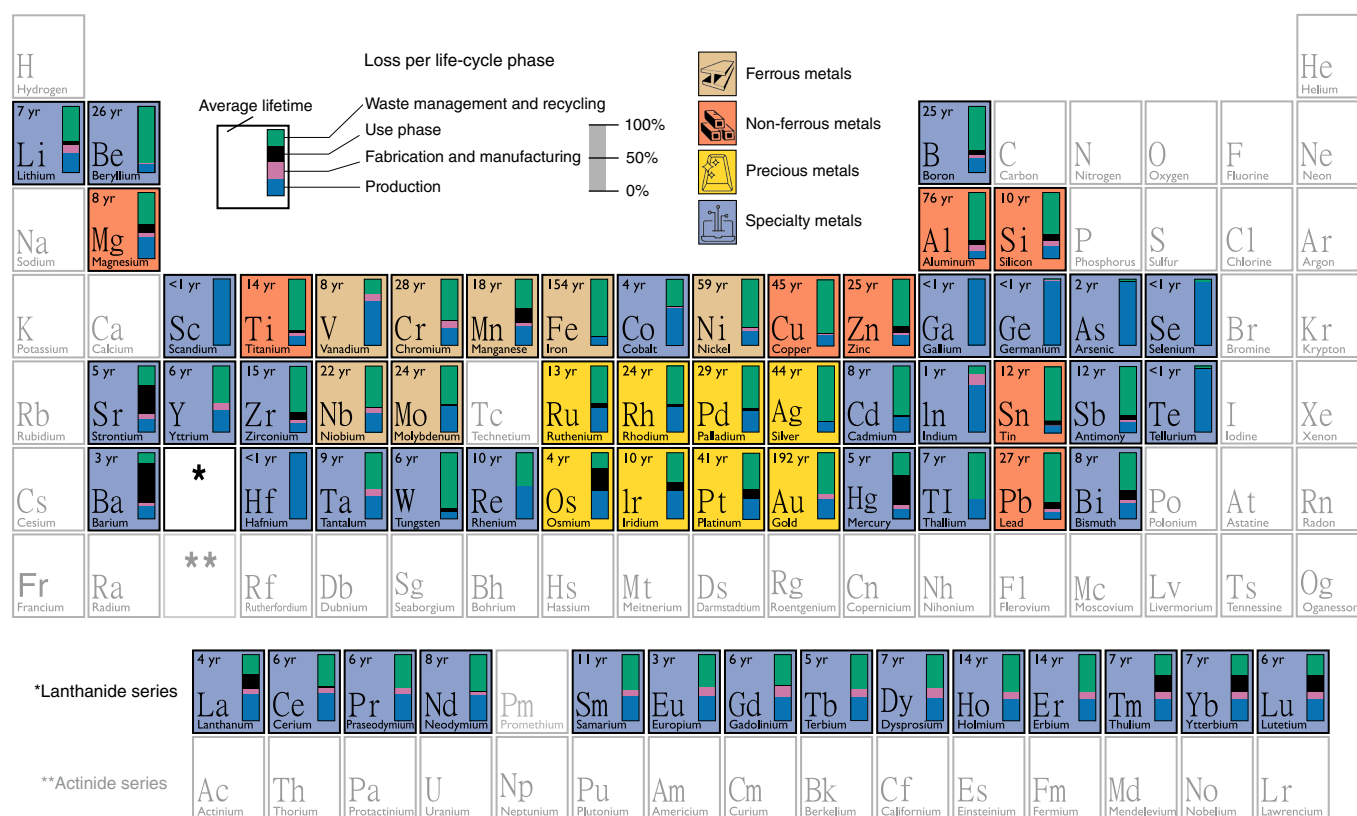
Fig. 2 | Distribution of metal losses per life-cycle phase and average lifetimes of metals in the economy. The shares of losses per life-cycle phase are detailed in the Supplementary Data.

in steel flows)[9,18,34]. Losses to recycling processes are the largest for metals widely used in ferrous alloys (for example, chromium, iron, manganese, molybdenum and niobium), aluminium and zinc, half of which is used to protect steel from corrosion[35]. These losses are greatest for ferrous metals (26% of their cumulative losses) and smaller among non-ferrous (8%), precious (2%) and specialty metals (0.4%).

Lifetimes of metals in the economy

The estimated lifetimes of metals range from less than a year (for example, gallium and selenium) to just under two centuries for gold (Figs. 2 and 3). High process yields and the use of metals in applications with long lifespans contribute to longer lifetimes. In general, metals with the longest lifetimes are widely produced ferrous (chromium, iron, manganese, molybdenum and nickel) and non-ferrous metals (aluminium, copper, lead, nickel and zinc) and precious metals (gold, palladium, platinum, rhodium and silver).

Average lifetimes among groups of metals are calculated by weighting the average lifetimes of metals within a group with their respective yearly extraction. Lifetimes are generally longer among non-ferrous (8 to 76 years, with a group average of 50 years), precious (4 to 192 years, with a group average of 61 years) and ferrous metals (8 to 154 years, with a group average of 150 years). The lifetimes of specialty metals are overall lower and range from less than a year to 26 years, with a group average of 12 years. Gold and, more important, iron increase average lifetimes for precious and ferrous metals, respectively. The former represents 12% of the volume of precious metals extracted, and its lifetime of 192 years is at least four times longer than that of other precious metals. Iron accounts for 97% of the mass of extracted ferrous metals, and its lifetime is at least two and a half times that of other ferrous metals.

Losses over time

The fate of a yearly cohort of extracted metals over time is depicted in Fig. 4. Losses for ferrous, non-ferrous and precious metals are expected to occur over far longer periods than losses for specialty metals. Most of the specialty metals are lost within the first 25 years due to high losses in each life-cycle phase, generally short application lifespans and negligible collection yields. The shares of losses to the production and use phases are lower among other metal groups. Nevertheless, metals that remain in the economy the longest see their share of losses to waste management and recycling increase over time. Indeed, these metals undergo multiple life cycles due to limited losses upstream in their life cycle before old scraps become available for recycling. Driven by the longevity of iron, approximately 0.13 Gt, 0.12 Gt, 0.21 Gt and 0.26 Gt of ferrous metals of 1.76 Gt extracted are expected to be lost to waste management in time intervals of 0–25, >25–50, >50–100 and >100–200 years, respectively. Approximately 32 Mt, 19 Mt, 19 Mt and 12 Mt of non-ferrous metals (out of 138 Mt extracted) and 10 kt, 7.5 kt, 6.9 kt and 3.8 kt of precious metals (out of 38 kt extracted) are expected to be lost to waste management over these respective intervals. Recycling losses are proportionally greater for ferrous and non-ferrous metals: it is expected that approximately 0.04 Gt, 0.06 Gt, 0.09 Gt and 0.12 Gt of ferrous metals and 4.2 Mt, 2.0 Mt, 2.3 Mt and 1.6 Mt of non-ferrous metals are lost over these same periods.

Half of the total weight of the cohort of extracted metals is projected to still be functionally in use in 100 years, most of which is iron. Specialty metals are expected to be completely lost by then. Aside from iron, approximately 4% of ferrous and 16% of precious and non-ferrous metals are expected to be in use in 100 years. These shares, respectively, drop to 0.4%, 5.0% and 5.0% after 200 years. Of all metals extracted recently, only around 5% of iron and 10% of gold are predicted to remain in the economy for 500 years.
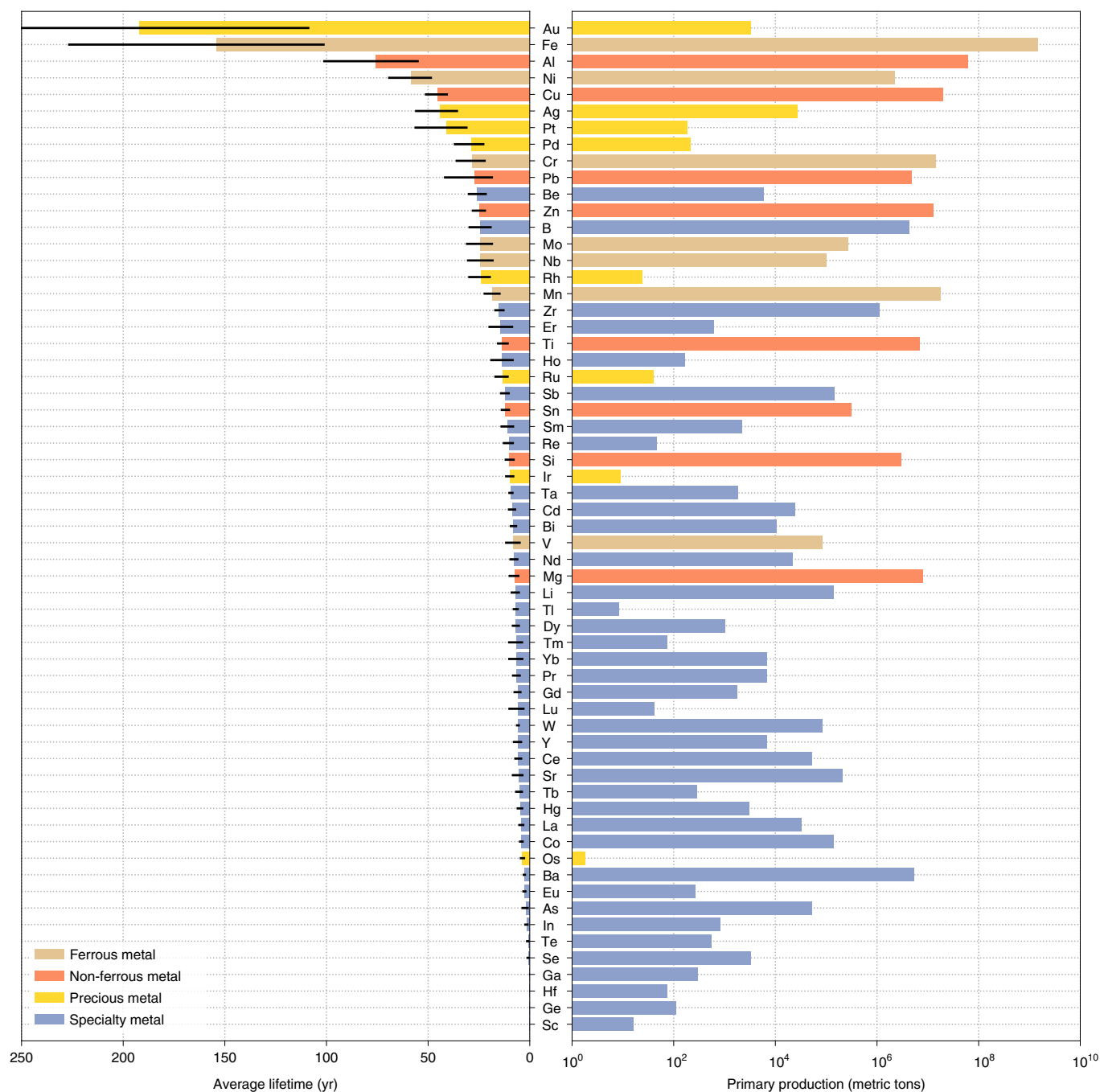
Fig. 3 | The average lifetimes of metals in the economy versus average global annual production between 2015 and 2019. The 95% confidence intervals for average lifetimes are indicated with black lines.

Loss rates versus recycling indicators

The recycled content and end-of-life recycling rate (EOL-RR) are useful global indicators when setting up recycling strategies for metals[34]. However, these recycling indicators do not take a full life-cycle perspective in identifying losses of metals over time. Conversely, loss rates are calculated as the inverse function of the average lifetime and represent the rate at which extracted metals become unavailable for further use. We compare the computed loss rates with EOL-RR and recycled content statistics reported by the UNEP[18] (Fig. 5). A few EOL-RRs were recently updated by ref. [36], and we report these updated values in the figure. The recycled content is the share of recycled metal (from new and old scraps) in the fabricated metal flow in relation to the total input of metal,

including primary and recycled metal[18], and the EOL-RR is the percentage of metal in old scraps that is functionally recycled[18,36]. New scraps are residues from fabrication and manufacturing processes, such as turnings and shavings resulting from the machining of components, and old scraps originate from end-of-life applications[18].

The EOL-RR tends to be greater than the recycled content as the demand for most metals keeps increasing, requiring additional inputs from primary production[18]. For metals presenting a larger recycled content than EOL-RR (for example, niobium and ruthenium) the implication is that their recycling content originates primarily from new scraps[18]. In general, metals with higher EOL-RR values and recycled content also have lower loss rates. This is most apparent for ferrous metals (for example, nickel and iron) and
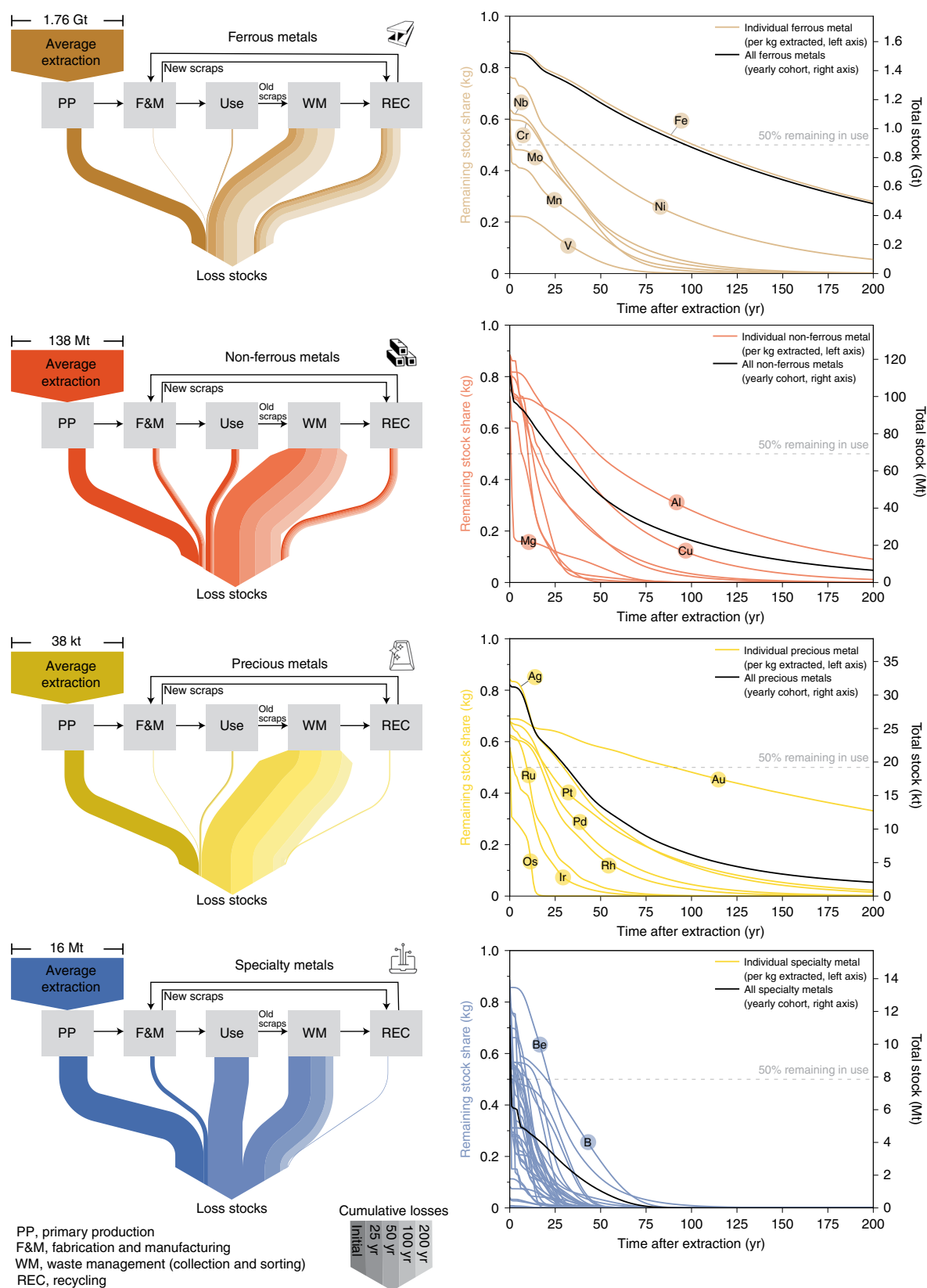
Fig. 4 | Predicted in-use stocks and losses of metals over two centuries for a yearly cohort of extracted metals. Sankey diagrams displayed on the left illustrate initial and cumulative losses to the different life-cycle phases over periods of 0–25, >25–50, >50–100 and >100–200 years. The graphs shown on the right depict the remaining stock shares for individual metals (coloured curves, left y axis), and the total projected in-use stock for a yearly cohort of extracted metals per category (black curve, right y axis). Lifetime distributions of metals are typically skewed towards earlier years because of initial production losses. In this case, half of the initial stock (dashed line) is lost before the average lifetime is reached. Supplementary Figs. 2–62 present detailed graphs for individual metals.
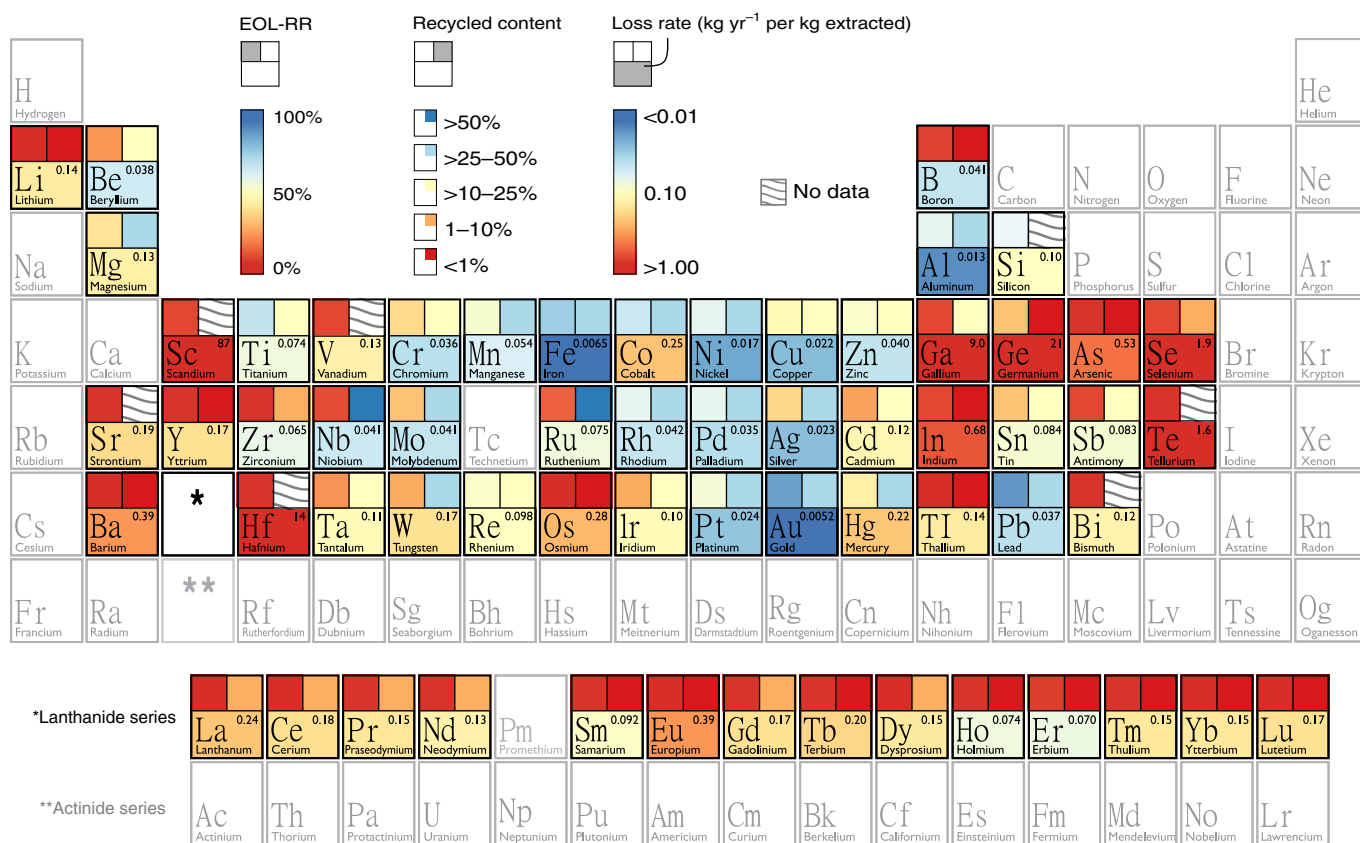
Fig. 5 | Loss rates versus EOL-RR and recycled content. EOL-RRs are presented on a continuous scale based on ref. [36], and recycled content data are presented on a discrete scale based on the UNEP report[18]. Loss rates are indicated on a blue to yellow to red scale, where blue represents a low loss rate relative to other metals, and red represents a high loss rate. The colour scale for loss rates is arbitrary and is meant to facilitate the comparison of loss rates with recycling statistics. It should not be interpreted as an evaluation. The comparison should be interpreted carefully for magnesium and titanium because the recycling statistics consider only their metal forms, whereas loss rates also include compounds of metallic elements such as magnesia used as a refractory material and titanium dioxide used in paint.

precious metals (for example, gold and silver), underlining relatively efficient waste-management and recycling channels.

Loss rates of metals with low EOL-RR values are determined mostly by process yields among life-cycle phases other than waste management and recycling and by the lifespans of applications in which they are used because they mostly undergo a single use phase. In such cases, identifying where losses occur helps explain their loss rates. For example, barium and tellurium have negligible EOL-RRs and recycled content, yet barium's loss rate is four times lower than that of tellurium. The former is lost mostly in the use phase, while the latter is lost mostly during the initial production phase (Fig. 2).

Some metals with low EOL-RRs also have loss rates competing with other relatively well-recycled metals because they are used in long-lived applications. For example, boron's loss rate is similar to that of rhodium despite its negligible EOL-RR and recycled content. Approximately half of boron is used in insulation-grade glass for the construction sector, with an average lifetime of 50 years in the model. By comparison, rhodium's EOL-RR is 60%[36], and its recycled content is between 25% and 50%[18]; however, it is used predominantly for catalytic converters in vehicle exhaust systems, with lifespans less than half as long as those for the construction sector reported in our dataset.

Discussion

Society requires a continuous intake of metals: first, to meet the increasing demand for global development and upcoming technologies and, second, to regenerate the share of metals that is unavoidably

lost in each cycle[9,37]. The SDGs advise that we decouple our global material consumption from human well-being, with SDG 12 explicitly aiming for more sustainable consumption and production patterns[2]. Increasing resource efficiency and shifting towards circular material flows is essential to pursue that SDG[38].

Despite considerable challenges awaiting future mineral supply[4], the life cycles of most metals remain linear today. Identifying where losses occur over time may support decision-making for reaching more resource-efficient supply chains for different metals and setting up circular economy strategies streamlined to the most relevant life-cycle stages. To do so, our dataset and model bring together state-of-the-art information on the anthropogenic cycles of 61 metals. Global dynamic MFAs are conducted for these metals using a consistent methodology, going further than other research covering losses for a wide range of metals for single life-cycle phases, such as in-use[31] or end-of-life losses[18], or including a limited number of metals at once[19].

Circularity indicators beyond recycling rates. Setting resource efficiency targets and monitoring progress is key to improve resource efficiency[38,39]. In *The Roadmap to a Resource Efficient Europe*[40], the European Commission states that robust and easily understandable indicators are necessary to do so. The average lifetimes and loss rates provide comprehensive insight into the conservation potentials of metals in the economy. They are useful indicators to determine how resource efficient our economies are globally. Moreover, they provide a more comprehensive overview

of global metal losses than do recycling statistics by accounting for the lifespans of applications and for other losses that are not clearly apparent in the recycling statistics. Lifetimes and loss rates might therefore be more useful indicators than recycling indicators to support policies and to develop strategies aiming for a more circular and efficient use of metals.

Implications for a sustainable use of metals. Our results reveal that the life-cycle phases contributing most to cumulative losses vary considerably between metals (Fig. 2). They are the greatest for the production phase for 15 metals, for the use phase for 3 metals, and for the waste-management and recycling phases for 43 metals.

Production losses are substantial for many specialty metals because they are often directly discarded as mining waste during production. This may be most concerning for by-product metals used increasingly in emerging applications for the energy transition such as lithium-ion batteries (cobalt), permanent magnets (neodymium), solar cells (for example, indium, gallium, germanium, selenium and tellurium) and solid oxide fuel cells (scandium)[41]. It is striking that out of 15 metals lost most during extraction and production, 13 are critical in the European Union[42] or the United States[43], including cobalt, indium, gallium, germanium, scandium and tellurium. Between 50% and >99% of these metals is directly lost during production, suggesting that efforts should be spent on recovering more of these metals as by-products where they are currently unexploited or from past mining waste storage facilities where they have been stockpiled[44]. Reducing losses of critical metals or substituting them with other materials would also help reduce the dependence of key supply chains on the few high-risk regions producing them[20].

While there is room to increase the production yield of some metals, this is not necessarily the case for all of them. For example, the large amounts of additional energy required to increase the production yield of platinum-group metals (which are already refined from ores with very low concentrations of these metals[45]) could detrimentally lead to burden shifting towards fossil fuel consumption and the associated climate change. However, even these precious metals produced with extensive efforts remain in the economy for under 35 years on average, closely matching the lifetimes of several much cheaper ferrous and non-ferrous metals. It is noteworthy that over half of the consumption of platinum-group metals is used in automotive catalysts, from which they are not systematically recovered[18,46], including over 80% of the demand for rhodium and palladium and one-third of the demand for platinum.

The fabrication and manufacturing phase and the use phase cause the fewest losses for most metals. Aside from iron, these life-cycle phases represent 6% and 11% of the cumulative losses of metals, respectively. Addressing these losses may become worthwhile to increase circularity for metals only after increasing their EOL-RRs as most metals currently undergo a single fabrication and manufacturing phase and use phase because they are not recycled from obsolete products. Dissipation in use is most prominent for only three metals (barium, mercury and strontium) and might be most problematic for toxic metals (for example, chrome and mercury) that remain in the environment. However, some dissipative uses are crucial to essential sectors (for example, barium and strontium for oil-well drilling) and may not always be totally avoided or possibly substituted by other substances. Additional research is required to identify and measure losses of metals to the environment and prioritize corrective actions.

The waste-management and recycling phases contribute greatly to cumulative losses for almost all metals and represent 84% of global cumulative losses (64% without iron). Thus, improving the circularity of most metals should rely mainly on designing recyclable products with longer lifetimes and improving their recovery from obsolete applications through improved collection and

recycling schemes[8,31,39]. Doing so may also help reduce the environmental burden of primary metal production[12] and especially that of GHG emissions[10,11]. For example, most rare earth elements are used in currently unrecyclable applications with short lifetimes (for example, over half of europium and terbium is used in unrecyclable phosphors for lighting applications[27,28,31], with an average lifespan of 2.5 years in the dataset). These contribute to relatively low average lifetimes for these metals: three years for europium and five years for terbium.

Metals with the highest loss rates generally also have low EOL-RRs (Fig. 5). This is most obvious for specialty metals that have the shortest lifetimes out of the four metal categories, with 12 years on average. Indeed, only a handful of applications of specialty metals are functionally recycled, with the most notable being antimony and cadmium from batteries, beryllium from copper alloys, mercury used in industrial processes, tantalum from alloys and cutting tools, tungsten from cutting tools, and cobalt and rhenium from their principal applications (details in Supplementary Information and Supplementary Data). However, aside from beryllium, none of these metals ranks among the longest-living specialty metals. As demonstrated for boron, the relatively long lifetimes of beryllium, boron and zirconium are driven by long-lived applications rather than recycling, putting forwards the crucial role of lengthening the lifespans of applications to improve the conservation of metals in the economy.

Finally, while it may intuitively seem more urgent to address losses of the most valuable or critical metals when prioritizing loss-reduction strategies, it is also essential to bear in mind the scale of global losses for different metals (Fig. 4). Indeed, almost 2 Gt of ferrous and non-ferrous metals are extracted every year, of which an impressive 14 Mt are lost every year on average. Thus, it is likely that marginal, yet systematic, improvements for widely used metals would also be worthwhile.

Other applications for the dataset and model. While we focused on the current state of process yields and end-use sectors, the dataset and model may support other studies on metal life cycles and sustainability. We organized the state-of-the-art information regarding all main process yields and end-use distributions for the 61 metals into a transparently documented dataset (Data availability). These could be of particular interest to industrial ecologists, metal sustainability and circular economy scholars, criticality researchers and life-cycle assessment practitioners. For example, the dataset and model could support developing impact assessment methods or filling in missing information on losses in life-cycle inventory databases used for life-cycle assessment[7,14]. Other further studies could aim to model the accumulation of anthropogenic stocks, to assess the environmental externalities of metal losses or to evaluate different development scenarios for improving the conservation of metals in the economy (for example, extending the lifetime of applications or increasing collection and recycling yields) and their associated environmental benefits. For example, reducing recycling and use losses may help reduce GHG emissions linked to primary production[47] while maintaining the beneficial functions of metals for society. Moreover, the dataset could be updated regularly to reflect the latest trends in demand per end-use sectors and for updating the process yields for different metals.

Limitations and uncertainty. Tracing many metals with a common method involves simplifications. The main assumptions and limitations of the model are described in Methods. Data uncertainty is accounted for with a semiquantitative assessment, and key results are computed with a Monte Carlo simulation, as described in Methods and detailed in Supplementary Methods. While our analysis and discussion focused on average results (considering the average value of each parameter), confidence intervals as displayed

in Fig. 3 should be kept in mind when analysing results or comparing metals. For example, it is not possible to assert which of gold or iron is longer living because there is an overlap between their average lifetimes when considering uncertainty (108–333 years and 101–227 years, respectively). Confidence intervals for the key results are provided in the Supplementary Data. Moreover, because we trace global cycles of metals, the data and results should not be expected to accurately represent smaller subsets of the global system (for example, a single process, a supply chain or a regional assessment of lifetimes and losses). For example, the lifespans of applications and process yields for different life-cycle phases are likely to vary among different regions of the world, as in the case of steel[48]. Despite these limitations, our dataset and results provide a useful screening of the losses of metals over time, which may, as we argue in this discussion, support decision-making for a more efficient and circular use of metals and help identify inaccuracies and data gaps in the current knowledge on metal cycles.

Methods

MaTrace dissipation model. The MaTrace dissipation model[17] allows for tracing losses of resources of an initial cohort of material along its anthropogenic cycle[17,19,48–51]. The model is extended to include the yield of the primary production process and runs using global average yields for each of the main life-cycle phases[19]. Here, it simulates the fate of one kilogram of metal extracted from the ground over 1,000 years at a global scale. Considering such an extended period guarantees that the remaining in-use stocks are negligible for all metals, therefore ensuring consistent results for the computed average lifetimes and loss rates. There is no regionalization of stocks and flows, and it is assumed that there are no structural changes to the economy or technology over time. While, in general, an increase in efficiency over time could be expected for some processes, in other situations, yields may decrease. For example, this could be the case for the collection and sorting yield resulting from the miniaturization of electronic components for high-tech applications. The conceptual model is depicted in Supplementary Fig. 1.

To avoid redundancy with the previous works of ref. [19], we refer readers to their article for details on the calculations, as well as to the Supplementary Methods. The main difference between this model and that of ref. [19] is that losses in the use phase and collection yields are defined here for each sector and metal, rather than per metal only. The initial cohort of extracted metal of 1 kg is allocated to end-use sectors using equation (1), resulting in an initial production x_i (in kg).

$$x_i(0) = \alpha_i \delta \pi \lambda \times 1 \text{ kg} \tag{1}$$

where α_i is the end-use sector allocation factor to the ith sector (%) and the sum of α_i equals 1, δ is the production yield (%), π is the new-scrap recycling loop factor (%), and λ is the fabrication and manufacturing yield (%).

Production encompasses the extraction, beneficiation, concentration, smelting and refining processes that generate resource flows of sufficient quality for the subsequent fabrication and manufacturing processes. Wastes from the production processes may be stored in tailings, slag ponds or landfills. Losses in primary production are accounted for only once in the model. The fabrication and manufacturing processes further transform resource flows into materials, semi-products and products. Fabrication and manufacturing process residues, that is, new scraps, may be collected for recycling (ξ, % recovery) or are lost ($1 - \xi$). Products remain in the use phase for each end-use sector depending on their lifetime distribution (ϕ_i, % as a function of time) until they become obsolete. The use of applications may imply some dissipation (ω_i, % dissipation in use). This may be voluntarily induced to obtain the product's function, such as applying pesticides in agricultural fields. At the same time, the involuntary dispersion of metals to the environment may also occur due, for example, to corrosion[52]. Obsolete products may be collected as old scraps. The metals or materials they contain are generally either sorted and recycled into new material flows (γ_i, % recovery) or incinerated and/or landfilled ($1 - \gamma_i$). Some obsolete products may also be abandoned in place or hoarded for some time before they enter the waste-management system[53]. Metals that enter the recycling streams may be either functionally or non-functionally recycled or lost to slags or dusts[18,54]. We consider functional end-of-life recycling (θ, % functional recycling) to include both closed and open-loop recycling, where the inherent properties of the recycled material are preserved; that is, the physical and chemical properties that make the material desirable are retained after recycling in the new material flow[18]. Conversely, non-functionally recycled metals represent the portion of recycled metals that end up as tramp elements or impurities in the material stream in which they accumulate[54]. By extension, we also considered the downcycling of metals to low-value applications as non-functional recycling (for example, copper elements contained in slags used in cement). Losses to recycling processes ($1 - \theta$) here include non-functional recycling on top of other losses. While landfilled and non-functionally recycled metals could theoretically be recovered at some point in

the future[14,53], they are conservatively considered losses[19]. Primary and secondary production are allocated to end-use sectors with the same factor α_i. The evolution of the cohort of metals at time $t > 0$ is modelled using transfer coefficients for each main life-cycle process as well as product lifetime distributions (equation (2)).

$$x_i(t > 0) = \lambda \pi \theta \alpha_i \sum_j \gamma_j \sum_{t'=0}^{t-1} \phi_j(t - t')(1 - \omega_j) x_j(t') \tag{2}$$

where the index j refers to sectors. Unlike in equation (1), the sum here runs over all sectors j; therefore, the index needs to be different to i.

The average lifetime τ (in years) of a metal is calculated as the sum over the mass-in-service ratio msr(t) (in %) for each year, where msr(t) is the ratio between the remaining total in-use stock at time t and the initial extraction, Δt is one year.

$$\tau = \sum_{t=0}^{t_{max}} \text{msr}(t) \ \Delta t \tag{3}$$

The loss rate (in kg lost per kg extracted per year) of a metal is calculated as the inverse function of the average lifetime τ, as shown in ref. [7].

$$\text{Loss rate} = 1/\tau \tag{4}$$

End-use distributions. We modified and adapted the list of end-use sectors of ref. [19] to represent the diversity of potential applications across the studied metals. We referenced 41 potential sectors with dedicated lifetime distributions, reported as Weibull distributions. Sectors include large-scale construction, mechanical equipment, transport and more-specialized applications such as cutting tools and solar cells.

Three end-use sectors are proposed to consider the diversity of batteries: consumer electronics and lead-acid, electric vehicles (including hybrid vehicles) and industrial batteries. Similarly, two sectors are referenced for magnets: small (for example, ferrite magnets used in various applications) and large magnets (for example, permanent magnets used in wind turbines and magnetic resonance imaging). Moreover, multiple generic end-use sectors are included. These sectors cover a diversity of materials for which actual end uses are not precisely determined (for example, glass and ceramics, paint and plastics) as well as undefined 'other uses' sectors reported in the literature for many metals. Other uses are split into four distinct categories based on the most common applications they include for each metal. The complete list of end-use sectors is provided in Supplementary Methods, along with the description of their lifetime distributions.

Data collection. A wide range of references were consulted to estimate or calculate transfer coefficients for each process yield, dissipation in use rate and end-use distribution for each metal. These references are provided for each studied metal throughout Supplementary Tables 10–70. Here, we briefly describe the main data sources underlying the dataset. The 18 MFAs underlying ref.[19] detail metal losses across their global cycles using a bottom-up approach and largely originate from peer-reviewed literature. The production, fabrication and recycling yields calculated by the authors are reused in the present article. These MFAs were available for aluminium, chromium, cobalt, copper, gallium, germanium, indium, iron, lead, nickel, rhenium, selenium, silver, tantalum, tellurium, tin, tungsten and zinc. Some modifications were required to obtain metal- and product-specific dissipation in use rates, collection and recycling yields. These modifications are described in Supplementary Methods.

Multiple other material flow studies were consulted, such as the global MFAs for ten of the rare earth elements[55], scarce metals[28] and antimony[56] and MFAs for the United States in 1998 realized by the US Geological Survey[57], among others. Articles published as outcomes of the Criticality of Metals project led by the Center for Industrial Ecology of Yale University (for example, ref. [20]) were also important in building this dataset. They provided insights into end-use distributions, production yields and EOL-RRs for numerous metals and applications. Moreover, a book chapter[46] was used to establish process yields for most platinum-group metals. Finally, ref. [31] provided most of the required information to calculate or estimate dissipation in use rates per metal and application.

Finally, end-use distributions were established for the most recent year or range of years available. The previously mentioned MFAs, articles from the Center for Industrial Ecology, the fact sheets released as part of the European criticality studies (for example, refs. [23,27]), the French geological survey's (BRGM) criticality fact sheets (for example, for titanium[58]) and the yearly US Geological Survey's Mineral Commodity Summaries (for example, that of 2020[59]) provided insights into the global end-use distribution of multiple metals. In addition, multiple industry reports were consulted, for example, for gold[60], lithium[61] and platinum-group metals[62].

Consistency and harmonization. While each metal was studied individually, we ensured consistency across the studied metals in three ways. First, we compared process yields and end-use distributions for metals used in the same large-magnitude material flows to ensure that the reported values were reasonably

correlated. For example, iron and its principal alloying metals, chromium, manganese, niobium and vanadium, are used in various steel and stainless steel applications[63]. Second, we ensured that end uses reportedly combining multiple metals at once, such as iridium–ruthenium catalysts, were aggregated in the same end-use sectors for each metal.

Third, we used dedicated methodologies for three distinct groups of metals to improve the quality of some of the available data, fill some data gaps and ensure additional harmonization across the studied metals, including the 18 metals covered by ref. [19] precious metals (especially platinum-group metals) and rare earth elements, including yttrium. Additional efforts were needed to estimate metal-specific production yields and end-of-life collection and recycling yields for rare earth elements. For the platinum-group metals, a specific method was developed to smooth the effects of the economic conjuncture on demand for investment products, which was also used for gold and silver used in investment products. The three group-specific approaches are detailed in Supplementary Methods.

Data quality and uncertainty. The quality of available data greatly varies among metals. In general, most information is available for major metals (iron, manganese, aluminium, copper, nickel, zinc and lead), precious metals (gold, silver and platinum-group metals) and potentially toxic metals (antimony, cadmium, chromium, mercury and lead). The cycles of gallium, germanium, indium, selenium and tellurium are also well documented due to available global MFAs published in scientific papers. Only partial data could be gathered from multiple sources for other metals, and estimations and assumptions were necessary to fill data gaps. The least information is available for boron, holmium, lutetium, osmium, silicon, thallium, thulium and ytterbium. Consequently, the results for these metals should be interpreted especially carefully. Of these, boron and silicon are used in relatively large amounts in the economy (over 1 Mt produced per year), highlighting the need to improve the characterization of their anthropogenic cycle.

We evaluated the uncertainty for each data point (that is, the distributions of metals to end-use sectors and the process yields for each life-cycle phase) using a semiquantitative approach derived from the Pedigree matrix[64,65]. Five criteria were evaluated for each data point: reliability (U1), temporal correlation (U2), geographic and technological correlation (U3), corroboration (U4) and base and exogenous uncertainty (U5). Qualitative evaluations for each parameter allowed us to estimate geometric standard deviations for each data point using the Pedigree matrix. Beta distributions were then computed from the geometric standard deviations as they are defined within an interval of [0,1] that is well suited for process yields. Multivariate beta distributions (Dirichlet distributions) accounted for the uncertainty of the end-use distributions. Uncertainty propagation was realized with a Monte Carlo simulation of 1,000 iterations, allowing us to define a 95% confidence interval on the computed in-use stocks over time and on the average lifetime of metals in the economy. The uncertainty rubric derived from the Pedigree matrix and the approach used to compute uncertainty are detailed in Supplementary Methods.

Assumptions. Three main assumptions are made in the model. First, the model results represent an up-to-date assessment of the trends of losses of metals along their anthropogenic cycles, considering the most recent evaluations of process yields and lifespans of applications possible, and not a prognosis[19]. Second, primary and secondary resources are assumed to have the same application share. Third, the fabrication and new-scrap recovery yields are assumed to represent the current global yield. However, as accumulated in the single global fabrication yield, the share of different fabrication processes may have evolved along with end-use applications.

Limitations of the model. Aside from the main assumptions, some methodological decisions made imply possible limitations. First, the selected end-use sectors may regroup diverse applications that have diverging lifetimes. It is possible that different metals used in the same end-use sector are used to a broader extent in some applications than in others and therefore that the reported lifetime distribution does not precisely represent that of the metal reported in the category. For example, the electronics sector includes multiple applications, such as laptops and mobile phones, with different expected average lifetimes. Because this is modelled as a single sector, the Monte Carlo simulation does not account for uncertainty in the allocation to these different electronics sectors. Second, both primary and secondary resources are attributed to the same share of end uses, which may not always represent reality. Third, no lifespans are reported for life-cycle phases other than the use phase. Finally, the model provides only an overview of total losses, and no distinction is made between the different loss stocks or losses to the environment. Similarly, in-use stocks are global, thus not attributed to specific regions. Additional efforts are needed to categorize metals into more specific end-use applications, distinguish between primary and secondary metals and identify where metal flows end up in more detail, as other authors have done, for example, for steel[48].

Projected in-use stocks and losses from recent production. We evaluated the evolution of global in-use stocks and cumulative losses of metals over time linked to a recent cohort of extracted metals. In-use stocks start with an initial cohort

for each sector, and recycled materials are re-allocated to those sectors. Therefore, in some cases of sectors with long lifetimes, intermediate in-use stock can be higher than their initial stock (for example, aluminium in the construction sector; Supplementary Fig. 6).

Global average production statistics were compiled for 2015–2019 on the basis of World Mining Data[66]. Data gaps were filled with complementary statistics from the US Geological Survey and the BRGM. Metal-specific references are detailed in Supplementary Data. The production of individual rare earth elements was estimated on the basis of global rare earth oxide production from World Mining Data[66] and the share of individual rare earth elements produced as reported by the European Commission[23] (page 663). The total extracted mass of metals was extrapolated using the production yield for each metal, and subsequent losses for the produced metals were determined with the losses for the production phase from the MaTrace dissipation model's results, as shown in Fig. 2. Production statistics and process yields are provided in Supplementary Data, along with in-use stocks from the recent yearly average production for the next 1,000 years.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
The data compiled for this research as well as the data and results depicted in Figs. 2–5 are provided in Supplementary Data and documented in Supplementary Information. The machine-readable datasets are provided in the standardized Open Dynamic Material Systems Model (ODYM) format[67] and are available in an OSF repository at https://doi.org/10.17605/OSF.IO/CWU3D (ref. [68]).

Code availability
The Python code is provided in the ODYM format[67] and is available at https://doi.org/10.17605/OSF.IO/CWU3D (ref. [68]).

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Author contributions

The initial design of this research project originates from C.H., A. Thorenz and A. Tuma. A.C.P. and C.H. conducted methodological developments. A.C.P. assembled and documented the data, drafted the article and produced Figs. 1, 2, 4 and 5. C.H. wrote the Python code and produced Fig. 3, the right side of Fig. 4 and Supplementary Figs. 2–62 (the supplementary figures are generated with the code). A.B. and P.L. substantially participated in revising the draft and the final paper. S.M., J.V., B.L., A. Thorenz, A. Tuma and G.S. supervised the work and revised the draft and the final paper.

Competing interests

The authors declare no competing interests.

Additional information

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The data compiled for this research as well as the data and results depicted in Fig. 2 to Fig. 5 are provided in the Supplementary Data and documented in the Supplementary Information. The machine-readable datasets are provided in the standardized Open Dynamic Material Systems Model (ODYM) format and are available in a OSF repository at: https://doi.org/10.17605/OSF.IO/CWU3D.

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Study description	We model the fate of a yearly cohort of 61 extracted metals over time and identify where losses are expected to occur through a life cycle lens.
Research sample	Not applicable.
Sampling strategy	Not applicable.
Data collection	ACP collected data from scientific articles and various reports published online. All of the collected data are referenced in the Supporting Information.
Timing and spatial scale	Data, including process yields for the main life cycle phases (production, fabrication and manufaturing, use, collection and recycling) and end-use sectors were collected through online literature surveys including scientific journals. The data collection period ranged from april 2020 to september 2021. We aimed for data representative of the global scale that were as up-to-date as possible.
Data exclusions	The best possible data (i.e., representative of the global scale and as up-to-date as possible) were derived from the available information. This may have lead to the exclusion of some available data in a few instances. Details for each metal are provided throughout Supplementary Tables 10-70.
Reproducibility	The model was run multiple times with the compiled data set throughout the study. The study is reproducible with the data and code provided with the article.
Randomization	Not applicable.
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We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒ ☐	Antibodies
☒ ☐	Eukaryotic cell lines
☒ ☐	Palaeontology and archaeology
☒ ☐	Animals and other organisms
☒ ☐	Human research participants
☒ ☐	Clinical data
☒ ☐	Dual use research of concern

Methods

n/a	Involved in the study
☒ ☐	ChIP-seq
☒ ☐	Flow cytometry
☒ ☐	MRI-based neuroimaging