Global mapping of Al, Cu, Fe, and Zn in-use stocks and in-ground resources

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Human activity has become a significant geomorphic force in modern times, resulting in unprecedented movements of material around Earth. An essential constituent of this material movement, the major industrial metals aluminium, copper, iron, and zinc in the human-built environment are mapped globally at 1-km nominal resolution for the year 2000 and compared with the locations of present-day in-ground resources. While the maps of in-ground resources generated essentially combine available databases, the mapping methodology of in-use stocks relies on the linear regression between gross domestic product and both in-use stock estimates and the Nighttime Lights of the World dataset. As the first global maps of in-use metal stocks, they reveal that a full 25% of the world's Fe, Al, Cu, and Zn in-use deposits are concentrated in three bands: (*i*) the Eastern seaboard from Washington, D.C. to Boston in the United States, (*ii*) England, Benelux into Germany and Northern Italy, and (*iii*) South Korea and Japan. This pattern is consistent across all metals investigated. In contrast, the global maps of primary metal resources reveal these deposits are more evenly distributed between the developed and developing worlds, with the distribution pattern differing depending on the metal. This analysis highlights the magnitude at which in-ground metal resources have been translocated to in-use stocks, largely from highly concentrated but globally dispersed in-ground deposits to more diffuse in-use stocks located primarily in developed urban regions.

metal | recycling | GDP | ore | urban

With the increasing consumption of metal resources, humanity is causing a significant reallocation of metal from in-ground ore deposits to the human-built environment (1). This built environment is comprised of material dubbed "in-use stocks," that amount used to provide various services. Such services include light at nighttime, with copper and aluminium allowing for the transport of electricity to power light bulbs, or the service of human transport, with iron and other metals comprising automobiles and other machines. These in-use stock deposits are growing in size (2), and the discards from them feed the recycling stream, providing for a secondary resource of metal. As the world trends toward the principles of sustainability, more emphasis is being placed on understanding in-use metal stocks as a sink for mined material and as an alternative source of mineral resources. Similar questions asked about in-ground resources are beginning to be asked about in-use stocks: in what form are they (3), where are they (4), and how much is there (5)?

Although significant databases exist for in-ground resource deposits (6–11), estimates of the size, form, and location of in-use metal stocks are disparate. The most-studied metal is copper, followed by iron (5). Other metals such as zinc, chromium, or aluminium have received little attention. This lack of information is in part because estimates of in-use stock sizes require extensive effort to produce. Both the so-called "top-down" and "bottom-up" methods for calculating in-use stocks require extensive data collection, whether it is the lifetime distributions and century-long, yearly consumption statistics required by the top-down approach, or the quantities, masses, and metal concentrations of all manmade objects required by the bottom-up approach (3, 12). Data availability often defines the spatial scale analyzed, with the bottom-up approach applied at smaller scales, and the top-down approach applied at larger scales. It follows that the knowledge of the spatial distributions of these in-use stocks is seriously deficient. Estimates have been made at different spatial scales for some metals, but these estimates are aggregate snapshots of a certain spatial extent. Most studies are focused in Japan, the United States, or Europe and provide overall information at country or regional levels. This paucity of information highlights the need for both further intensive research and the development of faster estimation techniques.

Natural resources are often described by using maps, because space is an essential variable related to management. Studies of forests (13), ecosystem services (14), water (15), fossil fuels (16), and mineral ores (17) all use GIS software and spatially explicit mapping of resource locations. Such modeling is done to define quantitatively resource concentration, total amount, and relationship to other spatial objects (e.g., logging roads). As a reservoir and source of materials, in-use stocks certainly have unique attributes. Unlike mineralogical ore bodies, in-use metal stocks cannot be explicitly managed for resource extraction. However, this does not preclude mapping these resources, because government regulations (18), economic incentives (19), and independent action by private enterprise (20) all can influence how soon and how completely in-use material enters the recycling stream.

Primary and secondary resource deposits are explicitly defined as follows. Mapped primary metal resources are presently "identified resources" as defined according to the U.S. Geological Survey (USGS): "resources whose location, grade, quality, and quantity are known or estimated from specific geological evidence. Identified resources include economic, marginally economic, and subeconomic components" (21). Secondary metal resources are those sources where metal is not in a form of a geological ore, having been manipulated to an extent by human action. Although landfills fall into this categorization, the largest metal mass is thought to be contained in in-use stocks, as deduced from comparing estimates of total copper lost to landfills over the past 300 years (175–225 Tg) and the total copper still residing in-use (≈350 Tg) (22).

In-use stocks are a unique resource because much of the metal is still required for its services, so the actual amount of metal available is only that which reaches the end of its useful life. Thus, the largest currently available metal mass of secondary resources is likely greater in landfills, although some landfills have been converted to other uses and are not amenable to mining. This deduction is with the caveat that the concentration of metal (secondary resource ore grade) depends on the spatial level of comparison; in-use stocks can be said to have a higher concentration of metal if the boundary is drawn around a building and compared with the same volume in a landfill, but may not if the boundary is expanded to include the forest and fields surrounding a rural house. An

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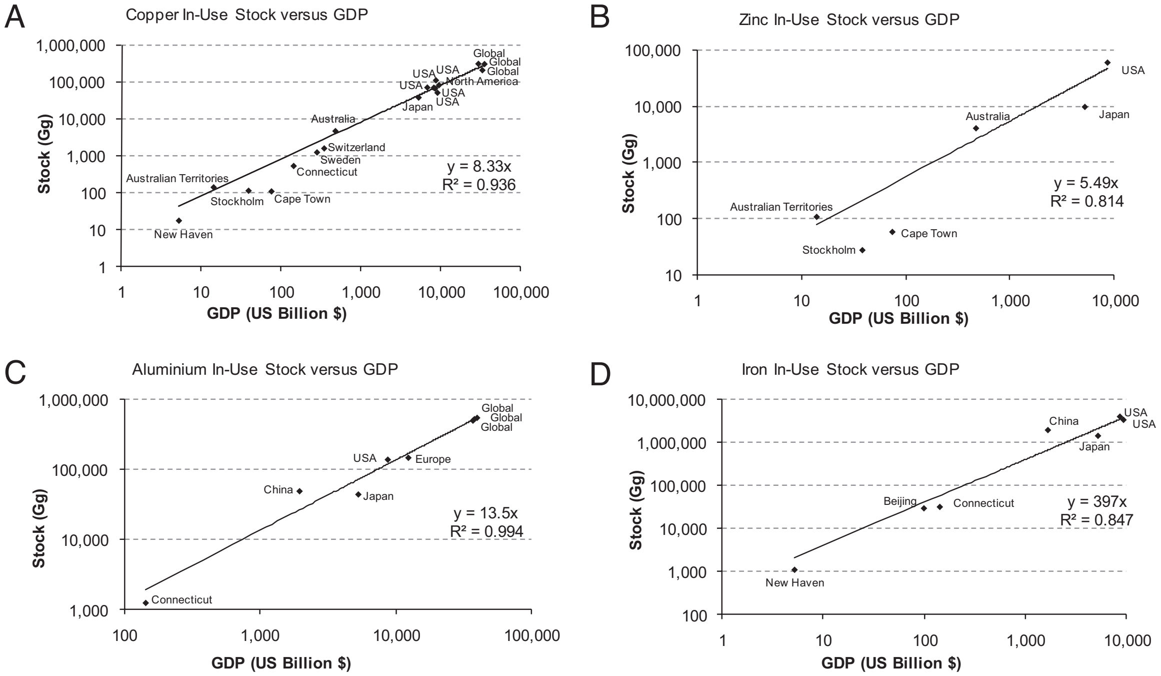

Fig. 1. Linear regressions between in-use stocks and GDP for Cu (*A*), Zn (*B*), Al (*C*), and Fe (*D*). The correlations have an $R^2 > 0.9$ for copper and aluminium, whereas zinc and iron still retain an $R^2 > 0.8$. The small sample sizes, Fe ($n = 7$), Al ($n = 8$), and Zn ($n = 6$), may be of some concern, yet the correlation appears to hold when more studies are available, Cu ($n = 18$). Each data sample represents a unique study of in-use stocks performed in the locality stated at some time after 1990 (see Table S1 for data).

unknown in this comparison is the secondary metal residing in hibernation between the in-use and landfill stages; these potentially large deposits are no longer in use but have not yet been discarded and therefore can essentially be considered as almost entirely available.

The most comprehensive mapping of in-use metal stocks has been for zinc and copper in Australia (4). To my knowledge, only two other locations have been explicitly mapped: copper in Beijing city center, China (23) and zinc and copper in Cape Town, South Africa (24, 25). However, given the important source of metal these secondary deposits provide via recycling, the relative attention given to mapping is disproportionate. To begin rectifying this imbalance in knowledge, an approximation method and results for mapping in-use stock deposits for the year 2000 at the global scale at 1-km resolution is presented. Although this approach generates relatively crude approximations, it is a fast-estimation technique that can quickly provide a reasonable estimate (according to back testing to known literature estimates) of in-use stocks at any desired spatial level larger than ≈ 10 km^2. To complement previous mapping of geological metal resources (6, 7), global maps of primary, in-ground Fe, Al, Cu, and Zn resources are generated that adjust for past production. These primary resource maps provide a contrast to the maps of in-use metal stocks.

Methods

The approach to mapping in-use stocks of metals relies on the linear regression of standing in-use metal stock to GDP. As an initial approximation, this relationship follows the observation that richer countries tend to consume and use more material than poorer countries. This higher consumption leads to an increased accumulation of material in in-use stocks. Although other relationships may better explain in-use metal stock quantities, globally mapping in-use metal stocks at a subnational resolution severely restricts what proxy data may be used. In the present case, a simple linear regression is used to ease calculation and minimize assumptions, while GDP is chosen over GDP/capita or population as a proxy because of the observed stronger linear relationship to in-use metal stocks.

For *n* estimates, the linear equations and associated R^2 values are presented in Fig. 1 for Fe ($n = 7$), Al ($n = 8$), Cu ($n = 18$), and Zn ($n = 6$) (data used to generate Fig. 1 are available in Table S1). The post-1990 in-use metal stock estimates used in this regression are summarized in a recent review (5). Multiple samples of the same locality represent independent studies, usually made in different years, and indicate the underlying variability in estimating in-use stocks even for the same geographic extent. The correlation between GDP and in-use stocks is not necessarily expected to hold true for all metals and all times. For instance, growth over time of Fe in-use stocks per capita appears to decouple from growth in GDP in a few developed nations such as the United States (26). So although a decent correlation ($R^2 > 0.8$) between iron in-use stocks and GDP is observed for the data available, with the future advent of more data a more precise representation of the relationship between GDP and in-use stocks will likely be better served by using alternative approaches other than a simple linear regression, so as to account for this decoupling of growth of GDP from growth of metal in-use stocks.

Using the linear regression relationships, a global map of GDP can be used as a proxy to generate maps of in-use metal stocks. To map in-use stocks at a higher resolution than the political boundaries of countries, GDP requires an effort in disaggregation. Fortunately, a global map of the world's GDP for the year 1990 has been produced at 1° × 1° resolution (27).

The first step in generating the necessary global map of GDP was to generate a map for the year 2000. The original data used are 1990 GDP [in purchasing power parity (PPP)] at 1995 dollars on a 1° × 1° global grid derived by the Nordhaus G-Econ group (27). GDP (PPP) in 2000 international dollars for the year 2000 on a country by country basis was taken from the World Bank World Development Indicators (accessed September 3, 2009 at www.worldbank.org/data) for most countries. Where not available, year 2000 GDP estimates from the Central Intelligence Agency World Factbook (www.cia.gov/library/publications/download/index.html) were used. These 2000 GDP values in 2000 dollars were scaled to 1995 dollars by dividing by the inflation coefficient 1.13 derived from the Consumer Price Index (inflation data compiled by Robert Sahr at http://oregonstate.edu/cla/polisci/faculty-research/sahr/sahr.htm). The 2000 country GDP (PPP) in 1995 international dollars was then disaggregated among 1° × 1° grid cells [to produce gross cell product (GCP)] proportional to the distribution of 1990 GCP. This step assumes all areas within a country grew or shrank at the same rate between 1990 and 2000. This rough assumption is an ecological fallacy, but expedited the update from the year 1990 to 2000, avoiding the use of the more accurate but much more research intensive original G-Econ group methodology. Once 2000 values were produced on a 1° × 1° grid, they were imported into ESRI's ArcGIS for representation and further analysis.

Although 1° × 1° resolution (111 km is 1° at the equator and ≈ 120 km is the average length of 1° globally) is acceptable for observing global patterns in metal

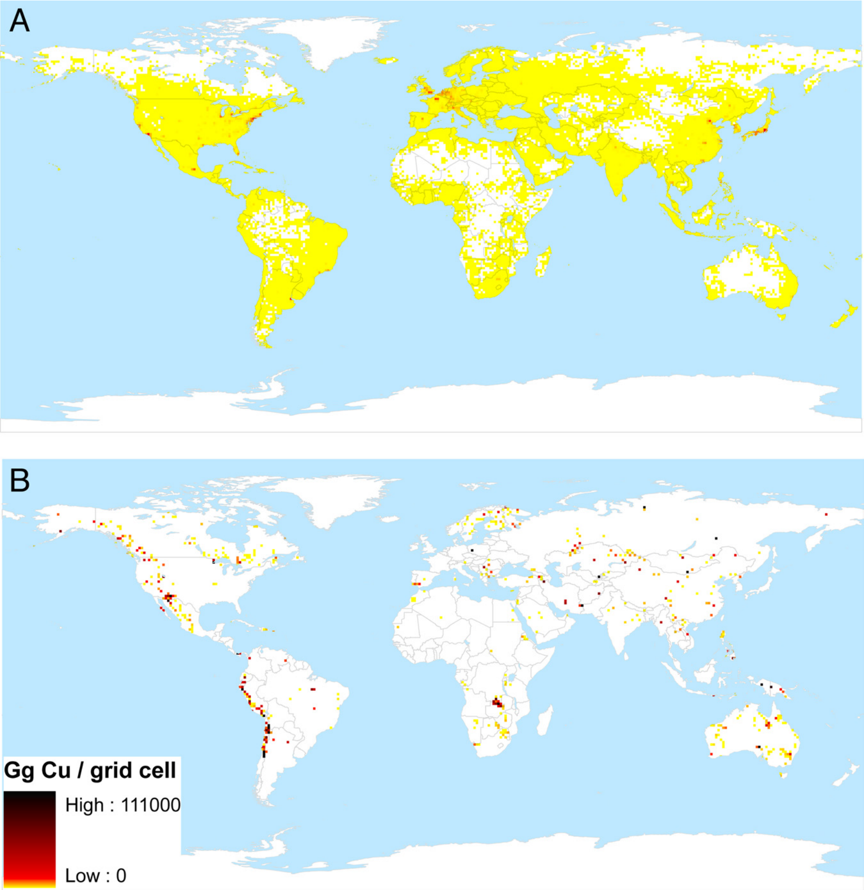

Fig. 2. Shown are 1° × 1° resolution global maps for the year 2000 of in-use (*A*) copper stock intensities (Gg/grid cell) compared with in-ground (*B*) copper resources. The in-use stocks of aluminium, iron, and zinc have the same distribution as copper, but the locations of in-ground resources differ according to their respective mining regions.

in-use stocks, a higher resolution was desired so as to be able to aggregate cells using political boundary masks at the state or national level. At coarser resolutions, more grid cell area is subject to straddling political and environmental (e.g., shoreline) boundaries, introducing more error during summation of cells in a particular spatial extent (during summation, a usual approach is to add the entire cell if the majority is contained within the boundary mask, or to exclude it entirely

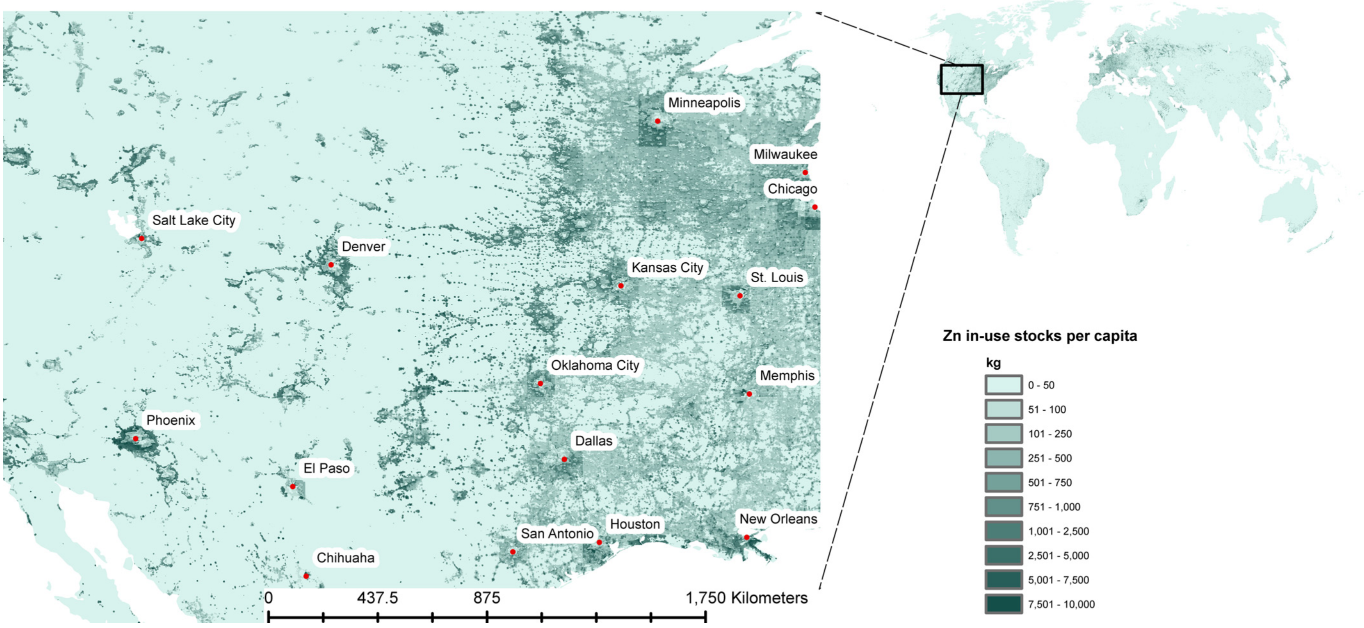

Fig. 3. Shown is a 1-km resolution global map of per-capita in-use stocks of zinc for the year 2000. The central United States provides a good illustration of the annulus pattern of per-capita in-use stock deposits around cities.

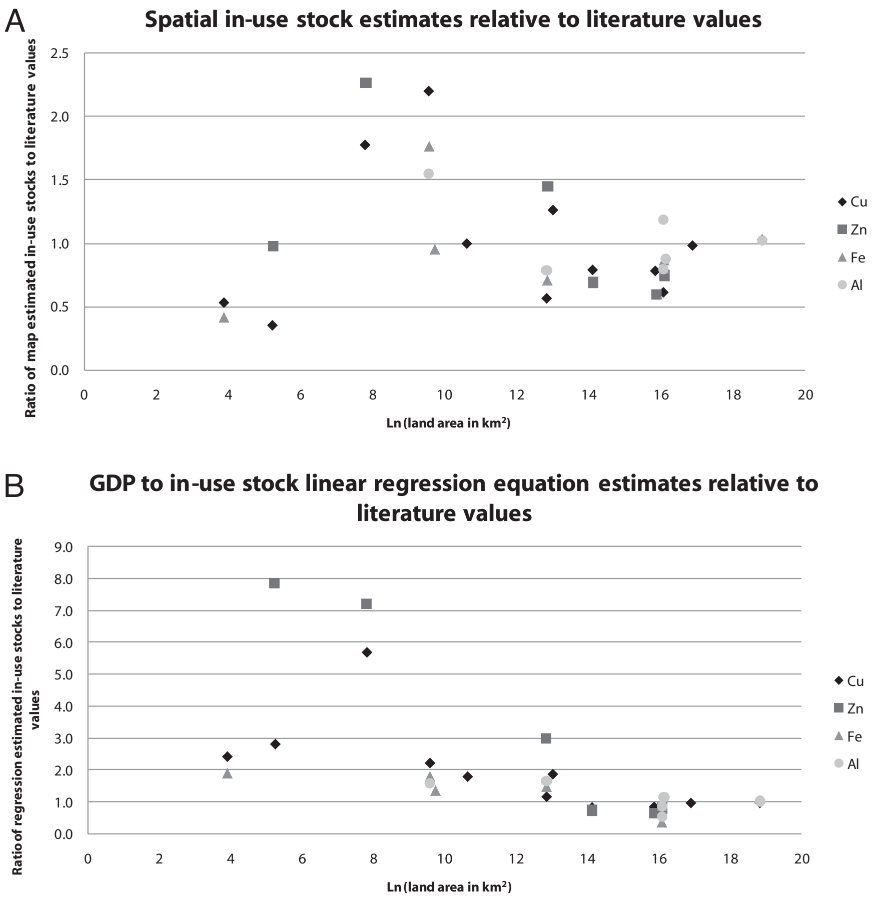

Fig. 4. A plot of the ratio of map-estimated (*A*) and linear regression equation-estimated (*B*) (see Fig. 1) in-use stocks relative to literature values. These ratios are plotted against the natural logarithm of land area to reveal the greater imprecisions of prediction at smaller spatial scales.

if otherwise). The 1° × 1° GCP grid was therefore disaggregated to 1-km resolution using a simple dasymetric approach. This disaggregation was accomplished by using the DMSP-OLS nighttime lights data, which have been used in previous studies as a proxy for income (28). Year 2000 nighttime lights data of human settlements were taken where available (from −65° to 65° latitude) with the extreme northern and southern latitudes using 1995 values. While specific GDP to nighttime light emission ratios for each nation were created by Sutton and Costanza (28) to estimate income per km², the GDP data used were at the country level. Their method can now be improved by using subnational scale GCP data available from the G-Econ 1° × 1° map. Therefore, implemented here is a similar approach as ref. 28, but derived instead are GDP to light emission ratios for each 1° × 1° cell, *b*. This GCP at 1 km produced can be defined in map algebra terms as:

$$\frac{n_{i,b}}{\sum_{i}^{m} n_{i,b}} \times w_b$$

where $1 \leq i \leq m$, for all *b*. For the total, *m*, of nighttime lights pixels, *n*, contained in each 1° × 1° cell, *b*, a fraction is created by dividing each nighttime lights pixel, n_i, by the neighborhood block sum of nighttime light pixels contained within the 1° × 1° cell. This fraction is multiplied by the estimated GCP of each 1° × 1° cell, w_b, disaggregating GCP to 1-km resolution. The final step transforms the 1-km resolution GCP map into metal in-use stock mass, using the aforementioned regressions.

Maps of in-ground primary metal resources were developed from a multitude of sources and include information on present size (geological resource less past production) and ore grade. Beginning with ore resource information from the Raw Materials Group (8), latitude and longitude locations were found by using the USGS Mineral Resource Data System (accessed January 11, 2009 at http://tin.er.usgs.gov/mrds), company reports, or other available news sources. Locations were visually verified to the extent possible by using Google Earth. Bauxite reserves were taken from ref. 7, because no data on resources are available. The initial database that was developed was cross-checked and supplemented with information from the Large and Superlarge Mineral Deposits of the World (9) and the Sedimentary Exhalative and Mississippi Valley Type databases provided by the Geological Survey of Canada (10, 11). Further resource deposits were found from company reports, academic literature, and government lists. The final dataset of point locations of resource deposits can be converted to raster form by summing all resource deposit sizes contained within each cell of a spatial resolution of interest, such as each 1° × 1° cell.

Results

Global in-use stocks in the year 2000 total 504 Tg for aluminium, 311 Tg for copper, 14.8 Pg for iron, and 205 Tg for zinc. Given the high correlation between gross domestic product (GDP) and all four metals examined, the general spatial patterns observed for one metal holds true for the others. The United States has the largest absolute amount of in-use stock of each metal (Al: 109 Tg; Cu: 67 Tg; Fe: 3205 Tg; Zn: 44 Tg), or ≈1/5 of the global totals, and only the small countries of Liechtenstein and Luxembourg exceed the United States in per-capita stocks (national totals are provided in Table S2). The higher per-capita stocks in these small countries, expected given the method's use of regression with GDP, is most likely caused by the variability inherent in the small spatial area sampled; per-capita in-use stocks in certain places within the United States with equal area exceed these small countries.

Three belts appear to comprise 25% of the world's in-use metal stocks: (*i*) the eastern seaboard of the United States, from Washington, D.C. to Boston, (*ii*) England across the Channel to Benelux and down into central Germany into northern Italy, and (*iii*) South Korea and Japan. Additional localities, such as southwestern California, also contain significant deposits (e.g., copper: Fig. 2*A*).

Note that while the underlying data are generated at 1-km resolution (Figs. S3–S6), Fig. 2*A* presents the in-use stock data aggregated to 1° × 1°.

On a per-capita basis, these belts become less prevalent, revealing instead the higher metal requirements of urban, and more so, suburban communities. This tendency appears in the central United States, where per-capita metal stocks are higher in the suburbs than in the urban centers (Fig. 3). This phenomenon has been documented in Cape Town, South Africa, where metal stocks are larger in lower population density suburban environments where more material is required per person (24).

Recently published estimates of in-use stocks that were not used to produce the GDP to in-use stock correlation provide some independent verification of the results. An estimate for the global in-use stock of Zn for the year 2000 (280 Tg of Zn) (29), is within 35% of the map derived estimate (205 Tg of Zn). This agreement is encouraging given the uncertainty in the underlying literature values.

Back testing of the in-use stock methodology was performed by summing areas for comparison with the existing literature estimates. Because the maps have been produced by using these nonspatial estimates, this is not a verification of the predictive capacity of the map (how it may predict in-use stocks where it has not yet been measured), but a verification of the methodological approach. At the global level, estimates are within 30% for metals with previously published figures (Cu: 304 Tg, Al: 492 Tg) derived from the top-down methodology (29). The results are within 50% on the national level, with greater discrepancies occurring at higher resolutions (Fig. 4*A*). Although the 1-km maps provide a view of the general distribution pattern of in-use stocks, and aggregate to national scales adequately, estimating in-use stocks at smaller spatial scales (less than ≈1°) becomes less precise (up to 150% error). The trend in aluminium in-use stocks across spatial levels illustrates that while at the global level the error between the literature and the map result is <10%, the national-level results (United States, Europe, Japan, and China) agree to within 25%, at the subnational level the error exceeds 50% (Connecticut). So although the map is still useful for an initial estimate of in-use stocks at small spatial levels, such numbers should be treated with more skepticism. This imprecision at smaller spatial levels is understandable given that metal stocks are estimated as a proportion of GDP and, to some extent, population and light emission. The results of Fig. 4*B* indicate that the additional spatial processing does not introduce further imprecision than exists in the initial linear regression between GDP and in-use stocks.

In fact, comparison to Fig. 4*B* indicates error at smaller spatial scales appears to be reduced with the spatial processing. It is suspected that the imperfect correlation between nighttime lights intensities and GDP may be part of the cause. The reduction in per-capita in-use metal stocks in urban centers is facilitated by full nighttime light saturation, where otherwise GDP should continue to rise. This effectively produces an underestimate of GDP for urban centers, but a more precise estimate of the metal stock in built infrastructure. In any case, the use of this method for fine-resolution estimates should be performed only with the utmost awareness of the imprecisions involved.

Error can be attributed to the imperfect correlation between GDP and in-use stocks, the imperfect correlation between nighttime lights and GDP, and the underlying variability in the in-use stock data. Literature estimates within a 5-year span for in-use stocks of Cu for the United States, for instance, vary by >100% (1, 30–32). In this sense, the estimate derived from the map for the United States (243 kg Cu/capita) may be closer to the true value, because it falls within the range of estimates (175–391 kg Cu/capita) and is close to their arithmetic mean (264 kg Cu/capita). Unfortunately, there are no other independently repeated multiple measurements at the same spatial level of the same metal to which comparison of the maps' results can be made.

The outlined procedure and the methods on which it is based (27, 28) are also subject to the modifiable areal unit problem (MAUP). The MAUP recognizes that both the scale chosen for data aggregation and the chosen locations of each zone of aggregation can themselves affect the results (33). Even the underlying pixel resolution of the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) suffers to some degree from the MAUP, because different data results would be observed if the satellite were to collect data at higher or lower resolutions, the pixel size being a level of data aggregation. Unfortunately, a widely applicable solution to the MAUP remains elusive (34).

The compiled global primary metal resource totals as of 2000 were found to be about the same for copper (1.6 Pg) as USGS estimates, whereas iron (170 Pg) and zinc (630 Tg) are below USGS estimates (21) (see Figs. S7–S9 in addition to Fig. 2). This discrepancy is likely caused in part by incomplete global coverage of individual deposits in the metal resource databases developed, despite the attempt to be as comprehensive as available data provide. The lack of data availability precludes accurate assessment of to what extent global resource estimates may be over or under estimates and highlights the high degree of rough estimation behind resource values. Given the vast reserves available of bauxite, little to no effort is expended to estimate bauxite resources, so data were not available to produce a map of aluminium resources. Rather, a map of the bauxite reserve base, adjusted to represent aluminium mass contained only, was used for comparisons (7). The reserve base of aluminium contained in bauxite (6 Pg) is approximately a quarter of the global bauxite reserve base (25 Pg), which is below USGS estimates of the global bauxite reserve base (33 Pg) largely because of incomplete coverage of Guinea's very large reserve base of bauxite deposits.

Although the total magnitude of primary resources is much larger than in-use stocks, secondary in-use stock deposits are more evenly distributed across Earth's surface. Primary copper and primary bauxite reserves of aluminium are more concentrated in specific regions unique to each metal: copper on the west coast of South America (see Fig. 2*B*), aluminium in Guinea and Suriname. The pattern of primary deposit size also varies. China has many small bauxite deposits, whereas Australia has a few very large deposits. Available ore grades vary spatially, and the highest ore grades tend to exist in lesser-developed countries. Brazil and Africa have very high iron ore grades (>60%), whereas in Europe and the United States iron ore deposits exist at grades half as rich. Despite the apparent high concentration of in-ground iron ore deposits, iron is a more diffuse in-ground resource than most metals. In this case, the difference in ore grade is likely to be because of the depletion of high-grade ore deposits in these older developed economies.

Discussion

The availability of metals is controlled not only by the quantity that is economically extractable, but the geopolitical backdrop on which these natural resources exist. Primary resource-rich countries that undergo political instability may impact global supplies. However, these highly concentrated primary resources are being depleted and replaced by the more spatially distributed secondary deposits of in-use stocks, which have the potential to alleviate supply disruptions in the long term. Yet the availability of in-use metal stocks for recycling is limited to those quantities entering discard management as determined by product lifetimes. The lifetime of various categories of in-use stocks tends to be longer in countries with lower per-capita incomes and in-use stocks, reducing the relative amount of metal discarded and available for recycling.

Further refinement of both primary resources and their reallocation to in-use stock deposits could be accomplished. Geological resource estimates are inherently economic, so the size of the resource changes as the technology and economics of extraction change. Resource estimates are also generated for specific purposes; individual companies may estimate resource sizes only up to their foreseeable operational needs, underestimating the actual size of the entire resource. Grade-tonnage curves for each resource deposit would therefore provide a truer representation of available resources and have been used to estimate American resource deposits of major metal commodities (35). Assembling this information on a global scale would be challenging, however, because of the scarcity of data.

In-use stock estimates would benefit from categorical and temporal resolution. Calibrated yearly nighttime lights data combined with other years of available geographically based economic data would provide understanding of how in-use stock deposits are changing over time. The form of the in-use stock deposit dictates its potential for recovery, and the age of in-use stocks in these various forms would give better insight into when these deposits are likely to enter the discard stream. Lifetime estimates of in-use stocks become more accurate at higher categorical resolutions (it is easier to estimate the lifetime of a television than the entire waste electrical and electronic equipment sector). As such, particular in-use stocks could be mapped independently (e.g., the iron contained in world railroad networks using Vector Map Level 0 data) to estimate amounts and lifetimes. Subtraction from the total estimated by the GDP correlation approach would ensure full coverage for what would be akin to a bottom-up in-use stock approach at a global scale. However, the mapping approach also highlights the limitations of understanding that exist in quantifying in-use stocks. The knowledge of in-use stock quantities at high resolutions remains imprecise, suggesting that future in-depth quantifications of in-use stocks should be carried out at high resolution in various localities, as opposed to national-level analyses. The maps of the age and form of in-use stocks could provide quantitative guidance for resource planners regarding the locations and potential rates of metal recovery.

The comparative mapping of in-use stocks and in-ground resources provides more than a visual aid for understanding how human society is redistributing in-ground metal resources. Understanding the relative locations and sizes of anthropogenic and geogenic resource reservoirs is essential to efficient raw material sourcing. Planning investments in primary and secondary production operations requires this spatial knowledge to minimize total costs, accounting for such constraints as the location of production facilities relative to both the requisite infrastructure, water, and energy resources and the end-user market. As sources of future secondary resources, mapping in-use stocks of metals also suggests that the long-term planning of metal discard management networks should focus on developed urban centers.

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