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# The legacy environmental footprints of manufactured capital

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**The foundations of today's societies are provided by manufactured capital accumulation driven by investment decisions through time. Reconceiving how the manufactured assets are harnessed in the production–consumption system is at the heart of the paradigm shifts necessary for long-term sustainability. Our research integrates 50 years of economic and environmental data to provide the global legacy environmental footprint (LEF) and unveil the historical material extractions, greenhouse gas emissions, and health impacts accrued in today's manufactured capital. We show that between 1995 and 2019, global LEF growth outpaced GDP and population growth, and the current high level of national capital stocks has been heavily relying on global supply chains in metals. The LEF shows a larger or growing gap between developed economies (DEs) and less-developed economies (LDEs) while economic returns from global asset supply chains disproportionately flow to DEs, resulting in a double burden for LDEs. Our results show that ensuring best practice in asset production while prioritizing well-being outcomes is essential in addressing global inequalities and protecting the environment. Achieving this requires a paradigm shift in sustainability science and policy, as well as in green finance decision-making, to move beyond the focus on the resource use and emissions of daily operations of the assets and instead take into account the long-term environmental footprints of capital accumulation.**

global manufactured assets | stock-based environmental assessment | investment | environmental efficiency metrics

Intergenerational well-being depends on the stocks of assets that sustain and enhance lives, including natural, social, manufactured, human, and knowledge capital (1). Yet, the accumulation of manufactured capital assets, such as buildings, machinery, and transport equipment, is at the expense of natural capital (e.g., stocks of geological and ecosystem resources) (2). As global investments in manufactured capital continue to rise, it becomes increasingly important to understand the resource and environmental impacts of this accumulation (3). Policymakers are becoming increasingly interested in manufactured capital investments as they can both facilitate or impede the attainment of the United Nations (UN) Sustainable Development Goals (SDGs) (1, 4, 5). Moreover, investment decisions made today could lock in unsustainable development patterns or require the early abandonment of working assets such as oil wells and fossil power stations to attain, leading to stranded assets representing the waste of social and natural capital that would have otherwise been available for future generations (6, 7).

Although the operation of manufactured capital is at the core of scenarios informing climate and biodiversity policy (8, 9), there has been no comprehensive assessment of the resource extractions and environmental impacts caused by historical asset production and embodied in the current stock of manufactured assets. Previous analyses have quantified the manufactured capital in terms of accumulated materials (10–12), the environmental footprints of traded and consumed commodities owing to the production of manufactured capital (13–17), the emission implications of manufactured capital for equitable development (18, 19), and deep decarbonization (20, 21). Others have investigated how investment decisions may facilitate resource efficiency and a circular economy (22). However, research on the resource inputs and environmental impacts of manufactured capital has, thus far, focused on individual environmental impact categories or specific assets and countries. Anticipating and mitigating the resource and environmental challenges of future manufactured capital accumulation requires an understanding of stock dynamics of all asset types, and as part of this, a measure of the stock of these assets.

The UN's System of Environmental and Economic Accounting (SEEA) is the most prominent framework for integrating economic and environmental data, supporting several global initiatives, including the UN SDGs, the post-2020 biodiversity agenda, and international climate policies (23). However, there are two significant shortcomings: the organization around national accounting fails to reflect ubiquitous global supply chains, and the stocks of manufactured capital assets are quantified in optional data that are either

## Significance

Understanding historical material needs, climate change, and health impacts of creating manufactured capital, i.e., the legacy environmental footprints (LEFs), can help us anticipate and mitigate the sustainability challenges of reducing global capital inequalities. We have developed a model that examines asset-, industry- and country-specific manufactured capital dynamics in the global value chain from 1970 to 2019. Over the last 25 y, global LEFs doubled or tripled depending on the environmental aspects, outpacing GDP and population growth. To significantly lower the environmental footprints of future capital accumulation and ensure a more equitable and sustainable future for all, we must adopt best practices in asset production, prioritize assets that promote well-being, and incorporate environmental footprints of capital stocks into investment decisions.

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The authors declare no competing interest.

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inaccessible, of poor quality, or nonexistent. In response to the first shortcoming, researchers developed multiregional input–output databases and models (MRIOs) that combine national economic activities and environmental accounts into a global framework. These models have provided insights into the environmental and social footprints of consumption (24, 25), SDG assessments (26–28), and many other sustainability research issues (29–32). While research has related investments to resource extraction and environmental impacts within the SEEA (13–17, 20, 33), the long-term dynamics of the stock of manufactured assets have not been explored, with most analyses focusing on annual snapshots of investment flows.

Here, we model global manufactured capital dynamics to consistently describe asset production, use, and retirement in the global value chain. We propose the legacy environmental footprint (LEF) metric as a measure of the historic environmental costs of the investments that created the current stock of manufactured assets. In other words, LEF enables a comprehensive overview of the historical material extractions and environmental impacts that have resulted from manufacturing the asset vintages that make up the manufactured capital at a given time. While conventional environmental footprint metrics are a flow measure, e.g., year *t*'s emissions of producing year *t*'s consumption, LEF is a stock measure. Both the stock and flow measures are of interest as they tell complementary stories in sustainability research, just like wealth is a complementary measure to income or debt.

We quantify the LEF by modeling asset-, industry- and country-specific dynamics of manufactured assets from 1970 to 2019. Annual investments that drive the additions of structures, machinery, transport equipment, and other long-lasting assets (e.g., software and other intellectual property products) constitute inflows to the stock of manufactured assets, consistent with the national accounts system (34–36). The annual retirement of assets, which we modeled from asset-specific lifetime tracking, forms the stock outflows. Just as retired assets are not part of the economic value of capital stocks, LEF does not include the environmental costs of creating the already-retired assets. These modeling choices mean we maintain consistency with the existing micro- and macro-economic frameworks and metrics of capital stocks, such as company-level balance sheets and macrolevel capital stock accounts. We calculate the LEF for extractions of various materials (iron ore, copper ore, nonmetallic minerals, and wood), climate change (greenhouse gas emissions, GHGs), and adverse health impacts from air pollution (in disability-adjusted life years, DALYs). We analyze the historical trends of LEF and map the LEF to the global production and consumption of today's goods and services to identify hotspots and mitigation levers. See *Materials and Methods* for full details.

## The Legacy Material Extraction and Emissions Embodied in Current Global Capital Stocks

Current manufactured capital represents significant past investments not only in human effort but also in materials, GHGs, and damages to human health. As of 2019, global manufactured assets accumulated since 1970 saw the emission of 254 $GtCO_2eq$ (5 times the annual emissions in 2020), requiring 31 Gt of iron ore, 24 Gt of copper ore, 507 Gt of nonmetallic minerals, and 23 Gt of wood materials and driving approximately 650 million DALYs (Fig. 1 *A* and *C*). For context, the remaining global carbon budget for 1.5 °C (at the 67% likelihood level) in 2020 was 400 $GtCO_2e$ (for 83% likelihood, 300 $GtCO_2e$) (37). There have been substantial increases in LEF in recent decades. In just over 25 y (1995 to 2019), global LEF more than tripled in extractions of iron ore and more than doubled in copper, nonmetallic minerals, GHG emissions, and health impacts (wood extraction nearly doubled). LEF growth outpaced both GDP and population growth in the same period (3) (except for wood extraction, see *SI Appendix*, Fig. S1).

## Global LEF Pyramids Demonstrate Different Investment Paths

Global LEF pyramids (Fig. 1) provide a comprehensive overview of the historical material extractions and emissions from manufacturing the current capital stock across low- to high-income economies. The recent accumulation of materials in China is well known (38), but we show that China's LEF growth between 1995 and 2019 is larger than the four leading emerging economies, Brazil, Russia, India, and South Africa, combined (except for wood). These other nations are also expected to exhibit, to varying degrees, a similar pattern of expansion as they develop (11). By 2019, China had accrued a higher LEF than any other country since 1970 in all environmental indicators we assessed, except for wood extraction (in which China ranks after the United States, India, and Japan). A recent slowing in China's annual LEF growth may suggest an end to this phase of exponential growth, and China may be transitioning to steady-state levels and patterns of investment seen in developed economies (DEs). Indeed, the regional distribution of LEF among DEs has stayed relatively stable.

To compare the role of LEF in societies, we scale LEF by population since a larger manufactured capital size for a smaller population will generally result in greater social benefits per person in terms of goods and services (39). The LEF per person (LEF/p) shows that for manufactured capital, this gap between DEs and less-developed economies (LDEs) is either stubbornly large or, in fact, growing, with China being an exception (Fig. 1 *B* and *D*). By 2019, the LEF/p in DEs was 70 to 530% higher than that in LDEs. This widening gap is most notable for nonmetallic mineral extractions, human health damages, and GHG emissions, up 38–48% from 1995 to 2019. Despite China's significant LEF growth in recent decades and its rapidly narrowing LEF/p gaps, its LEF/p in 2019 remained lower than that of DEs, except for iron ore extraction.

## The Global Origins of LEF across Nations

Manufactured capital accumulation increasingly relies on international supply chains for raw materials and refinement, resulting in an outsourcing of environmental pressures and impacts (Fig. 2). The construction of buildings and infrastructure relies largely on locally sourced nonmetallic minerals, yet machinery and vehicle production are truly global (40). By tracing accumulating manufactured capital assets globally between 1970 and 2019 across 49 countries/regions covering the world, we estimate that more than half of the legacy metal ore extractions (51%: iron ore, 67%: copper ore) and nearly half (47%) of the legacy human health damages occurred in nations other than those in which the capital stocks were accumulated. Overseas impacts driven by manufactured capital accumulation in DEs are even higher, reaching 67% of iron ore extraction, 73% of copper ore extraction, and 75% of human health damages in 2019. Our results also highlight the remarkable international implications of GHG emissions driven by the manufactured capital accumulation of the nations. By 2019, 37% of the legacy GHG emissions footprint of DEs and 20% of LDEs occurred abroad, growing from 29% and 15% in 1995, respectively.

There is a double burden for LDEs which provide most of the metallic material inputs supporting capital accumulation elsewhere, especially in DEs (Fig. 2), but receive a lower proportion of economic gains. For example, 59% of DEs' legacy copper ore

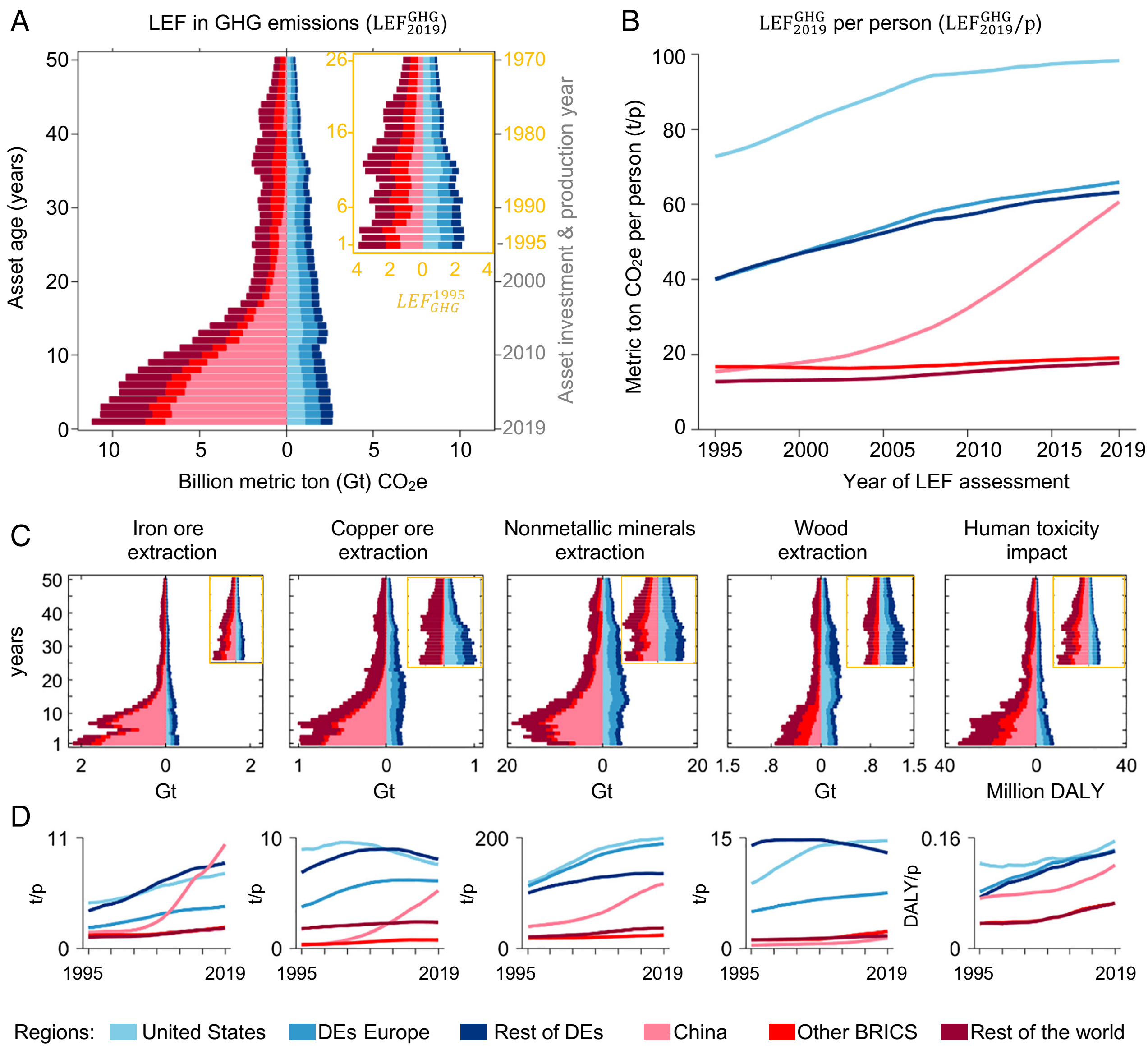

**Fig. 1.** Global scale, distribution, and trend of LEFs. (*A*) LEF pyramids showing GHG emissions accrued in global manufactured capital in 2019 ($LEF^{GHG}_{2019}$) and 1995 ($LEF^{GHG}_{1995}$) by asset age and location. Asset age is a function of the year of investment, e.g., asset *k* invested in year *t* reaches one year old at the end of year *t*. Note that the *y* axis of the 1995 and 2019 pyramids align, and the *x* axis are scaled together for direct comparison. (*B*) Recent trends of $LEF^{GHG}$ per person from 1995 to 2019. (*C*) The same as *A* but for other environmental indicators. (*D*) The same as *B* but for the environmental indicators presented in C. See *SI Appendix*, Table S1 for the classification of developed economies (DEs) included in "DEs Europe" and "Rest of DEs." DEs include OECD members in 1990, not those in the later enlargement (e.g., Poland, Mexico, and South Korea). BRICS: Brazil, Russia, India, China, and South Africa.

footprint and 46% of their legacy iron ore footprint in 2019 originated from LDEs. Impacts were extremely high for human health impacts, with 62% of the DEs' legacy human health impact footprint occurring in LDEs. At the country level, the United States, Indonesia, and Australia account for the highest overseas health damages in LDEs, amounting to 75 to 89% of their LEFs (*SI Appendix*, Fig. S2). However, in the gross value added (GVA) generated from the trade, we find that only a quarter of the economic gains from producing manufactured assets were received across borders each year, with DEs receiving more than half this fraction (*SI Appendix*, Fig. S3).

## Tracing LEF in the Economic System, from Production to Consumption

Manufactured capital enables production activities across many economic sectors, which combine to satisfy the final consumption of goods and services worldwide. All economic activities rely on capital stocks and drive the associated LEF, but not in equal amounts. In Fig. 3*A*, we present $LEF^{GHG}_{2019}$ in the global economy, linking legacy GHGs emitted from manufacturing the asset vintages that comprise manufactured capital in 2019 to the economic sectors using those assets and the final consumption ultimately facilitated by these assets (see *SI Appendix*, Fig. S4 for other environmental indicators). By 2019, structures, including residential dwellings and nonresidential structures, account for more than 80% of legacy GHG emissions and range from 70% (iron ore extraction) to 94% (nonmetallic minerals extraction) for the other five environmental indicators. Focusing on recent environmental pressures and impacts from 2010 to 2019, machinery and transport equipment supporting manufacturing and services also play a notable role, accounting for 29%, 35%, 38%, and 41% of GHGs, copper ore, human toxicity, and iron ore, respectively. Assessment of these asset classes is vital given their shorter lifetimes, as policy and technical interventions can offer substantial short-term opportunities in reducing impacts and meeting climate goals.

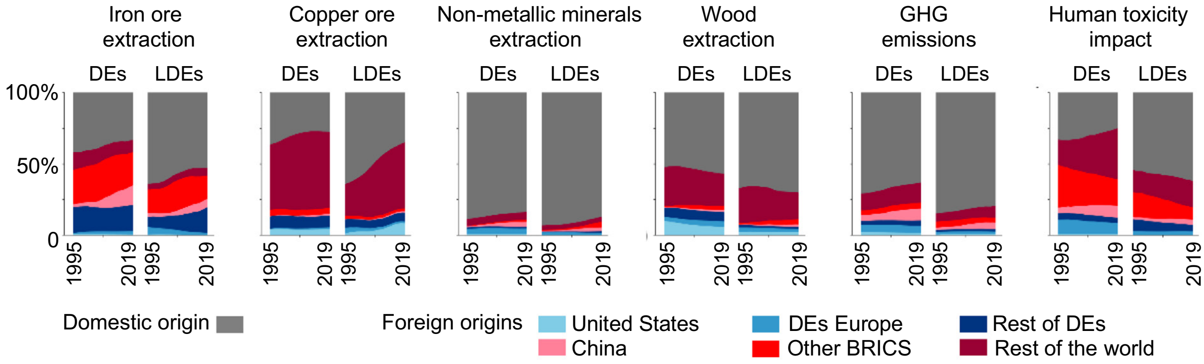

**Fig. 2.** The global environmental consequences of manufactured capital accumulation. DEs and LDEs depict the LEFs of manufactured capital located in developed and less developed economies, respectively, from 1995 to 2019 (see *SI Appendix*, Table S1 for countries classified in the DEs and LDEs). Foreign material extractions and environmental impacts are color-coded similarly as Fig. 1. For some countries, the overseas fraction of environmental consequences driven by capital accumulation was much higher than what regional averages suggest; we highlight those countries' reliance on international copper ore extraction, GHG emissions, and human health damages in *SI Appendix*, Fig. S2.

From a production perspective, we scale the $\mathrm{LEF}_{2019}$ of economic activities by their gross value added (GVA) in 2019 to compare the environmental efficiency in asset accumulation (Fig. 3*B* and *SI Appendix*, Fig. S6). The LEF per gross value added of production (LEF/GVA) also provides a new metric for assessing sustainable investments as it tracks the additional environmental costs incurred by a producer when adding an extra unit of manufactured assets. Unlike previous assessments focusing on flow variables considering direct or indirect impacts in a given year, the LEF-based metric isolates capital environmental efficiency from operational environmental efficiency.

Globally, "construction and real estate service" and "utilities" (e.g., electricity generation) saw the largest $\mathrm{LEF}_{2019} / \mathrm{GVA}_{2019}$. Comparing DEs and LDEs across the seven production activities, $\mathrm{LEF}_{2019} / \mathrm{GVA}_{2019}$ varies less in asset composition but more in magnitude. That is, national LEFs have been historically similar across the four broad asset classes but vary widely on a per gross value–added basis for the same production activity. $\mathrm{LEF}_{2019} / \mathrm{GVA}_{2019}$ is overall lower in DEs than that in LDEs, with a few exceptions, such as in extraction activities, agricultural production, and all production activities concerning legacy wood extraction. The lower estimates of DEs are likely the result of higher economic productivity and lower environmental intensities in asset production, which has also been noted in flow-based analysis (41, 42). The divergence for agriculture and extractive industries may be due to the different rates of mechanization across nations.

From a consumption perspective, when the use of assets and associated $\mathrm{LEF}_{2019}$ is attributed to the goods and services purchased by final consumers in 2019, LEF/p is higher in DEs than that in LDEs regardless of final consumption purpose or environmental pressure and impact category (Fig. 3*C* and *SI Appendix*, Fig. S6). The LEF difference between an average consumer in DEs and LDEs was the narrowest for iron ore extraction (133%) and largest for wood extraction (555%) in 2019. Differences between housing and public administration spending demonstrate the most significant gaps between developed and less-developed consumers, potentially due to larger floor areas, complex building practices, and generally larger administrative states in DEs. The majority of the global LEF (about 60 to 70%) is attributable to four purposes: shelter (including housing, heating & cooling, and house furniture and appliances), public administration and security, health, and mobility.

## Outlook and Conclusion

Human civilization has achieved an unprecedented level of manufactured capital, with the global stock of manufactured assets reaching a staggering 543 trillion US$ in 2019, more than four times the GDP of that year [in 2017 prices (36)]. In this study, we reveal the high environmental costs of this capital accumulation through the legacy environmental footprint or LEF. It is commonly assumed that resource use and emissions occur in the production of products and services that are consumed in the short term. However, we highlight that a significant part of environmental footprints occurred during the production of assets that are still in use today and will continue to be used in the future. Understanding the dynamics of capital stocks is crucial for understanding the long-term services they provide, inequalities in capital accumulation, and developing scenarios of future capital needs and impacts. In constructing and modeling LEFs, we strive to maintain compatibility with existing micro- and macro-economic frameworks and metrics of capital stock.

The LEF shows how manufacturing capital assets has become increasingly complex in a globalized world. Most countries relied on global supply chains, particularly in metals, to build their manufactured capital. This heavy reliance has resulted in significant environmental impacts in countries that extract, transport, and process ores from their natural environments. These impacts include soil erosion, biodiversity loss, water pollution, and occupational diseases and mine worker deaths (43). Moving from a fossil-fueled energy system to a renewable energy system will further alter the dependencies and impacts of global supply chains for manufactured assets. While trade may potentially reduce global environmental costs overall (43, 44), assessing this is beyond the scope of this study.

The LEF per capita shows a larger or growing gap between developed and less developed economies. If a good life involving the fulfillment of the social and economic SDGs requires a developed-country level of manufactured capital, then LDEs should have the right to and assistance in building up such a capital stock. This leads to the question of where resources will come from and if this can be done with fewer environmental and social impacts. Our quantification sheds some light on the size of the challenge that remains. In order to mitigate further environmental costs, it is crucial for economies to set ambitious reduction targets and implement policies that support the development of alternative capital accumulation pathways. Without such measures, the detrimental impact on the environment will continue to

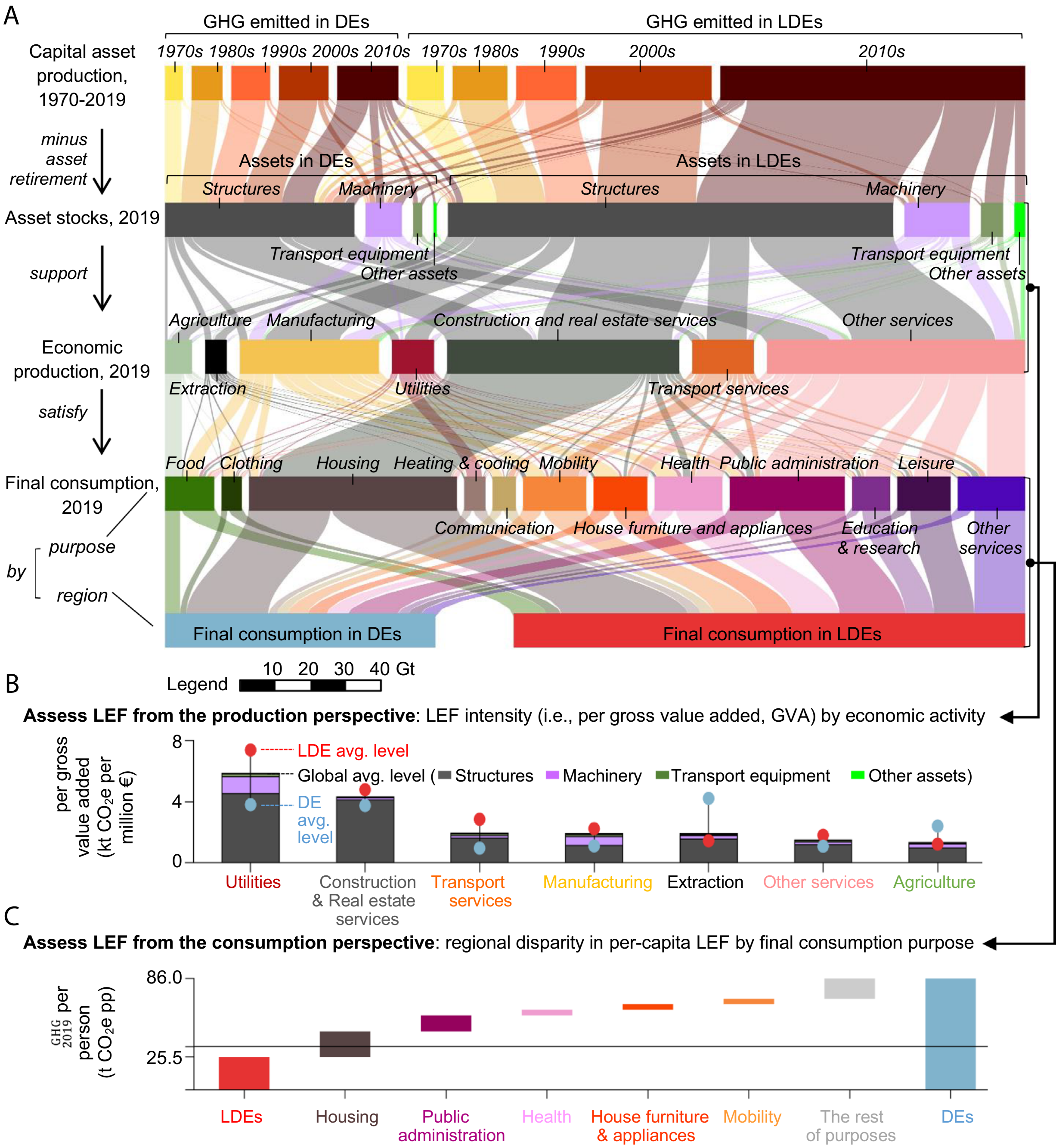

**Fig. 3.** Mapping LEF$^{GHG}_{2019}$ to global production and consumption in 2019. (*A*) Legacy GHG emissions (LEF$^{GHG}_{2019}$) mapped to the global value chain by region and sector of production and consumption in 2019. DEs: developed economies; LDEs: less-developed economies (see *SI Appendix*, Table S1 for countries classified in the DE and LDE regions). Based on the sectoral and regional LEF flows in (*A* and *B*) assesses the productive efficiency of capital stocks by normalizing the main economic activities' LEF$^{GHG}_{2019}$ by their gross value added in 2019 (adjusted for purchasing power parity), and (*C*) attributes LEF$^{GHG}_{2019}$ to final consumption purposes and population in DEs and LDEs; the horizontal line marks the global average of 34.0 metric tons of CO$_2$e per person.

persist (19, 45). These issues have strong links to ethical and economic considerations as they require an explicit quantification of future well-being needs, intergenerational investment decisions, and an appreciation of global inequality, which largely depend on norms and values (46, 47).

The wide range of LEF per gross value added of production (i.e., LEF/GVA) shown in Fig. 3*B* indicates that implementing best-practice asset production could significantly lower future impacts. The country and global LEF pathways in Fig. 4 reveal that reaching high well-being levels is possible with a wide range of LEF per person (LEF/p), although LEF/p keeps growing over time in all major economies. Promoting asset accumulation that more effectively fosters well-being can lead to reduced LEF/p, and, in turn, lower the total material extractions and environmental impacts of manufactured capital accumulation. Further, we must assess capital development pathways over time for different resource uses and environmental impacts (Fig. 4). For example, the high level of average Australian well-being is associated with a relatively low LEF/p in terms of nonmetallic minerals but is the highest in terms of GHG emissions. Crucially, we note that a best-practice assessment must take into account more than just the level of LEF, but also factor in the dynamic nature of asset production efficiencies, which can vary over time and space, as well as the composition of age cohorts in a nation's capital stocks. These variables can have a significant impact on both the environmental and service efficiency of a nation's capital stocks. Overall, it will be increasingly

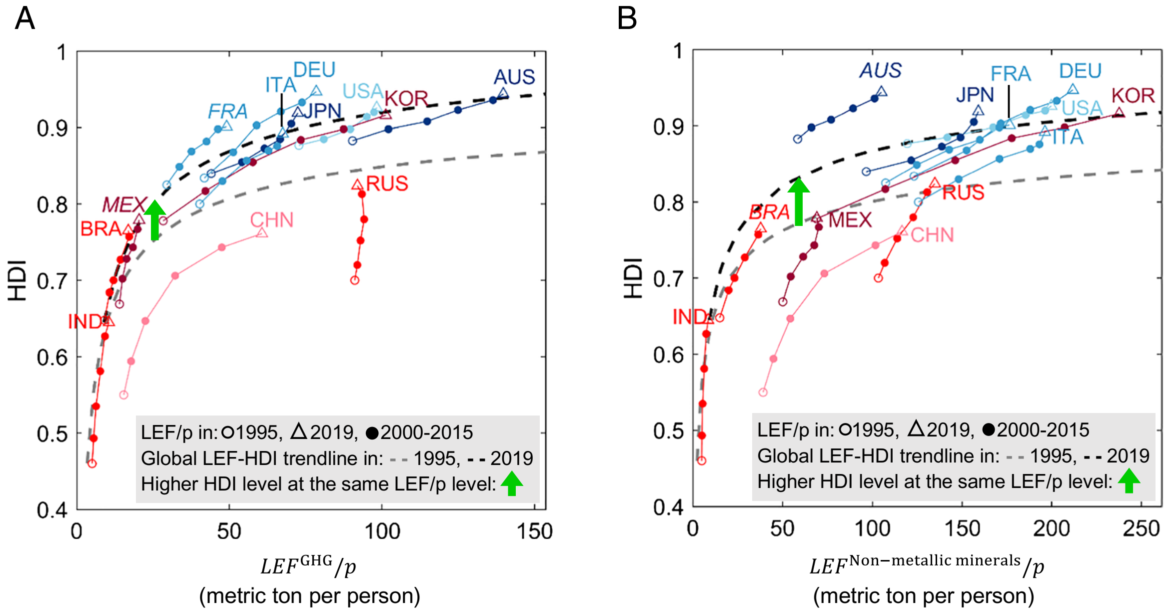

**Fig. 4.** National and global trajectories of LEF per person (LEF/p) levels and human development from 1995 to 2019. (*A*) Legacy GHG emission footprint per person and Human Development Index (HDI), the widely used well-being metric; HDI > 0.8 indicates high levels of well-being. (*B*) Legacy nonmetallic mineral extraction footprint per person and HDI. The same countries, i.e., those with the top-10 country-level LEFs in either environmental indicator, are highlighted in the plots; *italics* in *A* (*B*) indicate countries that are only top 10 regarding the other indicator. The countries are color-coded according to regional groups defined in Figs. 1 and 2.

important to develop capital stock scenarios and models that assess the connections between well-being, services, products, materials, and the environment (48, 49).

Our research highlights the need for a paradigm shift in sustainability science, policy, and green finance that moves beyond a narrow focus on daily resource use and emissions toward a consideration of the long-term environmental impact of capital accumulation. Our analysis takes a crucial step in incorporating the longevity of capital stock into environmental impact assessments that inform investment decisions. However, single indicators of manufactured capital are limited in describing complex societal services and resource endowments, a challenge not only in sustainability science but also in economic studies. For example, GDP components, such as household consumption, investment, and government spending, offer richer information on economic well-being than aggregated GDP. Similarly, the LEF framework considers asset creation through investments and retirement based on empirically estimated survival curves which are described by asset, industry, and country over time. Together, the LEF components provide a more complete understanding of manufactured capital accumulation and its environmental implications over its lifespan—a dimension that needs to be considered. Finally, this study analyzes LEFs to maintain comparability with the existing micro- and macro-economic frameworks and metrics of capital stock (for example, by subtracting retired assets from the total). However, our modeling approach can accommodate various quantifications and definitions of cumulative impacts of capital stocks, such as those related to retired assets (*SI Appendix*, Figs. S7–S9). The LEF provides a complementary environmental perspective to existing monetary capital stock metrics, which we hope provides a more comprehensive understanding of the long-term effects of investments on the environment.

## Materials and Methods

**Definition of Investment, Fixed Assets, and Capital Stocks.** In our analysis, investment follows its definition in the national account system: The acquisition of fixed assets intended for producing other goods and services for more than a year, also known as gross fixed capital formation (35). In general, there are four types of fixed assets: machinery (e.g., industrial mixers and office computers), transport equipment (e.g., tractors and airplanes), structures (e.g., warehouses and residential dwellings), and other long-lasting assets (e.g., software and artworks) (34, 36). By accumulating those assets through investments, a nation builds up its capital stock and productive capacity for the current and future generations (50, 51). Therefore, the capital stock we analyze here refers to all accumulated fixed assets still in use at any given time, also known as *capital, produced capital,* or *manufactured capital* in the literature. Although some consider durable goods households use for nonproductive purposes as part of produced capital (2), we exclude them except for residential dwellings following the definition of investments and fixed assets in the national account system.

There is a long tradition of monitoring investments in the national account system to estimate capital accumulation, analyze the role of accumulated capital stock in economic growth, and assess the wealth of capital owners based on capital stock accounts (34, 52, 53). A widely used measurement of capital stock in the monetary unit is *net capital stock*, which is "the stock of assets surviving from past periods, and corrected for depreciation" and intends to reflect the market values of fixed assets (54, 55).

Existing approaches mainly use monetary (rather than physical) metrics to measure the produced capital. As a result, there is a lack of analytical methodology to explore the linkage between the produced capital and natural capital regarding physical material transfer and ecosystem service depletion. For instance, while the *net capital stock* estimates the market value of the capital stock, the magnitude of the market value could deviate significantly from the upfront environmental impacts, such as the extraction of minerals and wood and GHG emissions caused by the building up of the capital stock.

**Data Sources.** The spatial and sectoral specifications and categorizations of environmental pressures and impacts of the model follow those employed in exiobase 3 (56), the multiregional input–output (MRIO) database on which our environmental–economic system modeling primarily relies. The model describes 44 individual economies and five rest-of-the-world (RoW) regions (based on continents) and defines each economy by 200 product groups, tracking six environmental pressures and impacts associated with the economic activities annually from 1970 to 2019. When analyzing the results, we aggregate the countries/regions into two or six world regions (*SI Appendix*, Table S1). The 200 product groups indicate 200 production activities or industries in the economy. We choose six environmental pressures and impact categories to present a more comprehensive understanding of potential environmental pressures and impacts caused by manufactured capital accumulation. They include extractions of various exhaustible materials (iron ore, copper ore, nonmetallic minerals aggregating eight industrial and construction minerals, and wood), GHG emissions indicating climate change impacts, and human toxicity impacts predominantly induced by air pollution. In addition, the time series of available national asset-specific investment data, i.e., KLEMS (57) and the Penn World Table (34), determines the temporal coverage of the model. The investment datasets also determine the asset details modeled per economy, ranging from three to ten asset categories.

**Model Description.** In the following sections, we first describe the modeling approaches employed to capture the physical existence of capital stock (***i***). We then describe the other modeling steps of the LEF and the estimates of LEF at the global, country, sector, and individual levels taking the *capital' ownership' perspective* (i.e., where the assets are located) (***ii***), the LEF attributable to the final consumption of regions and individuals and by consumption purpose (***iii***), and the sectoral and regional comparisons of LEF on a per-unit basis (***iv***).

***(i) Model asset retirement based on a dynamic stock modeling approach.*** Most capital stock estimates employ some variant of the perpetual inventory method (PIM). Eq. **1** illustrates the common PIM approach adopted by national and international statistical agencies and researchers for estimating capital stocks (57). The net capital stock ($K_t$) at the end of period $t$ is a function of the net capital stock at the end of the previous period $t-1$ ($K_{t-1}$), the gross investment in the period ($I_t$), and the capital consumption commonly measured by geometric depreciation (i.e., depreciation by a constant rate $\delta$).

$$K_t = K_{t-1} + I_t - (1-\delta)K_{t-1} \qquad [\mathbf{1}]$$

While adopting the overarching framework of the PIM, we implement a critical adaptation here to model the level of capital stock by its physical existence rather than for economic purposes. That is, rather than modeling the annual *outflows* as depreciation, we model it as the physical retirement of assets (i.e., loss of physical and functional capacity) using the dynamic stock modeling approach (58) and empirical asset discards data and statistics. Specifically, for asset type $k$ invested by industry $j$ in year $t$, the retirement in year $n$ ($n \geq t$) is:

$$r^k_{j,t,n} = h(y^k_{j,t}, g^k_{j\hat{A}}, \eta) \text{ where } \Sigma^{\infty}_{\mathrm{n=t}} r^k_{j,t,n} = y^k_{j,t} \quad \forall j, t, k \qquad [\mathbf{2}]$$

$y^k_{j,t}$ represents the initial investment value, $g^k_j$ represents the survival function specific to the type of the assets and asset-using industry or the locating country in the case of residential buildings (*SI Appendix*, Table S2), and $\eta = n - t$ is the asset age. Note that the survival functions vary by investing period for residential buildings in China and South Korea. $y^k_{j,t}$ is obtained from KLEMS (2007 release and 2017 release), WORLD KLEMS, or the Penn World Table (PWT 10.0).

By definition, the empirically estimated survival functions of the assets capture capital stocks' physical and functional losses better than depreciation. Moreover, the two methods can result in significant differences in estimating capital stock levels, as identified in the literature (59). We illustrate the difference in *SI Appendix*, Fig. S5.

***(ii) Legacy footprint accounting of capital stock from the ownership perspective.*** Environmentally extended input–output models (EE-IO), especially the multiregional input–output models (EE-MRIO), present a modeling approach for tracing and quantifying total environmental pressures and impacts caused by the production of goods and services, both directly and indirectly upstream of the supply chain and regardless of the national boundaries (25). Hence, we employ the MRIO to quantify the environmental pressures and impacts caused by asset production and those embodied in the retired assets (capital inflows and outflows). Specifically, for asset type $k$ (e.g., machinery) invested by industries and countries in year $t$ ($\mathbf{Y}^k_t$), we quantify the total environmental impacts (e.g., GHG emissions) caused by the production of the invested assets (Eq. **3**) or embodied in the retired assets (Eq. **4**):

$$\mathbf{E}^k_{t,\mathrm{INVEST}} = \mathbf{f}_t(\mathbf{I}-\mathbf{A}_t)^{-1}\mathbf{Y}^k_t \qquad [\mathbf{3}]$$

$$\mathbf{E}^k_{t,n,\mathrm{RETIRE}} = \mathbf{f}_t(\mathbf{I}-\mathbf{A}_t)^{-1}\mathbf{R}^k_{t,n} \qquad [\mathbf{4}]$$

$\mathbf{f}_t$ is a 1 × 9,800 row vector specifying the direct environmental impact intensity of 200 product types in 49 countries/regions. $(\mathbf{I}-\mathbf{A}_t)^{-1}$ is a 9,800 × 9,800 Leontief inverse matrix, where $\mathbf{A}_t$ is the multiregional matrix of technical coefficients (9,800 × 9,800) and $\mathbf{I}$ the identity matrix (9,800 × 9,800). Each column of the Leontief inverse matrix shows the total, both direct and indirect, requirements of intermediate inputs across the global supply chains for one unit output of a given product–country pair. Both $\mathbf{f}_t$ and $\mathbf{A}_t$ are from exiobase 3, available as time series from 1995 to 2019. For assets invested between 1970 and 1994, where the multiregional input–output data from exiobase 3 are unavailable, we used the data of the earliest year available (i.e., $\mathbf{f}_{1995}$ and $\mathbf{A}_{1995}$). In the following, we use the index $t$ for looking retrospectively at past years and the index $n$ for the current year.

$\mathbf{Y}^k_t$ is a 9,800 × 9,800 matrix expressing the monetary value of the invested assets $k$ in year $t$, with rows and columns aligning the capital products and their investing (using) sectors, respectively. The construction of $\mathbf{Y}^k_t$ uses a few data sources. They include gross fixed capital formation (i.e., investments) by capital product and investing country/region from 1995 to 2019 in exiobase 3, capital investment time series by asset and asset-investing industry and country from EU KLEMS (2007 release and 2017 release) and WORLD KLEMS, and the capital investment time series by asset and asset-investing country from the Penn World Table (PWT 10.0) to complement the missing data. Besides, we created a set of concordance tables to reconcile the differences in sectoral classifications of the different data sources. The construction of $\mathbf{Y}^k_t$ is described in detail by Ye et al. (13)

$\mathbf{R}^k_{t,n}$ is a 9,800 × 9,800 matrix expressing the monetary value of the assets $k$ retired in year $n$ ($n \geq t$), after having been invested in year $t$. $\mathbf{R}$ has elements $R_{ij}$, where $i$ (rows) and $j$ (columns) count the asset products and their investing (consuming) sectors, respectively. $\mathbf{R}^k_{t,n}$ is obtained from all ${r_{j,t,n}}^k$ calculated for the investing industries defined in the external capital datasets [i.e., KLEMS (2007 release and 2017 release), WORLD KLEMS, or the Penn World Table (PWT 10.0)]. Similar to the construction of $\mathbf{Y}^k_t$, we use concordance tables to reconcile the different sectoral classifications of the data sources.

$\mathbf{E}^k_{t,\mathrm{INVEST}}$ and $\mathbf{E}^k_{t,n,\mathrm{RETIRE}}$ are both row vectors (1 × 9,800). The columns represent the capital-investing sectors and countries according to the 200 products and the 49 countries/regions defined in exiobase 3. Note, previously, capital endogenization methods tend to model the underlying environmental requirements of a given year's capital stock based on the same year's $\mathbf{f}_t$ and $\mathbf{A}_t$, despite the assets being in different age cohorts. In comparison, our method enables an improved estimate of the capital stock's upfront environmental pressures and impacts by using the asset production year's environmental intensities and supply chain structure as long as data allow. Moreover, our modeling of $\mathbf{E}^k_{t,\mathrm{INVEST}}$ and $\mathbf{E}^k_{t,n,\mathrm{RETIRE}}$ in Eqs. **3** and **4**, respectively, neglects that asset productions in year $t$ depend on the capital stock available in year $t$ and comprising of assets produced in earlier years.

For the capital stock of all assets that remain in current year $T$, we establish the upfront environmental impacts caused in year $1, 2, \ldots, t$ ($t \leq T$) based on the above inflows (capital formation) and the outflows (we trace capital retirement at each year $n$, through year of investment $t$ to current year $T$) obtained above. $\mathbf{LEF}^k_T$ is a row vector (1 × 9,800) specifying the LEF in year $T$ for all age cohorts of asset type $k$, with the columns specifying the asset-using sectors and countries. Based on Eq. **5**, we can obtain the asset-, sector-, and region-specific LEF through alternative aggregations.

$$\mathbf{LEF}^k_T = \sum_{t=1970}^{T} \mathbf{E}^k_{t,\mathrm{INVEST}} - \sum_{t=1970}^{T} \sum_{n=t}^{T} \mathbf{E}^k_{t,n,\mathrm{RETIRE}} \qquad [\mathbf{5}]$$

Similar to the conventional environmental footprint accounts $EF_T$ (e.g., carbon footprint of a country's consumption in year $T$), $LEF_T$ captures the total (direct and indirect) environmental pressures and impacts caused by asset production and can go beyond national territorial boundaries owing to international trade. However, there are two crucial differences between the two. First, $LEF_T$ captures environmental pressures and impacts that occurred mostly before year $n$ due to capital's long-lasting feature. In contrast, $EF_T$ only accounts for the environmental pressures and impacts that occurred in year $T$ owing to the unspecified link between production and capital stock.

Second, $LEF_T$ calculated by Eq. **5** is not strictly a consumption-based account because the environmental impacts of asset production are not attributed to final consumption but the capital-using production activities in year $T$, i.e., *taking the ownership perspective*. For the $EF_T$ accounts, however, environmental pressures and impacts of all productions are attributable to final consumption. As described below, attributing $LEF_T$ to the final consumption of year $T$ could cause double-counting issues because the same assets and the associated LEF can be attributable to the final consumption of multiple years, even decades, throughout the assets' lifetime.

***(iii) Linking LEF to final consumption.*** While acknowledging the aforementioned double-counting issues, we specify the calculation that connects $LEF_{2019}$ to the final consumption in 2019 in Eqs. **6**–**8**. Eq. **6** attributes the environmental pressures and impacts accrued in the capital stock of asset *k* during past years (i.e., $\mathbf{LEF}^{k}_{2019}$, 1 × 9,800) by the asset investing (using) sectors to year 2019's total output $\boldsymbol{x}_{2019}$ (9,800 × 1).

$$\mathbf{S}^{k}_{2019} = \mathbf{LEF}^{k}_{2019}\hat{\mathbf{x}}^{-1}_{2019} \qquad [6]$$

where $\mathbf{x}_{2019}$ is a 9,800 × 1 column vector describing the gross output by sector and country in 2019; the hat symbol denotes diagonalization. $\boldsymbol{S}^{k}_{2019}$ (1 × 9,800) can be considered a vector of environmental intensities of year 2019's production activities owing to the reliance on the capital stock of asset *k*. By adding up $\mathbf{S}^{k}_{2019}$ for all asset types, we obtain the total environmental intensities of year 2019's production activities owing to the reliance on the capital stock K of all assets ($\mathbf{S}^{K}_{2019}$, 1 × 9,800):

$$\mathbf{S}^{K}_{2019} = \sum_{k} \mathbf{S}^{k}_{2019} \qquad [7]$$

From the consumption perspective, i.e., production activities and all associated environmental pressures and impacts are ultimately driven to meet final consumption, the legacy footprint in year 2019 can be expressed as:

$$\mathbf{LEF}^{C}_{2019} = \mathbf{S}^{K}_{2019}(\mathbf{I} - \mathbf{A}_{2019})^{-1}\mathbf{Y}^{C}_{2019} \qquad [8]$$

where $\mathbf{Y}^{C}_{2019}$ is a 9,800 × 49 matrix expressing the monetary value of the final consumption of 49 countries/regions in year 2019, available from exiobase 3. $(\mathbf{I} - \mathbf{A}_{2019})^{-1}\mathbf{Y}^{C}_{2019}$ traces the final consumption in 2019 to all economic productions that provide for it in 2019.

***(iv) Sectoral and regional comparisons of LEF on a per gross value–added basis.*** From the production perspective, the magnitudes of LEF vary significantly across the asset-using sectors and regions. To better assess and understand the heterogeneities, we compare the sectoral and regional LEF on a per GVA basis. Specifically, we quantify the LEF per gross value added of production in 2019 following Eq. **9**.

$$\mathrm{LEF/GVA}^{j}_{2019} = \frac{\mathrm{LEF}^{j}_{2019}}{\mathrm{GVA}^{j}_{2019}} \qquad [9]$$

*j* indicates one of the seven main economic production activities we aggregated from the 200 products (*SI Appendix*, Table S3). $\mathrm{LEF}^{j}_{2019}$ is calculated based on Eq. **5** and by selecting the relevant products while aggregating all asset types and asset-using countries. $\mathrm{GVA}^{j}_{2019}$ measures production *j*'s gross value added in 2019. We obtained the sector- and country-specific GVA data from exiobase 3 and adjusted price differences among countries using the purchasing power parity rate from the World Bank (3). Similarly, we calculate the $\mathrm{LEF}^{j}_{2019}$ for developed and developing economies by selecting the relevant products in the region of interest.

From the consumption perspective, we compare the LEF per person of DE and LDE, calculated in Eq. **10**.

$$\mathbf{LEF}/\mathbf{p}^{C}_{2019} = \frac{\sum_{i}\mathbf{S}^{K}_{2019}(\mathbf{I} - \mathbf{A}_{2019})^{-1}\widehat{\mathbf{Y}^{C}_{2019,i}}}{\sum_{i}p^{i}_{2019}} \qquad [10]$$

where $\mathbf{Y}^{C}_{2019,i}$ is a 9,800 × 1 vector expressing the monetary value of the final consumption of a country/region *i* in DEs or LDEs in 2019, and $p^{i}_{2019}$ is country/region *i*'s population in 2019.

$\mathbf{LEF}/\mathbf{p}^{C}_{2019}$ is a 1 × 9,800 vector; the columns correspond with the final consumption products and the providing countries. We can aggregate all columns to obtain the regional average per capita LEF. To breakdown $\mathbf{LEF}/\mathbf{p}^{C}_{2019}$ into consumption purposes, we aggregate the final consumption expenditure on the 200 products into 12 final consumption purposes.

**Data, Materials, and Software Availability.** All data and code in the analysis can be accessed from DOI 10.5281/zenodo.7877361 (60).

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