Title:

1) The Legacy Environmental Footprints of Capital Accumulation

2) The Legacy Environmental Footprints of Investments

Authors:

Abstract:

Investment is the vehicle through which we build up a stock of capital assets that our future livelihoods depend on. While the direct carbon emissions and pollution from the day-to-day running of the assets are well-known and a focus of science and policy solutions, information on the upfront environmental impacts that occurred at the time of asset production and accrued in the asset stock in use is fragmented. Here, we provide a global quantification of the legacy environmental footprints of investments (LEF), i.e., the upfront materials, emissions, and health impacts led by half-century's investments and accrued in the modern-day capital stock, we analyze the LEF trends across time and space, and we reveal novel information about where the legacy impact hotspots and associated mitigation leverages lie in the global value chain, from production and consumption perspectives. Our estimates show that in the next 2-3 decades, given expected changes in population and income levels, capital accumulation only could add 185-583 Gt of GHG emissions in the absence of ambitious technological changes, more than tripling current global LEF in terms of GHG emissions, various sorts of material extraction, and human health damages. Reconceiving investments is at the heart of a low-carbon and resource-efficient future. By quantifying the LEF and presenting a holistic view, our results could help prevent new investments from causing unwanted environmental and health consequences.

Main text

Fueled by investments, the built-up stock of capital assets, such as buildings, machinery, and transport equipment, is one of the clearest and most visible signs of development (*1*). They enable the production of goods and services with the intent of improving human well-being (*2*, *3*). Investments are increasingly the subject of policymaking because they could help build up the assets on which the United Nations (UN) Sustainable Development Goals (SDGs) depend (*4*-*6*). A holistic understanding of the environmental impacts of investments and built-up stock of assets is highly relevant as global investments in infrastructure and other assets are at an all-time high and an ever-increasing number of decisions being made now will lock in patterns of development and strand assets for future generations (*7*).

However, despite that the direct carbon emissions and pollution from using the asset stock are well-known, the upfront environmental impacts that occurred during the production phases of the assets and accrued during years and decades of capital accumulation, have not been as comprehensively and systematically assessed. New data indicates that, in 2019, more than a quarter of the gross global product went to investments, while the resulting asset productions claimed a more significant share of material extractions (62% of metal ores and 51% of nonmetallic minerals), climate change impacts (29% of greenhouse gas emissions), and ill-health (57% of air pollution-induced human health damages) in that year (see Supplementary Information).

Prior analyses have identified building up the asset stock at the cost of declining natural capital (e.g., stocks of geological resources and ecosystems) as the core of a broad debate about what is meant by "sustainable development". For metal and mineral resources, these costs can be unarguably observed in physical materials transfer from natural deposits to industrial products, and the subsequent adverse environmental impacts (*1*). For ecosystems, there has been an increasing effort to economically value the human benefits provided by their services, leading to a nation's natural capital valuation (*8, 9*). An emerging area of inquiry addresses the capital assets in terms of the accumulation of materials (*10, 11*), the contribution to environmental footprints of traded and consumed commodities (*12-16*), and the resource and environmental costs of more equitable development (*17*) or a shift to a low carbon economy (*18*).

The UN System of Economic and Environmental Accounting (SEEA) presents a framework that integrates economic and environmental data to provide a comprehensive and multipurpose view of the interrelationships between the economy and the environment (*19, 20*). This framework is now widely used in developing, assessing, and monitoring sustainability policy. However, the implementation of SEEA has two significant shortcomings: (1) an organization of accounts on the national level cannot adequately represent the global supply chains that have become ubiquitous; (2) economic and environmental flows are traced annually, yet, the stocks of capital assets are only quantified in optional satellite accounts that are of poor quality or inaccessible if they exist at all. In response, the research community has successfully combined measures of national economic activities and environmental accounts into a global framework and developed environmentally-extended multiregional input-output models (MRIOs), which have enabled scientists to quantify the environmental and social footprints of consumption (*21, 22*), to assess the impacts of trade on achieving each SDG (*23, 24*), and to address a wide range of research questions in sustainability science (*25-27*). While a modeling framework has been proposed that relates a year's investments and asset productions to the associated environmental impacts within the socio-economic system, quantitative understanding of the material demand and environmental emissions of built-up capital stocks, thus far, has been narrowly focused on individual impact categories or specific capital goods, such as power stations and vehicles (*17, 28-30*).

The objective of this study is to present a systematic and comprehensive estimate of the legacy environmental footprint of investment (LEF), i.e., the upfront environmental impacts led by all investments and accrued in the modern-day capital stock. Details of our analytic approach and accounting assumptions are described in Methods. In summary, we assess the LEFs by tracking asset-, industry-, and country-specific capital stock built-ups through investments (i.e., inflows) and asset retirement (i.e., outflows) in a global time series model that spans from 1970 to 2019. For a holistic view of the environmental requirements and consequences, we quantify LEFs in terms of key material extractions (iron ore, copper ore, nonmetallic minerals, and forestry), climate change impacts (greenhouse gas, GHG, emissions), and adverse health effects (potential harm to human health induced by air pollution). By analyzing the spatial and temporal trends of the LEFs and mapping the LEFs in an economic system linking production and consumption, we further identify the primary production and consumption drivers of current and prospective LEFs.

This study improves upon earlier environmental assessments of capital stocks (i.e., the legacy of historical investments) in several respects. First, while capital stock is traditionally measured in monetary terms which dictates further investment decisions (*31, 32*), we provide the first economywide quantification of global capital stock in six environmental impact categories by integrating 50 years of economic and environmental data. Second, by explicitly treating capital stock as consisting of cohorts of assets that were produced by global supply chains and acquired by industries, we capture the changing asset compositions in the evolving economy and changes in the environmental impact intensities and origins of asset production, which has not been done in earlier studies (*12, 13, 15, 16*). Third, we employ dynamic stock modeling based on asset retirement and disposal statistics, whereas earlier studies model the asset outflows by economic depreciation, a measure of assets' economic value decline over time rather than their physical availability (*12, 14, 16*). Besides, built upon earlier studies, we make better use of the empirical estimates available for modeling asset outflows, distinguishing asset time and asset-using industry, country, and period, thus enabling a robust estimate of the LEFs' spatial and temporal dynamics. Measured as the material extraction, GHG emission, and human health impacts, the LEFs quantified and the trends revealed provide new insights into the environmental impacts underlying wealth accumulation of industries and countries, supporting the adoption of environmental impacts and efficiency as an additional focus of future investment and capital accumulation.

Global LEF pyramids signify half-century investment paths

The global LEF pyramids reveal significant past investments and growths not only in human effort but also in various material extractions, GHG emissions, and human health damages (**Fig. 2**). Accrued in the global capital stock in 2019 are 254 Gt CO_2-eq GHG emissions, 31 Gt iron ore, 24 Gt copper ore, 507 Gt nonmetallic minerals, and 23 Gt forestry extractions, and 650 million DALY (disability-adjusted life years) losses since 1970. Just over the recent 25 years, from 1995 to 2019, the global LEFs more than tripled in terms of extracted iron ores and more than doubled in the rest of the environmental impacts assessed except for forestry extraction, which also experienced significant growth of 91%. The global LEF growths except forestry extraction outpaced global GDP and population growths, 110% and 35%, respectively (*33*), in the same period.

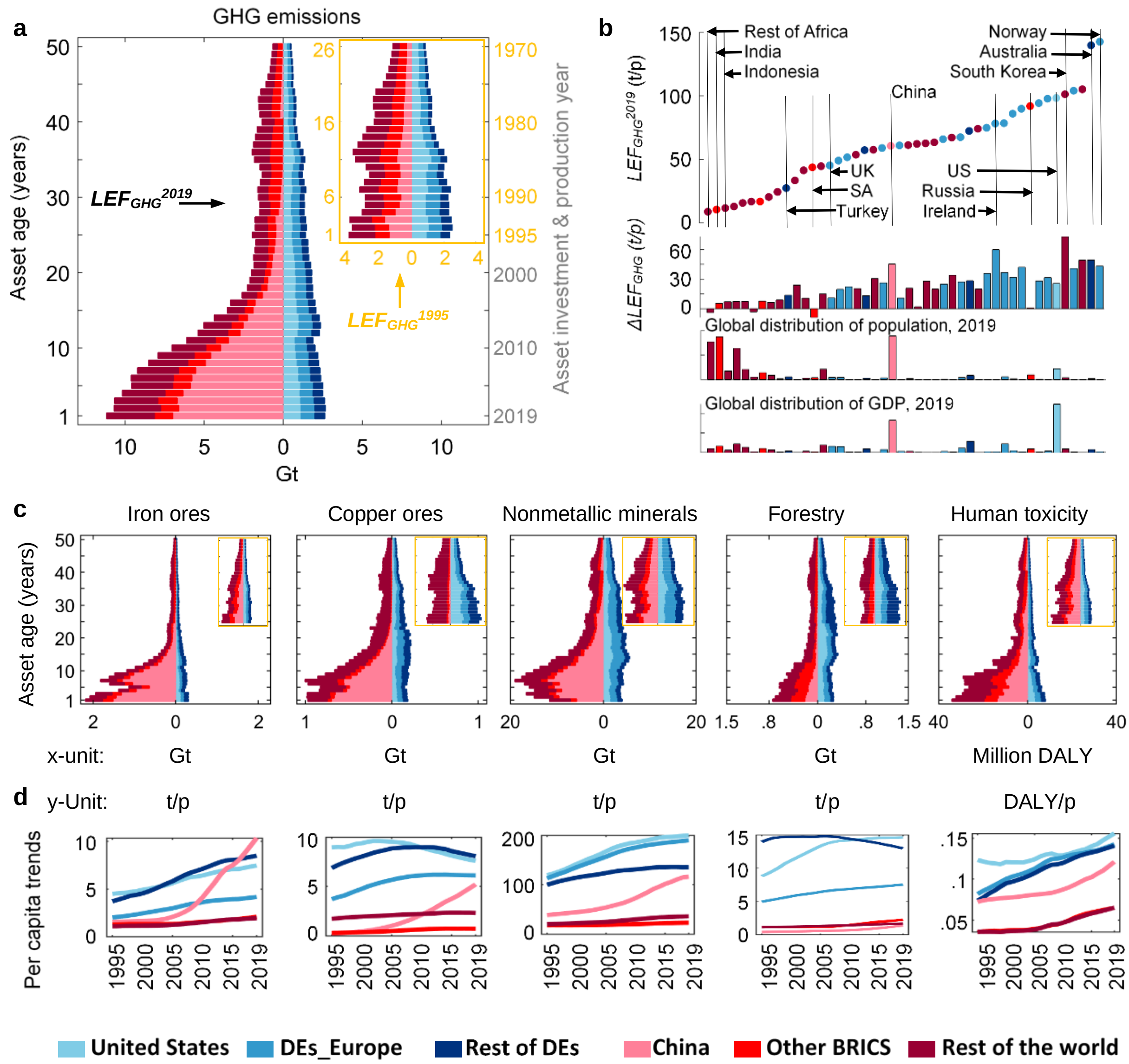


Figure 2. **Global scale, distribution, and trend of LEF**. **a**, LEF pyramids showing the GHG emissions accrued in the global capital stock in 2019 (LEF_{GHG}^{2019}, in the main plot) and in 1995 (LEF_{GHG}^{1995}, in the inset) by asset age and region. The age of the asset is derived from the year of investment, e.g., asset k invested in year t is assumed to be produced in year t and reaches 1 year old at the end of year t. To better illustrate the evolution from LEF^{1995} to LEF^{2019}, the y-axis of each LEF^{1995} pyramid aligns with that of the LEF^{2019} pyramid and tracks assets that were invested and produced from 1970 to 1995 and aged 26 years to 1 year, respectively, in 1995; the x-axis of the LEF^{1995} and LEF^{2019} pyramids are scaled the same so the bar lengths and the areas of the two pyramids are comparable. **b**, Per capita, country-level LEF_{GHG}^{2019}, and magnitude changes since 1995. '/p': per person. **c**, Same as **a** but show *LEFs* assessed in five more environmental impact categories. **d**, Recent trends of per capita *LEFs* by region, from 1995 to 2019, for the same environmental impact categories in **c**. For all plots, developed economies (DE) in 'DE_Europe' and Rest of DE' are detailed in the Supplementary Information. In general, all DEs are members of the Organisation for Economic Co-operation and Development (OECD) in 1990. OECD-1990 includes the 20 founding countries of OECD and Japan, Finland, Australia, and New Zealand, and does not include later members that joined during OECD's enlargement to Central Europe (e.g., Poland, Czech Republic, and Estonia),

Latin America (e.g., Chile and Mexico), and Asia (e.g., South Korea). BRICS: Brazil, Russia, India, China, and South Korea.

The global LEF pyramids also reveal the regional distribution of capital accumulation measured in environmental accounts, highlighting the LEFs' remarkable shifts from developed economies to less developed economies in recent decades. Such shifts are primarily driven by China's rapid capital accumulation during the recent two decades. Except for forestry extraction, the growths of China's LEFs between 1995 and 2019 were larger than those of four other main emerging economies combined (i.e., the rest of the BRICS countries: Brazil, Russia, India, and South Korea), but the latter will likely exhibit some pattern of expansion as they develop (*11*, *34*). By 2019, China had accrued higher LEFs than any other country in the world since 1970 in all six environmental impact categories we assessed, except for forestry extraction (after the U.S., India, and Japan). Yet, a recent slow-down of the annual increase in China's LEFs indicates that the exponential growth phase may be approaching an end, and China may be approaching developed-world levels and patterns of expansion. The global pyramids also show that the regional distribution of LEFs among the developed economies has stayed relatively stable. Moreover, the general pattern that less developed economies have younger LEFs compared to the developed economies suggests …

In terms of per capita LEFs, however, the widely-known environmental footprint gaps between developed and less developed economies remain and keep widening (**Fig. 2d**). In 2019, the LEF of an average person in the developed economies was 70-530% higher than that of an average person in the developing regions, depending on the environmental impact category. Despite China's remarkable LEF growths in recent decades, the LEFs of an average Chinese remain at 40% or less of the global highest levels in 2019 (GHG emissions: 40%, nonmetallic minerals, iron ore, and copper ore extractions: 23%, air pollution-induced human health damages: 20%, copper ore extraction: 18%, and forestry extraction: 2%). Intuitively, those gaps are consistent with the developed economies' long periods of high capital accumulation and a moderate but continuous expansion in more recent times. Our results reveal such expansions measured in various environmental accounts, on a per capita basis (except for copper ore extraction, **Fig. 2d**). Moreover, the widening of the per capita LEF gaps between developed and less developed economies is most notable in non-metallic mineral extractions, human health damages, and GHG emissions, by 38-48% from 1995 to 2019. Such a trend points to a faster per capita LEF growth in the developed economies and is illustrated by the country-level LEF estimates in GHG emissions (**Fig. 2b**). For example, Norway and Australia had the highest legacy GHG emissions per person in 2019 (143 and 136 tons of CO_2 eq., respectively), which increased by 44 and 45 tons of CO_2 eq. per person from the 1995 level. In comparison, the global average per capita LEF_{GHG}^{2019} is only 34 tons of CO_2 eq. with 14 tons of CO_2 eq. increase since 1995.

The global origins of national capital stocks and LEFs

Global supply chains, from materials to production and distribution, are of growing importance for building up capital stocks in both the developed and less developed economies. While construction of buildings and infrastructure relies primarily on non-metallic minerals sourced locally, the markets for machinery, equipment, and vehicles are truly global, resulting in considerable material extractions and waste emissions beyond the national borders (**Fig. 3**). At the country level, the overseas implications of national LEFs are particularly significant in the case of the metal ores, and sometimes even exclusive, owing to the uneven distribution of the mines in the world, while the lowest for non-metallic minerals which are of widespread occurrence (see Extended Fig. x). This pattern also reflects the situation of manufactured products more broadly (*35*) and led to an increasing reliance on overseas resource extractions (except forestry) and GHG emissions.

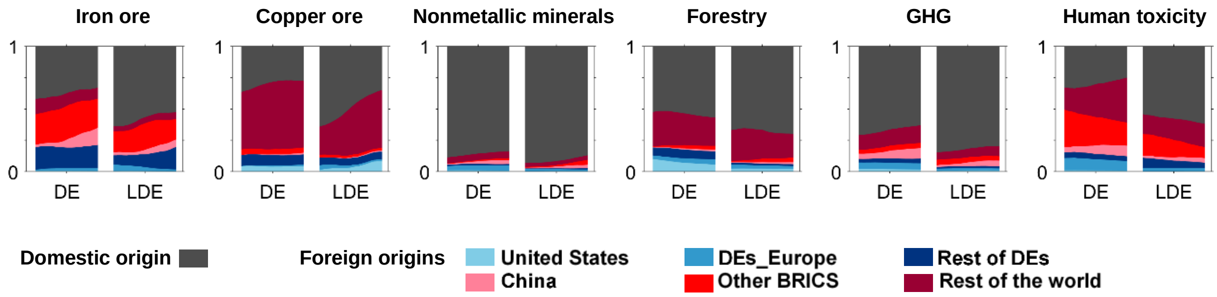


Figure 3. The global environmental consequences of capital accumulation. For the capital stock in developed economies (DE) and developing economies (i.e., less developed economies) in 2019, respectively, the fraction of non-domestic origins of legacy material extractions, GHG emissions, and human toxicity impacts. Compositions of the foreign origins are color-coded the same as in **Figure 1**.

Our results show developing economies' high and increasing importance in being the overseas materials suppliers for capital accumulation in both developed and less developed economies, especially the former. Country-level estimates in Extended Fig. x further highlighted those with the highest overseas reliance and the main origins of the overseas impacts, which are dominated by developed economies and less developed economies, respectively. Two developing regions, 'Rest of America' (i.e., all Northern and Southern American countries except the U.S., Canada, Brazil, and Mexico) and 'Rest of Asia and Pacific' (i.e., all countries in the region except China, Japan, South Korea, Indonesia, and Australia) supplied 32% and 10%, respectively, of the copper ores accrued in the developed economies' capital stock between 1970 and 2019. They are also the most important foreign sources for capital development in other less developed economies; those external supplies accounted for 28% and 10% of the copper ores underlying the capital stocks in less developed economies by 2019. The significant overseas environmental interventions are not limited to materials demand but are also seen in waste emissions and human health damages. By 2019, 75% of the developed economies' legacy human toxicity impacts occurred overseas, more than 80% of which were in the less developed economies. At the country level, the U.S., Indonesia, and Australia had the highest overseas health impacts in less developed economies, amounting to 75%-89% of the national LEFs in 2019. Attributing the capital stocks in developed economies in 2019 to an average resident there, the asset ownership entailed 20-60 tons of CO_2 eq. emitted overseas, which accounts for 25-75% of their LEF_{GHG}^{2019}.

Mapping LEFs throughout the global production-consumption system

Capital assets enable production activities in various sectors of an economy, which combine to satisfy final consumption across the world. All economic activities rely on capital stocks and hence the associated LEFs, but not in equal amounts. Based on the legacy GHG emissions of a half-century's investments, from 1970 to 2019, we present the overall emission profile of the built-up capital stock and their linkages to the global economy in 2019 (**Fig. 4a**) and include the profiles of other LEF estimates in Extended Data Figs. x-x. Among the four asset types, 'structures' (including all residential dwellings and non-residential structures) dominate the global LEFs. By 2019, 'structures' account for more than 80% of the legacy GHG emissions and range from 70% (iron ore extraction) to 94% (non-metallic mineral extraction) for the other five environmental impacts, primarily supporting construction, service, and manufacturing production. Focusing on the more-recently generated environmental impacts, machinery and transport equipment that mainly supports manufacturing and service productions also plays a notable role, partly reflecting the shorter lifetime of vehicles and machinery than 'structures'. In developed economies and less developed economies, respectively, they account for over 37% and over 26% of the LEF_{GHG}^{2019} emitted in the 2010s, and the figures rise to over 50% and 30%, respectively, for extraction of the metal ores and human toxicity impacts.

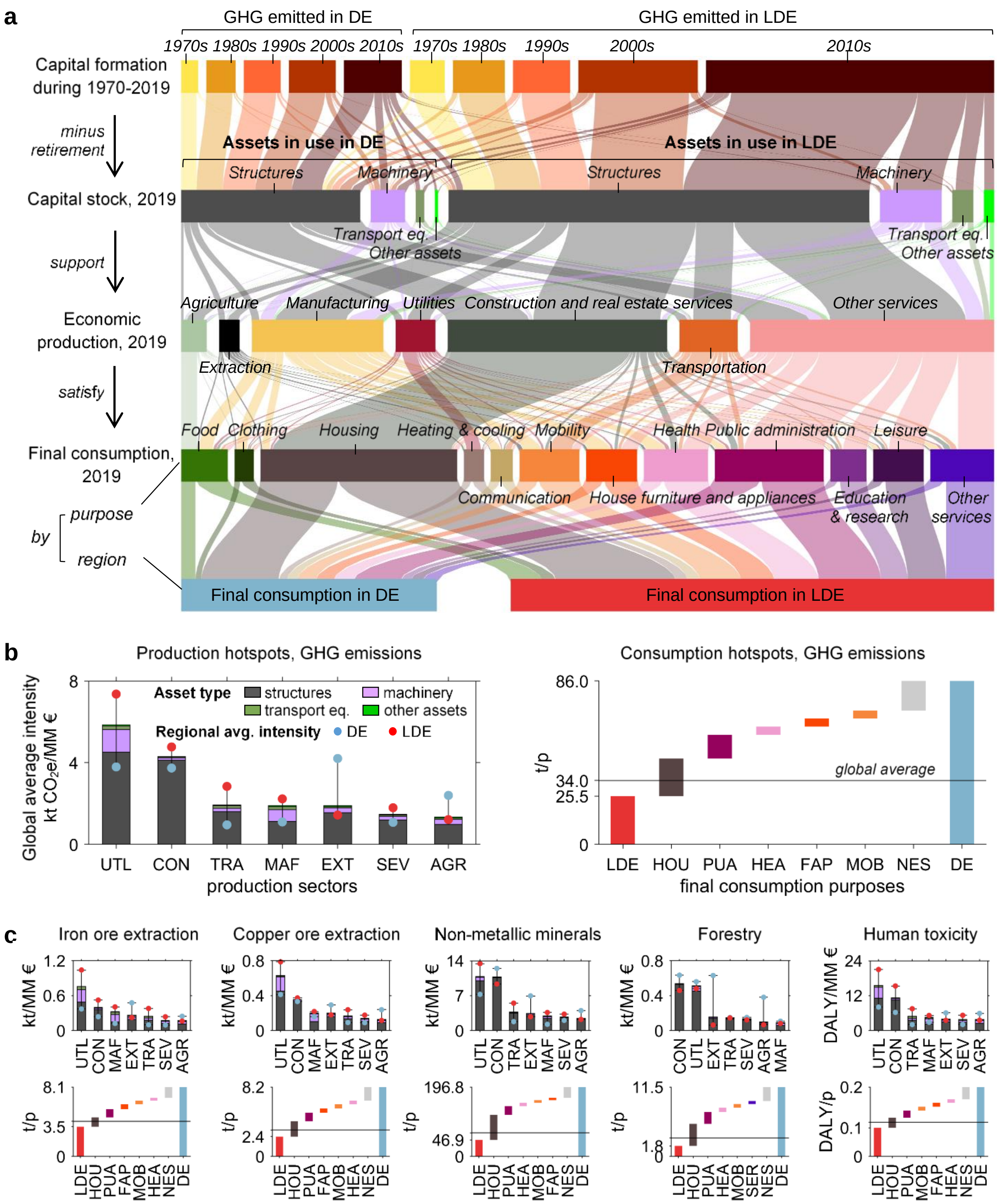


Figure 4. a. The legacy GHG emissions profile of the global value chain in 2019. DE: developed economies; LDE: less developed economies. **b. Production and consumption hotspots suggested by the legacy GHG emissions in 2019.** Seven production activities: AGR =Agriculture; EXT=Extractions; MAF=manufacturing; UTL=utilities; CON=Construction and real estate services; TRA=Transportation and communication services; SER=Other services. Top consumption purposes explaining the largest DE-LDE gaps: HOU=Housing, PUA=Public administration & security, HEA=Health, FAP= House furniture and appliances, MOB= mobility, SER=All services except those individually specified in **a**. NES (i.e., not elsewhere specified)= the rest of the top consumption purposes combined. **c** is the same as **Fig. 4b** except the plots are about the other five environmental categories.

The economywide profiles of the LEFs reveal novel information about where the legacy impact hotspots and associated mitigation leverages lie in the global value chain, from the production and the consumption perspectives (**Fig. 4b-c**). The LEF intensity of production (LEFI), i.e., the LEF per value added of production, enables a comparison of the environmental intensities of the various production activities owing to capital accumulation. Across the seven production activities and between developed economies and less developed economies, LEFI varies in asset composition but more so in magnitude. Globally, construction vies with utilities (e.g., electricity generation) for the highest LEFI in 2019. For the same production activity, LEFI tends to be lower in developed economies than in less developed economies with a few exceptions, such as in extraction activities and agricultural production and concerning forestry extraction.

However, taking the consumption perspective and attributing the ultimate use of assets and associated LEFs to final consumers, per capita LEF is always higher in developed economies than in less developed economies regardless of final consumption purposes or environmental impact categories. The LEF of an average consumer in developed economies in 2019 is 133% (iron ore extraction) to 555% (forestry extraction) higher than that in less developed economies, while final expenditures on housing and public administration explain the largest gaps between the two regions. Moreover, although the significance of each final consumption purpose depends on the environmental impact category and region of interest, the majority of the global LEFs (about 60-70%) are attributable to four main purposes: shelter (including housing, heating & cooling, and house furniture and appliances), public administration and security, health, and mobility.

Prospects following the legacy paths

Future investment and capital stock growth pathways have significant impacts on the climate change trajectories, material demand and security, and other environmental and human health impacts (**Fig.5**). From the production perspective, to support a global economy twice the current size (GDP doubled during 24 years from 1996 to 2019), even a relatively low-intensity path of capital accumulation means further accrument of legacy impacts by substantial amounts: 185 Gt of GHG emissions, 16, 18, and 20 Gt of iron ore, copper ore, and forestry extractions, 372 Gt of non-metallic mineral extractions, and 375 million disability-adjusted life year (DALY) losses. A high-intensity path is anticipated to add another 131 Gt of GHG emissions from the low-intensity path, making it a total of 316 Gt GHG emissions and more than double the current global LEFs across all environmental impact categories, primarily led by new capital asset productions that support service, construction, and manufacturing activities.

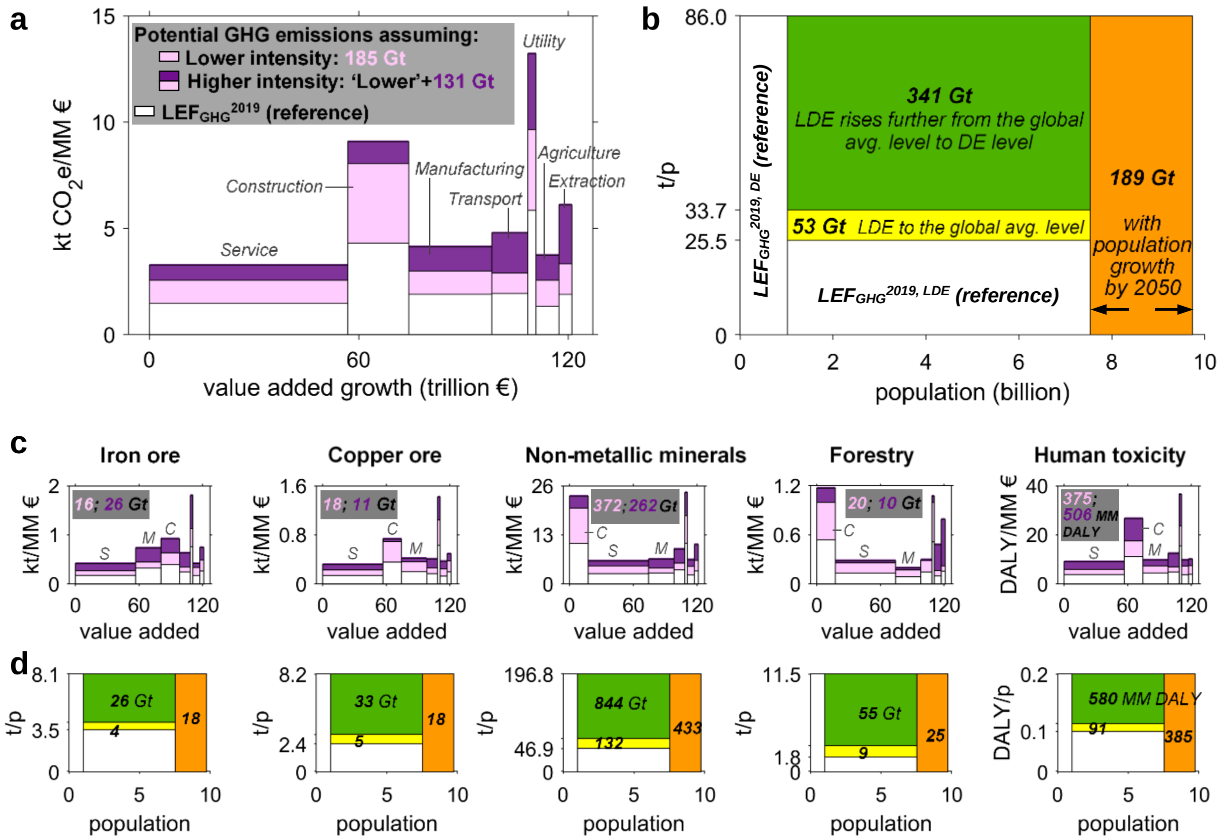


Fig. 5. LEF increases considering different investment and capital stock growth pathways from production and consumption perspectives. a. Potential increases of legacy GHG emissions to support a doubled global economy. The two production-side scenarios reveal the impacts of expanding productions with (i) the lower or (ii) the higher regional $LEFI_{GHG}^{2019}$ shown in **Fig. 4b**. The seven production activities are aligned from left to right according to their total legacy GHG emissions in 2019. **b. Potential increases of legacy GHG emissions to accommodate consumption growth.** Three consumption-side scenarios explore the impacts if the per capita consumption in LDE rises from its 2019 level to the global average level in 2019 (i), further to the high level in DE in 2019 (i), and (iii) accounting for population growth by 2050. **c** is the same as **Fig. 5a** except it illustrates the other five environmental categories. Across the six environmental categories we analyzed, the rank of the production activities from high to low total LEF only differs in the top three places and thus only those are labeled with the initials. **d** is the same as **Fig. 5b** except it illustrates the other five environmental categories.

Fig. 5 also illustrates the high environmental relevance of prospective investment and capital accumulation from the consumption perspective. We need to build up capital stocks to support the rising consumption level anticipated in the less developed economies. Supported by current technologies, global legacy GHG emissions would increase by 53 Gt when consumption in the less developed economies rises to the global average level in 2019. Yet, a globalization of the current consumption in the developed economies means increasing the global legacy GHG emissions by 394 Gt and adding another 189 Gt considering population growth by 2050. As a result of the expected changes in population and income levels, capital accumulation could more than double the global LEF^{2019} in terms of iron ore extraction and human toxicity impacts, and more than triple or quadruple in terms of GHG emissions and the other material extractions.

As such, demand-side measures focusing on the final consumption categories highlighted in **Fig. 4c**, deserve more attention in both regions, but especially in the less developed economies.

Policy implications

Discussion

Resources are required to build capital stock as the wealth of nations increases. As economies emerge, investment comes at high environmental costs, but it also yields substantial improvements in human development. When countries reach high-income status, capital stock growth continues, but the marginal benefit appears to flatten.

There is a significant disparity in the size of the capital stock across countries, reflecting disparities in national wealth and differences in industry structure. High-income countries have acquired more resources and used more of the carbon budget than countries with lower income levels to achieve higher levels of welfare, education, and life expectancy. As capital stock formation requires resources and consumes limited pollution absorption capacity, the further expansion of global capital stock becomes a question of distributive justice.

The capital stock of many industrialized countries has grown beyond what is necessary to achieve a high level of development. Key questions for sustainable development are whether a continued expansion of the capital stock in highly-developed nations is required for economic growth and whether it adds to human development or, via its environmental externalities and competition for scarce resources with developing countries, it impedes such development.

High-income countries often serve as an aspirational model for development for emerging economies. Our work confirms earlier findigs that equipping every person with a Western or Chinese capital stock level would breach the carbon budget. These findings were bottom-up and based on estimates of emissions associated with producing the materials contained in the capital stock; our modeling is more comprehensive.

Without the decarbonization of steel, cement, and electricity production, capital-intensive development endangers the climate. Steel and cement production are seen as hard-to-mitigate, having to rely on substantial investments for novel infrastructure like carbon-capture plants and CO_2 pipelines which take time to install and commercialize. The question hence arises whether decarbonization can be achieved as capital stocks expand further - and whether development can continue without expanding capital stock.

We are not aware of macro-level, empirical studies on the decoupling of human development from capital accumulation. Evidence for such decoupling can obviously only be found if it has already occurred, and it may not have been attempted. However, there is emerging literature of bottom-up studies exploring different strategies to meet human needs through various solutions of service provision. The design of provisioning systems has substantial impacts on the resources required and emissions associated with the initial investment as well as their operation. For example, shelter can be provided with many different structures, and multi-family residential buildings of up to eight floors are more efficient than either high-rises or single-family homes. Specific designs and material choices can further limit the carbon costs of construction without increasing the operational energy requirements. Settlements of a certain density support collective transport, car- and ride-sharing, which are more efficient than relying on individually-owned vehicles. The COVID pandemic has shown that knowledge workers can and likely prefer to work from home at least part of the time, reducing the need for transport and office space, although the increased investment in home offices and larger residences may offset and over-compensate those gains. Still, it indicates that the solution space is larger than previously imagined.

Societies will have to make use of all available options to reduce resource use and emissions if we are to attain just sustainable development. This study shows that pollution and resources associated with past investments were significant and shaped our opportunities for future development in important ways, giving rich countries opportunities to advance human development when resources and pollution adsorbing capacity were less limited. Both the responsibility for past emissions and the advantage conferred by the existing capital stock support the notion that high-income countries have a particular responsibility to reduce emissions and support climate mitigation and adaptation, as stated by the UN Framework Convention on Climate Change and the Paris Agreement.

Our results suggest that similar service levels can be achieved with very different LEF^K*s*. This suggests that other developing countries do not need to follow China's rapid investment-driven, capital accumulation growth model to realize high levels of HDI. It also means that high-income countries should halt the emissions-intensive expansion of their capital stock until zero-carbon technologies are in place.

Developing countries are building up their capital stock, and China has caught up with the industrialized countries. There is, however, a significant potential for other countries to expand their capital stock. While some analyses have suggested a leveling off of capital accumulation in material terms, our research indicates that even in rich countries, the supply of manufacturing capital continues to expand, albeit at a slower rate. China's capital stock is substantially younger than the capital stock of industrialized countries.

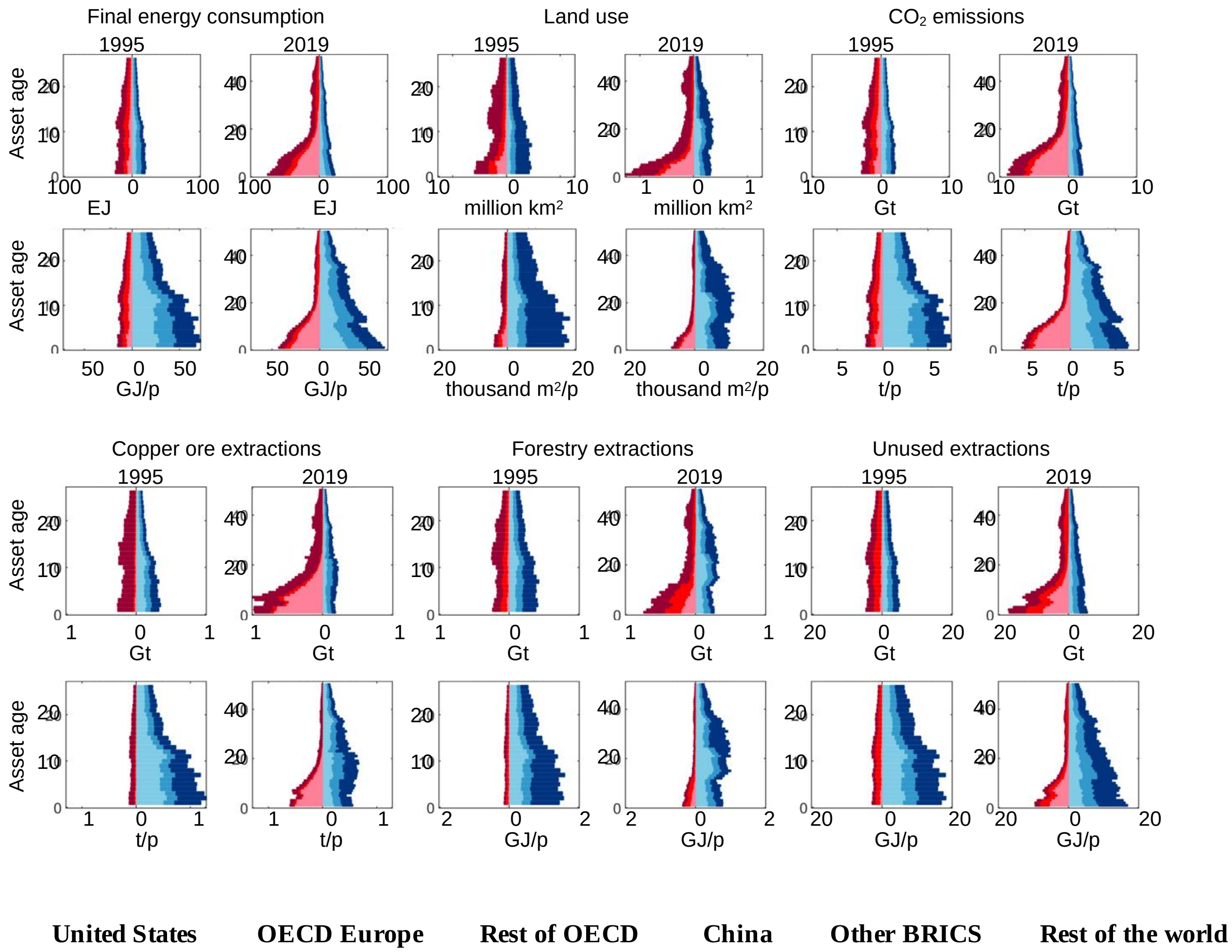
References

1. W.-Q. Chen, T. Graedel, In-use product stocks link manufactured capital to natural capital. *Proceedings of the National Academy of Sciences* **112**, 6265-6270 (2015).
2. N. G. Mankiw, M. P. Taylor, *Economics*. (Cengage Learning EMEA, 2014).
3. C. W. Cobb, P. H. Douglas, A theory of production. *The American Economic Review* **18**, 139-165 (1928).
4. S. Thacker *et al.*, Infrastructure for sustainable development. *Nature Sustainability* **2**, 324-331 (2019).
5. P. Matson, W. C. Clark, K. Andersson, *Pursuing sustainability: a guide to the science and practice*. (Princeton University Press, 2016).
6. N. Ameli *et al.*, Higher cost of finance exacerbates a climate investment trap in developing economies. *Nature Communications* **12**, 1-12 (2021).
7. J.-F. Mercure *et al.*, Reframing incentives for climate policy action. *Nature Energy* **6**, 1133-1143 (2021).
8. S. Polasky *et al.*, Inclusive wealth as a metric of sustainable development. *Annu Rev Env Resour* **40**, 445-466 (2015).
9. S. Polasky *et al.*, Role of economics in analyzing the environment and sustainable development. *Proceedings of the National Academy of Sciences* **116**, 5233-5238 (2019).

10. F. Krausmann *et al.*, Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences* **114**, 1880-1885 (2017).
11. D. Wiedenhofer *et al.*, Prospects for a saturation of humanity's resource use? An analysis of material stocks and flows in nine world regions from 1900 to 2035. *Global Environmental Change* **71**, 102410 (2021).
12. C.-J. H. Södersten, R. Wood, E. G. Hertwich, Endogenizing capital in MRIO models: the implications for consumption-based accounting. *Environmental science & technology* **52**, 13250-13259 (2018).
13. P. Berrill, T. R. Miller, Y. Kondo, E. G. Hertwich, Capital in the American carbon, energy, and material footprint. *Journal of Industrial Ecology* **24**, 589-600 (2020).
14. Q. Ye *et al.*, Linking the Environmental Pressures of China's Capital Development to Global Final Consumption of the Past Decades and into the Future. *Environmental science & technology* **55**, 6421-6429 (2021).
15. Z.-M. Chen *et al.*, Consumption-based greenhouse gas emissions accounting with capital stock change highlights dynamics of fast-developing countries. *Nature communications* **9**, 3581 (2018).
16. C.-J. Södersten, R. Wood, T. Wiedmann, The capital load of global material footprints. *Resources, Conservation and Recycling* **158**, 104811 (2020).
17. D. Müller *et al.*, Carbon Emissions from Infrastructure Development. Nat. *Clim. Change* **2103**, (2013).
18. S. Deetman, S. Pauliuk, D. P. Van Vuuren, E. Van Der Voet, A. Tukker, Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. *Environmental science & technology* **52**, 4950-4959 (2018).
19. United Nations. (2017).
20. M. Vardon, J.-P. Castaneda, M. Nagy, S. Schenau, How the System of Environmental-Economic Accounting can improve environmental information systems and data quality for decision making. *Environmental science & policy* **89**, 83-92 (2018).
21. A. Tukker *et al.*, Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. *Global Environmental Change* **40**, 171-181 (2016).
22. T. Wiedmann, M. Lenzen, Environmental and social footprints of international trade. *Nature Geoscience* **11**, 314 (2018).
23. M. Lenzen *et al.*, Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability*, 1-10 (2021).
24. Z. Xu *et al.*, Impacts of international trade on global sustainable development. *Nature Sustainability* **3**, 964-971 (2020).
25. D. W. O'Neill, A. L. Fanning, W. F. Lamb, J. K. Steinberger, A good life for all within planetary boundaries. *Nature sustainability* **1**, 88-95 (2018).
26. J. Liu *et al.*, Framing sustainability in a telecoupled world. *Ecology and Society* **18**, (2013).
27. D. Guan *et al.*, Global supply-chain effects of COVID-19 control measures. *Nature human behaviour* **4**, 577-587 (2020).
28. D. Tong *et al.*, Committed emissions from existing energy infrastructure jeopardize 1.5 C climate target. *Nature* **572**, 373-377 (2019).
29. E. Peter, K. Sivan, L. Michael, T. Kevin, Assessing carbon lock-in. *Environ. Res. Lett* **10**, 084023 (2015).
30. V. Fisch-Romito, C. Guivarch, F. Creutzig, J. C. Minx, M. W. Callaghan, Systematic map of the literature on carbon lock-in induced by long-lived capital. *Environmental Research Letters* **16**, 053004 (2021).

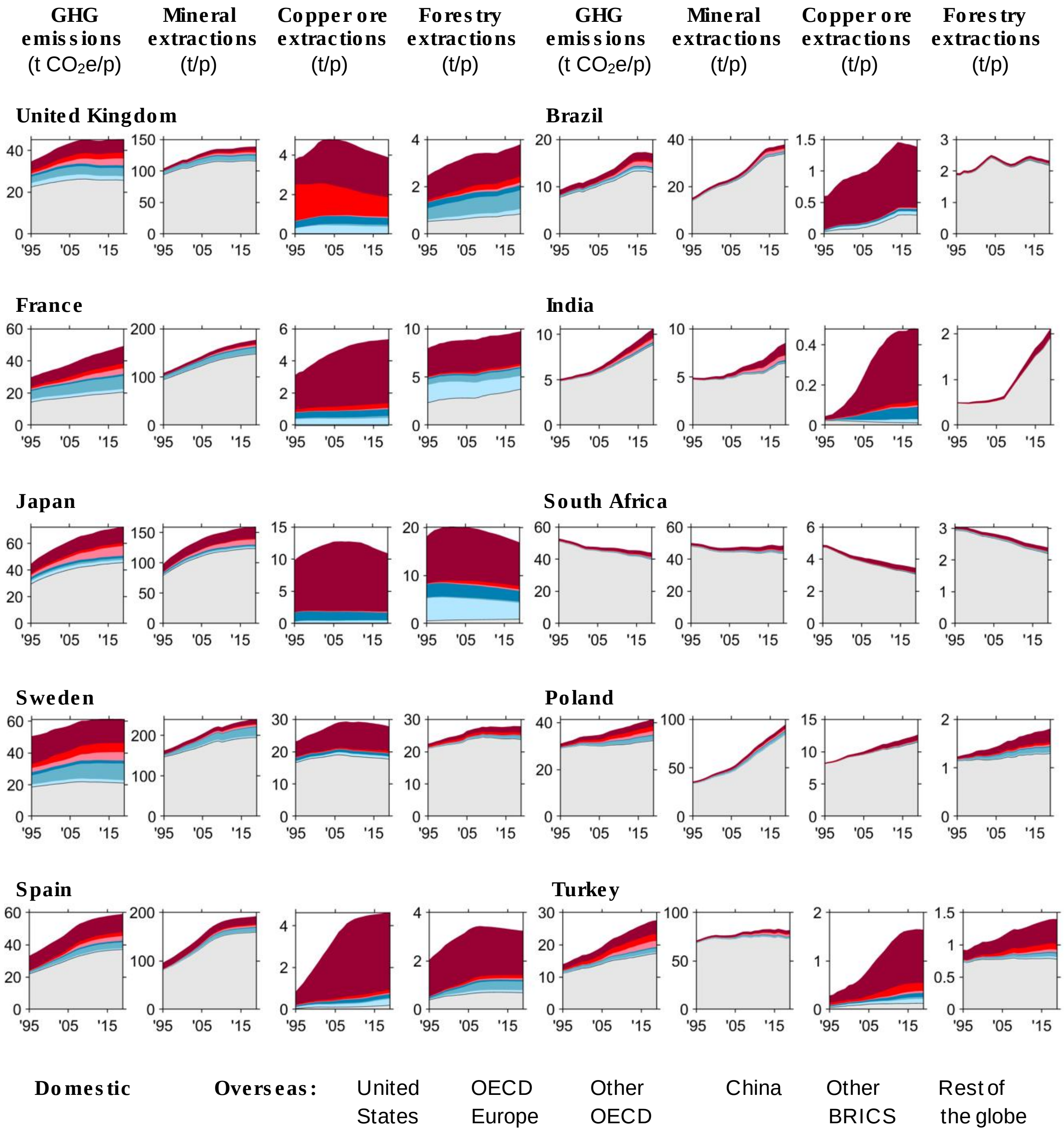
31. D. Usher, D. Usher, *The measurement of capital*. (University of Chicago Press Chicago, 1980).
32. K. J. Arrow, P. Dasgupta, L. H. Goulder, K. J. Mumford, K. Oleson, Sustainability and the measurement of wealth. *Environment and Development Economics* **17**, 317-353 (2012).
33. The World Bank, World Development Indicators.
34. T. Fishman, H. Schandl, H. Tanikawa, Stochastic analysis and forecasts of the patterns of speed, acceleration, and levels of material stock accumulation in society. *Environmental science & technology* **50**, 3729-3737 (2016).
35. E. G. Hertwich, Carbon fueling complex global value chains tripled in the period 1995–2012. *Energy Economics* **86**, 104651 (2020).

Extended data

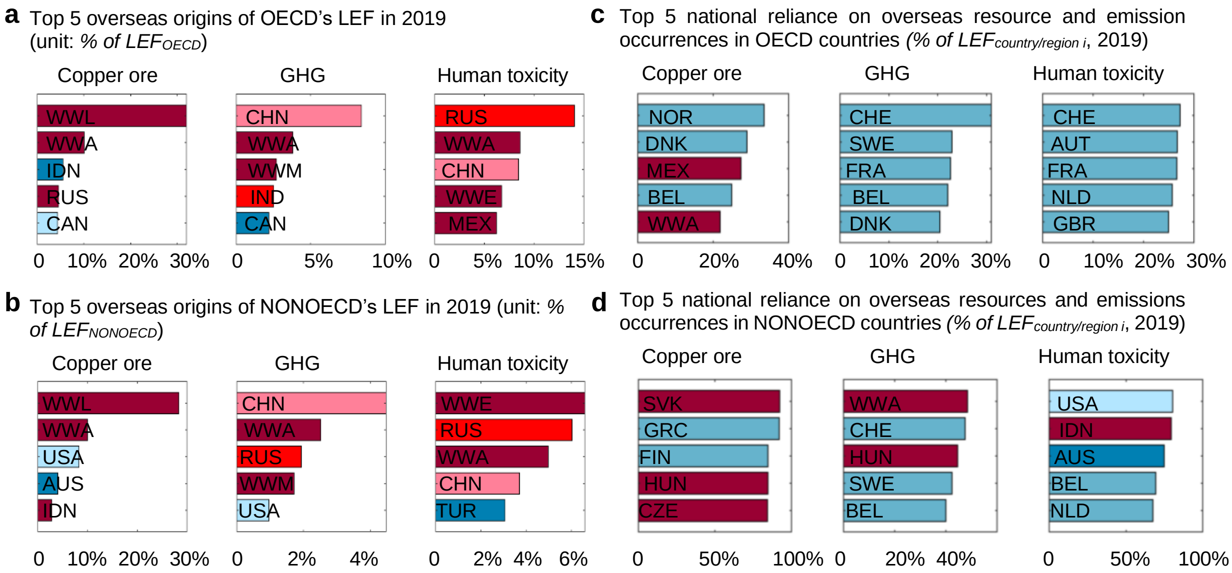


Extended Data Figure 1. **Historical final energy consumption, land use, CO_2 emissions, copper ore extractions, forestry extractions, and unused material extractions underlying the capital stocks in 1995 and 2015**. Bar length: asset stocks are measured as the quantity of emissions or material extractions that occurred along the production supply chains of the assets. Bars are colored by the regions where the asset stocks were located in 1995 and 2019. For both years, the assets inflow started in 1970 (see Methods). OECD (Non-OECD): countries in (outside) of the Organisation for Economic Co-operation and Development in

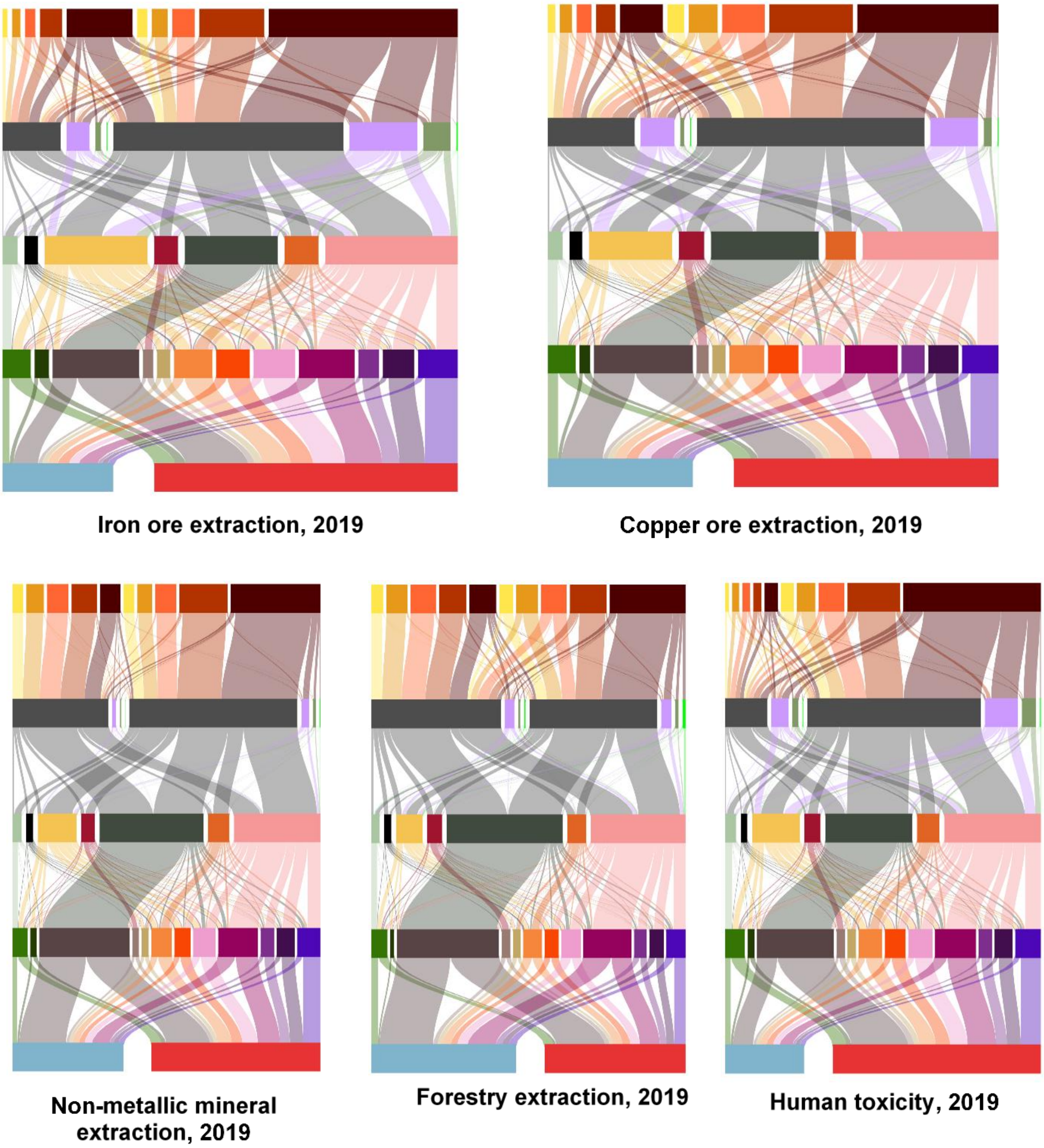
1990. OECD-1990 includes the 20 founding countries of OECD and Japan, Finland, Australia, and New Zealand. They do not include later members that joined during OECD's enlargement to Central Europe (e.g., Poland, Czech Republic, and Estonia), Latin America (e.g., Chile and Mexico), and Asia (e.g., South Korea). The first and second row plots show the regional total and per capita estimates, respectively. Regional totals and sub-regional split indicate regional shares in the total, whilst per capita estimates reflect regional distribution on a per capita basis.



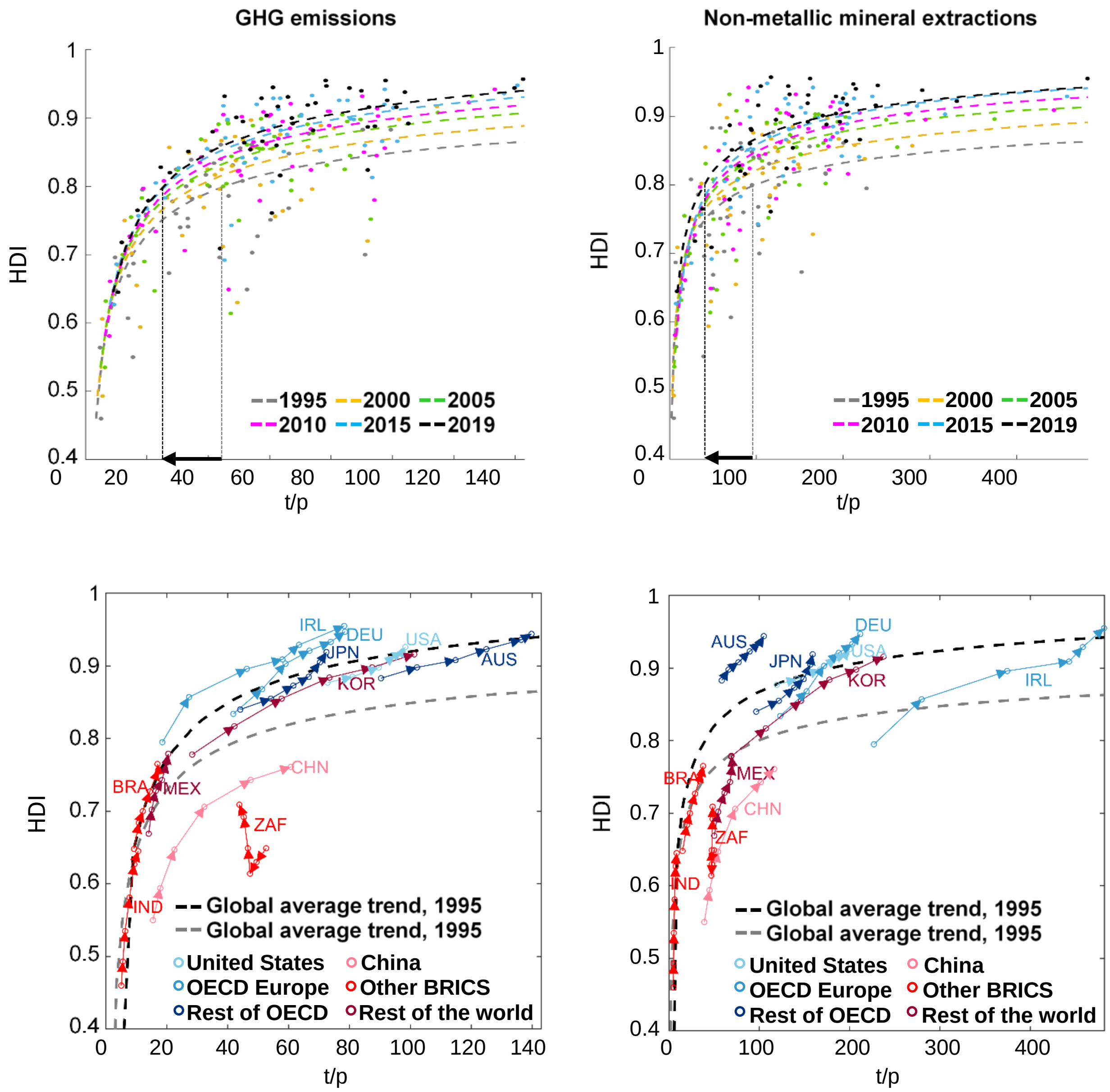
Extended Data Figure 2. LEF development of additional selected developed countries (left) and developing countries (right) distinguishing regions where environmental impacts occurred. In each subplot, years along the x-axis indicate when asset stocks were assessed; LEF is plotted along the y-axis, color-coded by region of emissions or resource extraction.



Extended Data Figure 3. **a,** Zoom into the top countries contributing to OECD's high foreign supplies shown**, b,** Same as **a** but show the top countries contributing to Non-OECD's overseas supplies**. c.** nations whose LEFs had the highest shares of overseas occurrences in OECD, indicating high reliance and impacts on OECD's natural resources and waste emissions. **d.** Same as **c** but show those with high reliance on Non-OECD countries. The top countries are color-coded based on the same regional classifications as in Fig. 1. 'WW' indicate the 5 'rest of the world' regions which are aggregates of the countries not individually specified in Exiobase: WWA (Rest of Asia and Pacific), WWL (Rest of America), WWE (Rest of Europe), WWF (Rest of Africa), and WWM (Rest of the Middle East).



Extended Data Figure 4. Sankey diagrams for the other five environmental categories.



Extended Data Figure 5. Coupling of capital stock GHG footprints with human development goals: global time trend by decade