a nectar-funded project

GLORIA MRIO database Release 059a

Release date: 8 August 2024

Authors: Manfred Lenzen and Mengyu Li, ISA, The University of Sydney

This database has been created in the Global MRIO Lab – a branch of the NeCTAR Industrial Ecology Virtual Laboratories (*IELabs*, NeCTAR 2013; Lenzen *et al.* 2014a; Geschke and Hadjikakou 2017) – by a collaboration between the University of Sydney, the CSIRO, Wirtschafts-Universität Wien, and UNSW Sydney.

Any use of this database must be acknowledged by citing

- Lenzen, M., A. Geschke, M.D. Abd Rahman, Y. Xiao, J. Fry, R. Reyes, E. Dietzenbacher, S. Inomata, K. Kanemoto, B. Los, D. Moran, H. Schulte in den Bäumen, A. Tukker, T. Walmsley, T. Wiedmann, R. Wood and N. Yamano (2017) The Global MRIO Lab - charting the world economy. *Economic Systems Research* **29**, 158-186.

- Lenzen, M., A. Geschke, J. West, J. Fry, A. Malik, S. Giljum, L.M.i. Canals, P. Piñero, S. Lutter, T. Wiedmann, M. Li, M. Sevenster, J. Potočnik, I. Teixeira, M.V. Voore, K. Nansai and H. Schandl (2021) Implementing the Material Footprint to measure progress towards SDGs 8 and 12. *Nature Sustainability*, https://doi.org/10.1038/s41893-021-00811-6.

Suggested wording: *We used Release 059a of the GLORIA global environmentally-extended multi-region input-output (MRIO) database (Lenzen et al. 2021), constructed in the Global MRIO Lab (Lenzen et al. 2017).*

Please note that this Release Note, the accompanying ReadMe file, and the Standard Diagnostics Reports supersede the Technical Documentation available on the Industrial Ecology Lab[1] and SCP-HAT[2] websites.

Table of contents

Funding: MRIO research leading to the GLORIA database has received funding from the United Nations Environment Programme (UNEP) through the UN Life-Cycle Initiative, the One Planet Network and the International Resource Panel (IRP) in the context of the development of the Sustainable Consumption and Production Hotspot Analysis Tool (SCP-HAT) and the IRP Metrics, Data and Indicators for Sustainable Resource Use workstream via the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia and the Vienna University of Economics and Business, Austria; and from the Australian Research Council through its Discovery Project grants DP0985522, DP130101293, DP190102277, DP200103005 and DP200102585; as well as through its Large Infrastructure, Equipment and Facilities (LIEF) grant LE160100066; and through the National eResearch Collaboration Tools and Resources project (NeCTAR) through its Industrial Ecology Virtual Laboratory VR201. The creators thank Sebastian Juraszek for expertly managing their advanced computation requirements.

Contact: About monetary tables, GHG and employment satellites, please contact Manfred Lenzen (manfred.lenzen (at) sydney.edu.au). About remaining satellites, please contact Stephan Lutter (stephan.lutter (at) wu.ac.at) and Stefan Giljum (stefan.giljum (at) wu.ac.at).

[1] https://ielab.info/app/site/media/documents/Technical%20Documentation_GLORIA_20210913.pdf.
[2] http://scp-hat.lifecycleinitiative.org/wp-content/uploads/2021/11/Technical-Documentation_GLORIA_20210913.pdf.

Summary of changes from Release 055

- **National input-output, UN Comtrade and UN Main Aggregates data update to 2021, and forecast of all tables starting 2022 until 2028**, based on GDP projections by the International Monetary Fund (IMF 2023) and the World Bank (World Bank 2023a), capturing developments caused by the Ukraine war;
- **Benchmarking** of GLORIA household expenditure on food items on **FAOSTAT Food Balances** (FAOSTAT 2022), via detailed matching with primary data on per-capita **dietary energy, protein, fat and carbohydrate** intake, for all countries;
- Inclusion of GLORIA **commodity price estimates for 1990-2019**, based on UN Comtrade (UNSD 2022c) and FAOSTAT producer prices (FAOSTAT 2019) databases, and converted into GLORIA regional and sectoral classifications;
- Update of greenhouse gas emissions and air pollution satellites to adhere to the **EDGAR** 7.0 database for greenhouse gases and the EDGAR 6.1 database for air pollution; casting of emissions satellite in EDGAR categories;
- Alignment of "Compensation of Employees" (wages and salaries) in the value added block with the employment satellite, using data from the International Labour Organisation (ILO 2022) to produce **estimates for per-worker wage, female labour participation and percentage of wages in value added** over time;
- Incorporation of **additional UN National Accounts Official Country data**, including data on intermediate demand, and on sectorally-disaggregated household consumption and value added, especially for non-OECD low-income countries;
- Extrapolation of OECD ICIO data to 1990 and 2028 to avoid sudden breaks; smoothing of OECD ICIO data with a moving-average window of 10 years;
- **Outlier removal** in MRIO and footprint data[3]; **mirroring** of negative 'Changes in inventories' as positive 'Consumption of fixed capital' in value added, to avoid negative total output and negative Leontief multipliers.
- Correction of concordances and allocation of EDGAR emissions data to economic sectors[4], correction of intermediate coefficients for the energy-steel nexus and value added of mining and utilities sectors[5], and improvement of reconciliation convergence, with a focus on simultaneous Main Aggregates and IO balance[6]; and
- Minor corrections: i) EDGAR greenhouse gas emissions and air pollution satellites for hospitality sectors; ii) misallocations in the GLORIA-HSCPC concordance; iii) enabling of fractional engineering constraints[7].
- <u>Change from Release 059</u>: Ensuring adding-up of emissions sub-total categories to totals; non-zero emissions estimates for construction sectors; inclusion of marine eutrophication and nitrogen satellites.

[3] Thanks to researchers from Rabobank for pointing out variabilities in Release 057.
[4] Thanks to researchers from EBP Schweiz for pointing out inconsistencies to us.
[5] Thanks to researchers from UNSW Sydney for pointing out misallocations due to aggregation errors, and to researchers from the World Bank, Washington D.C., for production recipe data.
[6] Thanks to researchers from the Universidad de Castilla-La Mancha for pointing out imbalances.
[7] Based on estimates from Jim West, CSIRO, Canberra.

Deposited files

i) **General information**: All region, sector, value added and final demand labels, a schematic of GLORIA's general multi-region supply-use table (MR-SUT) structure, a list of region-sector labels, as well as a concordance between GLORIA and ISIC Rev. 4 can be found in the Release file GLORIA_ReadMe.xlsx.
GLORIA's **region-sector sequence** is

- Region 1 industry 1
- …
- Region 1 industry 120
- Region 1 product 1
- …
- Region 1 product 120
- Region 2 industry 1
- …
- Region 2 industry 120
- Region 2 product 1
- …
- Region 2 product 120
- …
- …
- …
- Region 164 industry 1
- …
- Region 164 industry 120
- Region 164 product 1
- …
- Region 164 product 120

GLORIA's **MR-SUT structure** is[8]

		region1						region2					
		industry 1	industry 2	industry 3	product 1	product 2	product 3	industry 1	industry 2	industry 3	product 1	product 2	product 3
region 1	industry 1				x								
	industry 2		0			SUPPLY			0			0	
	industry 3						x						
	product 1	x	x	x				x	x	x			
	product 2	x	DOMESTIC USE	x		0		x	INTERNAT'L TRADE	x		0	
	product 3	x	x	x				x	x	x			
region 2	industry 1										x		
	industry 2		0			0			0			SUPPLY	
	industry 3												x
	product 1	x	x	x				x	x	x			
	product 2	x	INTERNAT'L TRADE	x		0		x	DOMESTIC USE	x		0	
	product 3	x	x	x				x	x	x			

[8] Thanks to Nieke Aerts from Statistics Netherlands for the MR-SUT schema.

ii) **GLORIA Multi-region input-output (MRIO) database,** in units of current '000 US$, 164 regions, 120 sectors each, supply-use transactions **T**, final demand **Y**, value added **v**, 5 valuations (basic prices, trade margins, transport margins, taxes on products, subsidies on products), continuous time series for 1990-2028.
Files: YYYYMMDD_120secMother_AllCountries_002_VAR-Results_YYYY_059_Markup00M(full).csv, with VAR = {T,Y,V} being supply-use transactions (**T**), final demand (**Y**) and value added (**v**), and M = 1,…,5 being valuations.
Note I: Transaction and satellite tables are sized 164 × (120×2) = 39,360 region-sector pairs, because of the supply-use format. For all labels and the MR-SUT structure, please consult the documentation file GLORIA_ReadMe.xlsx.
Note II: Monetary data satisfy the National Accounting Identity (compare UNSD 2018, §2.12) relating income- and expenditure-side GDP:
Intermediate inputs (including imports) at basic prices
+ Gross value added at basic prices
+ Taxes less subsidies on products (including imports)
= Intermediate output at basic prices (including exports)
+ Final consumption at basic prices
+ Gross fixed capital expenditure at basic prices.

iii) Accompanying **standard deviations**, same dimensions as transaction matrices.
Files: YYYYMMDD_120secMother_AllCountries_002_VAR-RsltSTDDEV_YYYY_059_Markup00M(full).csv, with VAR = {T,Y,V} being supply-use transactions (**T**), final demand (**Y**) and value added (**v**), and M = 1,…,5 being valuations.

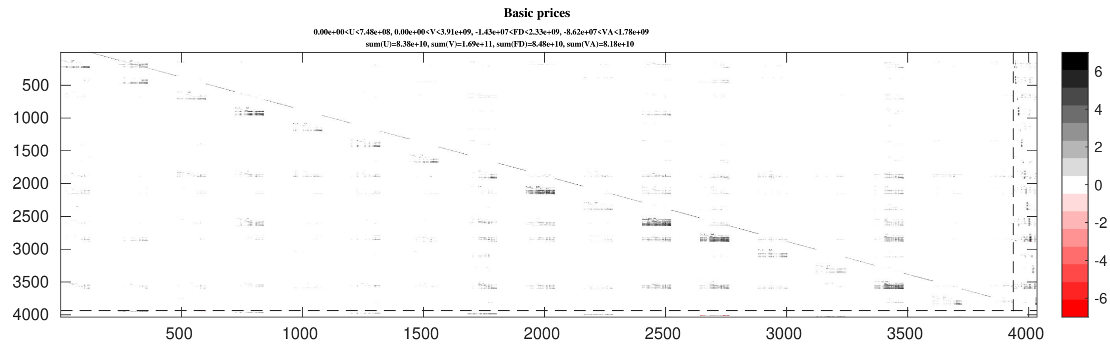
iv) Accompanying **satellite accounts (extensions)**, covering GHG emissions, materials, energy, air pollution, land use, water use, biodiversity, skills and employment.
Files: YYYYMMDD_120secMother_AllCountries_002_TQ-Results_YYYY_059_Markup00V(full).csv and *YYYYMMDD_120secMother_AllCountries_002_YQ-Results_YYYY_059_Markup00V(full).csv*, with TQ being the intermediate satellite block (matching intermediate transactions **T**), and YQ the final satellite block (matching final demand **Y**).

v) **GLORIA commodity prices,** in units of current US$/kg, 164 regions, 1990-2021.
Files: YYYYMMDD_120secMother_AllCountries_002_Prices_YYYY_059_Markup001(full).csv.
Note: Price tables are sized 164 regions × 120 sectors. For all labels and the MR-SUT structure, please consult the documentation file GLORIA_ReadMe.xlsx.

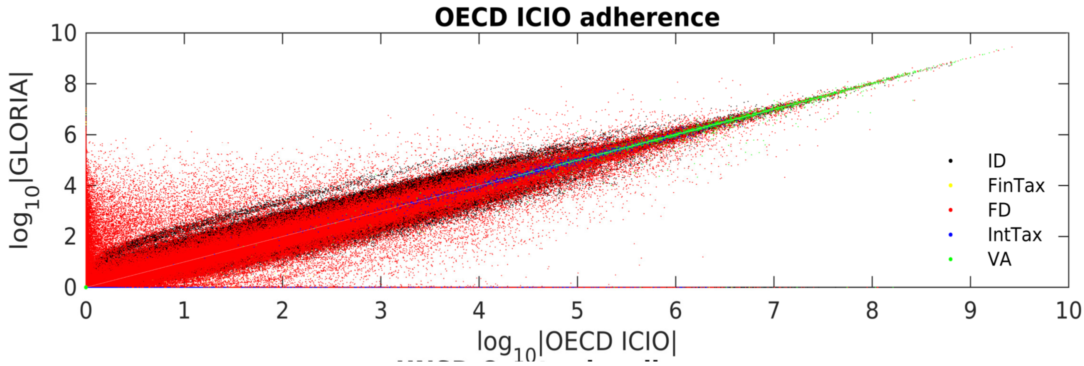
vi) **GLORIA footprint trends**, 1990-2021, for all satellites mentioned under iv).
Files: GLORIA_Footprints_SAT_trends.pdf, with SAT standing for GHG emissions, materials, energy, air pollution, land use, water use, biodiversity, skills or employment.
Note III: To avoid negative footprint values caused by negative changes in inventories, a mirroring operation can be applied. See Supplementary Information of Lenzen et al. 2021a, Section SI3.3 (https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-021-00811-6/MediaObjects/41893_2021_811_MOESM1_ESM.pdf). Trends feature isolated spikes that are mostly due to missing or spikey data (see an example for Ireland on page 9 below).
Note IV: Trade trends (central column of panels) are shown at points of extraction (exports and imports by indicator, and exports by commodity) and at points of final sale (imports by commodity, and exports and imports by final demand destination), therefore the central column of graphs differ correspondingly.

vii) **Footprint standard deviation trends**, 1990-2021, obtained using Monte-Carlo techniques, for all satellites mentioned under 0.
Files: GLORIA_Footprints_SAT_SD_trends.pdf, with SAT standing for GHG emissions, materials, energy, air pollution, land use, water use, biodiversity, skills or employment.

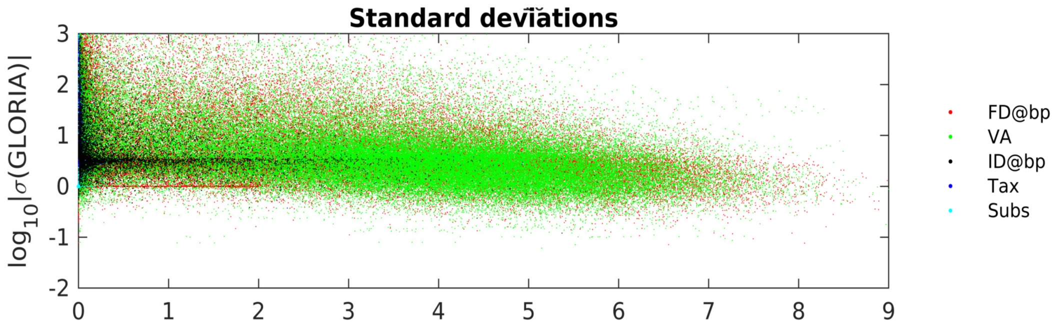
viii) Accompanying **diagnostics** for each year, i) MRIO heat maps, including totals, minima and maxima for **T**, **Y** and **v**; ii) MRIO Diagnostics graphs: rocket plots comparing GLORIA MRIO data with UN SNA Main Aggregates and Official Country National Accounts, OECD ICIO, FAO/UNIDO FAO/Fish/MIN/IND-STAT, and UN Comtrade and ServiceTrade data; engineering exclusions adherence histogram; IO balance adherence, standard deviations range; iii) FAOSTAT food balance adherence plots for every country and year; iv) GLORIA vs UN SNA United Nations SNA Main Aggregates comparison data table.
File: GLORIA_StandardDiagnosticsReport_YYYY.pdf
Note V: For those wishing to manually check the IO balance adherence, please consider the National Accounting Identity in point ii) above, and incorporate mark-ups 4 and 5 into your calculations.



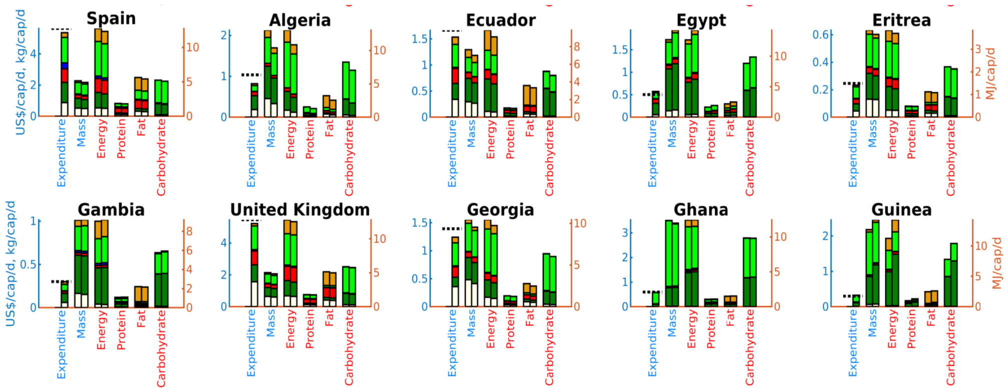
Example heat map (logarithmic colour scale).



Example rocket plot showing adherence to OECD ICIO data.

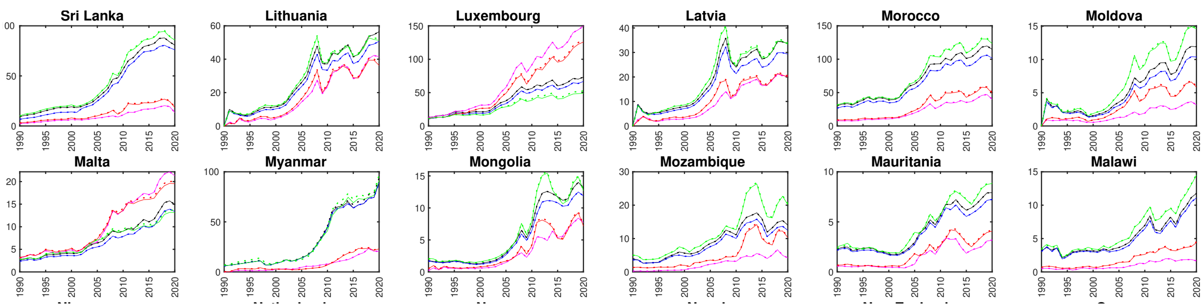


Example standard deviations hockey plot.



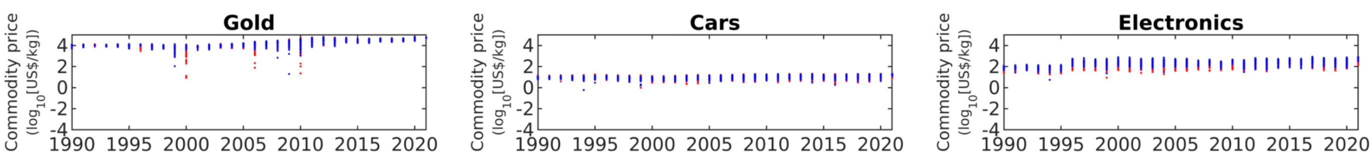
Excerpt from food balance adherence histograms. Left columns FAOSTAT, right columns GLORIA; expenditure is not available in FAOSTAT; it is instead benchmarked on UN National Accounts Official Country data (dashed line).

ix) Visual **comparison of GLORIA aggregates** (GDP, value added, imports, exports, labour wages; sectoral value added) with corresponding values in the United Nations Main Aggregates database and the ILO labour database; additional temporal stability comparison with Release 057. *File: GLORIA_trend_macrocomparison.pdf.*



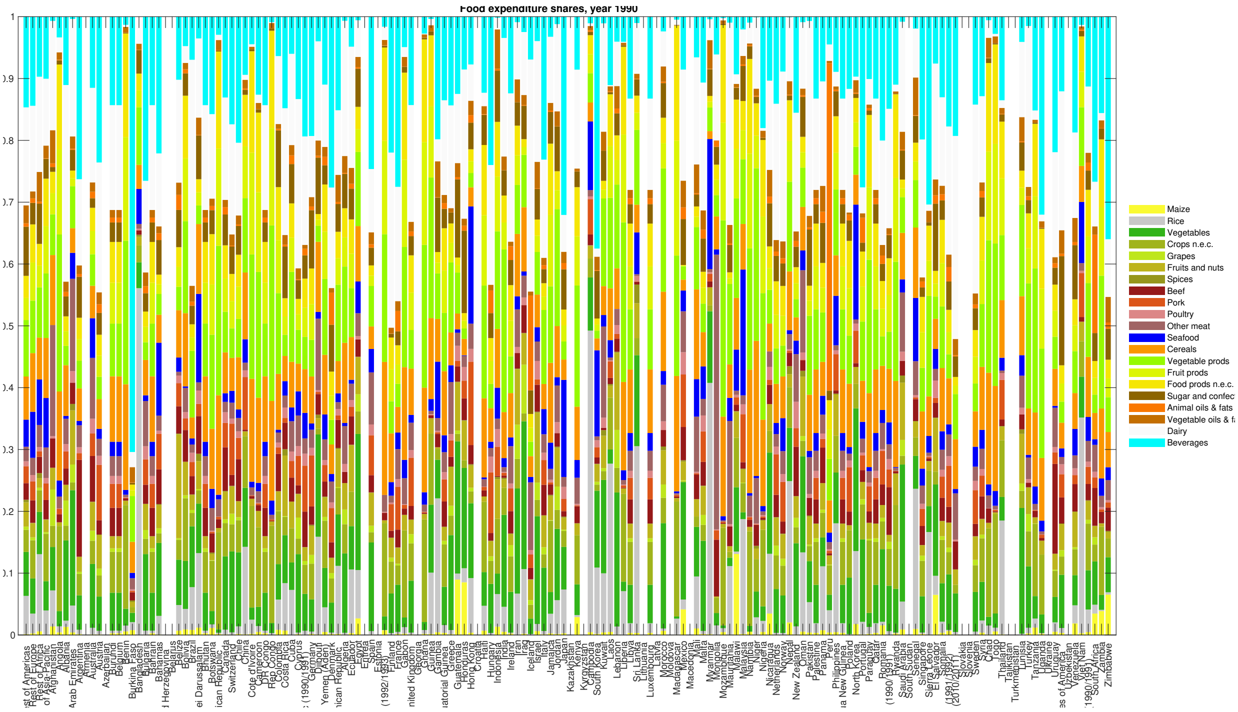
Excerpt from the GLORIA – UN Main Aggregates comparison.
UN Main Aggregates solid lines, GLORIA dashed lines.

x) **Price data visualisations**
File: GLORIA_StandardDiagnosticsReport_PriceData.pdf



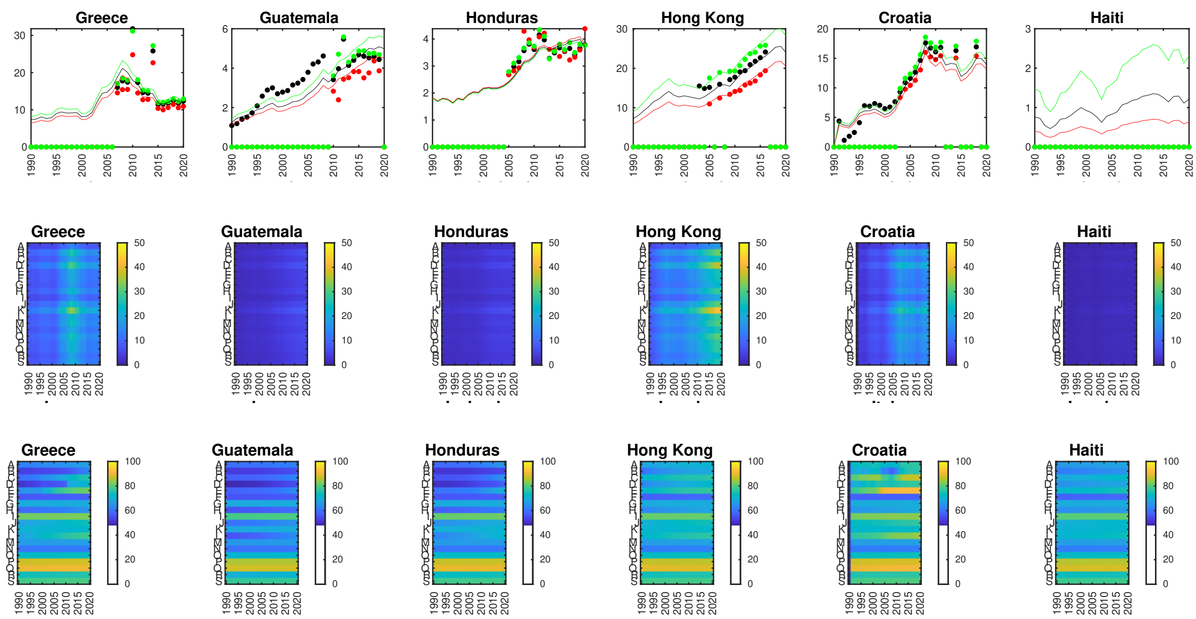
xi) Nutrition and food data visualisations

File: GLORIA_StandardDiagnosticsReport_FoodData.pdf



xii) Income and employment data visualisations

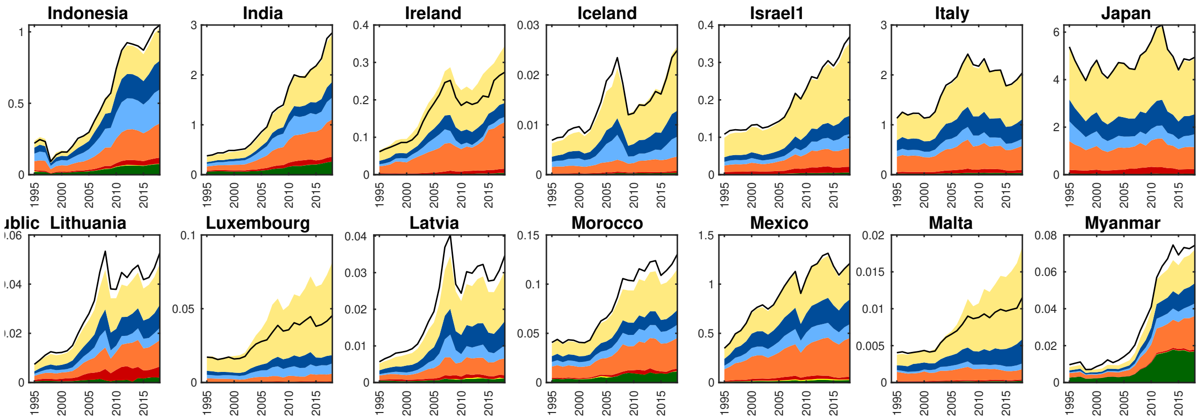
File: GLORIA_Diagnostics_labour&wages.pdf



Comparison of using data from the International Labour Organisation (ILO 2022) and regression estimates for per-worker wage (top and middle row), female labour participation (bottom row) and percentage of wages in value added over time.

xiii) **Graphic data source inter-comparisons**

Files: GLORIA_Diagnostics_OECDICIOvsSNA.pdf, GLORIA_Diagnostics_ComtradeVsSNA.pdf, GLORIA_Diagnostics_STATvsOECDICIO.pdf



Excerpt from the OECD-ICIO – UN Main Aggregates comparison of final demand primary data.

OECD areas (colour legend see *GLORIA_Diagnostics_OECDICIOvsSNA.pdf*), UN Main Aggregates solid black line.

<u>Release notes (over and above changes in prior releases)</u>

- Gaps in Comtrade data were filled by benchmarking against UN SNA Main Aggregates data (see report in *GLORIA_Diagnostics_ComtradeVsSNA.pdf*). UN Comtrade international trade data override OECD ICIO international trade entries.

- Commodity price estimates were taken from the UN Comtrade database and FAOSTAT producer prices database, and then re-classified into the GLORIA regional and sectoral classifications (see report in *GLORIA_Diagnostics_PriceData.pdf*). Missing entries were filled by regional averages, but otherwise the data reflect primary data, including large outliers. In particular, price data are not quality-adjusted (Feenstra and Romalis 2014). These price data are not necessarily fit for estimating price elasticities.

- The above price estimates were used in benchmarking household final consumption in GLORIA with FAOSTAT Food Balances (see report in *GLORIA_Diagnostics_FoodData.pdf*). We calibrated monetary consumption data in the MRIO's final consumption block (first column in **Y**) against food balances on dietary energy and macronutrient intake (FAOSTAT 2022). Because these data are cast in monetary and energy units, respectively, bridging information on dietary energy and macronutrient content and on commodity prices is required. The former is readily available from the USDA National Nutrient Database for Standard Reference (USDA 2019) as energy coefficients (in kJ/100 g) and coefficients for protein, fat and carbohydrate (in g/100 g). Macronutrient coefficients are converted into energy units using mass-specific energy contents (17 kJ/g for protein, 27 kJ/g for fat, and 17 kJ/g for carbohydrates). Price data were generated first by comparing monetary and mass values for international commodity trade by country (UNSD 2022c), then complemented with producer price data on crops, livestock and food items FAOSTAT 2019), and finally smoothed to achieve – for each commodity – a standard deviation across years and regions of about 52%. The latter value results out of an analysis of PPP-to-current-US$ estimates of national GDP for the past 35 years (World Bank 2022). The resulting global prices π_i^r for commodities *i* produced in regions *r* satisfy equivalence between a) food consumption $\sum_{i,r} y_{i1}^{rs}$ as stated in the MRIO table and benchmarked against National Accounts Official Country data (UNSD 2022b), and b) measured per-capita energy and macronutrient balances n^s in consuming regions *s*, as $n^s = \sum_{i,r} \frac{v_i y_{i1}^{rs}}{P^s} \pi_i^{r-1}$ (see Lenzen *et al.* 2021b), where y_{i1}^{rs} is the MRIO entry describing the consumption in region *s* of commodity *i* produced in region *r*, v_i is the energy and macronutrient content of commodity *i* re-classified from data in USDA 2019 into MRIO products by means of a binary concordance matrix, and P^s is the population in region *s* (UNSD 2022a).

- As explained above, shares of household expenditure on food are not available except for countries with household expenditure surveys, and even in those circumstances not for most years. In GLORIA, they are therefore often result of an estimation procedure described in the previous paragraph, involving a range of data sources, such as the nutritional attributes from USDA National Nutrient Database for Standard Reference, FAOSTAT food balances and producer prices, UN Comtrade trade data in mass and value units, purchasing power estimates from the World Bank, and total expenditure of food benchmarks from UN National Accounts Official Country data. Given differences in commodity definitions across these multiple databases, resulting expenditure shares can be uncertain and fluctuate. A few examples for unusual expenditure shares are listed and explained on page 2 of *GLORIA_Diagnostics_FoodData.pdf*.

- Forecasts to 2028 are based only on IMF GDP projections (IMF 2023), engineering constraints and input-output balancing requirements.

- Household expenditure information on 83 low- and middle-income countries (Rest of Africa, Rest of Asia-Pacific, Afghanistan, Albania, Armenia, Azerbaijan, Burundi, Benin, Burkina Faso, Bangladesh, Bulgaria, Bosnia and Herzegovina, Belarus, Bolivia, Brazil, Bhutan, China, Côte d'Ivoire, Cameroon, DR Congo, Rep Congo, Colombia, Djibouti, Egypt, Ethiopia, Gabon, Ghana, Guinea, Gambia, Guatemala, Honduras, Indonesia, India, Iraq, Jamaica, Jordan, Kazakhstan, Kenya, Kyrgyzstan, Cambodia, Laos, Liberia, Sri Lanka, Lithuania, Latvia, Morocco, Moldova, Madagascar, Mexico, Macedonia, Mali, Mongolia, Mozambique, Mauritania, Malawi, Namibia, Niger, Nigeria, Nicaragua, Nepal, Pakistan, Peru, Philippines, Papua New Guinea, Romania, USSR/Russian Federation, Rwanda, Senegal, Sierra Leone, El Salvador, Yugoslavia/Serbia, Chad, Togo, Thailand, Tajikistan, Turkey, Tanzania, Uganda, Ukraine, Viet Nam, Yemen Arab Republic/Yemen, South Africa, Zambia) is included.

- GLORIA's updated emissions satellite incorporates a number of features. First, the row classification replicates IPCC reporting classes, for example

IPCC codes	IPCC description
1A1a	Main Activity Electricity and Heat Production
1A1bc	Petroleum Refining - Manufacture of Solid Fuels and Other Energy Industries
1A1b	Petroleum Refining
1A1ci	Manufacture of Solid Fuels
1A1cii	Other Energy Industries
1A2	Manufacturing Industries and Construction
1A2a	Manufacturing Industries and Construction - Iron and steel
1A2b	Manufacturing Industries and Construction - Non-Ferrous metals
1A2c	Manufacturing Industries and Construction - Chemicals
1A2d	Manufacturing Industries and Construction - Pulp, Paper and Print
1A2e	Manufacturing Industries and Construction - Food Processing, Beverages and Tobacco
1A2f	Manufacturing Industries and Construction - Non-Metallic Minerals
1A2g	Manufacturing Industries and Construction - Transport Equipment
1A2h	Manufacturing Industries and Construction - Machinery
1A2i	Manufacturing Industries and Construction - Mining (excluding fuels) and Quarrying
1A2j	Manufacturing Industries and Construction - Wood and Wood products
1A2k	Manufacturing Industries and Construction - Construction
1A2l	Manufacturing Industries and Construction - Textile and Leather
1A2m	Manufacturing Industries and Construction - Non-specified Industry (ISIC Divisions 25,33,36 and 37)
1A3b	Road Transportation
1A3b_noRES	Road Transportation no resuspension
1A3b_RES	Road Transportation resuspension
1A3a	Civil Aviation
1A3c	Railways
1A3d	Water-borne Navigation
1A3e	Other Transportation
1A4	Other Sectors
1A4a	Other Sectors - Commercial/Institutional
1A4b	Other Sectors - Residential
1A4ci	Other Sectors - Stationary
1A4cii	Other Sectors - Off-road vehicles and other Machinery
1A4ciii	Other Sectors - Fishing
1A5	Non-Specified (military)
1B1	Solid Fuels
1B2	Oil and Natural Gas
2A1	Cement production
2A2	Lime production
2A3	Glass Production
2A4	Other Process Uses of Carbonates
2B	Chemical Industry
2C	Metal Industry
2D	Non-Energy Products from Fuels and Solvent Use
2E	Electronics Industry
2F	Product Uses as Substitutes for Ozone Depleting Substances
2G	Other Product Manufacture and Use
2H	Other
3A1	Enteric Fermentation
3A2	Manure Management
3B1	Forest land
3B2	Cropland
3B3	Grassland
3B4&6	Wetlands and other land
3B5	Settlements
3C1	Emissions from biomass burning
3C1a	Emissions from biomass burning - Forest lands
3C1b	Emissions from biomass burning - Croplands
3C1c	Emissions from biomass burning - Grasslands
3C1d	Emissions from biomass burning - other lands
3C2	Liming
3C3	Urea application
3C4	Direct N2O Emissions from managed soils
3C5	Indirect N2O Emissions from managed soils
3C6	Indirect N2O Emissions from manure management
3C7	Rice cultivations
3C8	Other
4A	Solid Waste Disposal
4B	Biological Treatment of Solid Waste
4C	Incineration and Open Burning of Waste
4D	Wastewater Treatment and Discharge
4E	Other waste handling
5B	Other
5A	Indirect N2O emissions from the atmospheric deposition of nitrogen in NOx and NH3

Second, there are two alternative emissions satellite blocks, one adhering to totals reported in the EDGAR database (EC 2021), and one adhering to totals reported in the OECD emissions database (OECD 2023). The latter are identical with emissions reported by Eurostat (Eurostat 2023). Whilst the EDGAR database cover 210 countries/regions, the OECD database covers 40 OECD countries, and the Eurostat database covers 32 European countries.

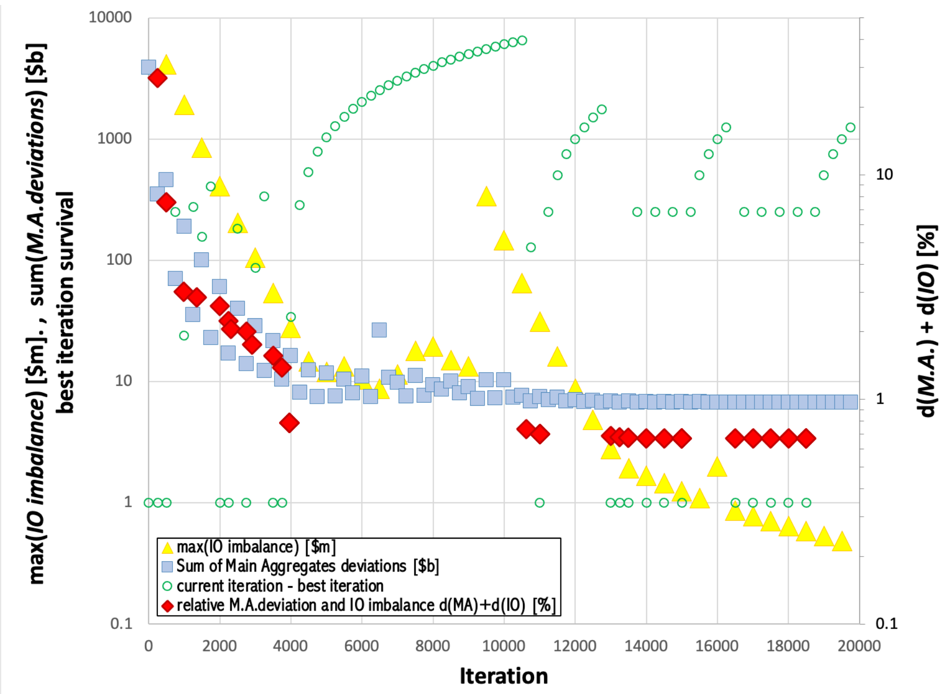
The EDGAR and OECD/Eurostat databases are incompatible, because the EDGAR database is an emissions inventory reporting on *activities*, while the OECD/Eurostat are emissions accounts reporting on *industries*. An example for the difference between activities and industries is EDGAR reporting items 1.A.3 Transport, which comprises "*Emissions from the combustion and evaporation of fuel for all transport activity (excluding military transport), regardless of the sector*" (IPCC 2006). In GLORIA's satellites, both perspectives are combined, in the sense that GLORIA's satellite rows represent activities, and satellite columns represent industries. EDGAR data provide a perfect row-wise breakdown but imperfect column breakdown, and OECD data vice versa for satellite columns. We use both data sources to arrive at activity-by-industry emissions estimates.

In order to show both activity and industry perspectives we needed to map the activity-to-industry correspondence. In a first step we attempted to generate binary (0-1-valued) *concordance* matrices to cast EDGAR's activity values into OECD's industries, using detailed definitions of activity reporting items (IPCC 2006) and corresponding ISIC industries from (UNSD 2008). Most EDGAR activities can be clearly allocated to industries, however a category for which this distinction is ambiguous is road transport, because as seen in the statement above, EDGAR data include all transport irrespective of using industry. We therefore consulted additional data sources (Pomponi *et al.* 2021) to split road transport emissions into private vehicles (allocated to households), and allocated the remainder to the road transport, and postal and courier services. Because of a lack of information, we were unable to allocate transport emissions to other sectors such as agriculture or construction; this remains work for future releases.

In a second step, we allowed these concordance matrices to not be normalised (ie not value-preserving), and to not be binary (ie allowing non-0-1 fractional values), and used constrained optimisation to find the *map* matrix that perfectly maps EDGAR into OECD, and that departs minimally from the initial binary concordance. As evident from the example for Germany below – such maps can be found for every gas and country. This procedure is the basis for the OECD-consistent satellite block in GLORIA. In a third step, we took the optimised maps that perfectly translate EDGAR activity into OECD industry data and normalised them to preserve EDGAR totals. The third procedure is the basis for the EDGAR-consistent satellite block in GLORIA. Emissions data for countries that do not exist in the OECD database adhere to EDGAR totals; corresponding satellite entries are identical.

The two satellite blocks represent mutual adjustment procedures, in that the EDGAR-consistent block adheres to EDGAR activity totals but makes use of OECD's industry splits. The OECD-consistent block adheres to OECD industry totals but makes use of EDGAR's activity splits.

- The convergence of GLORIA's reconciliation has been improved, with a focus on the strict adherence to the UN Main Aggregates and the Input-Output balance.



Various alternatives for emissions data mapping from EDGAR 7.0 into the OECD classification – CO_2 emissions for Germany in 2021.

IPCC code	EDGAR 7.0 k tonne in 2021	OECD code	OECD labels	Raw OECD values k tonne in 2021	EDGAR binary-concorded into OECD (1st step) k tonne in 2021	EDGAR optimised mapping into OECD (2nd step) k tonne in 2021	EDGAR optimised & normalised mapping into OECD (3rd step) k tonne in 2021
1A1a	228,187	A01	Crop and animal production	8,228	2,595	8,228	2,799
1A1bc	21,187	A02	Forestry and logging	524	141	524	311
1A1b	0	A03	Fishing and aquaculture	30	2	30	1
1A1ci	0	B	Mining and quarrying	4,301	22,988	4,301	3,398
1A1cii	0	C10-C12	Manufacture of food products	10,733	8,613	10,733	9,386
1A2	91,806	C13-C15	Manufacture of textiles	597	1,307	597	545
1A2a	0	C16	Manufacture of wood and of products of wood and cork	511	1,171	511	461
1A2b	0	C17	Manufacture of paper and paper products	8,861	2,392	8,861	8,344
1A2c	0	C18	Printing and reproduction of recorded media	789	303	789	765
1A2d	0	C19	Manufacture of coke and refined petroleum products	31,021	6,696	31,021	19,205
1A2e	0	C20	Manufacture of chemicals and chemical products	27,220	10,538	27,220	16,193
1A2f	0	C21	Manufacture of basic pharmaceutical products	1,207	3,878	1,207	820
1A2g	0	C22	Manufacture of rubber and plastic products	2,125	3,667	2,125	1,851
1A2h	0	C23	Manufacture of other non-metallic mineral products	37,982	21,781	37,982	31,991
1A2i	0	C24	Manufacture of basic metals	56,555	9,750	56,555	32,545
1A2j	0	C25	Manufacture of fabricated metal products	2,692	13,533	2,692	1,692
1A2k	0	C26	Manufacture of computer	903	66	903	686
1A2l	0	C27	Manufacture of electrical equipment	739	163	739	492
1A2m	0	C28	Manufacture of machinery and equipment n.e.c.	2,441	12,652	2,441	1,769
1A3b	0	C29	Manufacture of motor vehicles	6,478	17,677	6,478	5,326
1A3b_noRES	138,939	C30	Manufacture of other transport equipment	563	2,744	563	504
1A3b_RES	0	C31-C32	Manufacture of furniture; other manufacturing	796	70	796	605
1A3a	1,195	C33	Repair and installation of machinery and equipment	348	27	348	65
1A3c	714	D	Electricity	205,931	231,489	205,931	247,210
1A3d	748	E36	Water collection	73	97	73	49
1A3e	1,855	E37-E39	Sewerage	3,988	2,226	3,988	2,519
1A4	123,802	F	Construction	9,686	12,059	9,686	7,450
1A4a	0	G45	Repair of motor vehicles and motorcycles	1,628	2	194	6
1A4b	0	G46	Wholesale trade	6,440	41	4,111	116
1A4ci	0	G47	Retail trade	6,598	73	6,598	189
1A4cii	0	H49	Land transport and transport via pipelines	11,188	9,066	11,188	10,993
1A4ciii	0	H50	Water transport	25,478	748	25,478	748
1A5	170	H51	Air transport	16,153	1,195	16,153	1,195
1B1	4,599	H52	Warehousing and support activities for transportation	8,345	652	8,345	1,389
1B2	35	H53	Postal and courier activities	4,033	4,599	4,033	2,881
2A1	13,373	I	Accommodation and food service activities	2,225	0	0	0
2A2	5,325	J58	Publishing activities	317	5,109	317	214
2A3	532	J58-J60	Publishing	0	184	2	1
2A4	694	J61	Telecommunications	233	15	233	7
2B	14,865	J62-J63	Computer programming	564	36	564	16
2C	5,171	K64	Financial service activities	653	3	337	10
2D	10,000	K65	Insurance	388	38	388	11
2E	0	K66	Activities auxiliary to financial services and insurance	180	23	180	5
2F	0	L	Real estate activities	378	99	378	11
2G	0	M69-M70	Legal and accounting; head offices; management consultancy	1,886	5	456	13
2H	0	M71	Architectural and engineering; technical testing and analysis	840	29	840	840
3A1	0	M72	Scientific research and development	104	4	104	3
3A2	0	M73	Advertising and market research	331	1	62	2
3B1	0	M74-M75	Other professional	387	438	387	106
3B2	0	N77	Rental and leasing activities	314	11	314	9
3B3	0	N78	Employment activities	127	1	118	3
3B4&6	0	N79	Travel agency	126	1,049	126	14
3B5	0	N80-N82	Security and investigation	451	4,138	451	131
3C1	0	O	Public administration and defence; compulsory social security	4,637	238	4,637	244
3C1a	0	P	Education	2,996	43	2,996	85
3C1b	0	Q86	Human health activities	3,100	40	3,100	88
3C1c	0	Q87-Q88	Residential care and social work without accommodation	2,587	40	2,587	73
3C1d	0	R90-R92	Creative	440	105	440	271
3C2	2,298	R93	Sports activities and amusement and recreation activities	391	2	187	5
3C3	344	S94	Activities of membership organisations	1,878	1	108	3
3C4	0	S95	Repair of computers and personal and household goods	193	1	77	2
3C5	0	S96	Other personal service activities	2,294	1	133	4
3C6	0	SERVICES	Other services: G	0	12	1	0
3C7	0	T	Households as employers; goods and services for own use	0	10	4	3
3C8	0	U	Activities of extraterritorial organisations and bodies	0	0	0	0
4A	0	HH-TOTAL	Households	174,084	249,209	174,084	249,209
4B	0						
4C	45						
4D	0						
4E	0						
5B	0						
5A	0						
Total	665,884	Total		707,291	665,884	695,035	665,884

Various alternatives for emissions data mapping from EDGAR 7.0 into the OECD classification – CH_4 emissions for Germany in 2021.

IPCC code	EDGAR 7.0 k tonne in 2021	OECD code	OECD labels	Raw OECD values k tonne in 2021	EDGAR binary-concorded into OECD (1st step) k tonne in 2021	EDGAR optimised mapping into OECD (2nd step) k tonne in 2021	EDGAR optimised & normalised mapping into OECD (3rd step) k tonne in 2021
1A1a	14	A01	Crop and animal production	1,242	796	1,242	1,562
1A1bc	1	A02	Forestry and logging	1	0	1	0
1A1b	0	A03	Fishing and aquaculture	0	0	0	0
1A1ci	0	B	Mining and quarrying	4	248	4	98
1A1cii	0	C10-C12	Manufacture of food products	4	539	4	4
1A2	7	C13-C15	Manufacture of textiles	0	0	0	0
1A2a	0	C16	Manufacture of wood and of products of wood and cork	1	0	1	0
1A2b	0	C17	Manufacture of paper and paper products	3	7	3	3
1A2c	0	C18	Printing and reproduction of recorded media	0	0	0	0
1A2d	0	C19	Manufacture of coke and refined petroleum products	1	46	1	10
1A2e	0	C20	Manufacture of chemicals and chemical products	28	9	28	10
1A2f	0	C21	Manufacture of basic pharmaceutical products	0	1	0	0
1A2g	0	C22	Manufacture of rubber and plastic products	1	10	1	0
1A2h	0	C23	Manufacture of other non-metallic mineral products	1	1	1	1
1A2i	0	C24	Manufacture of basic metals	4	1	4	2
1A2j	0	C25	Manufacture of fabricated metal products	1	1	1	0
1A2k	0	C26	Manufacture of computer	0	0	0	0
1A2l	0	C27	Manufacture of electrical equipment	0	0	0	0
1A2m	0	C28	Manufacture of machinery and equipment n.e.c.	1	1	1	0
1A3b	0	C29	Manufacture of motor vehicles	1	1	1	0
1A3b_noRES	0	C30	Manufacture of other transport equipment	0	0	0	0
1A3b_RES	0	C31-C32	Manufacture of furniture; other manufacturing	0	0	0	0
1A3a	9	C33	Repair and installation of machinery and equipment	0	0	0	0
1A3c	0	D	Electricity	141	25	141	60
1A3d	0	E36	Water collection	0	0	0	0
1A3e	0	E37-E39	Sewerage	305	628	305	431
1A4	104	F	Construction	0	1	0	0
1A4a	0	G45	Repair of motor vehicles and motorcycles	0	0	0	0
1A4b	0	G46	Wholesale trade	0	0	0	0
1A4ci	0	G47	Retail trade	1	4	1	0
1A4cii	0	H49	Land transport and transport via pipelines	110	8	110	147
1A4ciii	0	H50	Water transport	0	0	0	0
1A5	0	H51	Air transport	1	9	1	9
1B1	105	H52	Warehousing and support activities for transportation	3	4	3	2
1B2	195	H53	Postal and courier activities	0	0	0	0
2A1	0	I	Accommodation and food service activities	0	0	0	0
2A2	0	J58	Publishing activities	0	0	0	0
2A3	0	J58-J60	Publishing	0	0	0	0
2A4	0	J61	Telecommunications	0	0	0	0
2B	7	J62-J63	Computer programming	0	0	0	0
2C	2	K64	Financial service activities	0	0	0	0
2D	0	K65	Insurance	0	0	0	0
2E	0	K66	Activities auxiliary to financial services and insurance	0	0	0	0
2F	0	L	Real estate activities	0	0	0	0
2G	0	M69-M70	Legal and accounting; head offices; management consultancy	0	0	0	0
2H	0	M71	Architectural and engineering; technical testing and analysis	0	0	0	0
3A1	945	M72	Scientific research and development	0	0	0	0
3A2	342	M73	Advertising and market research	0	0	0	0
3B1	0	M74-M75	Other professional	0	0	0	0
3B2	0	N77	Rental and leasing activities	0	0	0	0
3B3	0	N78	Employment activities	0	0	0	0
3B4&6	0	N79	Travel agency	0	0	0	0
3B5	0	N80-N82	Security and investigation	0	1	0	0
3C1	4	O	Public administration and defence; compulsory social security	1	0	1	0
3C1a	0	P	Education	1	0	1	0
3C1b	0	Q86	Human health activities	1	0	1	0
3C1c	0	Q87-Q88	Residential care and social work without accommodation	1	0	1	0
3C1d	0	R90-R92	Creative	0	0	0	0
3C2	0	R93	Sports activities and amusement and recreation activities	0	0	0	0
3C3	0	S94	Activities of membership organisations	0	0	0	0
3C4	0	S95	Repair of computers and personal and household goods	0	0	0	0
3C5	0	S96	Other personal service activities	0	0	0	0
3C6	0	SERVICES	Other services: G	0	0	0	0
3C7	0	T	Households as employers; goods and services for own use	0	0	0	0
3C8	0	U	Activities of extraterritorial organisations and bodies	0	0	0	0
4A	369	HH-TOTAL	Households	56	104	56	104
4B	37						
4C	95						
4D	210						
4E	0						
5B	0						
5A	0						
Total	2446	Total		1917	2446	1919	2446

- Data on compensation of employees and employment in full-time equivalents (FTE) come from different sources, the National Accounts Official Country database (UNSD 2022b) and the LABORSTA and ILOSTAT database (ILO 2022), respectively. This means that they are not aligned in the sense that the quotient of income and employment yields reasonably consistent wage estimates. In addition, these data sources contain gaps and internal inconsistencies, for example in Belgium's ISIC divisions P and Q, and Zimbabwe's wage magnitude.

Belgium	1994	Women	ISIC-Rev.3	O. Other Community,Social and Personal S	Official estimates	# 0	78.71
Belgium	1994	Women	ISIC-Rev.3	P. Households with Employed Persons	Official estimates	# 0	84.82
Belgium	1994	Women	ISIC-Rev.3	P-Q.	Labour force survey	# 0	10.75

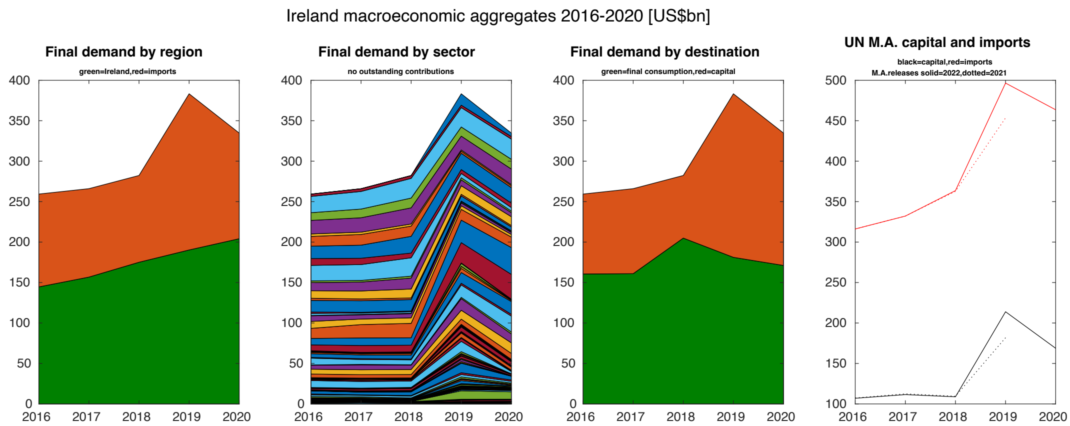
ZWE	Zimbabwe	DA:1824	ES - Employr	EAR_4MTH_	Average monthly earnings	SEX_T	Sex: Total	ECO_ISIC2_3	Economic activity (ISIC-Rev.2): 3. Manufacturing	CUR_TYPE_U	Currency: U.S. dollars	2001	232673.12
ZWE	Zimbabwe	DA:1824	ES - Employr	EAR_4MTH_	Average monthly earnings	SEX_T	Sex: Total	ECO_ISIC2_4	Economic activity (ISIC-Rev.2): 4. Electricity, Gas and Water	CUR_TYPE_U	Currency: U.S. dollars	2001	1000006.17
ZWE	Zimbabwe	DA:1824	ES - Employr	EAR_4MTH	Average monthly earnings	SEX_T	Sex: Total	ECO_ISIC2_5	Economic activity (ISIC-Rev.2): 5. Construction	CUR_TYPE_U	Currency: U.S. dollars	2001	158570.15

To arrive at complete and mutually consistent income, wage and employment estimates therefore requires applying regression and reconciliation techniques. Multiple regressions were applied to three variables:

i. percentage χ of compensation of employees in value added in units of %,
ii. wages ω in units of US$/worker/annum, and
iii. female, male and total participation λ in the labour force in units of %.

The Compensation of Employees (CoE) row in the value added block was then estimated via $C(t,c,s) = \chi(t,c,s) \times VA(t,c)$. The employment satellite was then estimated via $E(t,c,s) = C(t,c,s) \div \omega(t,g,c,s)$. The employment satellite was finally split into gender parts via $E(t,g,c,s) = E(t,c,s) \times \lambda(t,g,c,s)$, where t is time in years, $\in g$ is gender (total, female, male), $c \in [1,164]$ is GLORIA's region index, and $s \in [1,120]$ is GLORIA's sector index. Note that in making income, wage and employment consistent, there may exist aberrations in terms of the share of CoE in value added, and of the national labour participation.

- A conspicuous spike exists in Ireland's footprints for 2019. This can be explained by UN Main Aggregates data (see Figure below).



Ireland's macroeconomic aggregates 2016-2020. Two notable spikes exist in 2019 for imports (panel 1 from left) and gross fixed capital expenditure (panel 3), and are not due to any particular sector contribution (panel 2). These are reflected in UN Main Aggregates primary data (panel 4) for gross fixed capital expenditure (black; more than doubling from 2018 to 2019) and imports (red; almost 50% increase). The discontinuity in the UN primary data has even increased from the 2021 data release (dotted; underlying GLORIA release 055) to the 2022 data release (solid; underlying GLORIA release 059).

- Missing UN SNA Main Aggregates 1990 exports and imports data for Czechoslovakia and the former Soviet Union (that were likely responsible for 1990 material footprint spikes) were imputed from 1990 data for the Czech Republic and Slovakia, and the individual Soviet Republics, respectively.

- Isolated sign violations were rectified using the sign-flip GRAS method documented in Lenzen *et al.* 2014b.

- Monetary data were compiled in the Global MRIO Lab (Lenzen *et al.* 2017). MRIO data sources are listed in the Supplementary Information of Lenzen *et al.* 2021a. Satellite data were compiled by the SCP-HAT team (http://scp-hat.lifecycleinitiative.org, except GHG and employment) at the 97-sector detail, and then mapped to 120 sectors using a concordance matrix (provided in the ReadMe.xlsx file).

- Primary data sources were imposed on MRIO elements as constraints. More internally consistent, (temporally, regionally and sectorally) complete and detailed data sources override less internally consistent, complete and detailed data sources in the reconciliation process. The table below provides an overview of data sources, their level of completeness and detail, in descending order of priority in the overall reconciliation. For information on satellite data sources (except GHG emissions and employment) please see the SCP-HAT technical documentation (Piñero *et al.* 2021) and website (http://scp-hat.lifecycleinitiative.org/methods).

Data source	Reference	Years	Regions	Sectors	Notes
IO balance	n.a.	1990-2028	all	all	
National Accounts Main Aggregates	UNSD 2022a	all[1]	all	None	
Food balances[3]	FAOSTAT 2022	1990-2019	all	Food-related sectors only	Physical data for mass, energy and macronutrient intake
	FAOSTAT 2019	1991-2020	122[2]	Food-related sectors only	Commodity prices
Compensation of employees	UNSD 2022b	1990-2017	91	Totals[6] only	Missing regions regressed, sectors proxied[4]
Wages	LO 2022	all[1]	116	≤ 21 (ISIC sections)	Missing regions regressed, sectors proxied[4]
	ILO 2012	1990-2008	62	Totals[6] only	Missing regions regressed, sectors proxied[4]
Employment	ILO 2022	1992-2020	146	≤ 88 (ISIC divisions)	Missing regions regressed, sectors proxied[4]
	ILO 2012	1990-2008	105	≤ 21 (ISIC sections)	Missing regions regressed, sectors proxied[4]
	World Bank 2023b	all[1]	159	Totals[6] only	Used for setting national totals
Energy-steel production recipes	World Bank	all[1]	all	Coal, oil, gas, iron ore, steel, electricity	Personal communication
Comtrade and Servicestrade	UNSD 2022c	all[1]	all	all	Imports and exports data internally conflicting; reconciled as described in GLORIA_Diagnostics_ComtradeVs SNA.pdf[5]

GDP projections	IMF 2023, World Bank 2023a	2021-2028	all	Totals[6] only	
MRIO data	OECD 2022	1995-2018	64	36	2018 Edition
Household consumption	World Bank 2017	various	83	61	Collation of household expenditure surveys from around 2003
Total output	FAO 2020a; b; UNIDO 2020a; b	1990-2019	112	<238 (ISIC groups)	Large temporal, regional and sectoral data gaps
National Accounts Official Country data	UNSD 2022b	1990-2017	136	Mostly totals[6] only	Limited sectoral info for household expenditure and value added; large temporal, regional and sectoral data gaps; some currency identities and exchange rates ambiguous
Engineering exclusions	Lenzen *et al.* 2022	all	all	all	
National IO databases	Lenzen *et al.* 2012	1990-2013	74	varying	Supplementary Information Text S6

Note: Coverage information refers to maximum coverage. For example, maximum regional and/or sectoral coverage may not exist for all years.
[1] "all" under years means 1990-2021.
[2] Remainder imputed by mean.
[3] Quotient of mass and price conflicts with consumption data in National Accounts Official Country data (UNSD 2022b).
[4] Sectoral proxying procedure is described in Lenzen *et al.* 2017 Section 2.1.
[5] Thanks to Jacob Fry and Keisuke Nansai for undertaking the reconciliation.
[6] "Totals" means national totals.

General explainer and disclaimer

- **Supply-Use format**: The GLORIA database is released as a set of Multi-Region Supply-Use Tables (MR-SUTs). The advantage of SUTs over input-output tables is the ability to incorporate co-production. Whilst co-production does not feature in the current and past releases of GLORIA, as the supply tables are diagonal matrices, GLORIA use matrices essentially equate to input-output tables. The database nevertheless adopts the SUT format, to enable future incorporation of co-production. For an introductory exposition on MRIO databases, see Tukker and Dietzenbacher 2013.
- **Sector homogeneity**: In contrast to the Eora MRIO database, GLORIA features a homogeneous number of sectors across countries. This is because having different sector resolutions across countries
  - makes transformations of an MRIO database into other formats unwieldy, needing many concordances;
  - introduces a systematic aggregation bias;
  - prevents Structural Decomposition Analysis; and
  - prevents inter-country comparisons.
- **Interpreting data**: Constructing a global MRIO database is an underdetermined problem – there are vastly more data points to estimate than primary data to support that estimation. As a consequence, *many MRIO data points are estimates, not measurements*. This is a common feature not only across global MRIO databases, but also of national IO databases. The ratio between the number of primary data support points and MRIO elements usually improves over time, as more databases update their coverage. This means nevertheless that generally, tables for more recent years

are represented by fewer measured primary data than years in the past. *Typically, for a release in year N, the most recent measured data would be the UN Main Aggregates for the year N – 2*. UN Main Aggregates however contains relatively few data points, at least compared to UN National Accounts Official Country and Comtrade data that are published with delays of three or more years.

- **Relationship to primary data**: GLORIA MRIO data may deviate from primary data sources. This can be because these primary data sources conflict with each other, and databases that are highly prioritised (see table above) can override lower-prioritised databases during constraints imposition and reconciliation.
- **Relationship to National Statistical Offices data**: GLORIA MRIO data may deviate from National Statistical Offices' input-output databases and results of national footprint studies. This can be because i) these data conflict amongst nations (through import and export linkages) and with global data (UN, OECD, FAO etc) and ii) some national input-output data have not yet been incorporated into GLORIA. If you would like a particular input-output database incorporated, please email manfred.lenzen@sydney.edu.au.
- **Non-OECD countries**: MRIO data for most non-OECD countries have not undergone diagnostics and quality assurance, and may be associated with substantial uncertainty.
- **Discontinuities, spikes and fluctuations** in MRIO, satellite and footprint data may occur
  - i) for the years 2019 and 2020 as the MRIO entries for these years are only weakly constrained by primary data,
  - ii) for countries experiencing hyper-inflation, such as Zimbabwe or Venezuela,
  - iii) countries during periods of conflict, such as Iraq, Afghanistan, Bosnia and Herzegovina, South Sudan, Libya, Syria, Palestine, Somalia;
  - iv) during transition periods, such as for the Soviet Union (1990), Yugoslavia (1991), Czechoslovakia (1990), Ethiopia (1992), Yemen (1990), Sudan (2010);
  - v) for countries with missing, conflicting or uncertain primary data, such as North Korea, Moldova, Turkmenistan, Equatorial Guinea (not in Eora), Belarus;
  - vi) for small economies, such as Burundi, Bhutan, Eritrea, Djibouti, Gambia, Liberia;
  - vii) for strongly trade-dependent economies, such as UAE, Luxembourg, Hong Kong, Kuwait, Malta, Singapore;
  - viii) for residual "rest-of" regions XAM (Guyana, Suriname, Greenland, Bermuda, Caribbean), XEU (Liechtenstein, San Marino, Andorra, Monaco), XAF (Cabo Verde, Comoros, Seychelles, Mauritius, São Tomé e Príncipe, Guinea Bissau, Lesotho, Eswatini), and XAS (Taiwan, Timor-Leste, Maldives, Pacific Islands);
  - ix) in cases where monetary and satellite information comes from independent sources; for example, comparing sectoral employment from ILO sources with sectoral compensation of employees may yield large and unrealistic per-worker wage estimates.
  - x) in cases where information exists on economic flows, but not satellites, where countries can exhibit zero domestic and non-zero imported footprint (for example materials footprint for Republic of Congo, Serbia or Sudan). Under such occurrences, the standard deviations of the footprints (see under files v) are solely those relating to imports.

A plain-English short philosophy of MRIO-building

Constructing an (MR)IO database is a severely underdetermined problem. Typically, MRIO tables for one year comprise in the order of ten million to a few billion elements[9]. These are constrained by primary data numbering between a few thousand up to a million points. This means that an MRIO needs to be constructed by starting with an initial estimate, and then by imposing constraints using optimisation. A particularly challenging feature of MRIO-building is that primary data sources do not agree with each other, and sometimes are even internally inconsistent.

Most primary data address fields in an MRIO matrix that interact with each other. For example, international trade data combines regions of origin with regions of destination, which are in turn represented by their own national accounts data, which in turn must comply with theoretical input-output balances. Information valued in purchasers' prices connects trade and transport margins with taxes and subsidies, and factory- and farm-gate (basic) prices. A single value of an individual country's GDP connects elements across the entire MRIO table. As a result, any oddity in one primary data source has consequences for the imposition of all other sources!

This means that there is no way that an MRIO database can be built in a way that perfectly represents all primary data. Instead, MRIO compilers use constrained optimisation techniques to find the MRIO table that has the best fit to all primary data simultaneously. For large MRIO tables, this requires uses high-performance computers with many terabytes of memory, and many processing units, to enable parallel computing.

More importantly, this also means that MRIO elements are not fixed numbers. They are estimates characterised by uncertainties. In the GLORIA database, these uncertainties are represented in the accompanying standard-deviations tables. These uncertainties tend to be larger for areas of the table that are only weakly constraint by primary data, such as low-income economies or small industries. During construction, such weakly-constrained areas "react" and "budge" to constraints being imposed on more densely constrained table areas. It's very much like a water bed – if you try to hold it in shape in one spot, it keeps bulging out in other spots where you're not holding it!

When primary data sources disagree with each other, one has to make a decision about how to handle any discrepancies. Some teams make binary decisions by excluding one or more databases entirely from the construction process. When constructing GLORIA, we take the perspective that no data source is entirely incorrect, but that different data sources have different degrees of reliability. Accordingly, we assign levels of uncertainty to each primary data point. Then, during the construction process more uncertain primary data are overridden by less uncertain primary data.

Importantly, this means that there is no single one "true" MRIO database. Depending on compilers' different selection of primary data, their different deeming of reliability and hence different relative priority settings, and their different classifications and degrees of regional and sectoral aggregation, amongst further criteria, mean that there are many ways to portray

[9] GLORIA comprises $(164 \times 164) \times [120 \times (120+6+6)] \times 5 = 2{,}130{,}163{,}200$ elements for every year, and 80,946,201,600 elements for a time series spanning the years 1990 to 2028.

the structure of economies, and in general these do not perfectly agree (see an assembly of intercomparisons by Inomata and Owen 2014).

Any MRIO database will always mis-represent certain primary data, and users and compilers can have differing opinions about a preferred representation. For example, an officer from Japan's statistical bureau might require an MRIO to exactly represent Japan's domestic and external transactions, and an MRIO can in principle be built that sets adherence to Japan's own accounts as its highest priority. However, as a consequence, in the ensuing MRIO database, other countries' primary data may not be exactly represented, for example because their information on trade with Japan differs from Japan's own trade information.

For further details on issues of uncertainty, feel free to read "*Uncertainty and Reliability in the Eora MRIO tables*" at https://worldmrio.com/documentation/EoraConfidence.jsp.

A plain-English explanation of MRIO-based footprinting

Many researchers use multi-region input-output (MRIO) data to calculate environmental, economic and social footprints that take into account numerous supply-chain transactions between regions and sectors of the global economy. MRIO data distinguish the entire flow of money through an economy, that is, i) intermediate demand (a matrix **T**) are transactions between producing sectors, ii) final demand (a matrix **Y**) are sales of sectors to agents such as households, the government and the capital sector, and iii) value added (a matrix **W**) are payments of sectors to the same agents. The entire economy is in balance according to **T** + **Y** = **W** + **T** (Tukker and Dietzenbacher 2013).

		Region 1		Region 2		Final demand	
		Goods	Services	Goods	Services	Region 1	Region 2
Region 1	Goods	100	10	5	0	30	0
	Services	0	20	0	0	20	5
Region 2	Goods	30	0	20	0	15	10
	Services	10	10	0	5	0	10
Value added		5	5	50	30		

Schematic of multi-region input-output data for a simplified 2-region economy. Blue: intermediate demand **T**, red: final demand Y, green: value added W (taken from Kanemoto and Murray 2010). Here, producers in region 2 supply producers in region 1 with 30 units of goods, and final demand agents in region 1 with 15 units of goods.

The founder of input-output analysis, Nobel-Prize laureate Wassily Leontief, had environmental (Leontief and Ford 1970) and social (Leontief 1986; Leontief and Duchin 1986) applications in mind already in the 1970s! Other early work connects input-output tables with local ecologies and trophic chains (Isard *et al.* 1967; Isard 1975). Considering that input-output tables are able to capture regional and sectoral relationships across complex supply-chain networks, Leontief's work had enormous influence on research aimed at enumerating the direct and indirect effects of consumption decisions (such as in Life-Cycle Assessment, LCA) or economic disruptions (such as from the early oil crises). Following Leontief's work, the disciplines of LCA ((Bullard *et al.* 1978) and energy analysis (Herendeen 1973) adopted input-output analysis into best-of-many-worlds hybrid methods (Suh *et al.* 2004). Later, footprinting emerged out of LCA, and input-output analysis became central to its technical repertoire (Wiedmann 2009).

Leontief's basic idea was to couple environmental accounts to the input-output system (Leontief and Ford 1970), as additional rows in the schema above (Forssell 1998), and his idea is still followed in today's footprinting. This matrix coupling enables environmental and social externalities to be connected to the monetary representation of the global economy, which is precisely the feature that footprints offer: the embodiment of environmental and social quantities in monetary amounts of final demand. Analytical techniques from the input-output toolbox such as series expansion (Waugh 1950) and structural path analysis (Treloar 1997) then enable the dissection of footprints into contribution by regions, sectors, upstream production stages and even individual supply chains.

Thanks to the ability of MRIO assessments to capture direct and indirect supply-chain contributions, the input-output-based carbon footprint of, for example, the usage of a motor vehicle, includes:

- direct emissions from combusting petrol or diesel in the engine;
- 1st-order emissions for example by vehicle assembly plants welding parts together for making finished motor vehicles;
- 2nd-order emissions for example by metal rolling plants manufacturing the vehicle body's sheet metal for assembly plants for making finished motor vehicles;
- 3rd-order emissions for example by smelters making steel for rolling plants making steel sheet for assembly plants making finished motor vehicles;
- 4th-order emissions for example by iron ore mines supplying iron ore to steel smelters making steel for rolling plants making steel sheet for assembly plants making finished motor vehicles;
- 5th-order emissions for example by mining machinery manufacturers making excavators for iron ore mines supplying iron ore to steel smelters making steel for rolling plants making steel sheet for assembly plants making finished motor vehicles;
- and so on.

MRIO-based carbon footprints are thus complete, that is they capture upstream supply-chain contributions of infinite order, in a ***collectively exhaustive and mutually exclusive*** way. This means that MRIO-based carbon footprints are complete and are not affected by any double-counting. Mathematically, this is facilitated by the so-called Leontief inverse, a matrix conceived by Wassily Leontief. Evaluating upstream supply-chain contributions to footprints is important for policy-making, procurement and product design, in order to enable valid comparisons and benchmarking (Foran *et al.* 2005), and to avoid misleading conclusions and recommendations (Lenzen and Treloar 2003).

References

Bullard, C.W., P.S. Penner and D.A. Pilati (1978) Net energy analysis - handbook for combining process and input-output analysis. *Resources and Energy* 1, 267-313.

EC (2021) *Emission Database for Global Atmospheric Research (EDGAR), release version 7.0*. Internet site https://data.jrc.ec.europa.eu/collection/edgar, Bruxelles, Belgium, European Commission Joint Research Centre (JRC).

Eurostat (2023) *Greenhouse gas emission statistics - emission inventories*. Internet site https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_statistics_-_emission_inventories, Bruxelles, Belgium, European Commission.

FAO (2020a) *FishStatJ - Fishery and Aquaculture Statistical Time Series*. Fishery Statistical Collection http://www.fao.org/fishery/statistics/software/fishstatj/en, Rome, Italy, Food and Agriculture Organization

FAO (2020b) *Value of Agricultural Production*. Internet site http://www.fao.org/faostat/en/#data/QV, Rome, Italy, Food and Agriculture Organization of the United Nations (FAO).

FAOSTAT (2019) *Producer Prices*. Internet site http://www.fao.org/faostat/en/#data/PP, Rome, Italy, Food and Agriculture Organization of the United Nations (FAO).

FAOSTAT (2022) *New Food Balances*. Internet site http://www.fao.org/faostat/en/#data/FBS, Rome, Italy, Food and Agriculture Organization of the United Nations (FAO).

Feenstra, R.C. and J. Romalis (2014) International Prices and Endogenous Quality. *The Quarterly Journal of Economics* 129, 477-527.

Foran, B., M. Lenzen, C. Dey and M. Bilek (2005) Integrating Sustainable Chain Management with Triple Bottom Line Reporting. *Ecological Economics* 52, 143-157.

Forssell, O. (1998) Extending economy-wide models with environment-related parts. *Economic Systems Research* 10, 183-199.

Geschke, A. and M. Hadjikakou (2017) Virtual laboratories and MRIO analysis – an introduction. *Economic Systems Research* 29, 143-157.

Herendeen, R.A. (1973) Use of input-output analysis to determine the energy cost of goods and services. In: M.S. Macrakis (ed.) *Energy: Demand, Conservation, and Institutional Problems*. Cambridge, MA, USA, Massachusetts Institute of Technology, 141-158.

ILO (2012) *LABORSTA - Main statistics (annual): employment general level, by economic activity, by occupation, by status in employment*. Internet site http://laborsta.ilo.org, Genève, Switzerland, International Labour Organization.

ILO (2022) *ILOSTAT - Statistics on employment*. Internet site https://ilostat.ilo.orghttps://ilostat.ilo.org/topics/employment/, Genève, Switzerland, International Labour Organization.

IMF (2023) *Gross domestic product, current prices, 2020-2028*. World Economic Outlook (October 2023) http://www.imf.org/external/datamapper/NGDPDPC@WEO/OEMDC/ADVEC/WEOWORLD, Washington, D.C., USA, International Monetary Fund.

Inomata, S. and A. Owen (2014) Comparative evaluation of MRIO databases. *Economic Systems Research* 26, 239-244.

IPCC (2006) Reporting Guidance and Tables. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Geneva, Switzerland.

Isard, W. (1975) Economic-ecologic conflict and environmental quality. *Introduction to Regional Science*. Englewood Cliffs, NJ, USA, Prentice-Hall, Inc, 341-371.

Isard, W., K. Bassett, C. Choguill, J. Furtado, R. Izumita, J. Kissin, E. Romanoff, R. Seyfarth and R. Tatlock (1967) On the linkage of socio-economic and ecologic systems. *Papers and Proceedings of the Regional Science Association* 21, 79-99.

Kanemoto, K. and J. Murray (2010) What is MRIO: Benefits and limitations. In: J. Murray and R. Wood (eds.) *The Sustainability Practitioner's Guide to Input-Output Analysis*. Champaign, USA, Common Ground, 167-178.

Lenzen, M., A. Geschke, M.D. Abd Rahman, Y. Xiao, J. Fry, R. Reyes, E. Dietzenbacher, S. Inomata, K. Kanemoto, B. Los, D. Moran, H. Schulte in den Bäumen, A. Tukker, T. Walmsley, T. Wiedmann, R. Wood and N. Yamano (2017) The Global MRIO Lab - charting the world economy. *Economic Systems Research* 29, 158-186.

Lenzen, M., A. Geschke, J. West, J. Fry, A. Malik, S. Giljum, L.M.i. Canals, P. Piñero, S. Lutter, T. Wiedmann, M. Li, M. Sevenster, J. Potočnik, I. Teixeira, M.V. Voore, K. Nansai and H. Schandl (2021a) Implementing the Material Footprint to measure progress towards SDGs 8 and 12. *Nature Sustainability* 5, 157-166.

Lenzen, M., A. Geschke, J. West, J. Fry, A. Malik, S. Giljum, L. Milà i Canals, P. Piñero, S. Lutter, T. Wiedmann, M. Li, M. Sevenster, J. Potočnik, I. Teixeira, M. Van Voore, K. Nansai and H. Schandl (2022) Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. *Nature Sustainability* 5, 157-166.

Lenzen, M., A. Geschke, T. Wiedmann, J. Lane, N. Anderson, T. Baynes, J. Boland, P. Daniels, C. Dey, J. Fry, M. Hadjikakou, S. Kenway, A. Malik, D. Moran, J. Murray, S. Nettleton, L. Poruschi, C. Reynolds, H. Rowley, J. Ugon, D. Webb and J. West (2014a) Compiling and using input–output frameworks through collaborative virtual laboratories. *Science of The Total Environment* 485–486, 241-251.

Lenzen, M., K. Kanemoto, D. Moran and A. Geschke (2012) Mapping the structure of the world economy. *Environmental Science & Technology* 46, 8374–8381, http://dx.doi.org/10.1021/es300171x.

Lenzen, M., M. Li and S.A. Murray (2021b) Impacts of harmful algal blooms on marine aquaculture in a low-carbon future. *Harmful Algae* 110, 102143.

Lenzen, M., D.D. Moran, A. Geschke and K. Kanemoto (2014b) A non-sign-preserving RAS variant. *Economic Systems Research* 26, 197-208.

Lenzen, M. and G. Treloar (2003) Differential convergence of life-cycle inventories towards upstream production layers. *Journal of Industrial Ecology* 6, 137-160.

Leontief, W. (1986) An information system for policy decisions in a modern economy. *Input-Output Economics*. New York, NY, USA, Oxford University Press, 418-428.

Leontief, W. and F. Duchin (1986) *The future impact of automation on workers*. Oxford, UK, Oxford University Press.

Leontief, W. and D. Ford (1970) Environmental repercussions and the economic structure: an input-output approach. *Review of Economics and Statistics* 52, 262-271.

NeCTAR (2013) *The Industrial Ecology Virtual Laboratory*. Internet site http://nectar.org.au/industrial-ecology-virtual-laboratory, Melbourne, Australia, University of Melbourne.

OECD (2022) *OECD Inter-Country Input-Output (ICIO) Tables*. Internet site https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm, Paris, France, Organisation for Economic Co-operation and Development.

OECD (2023) *Air and GHG emissions*. Internet site https://data.oecd.org/air/air-and-ghg-emissions.htm, Paris, France, OECD,.

Piñero, P., M. Sevenster, S. Lutter and S. Giljum (2021) *Technical documentation of the Sustainable Consumption and Production Hotspots Analysis Tool (SCP-HAT) version 2.0.* . Commissioned by UN Life Cycle Initiative, One Planet Network, and UN International Resource Panel; available at http://scp-hat.lifecycleinitiative.org/wp-content/uploads/2021/11/SCP-HAT-2.0_Technical-documentation_Oct2021_final02.pdf, Paris, France.

Pomponi, F., M. Li, Y.-Y. Sun, A. Malik, M. Lenzen, G. Fountas, B. D'Amico, O. Akizu-Gardoki and M. Luque Anguita (2021) A Novel Method for Estimating Emissions Reductions Caused by the Restriction of Mobility: The Case of the COVID-19 Pandemic. *Environmental Science & Technology Letters* 8, 46-52.

Suh, S., M. Lenzen, G.J. Treloar, H. Hondo, A. Horvath, G. Huppes, O. Jolliet, U. Klann, W. Krewitt, Y. Moriguchi, J. Munksgaard and G. Norris (2004) System boundary selection in Life-Cycle Inventories. *Environmental Science & Technology* 38, 657-664.

Treloar, G. (1997) Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method. *Economic Systems Research* 9, 375-391.

Tukker, A. and E. Dietzenbacher (2013) Global multiregional input-output frameworks: An introduction and outlook. *Economic Systems Research* 25, 1-19.

UNIDO (2020a) *Industrial Statistics Database at the 4-digit level of ISIC (INDSTAT4)*. Internet site http://www.unido.org/resources/statistics/statistical-databases.html, New York, USA, United Nations.

UNIDO (2020b) *Mining and Utilities Statistics Database (MINSTAT)*. Internet site http://www.unido.org/resources/statistics/statistical-databases.html, New York, USA, United Nations.

UNSD (2008) *International Standard Industrial Classification of All Economic Activities (ISIC), Rev. 4*. Statistical papers Series M No.4/Rev.4, ST/ESA/STAT/SER.M/4/Rev.4, New York, USA, United Nations Department of Economic and Social Affairs, Statistics Division.

UNSD (2018) *Handbook on Supply, Use and Input-Output Tables with Extensions and Applications*. Studies in Methods Series F No.74, Rev.1, New York, USA, United Nations Statistics Division.

UNSD (2022a) *National Accounts Main Aggregates Database*. Internet site https://unstats.un.org/unsd/snaama/, New York, USA, United Nations Statistics Division.

UNSD (2022b) *National Accounts Official Data*. Internet site http://data.un.org/Browse.aspx?d=SNA, New York, USA, United Nations Statistics Division.

UNSD (2022c) *UN comtrade - United Nations Commodity Trade Statistics Database*. Internet site http://comtrade.un.org/, New York, USA, United Nations Statistics Division, UNSD.

USDA (2019) *USDA National Nutrient Database for Standard Reference*. Washington D.C., USA, United States Department of Agriculture.

Waugh, F.V. (1950) Inversion of the Leontief matrix by power series. *Econometrica* 18, 142-154.

Wiedmann, T. (2009) Carbon footprint and input-output analysis: an introduction. *Economic Systems Research* 21, 175–186.

World Bank (2017) *Global Consumption Database*. Internet site http://datatopics.worldbank.org/consumption/, Washington, USA, World Bank.

World Bank (2022) *GDP, PPP (current international $)*. Excel file API_NY.GDP.PCAP.PP.CD_DS2_en_excel_v2_4355406 https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD, Washington D.C., USA, World Bank.

World Bank (2023a) *Global Economic Prospects*. http://www.worldbank.org/en/publication/global-economic-prospects, Washington DC, USA, World Bank,.

World Bank (2023b) *Labor force, total*. DataBank https://data.worldbank.org/indicator/SL.TLF.TOTL.IN, Washington D.C., USA, World Bank.