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Institute of Social Ecology

Mapping and weighing global terrestrial infrastructures

Implications for resource demand & social wellbeing

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European Research Council
Established by the European Commission

CircEUlar

reMASS

https://remass.boku.ac.at/

European Research Council (ERC; MAT_STOCKS), grant agreement No 741950), European Union's Horizon Europe programme (CircEUlar, grant agreement No 101056810)

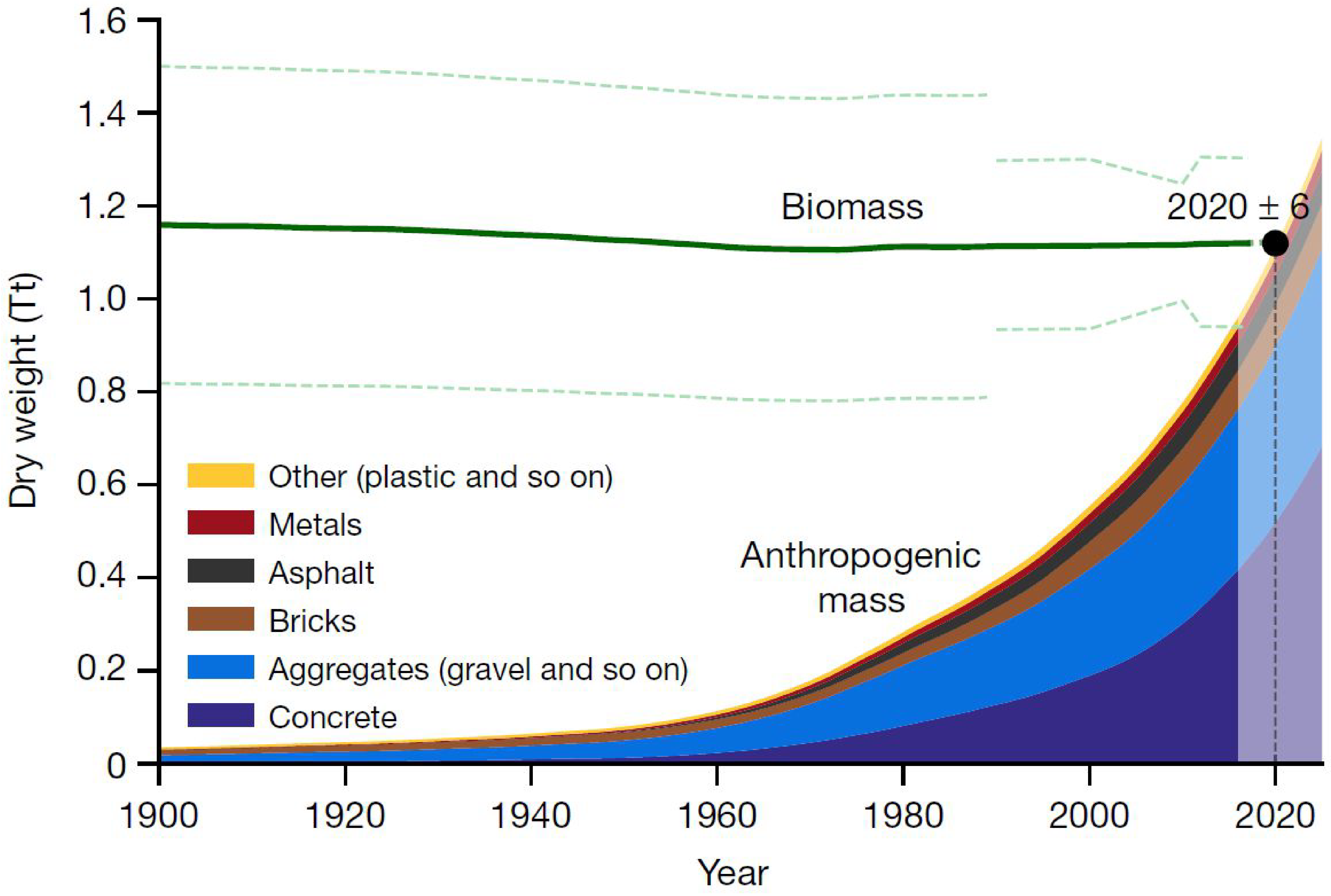
FWF Österreichischer Wissenschaftsfonds

This research was funded in whole or in part by the Austrian Science Fund (FWF) [10.55776/EFP5]

Infra North | Building Arctic Futures

Anthropocene & the ‚biophysical scale' of society

Global societal vs biospheric material stocks in comparison



Infrastructures (buildings, transport, etc.) account for ~98% of all societal stocks („*anthropogenic mass*"). Globally, they rise almost 1:1 coupled with GDP, i.e. increased by factor 20-30 over the last century – in contrast to the mass of all living organisms, which is slightly decreasing, due to human activities.

Elhacham *et al*. 2020, *Nature* 588; based on Krausmann *et al*. 2017, *PNAS* 114 and Erb *et al*. 2018, *Nature* 553

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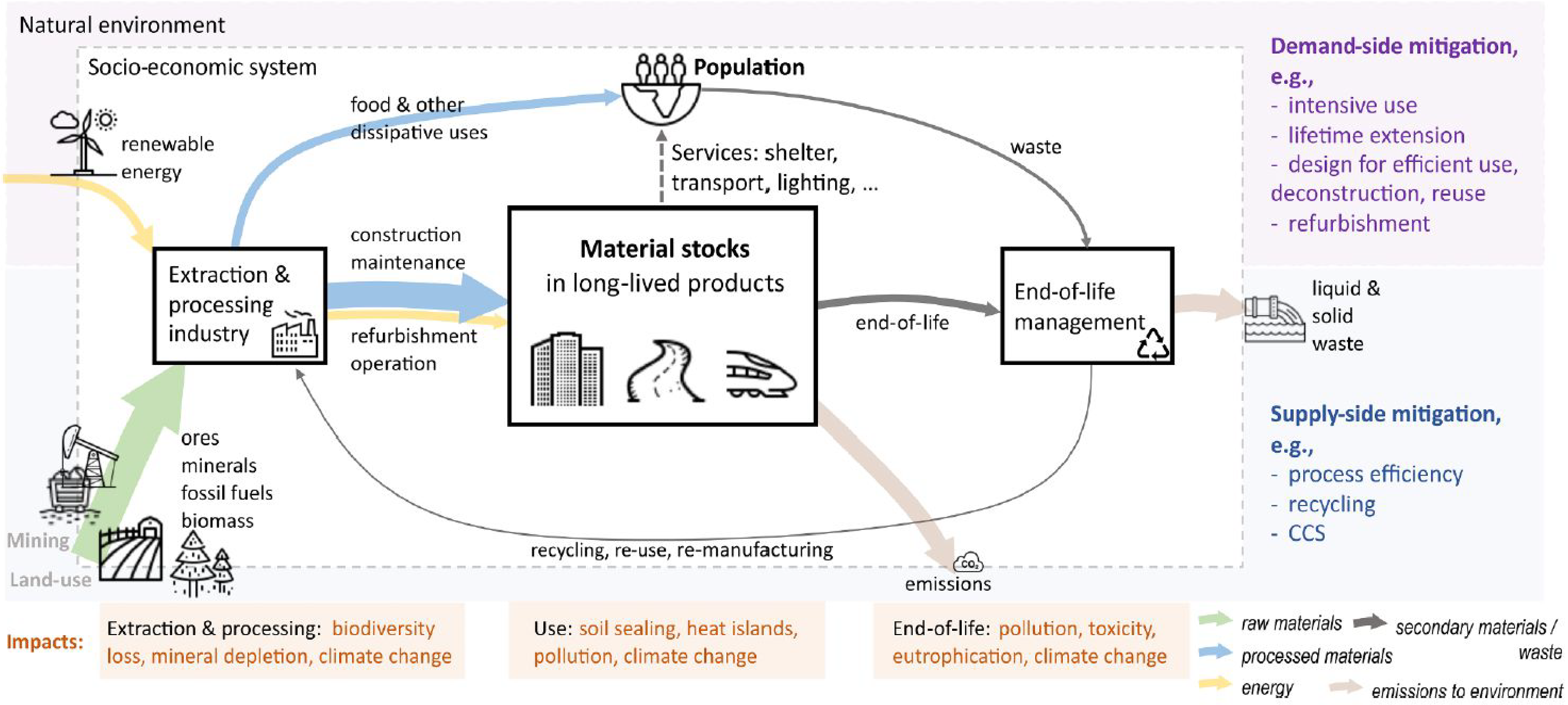
Socio-metabolic research

Studying stocks and flows of materials and energy that provide key services to society



Stocks and flows of materials and **energy** provide **societies‘ material basis**: nourishment, shelter, mobility, education, healthcare, etc.

They are key to **sustainability.**

Streeck et al. 2025. *Res., Conserv. Recycl* **221**, 108324, https://doi.org/10.1016/j.resconrec.2025.108324

This research was funded in whole or in part by the Austrian Science Fund (FWF) [10.55776/EFP5]

Motivation: The Stock-Flow-Service nexus

Stocks Buildings, infrastructures, machines, human bodies, livestock

Practices of everyday living

Flows Energy, materials, wastes, emissions

Services Contributions to social well-being

- Services depend on **specific stock-flow relations**
- For example, car-based mobility services need roads, cars and fuel (or electricity)
- Stocks need **huge amounts of resources to be built and maintained** *(autocatalytic)*
- Specific stock patterns (e.g. design of settlements & infrastructures) **foster or inhibit certain practices**
- For example, **urban sprawl** is linked with car-dependent mobility
- Stock patterns are linked with specific **social practices and lock-ins**

Haberl *et al.* 2021. *Ecological Economics*, **182**, 106949
https://doi.org/10.1016/j.ecolecon.2021.106949

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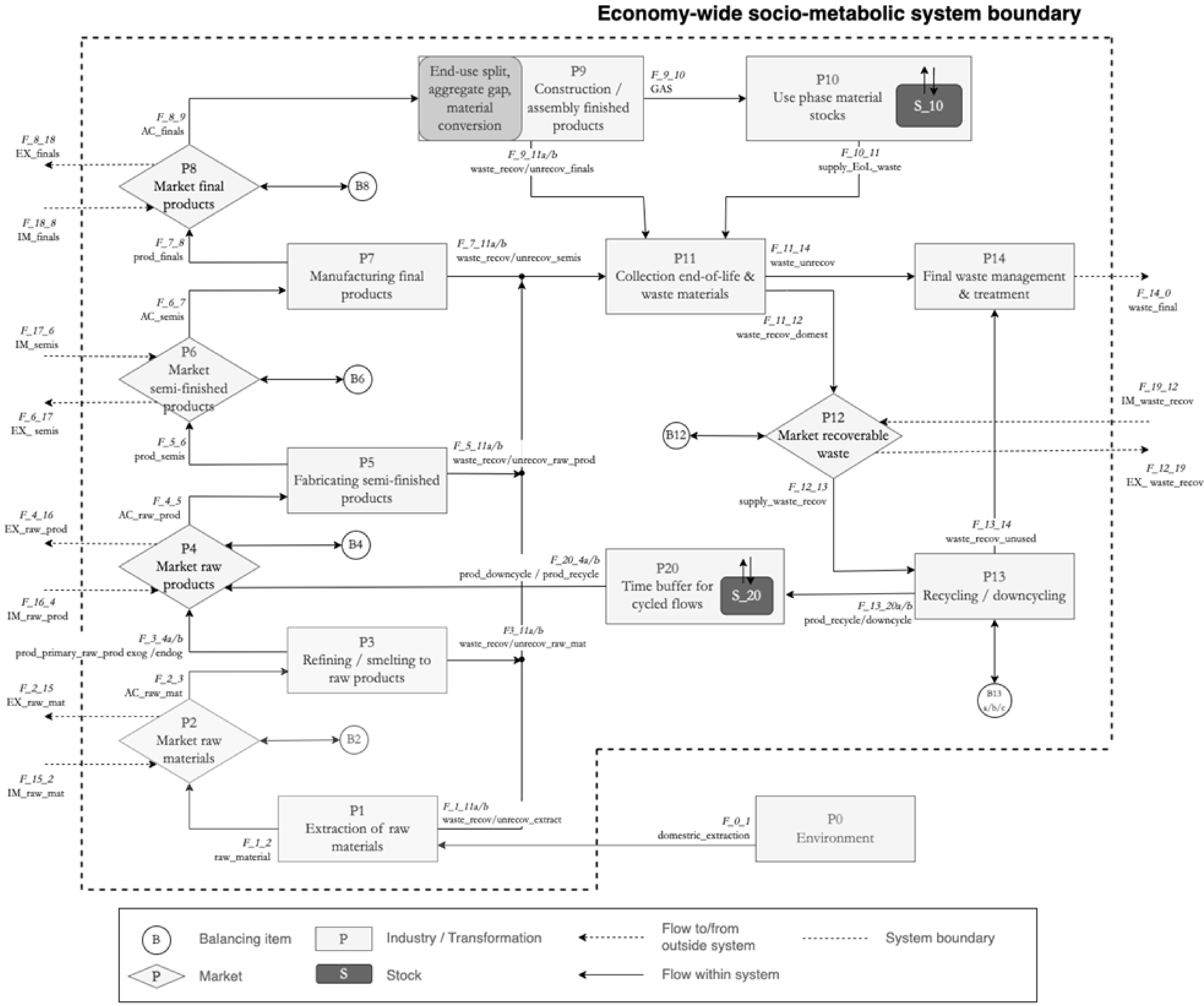
The MISO-2 model

Quantifying material stocks globally

- Country-level, global, 1900-2016
- 16 processes (each material balanced)
- 23 raw materials
- 21 stock-building material
- 13 end-use product groups
- Stock-flow and process consistent
- Economy-wide



Wiedenhofer et al. 2024. *Journal of Industrial Ecology* **24**, 1464-1480
https://doi.org/10.1111/jiec.13575

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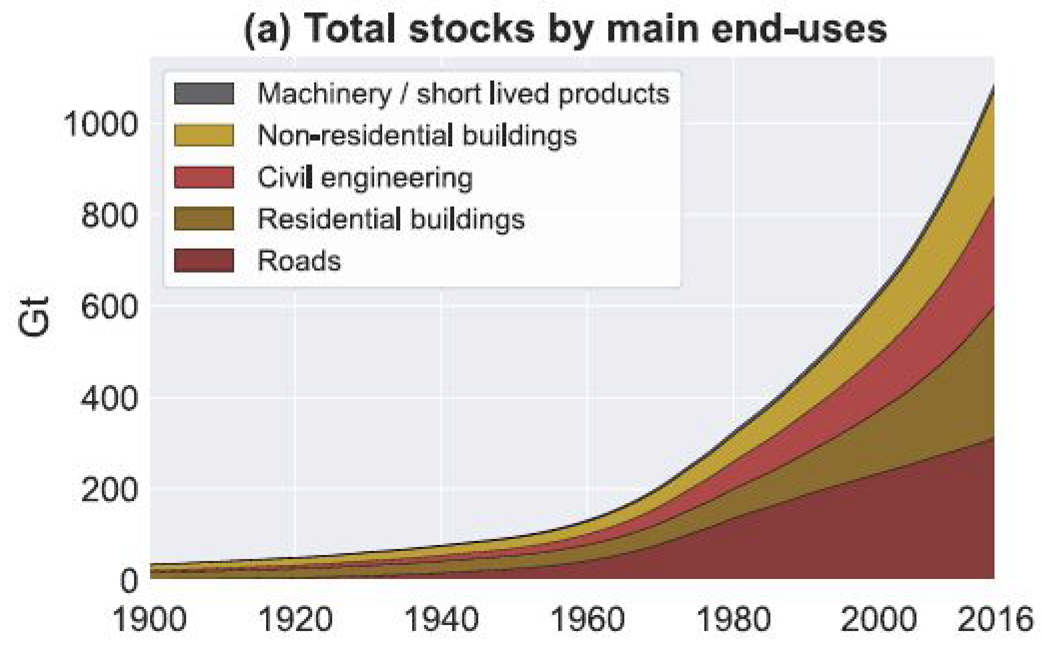

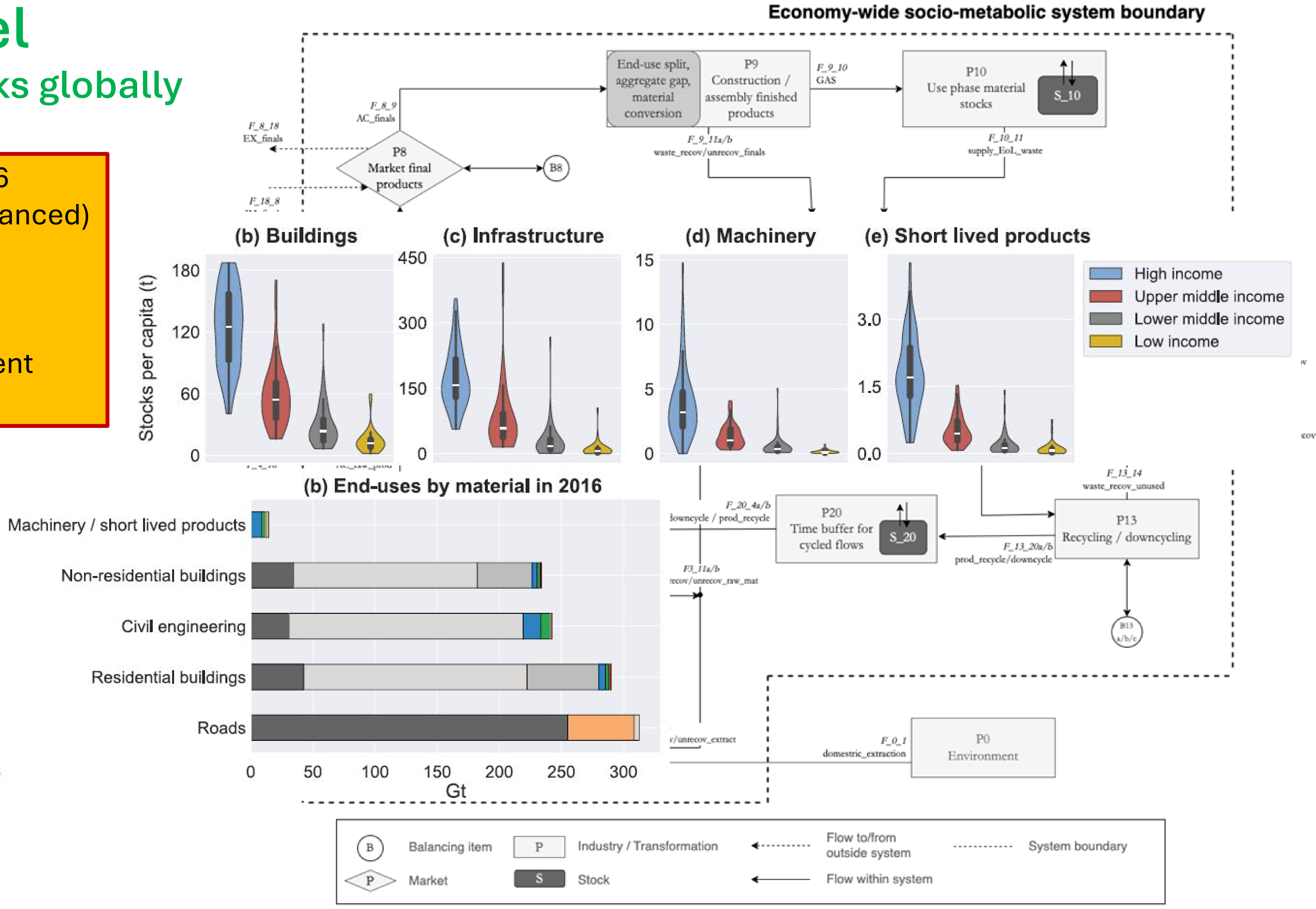

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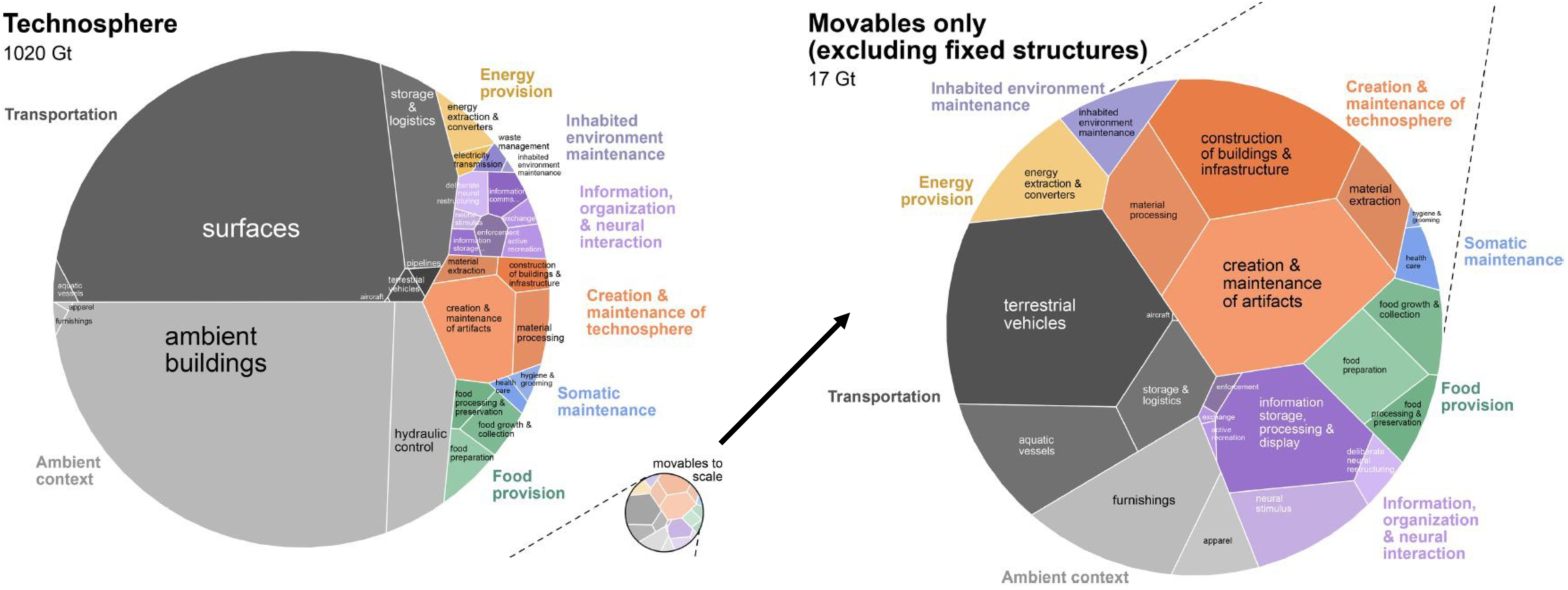
Functions of socioeconomic material stocks

Left: infrastructures (buildings, mobility, etc.), Right: vehicles, machinery & other products)



Galbraith et al. 2025. Earth System Dynamics, 16, 979–999, https://doi.org/10.5194/esd-16-979-2025

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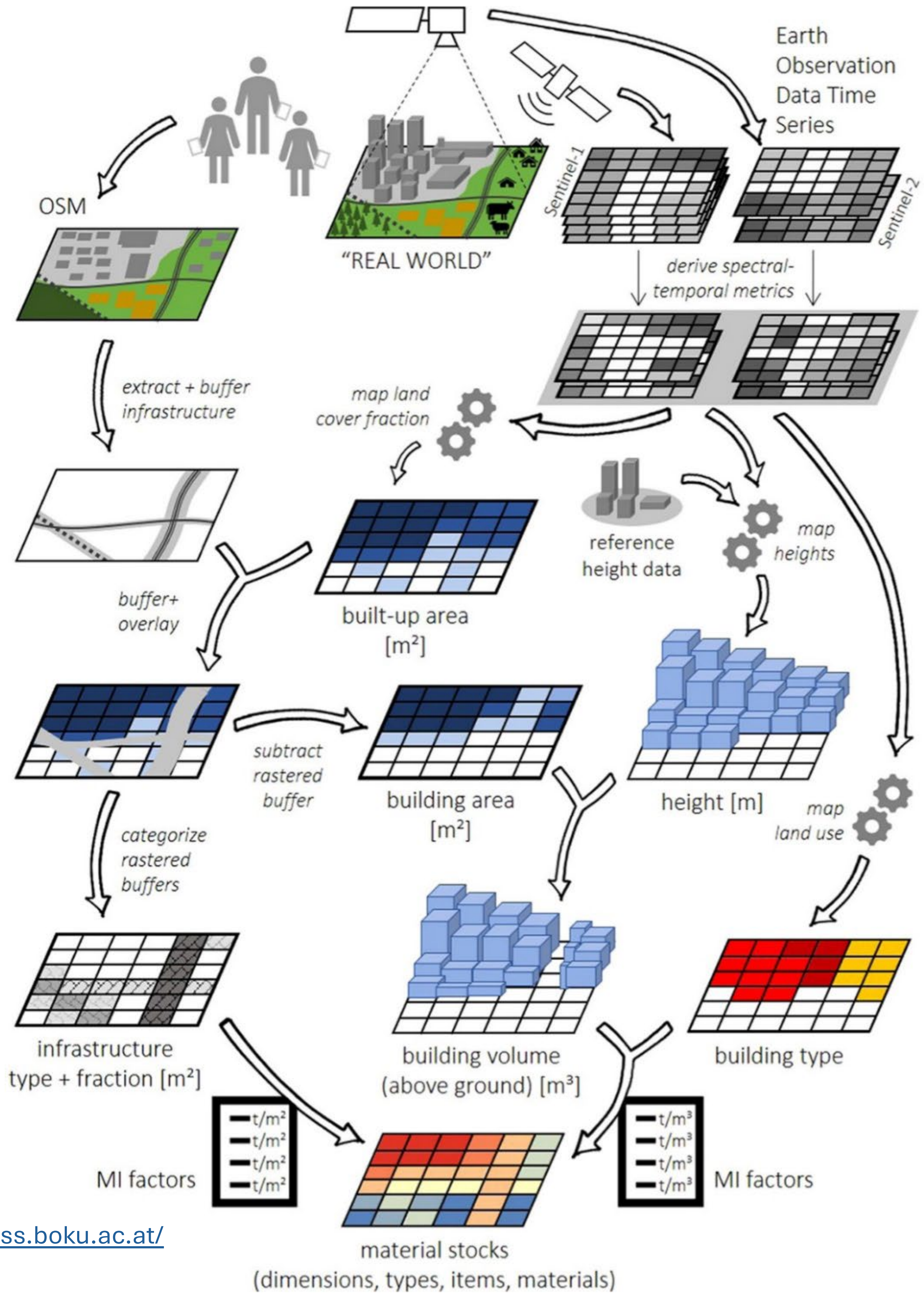
Mapping material stocks in built structures

Novel methods help generating high-resolution maps

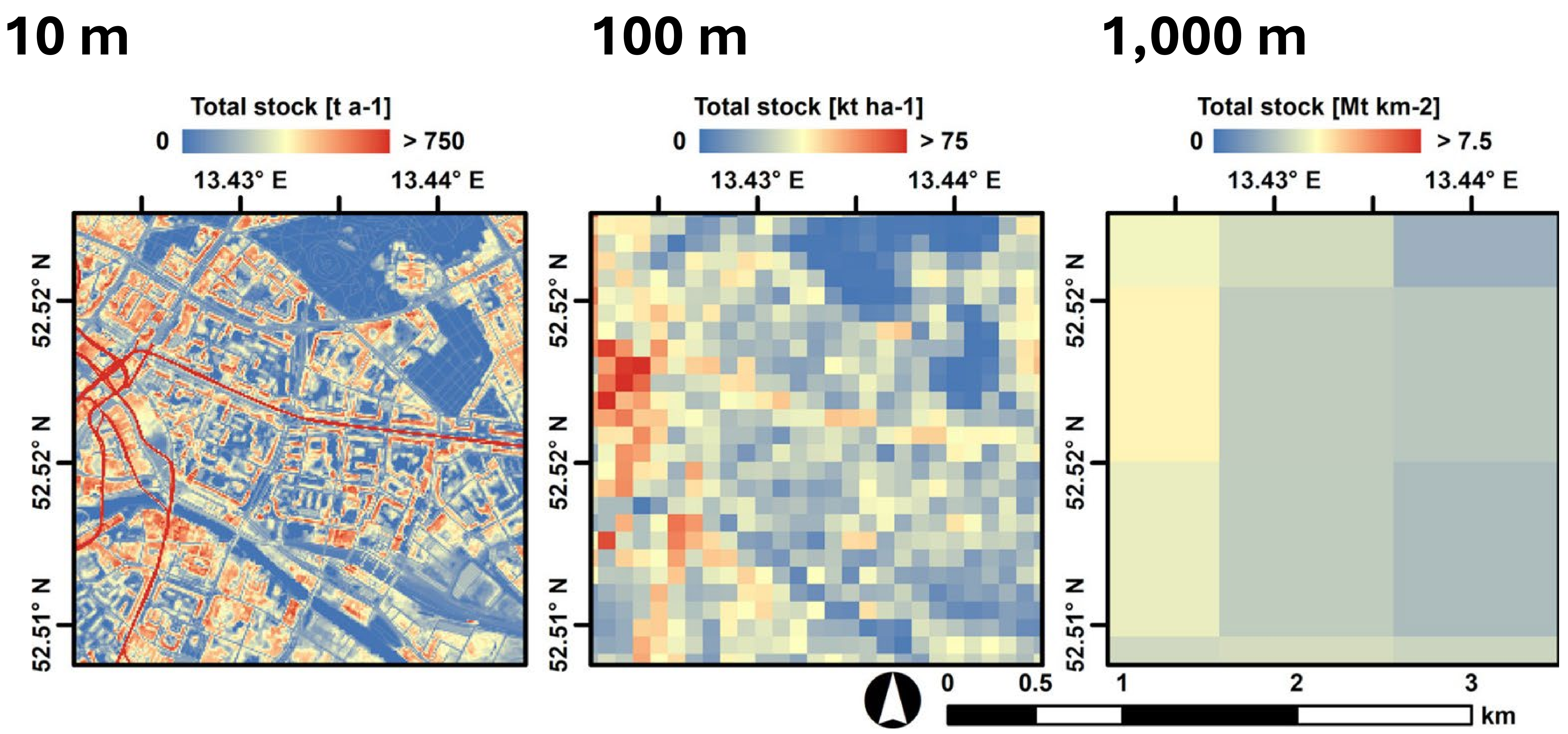
- Earth Observation data from newest-generation satellites (Copernicus) allow creating maps at **10m spatial resolution**
- Crowd-sourced data from Open Street Maps are used to **map linear structures**, in particular mobility infrastructures
- **Material intensities** are used to calculate mass of structures based on info on their dimensions (type, volume, length: kg materials of various types per m^3 building volume or m^2 road surface)
- Can be applied to **quantify and map material stocks** for entire countries and globally



Haberl et al., 2021. *Environmental Science & Technology.* https://doi.org/10.1021/acs.est.0c05642.

Why do we need high spatial resolution?

Types of built structures can only be discerned at high resolution



- Material stock maps derived with **nighttime lights** achieve 0.5-1 km resolution
- Distinguishing important features (types and spatial patterns of built structures) impossible at 1km
- 10 m resolution provides rich and meaningful information on **function of stocks**

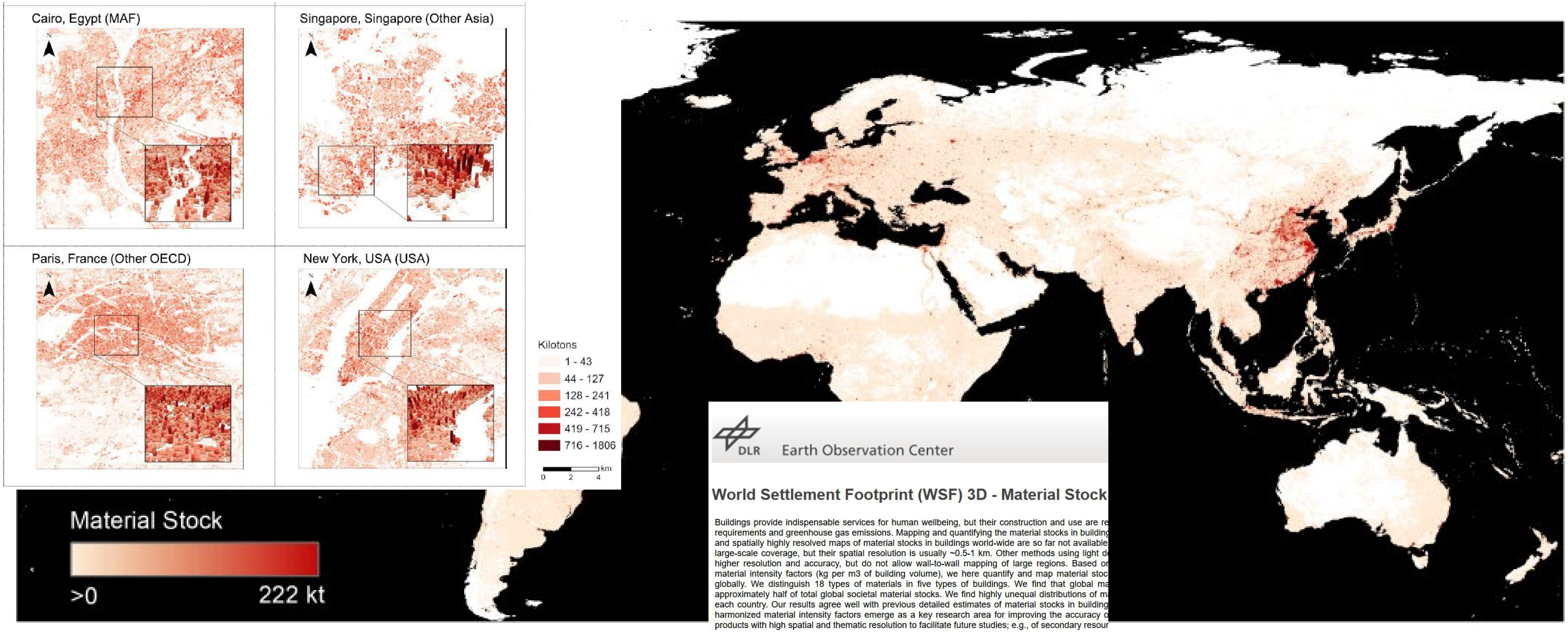
Maps of built structures (buildings & transportation infrastructures) at 10m resolution are meanhwile available for several countries, e.g. Austria & Germany (https://dx.doi.org/10.1021/acs.est.0c05642), also in >30 time series (https://doi.org/10.1111/jiec.13343), UK https://doi.org/10.1016/j.resconrec.2024.107630, conterminous USA (https://doi.org/10.1038/s41467-023-43755-5)

Haberl et al., 2021. *Env. Sci. Tech.* https://doi.org/10.1021/acs.est.0c05642.

This research was funded in whole or in part by the Austrian Science Fund (FWF) [10.55776/EFP5]

Global map of material stocks in buildings

Year 2018, 90m resolution, 18 types of materials, 5 types of buildings. Mass of all buildings 547 (391-672) Gt, 60% of all socioeconomic material stocks



DLR Earth Observation Center

World Settlement Footprint (WSF) 3D - Material Stock

Buildings provide indispensable services for human wellbeing, but their construction and use are re
requirements and greenhouse gas emissions. Mapping and quantifying the material stocks in building
and spatially highly resolved maps of material stocks in buildings world-wide are so far not available
large-scale coverage, but their spatial resolution is usually ~0.5-1 km. Other methods using light d
higher resolution and accuracy, but do not allow wall-to-wall mapping of large regions. Based or
material intensity factors (kg per m3 of building volume), we here quantify and map material stoc
globally. We distinguish 18 types of materials in five types of buildings. We find that global ma
approximately half of total global societal material stocks. We find highly unequal distributions of m
each country. Our results agree well with previous detailed estimates of material stocks in building
harmonized material intensity factors emerge as a key research area for improving the accuracy o
products with high spatial and thematic resolution to facilitate future studies; e.g., of secondary resour

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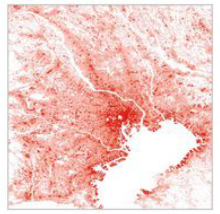
Haberl *et al.* 2025. *Journal of Industrial Ecology*
doi: 10.1111/jiec.13585

Data product freely available online:
https://doi.org/10.15489/h80jhtr41x48



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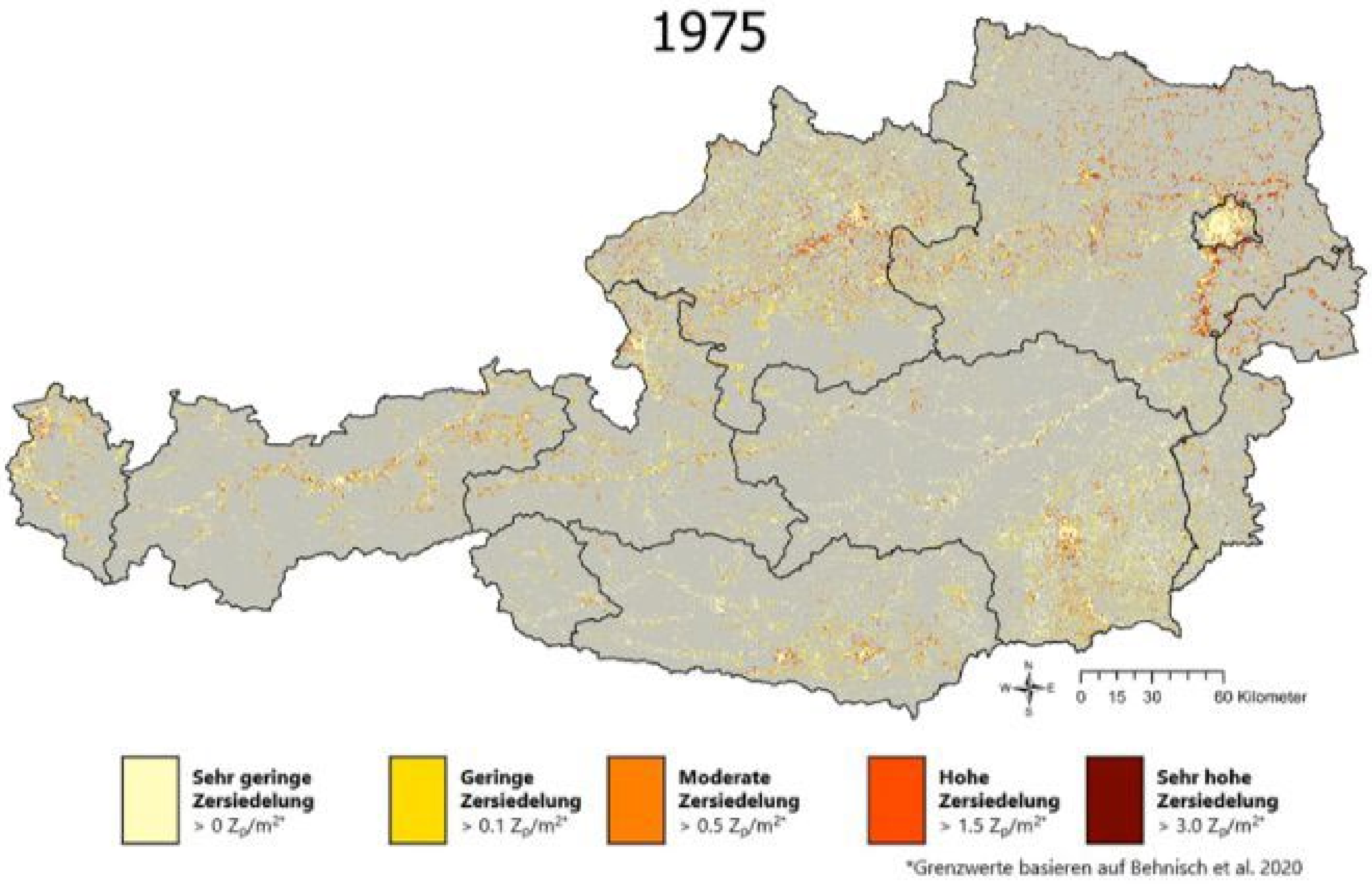
Development of urban sprawl in Austria 1975-2020

Resource-intensive stock/flow patterns spread rapidly



Highly sprawled areas (orange, brown) rise rapidly

→ Massive resource demand for construction (buildings, infrastructure)
→ Emerging patterns promote resource-guzzling practices (high energy, land and materials demand)
→ Delivery of services requires more, not less resources

Grey: no data
Warm colors: gradient of sprawl intensity (yellow low – deep purple: very high)

Brenner *et al*. 2024. *Social Ecology Working Paper* No. 198, Vienna, BOKU University

Leibniz Institute of Ecological Urban and Regional Development

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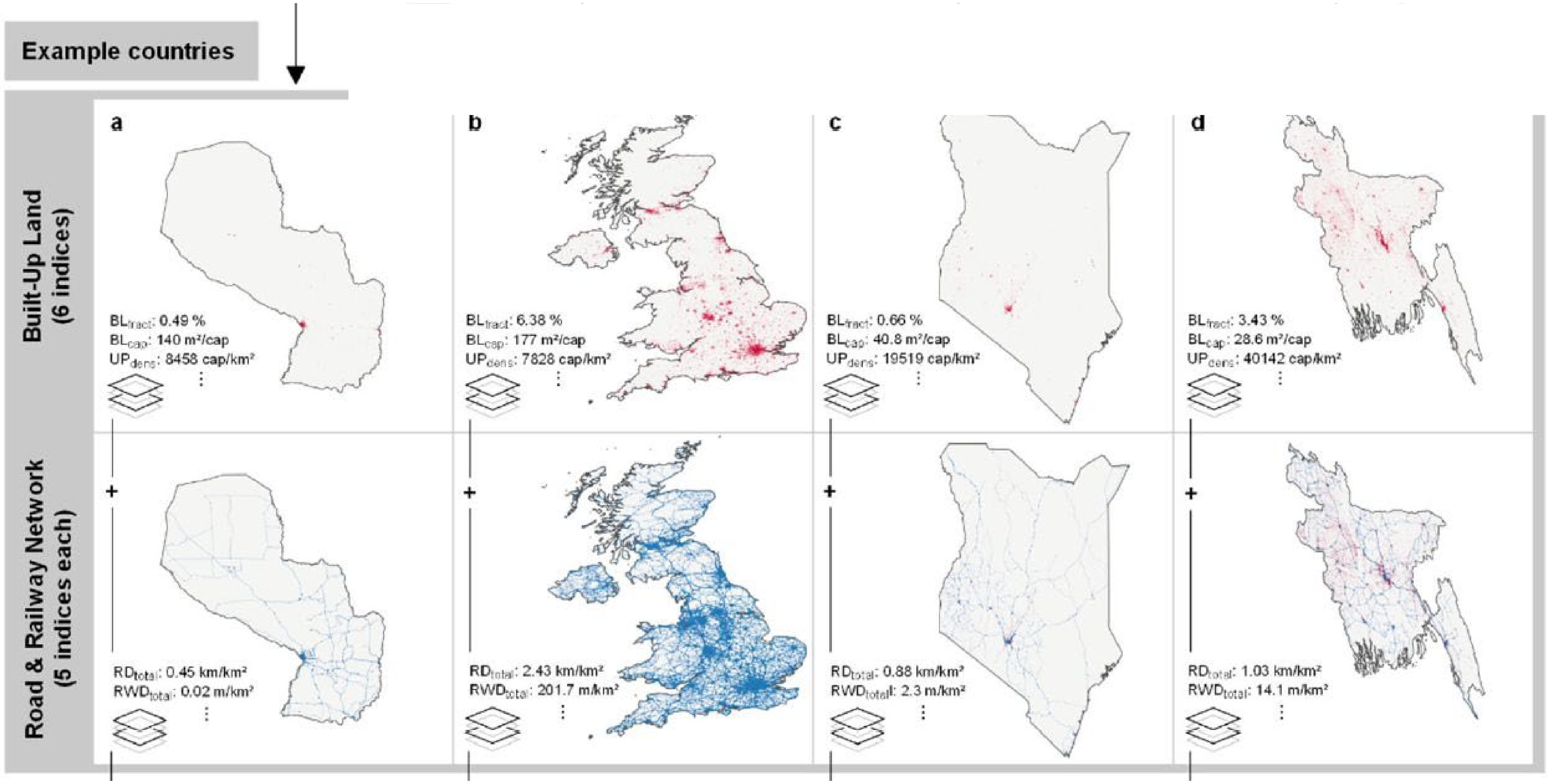
Importance of material stocks for resource demand

Built structures co-determine per-capita resource use and CO_2 emissions



Question: How strongly do extent and spatial patterns of built structures affect **national resorce use and emissions** (final energy, GHG) per capita, on top of other drivers?

Method: Various **advanced statistical cross-country analyses** including usual IPAT/STIRPAT variables (GDP, pop.dens, energy prices, heating-degree days…) and 16 material stock pattern indicators

RESULTS

- Material stock patterns are **strongly correlated with energy use and emissions**, and play an important role in statistical models of cross-country differences in energy/GHG. These models are much better than classical STIRPAT models
- Per-capita **area of built-up land** is almost as important as GDP, 2nd-most important factor in almost all analyses
- Very similar results obtained for material use indicators (domestic material consumption, material footprint)

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Haberl *et al* , 2023. *Nature Communications*, 14, 3898 https://doi.org/10.1038/s41467-023-39728-3
Duro *et al.*, 2024. *Journal of Industrial Ecology*, https://doi.org/10.1111/jiec.13470

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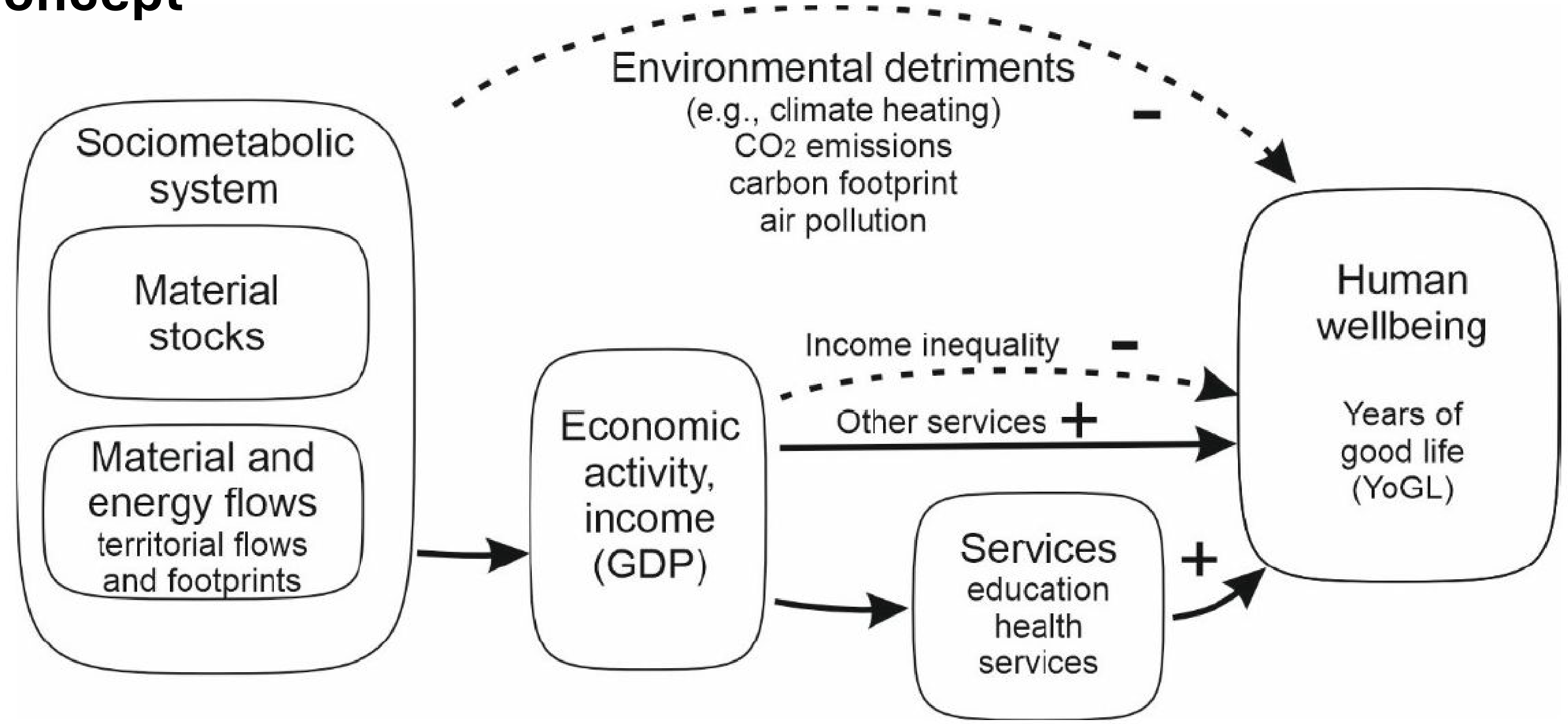
reMASS

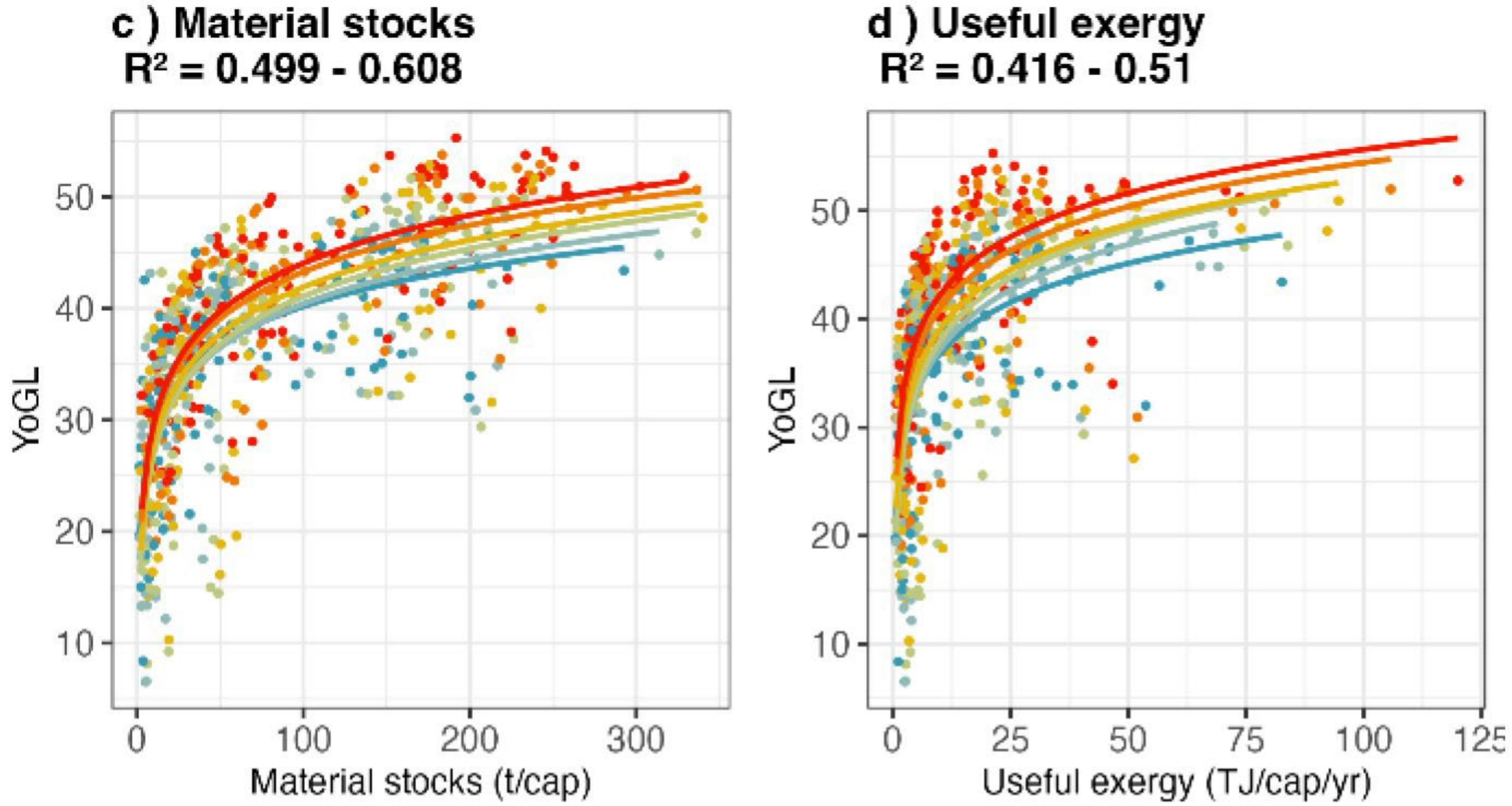
Contributions of resources to human wellbeing

Panel analysis 1990-2019 of factors influencing Years of Good Life (YOGL) in >100 countries

Concept



Bivariate *(no intervening variables)*



Multivariate panel analysis considering intervening variables

- GDP significantly contributes to YOGL when all countries are considered
- **But:** GDP is not significant when only ‚High-YOGL' countries (top 3 deciles) are analyzed
- Education and health service always have a strong positive effect, as expected (highly consistent)
- Air pollution (PM2.5) and inequality have strong negative effects (inequality only for differences between countries)
- Resource and emission indicators seldom significant, and sometimes negatively correlated (e.g. CO2 emissions)

→ **Resources per se are not important for YOGL, but their services are**

→ **Key focus on improving education & healthcare, reducing emissions & inequality, eco-efficiency & sufficiency**

REMASS | Resilience and Malleability of Social Metabolism | doi: 10.55776/EFP5 | https://remass.boku.ac.at/
Haberl et al, submitted

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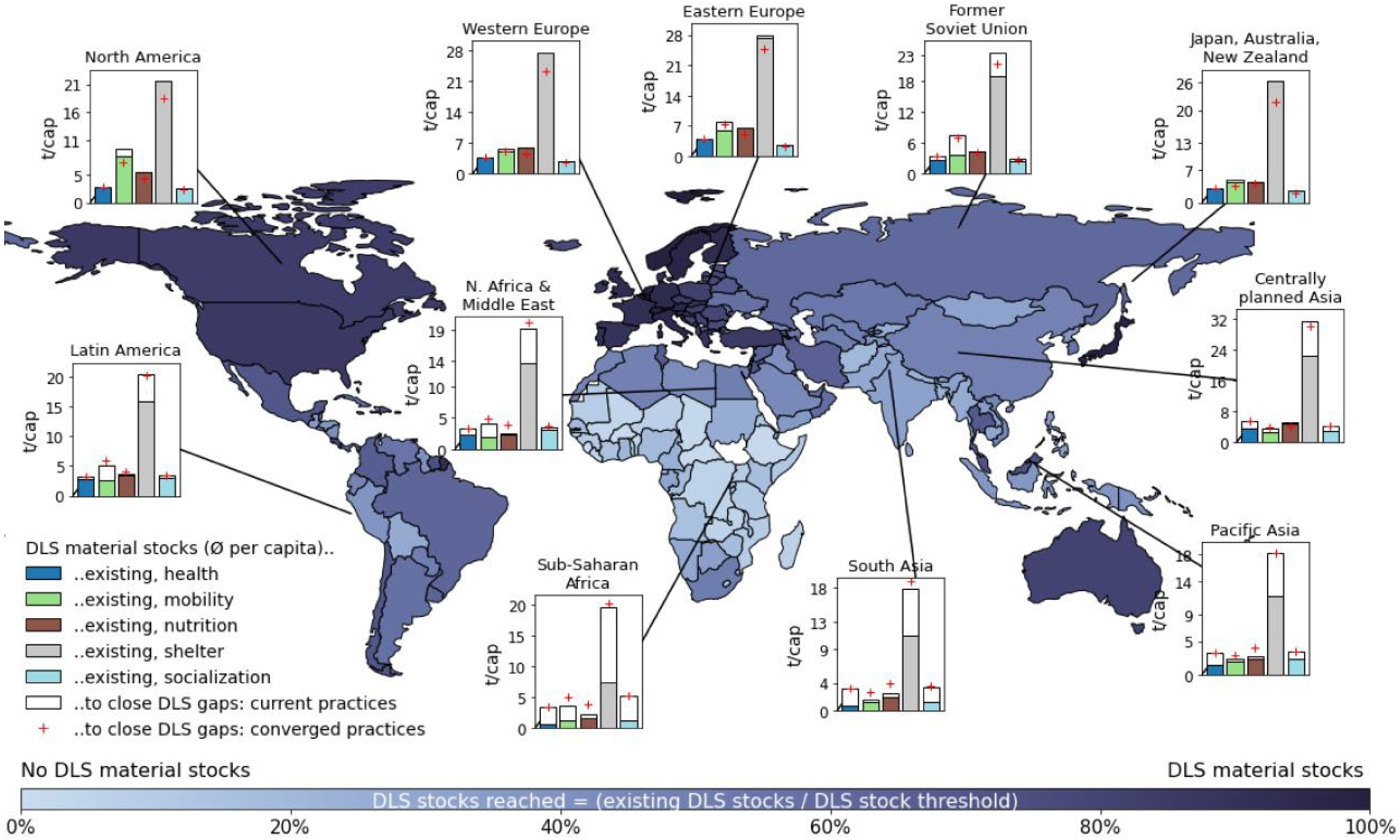
Material stocks providing services for Decent Living Standards (DLS); regional gaps for achieving DLS for all



- Some countries have material stocks far exceeding those required for DLS
- Still, even in those countries gaps persist for some services
- Study finds that closing DLS gaps would be feasible and require relatively little resources
- But only if DLS stocks are prioritized

Streeck et al., *in review*

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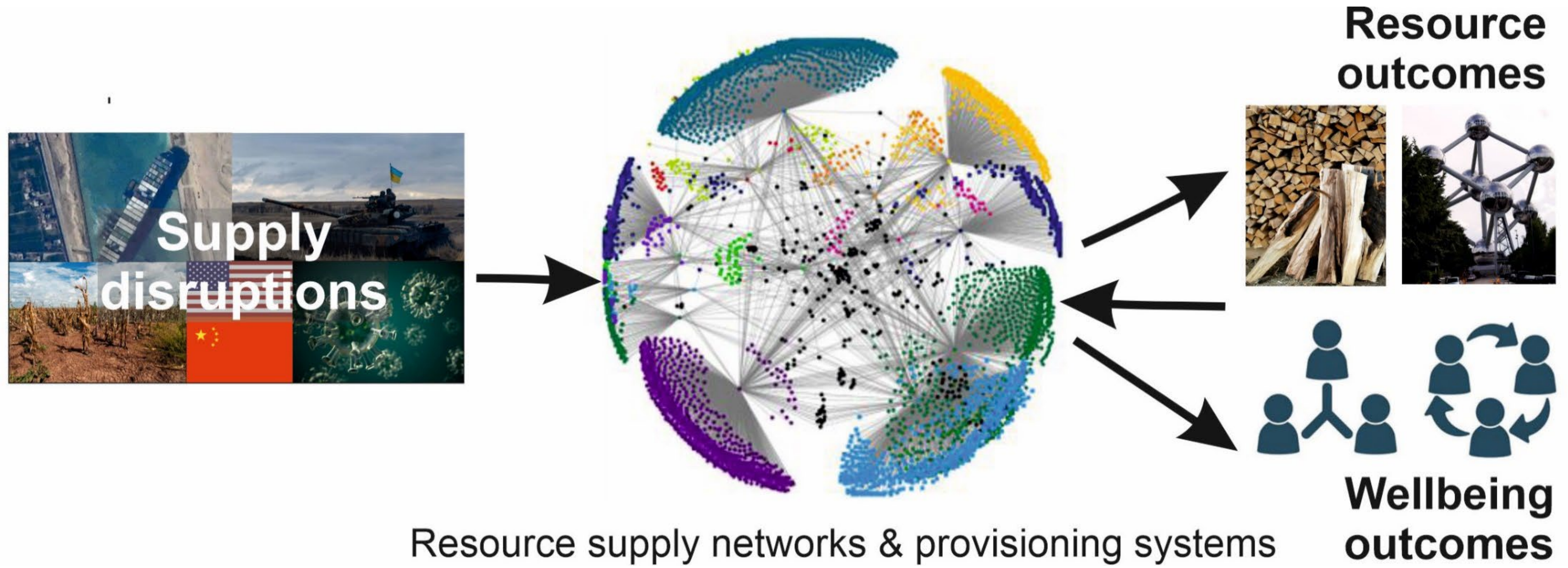
Current directions: resilience and malleability of social metabolism



- Disruptive events hit **highly complex global supply networks** and may result in a wide range of tipping phenomena
- They may contribute to **changes in resource use** as well as **wellbeing and distribution**
- They alter **power relations** and **option spaces** of actors and institutions aiming to work towards sustainability

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Conclusions

- Infrastructures are a key driver of resource use. Their buildup currently requires ~60% of all material resources globally.
- Size and patterns of infrastructures are key determinants of dissipative use of resources (e.g., energy use) and thereby drive GHG emissions and other environmental pressures
- They play a crucial role for lock-in effects (e.g., stabilization of resource-intensive lifestyles)
- Infrastructures play a crucial role in providing societies with services of key importance for human wellbeing
- Better design of infrastructures can help to improve well-being contributions while reducing resource use and emisions

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