

Spatial data approaches for assessing the environmental and socioeconomic impacts of mining activities

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Overview

Contextual risks
associated with mining
expansion

Local impacts and
spillover effects

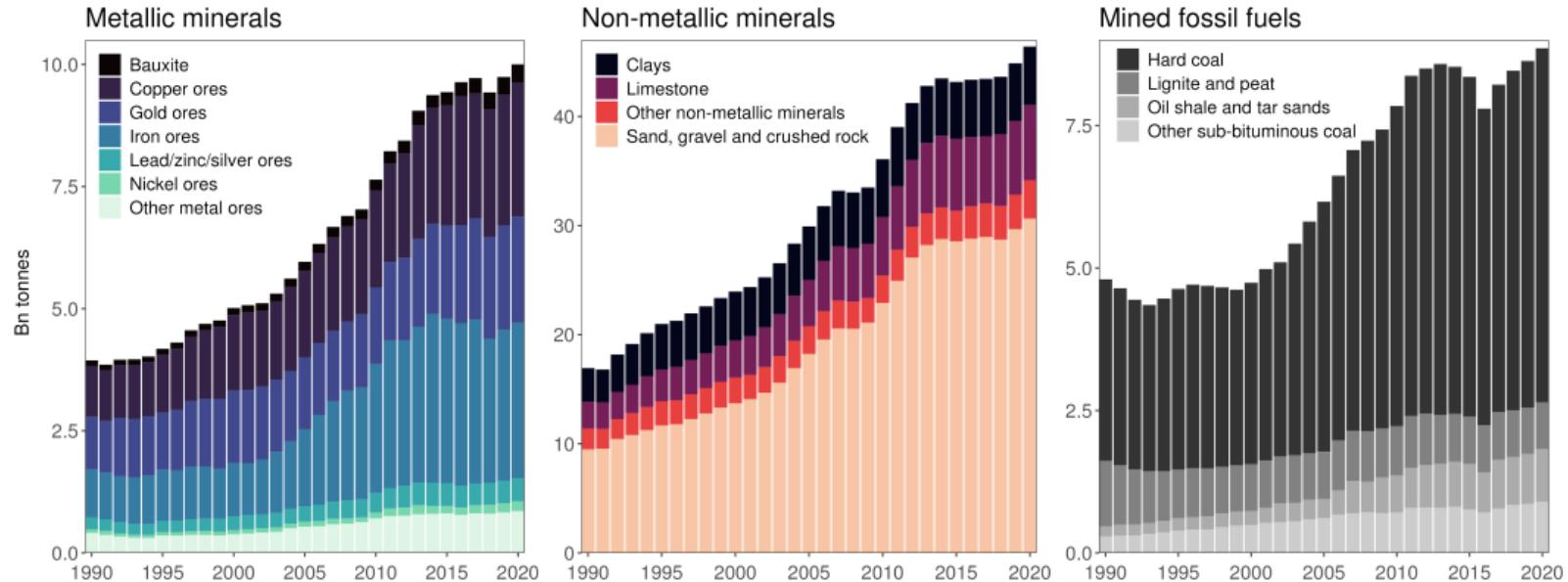
Spatial disconnect
between impacts and
consumption

1. Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V., and Tost, M. (2021): “**Surge in global metal mining threatens vulnerable ecosystems**”, *Global Environmental Change*.
2. Luckeneder, S., Maus, V., Siqueira-Gay, J., Krisztin, T., and Kuhn, M. (2024): “**Transient economic benefit and persistent forest loss: regional impacts of mining in Brazil**”, under revision for *Nature Communications*.
3. Luckeneder, S., Giljum, S., Maus, V., Sonter, L., and Lenzen, M. (2024): “**EU consumption’s hidden link to global deforestation caused by mining**”, submitted to *Science*, under review.

Other publications

1. Maus, V. et al. (2020): “**A global-scale data set of mining areas**”, *Scientific Data*.
2. Tost, M. et al. (2020): “**Ecosystem services costs of metal mining and pressures on biomes**”, *The Extractive Industries and Society*.
3. Maus, V. et al. (2022): “**An update on global mining land use**”, *Scientific Data*.
4. Giljum, S. et al. (2022): “**A pan-tropical assessment of deforestation caused by industrial mining**”, *Proceedings of the National Academy of Sciences*.
5. Cerny, M. and Luckeneder, S. (2023): “**Undermined efforts? The ambiguous role of mining jobs in a just transition**”, *Journal für Entwicklungspolitik*.
6. Kramer, M. et al. (2023): “**Extracted forests. Unearthing the role of mining-related deforestation as a driver of global deforestation**”. Berlin: WWF.
7. Sonter, L. et al. (2023): “**How to fuel an energy transition with ecologically responsible mining**”, *Proceedings of the National Academy of Sciences*.
8. Giljum S. et al. (2024): “**Global metal mining is a growing driver of environmental change**”, *Nature Reviews Earth & Environment*, under review.

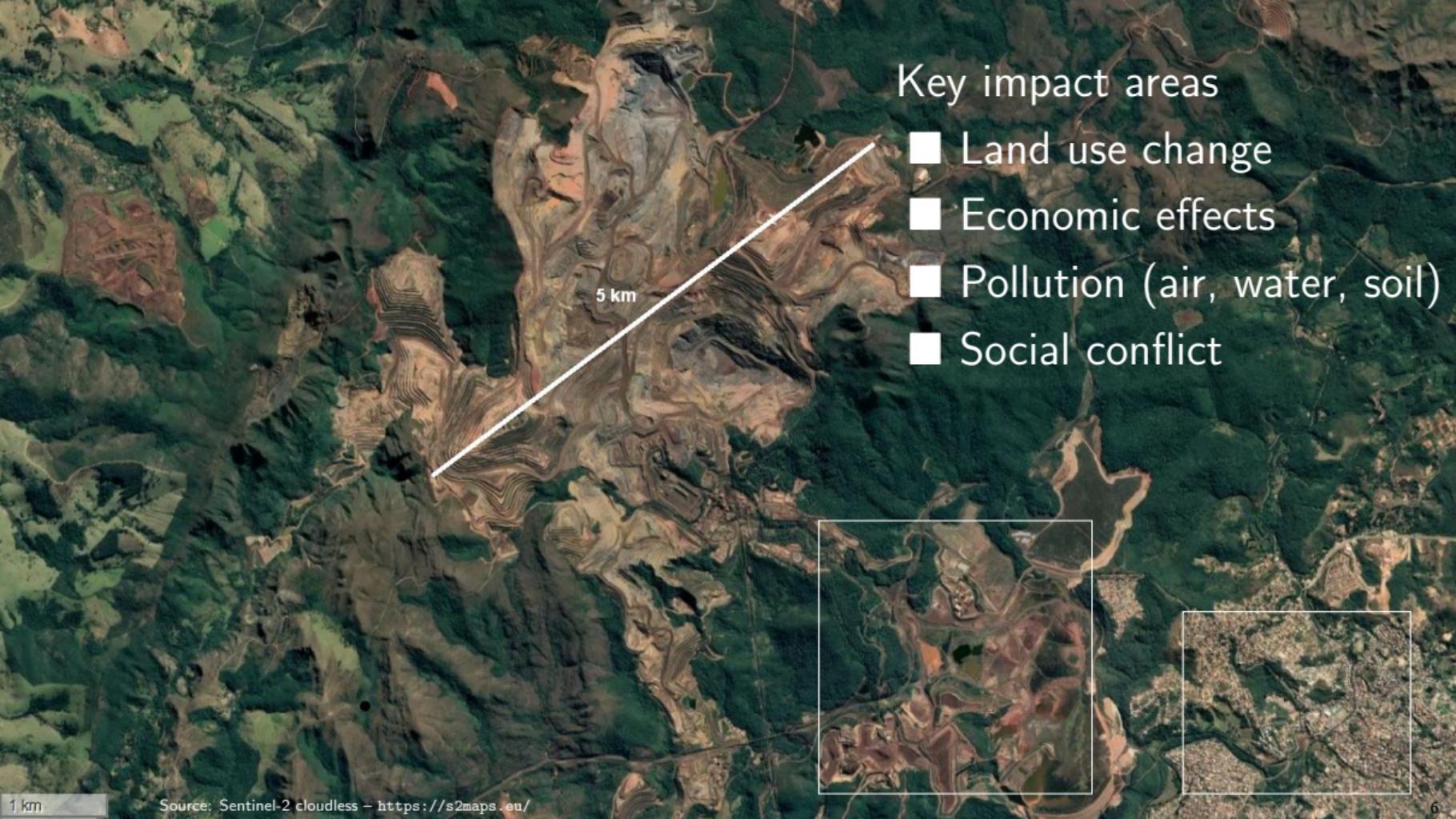
Historically high level of material extraction



UN IRP Material Flows Database, Lenzen et al. (2017; 2022)



Photo: Sebastian Luckeneder



A satellite map showing a large industrial mining operation. The site features extensive open-pit mining with deep, irregular pits and surrounding processing facilities. A white diagonal line points from the top right towards the center of the mining area. In the bottom right corner, there are two inset boxes: one showing a close-up of agricultural fields and another showing a residential or industrial area. A scale bar indicates 5 km. A small black dot is located near the bottom left corner of the main map area.

Key impact areas

- Land use change
- Economic effects
- Pollution (air, water, soil)
- Social conflict

What we know

- Vast amount of **case studies** on social and environmental consequences (Temper et al. 2015)

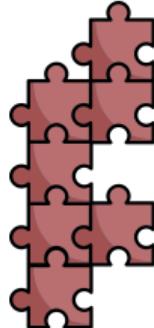


Giljum et al., *in preparation*

- Continued **acceleration of mining activities**
 - Demand for housing, transport and energy infrastructure in emerging economies (JRC 2023; UN IRP 2024)
 - Increasing adoption of renewable energy technologies (Watari et al. 2019; Watari et al. 2020)
 - Declining ore grades and mining engineering advancements (Prior et al. 2012)



Research gaps



Limited **systematic quantitative assessments** of mining impacts

- ▶ Persistent data gaps (Maus and Werner 2024)
- ▶ Indirect and cumulative impacts of mining (Franks et al. 2013; Lechner et al. 2017)



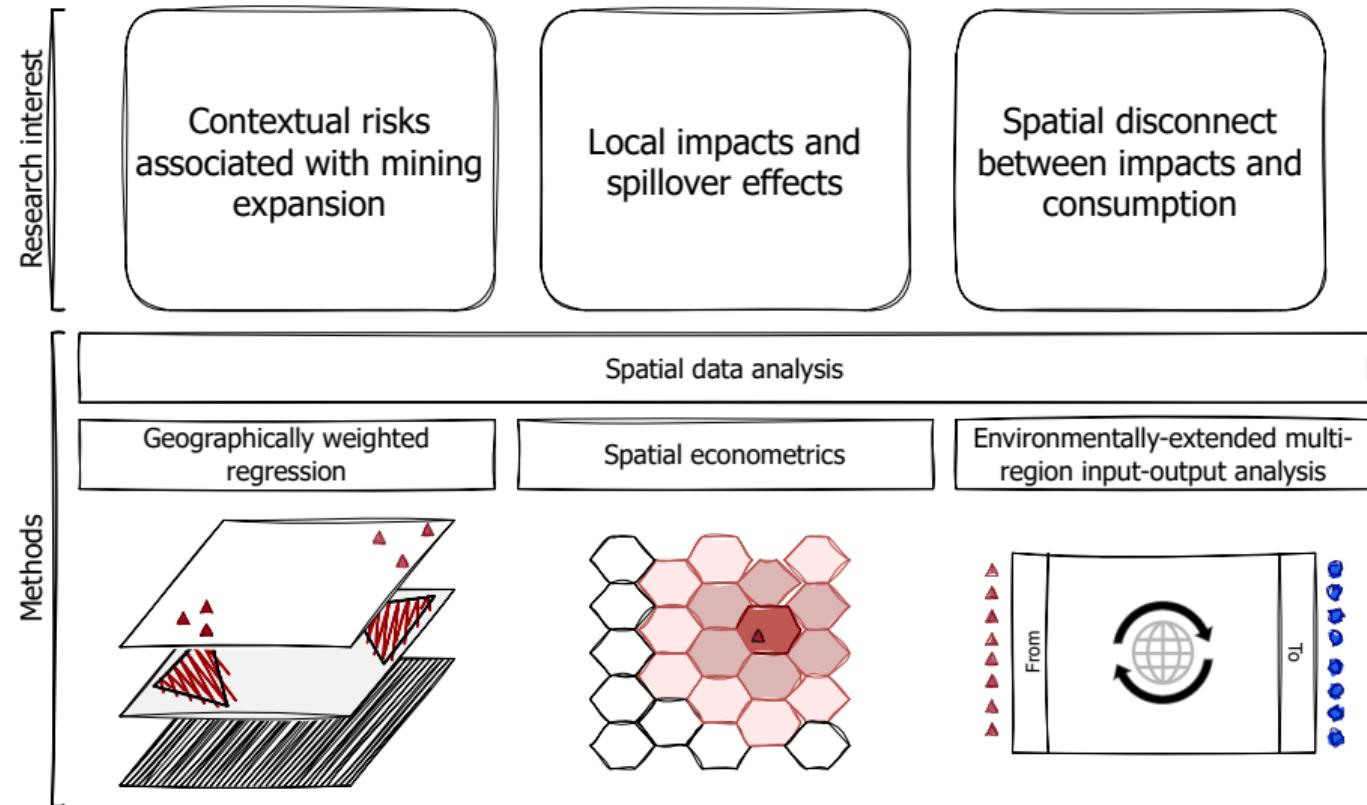
Lack of **transparency for mineral supply chains** (Calderon et al. 2020)

- ▶ Difficulties in tracing localised mining impacts to final demand elsewhere



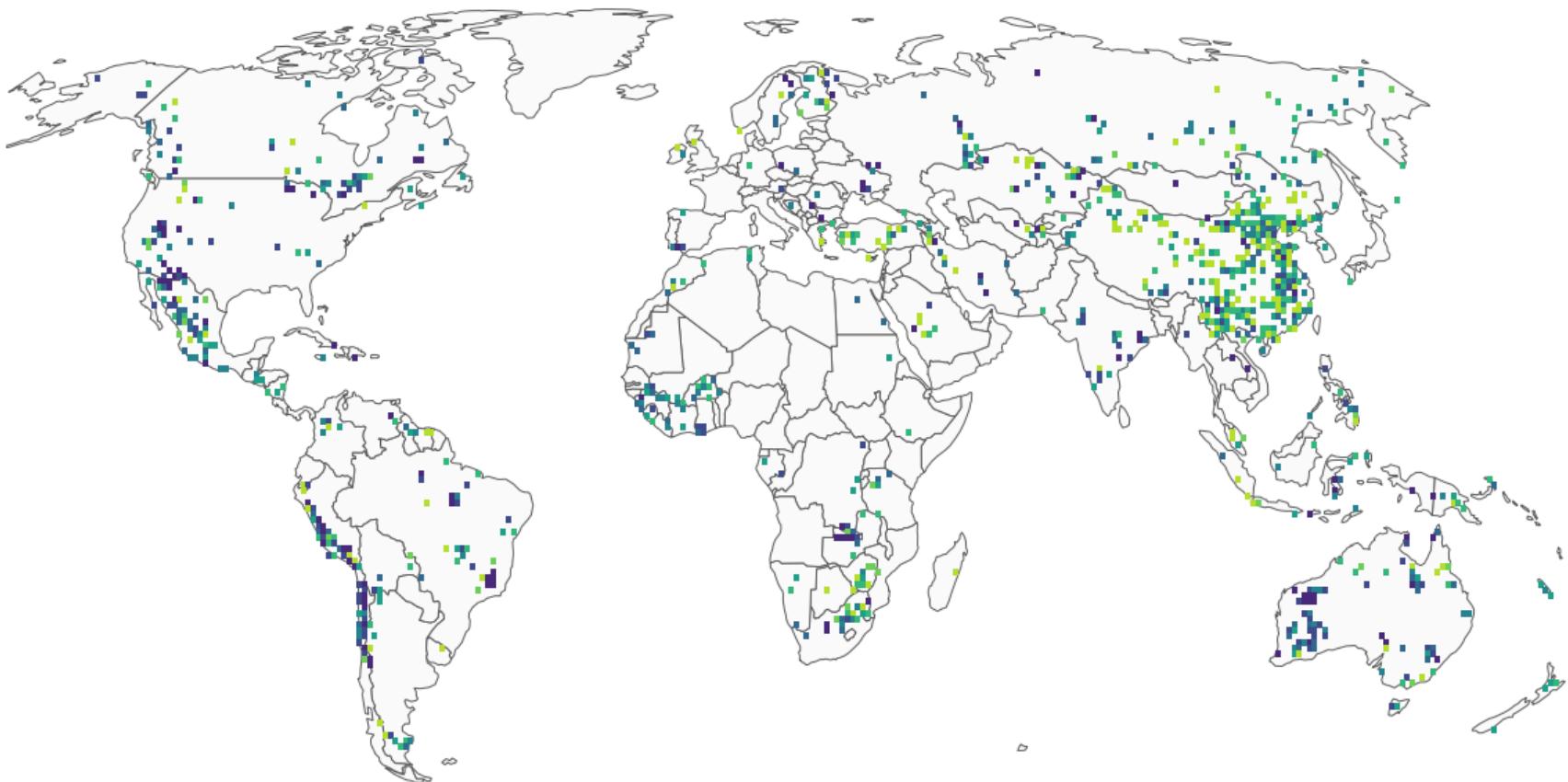
Huge **potential of GIS** and remote sensing (Werner et al. 2019; Werner et al. 2020)

Spatial data approaches

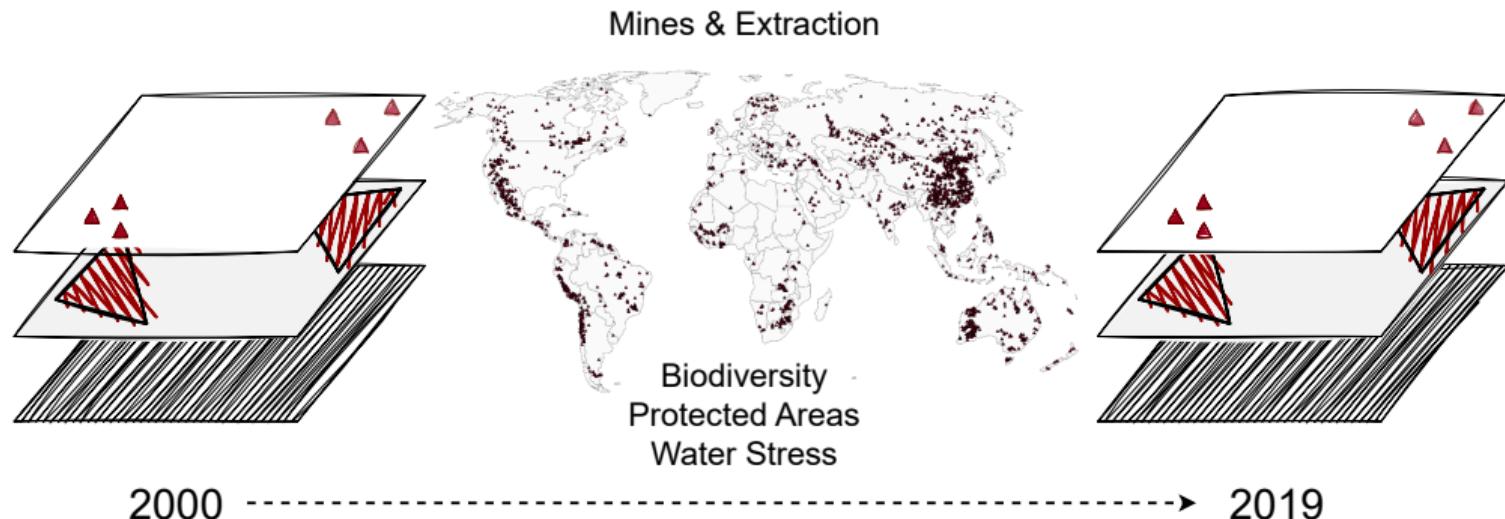


Contextual risks associated with mining expansion

Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V., and Tost, M. (2021): “**Surge in global metal mining threatens vulnerable ecosystems**”, *Global Environmental Change*.



Mining expansion threatens vulnerable ecosystems

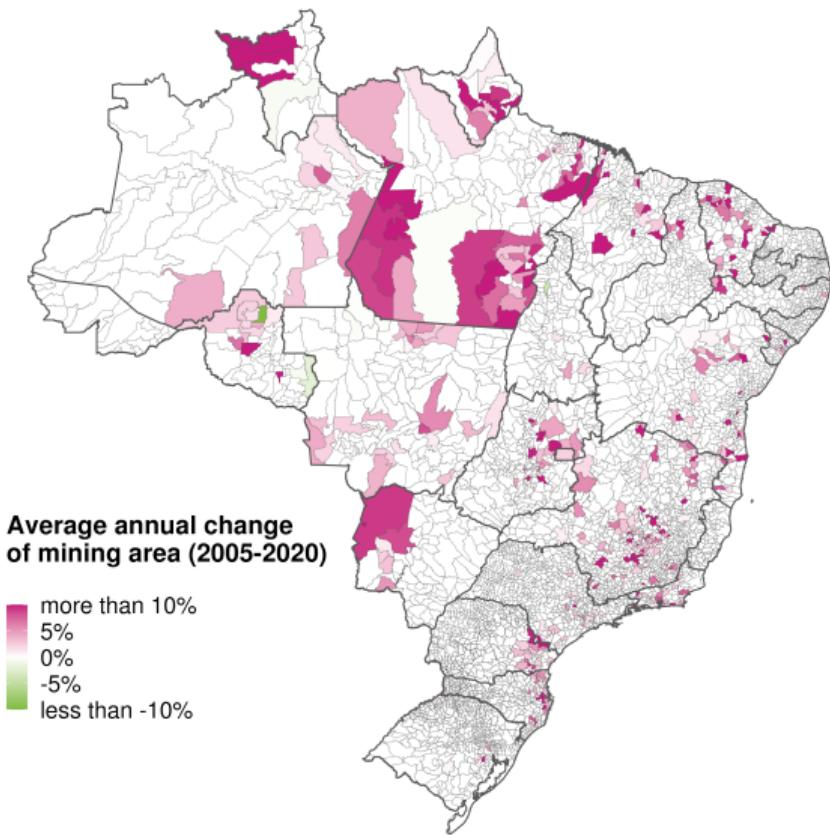


- ▶ 5 of the 6 most biodiverse biomes originate 79% of total ore mined in 2019.
- ▶ Half of all metal mining worldwide occurs at less than 20 km from protected lands.
- ▶ Intensification of extraction at detected hotspots (Peru, **Brazil**, DRC, Zambia, etc.)

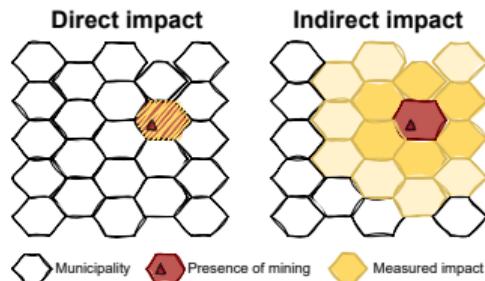
Local impacts and spillover effects

Luckeneder, S., Maus, V., Siqueira-Gay, J., Krisztin, K., and Kuhn, M. (2024): “**Transient economic benefit and persistent forest loss: regional impacts of mining in Brazil**”, under revision for *Nature Communications*.

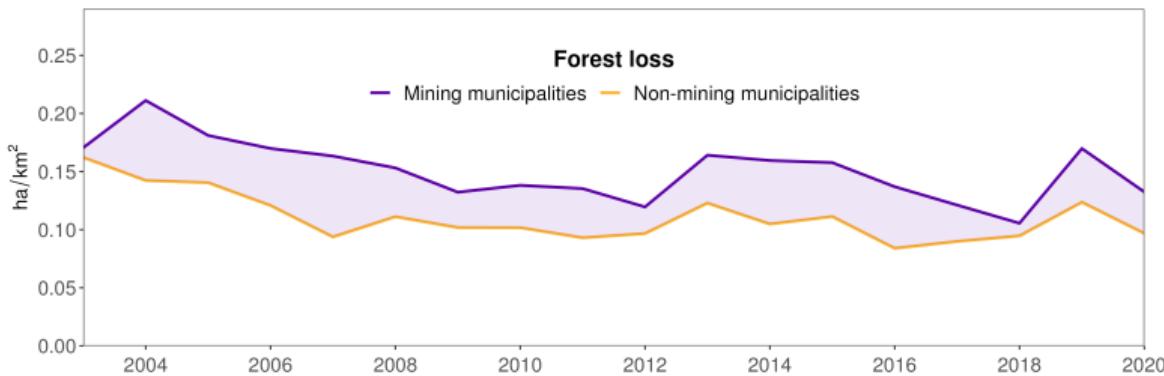
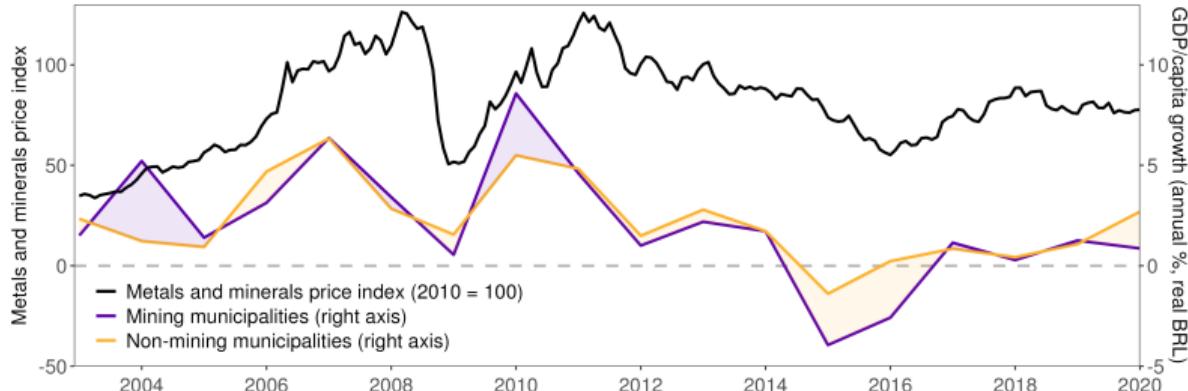
Brazil - extraction and biodiversity hotspot



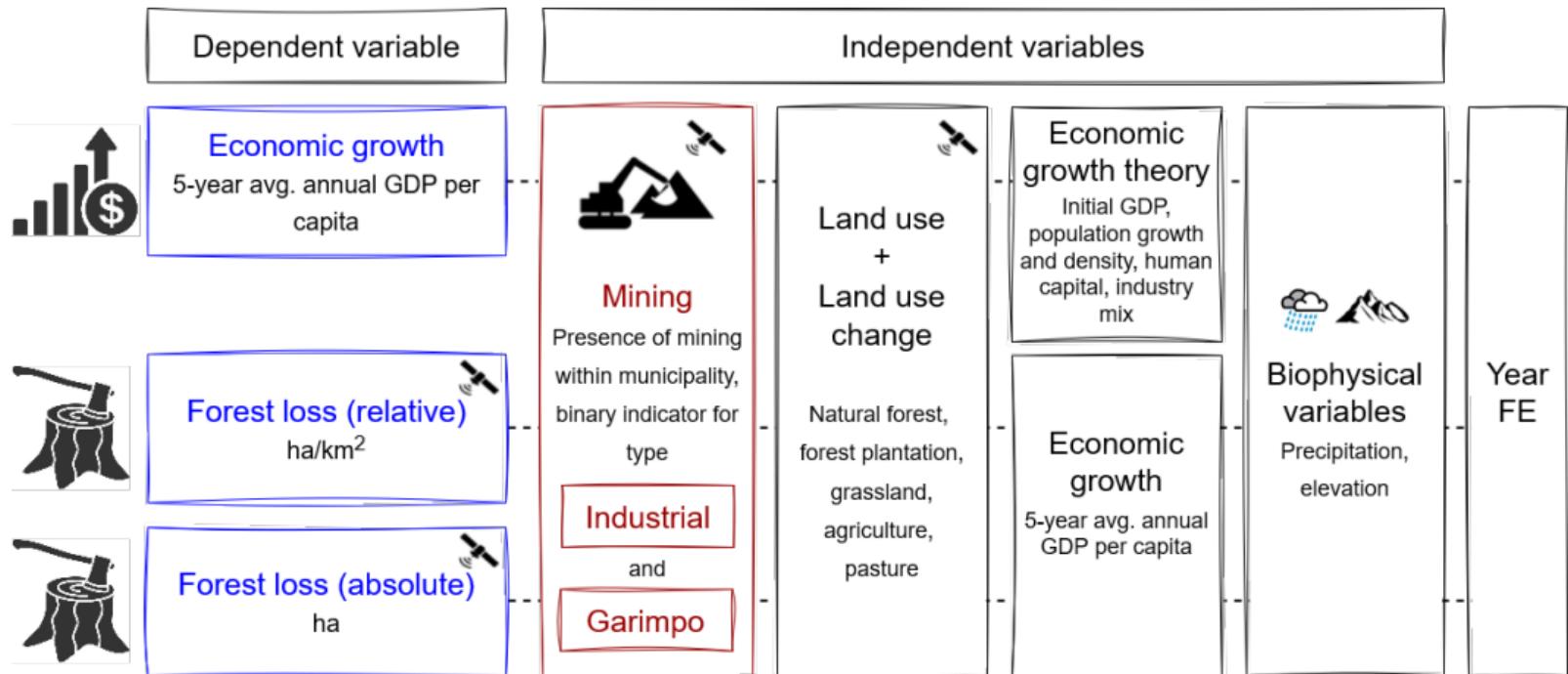
- ▶ Economic impacts?
→ Municipality GDP
- ▶ Environmental impacts?
→ Forest cover loss
- ▶ Spillovers across municipalities?



Trade-offs between economic and environmental impacts?



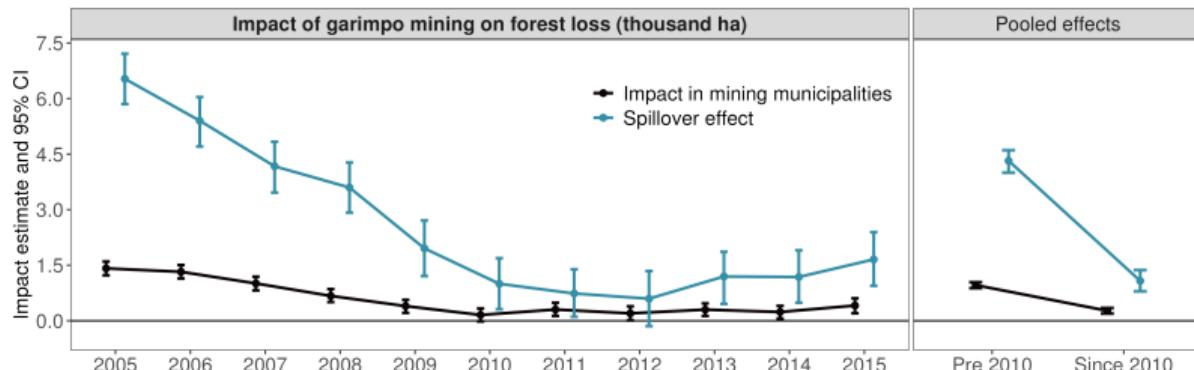
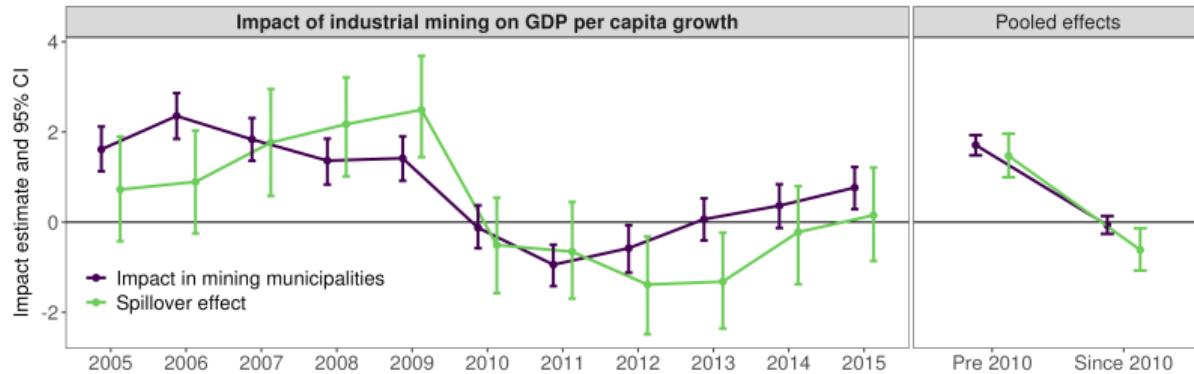
Empirical framework paper 2



5,262 Brazilian municipalities, yearly data 2005-2020

$$\mathbf{y}_t = \rho \mathbf{W} \mathbf{y}_t + \mathbf{X}_t \boldsymbol{\beta} + \mathbf{W} \mathbf{X}_t \boldsymbol{\theta} + \boldsymbol{\xi}_t + \epsilon_t, \quad \epsilon_t \sim N(\mathbf{0}, \sigma^2 \mathbf{I}_n)$$

Transient economic benefit and persistent forest loss in Brazil

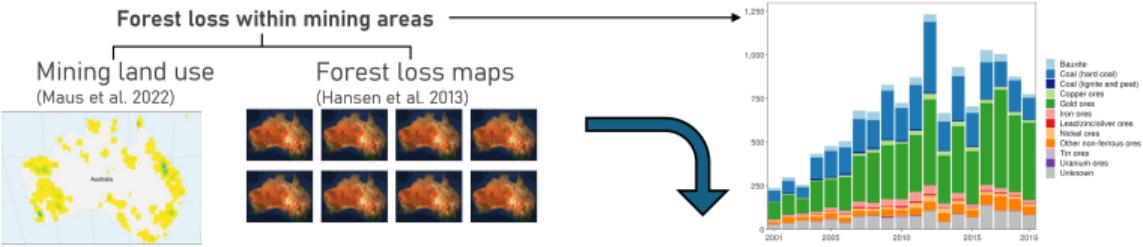


Spatial disconnect
between impacts and
consumption

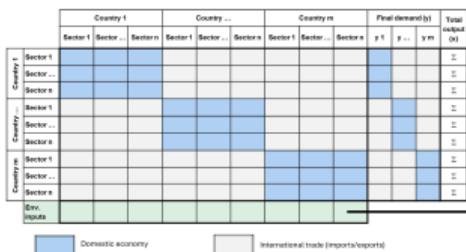
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Empirical framework paper 3

Production Perspective



Multi-region input-output (MROI) model

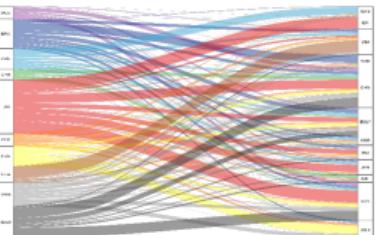


GLORIA IO tables (Lenzen et al. 2017, 2022)
160 countries + 4 ROW
120 industry sectors

"Forest loss intensity"
(area forest loss / \$ output in mining sector)

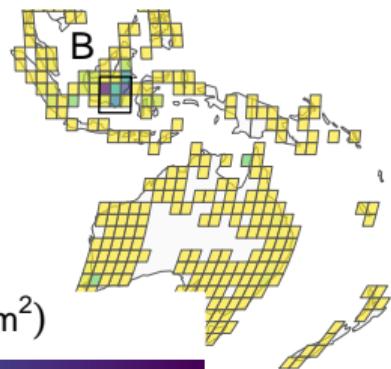
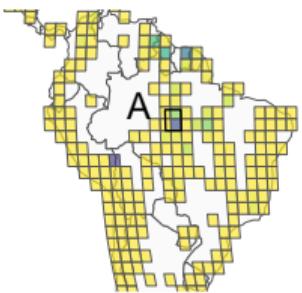
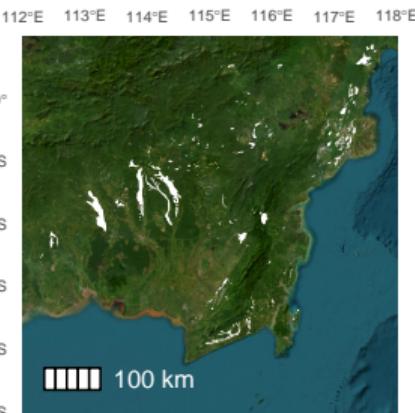
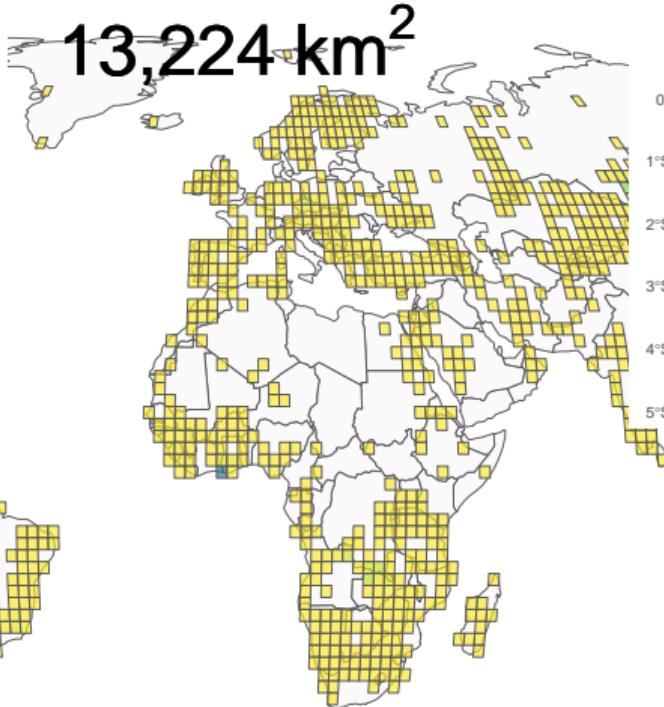
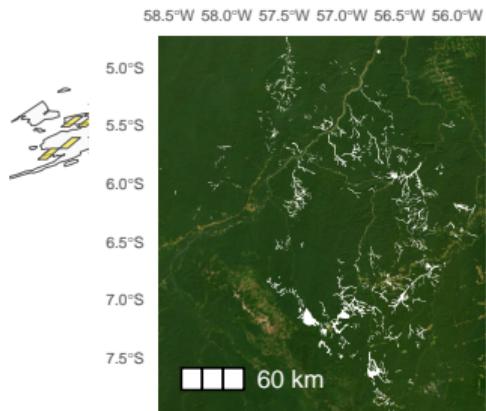
Consumption Perspective

Local forest loss impacts

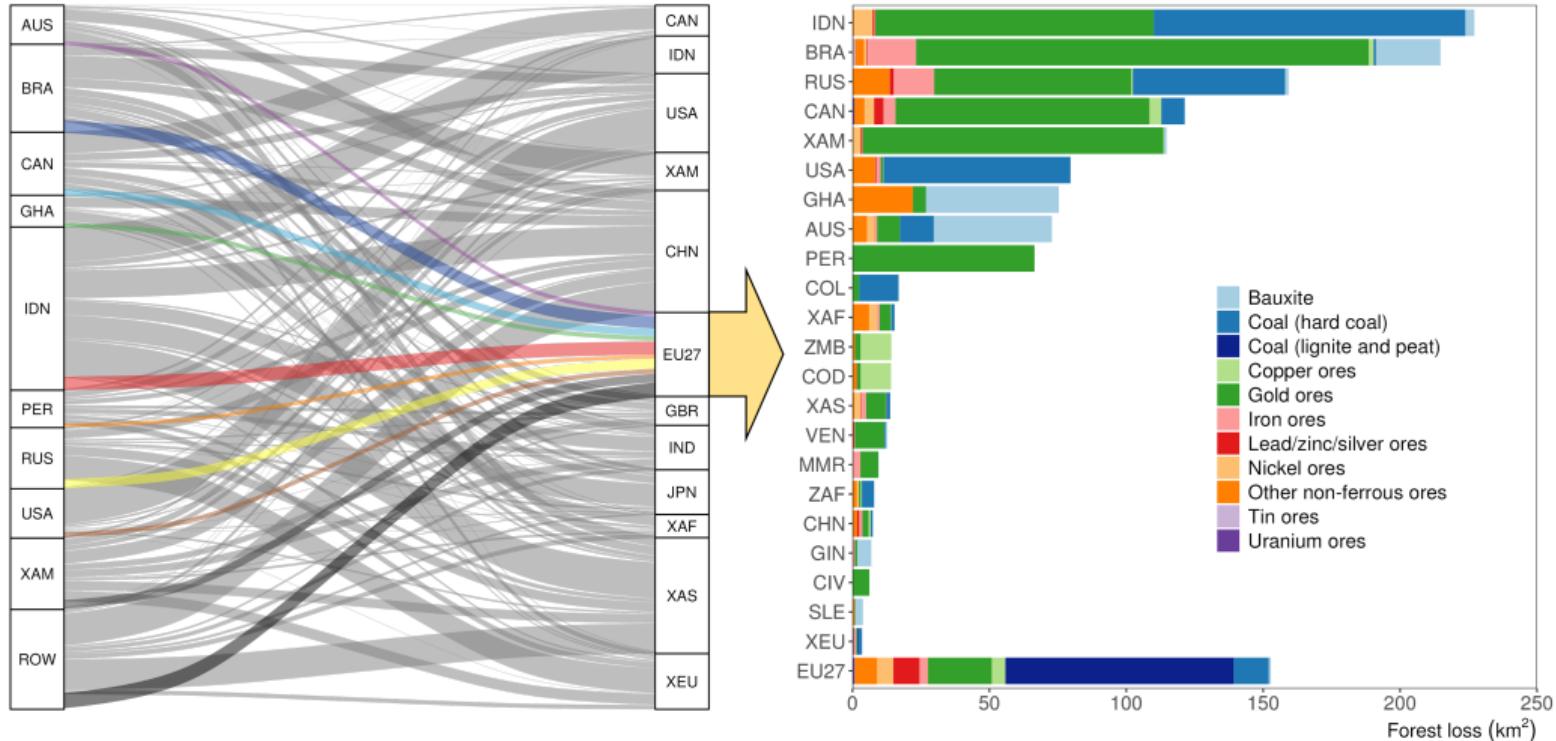


Forest loss embodied in consumer countries and sectors

From local impacts...



... to deforestation embodied in the European Union's final demand



Conclusions

Recap: the mined materials dilemma

Historically high extraction levels



Finding balance: needs vs. limits



Conclusions



► Spatial approaches provide insight

- Geographic data helps understanding extraction impacts
- Tools for more responsible sourcing and mining management



► Local impacts, global drivers

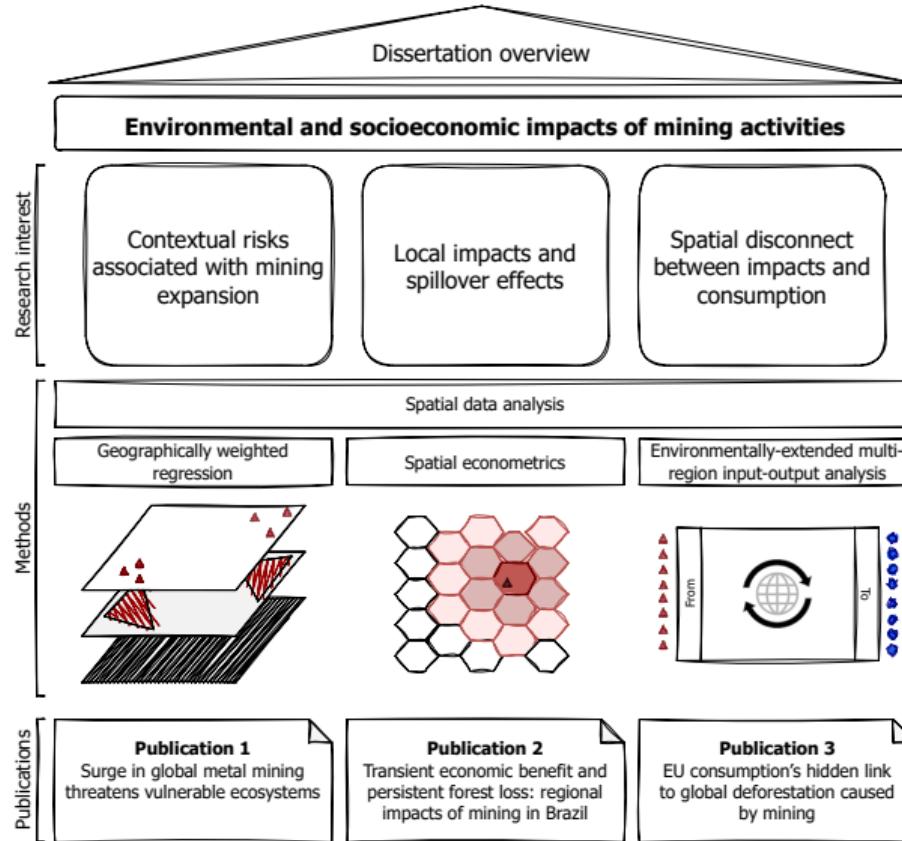
- Local impacts tied to global consumption and inequalities
- Global, integrated approach needed



► Pathways to action

- Supply-side: monitoring, international cooperation, global standards
- Demand-side: efficiency, sufficiency, resource prioritisation

Thank you!



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Appendix paper 1 – data

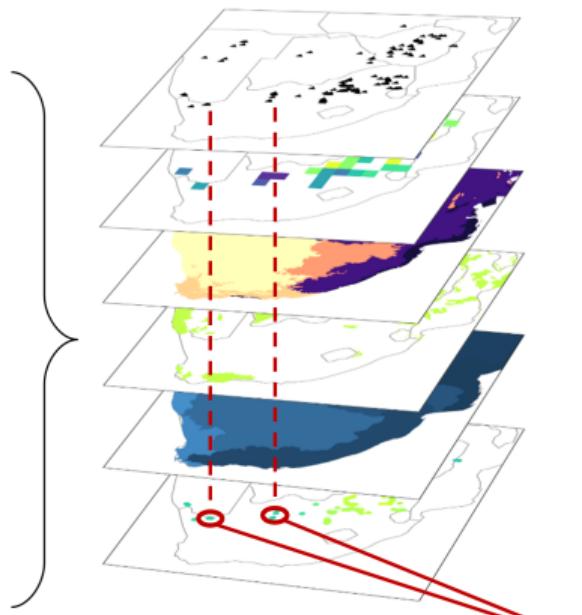
- ▶ 2,935 individual mines
- ▶ Bauxite, copper, gold, iron, lead, manganese, nickel, silver, zinc
- ▶ Time period 2000–2019

Source	Description
SNL Metals and Mining Database (S&P 2024)	Global database of mining projects, including geographic coordinates, commodity and production information of extraction sites
Global Material Flows Database (UN IRP 2017)	Country- and commodity-specific conversion factors between metal content and crude ore
Ecoregions (Dinerstein et al. 2017)	Global map of terrestrial biome categorisations
Millennium Ecosystem Assessment (2005)	Species richness per biome
World Database on Protected Areas (UNEP-WCMC and IUCN 2020)	Global map of PAs used to calculate distance to closest PA for each mine
AWARE index (WULCA 2019)	Available Water Remaining index, global map at watershed level

Appendix paper 1 – empirical framework

Data layers

- Individual mines
annual extraction
- Annual 1 x 1 degree grid cell aggregates from individual mines
- Biome classifications
- Protected areas
- AWARE water stress
- Geographically Weighted Regression (GWR) on the production time series of individual mines



Analytical steps

Assessing global distribution per year (1)

Analysing 2000-2019 mining expansion (2)

Identifying expansion hotspots (3)

Analysing hotspot cases (3)

Levels

1 degree grid cells

Biomes

5 km distance intervals

Watersheds

Individual mines

Individual mines

Scales

Global

Local

Appendix paper 1 – GWR (1)

For $s = 1, \dots, n$ mining locations the GWR model at location s is:

$$y(s) = \mathbf{X}(s)\boldsymbol{\beta}(s) + \epsilon(s)$$

- ▶ where $y(s)$ denotes the log-transformed extraction volume of a mine at location s ,
- ▶ $\mathbf{X}(s)$ is the design matrix including only intercept and year,
- ▶ $\boldsymbol{\beta}(s)$ is a vector of corresponding regression coefficients,
- ▶ and $\epsilon(s)$ denotes the random error at location s following a Gaussian distribution.
- ▶ More detail: Brunsdon et al. (1996).

Appendix paper 1 – GWR (2)

The vector of estimated parameters in a GWR model at location s is derived as

$$\hat{\beta}(s) = [\mathbf{X}' \mathbf{W}(s) \mathbf{X}]^{-1} \mathbf{X}' \mathbf{W}(s) \mathbf{y},$$

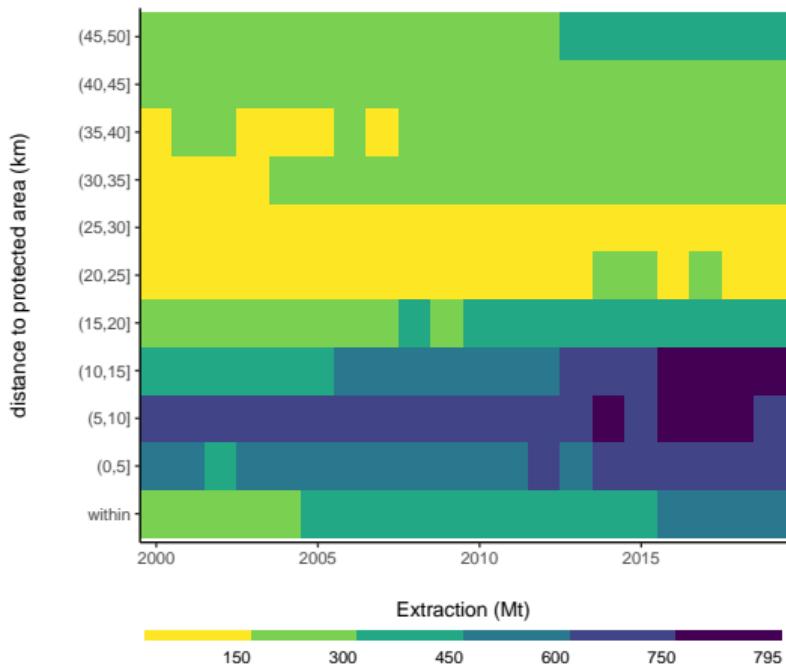
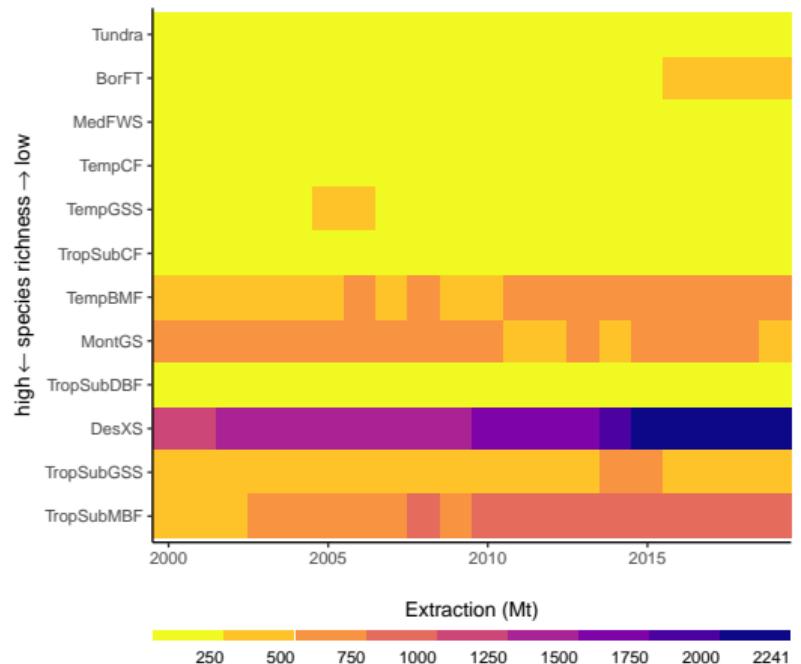
- ▶ where \mathbf{X} is the design matrix of explanatory variables, and
- ▶ $\mathbf{W}(s)$ a diagonal weights matrix of dimension n that is calculated for each calibration location s .

The elements of $\mathbf{W}(s)$ are obtained from the kernel function

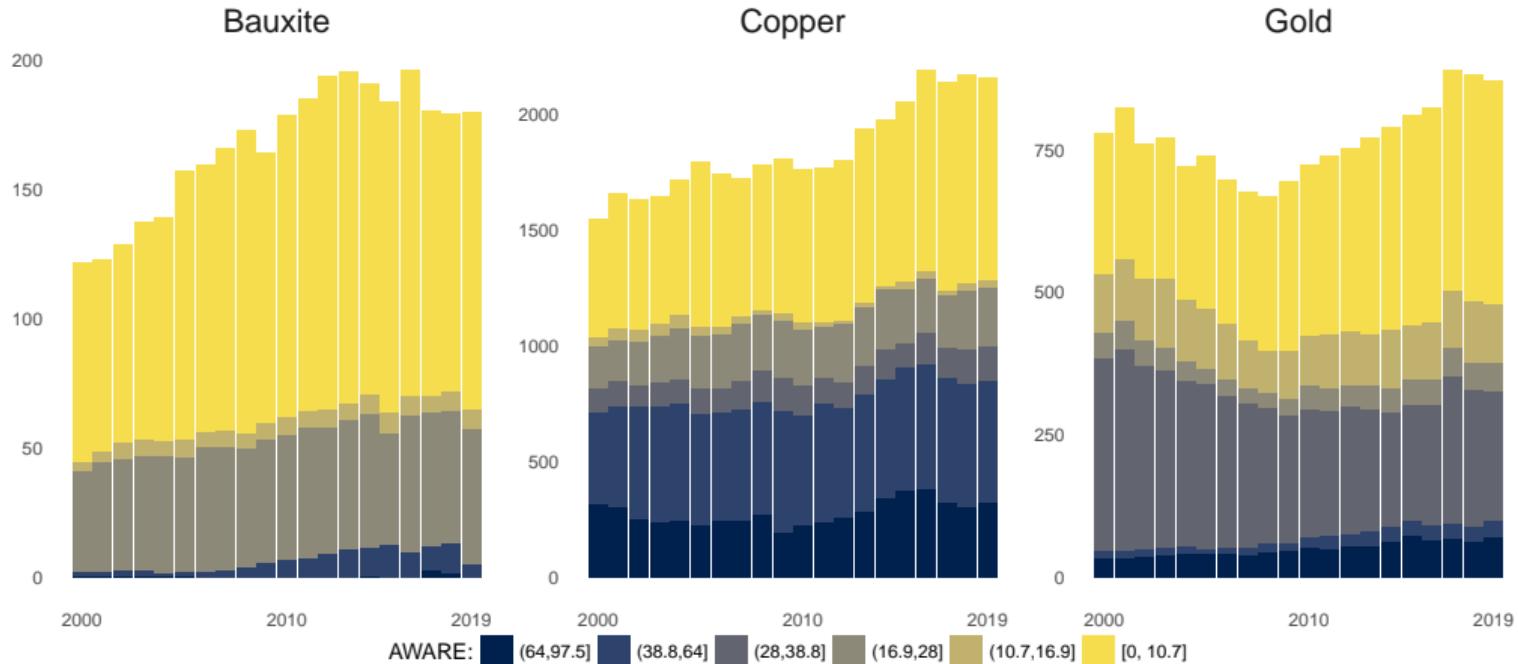
$$w_j(s) = \exp(-1/2(d_{sj}/h)^2),$$

- ▶ where d_{sj} is the distance between locations s and j , and
- ▶ h is the kernel bandwidth parameter, which is pre-estimated by cross-validation across all the calibration locations.

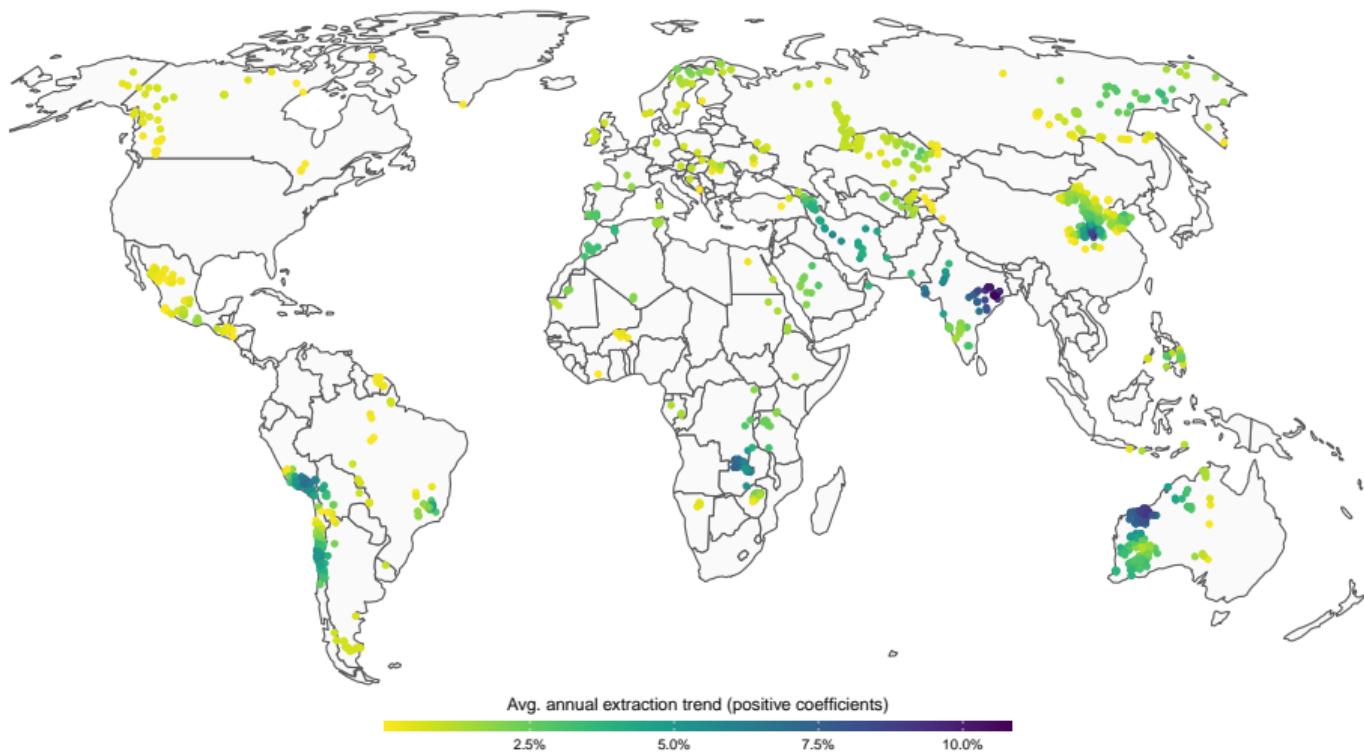
Appendix paper 1 – more results (1)



Appendix paper 1 – more results (2)



Appendix paper 1 – GWR results



Appendix paper 2 – data

Variable	Description	GM	FLM
Economic growth	Five-year average annual growth rate of gross domestic product per capita. <i>Source:</i> IBGE (2023a; 2023b)	D	I
Forest loss (relative)	Annual decrease in natural forest formation relative to municipality area (ha/km ²). <i>Source:</i> MapBiomas (2023)	D	
Forest loss (absolute)	Annual decrease in natural forest formation (ha). <i>Source:</i> MapBiomas (2023)	D	
Mining industrial	Presence of industrial mining within municipality, binary indicator. <i>Source:</i> MapBiomas (2023)	I	I
Mining garimpo	Presence of garimpo mining within municipality, binary indicator. <i>Source:</i> MapBiomas (2023)	I	I
Land use change (LUC ^{1,2})	Land use change from classification LUC ¹ to LUC ² for the classifications forest formation, forest plantation, grassland, agriculture and pasture (5-year average change in ha, log). <i>Source:</i> MapBiomas (2023)	I	I
Initial natural forest	Share classified as forest formation. <i>Source:</i> MapBiomas (2023)	I	I
Initial forest plantation	Share classified as forest plantation. <i>Source:</i> MapBiomas (2023)	I	I
Initial grassland	Share classified as grassland. <i>Source:</i> MapBiomas (2023)	I	I
Initial agriculture	Share classified as agriculture. <i>Source:</i> MapBiomas (2023)	I	I
Initial pasture	Share classified as pasture. <i>Source:</i> MapBiomas (2023)	I	I
Initial income	Per capita gross domestic product (million BRL, current PPP, log). <i>Source:</i> IBGE (2023a; 2023b)	I	
Human capital	Education index from 0 (worst) to 1 (best): schooling coverage (pre-school attendance) and quality in elementary school. <i>Source:</i> FIRJAN (2018)	I	
Population growth	Population growth rate (%). <i>Source:</i> IBGE (2023a)	I	
Population density	Population density (thousand per km ²). <i>Source:</i> IBGE (2023a)	I	
GVA agriculture	Gross value added in agriculture (million BRL, current PPP, log). <i>Source:</i> IBGE (2023b)	I	
GVA industry	Gross value added in industry (million BRL, current PPP, log). <i>Source:</i> IBGE (2023b)	I	
GVA services	Gross value added in services (million BRL, current PPP, log). <i>Source:</i> IBGE (2023b)	I	
Precipitation	Precipitation yearly average (standardised). <i>Source:</i> CRU (2021)	I	I
Elevation	Average elevation (m). <i>Source:</i> USGS (2021)	I	I

Appendix paper 2 – econometric framework

$$\mathbf{y}_t = \rho \mathbf{W} \mathbf{y}_t + \mathbf{X}_t \boldsymbol{\beta} + \mathbf{W} \mathbf{X}_t \boldsymbol{\theta} + \boldsymbol{\xi}_t + \boldsymbol{\epsilon}_t, \quad \boldsymbol{\epsilon}_t \sim N(\mathbf{0}, \sigma^2 \mathbf{I}_n)$$

- ▶ \mathbf{y}_t denotes a vector for n municipalities
 - ▶ Growth model: 5-year average annual economic growth rates from t onward
 - ▶ Forest loss models: cleared land per year (relative and absolute)
- ▶ \mathbf{W} is an $n \times n$, non-negative, row-stochastic spatial weights matrix with zero main diagonal. $W_{ij} > 0$, if regions i and j are defined as neighbours.
I use a $k = 5$ nearest neighbours specification.
- ▶ Scalar ρ measures strength of spatial dependence; stability condition $|\rho| < 1$.
- ▶ \mathbf{X}_t is an $n \times k$ matrix of k regional characteristics in the initial period.
- ▶ $k \times 1$ vectors $\boldsymbol{\beta}$ and $\boldsymbol{\theta}$ correspond to \mathbf{X}_t and $\mathbf{W} \mathbf{X}_t$.
- ▶ Time-period-specific fixed effects $\boldsymbol{\xi}_t$.
- ▶ Assumption of independence of observations does not hold → Interpretation as marginal changes becomes redundant!

Appendix paper 2 – spatial weights



Appendix paper 2 – direct effects and spillovers

- ▶ Following LeSage and Pace (2009), we derive

$$\frac{\partial y_i}{\partial x_{jk}} = \mathbf{S}_k(\mathbf{W})_{ij} = (\mathbf{I}_n - \rho \mathbf{W})^{-1}(\mathbf{I}_n \boldsymbol{\beta}_k + \mathbf{W} \boldsymbol{\theta}_k)_{ij}$$

from our SDM

$$\mathbf{y} = (\mathbf{I}_n - \rho \mathbf{W})^{-1}(\mathbf{X} \boldsymbol{\beta} + \mathbf{W} \mathbf{X} \boldsymbol{\theta} + \boldsymbol{\epsilon})$$

- ▶ The diagonal elements of the $n \times n$ matrix $\mathbf{S}_k(\mathbf{W})$ contain the direct effects, and off-diagonal elements represent indirect effects (spillovers) → take averages.
 - ▶ Average Total Impact = $\frac{1}{n} \boldsymbol{\iota}'_n \mathbf{S}_k(\mathbf{W}) \boldsymbol{\iota}_n$
 - ▶ Average Direct Impact = $\frac{1}{n} \text{tr}(\mathbf{S}_k(\mathbf{W}))$
 - ▶ Average Indirect Impact = Average Total Impact – Average Direct Impact

Appendix paper 2 – Bayesian estimation approach

We combine **likelihood** with **prior** information:

- The **likelihood**:

$$p(\mathbf{y}|\boldsymbol{\beta}, \sigma^2, \rho) = (2\pi\sigma^2)^{-\frac{n}{2}} |\mathbf{A}| \exp\left(-\frac{1}{2\sigma^2}(\mathbf{Ay} - \tilde{\mathbf{X}}\boldsymbol{\beta})'(\mathbf{Ay} - \tilde{\mathbf{X}}\boldsymbol{\beta})\right)$$

where $\mathbf{A} = \mathbf{I}_n - \rho \mathbf{W}$.

- The **prior**: LeSage and Pace (2009) propose NIG setting for $\boldsymbol{\beta}$ and σ^2 and a $B(d, d)$ prior for ρ (LeSage and Parent 2007)

Sampling:

- $\boldsymbol{\beta}$ and σ^2 can be sampled efficiently using Gibbs sampling
- Gridy Gibbs approach proposed by Ritter and Tanner (1992) for ρ

Appendix paper 2 – MCMC algorithm

1. **Sample σ^2 from** $p(\sigma^2 | \cdot) \sim G^{-1}(\bar{a}, \bar{b})$

$$\bar{a} = \underline{a} + N/2, \quad \bar{b} = \underline{b} + \epsilon' \epsilon / 2$$

2. **Sample β from** $p(\beta | \cdot) \sim N(\bar{\beta}, \bar{\Sigma})$

$$\bar{\Sigma} = (\underline{\Sigma}^{-1} + X' \Omega^{-1} X)^{-1}$$

$$\bar{\beta} = \bar{\Sigma} (\underline{\Sigma}^{-1} \underline{\beta} + X' \Omega^{-1} A y)$$

3. **Update ρ using a Griddy-Gibbs step** using the $Beta(d, d)$ prior defined on the interval $(-1, 1)$ and centred on zero (LeSage and Parent 2007):

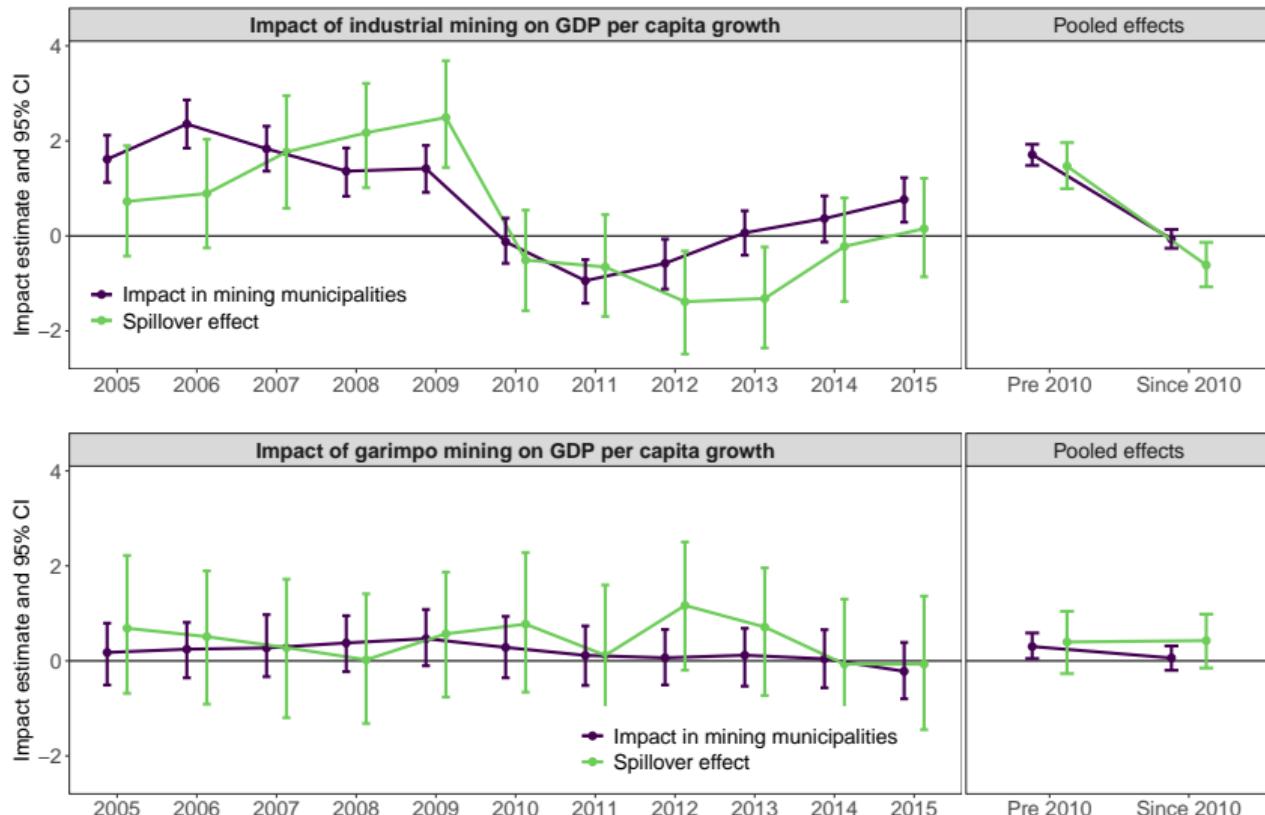
$$\rho \sim \frac{1}{Beta(a_0, a_0)} \frac{(1 + \rho)^{a_0 - 1} (1 - \rho)^{a_0 - 1}}{2^{2a_0 - 1}}$$

→ σ^2 was drawn from $G^{-1}(0.01, 0.01)$

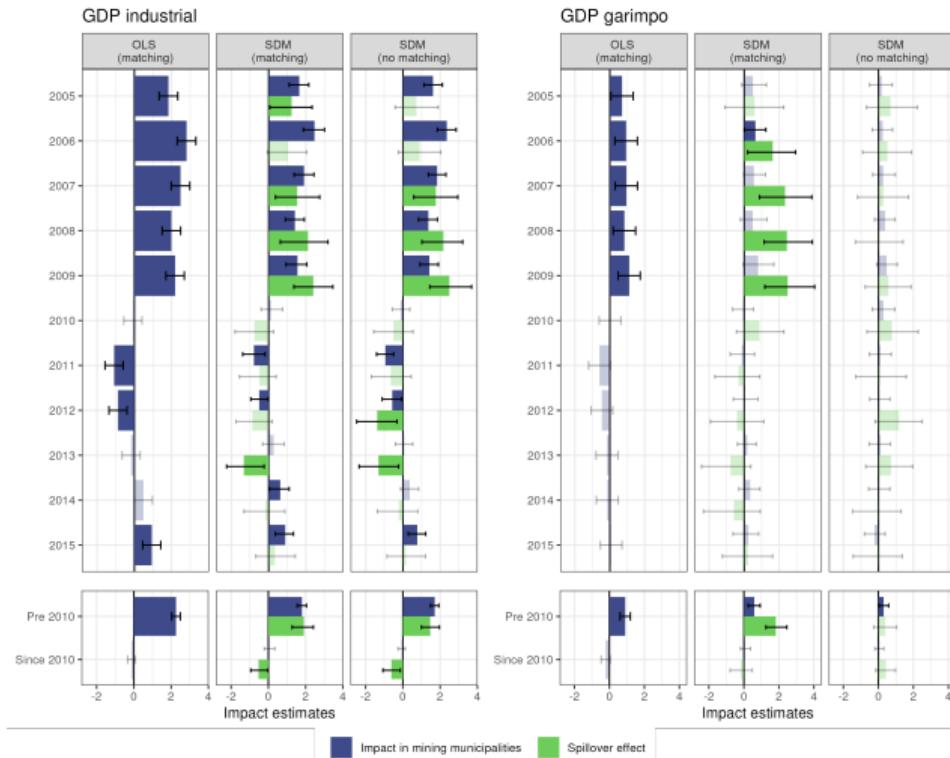
→ Weakly informative $N(0, 10^4)$ were used for β and θ .

→ For ρ , we used a prior distribution with hyperparameter value $a_0 = 1.01$.

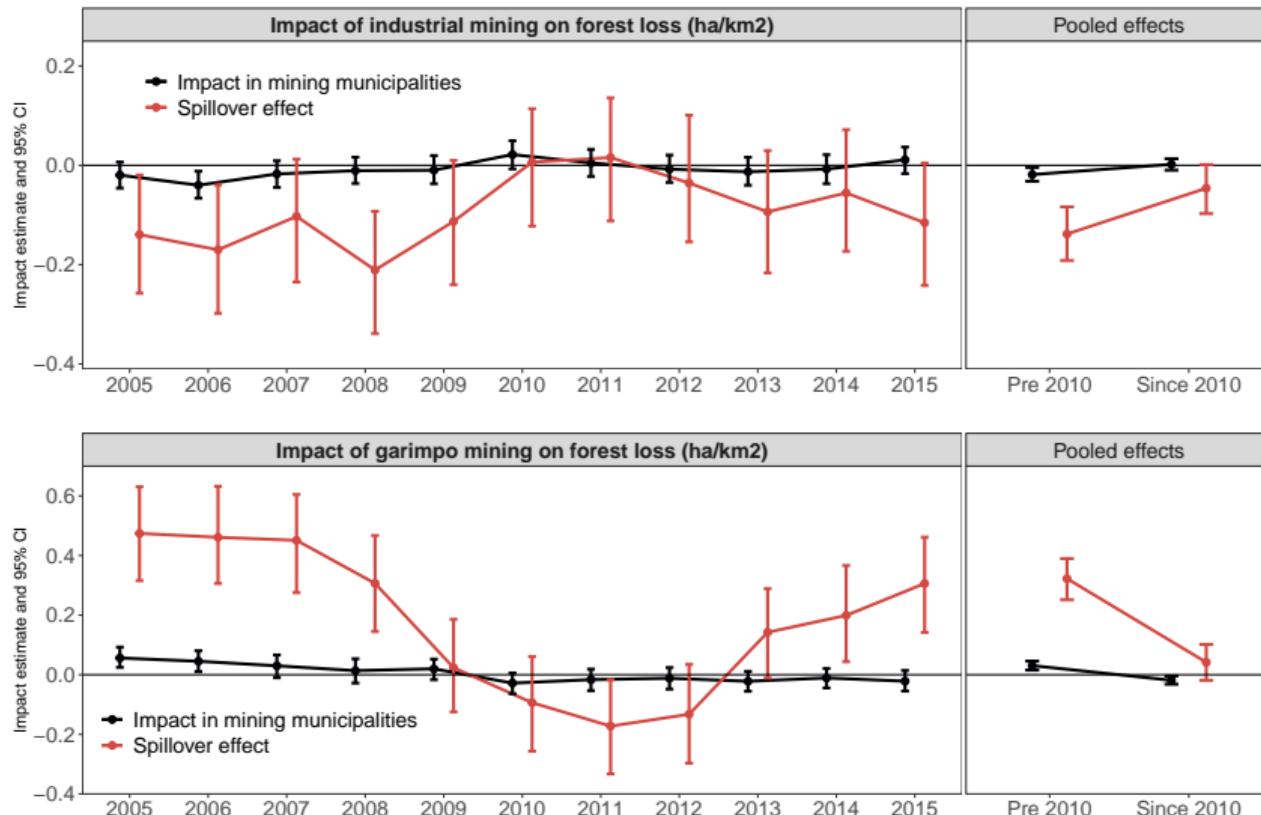
Appendix paper 2 – GDP results



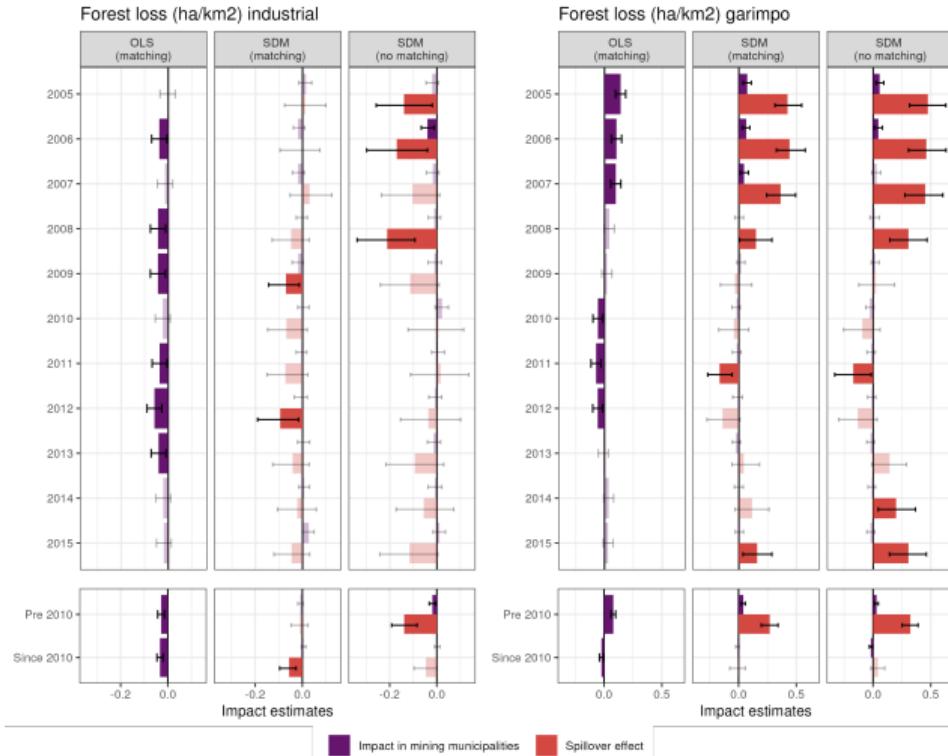
Appendix paper 2 – GDP results (matching)



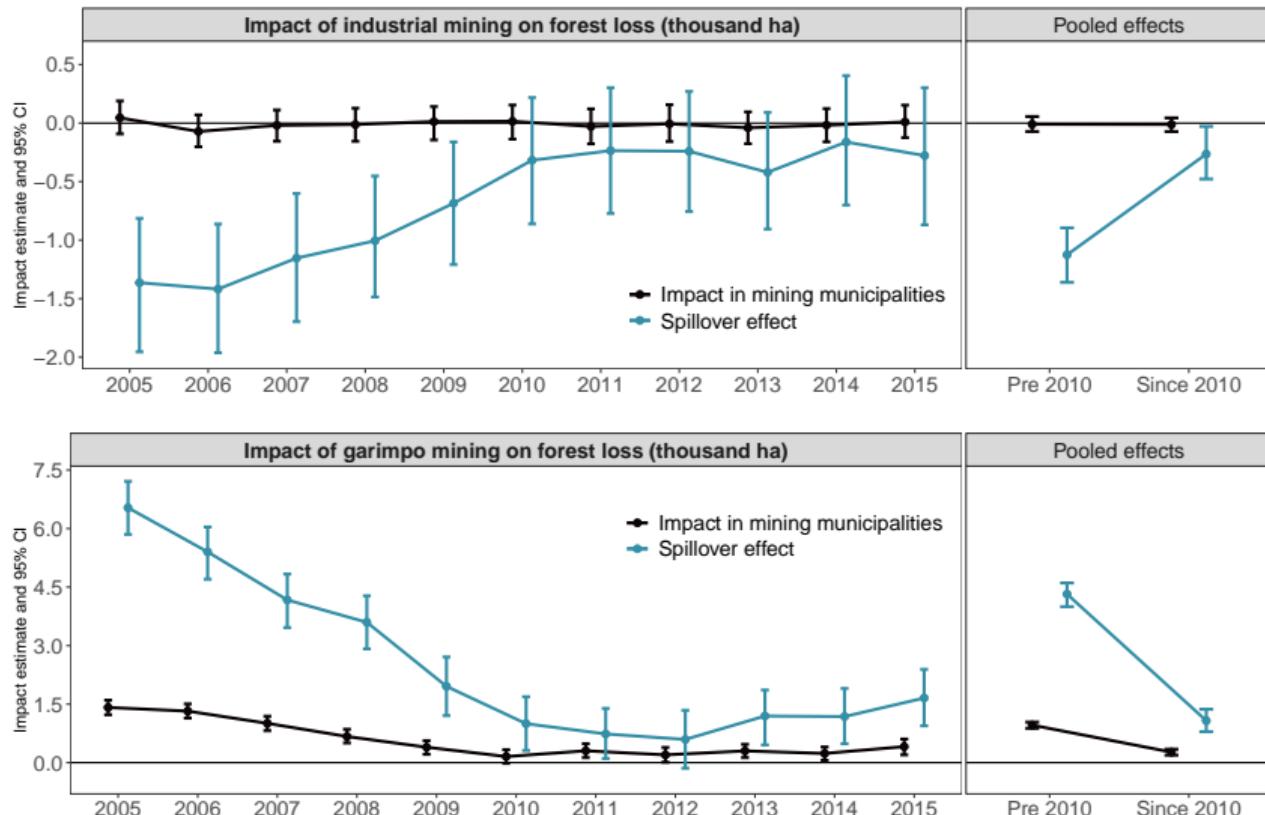
Appendix paper 2 – forest loss (relative) results



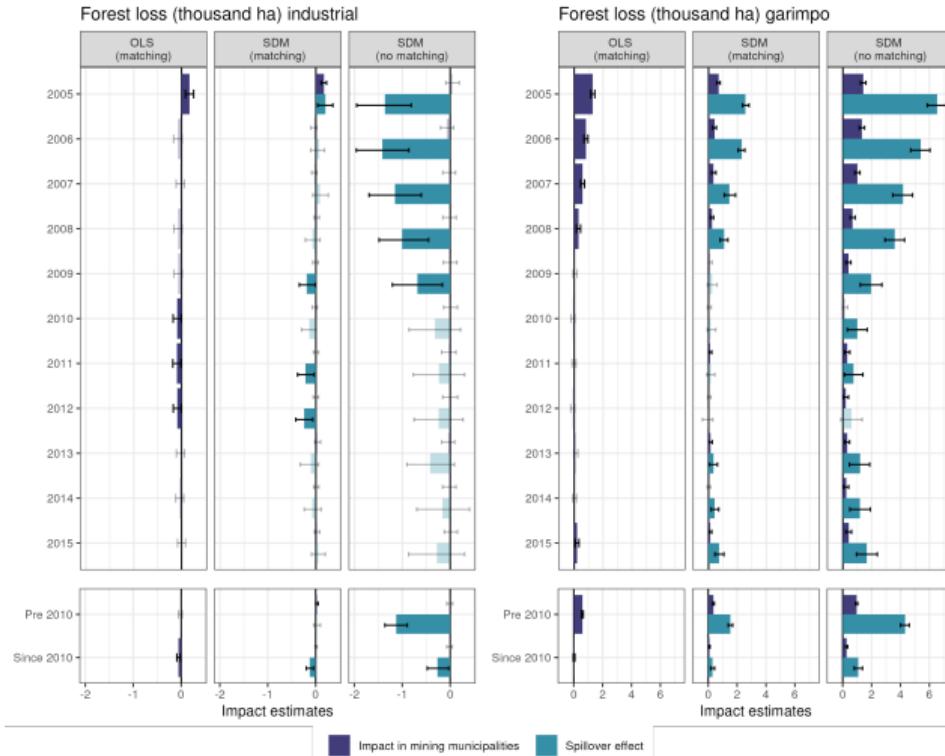
Appendix paper 2 – forest loss (relative, matching)



Appendix paper 2 – forest loss (absolute) results



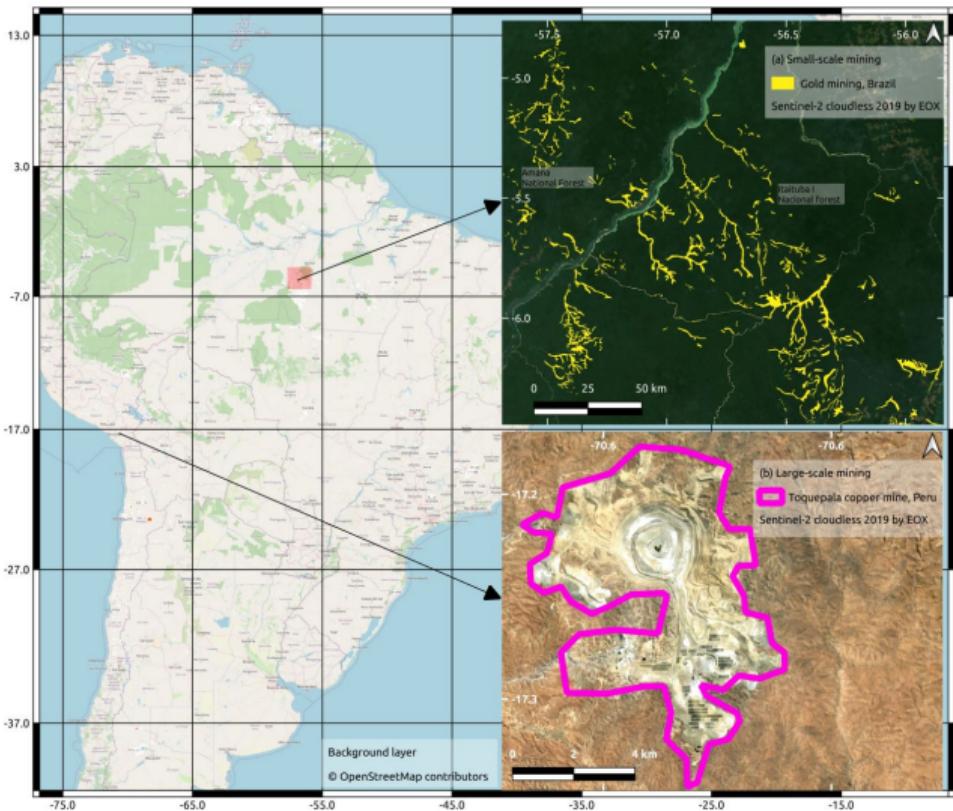
Appendix paper 2 – forest loss (absolute, matching)



Appendix paper 3 – data

Data	Source	Description
Mining area	Maus et al. 2022	Dataset based on visual interpretation of satellite imagery, 44,929 spatial polygons, 101,583 km ² of land area occupied by ground features related to the activities of large-scale, artisanal and small-scale mining, such as open cuts, tailings dams, waste rock dumps, water ponds and processing plants.
Mine-specific information	S&P 2024	Mine-specific information on mined commodities and extraction volumes, used for allocation of forest loss to respective commodities.
Forest cover	Hansen et al. 2013	Yearly information on tree cover and tree cover loss at 1 arcsec resolution (approximately 30 by 30 m at the equator) on a global scale.
MRIO tables	Lenzen et al. 2017; 2022	Release 057 of the GLORIA global environmentally-extended MRIO database featuring 160 countries and 4 rest of the world accounts, each divided into 120 industry sectors to describe the structure of the global economy

Appendix paper 3 – mining area dataset (Maus et al. 2022)



Update 2022:

- ▶ 34,820 mining locations across the globe
- ▶ 44,929 polygon features covering 101,583 km^2 of large-scale and artisanal and small-scale mining
- ▶ Open source geodata
- ▶ Online tool available for exploring the data

Appendix paper 3 – MRIO model

Total output of an economy is the sum of all intermediate consumption and final consumption :

$$\mathbf{x} = \mathbf{Z} \boldsymbol{\iota}_n + \mathbf{y}$$

Technology matrix:

$$\mathbf{A} = \mathbf{Z} \hat{\mathbf{x}}^{-1} \Rightarrow \mathbf{Z} \boldsymbol{\iota}_n = \mathbf{A} \mathbf{x}$$

$$\mathbf{x} = \mathbf{A} \mathbf{x} + \mathbf{y} \Rightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y} = \mathbf{L} \mathbf{y}$$

Combining with direct intensity vector of environmental inputs yields environmental footprint:

$$\mathbf{f} = \mathbf{e}^T \mathbf{L} \odot \mathbf{y}$$

\mathbf{f}_i : all environmental inputs required by sector i to provide goods and services to final consumers.

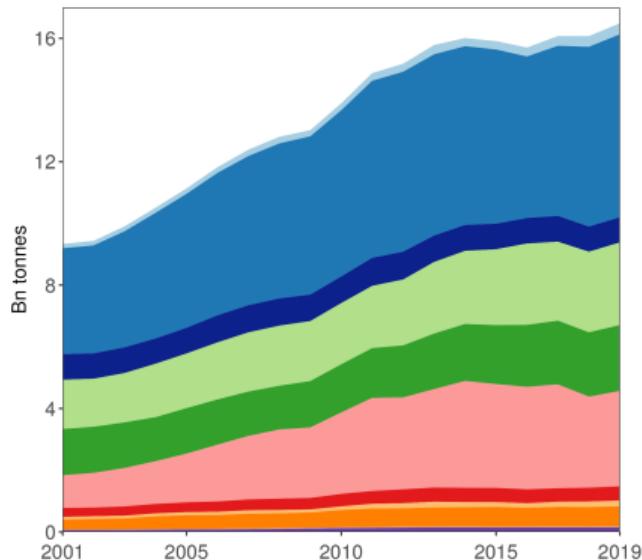
	Country 1			Country ...			Country m			Final demand (\mathbf{y})			Total output (\mathbf{x})
	Prod 1	Prod ...	Prod n	Prod 1	Prod ...	Prod n	Prod 1	Prod ...	Prod n	y_1	$y_{...}$	y_m	
Country 1	Prod 1	Prod ...	Prod n										
Country ...	Prod 1	Prod ...	Prod n										
Country m	Prod 1	Prod ...	Prod n										
Res. use										Y			X
										e			

GLORIA IO database, Release 057
(Lenzen et al. 2017; 2022)

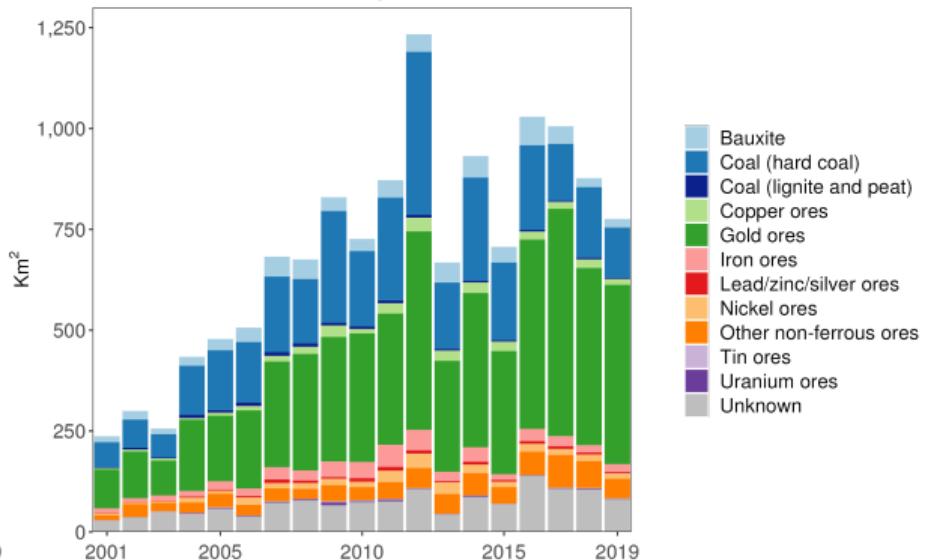
- ▶ 160 countries + 4 ROW
- ▶ 120 industry sectors
- ▶ 11 primary extraction sectors

Appendix paper 3 – more results

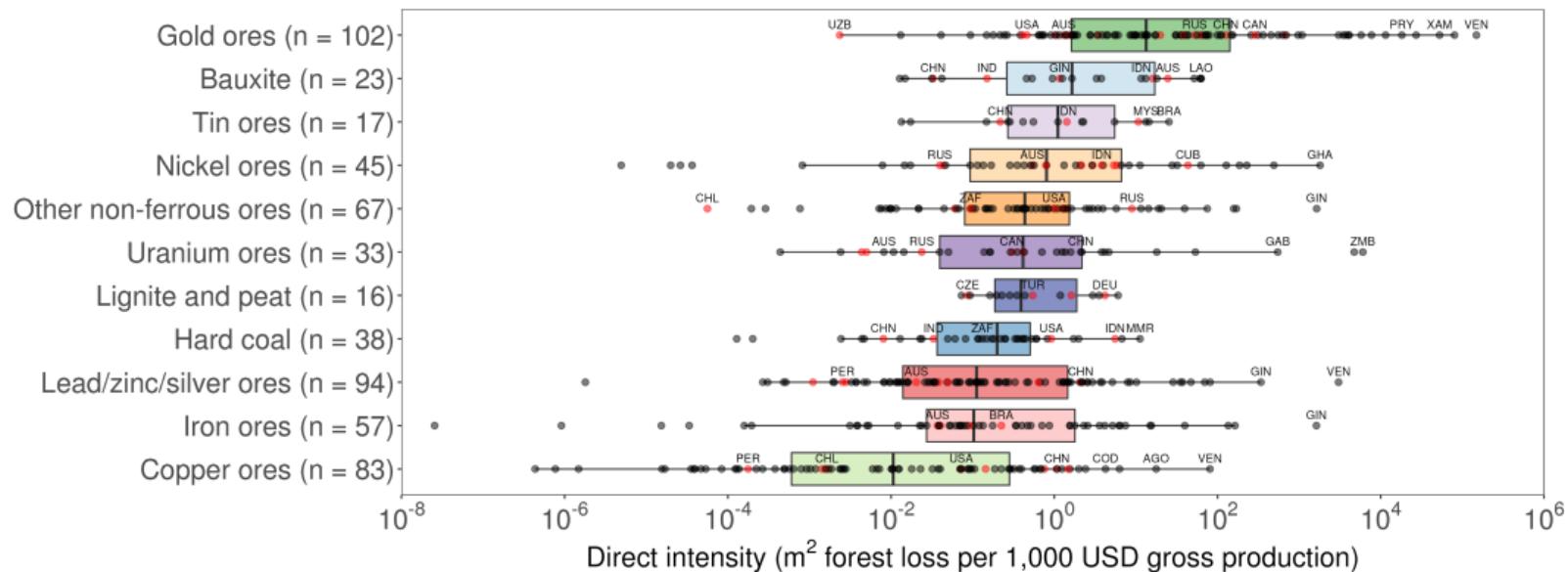
A Global extraction



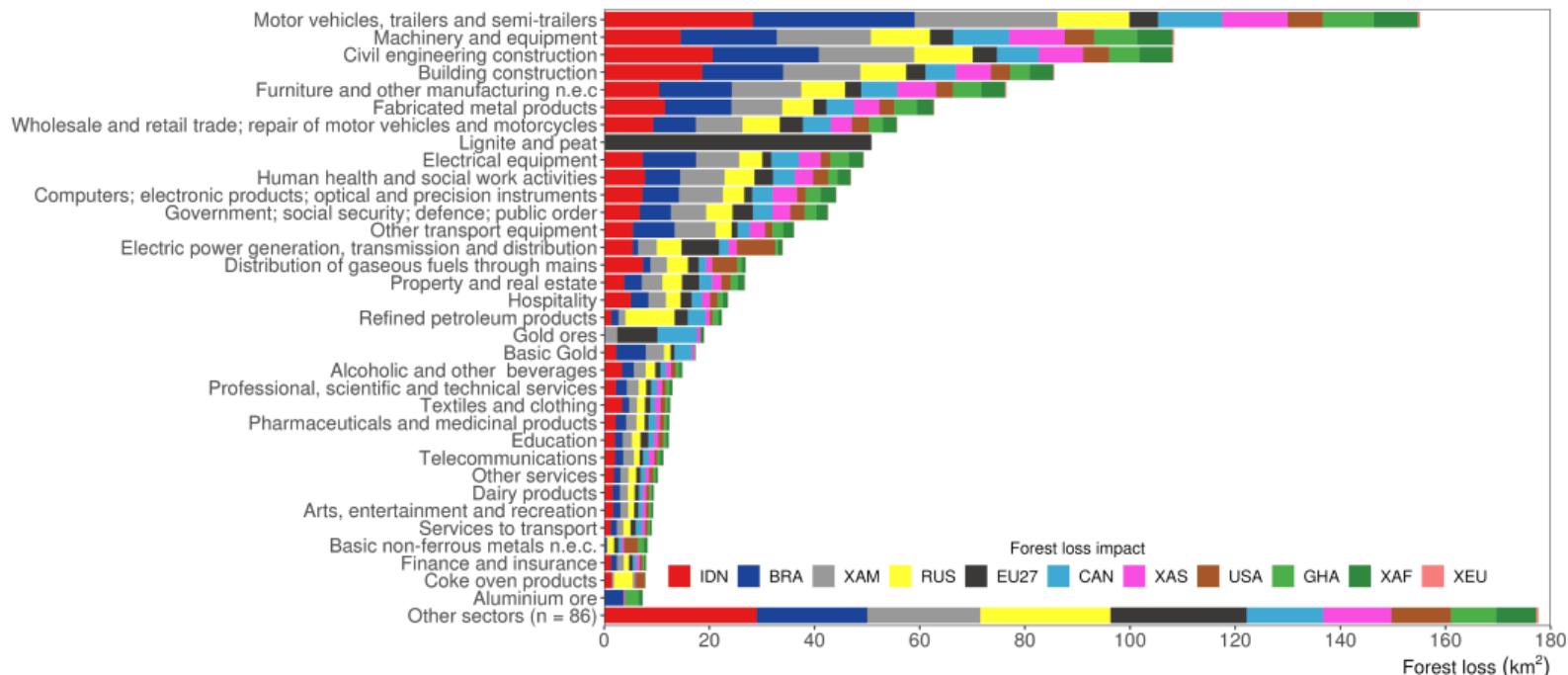
B Forest loss within mining areas



Appendix paper 3 – more results



Appendix paper 3 – more results



Appendix paper 3 – more results

