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

Sebastian Luckeneder

Institute for Ecolocical Economics, WU Vienna University of Economics and Business, sebastian.luckeneder@wu.ac.at

Defensio Dissertationis, 20 December 2024

Overview

Contextual risks associated with mining expansion

Local impacts and spillover effects

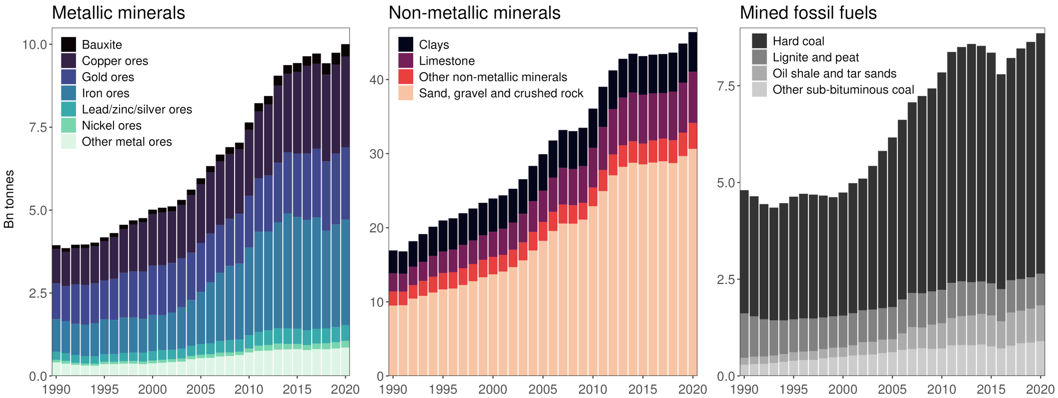
Spatial disconnect between impacts and consumption

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

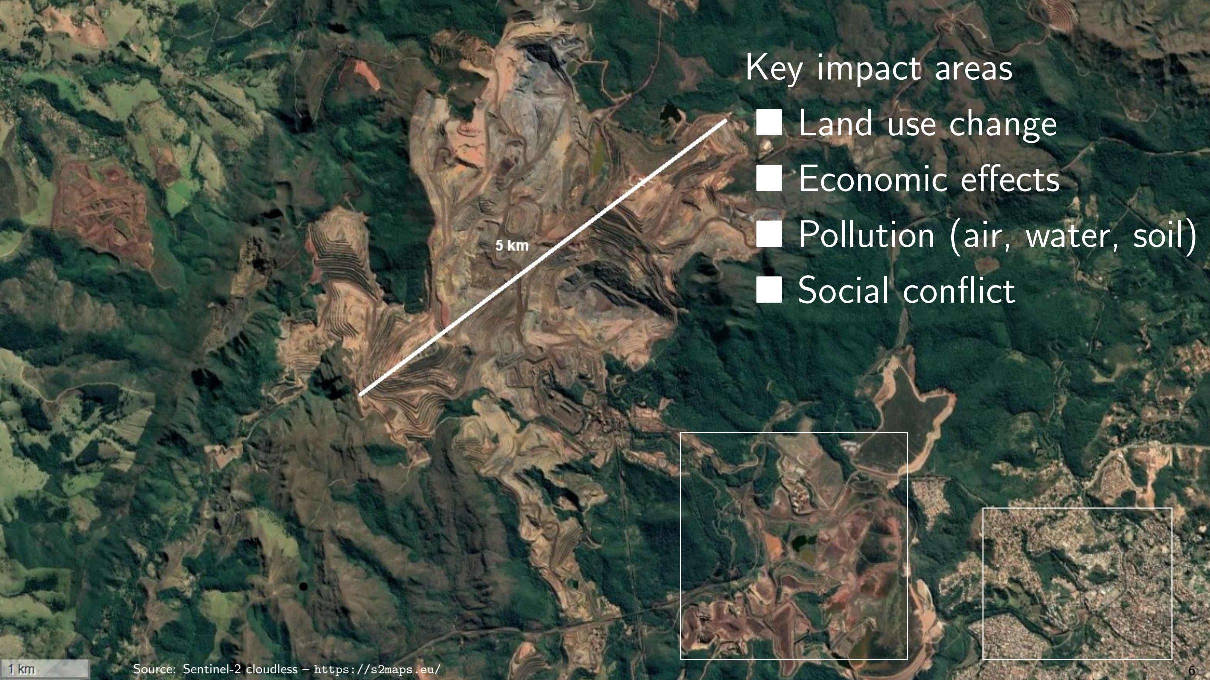
1. Maus, V. et al. (2020): **"A global-scale data set of mining areas"**, *Scientific Data*.
2. Tost, M. et al. (2020): **"Ecosystem services costs of metal mining and pressures on biomes"**, *The Extractive Industries and Society*.
3. Maus, V. et al. (2022): **"An update on global mining land use"**, *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



Key impact areas

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

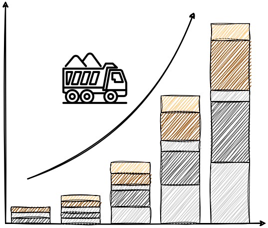
Source: Sentinel-2 cloudless – https://s2maps.eu/

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

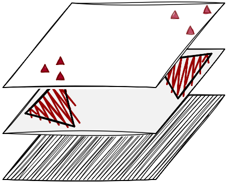
Research interest

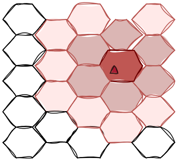
- Contextual risks associated with mining expansion
- Local impacts and spillover effects
- Spatial disconnect between impacts and consumption

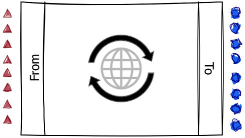
Methods

Spatial data analysis

- Geographically weighted regression
- Spatial econometrics
- Environmentally-extended multi-region input-output analysis

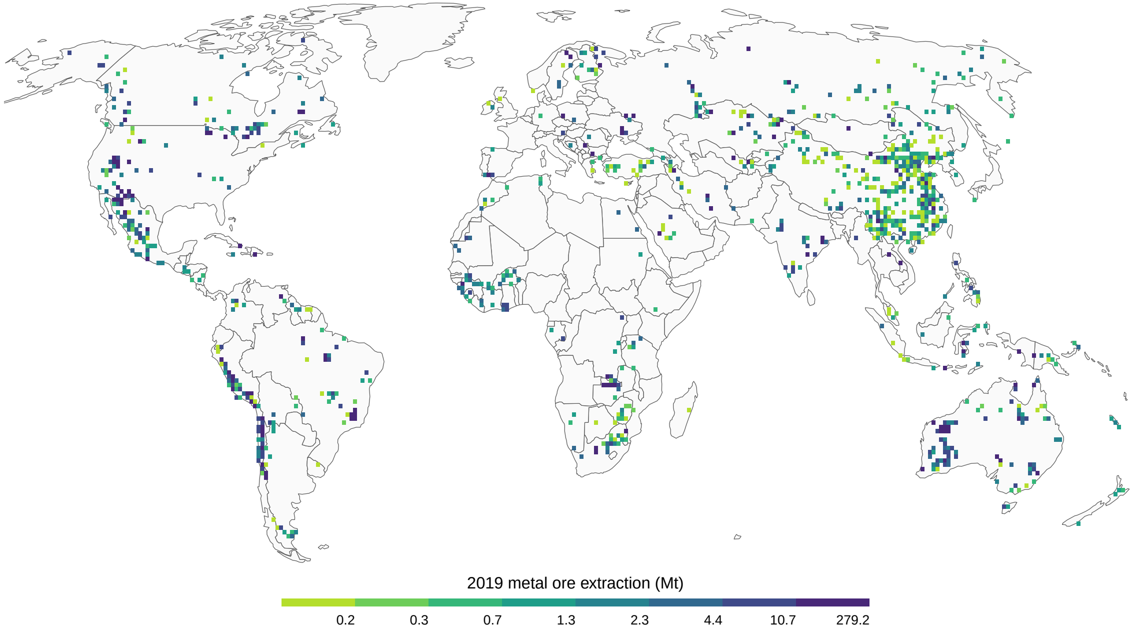




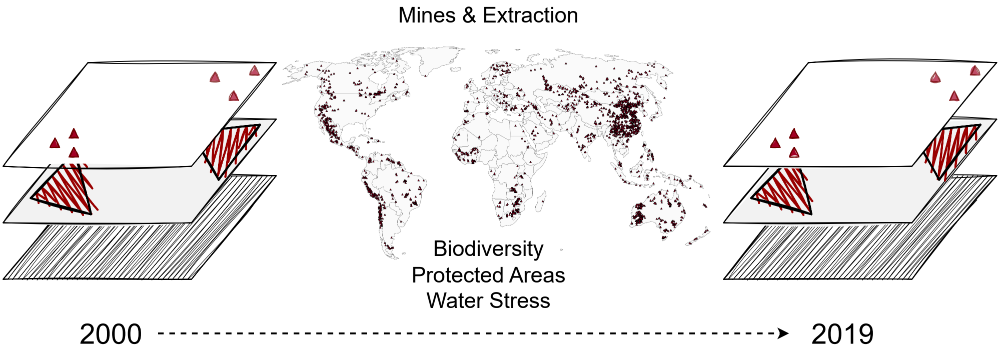


Contextual risks associated with mining expansion

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


2019 metal ore extraction (Mt)
0.2
0.3
0.7
1.3
2.3
4.4
10.7
279.2

Mining expansion threatens vulnerable ecosystems

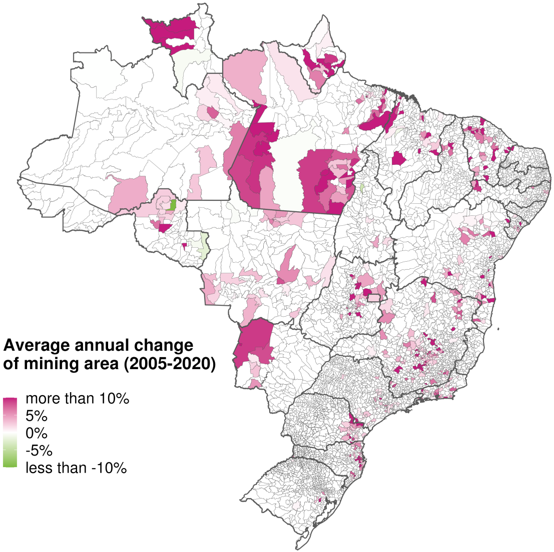


- 5 of the 6 most biodiverse biomes originate 79% of total ore mined in 2019.
- Half of all metal mining worldwide occurs at less than 20 km from protected lands.
- Intensification of extraction at detected hotspots (Peru, **Brazil**, DRC, Zambia, etc.)

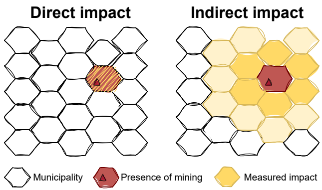
Local impacts and spillover effects

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

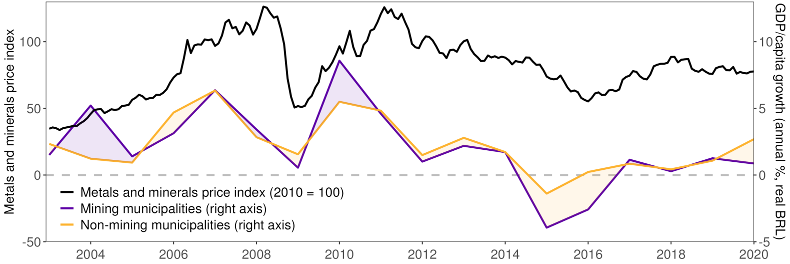
Brazil - extraction and biodiversity hotspot

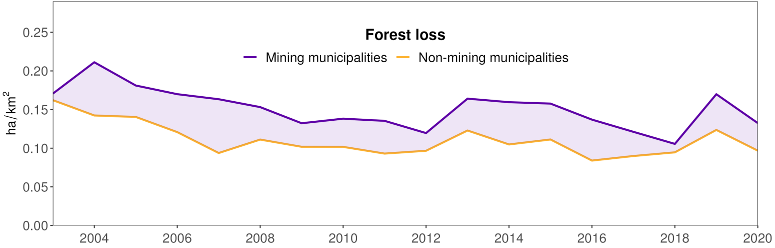


- Economic impacts?
  → Municipality GDP
- Environmental impacts?
  → Forest cover loss
- Spillovers across municipalities?

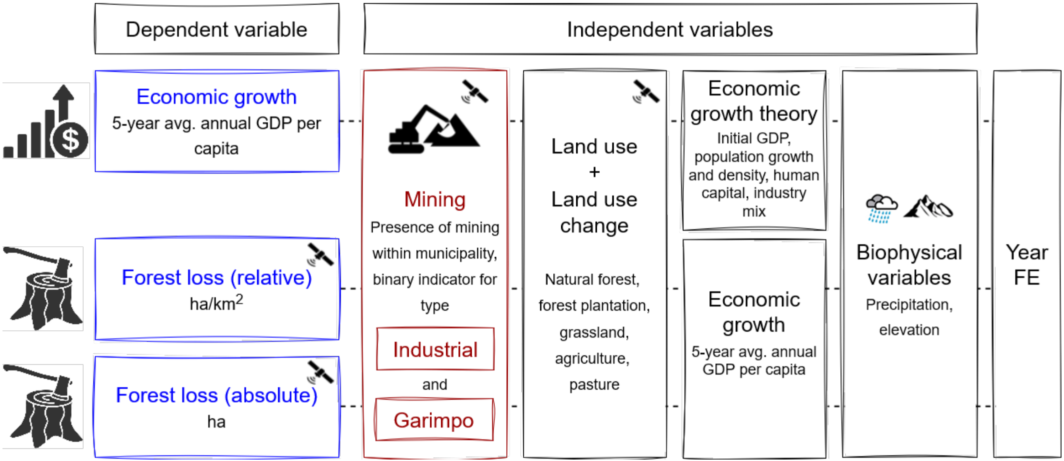


Trade-offs between economic and environmental impacts?





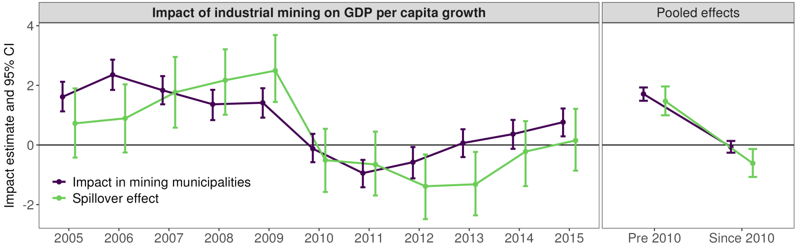
Empirical framework paper 2

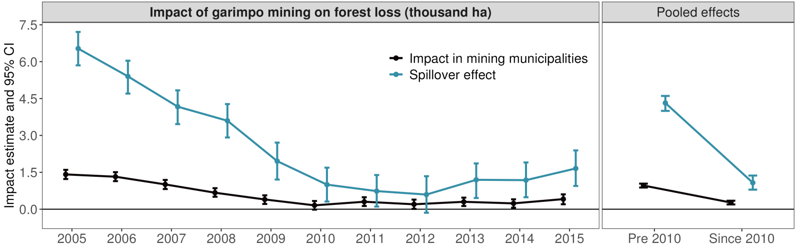


5,262 Brazilian municipalities, yearly data 2005-2020

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

Transient economic benefit and persistent forest loss in Brazil





Spatial disconnect between impacts and consumption

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.

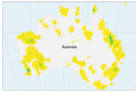
Empirical framework paper 3

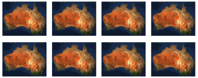
Forest loss within mining areas

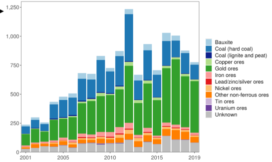
Mining land use
(Maus et al. 2022)

Forest loss maps
(Hansen et al. 2013)

Production Perspective







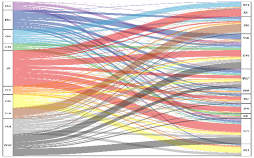
Multi-region input-output (MRIO) model

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)

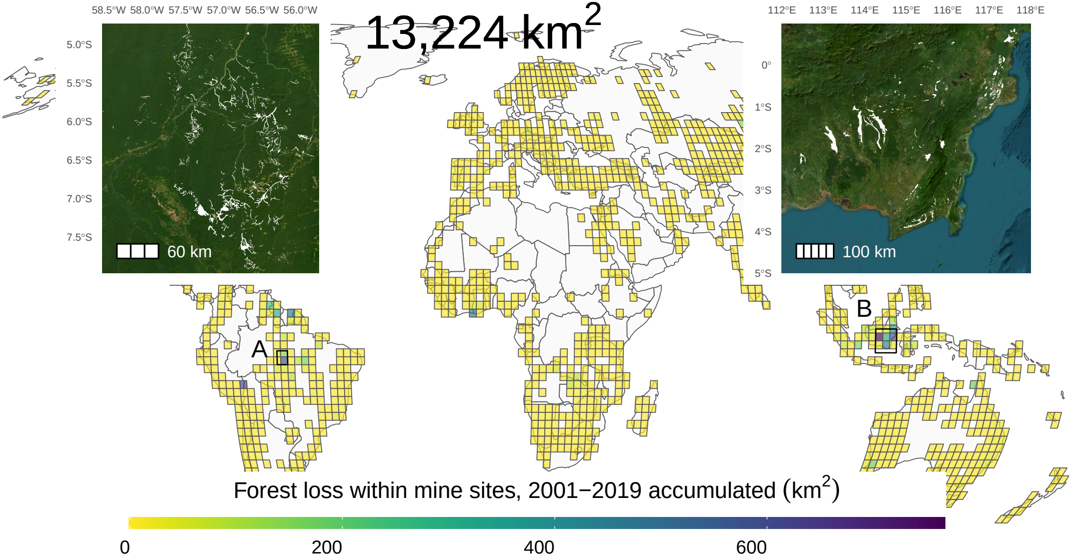
Consumption Perspective

Local forest loss impacts

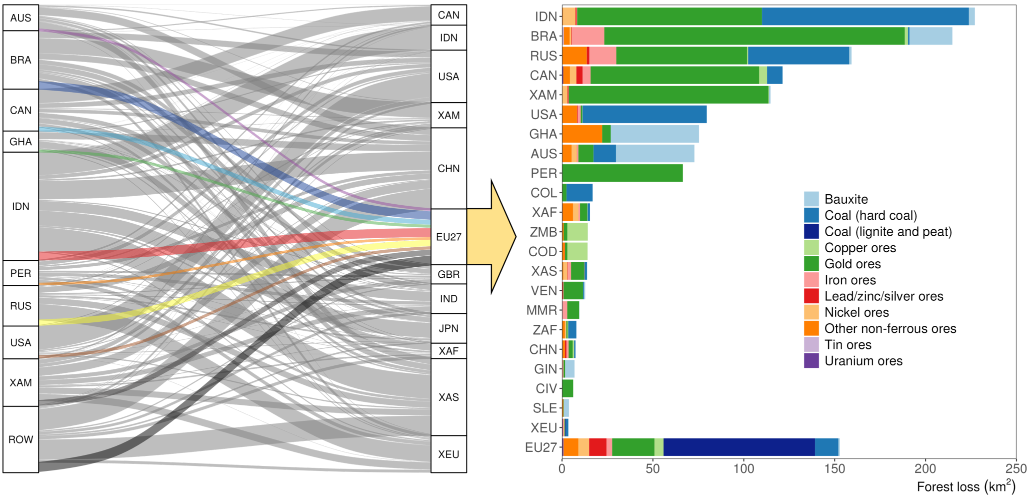


Forest loss embodied in consumer countries and sectors

From local impacts...



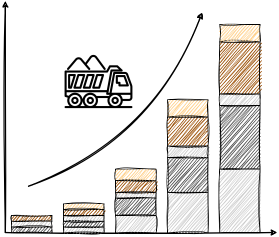
… to deforestation embodied in the European Unions's final demand



Conclusions

Recap: the mined materials dilemma

Historically high extraction levels

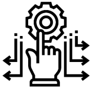


Finding balance: needs vs. limits

Conclusions

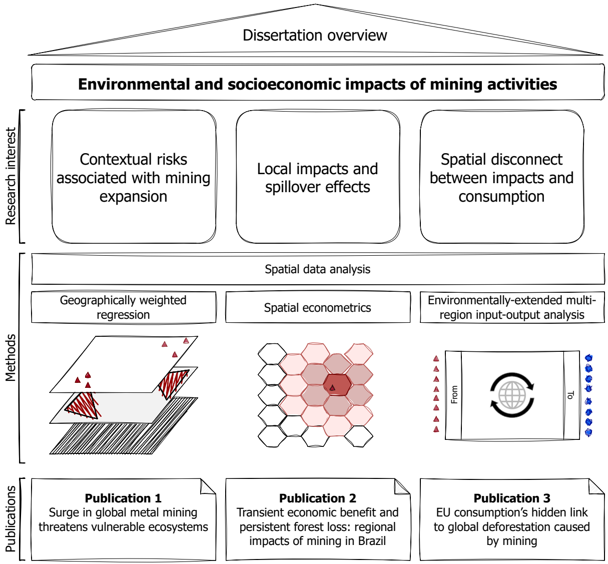
- **Spatial approaches provide insight**
  - Geographic data helps understanding extraction impacts
  - Tools for more responsible sourcing and mining management

- **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!



Dissertation overview
Environmental and socioeconomic impacts of mining activities
Research interest
Contextual risks associated with mining expansion
Local impacts and spillover effects
Spatial disconnect between impacts and consumption
Methods
Spatial data analysis
Geographically weighted regression
Spatial econometrics
Environmentally-extended multi-region input-output analysis
From
To
Publications
Publication 1
Surge in global metal mining threatens vulnerable ecosystems
Publication 2
Transient economic benefit and persistent forest loss: regional impacts of mining in Brazil
Publication 3
EU consumption's hidden link to global deforestation caused by mining

References I

Brunsdon, Chris, A. Stewart Fotheringham, and Martin E. Charlton (1996). "Geographically Weighted Regression: A Method for Exploring Spatial Nonstationarity". In: *Geographical Analysis* 28.4, pp. 281–298. DOI: 10.1111/j.1538-4632.1996.tb00936.x.

CRU (2021). *Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate*. http://dx.doi.org/10.5285/D0E1585D-3417-485F-87AE-4FCECF10A992. Accessed: 3 Aug 2023.

Calderon, Jordan Lee et al. (2020). "Responsible or reckless? A critical review of the environmental and climate assessments of mineral supply chains". In: *Environ. Res. Lett.* 15.10, p. 103009. DOI: 10.1088/1748-9326/ab9f8c.

Dinerstein, Eric et al. (2017). "An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm". In: *BioScience* 67.6, pp. 534–545. DOI: 10.1093/biosci/bix014. URL: http://ecoregions2017.appspot.com.

FIRJAN (2018). *Education index (IFDM Educação) Version 2018*. https://www.firjan.com.br/ifdm/downloads/. Accessed: 6 Sep 2023.

References II

Franks, Daniel M., David Brereton, and Chris J. Moran (2013). “The cumulative dimensions of impact in resource regions”. In: *Resour. Policy* 38.4, pp. 640–647. DOI: 10.1016/j.resourpol.2013.07.002.

Hansen, MC et al. (2013). “High-resolution Global Maps of 21st-century Forest Cover Change”. In: *Science* 342.6160, pp. 850–853. DOI: 10.1126/science.1244693.

IBGE (2023a). *Instituto Brasileiro de Geografia e Estatística, Estimativas de Populacao*. https://ftp.ibge.gov.br/Estimativas_de_Populacao/. Accessed: 4 Sep 2023. Rio de Janeiro.

— (2023b). *Instituto Brasileiro de Geografia e Estatística, PIB municipios*. https://ftp.ibge.gov.br/Pib_Municipios/. Accessed: 10 Aug 2023. Rio de Janeiro.

JRC (2023). *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study*. Luxembourg: Joint Research Centre.

LeSage, JP and O Parent (2007). “Bayesian Model Averaging for Spatial Econometric Models”. In: *Geographical Analysis* 39.3, pp. 241–267. DOI: 10.1111/j.1538-4632.2007.00703.x.

LeSage, James P and Robert K Pace (2009). *Introduction to spatial econometrics*. Boca Raton: Taylor & Francis.

References III

Lechner, Alex M. et al. (2017). "Challenges of integrated modelling in mining regions to address social, environmental and economic impacts". In: *Environ. Model. Softw.* 93, pp. 268–281. DOI: 10.1016/j.envsoft.2017.03.020.

Lenzen, Manfred et al. (2017). "The Global MRIO Lab – charting the world economy". In: *Economic Systems Research* 29.2, pp. 158–186. DOI: 10.1080/09535314.2017.1301887.

Lenzen, Manfred et al. (2022). "Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12". In: *Nature Sustainability* 5.2, pp. 157–166. DOI: 10.1038/s41893-021-00811-6.

MapBiomas (2023). *Project MapBiomas – Collection 8.0 of the Annual Series of Land Use and Land Cover Maps of Brazil*. https://brasil.mapbiomas.org/estatisticas/. Accessed: 7 Sep 2023.

Maus, Victor and Tim T Werner (2024). "Impacts for half of the world's mining areas are undocumented". In: *Nature* 625.7993, pp. 26–29. DOI: https://doi.org/10.1038/d41586-023-04090-3.

Maus, Victor et al. (2022). "An update on global mining land use". In: *Scientific Data* 9.1, pp. 1–11. DOI: 10.1038/s41597-022-01547-4.

References IV

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-being: Biodiversity Synthesis*. https://www.millenniumassessment.org/documents/document.354.aspx.pdf. Accessed: 18 Nov 2024. Washington, DC: World Resources Institute.

Prior, T. et al. (2012). "Resource depletion, peak minerals and the implications for sustainable resource management". In: *Glob. Environ. Change* 22.3, pp. 577 –587. DOI: 10.1016/j.gloenvcha.2011.08.009.

Ritter, C and MA Tanner (1992). "Facilitating the Gibbs sampler: The Gibbs stopper and the Griddy-Gibbs sampler". In: *Journal of the American Statistical Association* 87.419, pp. 861–868.

S&P (2024). *Metals and Mining Database*. New York: S&P Global Market Intelligence.

Temper, Leah, Daniela Del Bene, and Joan Martinez-Alier (2015). "Mapping the frontiers and front lines of global environmental justice: the EJAtlas". In: *J. Polit. Ecol.* 22.1, pp. 255–278. DOI: 10.2458/v22i1.21108.

UN IRP (2017). *Global Material Flows Database: Version 2017*. http://www.resourcepanel.org/global-material-flows-database. Paris: United Nations Environment Programme.

References V

UN IRP (2024). *Global Resources Outlook 2024: Bend the Trend. Pathways to a liveable planet as resource use spikes.* Nairobi: United Nations Environment Programme. URL: https://wedocs.unep.org/20.500.11822/44901.

UNEP-WCMC and IUCN (2020). *Protected Planet: The World Database on Protected Areas 03/2020*. www.protectedplanet.net. Cambridge: UNEP-WCMC and IUCN.

USGS (2021). *Global Multi-resolution Terrain Elevation Data GMTED2010*. https://www.usgs.gov/core-science-systems/eros/coastal-changes-and-impacts/gmted2010. Accessed: 3 Aug 2023.

WULCA (2019). *Consensus-based method development to assess water use in LCA, AWaRe v1.2c*. http://www.wulca-waterlca.org. Montreal: Water Use in LCA working group.

Watari, Takuma, Keisuke Nansai, and Kenichi Nakajima (2020). "Review of critical metal dynamics to 2050 for 48 elements". In: *Resour. Conserv. Recycl.* 155, p. 104669. DOI: 10.1016/j.resconrec.2019.104669.

Watari, Takuma et al. (2019). "Total material requirement for the global energy transition to 2050: A focus on transport and electricity". In: *Resour. Conserv. Recycl.* 148, pp. 91–103. DOI: 10.1016/j.resconrec.2019.05.015.

References VI

Werner, T. T., Anthony Bebbington, and Gillian Gregory (2019). "Assessing impacts of mining: Recent contributions from GIS and remote sensing". In: *Extr. Ind. Soc.* 6.3, pp. 993 –1012. DOI: 10.1016/j.exis.2019.06.011.

Werner, Tim T. et al. (2020). "Global-scale remote sensing of mine areas and analysis of factors explaining their extent". In: *Glob. Environ. Change* 60, p. 102007. DOI: 10.1016/j.gloenvcha.2019.102007.

Appendix paper 1 – data

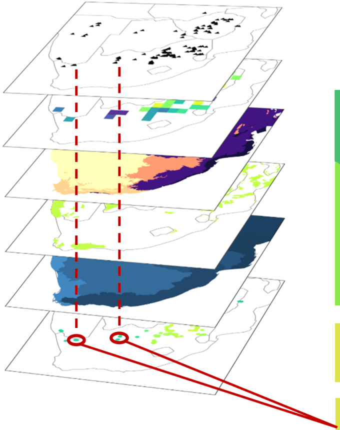
- 2,935 individual mines
- Bauxite, copper, gold, iron, lead, manganese, nickel, silver, zinc
- Time period 2000–2019

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	Levels	Scales
Assessing global distribution per year (1)	1 degree grid cells	Global
Analysing 2000-2019 mining expansion (2)	Biomes	Global
	5 km distance intervals	Global
	Watersheds	Global
Identifying expansion hotspots (3)	Individual mines	Global
Analysing hotspot cases (3)	Individual mines	Local

Appendix paper 1 – GWR (1)

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

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

- where $y(s)$ denotes the log-transformed extraction volume of a mine at location s,
- $\boldsymbol{X}(s)$ 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

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

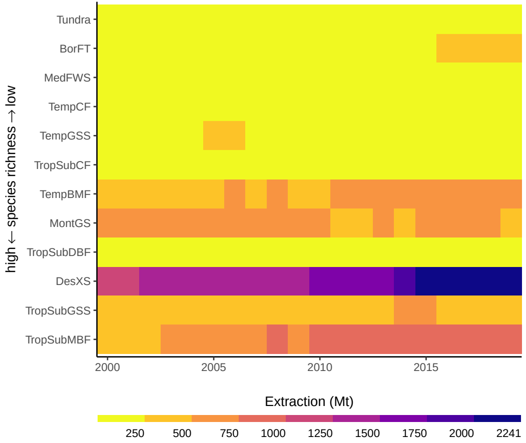
- where X is the design matrix of explanatory variables, and
- $\boldsymbol{W}(s)$ a diagonal weights matrix of dimension n that is calculated for each calibration location s.

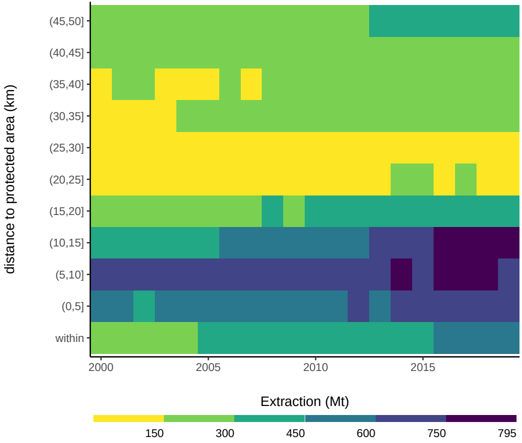
The elements of $\boldsymbol{W}(s)$ are obtained from the kernel function

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

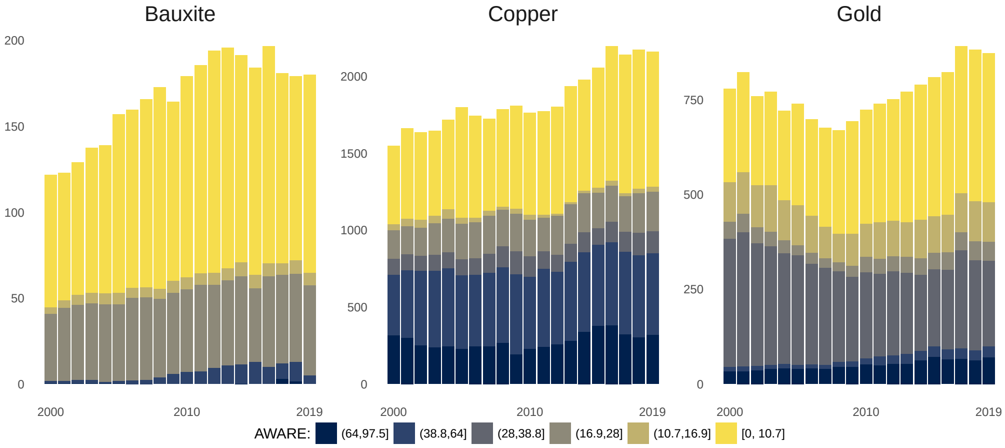
- where d_{sj} is the distance between locations s and j, and
- h is the kernel bandwidth parameter, which is pre-estimated by cross-validation across all the calibration locations.

Appendix paper 1 – more results (1)

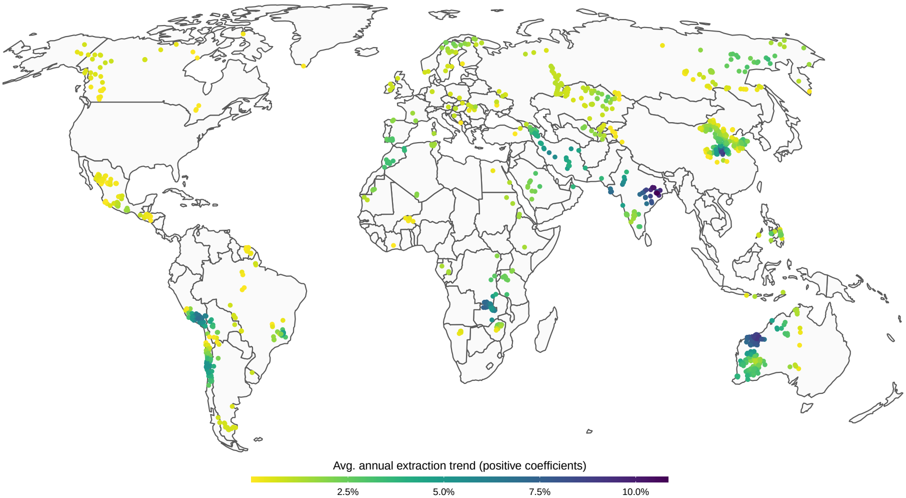




Appendix paper 1 – more results (2)



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

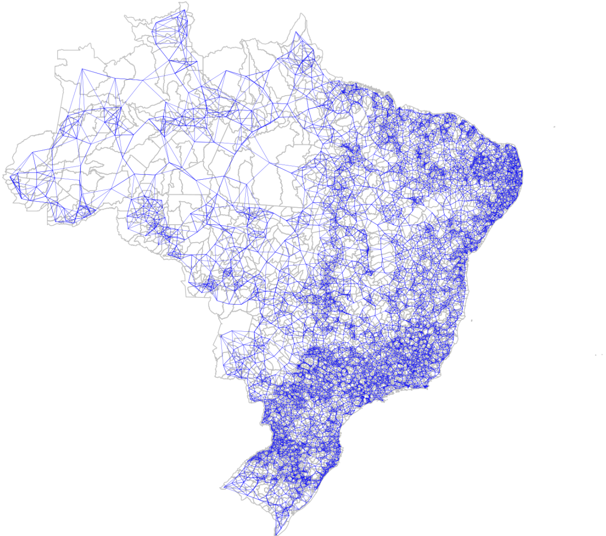
Appendix paper 2 – econometric framework

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

- $\boldsymbol{y}_t$ 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)
- $\boldsymbol{W}$ 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 $|\rho| < 1$.
- $\boldsymbol{X}_t$ 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 $\boldsymbol{X}_t$ and $\boldsymbol{W}\boldsymbol{X}_t$.
- Time-period-specific fixed effects $\boldsymbol{\xi}_t$.
- Assumption of independence of observations does not hold $\rightarrow$ Interpretation as marginal changes becomes redundant!

Appendix paper 2 – spatial weights

Paper 2



◂ Paper 2

Appendix paper 2 – direct effects and spillovers

- Following LeSage and Pace (2009), we derive

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

  from our SDM

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

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

Appendix paper 2 – Bayesian estimation approach

We combine likelihood with prior information:

- The likelihood:

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

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

- 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
- Griddy Gibbs approach proposed by Ritter and Tanner (1992) for ρ

Appendix paper 2 – MCMC algorithm

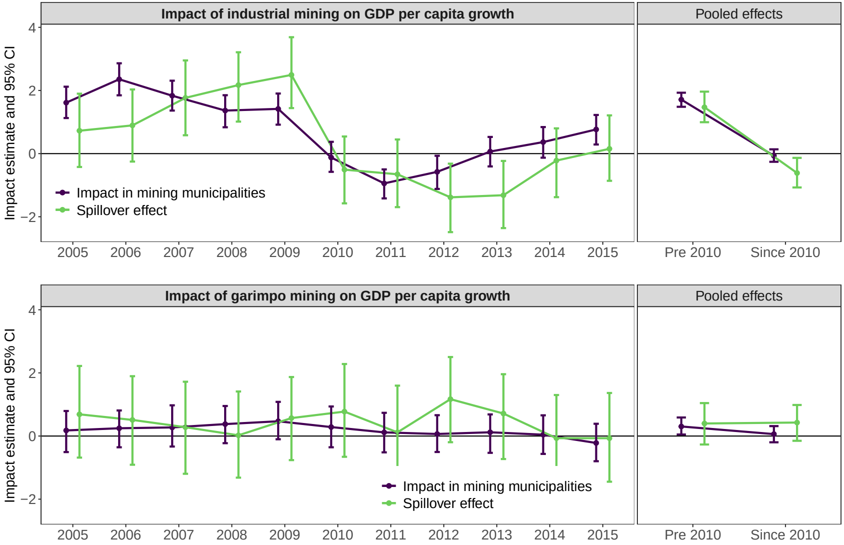
1. **Sample** σ^2 **from** $p(\sigma^2|\cdot) \sim G^{-1}(\overline{a}, \overline{b})$
   $\overline{a} = \underline{a} + N/2, \quad \overline{b} = \underline{b} + \epsilon'\epsilon/2$
2. **Sample** β **from** $p(\beta|\cdot) \sim N(\overline{\beta}, \overline{\Sigma})$
   $\overline{\Sigma} = (\underline{\Sigma}^{-1} + X'\Omega^{-1}X)^{-1}$
   $\overline{\beta} = \overline{\Sigma}(\underline{\Sigma}^{-1}\underline{\beta} + X'\Omega^{-1}Ay)$
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):

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

→ 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 $a_0 = 1.01$.

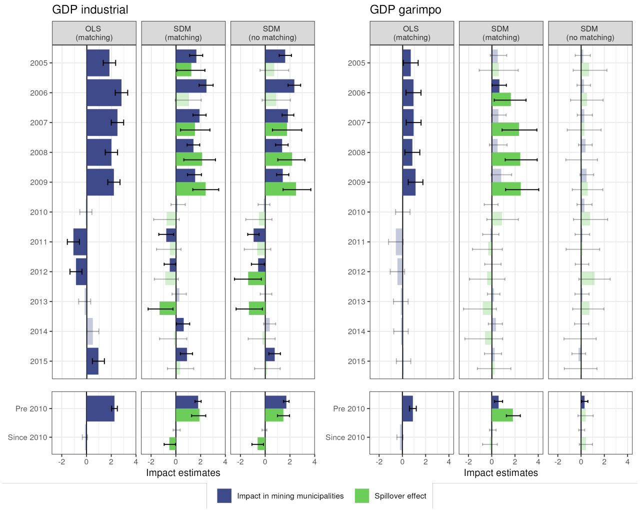
Paper 2

Appendix paper 2 – GDP results



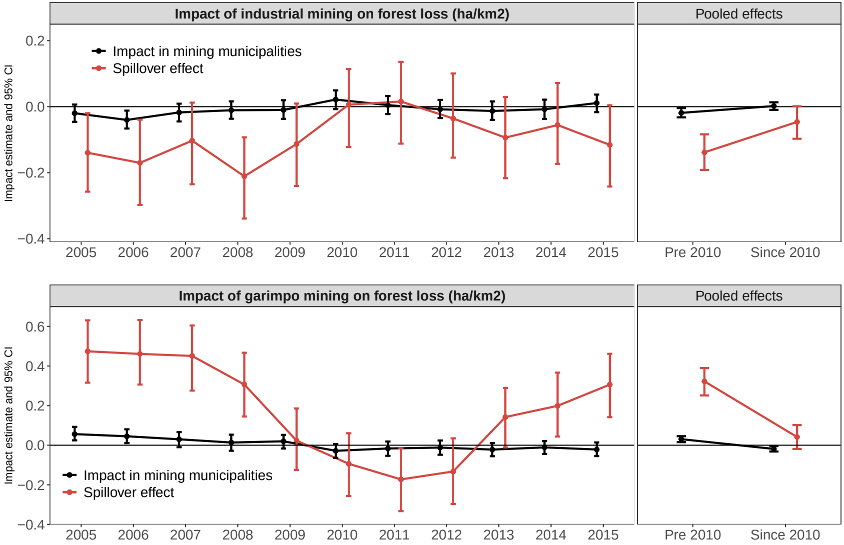
Appendix paper 2 – GDP results (matching)

Paper 2



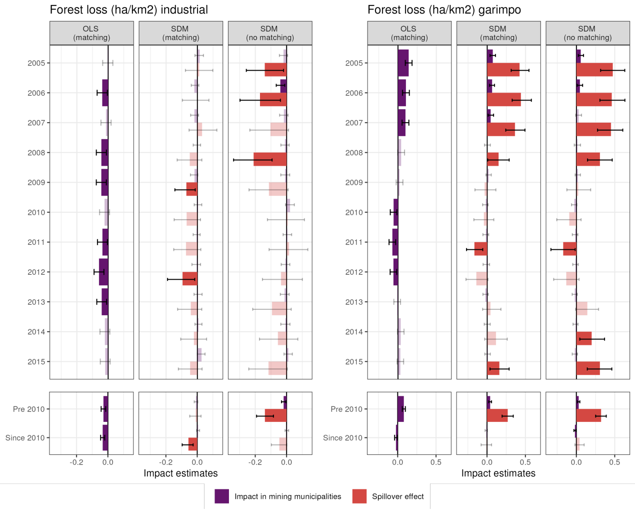
Appendix paper 2 – forest loss (relative) results

Paper 2



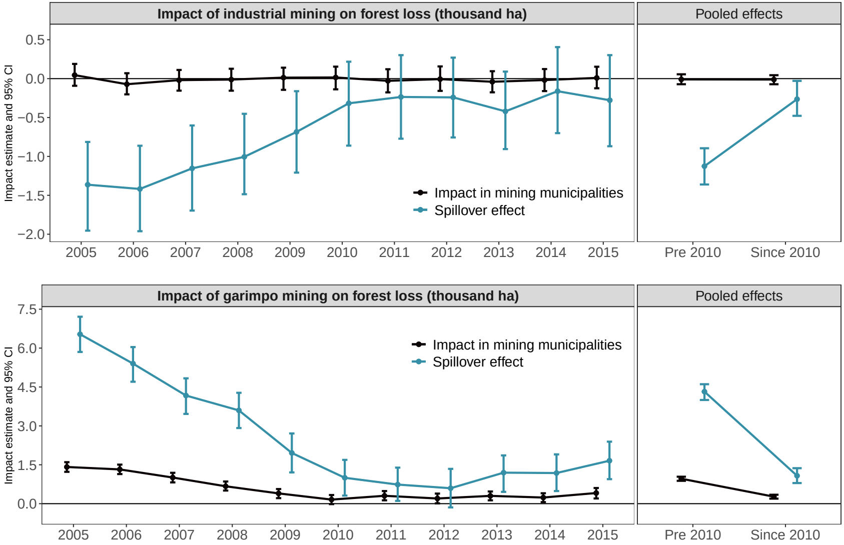
Paper 2

Appendix paper 2 – forest loss (relative, matching)



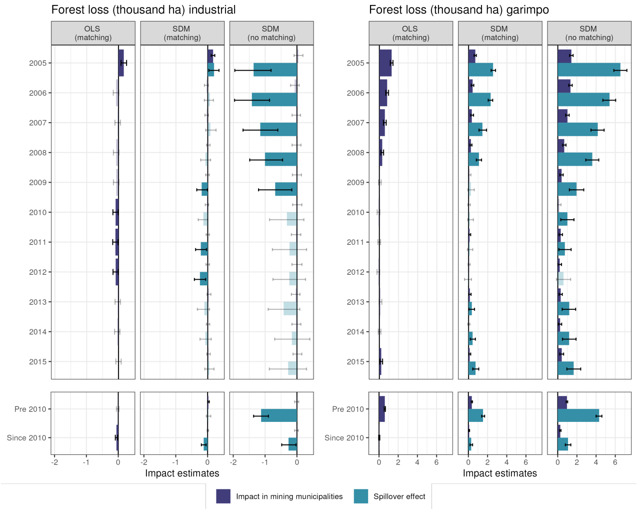
Appendix paper 2 – forest loss (absolute) results

Paper 2



Appendix paper 2 – forest loss (absolute, matching)

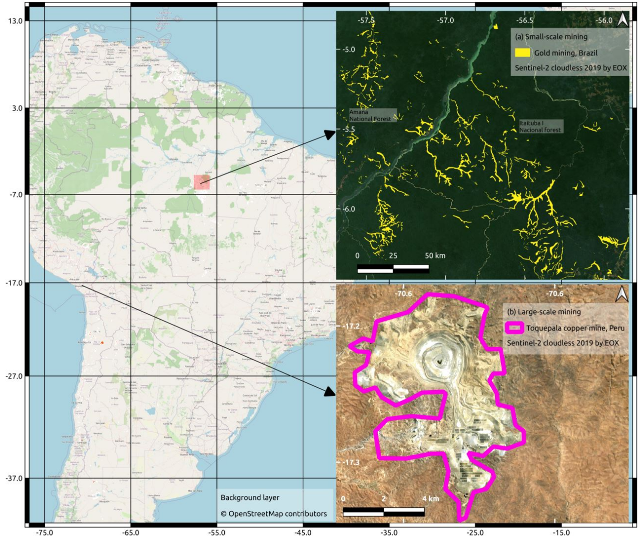
Paper 2



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

Paper 3

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

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

Technology matrix:

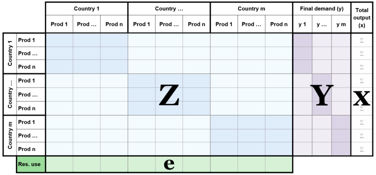
$$\boldsymbol{A} = \boldsymbol{Z}\hat{\boldsymbol{x}}^{-1} \Rightarrow \boldsymbol{Z}\boldsymbol{\iota}_n = \boldsymbol{A}\boldsymbol{x}$$

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

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

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

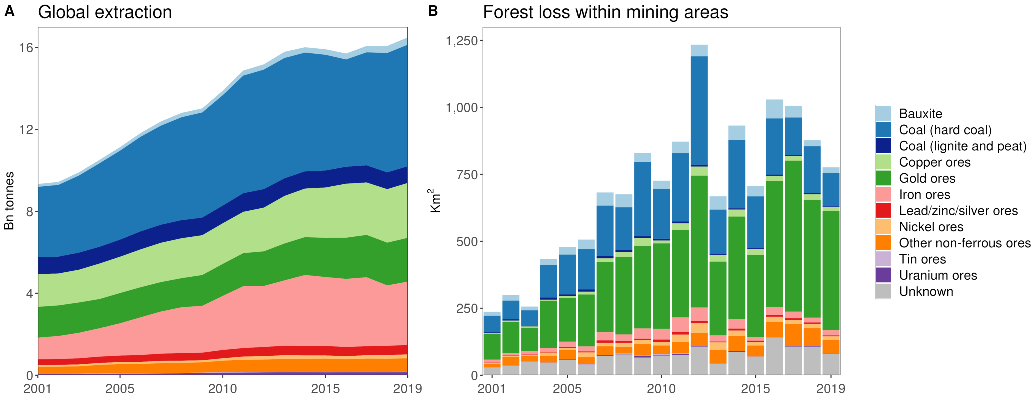
$\boldsymbol{f}_i$: all environmental inputs required by sector i to provide goods and services to final consumers.



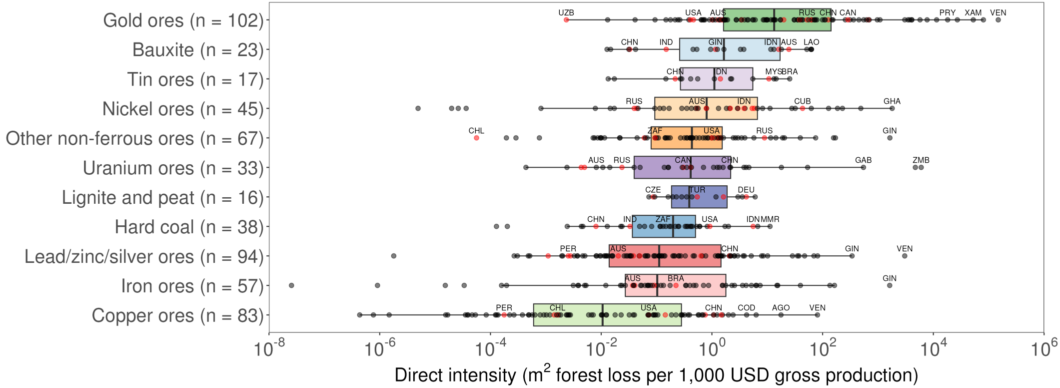
GLORIA IO database, Release 057 (Lenzen et al. 2017; 2022)

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

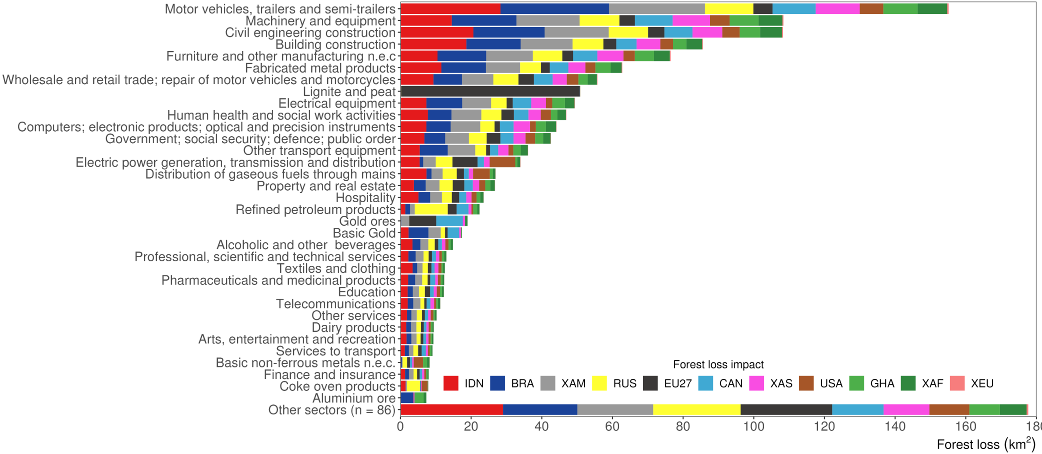
Appendix paper 3 – more results



Appendix paper 3 – more results



Appendix paper 3 – more results



Appendix paper 3 – more results