

Supplementary Information for
Overlooked deforestation from global mining activities in the 21st century

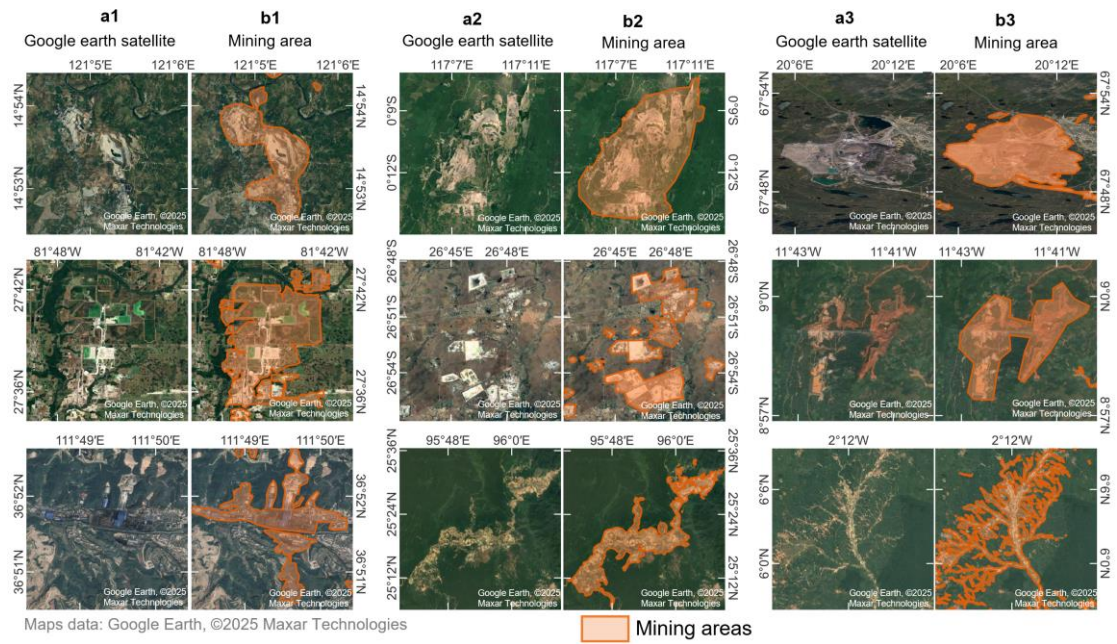
Xiaoxin Zhang¹, Bin Chen^{1,2,*}, Jiafu An^{2,3}, Chen Lin^{2,4,*}, Peng Gong^{2,5,*}

1. Future Urbanity & Sustainable Environment (FUSE) Lab, Division of Landscape Architecture, Faculty of Architecture, The University of Hong Kong, Hong Kong SAR, China
2. Urban Systems Institute and Institute for Climate and Carbon Neutrality, The University of Hong Kong, Hong Kong SAR, China
3. Department of Real Estate and Construction, Faculty of Architecture, The University of Hong Kong, Hong Kong SAR, China
4. Faculty of Business and Economics, The University of Hong Kong, Hong Kong SAR, China
5. Department of Geography and Department of Earth and Planetary Sciences, The University of Hong Kong, Hong Kong SAR, China

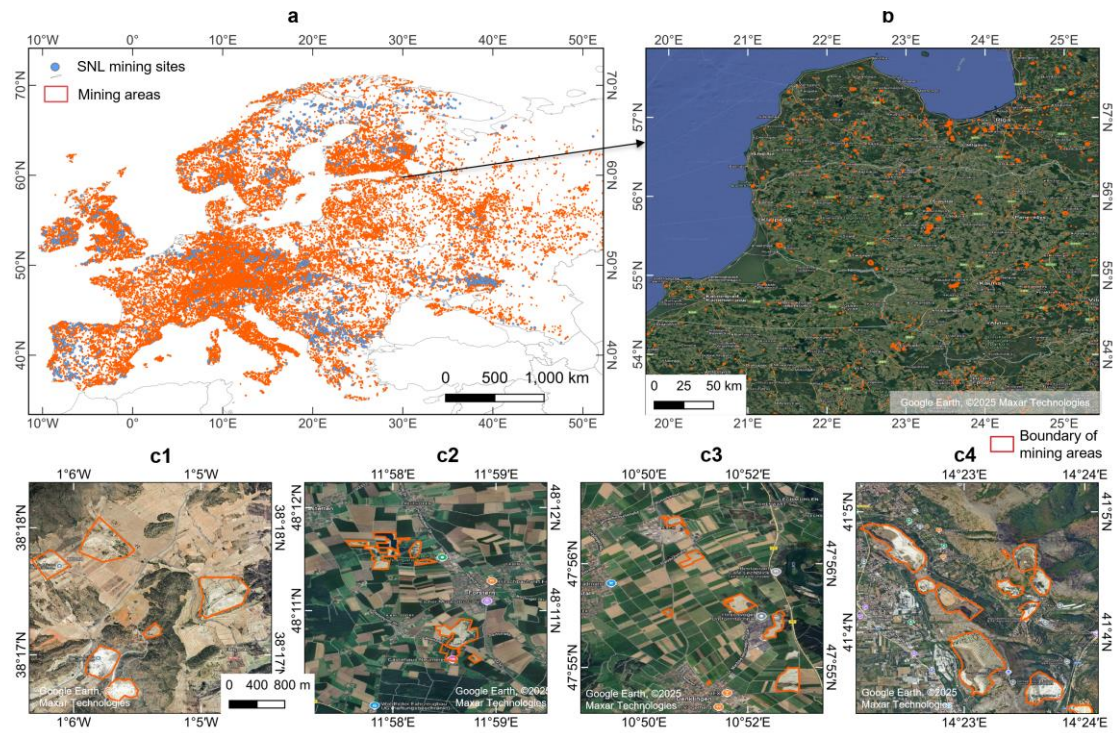
*Corresponding author: Bin Chen (binley.chen@hku.hk), Chen Lin (chenlin1@hku.hk), Peng Gong (penggong@hku.hk)

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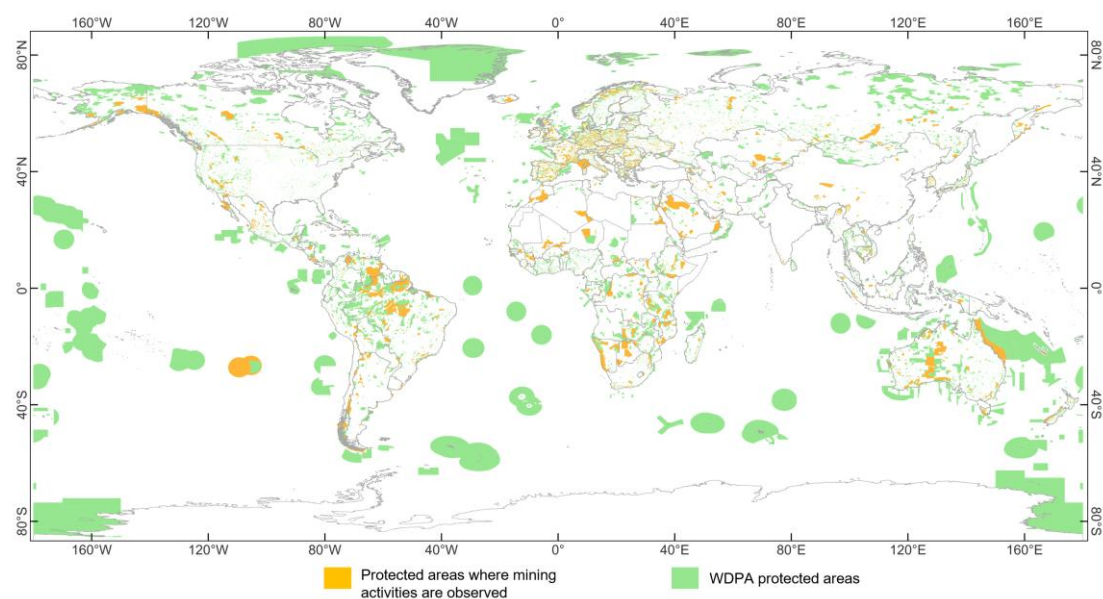
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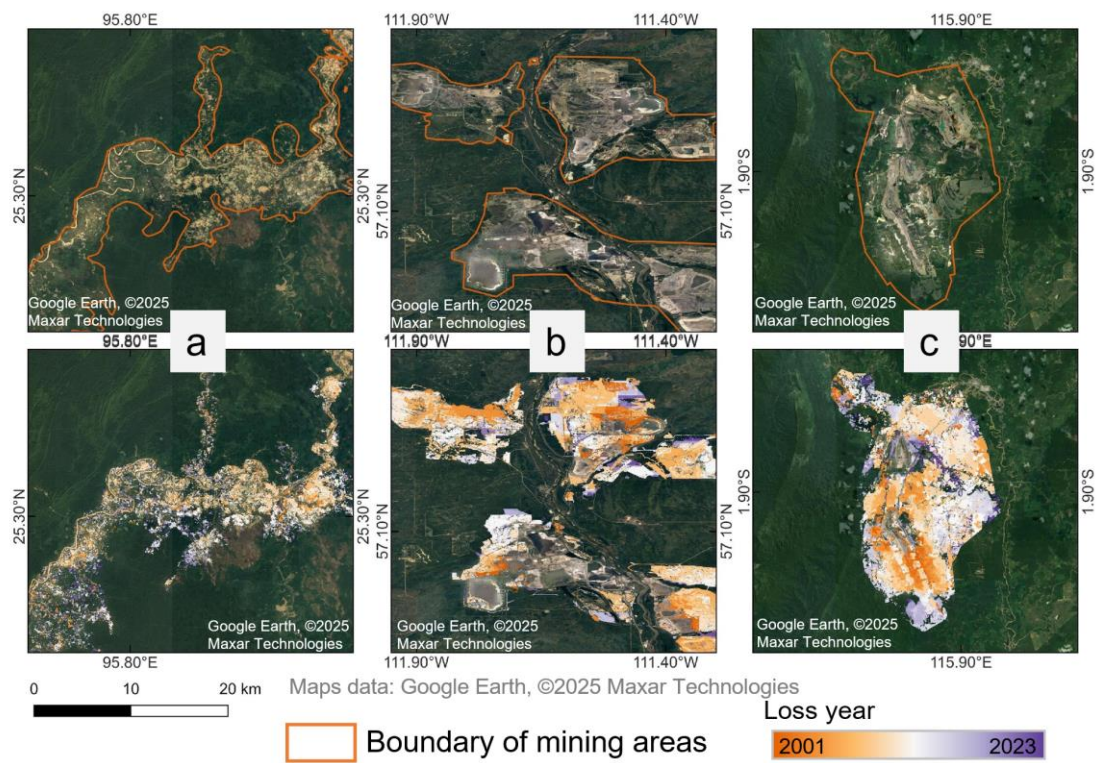
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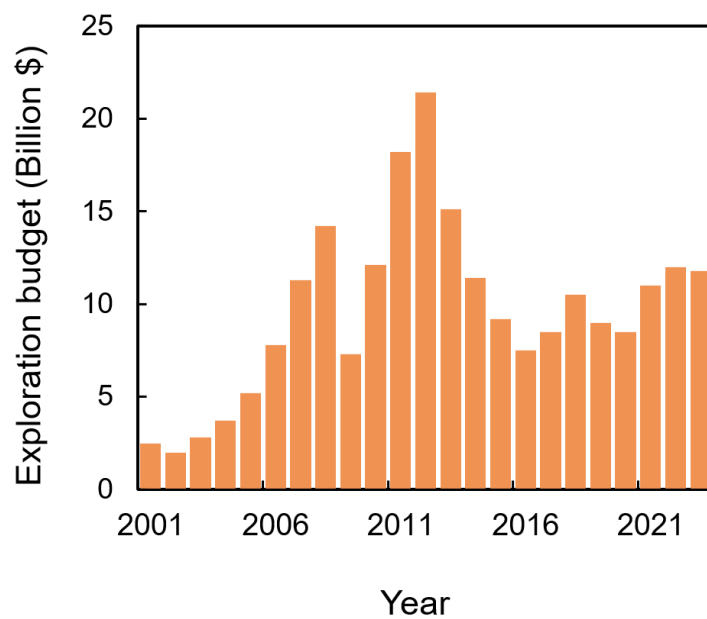
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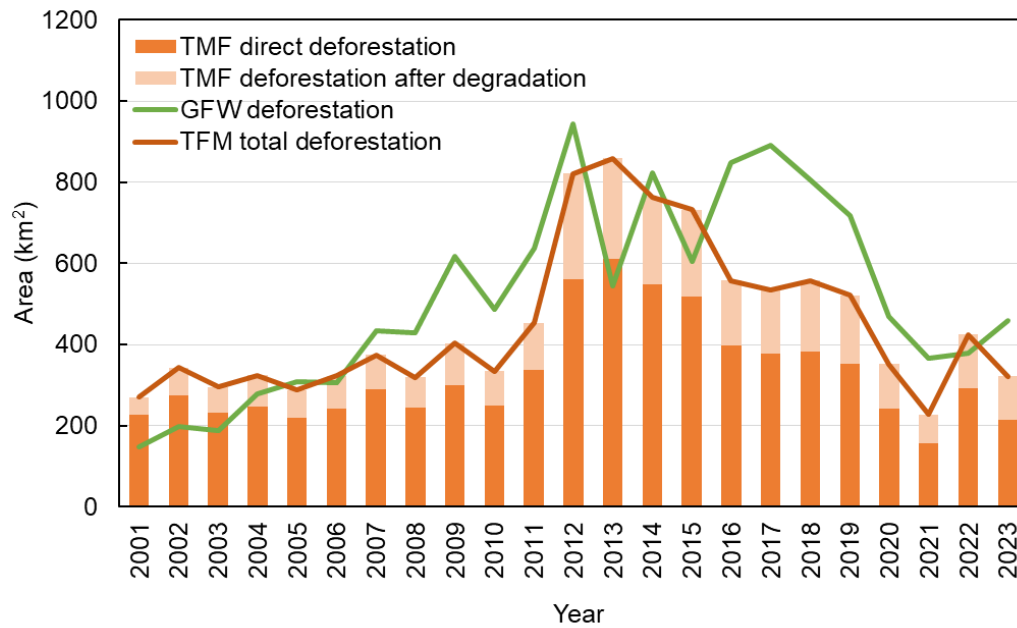
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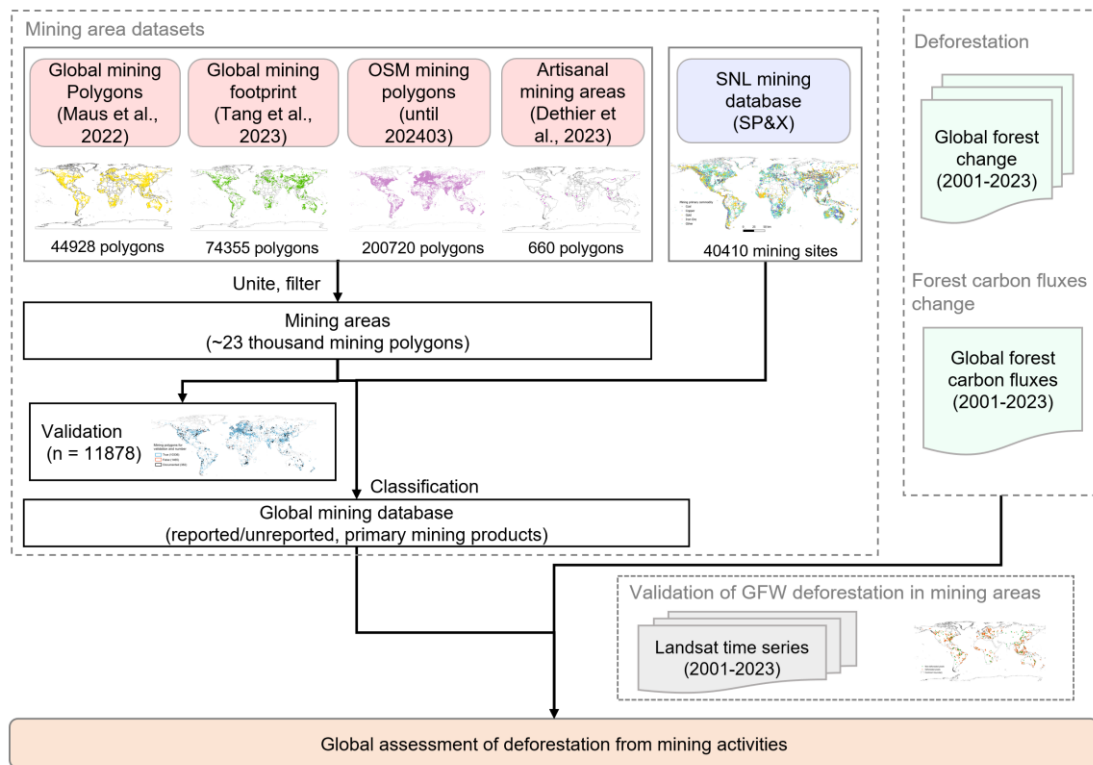
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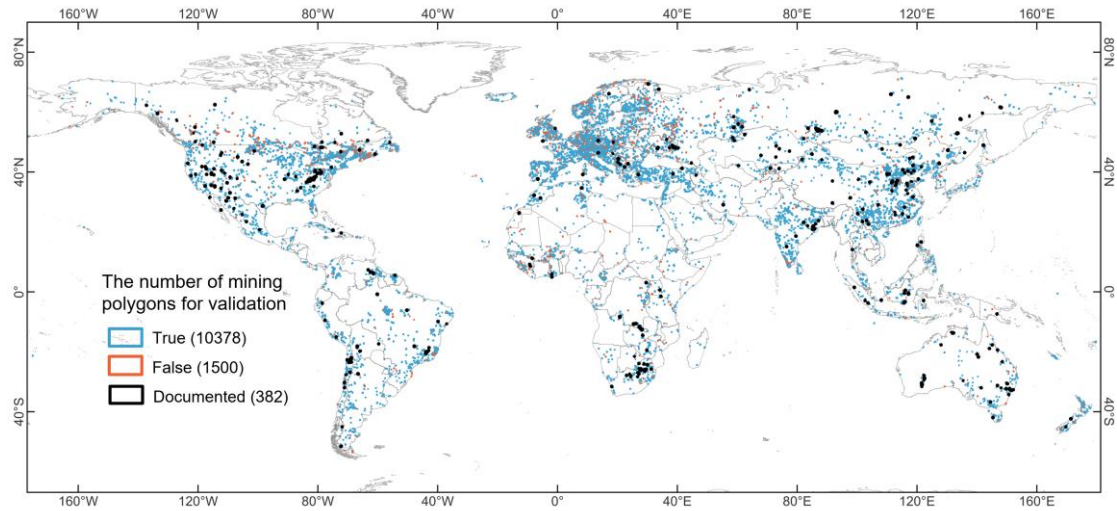
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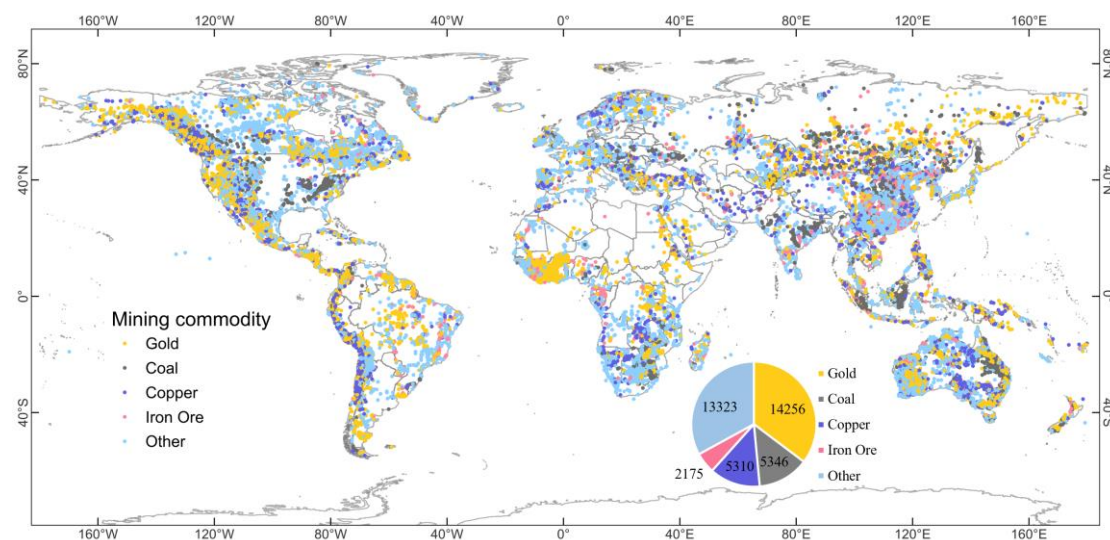
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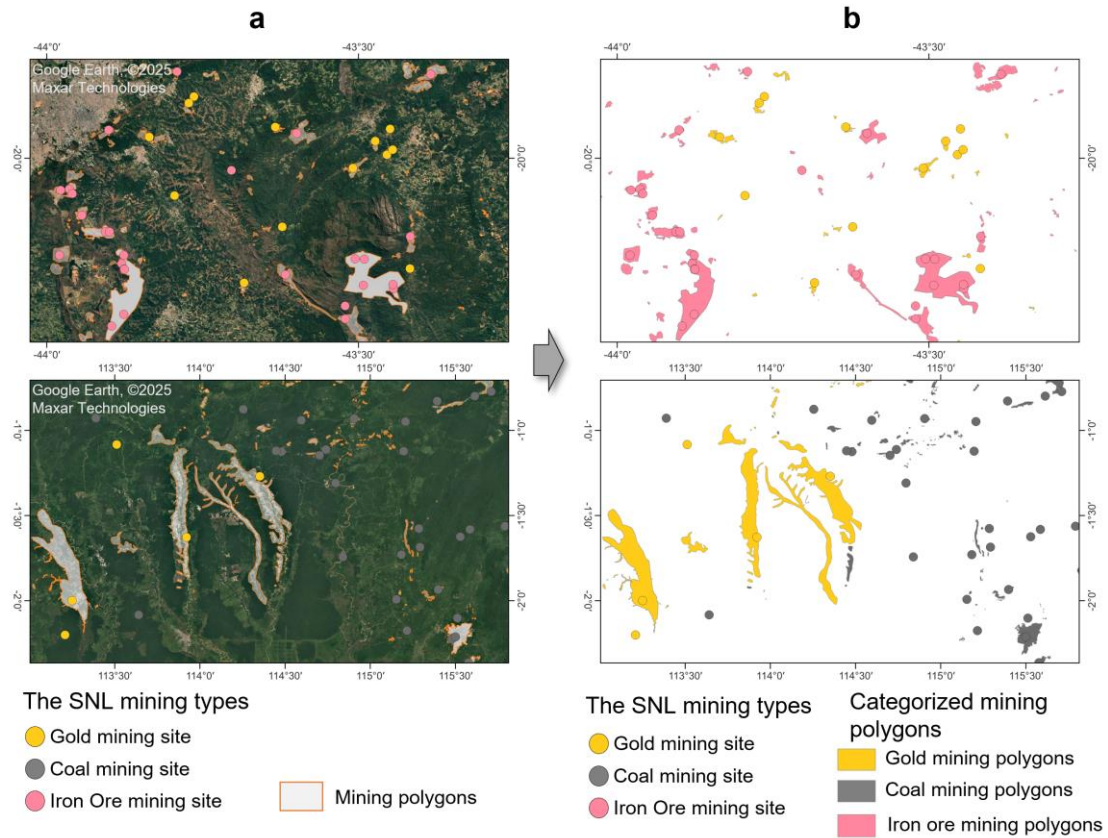
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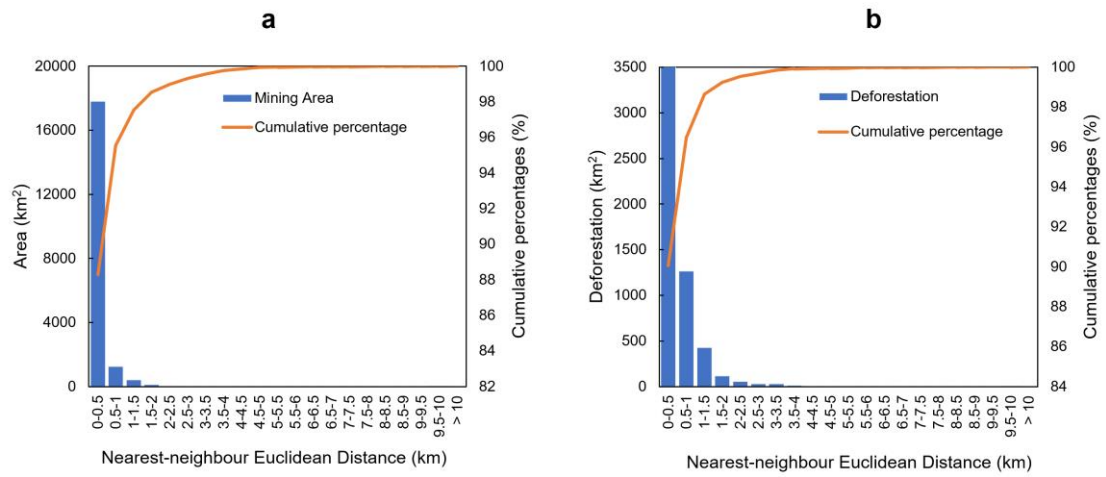
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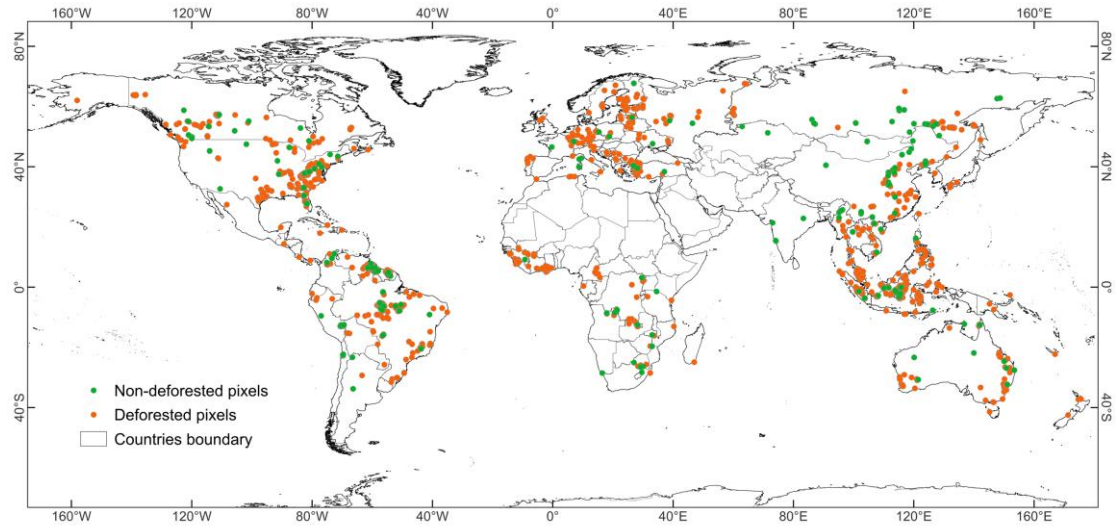
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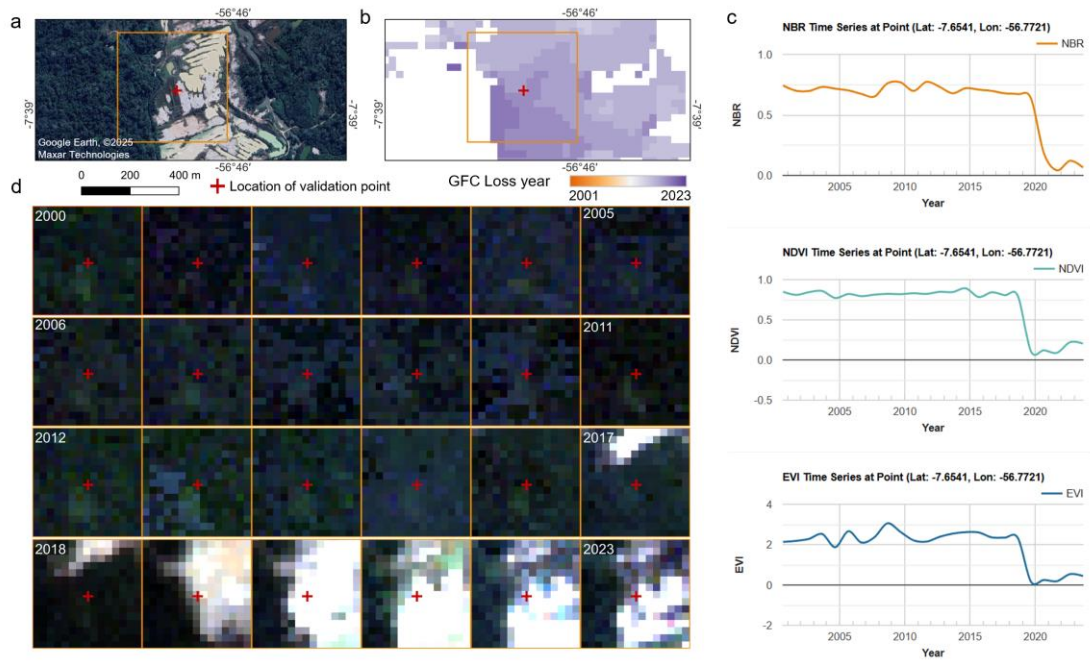


Supplementary Fig. S11. The Euclidean distance between each mining polygon and its nearest SNL data point. a, Total mining areas and the cumulative percentage of mining areas for various nearest distances groups. **b,** Mining-related deforestation and the cumulative percentage for various distance groups.

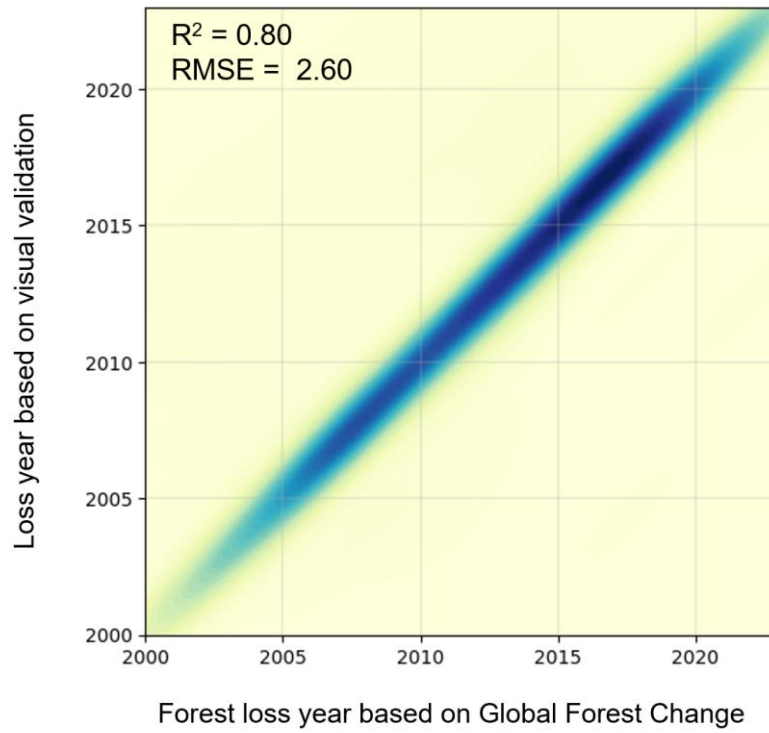


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Supplementary Fig. S13. Examples of validated GFW deforestation using Landsat time series from 2001 to 2023. **a**, The validation point overlaid on Google Earth Satellite Imagery (Map data: Google Earth, ©Maxar Technologies, 2025). **b**, The loss year of deforestation from Global Forest Change within the mining areas from 2001 to 2023. **c**, Annual medoid value for NBR, NDVI, EVI time series for the validation pixel. **d**, Landsat true color visualization (RGB) from 2000-2023 (<https://landsat.gsfc.nasa.gov/data/data-access/>).



Supplementary Fig. S14. Validation of the forest loss year from Global Forest Change. The density scatter plot for the loss year based on Global Forest Change dataset and visual validation for deforested pixels.

Supplementary Table S1. Sources and details for the mining datasets were used in this study.

Sources	Time period	Mining polygons	Mining total area (km ²)	Regions	Describes
Maus, V., et al, 2022 ³	2019	44,928	101,583	Globe	Mining polygons were manually delineated to include all land used by the mining sector during different stages of extraction and processing, restricted to a 10 km buffer around the 34,820 mining coordinates reported in the S&P Metals and Mining database using the 2019 Sentinel-2 cloudless mosaic. The datasets captured various ground features, including open cuts, tailings dams, waste rock dumps, water ponds, processing plants, and other infrastructure associated with both large-scale mining (LSM) and artisanal small-scale mining (ASM) activities, encompassing all visible underground and above-ground mining infrastructure.
Tang, L., et al. 2023 ³	2022	74,548	65,585	Globe	The global mining footprint was identified and delineated using remote sensing analysis of high-resolution, publicly available satellite imagery and manual visual inspection methods. This footprint included various mining-related features, such as waste rock dumps, pits, water ponds, tailing dams, heap leach pads, and processing/milling infrastructures.
Dethier, E., et al. 2023 ⁴	2022	660	396	Tropics	Artisanal mining areas were manually identified and outlined by reviewing literature and popular media, national reports, and extensive satellite imagery. The study primarily focused on riverine artisanal mining activities, including gold and diamond mines, as well as some nickel mines located in New Caledonia, Indonesia, and the Philippines.
OpenStreetMap	March 2024	200,720	52,236	Globe	Land parcels were categorized as quarry, defined as an area for surface extraction (open-pit mining) of mineral or organic resources like gravel, sand, coal, or other materials.

Supplementary Table S2. The number of mining polygons grouped by mining size (Area: km²).

	(0.0, 0.01]	(0.01, 0.05]	(0.05, 0.1]	(0.1, 0.5]	(0.5, 1]	(1, 5]	(5, 10]	(10, 50]	>50	Sum
Maus, V., et al, 2022⁵	1264	7214	5513	14519	5350	7781	1530	1499	259	44929
Tang, L., et al. 2023³	7441	16967	9974	22278	6841	8407	1416	960	71	74355
Dethier, E., et al. 2023⁴	110	197	81	158	46	53	10	5		660
OpenStreetMap (March 2024)	60389	60017	25700	39504	7396	6237	841	587	49	200720
This study	47828	72990	32607	53732	12015	12662	2035	1848	311	236028

Supplementary Table S3. Number of mining polygons used for validation and the overall accuracy categorized by mining sizes.

Mining size (Area: km²)	Total mining polygons	Number of validated mining polygons	Ture samples	False samples	Accuracy (%)
<0.01	47828	2387	1672	715	70.05
(0.01, 0.05]	72990	3653	3147	506	86.15
(0.05, 0.1]	32607	1629	1534	95	94.17
(0.1, 0.5]	53732	2690	2556	134	95.02
(0.5, 1]	12015	603	570	33	94.53
(1, 5]	12662	657	640	17	97.41
(5, 10]	2035	108	108	0	100
(10, 50]	1848	125	125	0	100
>50	311	26	26	0	100
Sum	236028	11878	10378	1500	87.37

Supplementary Table S4. Number of mining polygons for validation by continent and the overall accuracy.

Continent	Number of mining polygons for validation	True samples	False samples	Accuracy (%)
Africa	1341	1136	205	84.71
Asia	3877	3588	289	92.55
Australia	325	296	29	91.08
Europe	3365	2783	582	82.70
North America	2033	1724	309	84.80
South America	937	851	86	90.82
Global	11878	10378	1500	87.37

Supplementary Tables S5. Unreported areas and reported mining areas in Europe.

Mining size (Area: km²)	Unreported mining areas	Number of unreported mining polygons	Reported mining areas	Number of reported mining polygons	The ratio of unreported mining areas
<0.01	83.75	18660	0.04	6	99.96%
(0.01, 0.05]	586.22	22665	0.65	22	99.89%
(0.05, 0.1]	722.25	10095	1.67	23	99.77%
(0.1, 0.5]	3281.04	14905	46.54	161	98.60%
(0.5, 1]	1535.40	2242	67.45	92	95.79%
(1, 5]	2674.23	1411	367.86	171	87.91%
(5, 10]	924.95	133	255.86	35	78.33%
(10, 50]	1713.93	91	1354.79	56	55.85%
>50	741.75	5	675.52	8	52.34%
Sum	12263.53	70207	2770.38	574	81.57%

Supplementary Table S6. Comparison of mining-related deforestation estimates generated by existing research and this study.

References	Time period	Mining types	Reference areas	Directly Mining-related deforestation
Ref⁶	2001-2019	Industrial mining	Pantropical countries	3,264 km ²
Ref⁷ from World Wide Fund (WWF) report	2001-2022	Industrial and small-scale mining	Worldwide	13,650 km ²
Ref⁸	2001–2018	Legal and illegal	Colombia	4000 km ²
Ref⁹ from World Resources Institute(WRI) report	2001-2020	Large-scale mining and small-scale mining areas	Worldwide	~14000 km ²
This study	2001-2023	Reported and unreported mining	Worldwide	19,765 km ²

Supplementary Table S7. Mining properties targeting materials required for renewable energy technology and infrastructure and other non-renewable commodities, following the classification by Sonter et al.¹⁰.

Critical for renewable energy	Not critical for renewable energy
Gold, Copper, Silver, Zinc, Lead, Iron Ore, Nickel, Molybdenum, Cobalt, Platinum, Palladium, Lanthanides, Lithium, Tin, Tungsten, Manganese, Graphite, Vanadium, Bauxites, Tantalum, Chromite, Antimony, Titanium, Niobium, Zircon, Yttrium, Scandium, Chromium, Alumina, Aluminum, Platinum Group Metals	Coal, U3O8, Diamonds, Phosphate, Potash, Ilmenite, Rutile, Borates.

Supplementary Table S8. The number of samples used for validation in various continents, employing a stratified random sampling method.

Continent	Percentage of deforestation (%)	Number of deforested samples	Number of non-deforested samples	Total samples of validation
Africa	8.10	162	16	178
Asia	40.01	800	80	880
Australia	5.05	101	10	111
Europe	6.26	125	13	138
North America	16.63	333	33	366
South America	23.96	479	48	527
Global	100	2000	200	2200

Supplementary Table S9. Number of samples and accuracy for Global Forest Change deforestation in mining areas across continents.

GF C data set	Contine nt	Reference					
			Loss	No Loss	Overall accuracy (OA)	Producer's accuracy (PA)	User's accuracy (UA)
Africa		Los s	140	22	85.96%	86.42%	97.90%
		No loss	3	13			
Asia		Los s	797	83	98.41%	90.57%	98.64%
		No loss	11	69			
Australi a		Los s	82	19	82.88%	81.19%	100.00%
		No loss	0	10			
Europe		Los s	102	23	83.33%	81.60%	100.00%
		No loss	0	13			
North America		Los s	303	30	90.98%	90.99%	99.02%
		No loss	3	30			
South America		Los s	413	66	87.29%	86.22%	99.76%
		No loss	1	47			
Global		Los s	1837	243	91.77%	88.32%	99.03%
		No loss	18	182			

Supplementary Table S10. Land transition of shrubland and grassland in global mining areas using GLC_FCS30D land cover map¹¹ from 2000 to 2022.

		Land cover 2000	
		Shrubland	Grassland
Land cover 2022			
	Cropland	945.52	1348.35
	Forest	812.64	616.41
	Shrubland	8716.74	1107.12
	Grassland	1166.64	7868.57
	Tundra	38.65	15.37
	Wetland	149.14	178.31
	Impervious surface	683.86	1123.99
	Bare areas	1252.64	1589.12
	Water body	241.04	292.05

Supplementary Table. S11. Protected areas category and description from World Database Protected Areas (WDPA) ¹.

Protected areas category	Descriptions	The limitation of human activities in mining areas
Ia. strict nature reserve	Areas set aside to protect biodiversity and possibly geological or geomorphological features, which are usually managed for scientific research.	Limited to scientific research and education; no extractive or recreational uses allowed.
Ib. wilderness area	Areas are a protected domain in which biodiversity and ecosystem processes (including evolution) are allowed to flourish or experience restoration if previously disturbed by human activity.	Allows non-motorized recreational activities (e.g., hiking), but no infrastructure or motorized access.
III. national park	Large natural areas set aside to protect natural biodiversity and provide for environmentally compatible recreation.	Allows for recreational activities, education, and tourism but restricts damaging activities (e.g., mining and logging).
III. natural monument or Feature	Areas that are set aside to protect a specific natural monument, which can include landforms, sea mounts, or a combination of features that are significant for their environmental or cultural value.	May permit limited recreational activities, but extraction activities are generally prohibited.
IV. habitat/species management area	Areas managed to protect particular species or habitats, often involving active management intervention.	May allow for sustainable level extraction or land use but focuses on conservation of habitats and species.
V. protected landscape/seascape	Areas that are protected to maintain the interaction between people and nature, where the landscape is shaped by human activity but still retains ecological significance.	Encourages sustainable land use and conservation of cultural landscapes, allowing for agricultural and recreational activities.
VI: protected area with	Areas that aim to protect ecosystems while allowing for sustainable use of	Allows for sustainable extraction and use of resources (e.g., forestry, fishing) that do

sustainable use of natural resources	natural resources, balancing conservation and resource extraction.	not compromise conservation goals.
Other	- No application: The protected area does not fit the IUCN's definition or management categories - Not Assigned: The IUCN category has not yet been assigned to the protected area. - Not reported: The IUCN category exists but has not been reported to the WDPA.	Noted: The absence of a management category does not in any way reduce the importance of a protected area, nor does it imply that the site is not being adequately managed or should be excluded from analyses.

Supplementary Table S12. Total areas of mining polygons and mining-related deforestation from 2001 to 2023 categorized by different mining sizes.

Mining size (Area: km²)	Number of mining polygons	Mining area (km²)	Percentage of mining area	Mining- related deforestation 2001-2023 (km²)	Perce ntage of defore station
<0.01	47828	232.05	0.16%	13.79	0.07%
(0.01, 0.05]	72990	1884.51	1.29%	167	0.84%
(0.05, 0.1]	32607	2334.54	1.60%	234.87	1.19%
(0.1, 0.5]	53732	12174.14	8.34%	1259.39	6.37%
(0.5, 1]	12015	8425.08	5.77%	927.92	4.69%
(1, 5]	12662	26641.16	18.26%	3270.99	16.55%
(5, 10]	2035	14235.77	9.76%	1879.96	9.51%
(10, 50]	1848	37750.5	25.87%	5113.96	25.87%
>50	311	42222.78	28.94%	6897.47	34.89%
Sum	236028	145900.5	-	19765.35	-

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