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## Unveiling nitrogen oxide emissions from open-pit copper mines through satellite observations

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## LETTER

## Unveiling nitrogen oxide emissions from open-pit copper mines through satellite observations

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Iolanda Ialongo<sup>1,\*</sup> , Henrik Virta<sup>1</sup> , Janne Hakkarainen<sup>1</sup> , Cem Özcan<sup>2</sup> , Mikko Ranta<sup>2</sup> and Simon Zieleniewski<sup>3</sup> <sup>1</sup> Space and Earth Observation Centre, Finnish Meteorological Institute, Helsinki, Finland<sup>2</sup> University of Vaasa, Vaasa, Finland<sup>3</sup> Rovjok Oy, Helsinki, Finland

\* Author to whom any correspondence should be addressed.

E-mail: [iolanda.ialongo@fmi.fi](mailto:iolanda.ialongo@fmi.fi)**Keywords:** copper mining, TROPOMI, nitrogen dioxide, emissionsSupplementary material for this article is available [online](#)**Abstract**

Copper is a critical mineral for clean energy and transportation, and it is necessary for a sustainable economy that aims at reducing fossil fuel usage. Assessing the performance and environmental impacts of copper mining is therefore necessary to evaluate the progress towards sustainable development. In this study, we estimate the nitrogen oxide (NO<sub>x</sub>) emissions (largely attributable to the diesel-powered mobile fleet) over 14 of the world's largest open-pit copper mines. We derive the emissions by applying a data-driven approach to the satellite-based nitrogen dioxide (NO<sub>2</sub>) observations from the TROPospheric Monitoring Instrument on board the Sentinel-5 Precursor satellite. We find that the annual NO<sub>x</sub> emissions over the different mines are coupled to the corresponding copper production, ore processed and total material moved. The time series analysis reveals that the annual amount of total material moved over the open pit of each mine best reproduces the year-to-year variability of the NO<sub>x</sub> emissions. Overall, satellite NO<sub>2</sub> observations show good potential in tracking mining activities and for improving the assessment of the environmental impact of the mining industry.

**1. Introduction**

Copper is a highly conductive metal used in electrical equipment, construction and industrial machinery. Copper is a critical material for the green transition towards a more sustainable economy, as it is used for electric vehicles as well as for solar and wind energy production and is highly recyclable. The production of copper also poses environmental and social challenges that must be addressed responsibly. The mining industry is under increased scrutiny to adopt sustainable practices that align with environmental, social, and governance (ESG) principles. Transparent accounting of environmental impacts, including emissions and resource utilization, is essential for companies to demonstrate their commitment to sustainability and to meet the expectations of stakeholders and investors.

Chile is the world's leading producer of copper. Other major producers include Peru, Mexico, Zambia and the United States. The extraction of copper from mineral ores is accompanied by the emission of nitrogen oxide (NO<sub>x</sub> = NO<sub>2</sub> + NO) mainly from combustion processes from trucks and other diesel-fueled machinery over the quarry of open-pit mines. Nitrogen dioxide (NO<sub>2</sub>) is an atmospheric trace gas with a short lifetime of just a few hours in the troposphere. It is primarily produced by combustion activities from human-related sources such as energy production, transportation, and other industrial processes. NO<sub>2</sub> influences tropospheric chemistry by contributing to the formation of ozone and aerosols. Exposure to high concentrations of nitrogen dioxide (as well as sulfur dioxide and particulate matter) can negatively affect the health of communities living near mining sites (Yu *et al* 2024). Air polluting emissions from the mining activities can

cause several health issues, including an increased risk of respiratory infections and other long-term health complications.

Currently available satellite observations of  $\text{NO}_2$  can be exploited to monitor air polluting emissions from point sources at global scale. The Tropospheric Monitoring Instrument (TROPOMI) aboard the European Space Agency's Copernicus Sentinel-5 Precursor (S5P) satellite has been providing  $\text{NO}_2$  tropospheric column data since April 2018 with current spatial resolution of  $3.5 \times 5.5 \text{ km}^2$  ( $3.5 \times 7 \text{ km}^2$  from the beginning of the mission up until 6 August 2019) and excellent signal-to-noise ratio (Veeffkind *et al* 2012). Numerous data-driven techniques have leveraged TROPOMI and earlier satellite instruments to detect and quantify air pollution emissions from point sources (Beirle *et al* 2011, 2019, 2021, Fioletov *et al* 2015, Goldberg *et al* 2019, Hakkarainen *et al* 2021, 2024). Since  $\text{NO}_2$  is a good indicator of human activities, satellite-based  $\text{NO}_2$  observations and their trends have often been used to track socioeconomic changes such as the 2008–2009 global economic crisis, the 2020 COVID-19 pandemic and the 2022 war in Ukraine as well as to verify the efficacy of environmental policy measures (Castellanos and Boersma 2012, de Foy *et al* 2016, Goldberg *et al* 2020, Ialongo *et al* 2021, 2023, Cooper *et al* 2022). Recently, Kerr *et al* (2024) uncovered the air pollution impacts from warehousing in the United States using satellite data.

In this study, we use S5P/TROPOMI  $\text{NO}_2$  observations to link the  $\text{NO}_x$  emissions to the mining extraction activities for 14 of the largest open-pit copper mines in the world. Section 2 describes the data and the emission estimation approach. The results are presented in section 3. Section 4 concludes the paper.

## 2. Data and methodology

### 2.1. Selected copper mines

We analyse 14 of the largest open-pit copper mines in the world: Morenci, Bagdad, Sierrita and Mission mines in Arizona, USA; Buenavista and La Caridad in Mexico; Antapaccay and Toquepala in Peru; Centinela, Sierra Gorda and Spence in Chile; Sentinel, Lumwana and Kansanshi in the Copperbelt region in Zambia (the last three were previously analysed by Martínez-Alonso *et al* 2023). The mines analysed in this paper were selected among the world's largest copper mines according to the following criteria: sufficient satellite data coverage,  $\text{NO}_2$  enhancements detectable from the background and  $\text{NO}_2$  signal isolated from neighbouring sources. Operational data such as mill capacity, copper production, ore processed, and strip ratio were collected from the companies' annual reports and sustainability disclosures (figure 1, table 1, and table S1 in the supplement).

The strip ratio indicates the ratio of the amount of waste material moved to the total amount of ore mined. The total material moved is calculated as the sum of the ore processed and waste (where waste = ore processed  $\times$  strip ratio). Air polluting emissions are expected from the combustion of fossil fuels from stationary and mobile sources, explosions, and mineral processing. Therefore, the  $\text{NO}_x$  emissions are expected to change with the copper production and, even more directly, with the total amount of moved material over the open pit of the mine. The Morenci mine has the largest annual copper production, followed by Buenavista and Toquepala. On the other hand, the Chilean mines Centinela and Sierra Gorda and the Peruvian Antapaccay have the largest strip ratios.

### 2.2. TROPOMI $\text{NO}_2$ product and $\text{NO}_x$ emission estimation method

We estimate the  $\text{NO}_x$  emissions over 14 selected open-pit mines by leveraging the satellite-based  $\text{NO}_2$  tropospheric columns from the TROPOMI. TROPOMI is a passive hyperspectral nadir-viewing imager that observes across the ultraviolet–visible (UV–VIS), near-infrared (NIR), and short-wavelength infrared spectral bands. The tropospheric  $\text{NO}_2$  columns are calculated using the spectrometer measurements of back-scattered solar radiation from the UV–VIS channel (van Geffen *et al* 2022). TROPOMI was launched on 13 October 2017 onboard the Copernicus S5P satellite. The S5P satellite operates in a near-polar, Sun-synchronous orbit with a local overpass time of 13:30 (Veeffkind *et al* 2012). The  $\text{NO}_2$  products have been available since April 2018 with a near-nadir spatial resolution of  $3.5 \times 7 \text{ km}^2$  at the beginning of the mission, and  $3.5 \times 5.5 \text{ km}^2$  since 6 August 2019. The orbit swath is 2600 km wide and it is divided into 450 measurement pixels. For this analysis, we use the TROPOMI  $\text{NO}_2$  reprocessed data product version 2.4.0 or later. TROPOMI  $\text{NO}_2$  measurements are routinely validated by the S5P Mission Performance Center Validation Data Analysis Facility using ground-based observations. Previous versions of the TROPOMI  $\text{NO}_2$  product have been validated with ground-based observations also by Griffin *et al* (2019), Ialongo *et al* (2020), Judd *et al* (2020) and Lange *et al* (2023), among others. For the analysis, we consider TROPOMI  $\text{NO}_2$  data with quality assurance value larger than 0.75.

For the  $\text{NO}_x$  emission estimation we use the divergence method introduced by Beirle *et al* (2019). The emission maps are derived as  $E = D + S$ , where  $D = \nabla \cdot F$  is the divergence of the mean fluxes and  $S = LV/\tau$  is the sink term. Here we assume a constant  $\text{NO}_2$  lifetime of 4 h. This choice discards the seasonal variability of the  $\text{NO}_2$  lifetime, which is

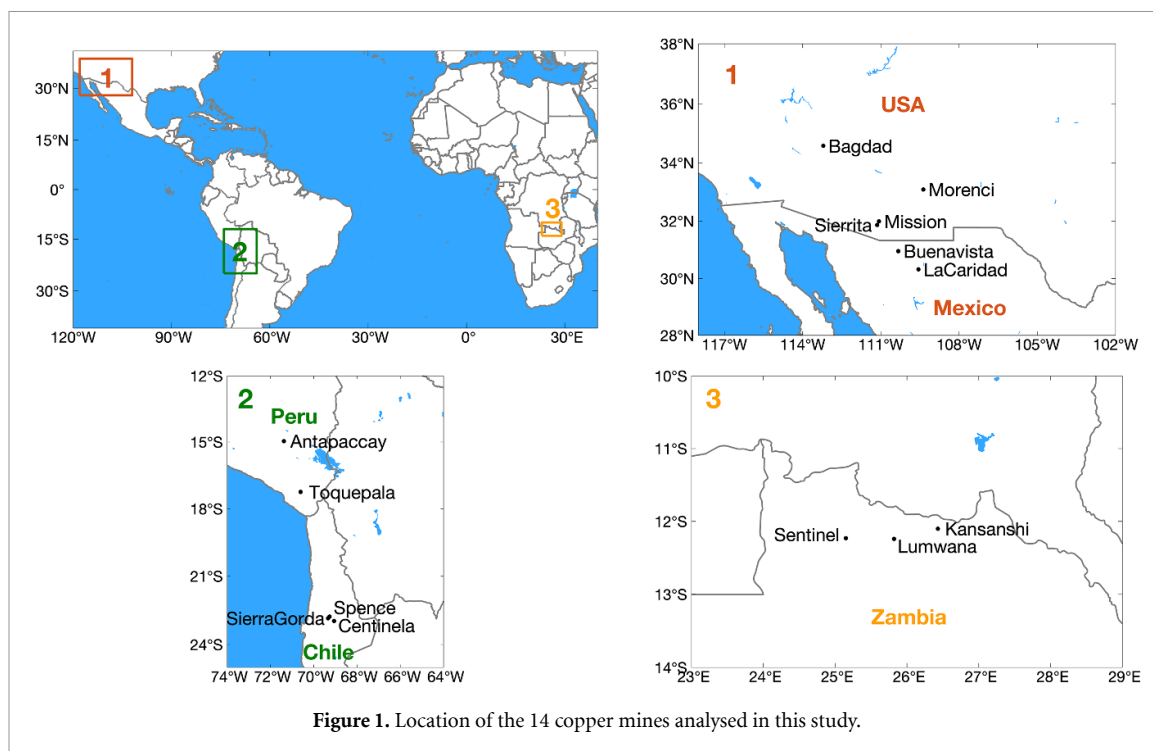


Figure 1. Location of the 14 copper mines analysed in this study.

typically shorter in summer due to accelerated photochemistry. Beirle *et al* (2021) noted that the seasonal dependency of the lifetime is generally rather weak. Moreover, satellite  $\text{NO}_2$  observations are only available under clear-sky conditions, which may introduce uneven seasonal representation. The flux  $F$  is defined as  $F = (F_x, F_y) = (V \cdot u, V \cdot v)$ , where  $V$  is the  $\text{NO}_2$  tropospheric column densities observed by S5P/TROPOMI, and  $u$  and  $v$  are the eastward and northward winds, respectively, at the level of the enhanced concentrations. The emissions are derived using the peak fitting technique as in Beirle *et al* (2019). For the scenes including more than one mine (and corresponding  $\text{NO}_2$  enhancement) we fit the sum of multiple 2D Gaussian functions to the emission fields. The uncertainty in the emission estimates (40%–60%) depends on different factors including the fitting error (a few percents), the TROPOMI  $\text{NO}_2$  retrieval error (about 30%–50%), the uncertainties in the wind information (20%–30%) and in the assumed  $\text{NO}_x$ -to- $\text{NO}_2$  ratio (10%–20%) and  $\text{NO}_2$  lifetime (35%–50%) (Beirle *et al* 2019). Other uncertainties are related to the accuracy of air mass factor (AMF) used to convert the slant to vertical columns as well as to the clear-sky bias of passive satellite observations. Here, we do not apply a correction for the AMF, thus the emissions are expected to be biased low (Beirle *et al* 2019, 2021, Hakkarainen *et al* 2024). We note that most of the errors associated with the emission estimates are systematic, and they come from the uncertainties in the satellite observations themselves and the other input information used in the methodology.

### 2.3. Auxiliary data

For the calculation of the emissions we use the ECMWF ERA5 10 m-wind available for download at 0.1 degrees resolution, interpolated to the closest satellite pixel and to the overpass time of the S5P satellite. We compare the satellite-based  $\text{NO}_x$  emission estimates to the CAMS Global anthropogenic emission (CAMS-GLOB-ANT, Granier *et al* 2019) v5.3 inventory based on the historical Emissions Database for Global Atmospheric Research (EDGAR V5.0, Crippa *et al* 2020) and Community Emissions Data System (CEDS) global databases. The linear trend from the CEDS data for the years 2011–2014 is used to project the EDGARv4.3 2010 emission estimates forward. The spatial resolution of the inventory is  $0.1^\circ \times 0.1^\circ$ .

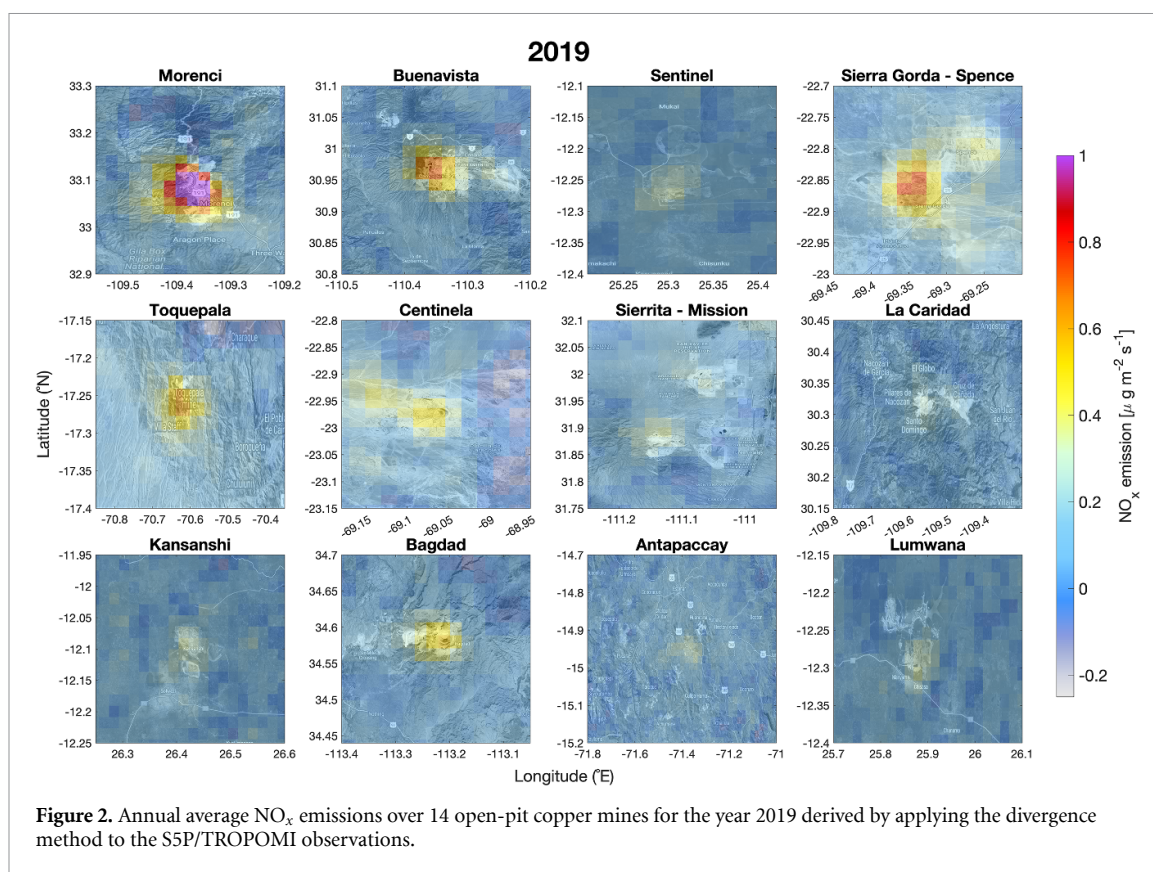
## 3. Results

Figure 2 shows the annual  $\text{NO}_x$  mean emissions for the year 2019 over the 14 selected copper mines derived using the divergence method (Beirle *et al* 2019). The enhancements are located over the open pit of each mine, suggesting a direct link to the mining extraction activity.

The largest emissions are observed over the Morenci mine in Arizona (USA), which also has the largest copper production and mill capacity among the mines studied here. Figures S1–S4 in the supplementary material include the corresponding  $\text{NO}_x$  emission maps for the year 2020–2023. Based on such emission maps, the emissions for each point source are derived using the peak fitting method. The annual

**Table 1.** Summary of the copper mines analysed in this study and corresponding properties. The mines are ordered based on decreasing mill capacity from top to bottom.

Name	Country	Latitude (°N)	Longitude (°E)	Mill capacity (kt yr <sup>-1</sup> )	Copper production (tonnes)					Strip ratio				
					2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
Morenci	USA	33.09	-109.37	74 600	459 942	445 400	397 523	400 658	362 873	1.4	1.4	1.4	1.4	0.8
Buenavista	Mexico	30.96	-110.33	71 905	337 960	333 570	341 200	338 630	328 950	0.7	0.7	0.6	0.8	0.8
Sentinel	Zambia	-12.23	5.15	55 000	220 006	251 216	232 688	242 451	214 046	1.9	1.6	1.8	1.7	1.9
Mission	USA	31.99	-111.07	52 560	54 800	57 800	54 900	42 800	54 697	1.8	1.6	1.6	1.8	1.8
Sierra Gorda	Chile	-22.85	-69.34	47 500	108 182	148 727	189 818	165 091	143 000	3.5	3.7	2	2	2.7
Toquepala	Peru	-17.25	-70.61	40 000	231 670	229 120	203 620	175 060	199 660	0.9	0.8	1.2	1.5	3.2
Centinela	Chile	-22.97	-69.06	34 650	195 500	153 500	185 400	149 300	162 700	4	4	4	4	4
Sierrita	USA	31.87	-111.14	33 000	72 574	80 739	85 729	83 460	83 915	0.6	0.6	0.3	0.1	0.1
La Caridad	Mexico	30.32	-109.56	31 185	107 161	109 671	102 689	88 492	87 810	0.5	0.5	0.4	0.7	0.6
Kansanshi	Zambia	-12.17	26.38	28 200	232 243	221 487	202 159	146 282	134 827	1.5	1.8	2	2.7	2.1
Bagdad	USA	34.58	-113.21	28 100	98 883	97 975	83 461	74 842	66 224	1.48	1.7	0.6	1.8	1.8
Antapaccay	Peru	-14.96	-71.38	23 100	197 600	185 600	170 800	151 000	173 000	4	4.1	3.9	4	4
Lumwana	Zambia	-12.24	25.82	20 000	107 955	125 191	109 769	121 109	117 934	2.7	2.7	2	3.9	1.5
Spence	Chile	-22.78	-69.27	18 300	171 300	175 200	130 600	115 000	114 300	—	—	2.4	2.1	3



emission estimates for each year between 2019 and 2023 are summarized in table 2. The satellite-based emission estimates are generally larger by at least one order of magnitude as compared to emissions from bottom-up inventories (as also reported by Martínez-Alonso *et al* 2023 for the Zambian mines), suggesting missing or incomplete information in the reported emission estimates but also possible systematic errors in the satellite-based estimates.

Emissions from fossil fuel combustion from open-pit mines are expected to increase with the copper production as well as the strip ratio, which is a good indicator of the extraction efficiency and its environmental impact at a specific mine. Figure 3 shows the annual NO<sub>x</sub> emissions as a function of the annual copper production. These quantities show an approximately linear relationship, suggesting that the NO<sub>x</sub> emissions increase with the copper production. There are also some departures from this correspondence between production and NO<sub>x</sub> emissions, which could be partly explained by differences in the strip ratios. High strip ratios correspond to conditions where a relatively large amount of waste need to be moved in order to extract a certain amount of metal. The fossil fuel usage from trucks and other machinery (and the corresponding NO<sub>x</sub> emissions) is therefore expected to increase with increasing strip ratio.

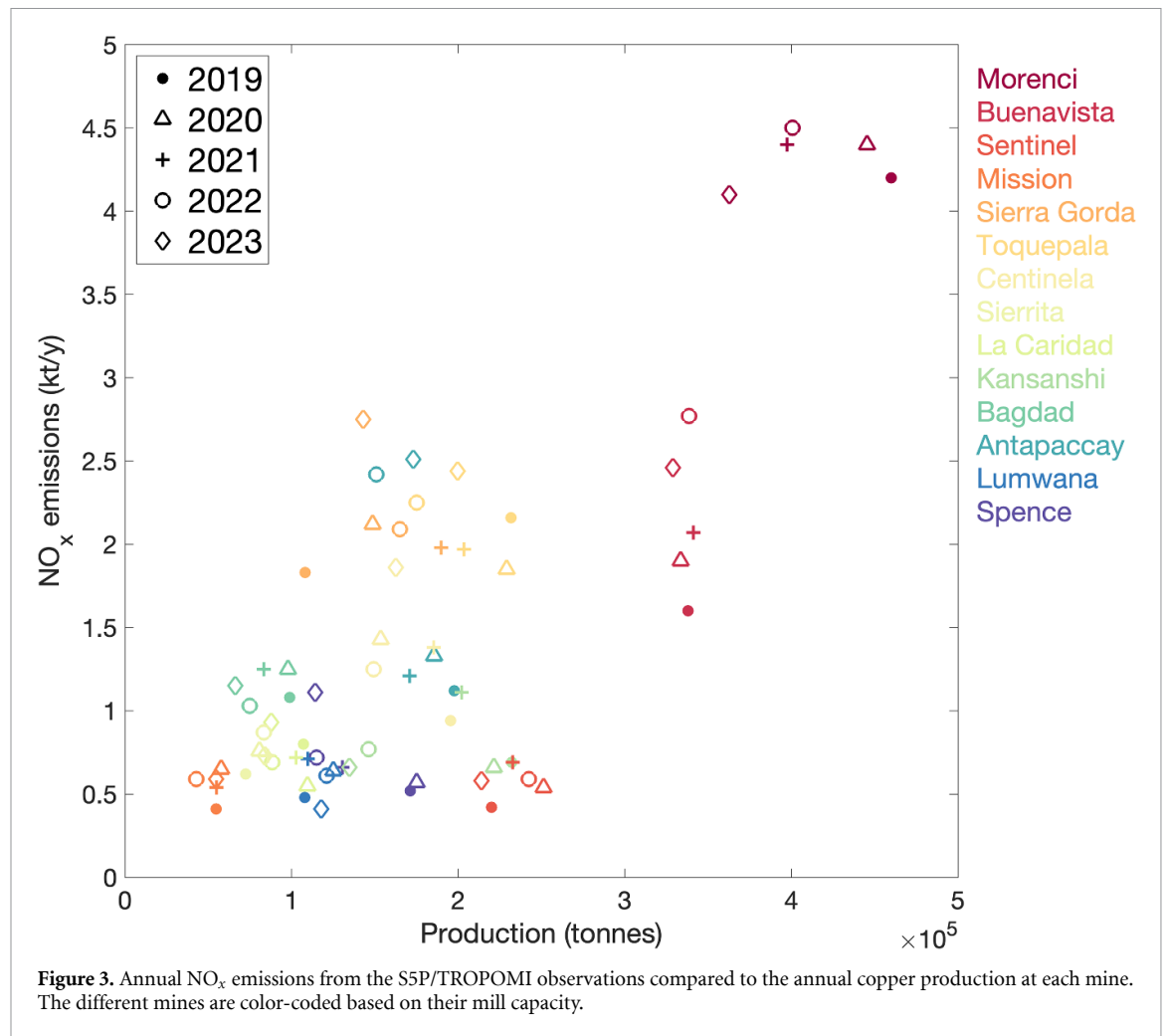
Also, we note that the mines in Zambia's Copperbelt region (Sentinel and Kansanshi, in particular) have relatively low emissions (with respect to

other sources with similar copper production), which possibly suggests a reduced fossil fuel usage as compared to other regions in the world. Variability in the emission values from different mines can be related for example to different technologies employed in the mining process, as well as local biases in the data or in the emission estimation approach. For example, the First Quantum Minerals company reports that their Zambian mines (Kansanshi and Sentinel) use electric shovels and trolleys instead of diesel-powered machinery.

In order to better assess the effect of the mining activities over the open pit, we also consider information of ore processed and total material moved, which is defined as the sum of the ore processed and waste (where waste = ore processed × strip ratio). The emissions from the diesel-powered mobile fleet needed for the mining activities are expected to be most directly linked to the total material moved. Unfortunately, these data are not always reported by the mining companies. Figure S5 and S6 in the supplementary material include the scatter plots of the annual NO<sub>x</sub> emissions as a function of the annual ore processed and total material moved, respectively. The emissions show an approximately linear relationship to these parameters as well, with some outliers. For example, the Sentinel mine has relatively low emission values as compared other mines with similar values of ore processed or total material moved. This can be related to both reduced fossil fuel usage at the Sentinel mine as well as biases in the satellite

**Table 2.** Summary of the NO<sub>x</sub> emission estimates over the selected copper mines. The uncertainties include the fitting errors, the uncertainty on the wind choice as well as the NO<sub>2</sub> retrieval uncertainty.

Name	Satellite-based emissions (Kt yr <sup>-1</sup> )					Inventory emission (Kt yr <sup>-1</sup> )				
	2019	2020	2021	2022	2023	2019	2020	2021	2022	2023
Morenci	4.2 ± 1.7	4.4 ± 1.8	4.4 ± 1.8	4.5 ± 1.8	4.1 ± 1.6	0.0728	0.0702	0.0674	0.0649	0.0625
Buenavista	1.6 ± 0.6	1.9 ± 0.8	2.1 ± 0.8	2.8 ± 1.1	2.5 ± 1	0.0274	0.0270	0.0263	0.0258	0.0253
Sentinel	0.4 ± 0.2	0.5 ± 0.2	0.7 ± 0.3	0.6 ± 0.2	0.6 ± 0.2	0.0107	0.0108	0.0108	0.0108	0.0108
Mission	0.4 ± 0.2	0.7 ± 0.3	0.5 ± 0.2	0.6 ± 0.2	0.6 ± 0.2	0.0427	0.0415	0.0401	0.0389	0.0377
Sierra Gorda	1.8 ± 0.7	2.1 ± 0.9	2.0 ± 0.8	2.1 ± 0.9	2.8 ± 1.1	0.0225	0.0229	0.0232	0.0236	0.0240
Toquepala	2.2 ± 0.9	1.9 ± 0.7	2.0 ± 0.8	2.3 ± 0.9	2.4 ± 1	0.1453	0.1485	0.1509	0.1538	0.1567
Centinela	0.9 ± 0.4	1.4 ± 0.6	1.4 ± 0.6	1.3 ± 0.5	1.9 ± 0.8	0.0028	0.0029	0.0029	0.0030	0.0030
Sierrita	0.6 ± 0.3	0.8 ± 0.3	0.7 ± 0.3	0.9 ± 0.4	0.7 ± 0.3	0.0209	0.0202	0.0195	0.0189	0.0183
La Caridad	0.8 ± 0.3	0.6 ± 0.2	0.7 ± 0.3	0.7 ± 0.3	0.9 ± 0.4	0.0041	0.0041	0.0040	0.0040	0.0040
Kansanshi	0.7 ± 0.3	0.7 ± 0.3	1.1 ± 0.4	0.8 ± 0.3	0.7 ± 0.3	0.1196	0.1200	0.1198	0.1199	0.1200
Bagdad	1.1 ± 0.4	1.3 ± 0.5	1.3 ± 0.5	1.0 ± 0.4	1.2 ± 0.5	0.0138	0.0133	0.0128	0.0123	0.0119
Antapaccay	1.1 ± 0.5	1.3 ± 0.5	1.2 ± 0.5	2.4 ± 1	2.5 ± 1	0.0145	0.0147	0.0148	0.0150	0.0152
Lumwana	0.5 ± 0.2	0.6 ± 0.3	0.7 ± 0.3	0.6 ± 0.3	0.4 ± 0.2	0.0457	0.0459	0.0459	0.0460	0.0461
Spence	0.5 ± 0.2	0.6 ± 0.2	0.7 ± 0.3	0.7 ± 0.3	1.1 ± 0.5	0.0953	0.0967	0.0975	0.0987	0.0998



observations (e.g. related to surface albedo, altitude or background levels).

Figure 4 shows the time series of both  $\text{NO}_x$  emissions and copper production for each copper mine analysed. In some cases, the satellite-based  $\text{NO}_x$  emission estimates qualitatively reproduce the year-to-year changes in copper production (e.g. Sierrita, Bagdad, Sentinel, Lumwana). For other mines, the temporal evolution of the emission and the production might be somewhat different. Figure S7 in the supplement includes time series similar to figure 4, but with the total material moved instead of the copper production in the vertical axis. The time series of total material moved appear to better reproduce the year-to-year variability in the  $\text{NO}_x$  emissions at many locations, but the data at several sites are missing. The correlation between the  $\text{NO}_x$  emissions and the total moved material is always higher (or more positive) compared to the correlation with the copper production (figure S8 in the supplement). This appears to confirm the hypothesis that the mining activities are more directly linked to the total material moved over the open pit of the mine (as also suggested by Martínez-Alonso *et al* 2023).

Overall,  $\text{NO}_x$  emissions appear to increase at most sites, particularly in South America, with the exception of African mines, where reductions are expected due to the gradual electrification of the mobile fleet. In Kansanshi (ZM), there is an apparent outlier in 2021, with relatively high emission estimates compared to other years, which do not correspond to an increase in production or total material moved. Increasing annual emissions often correspond to increases in total material moved, particularly in Toquepala, Spence, and La Caridad. In South America, emissions increased by more than 30% from 2022 to 2023 in Sierra Gorda, corresponding to an approximately 40% increase in total material moved (figure S7 in the supplement). Similarly, in Spence, the total material moved almost doubled from 2021 to 2023, corresponding to a nearly 60% increase in annual emissions over the same period. Emissions in Centinela, Antapaccay, and Spence more than doubled between 2019 and 2023.

Several factors can affect the year-to-year variability of the  $\text{NO}_x$  emissions over the open-pit mines and the uncertainties associated with these emission estimates (about 40%) might be too large to

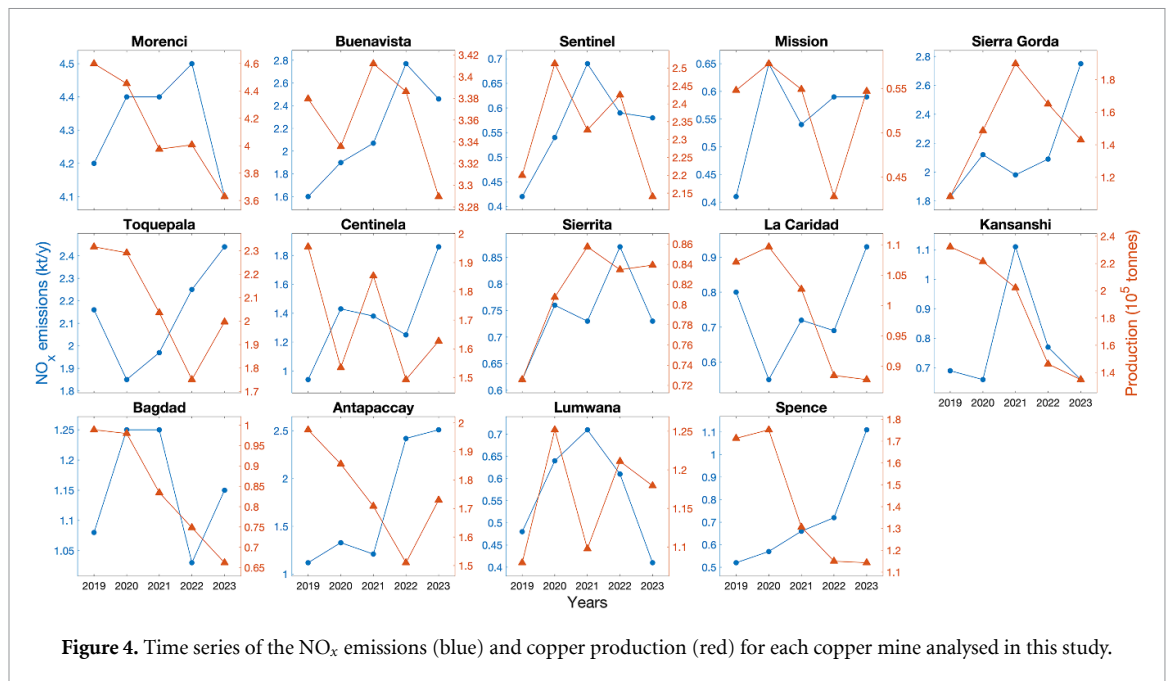


Figure 4. Time series of the NO<sub>x</sub> emissions (blue) and copper production (red) for each copper mine analysed in this study.

accurately describe the year-to-year variability of the emissions in all cases. Further temporal variability can be related to additional emission sources in the vicinity of the mines, varying data availability as well as other errors in the emission estimation method.

#### 4. Summary and discussion

We analysed the NO<sub>x</sub> emissions over some of the largest surface copper mines in the world using satellite data. The NO<sub>x</sub> emissions estimated from TROPOMI NO<sub>2</sub> observations are generally higher than the existing inventories. This suggests that bottom-up emission inventories from the mining industry might be incomplete, indicating potential gaps in corporate environmental reporting. However, the discrepancies can also be due to substantial uncertainties in the satellite-based emission estimates.

We found that the NO<sub>x</sub> emissions can increase with increasing copper production and total moved material over the open pit, while some of the variability cannot be explained by changes in such mining-related parameters. Aligned emissions and production volumes highlights the need for integrating ESG considerations into operational planning. Companies can implement site-specific strategies that decouple emissions from production growth, such as optimizing logistics and investing in cleaner technologies or alternative energy sources.

Information about the total moved material appear to be more directly related to the NO<sub>x</sub> emissions, but they are generally available only for a limited number of mines. Satellite-based NO<sub>2</sub> observations could be possibly used to track sudden changes in mining activities related to changes in fossil fuel usage, e.g. the electrification of the mobile fleet. Other

factors related to the mines' properties, employed technologies or nearby sources as well as to biases in the data and the methodology can affect the resulting emissions. The uncertainties associated with the emission estimates depend on the parameters as well as the assumptions used in the method. These uncertainties could be reduced for example by refining the method (as described e.g. by Beirle *et al* 2021) or by using more accurate input information (e.g. wind data). Nevertheless, systematic errors are still expected to remain from the satellite observations themselves and from the other input information.

Satellite-based observations are useful in providing more complete and timely emission estimates to assess the environmental impact of mining activities. The high resolution and accuracy of the TROPOMI NO<sub>2</sub> retrievals enabled the detection of relatively small emission areas such as surface mines (as compared to industrial facilities from other sectors, power plants or urban areas). With increasing requirements for ESG reporting on the horizon, new independent information will be needed for compliance monitoring. Currently, most sustainability reporting of mining activity is based on self-reporting by the companies operating/owning the mines and can be patchy and incomplete. Satellite observations provide an independent metric for tracking mining emissions, contributing to more transparent corporate sustainability reporting, improving investor interest and stakeholder trust. Our approach offers a way to harmonize diverse regulatory frameworks for mining operations. A persistent issue in environmental governance is the misalignment between these frameworks and corporate reporting practices (Christensen *et al* 2022). By providing a standardized methodology for generating data for key indicators,

such as emissions, we help regulators to enforce environmental standards while supporting corporations in delivering transparent and credible reports. The results presented here demonstrate how emission estimates derived from satellite observations can enhance the monitoring of mining activities and their environmental impacts. Instruments like S5P/TROPOMI provide atmospheric data that can complement optical and NIR imagery, which are currently used by monitoring companies and organizations for assessing site expansion, land-use changes, deforestation, and tailings composition. Moreover, integrating such satellite-based assessments into sustainability reports, as described for example by Ialongo *et al* (2018), strengthens corporate transparency and accountability.

Advancing satellite-based approaches for emission assessments will help different types of stakeholders to better track the impacts and performance of mining activities. Specifically, Boiral *et al* (2019) emphasized that meaningful engagement with indigenous communities requires recognizing the interconnectedness of their needs with global sustainability goals. Our approach can facilitate trust-building by supporting participatory practices and providing transparent information that align with community priorities and concerns. Also, Lauwo *et al* (2016) noted that, Non-Governmental Organizations (NGOs) play a critical role in advocating for corporate accountability and transparency, particularly in regions where regulatory frameworks are weak or inconsistently enforced. The approach presented here equips NGOs with tools to collect, analyze, and present evidence of corporate practices, such as environmental damage or social harm, thereby strengthening advocacy actions. Similarly, local governments can use these results to assess corporate social responsibility practices, track environmental and social impacts, and identify gaps in compliance. Analyzing satellite observations to generate actionable data for non-academic users often requires expert interpretation. However, emerging user-friendly platforms and tools for data distribution and analysis are continually evolving, potentially enabling quicker and more accessible assessments in the future.

Given the global coverage of satellite observations, the approach outlined here can be applied in other regions to evaluate air polluting emissions linked to surface mining activities (not limited to copper extraction). This is particularly valuable in areas lacking other monitoring systems, such as remote and developing regions. Underground mines are expected to have lower emissions compared to open-pit mines due to lower stripping ratios, higher ore grades, and the use of smaller mobile equipment. Nevertheless, multiple studies demonstrated how satellite observations can detect methane emissions from venting at underground coal mines (Sadavarte *et al* 2021, Tu

*et al* 2022, 2024). Such assessments provide valuable information for monitoring the impacts of extracting activities also from underground mining that can be used by mining companies and environmental authorities to plan emission reduction strategies.

Since copper mining is a critical industrial sector for the green transition, our results highlight that an accurate assessment of its environmental impacts is needed to ensure the progress towards a more sustainable future.

### Data availability statement

The reprocessed and offline TROPOMI NO<sub>2</sub> data v. 2.4.0+ are available from the Copernicus Data Space Ecosystem (<https://dataspace.copernicus.eu/>). CAMS-GLOB NO<sub>x</sub> emission inventories are available at the Emissions of atmospheric Compounds and Compilation of Ancillary Data (ECCAD) website <https://eccad.aeris-data.fr>. The mining activity data are collected from the companies' annual reports.

No new data were created or analysed in this study.

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### Author contribution statement

**Iolanda Ialongo:** Conceptualization, Formal analysis, Methodology, Investigation, Software, Visualization, Writing—original draft, Funding acquisition. **Henrik Virta:** Data curation, Investigation, Writing—Review & Editing. **Janne Hakkarainen:** Methodology, Software, Investigation, Writing—Review & Editing. **Cem Özcan:** Investigation, Writing—Review & Editing. **Mikko Ranta:** Investigation, Funding acquisition, Writing—Review & Editing. **Simon Zieleniewski:** Data curation, Investigation, Writing—Review & Editing.

### ORCID iDs

Iolanda Ialongo  <https://orcid.org/0000-0002-1125-0756>

Henrik Virta  <https://orcid.org/0000-0002-0660-0926>

Janne Hakkarainen  <https://orcid.org/0000-0002-5281-8985>

Cem Özcan  <https://orcid.org/0009-0002-6024-996X>

Mikko Ranta  <https://orcid.org/0000-0002-9096-1635>

Simon Zieleniewski  <https://orcid.org/0009-0008-2760-9488>

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