2-2024

Increasing mine waste will induce land cover change that results in ecological degradation and human displacement

John R. Owen
University of the Free State

Deanna Kemp
University of Queensland

Alex M. Lechner
Monash University

Michelle Ang Li Ern
University of Nottingham

Éléonore Lèbre
University of Queensland

See next page for additional authors

Authors

John R. Owen, Deanna Kemp, Alex M. Lechner, Michelle Ang Li Ern, Éléonore Lèbre, Gavin M. Mudd, Mark G. Macklin, Muhamad Risqi U. Saputra, Tahjudil Witra, and Anthony J. Bebbington

Journal of Environmental Management 351 (2024) 119691

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Increasing mine waste will induce land cover change that results in ecological degradation and human displacement

John R. Owen [a], Deanna Kemp [b,*], Alex M. Lechner [c], Michelle Ang Li Ern [d], Éléonore Lèbre [e], Gavin M. Mudd [f], Mark G. Macklin [g], Muhamad Risqi U. Saputra [c], Tahjudil Witra [c], Anthony Bebbington [h]

[a] Centre for Development Support, University of the Free State, 205 Nelson Mandela Dr, Park West, Bloemfontein, 9301, South Africa
[b] Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland, Brisbane, QLD, 4072, Australia
[c] Urban Transformations Hub, Monash University Indonesia, Green Office Park 9, The Breeze, BSD City, Tangerang Selatan, Banten, 15345, Indonesia
[d] Landscape Ecology and Conservation Lab, School of Environmental and Geographical Sciences, University of Nottingham Malaysia, Semenyih, 43500, Malaysia
[e] Sustainable Minerals Institute, The University of Queensland, Brisbane, QLD, 4072, Australia
[f] Environmental Engineering, School of Engineering, RMIT University, Melbourne, VIC, Australia
[g] Lincoln Centre for Water and Planetary Health, School of Geography, University of Lincoln, Lincoln, LN6, 7TS, UK
[h] Graduate School of Geography, Clark University, 950 Main St, Worcester, MA, 01610, USA

A R T I C L E I N F O

Handling Editor: Jason Michael Evans

1. Introduction

Every unit of mined commodity results in a large volume of waste material. Exponential increases in mine waste create conditions for population displacement – a known driver of human rights impacts that result in poverty, isolation, and food insecurity. The World Bank estimates a 500% increase in mining activity over the next two decades to produce more than three billion tons of minerals required for wind, solar, geothermal power, as well as energy storage products. Most scholars agree that vast mineral resource inventories must be exploited at an unprecedented rate to achieve climate change targets (Mudd and Jowitt, 2022). Our results indicate that mined waste is a major driver of population displacement, often in remote and vulnerable areas. This research can assist policy makers to develop comprehensive and more ethically-informed responses for mitigating climate change.

By volume, the main output of most mining activity is hazardous waste (Lottermoser, 2010). At this late stage of industrialisation, resource extraction involves exploiting mineral deposits with historically low grades, and geological resources located at greater depth, producing exponentially more mine waste and mobilising deleterious elements such as arsenic and cadmium into riparian and terrestrial systems (Northey et al., 2014). Recent studies of four prominent energy transition minerals estimate that the total amount of tailings ever produced by copper, manganese, lithium, and nickel is in the order of 200 billion tonnes. This is estimated to increase to 1000 billion tonnes between 2020 and 2050 (Valenta et al., 2023). The exponential increase in mine waste over the coming decades will be one of the most significant ecological and social development challenges we face in enabling the global energy transition and for feeding future urbanisation and industrialisation (Lèbre et al., 2020).

Against this backdrop, we demonstrate that mine waste is the predominant cause of human displacement, and that this displacement is more likely to occur at later stages in the mine life cycle. A detailed analysis of the "boundary relationship" between landcover types reveals clear intersections between the spatial extent of mine waste and areas used for human settlement. Despite the scale and significance of this problem, the connection between the waste profile of large-scale mining projects and patterns of human displacement has been overlooked in research and policy making. Our contribution is to visualise and quantify the mining-induced displacement and resettlement (MIDR) problem.

* Corresponding author.
E-mail addresses: OwenJ@ufs.ac.za (J.R. Owen), d.kemp@smi.uq.edu.au (D. Kemp), alex.lechner@monash.edu (A.M. Lechner), Michelle.Ang@nottingham.edu.my (M. Ang Li Ern), e.lebre@uq.edu.au (É. Lèbre), gavin.mudd@rmit.edu.au (G.M. Mudd), MMacklin@lincoln.ac.uk (M.G. Macklin), risqi.saputra@monash.edu (M.R.U. Saputra), tahjudil.witra@monash.edu (T. Witra), abebbington@clarku.edu (A. Bebbington).

https://doi.org/10.1016/j.jenvman.2023.119691
Received 12 September 2023; Received in revised form 10 November 2023; Accepted 21 November 2023
Available online 7 December 2023
0301-4797/

1.1. Mine waste and land conversion

Resource development induces an industrial pattern of land conversion that radically alters prior land covers into an extractive form. Scholarship from across disciplines has articulated distinct processes of land use change resulting from mining activity (Sonter et al., 2014) with more recent attempts at estimating mine-induced disturbance as a proportion of total global land cover (Maus et al., 2022). According to recent research, the conversion risk of ecologically sensitive areas is becoming more acute (Kennedy). The interplay between social and technical process across the resource development lifecycle is scantly described in the literature, but recent assemblages of case records reveal a dominant pattern of incremental project expansions that contaminate and extinguish prior land cover types (Owen and Kemp, 2015).

This pattern unfolds as low value waste accumulates in the host environment encroaching on village settlements and important ecosystem services that are necessary for supporting human life. The locality and selective acceptability of where, and which ecosystem services can be subject to catastrophic risk and erasure is similarly gathering attention as the impact of industrial waste streams becomes increasingly evident (Ahmed et al., 2021; Owen et al., 2020; Adiansyah et al., 2015). Displacement scholar Theodore Downing has described this industrial pattern as "step wise mine expansion and land take" (SMELT), while Owen and Kemp have used the phrase "brownfield effect" to denote the late stage and cumulative effects associated with this pattern of resource development (Owen and Kemp, 2015; Downing, 2002). The direct implication of this pattern is that displacement outcomes are more likely as mining lifecycles advance due to diminishing levels of public accountability and due process as mining footprint extend beyond their initial permitting and lease conditions (Owen and Kemp, 2019).

Qualitative case studies produced over the last four decades indicate repeated instances of these patterns but without a concerted effort to consolidate learnings, these cases have appeared in the literature as isolated examples. Case studies are dispersed across all continents and, in several instances, draw on data sources suggesting that the acceptance of poor waste management outcomes is emblematic of regional or country-scale practices in terms of the sector's regulation (Brown, 1974; Hettler et al., 1997; Terminski, 2012; Perreault, 2013; Yang et al., 2017; Baeten, 2018; Milanez et al., 2021). Sudden and catastrophic tailings dam disasters represent the most dramatic outcomes of regulatory failure (Milanez et al., 2021), but emerging research suggests that chronic forms of contamination from mining re far more extensive than has been documented to date. In the first global assessment of the downstream transport of mine wastes on land, rivers, and people, Macklin et al. (2023) estimate that metal mines impact 479,200 km^2 of river channels and 164,000 km^2 of floodplains, and that the likely number of people exposed to contamination from the long-term discharge of mining waste into rivers is almost 50 times greater than the number directly impacted by sudden tailings facility failures. The displacement effects of mine waste are both under-estimated and under-studied.

Improvements in the availability and application of remote sensing technologies allow for these patterns to be quantified, tested, and compared within individual lifecycles and across cases in other project locations. Historical assessments of land use change, combined with the use of high-resolution remote sensing techniques provides an avenue for interrogating claims about patterns of mine development that otherwise remain undocumented (Lechner et al., 2019). According to Terminski, the limitations associated with estimating the number of global mining-induced displacements are a product of nation states failing to collect and publicise records, compounded by what he describes as "a small degree of interest within international institutions" in MIDR. Our study helps to address a significant gap in available knowledge on this global problem.

1.2. Empirical strategy for engaging the MIDR problem

The empirical strategy used to engage the MIDR problem has three distinct parts. First, the global MIDR dataset (Owen et al., 2019), the largest public account of MIDR events available globally, is utilised to analyse sources of displacement. This dataset provides a global context in which project-induced displacement occurs by highlighting lifecycle and related activities associated with individual resettlement events. Based on our analysis of events, incremental expansion in the resource footprint is the dominant pattern across events. Second, the footprints of four large scale mining projects are analysed using time-series of historical Landsat satellite imagery. The selection is based on sites where public information is available to tie milestones to footprint expansions. All mine footprints expand, but not all expand with public information to account for what other land uses they extinguish. The time-series analysis clearly depicts the incremental development of the four project footprints (Owen and Kemp, 2015; Downing, 2014a; Banks, 2013). These four sites are also representative of records in the global MIDR dataset in that they present a diverse array of commodities, company types, and geographies.

Third, using two of these four cases, we develop detailed historic data points (see ref. 24), enabling the quantification of land cover types that comprise the incremental change indicated in the global dataset and depicted in the time-series analysis. This detailed assessment establishes the boundary relationship between mine waste, ecological degradation, and human displacement over time. Defining land-cover interactions between resource projects, community-users and the local environment is essential because without identifying these points of intersection or "boundaries", researchers and policy makers will continue to focus only on the industrial landcover understood as "the mine".

2. Materials and methods

The research design integrates global and local elements to demonstrate the effects of temporal and spatial changes in mining footprints. To establish global patterns and the basis for selection in subsequent steps, we analysed selected features of the MIDR dataset. Time-series were developed for four (Valenta et al., 2023) cases where data was available to demarcate and assign project milestones with land cover changes. A higher level of resolution was available for the two detailed case studies due to previous land cover analysis at those project sites and the quality of records relating to displacement in the MIDR dataset.

2.1. The MIDR dataset

The dataset is built from a diverse range of sources including Resettlement Action Plans (RAPs), peer-reviewed academic literature, news media and grey literature, sustainability reports, and the S&P Global Market Intelligence database (Global, 2023). RAPs contain the most comprehensive accounts for individual displacement events, often linking the mining activity or lifecycle change to the project's claim that displacement is unavoidable. However, these are imperfect sources of displacement data for two important reasons: (i) there is no legal basis requiring that RAPs be made public or that the information contained in them is accurate, (ii) as planning documents RAPs are forward looking meaning that the size and significance of the actual displacement event is frequently different from the resettlement described in the plan. In other words, RAPs describe a future act. There is no requirement to produce a retrospective account of the event. The S&P and other data sources were used to confirm date and activity markers, in an addition to completing missing fields relating to village names, project commencement year, and ownership details at the time of displacement.

2.2. Remote sensing time-series and quantitative analysis of case studies

In our first step, true colour surface reflectance Landsat imagery was acquired using Google Earth Engine and visualised for four representative periods, for four locations: Bonkiro (Côte d'Ivoire), Kosovo, Porgera (Papua New Guinea), Sepon (Laos). Then we used a supervised classification of Landsat multispectral data with manual interpretation and digitizing to map land cover change at Porgera and Sepon for multiple years based on the analysis produced by Lechner et al. (2019). Mining land covers were mapped from the start of the mining operations to 2017 utilising High Level atmospheric and topographically corrected surface reflectance Landsat 5, 7 and 8 with seven Landsat images for each site (Table 1). The Landsat primary data used for the timeseries analysis was validated with a range of higher resolution auxiliary data including WorldView 2, SRTM and pansharpened Landsat (Table 1). We mapped a range of land cover classes which are important for characterising the spatial and environmental dimensions of impacts in and around a mine (Table 2). These land cover classes include land uses related to human settlements, mining land uses and also land uses related to specific mining features which were found only at one of the two locations.

The imagery was classified first with a Maximum Likelihood classifier and then updated and attributed with manual image interpretation for all land covers apart from Agriculture, Forestry and Others. The initial linework (i.e., boundaries of land cover features) were derived from the classifier and manual digitization and reclassification was conducted with the aid of the auxiliary data (Table 1). For Agriculture, Forestry and Others which included swidden (i.e., shifting) agriculture we utilised CLASlite (Asner et al., 2009), a remote sensing software for mapping forest cover change which uses multi-date imagery and includes calibration, pre-processing, atmospheric correction, and cloud masking steps. The overall classification accuracy for the timeseries was greater than 90% for every year. All the GIS processing except for Agriculture, Forestry and Others was carried out using ArcGIS Pro (ESRI ArcGIS Pro, 2020) and ArcMap (ESRI ArcGIS Desktop, 2020).

We performed two GIS analyses to quantify how land covers changed over time in terms of proximity and land use transition. The initial land covers were first aggregated to courser resolution: Agriculture Forestry and Others (AFAO), Settlement, Rehabilitation, Mining Infrastructure, Mining Productive, Mining Waste and Undisturbed (Table 2). We then characterised the relationship between mining waste and settlements within the mine footprint through the change in area of the following land cover classes: Settlement, Mining Productive, Mining Waste and AFAO. Secondly, we characterised how human settlement grows in proximity to Mining Productive areas calculated by the total area of Settlement with 0.05 km, 0.1 km, 0.5 km, 1 km, 2 km, 3 km, 4 km, 5 km and 6 km buffers around Mining Waste landcover.

Table 1
Primary data used for the timeseries analysis and auxiliary reference data used as ground truth.

Site	Sensor	Data type	Pixel size	Source	Date
Porgera	Landsat 8	Multispectral	30 m	USGS	2015, 2017
Primary	Landsat 7	Multispectral	30 m	USGS	2009
data	Landsat 5	Multispectral	30 m	USGS	1987, 1991, 1994, 2001
Porgera	Landsat 7, 8	Pansharpened	15 m	USGS	2009, 2015, 2017
Auxiliary data	World view 2	True Colour	0.5 m	ArcGIS base map	2014
	World view 2	True Colour	0.5 m	Google Earth	2010, 2014 (part of scene)
	SRTM	DEM	90 m	USGS	2001
Sepon	Landsat 8	Multispectral	30 m	USGS	2013, 2015, 2017
Primary	Landsat 7	Multispectral	30 m	USGS	2010, 2011
data	Landsat 5	Multispectral	30 m	USGS	2002, 2005
Sepon	Landsat 7, 8	Pansharpened	15 m	USGS	2010, 2011, 2013, 2015, 2017
Auxiliary data	World view 2	True Colour	0.5 m	ArcGIS base map	2015
	World view 2	True Colour	0.5 m	Google Earth	2002, 2005 (part of scene)
	SRTM	DEM	90 m	USGS	2001

Table 2
Detailed and coarse landcover classes and specific information used for guiding manual classification for Porgera and Sepon. Note main roads, which accounted for a very small area were included as undisturbed in the land cover maps.

Detailed Land cover classes	Coarse Land cover classes	Definition
Land cover class for Porgera and Sepon		
Mine Pit	Mining Productive	Mine pit identified by presence of benches and conjunction with DEM
Mining Disturbance	Mining Waste	Areas surrounding the mine pit primarily waste rock
Tailings Dam/ Erodible Waste*	Mining Waste	Identified by shape and location with respect to mine pit and disturbance area
Mining Infrastructure	Mining Infrastructure	Administrative buildings and processing facilities
Settlement	Settlement	Settlement areas include houses and building not used specifically for the mining operations. Also includes small roads.
Rehabilitation	Rehabilitation	Areas that were once mining disturbance that now have vegetation (assumed to be rehabilitation, though may have naturally regrown)
Undisturbed	Undisturbed	Areas that are predominately covered by vegetation
Agriculture, Forestry and Others (AFAO)	Agriculture, Forestry and Others (AFAO)	Areas that were once cleared and are likely to have been used for swidden (i.e. shifting) agriculture.
Porgera specific land covers		
Competent Dump	Mining Waste	Identified by shape and location with respect to mine pit and disturbance area
Impacted Stream	Mining Waste	Identified by shape and location with respect to mine pit, disturbance area and presence of stream. These rivers and/or streams that are directly connected to mine waste areas (Ie: Tailings Dam and Competent Dump)
Sepon specific land covers		
Pit Water	Mining Productive	Water found within mine pit
Sediment Dam	Mining Waste	Identified by shape and location with respect to mine pit and disturbance area
Water Body	Water Body	Water in areas outside of mine pit

2.3. Limitations

The global MIDR dataset (Owen et al., 2019) contains 270 entries with several key fields relating to source of displacement remaining incomplete. This database is the product of collecting and collating publicly available resettlement plans and/or studies. The authors recognise this to be a gross under-statement of the number of displacement events caused by large-scale mining activity globally. We sought to reconcile the MIDR dataset with the S&P Market Intelligence Database to yield further detail about commodity, ownership, and year of permitting. However, the S&P Database is likewise dependant on public disclosures and project proponents tend not to report displacement events. Improved access to satellite imagery increases the potential visibility over mining footprints, and the displacement of affected people. To confirm the precise causes and consequences of displacement requires exacting tools and parameters for measuring land cover change.

Researchers have demonstrated the difficulty of achieving this level of resolution for individual projects, and by extension, the effort needed to produce estimates at global scale. While there are limitations, the present study nonetheless significantly advances knowledge about mining footprints, and their displacement effects.

3. Results

Our results confirm that displacement can occur at any stage of the lifecycle of a mine, with variation in the time of occurrence being a result of site-specific factors, and brownfield resettlement the primary type of displacement. The four case studies illustrate these patterns, with the calculations performed on two of the four revealing how mine waste dominates the land class in nearest proximity to human settlement and agricultural activity areas. From this, we conclude that mine waste is both the principal source of human displacement and, over time, becomes the predominant landcover type surrounding community areas.

3.1. Global patterns of mine waste as the source of human displacement

The MIDR dataset, assembled in 2019 by Owen et al. (2019), includes records of 270 displacement events covering 43 countries and 30 different mineral commodities (see Fig. 1). Events represent individual developments based on specific activities of the mining asset. This distinction between a displacement event and a mining asset enables researchers to identify the source of displacement within the overall context of the project lifecycle. Fig. 2 summarises the key lifecycle and source activity characteristics from across the 270 events.

Several patterns can be observed. First, that displacement events occur across the project lifecycle, with some occurring within a year after the commencement of mining activities, and others more than 20 years into the life of mine. In the 2019 dataset approximately 47% of MIDR events commenced between 6 and 25 years + post-permitting. The dataset also records instances of displacement prior to government permitting further suggesting an absence of regulatory safeguards. Second, most displacement events are "brownfield" as they occur during the operational phase of mine life. This type of resettlement sits in contrast to "greenfield" resettlements, which take place for a new mining development and at the commencement of a project. Brownfield resettlements make up 57% of the dataset. Third, the activity source of displacement is directly related to the project's development stage. For a large number of records (n = 119), the source activity that induces human displacement is poorly reported. This accounts for the large number of "multiple" and "mine area clearance" entries in the dataset. When a single source is discernible, these are characteristic of the development stage. Most notable is the high proportion of cases in the "operational" and "late stage" of mine life where the source of displacement was waste and excavated material. Tailings dam failures were identified as another waste-related source, recorded predominantly in the post-closure phase. These records do not report the total displacement effect on people displaced or dispossessed by tailings disasters, likely to be far higher than officially recorded fatalities.

3.2. Illustrating incremental land take at four large scale mines

This stage of the research strategy involves examining incremental land take at four large-scale mining projects. The time intervals provide a context for depicting the rate of landcover change. For the case studies a) and b) this visualisation corresponds with project milestones and recorded cases of displacement, whereas for case studies c) and d) these intervals correspond with pre-development, expansion and present day landcover configurations. First, the Bonikro gold mine project located in central Côte d'Ivoire, 230 km northwest of the nation's capital, Abidjan. Second, the Sibovc Coal Mine project, located in Obiliq, immediately west of Kosovo's capital Pristina. Sibovc is operated by the state-owned enterprise Korporata Energjetike e Kosovës or Kosovo Energy Company (KEK). Large-scale mining of lignite commenced at the site in 1958. The third project, the Porgera Gold Mine is a large gold and silver mining operation in the Enga province of Papua New Guinea. Porgera is located in the highlands at an altitude of 2,200 m to 2,700 m. The mine utilises both open-pit and underground mining methods for ore extraction. Barrick (Niugini) has a 95% ownership of the operation, and Barrick Gold Corporation and Zijin Mining Group each own 50% of Barrick (Niugini). The remaining 5% of the operation is owned by Mineral

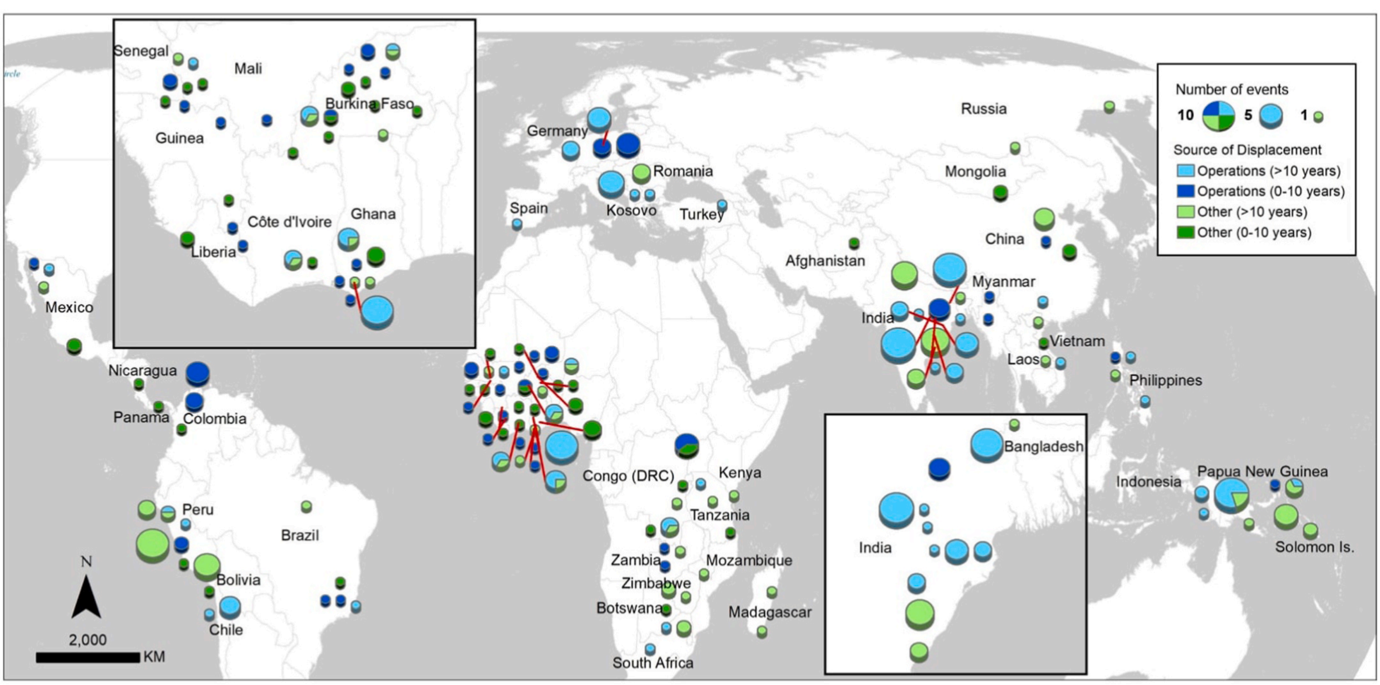

Fig. 1. Geographical distribution of MIDR events. Events are displayed according to the lifecycle stage of the mining project (either operations stage or other). The size of the circles corresponds to the number of events linked to the same mining operation with a minimum of 1 and maximum of 10 events.

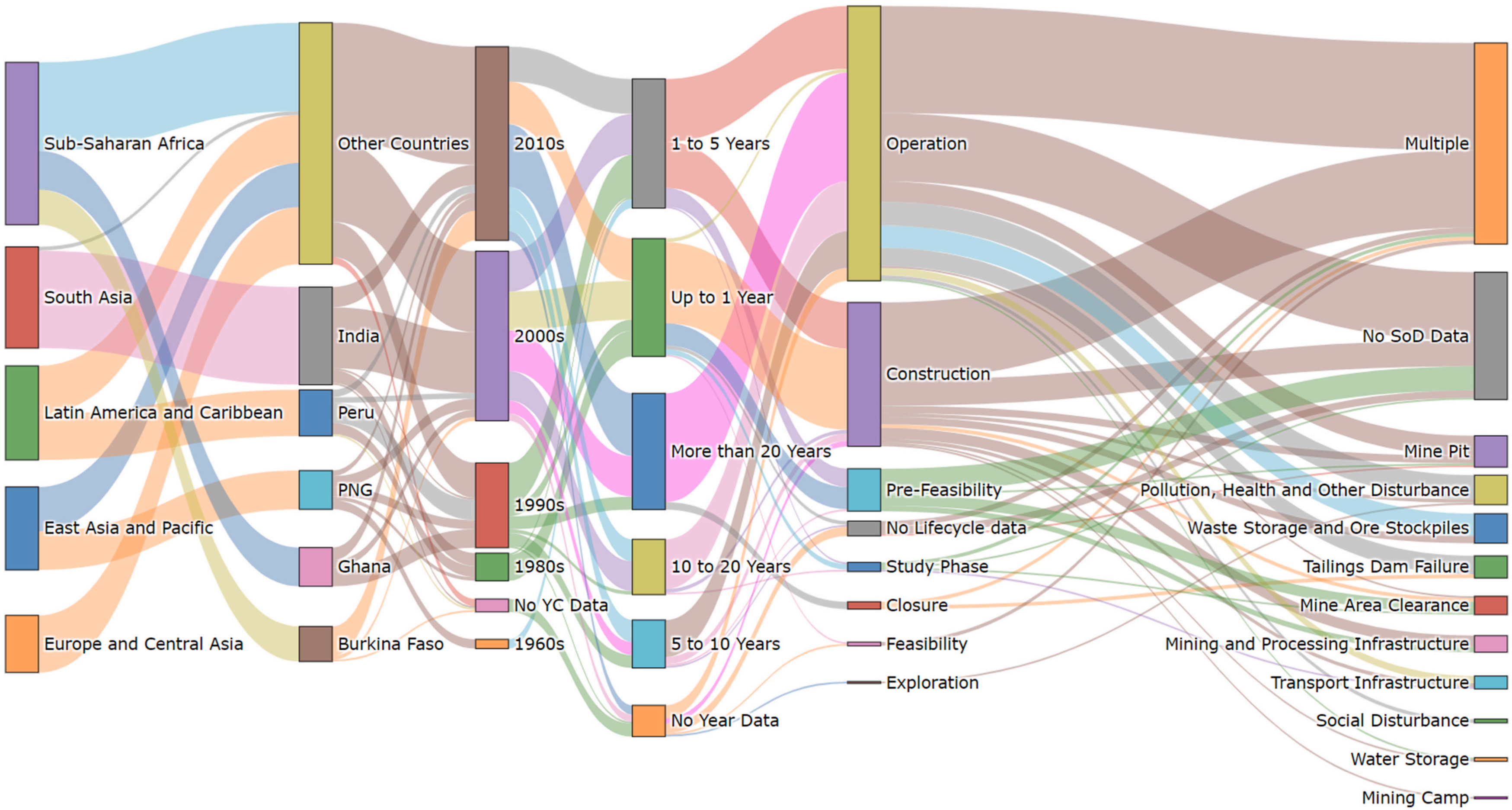

Fig. 2. Characteristics of events in the MIDR dataset including geography, the decade when the events took place, the years into the life of the mine, the mining project's development stage, and the sources of displacement disaggregated into three main development stage groups.

Resources Enga (MRE), which is owned by the Enga Provincial Government, the Government of Papua New Guinea, and the Porgera Landowners Association. Fourth, Sepon is an open-pit copper and gold mine in the Savannakhet Province, southern Laos. The current operating entity, Lane Xang Minerals Limited (LXML), is jointly owned by Chifeng Jilong Gold Mining Co, Ltd (90%) and the Government of Laos (10%). See Table 3 for case details.

All four mining projects exhibit patterns of incremental expansion (see Fig. 3). Bonikro's project area comprises an open-pit gold mine at Bonikro and three open-pit mines in the Hiré area (Akissi-So, Assonji-So, Chappelle), located approximately 12 km south-east of Bonikro. The Bonikro Mining Convention was granted in 2007, with construction of the main Bonikro pit commencing in the same year. Over the next several years, numerous communities were displaced to allow for the construction of the pit along with waste facilities. The New Concession Area, which covers three Hiré pits, was gradually developed over the next decade, leading to large-scale displacement from Hiré's eastern suburbs. The Sibovc Coal Mine project comprises four open pit lignite mines (Mirash, Bardh, Sibovc South West and Sitnica). Large-scale mining of lignite commenced with the first production from the Mirash (1958) and Bardh (1969) open-pit mines, both of which are now exhausted. The development of Sibovc South West mine over the past two decades has led to gradual forced displacement of communities in Hade and other villages in the New Mining Lease (NML) area. In Porgera, the Special Mining Lease (SML) was granted in 1989. While the size of the SML has not changed since the project was permitted, the land area used by the operation has increased significantly. Leases for Mining Purposes (LMPs) have been granted by the State to accommodate the changing needs of the operation. As in other cases, the expansion of the mine's footprint was accompanied by the displacement of several communities. In the case of Sepon, the mining concession was granted in 2001 after construction had already commenced. Successive project expansions have seen the development of a complex mining footprint in near proximity to an emerging mining township as well as villages, agricultural land and forested areas.

3.3. Quantification through case analysis

This stage in the research process was to use historic remote sensing techniques to quantify the footprint data of two of the case studies described above: Sepon (Laos) and Porgera (Papua New Guinea). Lechner et al. (2019) found that in these mining localities, Mine Waste far exceeded all other land cover types with an exponential increase in land area and a concurrent decrease in the availability of land for Settlement and livelihood purposes associated with agricultural lands. Further analysis of the incremental change in landcover boundaries reveals that Mine Waste dominates the land class in nearest proximity to the areas designated for human settlement and agricultural activities. These relationships are driven by dynamic changes in both mining footprints and the community land uses. In sum, our results confirm that mine waste is both the principal source of human displacement in these two case examples, and over time, becomes the main landcover type surrounding community areas.

Sepon exhibits complex and dynamic spatial patterns of mining footprint change, bringing mining and human settlement areas in proximity to each other over time. In Fig. 4a and b, large changes in both the spatial pattern and total area of anthropogenic land cover classes are shown between 2002 and 2017 as the mine operation grows. There is an overall increase in the total area of landcovers associated with mining and settlements (Fig. 4c). Notably, the growth in Mining Waste outpaces that of the Mining Production area, with an increase of 11.85 km^2 from 1.19 km^2, compared to production area gains of 4.51 km^2 from 0.03 km^2. By 2017, 2.25%, 6.47% and 2.33% of the study area is Mining Productive, Mining Waste and Settlement respectively. The growth in the mining footprint, mainly in waste, resulted in a rapid rise in the total settlement area in the vicinity of the mine from 2002 to 2010, which then continued to expand at a slower pace. While AFAO underwent an initial rapid increase in area in proximity to Mining Waste, this was subsequently followed by a decrease over the next six years, before rising once again in 2014. The complex patterns of AFAO are associated with highly dynamic land uses, such as swidden farming (Rasmussen and Lund, 2021). AFAO areas represent land utilised by the community to support traditional economic activities and subsistence agriculture, present before mining.

Similar patterns can be observed at Porgera, Papua New Guinea, in terms of the increase in the Mine Waste area relative to Mining Productive, and an increase in the proximity of Settlements to Mining Waste. Fig. 5a and b, describes large changes in the area and the spatial patterns of mining and non-mining landcover over time in Porgera. All landcovers increase over time between 1987 and 2017 (Fig. 5c), however, the growth in mining waste area outpaced the productive mine area and a large growth in human settlement areas was observed over the previous 30 years. By 2017 Mining Productive, Mining Waste and Settlement accounted for 0.83%, 8.42% and 3.98% of the study area respectively.

4. Discussion

Our results include three significant findings that warrant further discussion. First, that mine-waste related displacement has not received adequate treatment in the literature. The extraction of mineral commodities creates exponential volumes of mine waste relative to valuable

Table 3
Case details.

Operation	Bonikro	Sibovc	Porgera	Sepon
Start Date	2008	1958	1990	2003
Country	Côte d'Ivoire	Kosovo	Papua New Guinea	Laos
Primary Commodities	Gold	Coal	Gold and Silver	Copper and Gold
Present Ownership	Afrique Gold Consortium	Kosovo Energy Company	Barrick Niugini and Mineral Resources Enga	Lane Xang Minerals Limited
Historical owners/operators	Multiple	Single	Multiple	Multiple
Production/processing volume[a]	35.5 tonnes	Undisclosed	650 tonnes	Gold: 39.4 tonnes Copper: 996 kilotons
Waste rock produced[a]	115 million tonnes	Undisclosed	956 million tonnes	Gold: 46 million tonnes Copper: 107 million tonnes
Tailings produced[a]	20.8 million tonnes	Undisclosed	136 million tonnes	Gold: 23.9 million tonnes Copper: 24.7 million tonnes
Notes	Open Pit	Thermal Coal open pit	Riverine tailings disposal and erodible dumps; open pit and underground	Multiple open pits

[a] Over life of mine.

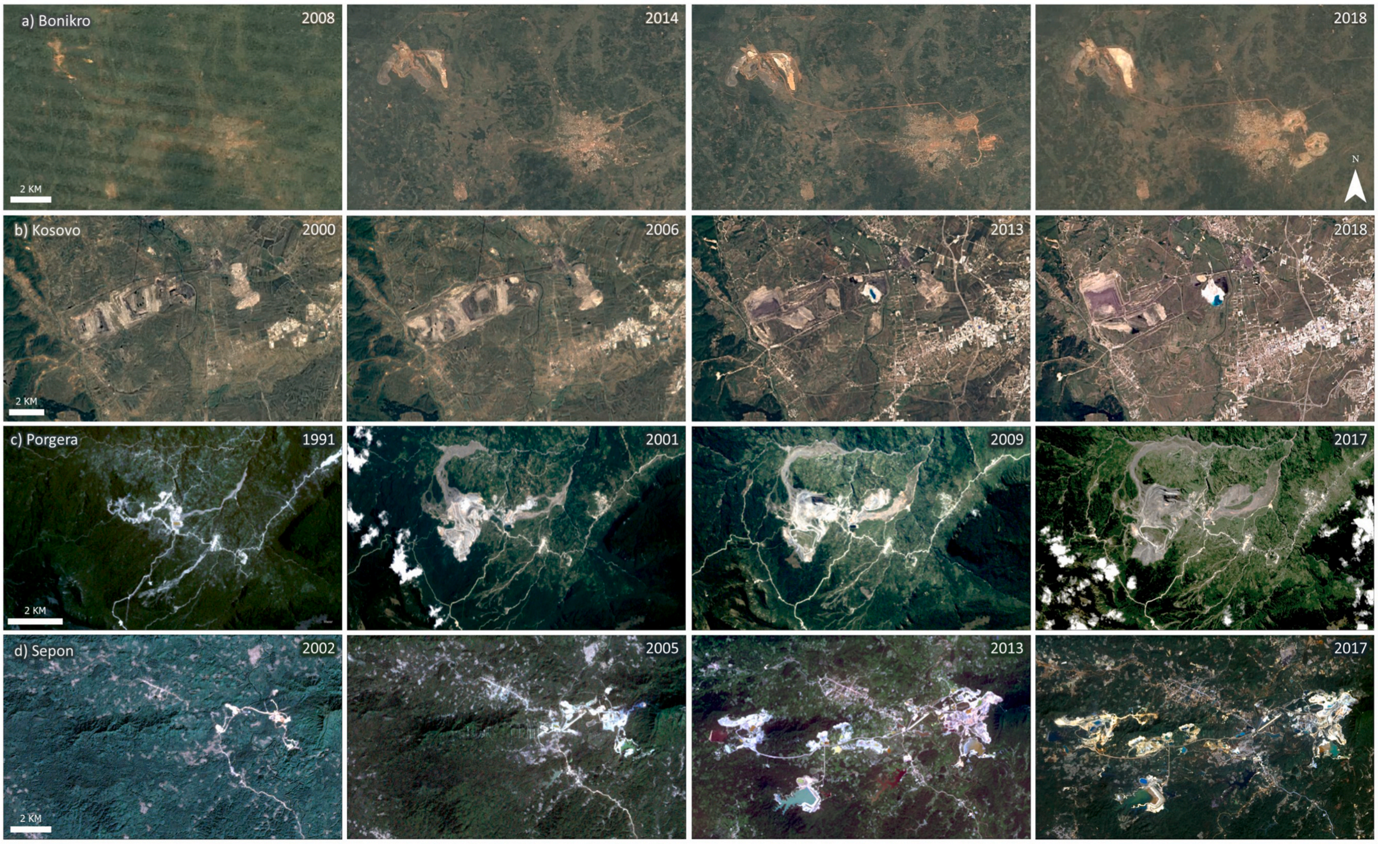

Fig. 3. Land cover changes observed via Landsat satellite imagery for all four study sites: a) Bonikro, b) Kosovo, c) Porgera, and d) Sepon.

product. Ratios between waste and ore vary, based on a range of geological and metallurgical factors, however the exponential difference between waste and valuable product persists. Our mine-specific land-cover classification enables the measurement of spatial changes in activity associated with mineral resource projects. In this article, the historical measurement of landcover at two large scale mining operations shows the patterns of project development and the spatial relationship between waste and human settlements. Our key finding is that mine waste landcovers dominate all other landcovers and represent the primary boundary relationship with human populations. By studying this boundary, we find that mine waste is the predominant cause of human displacement in mining.

The historical dimension of our methodology exposes the boundary effects formed by exponential growth in mine waste over of the life of projects. In the two case examples, Porgera and Sepon, expanding mine waste converges with villages areas, causing physical and economic displacement. This displacement is caused by both the growth in waste by volume and the mobilisation of waste into the local environment such that waste far exceeds other forms of landcover by area, a finding consistent with the global study by Werner et al. (2020). This same pattern is observable for the Kosovo coal/lignite and the Bonikro Gold projects where expansion of the project footprint necessitated the involuntary resettlement of residents, confirming Downing's work on the incremental expansion of mining footprints and their displacement effects (Downing, 2014b).

Second, that the increasing demand for energy transition minerals and continuing urbanisation will drive the production of mine waste, and thus displacement, in coming decades. MIDR and associated boundary issues will worsen based on the projected speed and scale of mining being demanded by global markets. The production volumes of deeper and lower-grade ores (Prior et al., 2012), the deleterious elements contained within those future orebodies (Schwartz et al., 2017), and a growing and urbanising world population (Leeson, 2018) paints a bleak future. While the extent of human displacement by mining and mine waste is disturbing, the long-run effects are more so, with involuntary and forced displacement known to drive illnesses, disease, mortality, morbidity, and social fragmentation (Cernea, 1997). All this, without these costs being accounted for in the price paid for mineral resources. Instead, the price paid resides locally, with people who are least able to bear it.

Third, that accountability mechanisms for waste induced displacement are few, or non-existent, and this has allowed project design and financing to overlook this issue (Kemp et al., 2021). There is little recognition by major actors that a MIDR pattern exists, let alone a "problem" warranting forensic examination. There are several explanations for this situation. First, the practice of land sterilisation and the creation of local "sacrifice zones" (Rasmussen and Gjertsen, 2018) has become normalised. This normalisation is reinforced in the context of global-scale objectives being set around climate rescue and energy security, where local impacts of resource extraction tend to become insignificant against the global challenge of climate change. Public interest in mine-waste and extreme consequences spiked in the immediate aftermath of the catastrophic tailings facility failures in Brazil in the years 2015 and 2018 where 289 lives were lost (Hopkins and Kemp, 2021). Aside from the fatalities, the impacts on human settlements from the aftermath of acute failures, or displacements from the more slow-moving impacts of mine waste, are absent from public debates and receive little specialist attention with respect to national policy protections and safeguards enforcement (Kemp et al., 2021).

Once mines commence production, capital begins to flow to the state through taxes and royalties, and to shareholders and investors in the form of profits shares and dividends. Project costs are sunk, and appetites to adjust, slow or stop a major resource project to address impacts have contingent economic effects. Economic dependencies can mask,

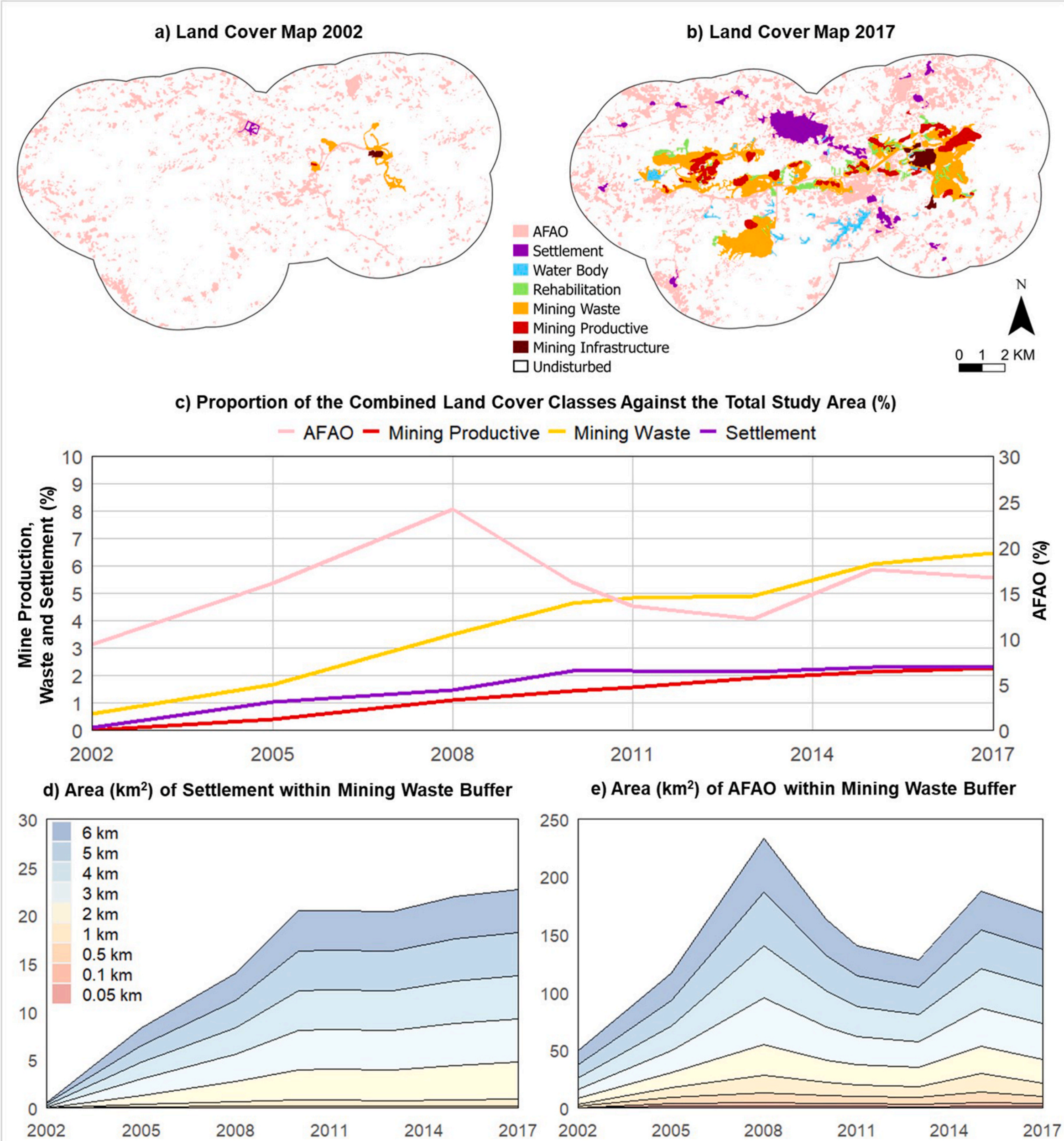

Fig. 4. Simplified land cover maps for (a) 2002 and (b) 2017 for Sepon. (c) Change in the proportion of Mining Productive, Mining Waste, Agriculture Forestry and Others (AFAO), and Settlement. The total area of (d) Settlement and (e) AFAO (km2) within successive buffer distances of 0.05 km, 0.1 km, 0.5 km, 1 km, 2 km, 3 km, 4 km, 5 km and 6 km from the Mining Waste land covers.

and indeed deepen, the difficulties of consultation and consent among affected peoples and rights-holding groups or for regulators to make decisions that would be considered “responsible” or “sustainable” (Bebbington and Bury, 2009). For example, governments may be more inclined to trade-off local impacts for improvements to state revenues (Owen and Kemp, 2017). Likewise, affected people, having already lost land or witnessed a rapid transformation in the local economy, may be ill equipped to deal with the economic shock of mine closure. The vulnerability of the operating or host context means that states and resident populations may be taken as tacit supporters of these projects, when the context can drastically limit the perceived range of viable alternatives.

At a global level, financial systems drive resource developers to define bankable projects, the point at which lenders are prepared to finance (van Zyl, 2015). Bankability focuses on declared resources and reserves, upfront capitalisation, and a preliminary assessment of project risks to understand potential impacts to profitability over the lifecycle of the asset. Compensation for land and the cost of resettlement may appear on ledgers for the immediate capitalisation of the project, such as project-start-up (Wang et al., 2020) but research indicates that these early estimates significantly understate the area of land required to execute projects (Banks, 2013). Bankability relies on calculations of net present value (NPV), the application of a discount rate to future costs, which includes the remediation of impacts, such as resettlement. Moreover, financial, and economic impact assessments provided to government regulators do not account for the long-run value of land, the knock-on effects of sterilising residential and agricultural land, or the potential impact of poor waste management into the future. This is all to suggest that MIDR is a product of standard market and regulatory processes and an entirely normalised practice, with few or non-existent

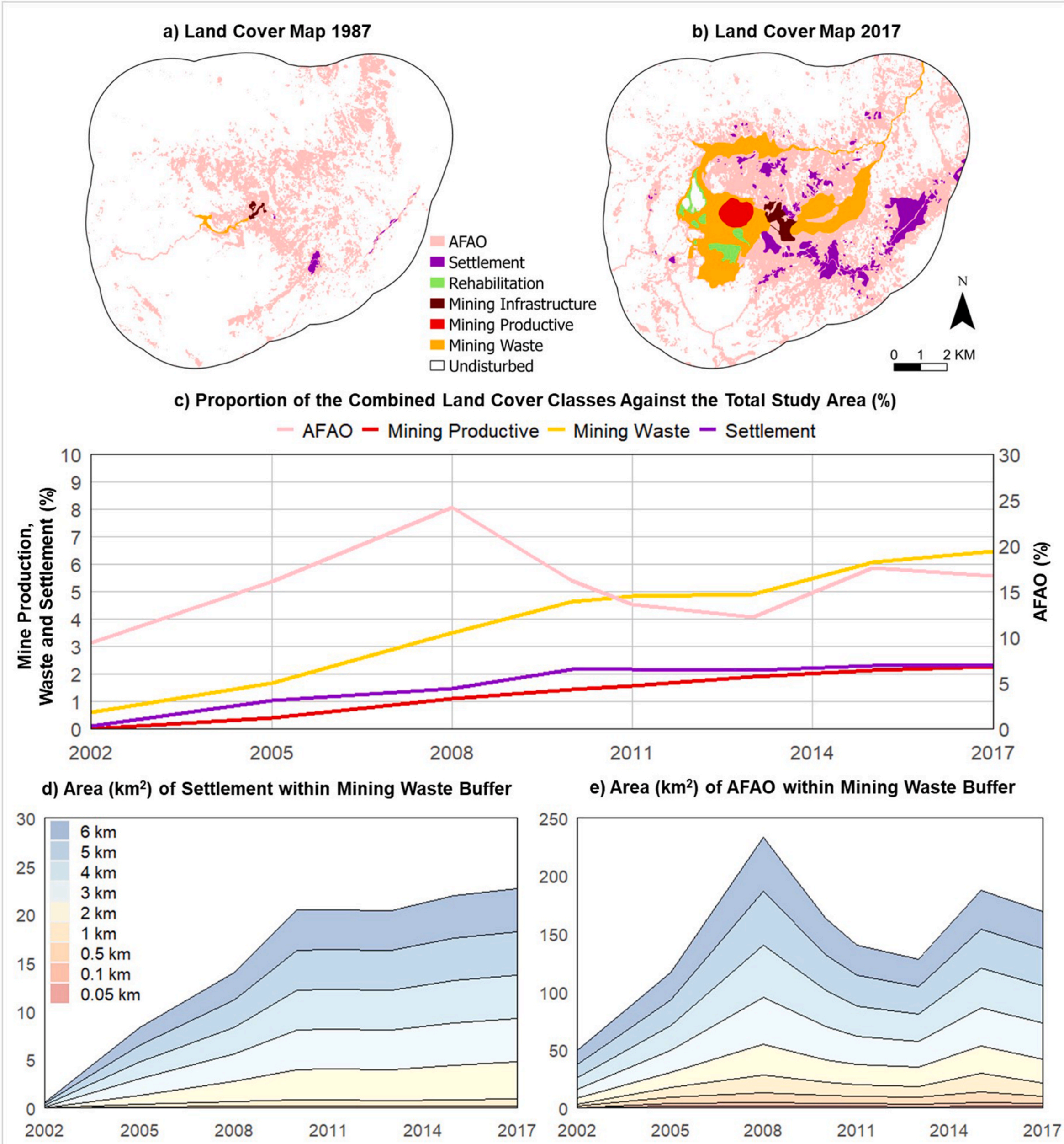

Fig. 5. Simplified land cover maps for (a) 1987 and (b) 2017 for Porgera. (c) Change in the proportion of Mining Productive, Mining Waste, Agriculture Forestry and Others (AFAO), and Settlement. The total area of (d) Settlement and (e) AFAO (km2) within successive buffer distances of 0.05 km, 0.1 km, 0.5 km, 1 km, 2 km, 3 km, 4 km, 5 km and 6 km from the Mining Waste land covers.

market accountability mechanisms built into the global financial system.

Our research demonstrates the importance of interrogating patterns in the interface between large-scale mining, human settlements, and the environment. Without research that examines the prevalence of waste-displacement relationships – both fast and slow moving – there is a genuine risk that these externalities will continue to be concealed from global and state-based accountability systems. The concern, when read against international trends in energy security and urbanisation, is that human displacement will remain invisible and continue as a tacitly accepted outcome of resource development initiatives. Therefore, our work to make such displacement visible is important as an accountability mechanism, in and of itself, to inform discussion of what accountability mechanisms should look like, and to inform how project preparation, financing and monitoring arrangements should change.

5. Conclusion

The system of legal and policy protections governing risk management for human displacement and resettlement in the mining sector is uneven and incomplete (Cernea and Maldonado, 2018). A fundamental implication of continuing negligence in favour of resource security, industrialisation, and profit is the steady erosion in the practical utility of the international, national, and corporate accountability instruments. Our spatial, empirically-grounded study adds important and novel evidence as a foundation for public awareness about the displacement of people by resource projects. Historical analysis that quantifies land cover change means that land use patterns that cause MIDR can be examined and made visible. In one respect, the availability of historical satellite imagery should make this serious problem easier for scientists to visualise and quantify. An enduring challenge is the availability of geo-referenced data on the location of mine sites globally. Advances in data availability are critical for eliminating dependency on company self-disclosures as the primary source of information and knowledge building. In this article we contribute, alongside the work of other scholars, toward reducing knowledge gaps in this area.

Finally, the current trajectory of global industrial growth could drive us towards catastrophic outcomes for the environment and human development. Exponential increases in mine waste will exacerbate the likelihood of chronic issues and create additional risk burden with respect to the management of tailings – mining's most abundant waste stream. Instead, innovations are focused on safeguarding the physical structures used to impound materials, or re-mine waste to maximise value and reduce overall volume. There is no parallel and equivalent set of policy innovations focused on the interaction of mine waste with social systems, and the safeguarding affected people. This aspect of mining policy must move from the periphery of debates about mining and development to the centre.

Author credit statement

John R. Owen: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Roles/Writing - original draft; and Writing - review & editing. Deanna Kemp: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Roles/Writing - original draft; and Writing - review & editing. Alex M. Lechner: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft. Michelle Ang Li Ern: Data curation; Formal analysis Methodology; Resources; Software; Validation; Visualization. Éléonore Lèbre: Data curation; Formal analysis; Investigation; Methodology; Validation; and Writing - review & editing. Gavin M. Mudd: Data curation; Validation; Writing - review & editing. Mark G. Macklin: Data curation; Validation; Writing - review & editing. Muhamad Risqi U. Saputra: Data curation; Validation; Visualization. Tahjudil Witra: Data curation; Validation; Visualization. Anthony Bebbington: Conceptualization; Writing - review & editing.

Authors

This work was in part supported by Australian Research Council grant LP200301160.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Data availability

The MIDR dataset is available publicly.

References

Adiansyah, J.S., Rosano, M., Vink, S., Keir, G., 2015. A framework for a sustainable approach to mine tailings management: disposal strategies. J. Clean. Prod. 108, 1050–1062.

Ahmed, A.I., Bryant, R.G., Edwards, D.P., 2021. Where are mines located in sub Saharan Africa and how have they expanded overtime? Land Degrad. Dev. 32, 112–122.

Asner, G.P., Knapp, D.E., Balaji, A., Páez-Acosta, G., 2009. Automated mapping of tropical deforestation and forest degradation: CLASlite. J. Appl. Remote Sens. 3, 033543.

Baeten, J., 2018. A century of red water: mine waste, legacy contamination, and institutional amnesia in Minnesota's Mesabi Iron Range. Water Hist. 10, 245–266.

Banks, G., 2013. Little by little, inch by inch: project expansion assessments in the Papua New Guinea mining industry. Resour. Pol. 38, 688–695.

Bebbington, A.J., Bury, J.T., 2009. Institutional challenges for mining and sustainability in Peru. Proc. Natl. Acad. Sci. USA 106, 17296–17301.

Brown, M.J.F., 1974. A development consequence — disposal of mining waste on Bougainville, Papua New Guinea. Geoforum 5, 19–27.

Cernea, M.M., 1997. The risks and reconstruction model for resettling displaced populations. World Dev. 25, 1569–1587.

Cernea, M.M., Maldonado, J.K., 2018. Challenging the prevailing paradigm of displacement and resettlement. In: Challenging the Prevailing Paradigm of Displacement and Resettlement: Risks, Impoverishment, Legacies, Solutions. Routledge, pp. 1–42. https://doi.org/10.4324/9781315163062.

Downing, T.E., 2002. Avoiding New Poverty: Mining-Induced Displacement and Resettlement. (Mining, Minerals and Sustainable Development. International Institute for Environment and Development.

Downing, B.W., 2014a. Natural Acid Rock Generation, Drainage, and Metal Leaching: Impact on Exploration, Mining, and Reclamation. *Acid Mine Drainage, Rock Drainage, and Acid Sulfate Soils: Causes, Assessment, Prediction*. Prevention, and Remediation, p. 67.

Downing, T.E., 2014b. Does the Kosovo Power Projects Proposed Forced Displacement of Kosovars Comply with International Involuntary Resettlement Standards? The Kosovo Civil Society Consortium for Sustainable Development.

ESRI ArcGIS Desktop, 2020. Release 10.3. Environmental Systems Research Institute, Redlands, CA, USA.

ESRI ArcGIS Pro, 2020. Version 3.0. Environmental Systems Research Institute, Redlands, CA, USA.

Global, S.&P., 2023. S&P Capital IQ Pro. Thomson Reuters, New York.

Hettler, J., Irion, G., Lehmann, B., 1997. Environmental impact of mining waste disposal on a tropical lowland river system: a case study on the Ok Tedi Mine, Papua New Guinea. Miner. Deposita 32, 280–291.

Hopkins, A., Kemp, D., 2021. Credibility Crisis: Brumadinho and the Politics of Industry Reform.

Kemp, D., Owen, J.R., Lèbre, É., 2021. Tailings facility failures in the global mining industry: will a 'transparency turn'drive change? Bus. Strat. Environ. 30, 122–134.

C. M. Kennedy, Conversion risk to Indigenous Peoples' lands: global challenges and opportunities in the face of industrial development. One Earth (in press).

Lèbre, É., et al., 2020. The social and environmental complexities of extracting energy transition metals. Nat. Commun. 11, 4823.

Lechner, A.M., et al., 2019. Historical socio-environmental assessment of resource development footprints using remote sensing. Remote Sens. Appl.: Soc. Environ. 15, 100236.

Leeson, G.W., 2018. The growth, ageing and urbanisation of our world. J. Popul. Ageing 11, 107–115.

Lottermoser, B.G., 2010. Mine Wastes: Characterization, Treatment and Environmental Impacts. Springer, Berlin, Germany.

Macklin, M.G., Mudbhatkal, A., Thomas, C.J., Hudson-Edwards, K.A., Lewin, J., Scussolini, P., Eilander, D., Lechner, A., Brewer, P., Owen, J., Bird, G., Kemp, D., Mangalaa, K.R., 2023. Impacts of metal mining on river systems: a global assessment. Science. Forthcoming.

Maus, V., et al., 2022. An update on global mining land use. Sci. Data 9, 433.

Milanez, B., Ali, S.H., Puppim de Oliveira, J.A., 2021. Mapping industrial disaster recovery: lessons from mining dam failures in Brazil. Extr. Ind. Soc. 8, 100900.

Mudd, G.M., Jowitt, S.M., 2022. The new century for nickel resources, reserves, and mining: reassessing the sustainability of the devil's metal. Econ. Geol. 117, 1961–1983.

Northey, S., Mohr, S., Mudd, G.M., Weng, Z., Giurco, D., 2014. Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. Resour. Conserv. Recycl. 83, 190–201.

Owen, J.R., Kemp, D., 2015. Mining-induced displacement and resettlement: a critical appraisal. J. Clean. Prod. 87, 478–488.

Owen, J.R., Kemp, D., 2017. Extractive Relations: Countervailing Power and the Global Mining Industry. Greenleaf Publishing. Routledge, London and New York.

Owen, J.R., Kemp, D., 2019. Displaced by Mine Waste: the Social Consequences of Industrial Risk-Taking. The Extractive Industries and Society. https://doi.org/10.1016/j.exis.2019.02.008.

Owen, J., Lèbre, É, Northcott, D., Harris, J., Huda, M., Verrier, B., 2019. Global mining induced displacement and resettlement (MIDR) events dataset. The University of Queensland. https://espace.library.uq.edu.au/view/UQ:3a1f616. Data Collection.

Owen, J.R., Kemp, D., Lèbre, É., Svobodova, K., Pérez Murillo, G., 2020. Catastrophic tailings dam failures and disaster risk disclosure. Int. J. Disaster Risk Reduc., 101361 https://doi.org/10.1016/j.ijdrr.2019.101361.

Perreault, T., 2013. Dispossession by accumulation? Mining, water and the nature of enclosure on the Bolivian Altiplano. Antipode 45, 1050–1069.

Prior, T., Giurco, D., Mudd, G., Mason, L., Behrisch, J., 2012. Resource depletion, peak minerals and the implications for sustainable resource management. Global Environ. Change 22 (3), 577–587.

Rasmussen, R.O., Gjertsen, A., 2018. Sacrifice zones for a sustainable state? Greenlandic mining politics in an era of transition. Will Drill-Mining Arctic Commun. 127–149.

Rasmussen, M.B., Lund, C., 2021. 10. Frontiers: commodification and territorialization. Handb. Critic. Agrar. Stud. 80.

Schwartz, D.M., Omaynikova, V.Y., Stocker, S.K., 2017. Environmental benefits of the CESL Process for the treatment of high-arsenic copper-gold concentrates. April. In: Ninth International Seminar on Process Hydrometallurgy: International Conference on Metal Solvent Extraction. Santiago de Chile, Chile.

Sonter, L.J., Moran, C.J., Barrett, D.J., Soares-Filho, B.S., 2014. Processes of land use change in mining regions. J. Clean. Prod. 84, 494–501.

Terminski, B., 2012. Mining-induced Displacement and Resettlement: Social Problem and Human Rights Issue.

Valenta, R.K., et al., 2023. Decarbonisation to drive dramatic increase in mining waste–Options for reduction. Resour. Conserv. Recycl. 190, 106859.

van Zyl, E., 2015. Investing in the ESIA and stakeholder engagement process to improve project bankability. In: Responsible Investment Banking: Risk Management

Frameworks, Sustainable Financial Innovation and Softlaw Standards. Springer International Publishing, Cham, pp. 371–387.
Wang, H., Owen, J.R., Shi, G., 2020. Land for equity? A benefit distribution model for mining-induced displacement and resettlement. Bus. Strat. Environ. 29, 3410–3421.
Werner, T.T., et al., 2020. Global-scale remote sensing of mine areas and analysis of factors explaining their extent. Global Environ. Change 60, 102007.
Yang, X., Zhao, H., Ho, P., 2017. Mining-induced displacement and resettlement in China: a study covering 27 villages in 6 provinces. Resour. Pol. 53, 408–418.