Resources Policy 77 (2022) 102696

Contents lists available at ScienceDirect

Resources Policy

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

Complex orebodies and future global metal supply: An introduction

Éléonore Lèbre[a,*], John R. Owen[b], Deanna Kemp[a], Rick K. Valenta[c]

[a] Centre for Social Responsibility in Mining, Sustainable Minerals Institute, Sir James Foots Building (47a), The University of Queensland, St Lucia Campus, QLD, 4072, Australia

[b] Centre for Development Support, University of the Free State, 205 Nelson Mandela Dr, Park West, Bloemfontein, 9301, South Africa

[c] W.H.Bryan Mining & Geology Research Centre, Sustainable Minerals Institute, Sir James Foots Building (47a), The University of Queensland, St Lucia Campus, QLD, 4072, Australia

ARTICLE INFO

Keywords:
Mining
Mineral resources
Industrial ecology
Supply risk
ESG
Sustainable development

ABSTRACT

This special issue aims to create a space for rethinking current approaches to "complex orebodies". Our introductory paper surveys recent developments in the field and identifies a range of challenges that are affecting our collective ability to engage the complex systems associated with future global metal supply. Interdisciplinary mining research remains in its infancy, with single-discipline, technical studies continuing to dominate. Social and environmental factors that lie "beyond the fence" are too often over-simplified and overlooked in resource characterisation and extractive industries. In this special issue, we profile developments in the field and engage the challenges of working in inter-disciplinary, boundary-spanning research in mining. Our paper introduces the special issue, and invites contributing authors to critically engage the conditions and prospects that lie ahead.

1. Introduction

Current world challenges are complex and multifaceted. There is widespread recognition that cross-disciplinary reasoning and collaboration are required to address these challenges (Okamura, 2019). In academic research, fields such as industrial ecology, ecological economics, and political ecology are built on this need for interdisciplinarity. They stem from the premise that social, economic, political, and industrial systems interact within and between themselves and are embedded in a larger ecological system. Research in these fields is outcome-focussed: generating high-impact research that tackles planetary scale issues such as climate change, global inequalities, and sustainable development.

In the resource sector, interdisciplinarity remains in its infancy. Mining is distinguished from other industrial processes because the location of mines cannot be controlled. Resource projects like mines are nested within a given local context, and the mining process is dictated by natural and man-made factors that generate complexity around these project sites. However, mine planning commonly simplifies and underestimates this complexity, reducing it to technological and geological factors. Generally speaking, mine planning is viewed as a linear flow of studies and activities spanning resource discovery; resource definition; mining; processing; production; and waste disposal, with external regulatory, social and environmental factors positioned as a step in the flowchart. While companies allocate significant resources to activities such as topographic studies, drilling programs, and metallurgical testing and piloting in order to define and minimise the risks associated with the geological complexity of orebodies, factors "beyond the fence" are often simplified and treated in a transactional manner. The flowchart of the mining process from definition to market is the key consideration, and technical studies directed at the mine site take precedence over other areas of study.

As a consequence, the sector has historically generated large social and environmental legacies. The geology and metallurgy-focused studies used to plan orebody development have failed to address the significant complexities which lie outside the mine gate; complexities that generate risk to people and the environment, as well as risk to the business. A number of well-studied and technically feasible orebodies have been stranded over long periods (e.g. Valenta et al., 2019) due to environmental, social, political or regulatory conditions that affect their prospects for success.

Novel approaches are needed if mining projects in these historically vexed locations are to be brought to market. The new complex ore body represents a "node" introduced into an already diffuse, fractal, polynodal and evolving system of social, cultural, political, economic, and ecological flows and stocks. This new mining node interacts with the

* Corresponding author.
E-mail address: e.lebre@uq.edu.au (É. Lèbre).

https://doi.org/10.1016/j.resourpol.2022.102696
Received 22 March 2022; Accepted 23 March 2022
Available online 31 March 2022

existing local and regional context, producing risks and impacts in both directions, which then become embedded in metal supply chains. The multi-directionality of risks and impacts must be defined and understood with all aspects of the interaction between those complex systems.

This redefinition of complex ore bodies is supported by recent surveys of mining companies themselves, who are now consistently placing "ESG" factors at the top of their risk hierarchies (Evans et al., 2021). As a knowledge generator, academic research has been dedicated to filling critical knowledge gaps. However, new interdisciplinary research fields have sometimes reinforced old disciplinary boundaries and created new ones. Research needs to constantly rethink the way it integrates information, data, techniques, concepts, and theories from different disciplines, and be mindful of what the new field's boundaries encompass, and what they exclude.

This special issue aims to create a space for a collective rethinking of current research advances and for the cross-pollination of ideas. This introductory paper starts by surveying recent developments in relevant interdisciplinary research fields, spanning a range of approaches across established, emerging, experimental, and alternative research areas. It then identifies a range of recurring challenges that directly affect our ability to comprehend the complex systems associated with mineral resource governance. We then introduce the special issue's goal and scope, and formally invite contributing authors to reflect on identified themes and to engage critically on the conditions and prospects that lie ahead.

2. Current state of play

In his 1968 paper, Dr. Walter Hibbard Jr., Director of the U.S. Bureau of Mines, asked whether the mining industry could meet society's needs for minerals while preserving a liveable environment (Hibbard, 1968). Hibbard 's question was driven by three observations. First, that the industry had failed to manage stakeholder expectations about land use change. Second, the industry's mismanagement of this issue had triggered opposition, which could constrain development. Third, that future metal supply is inextricably linked to the way the industry manages its footprint. Hibbard essentially argued that mining industry malpractice has consequences, not only for local communities and the environment, but also for mineral supply chains.

Half a century later, these concerns are represented by the "ESG banner". The ESG acronym has become mainstream amongst industry and investor groups (Gri, 2020). For investors, addressing ESG risk has a dual function. First, by demonstrating ESG performance, companies can build a positive reputation and in doing so can expect a higher long-term return. Second, proactive management of ESG matters can help to prevent or mitigate social and environmental consequences and costs. An increasing number of investors are committing to incorporating ESG factors into their investment making processes (Unpri, 2019). Likewise, there is an increasing number of methodologies and metrics available for companies to disclose ESG performance and for investors to evaluate this performance.

Despite growing investor scrutiny and corporate commitments to ESG standards and schemes, questions remain about industry performance. A 2020 UNEP study on sustainability reporting in the mining sector found that both the quality of ESG disclosures and actual ESG performance are insufficient to meet stakeholder expectations (Unep, 2020). Poor performance across the sector is evidenced by frequent allegations of human rights abuses involving mining companies (Bhrrc, 2020) and by disasters such as tailings dam failures. These incidents signal performance issues. It seems that the ESG trend may be a simple rebranding of pre-existing issues present since the beginning of the industrialisation.

Application of ESG is also uneven. Certain areas receive more attention than others. Surveys reveal that CEOs rank climate change mitigation as the most important ESG issue (Campbell et al., 2021). BHP, Rio Tinto and Anglo American have all set carbon neutrality targets. The UN PRI considers climate change to be the highest priority ESG issue (Unpri, 2019). The urgency of climate action is unquestionable. However, taken in isolation, emissions reduction becomes disconnected from mining's local-level social and environmental impacts. Local impacts sit at the core of the 'just transition' debate, which aims to achieve climate mitigation objectives without placing an unacceptable burden on mining communities and environments (Bainton et al., 2021). There is a risk, though, that local, complex and multistakeholder ESG matters that do not advance the climate agenda do not receive adequate attention under this banner.

Hibbard's concerns are as relevant as ever. With predictions of an exponential increase in metal demand (Iea, 2021), it is likely that incentives to produce metals will outweigh incentives to address ESG challenges (Denina and Reid, 2021). Fast-tracking is one such incentive. As part of post COVID-19 economic recovery, major mining projects are set to be fast-tracked. Price is another incentive. High metal prices incentivise development, including in new frontiers, such as the Arctic (Hansen and Johnstone, 2019) and the deep sea (Kung et al., 2021). If production increases without a concomitant increase in industry capability to address social and environmental impacts, ESG risks will accumulate.

Against this backdrop, questions about 'scale' become relevant. What is the global footprint of the mining sector now and into the future? How will this footprint grow given demand and production projections? With clean energy technologies becoming a leading consumer of metals, how much land will be needed to supply metals for the energy transition? What new impacts will come with new extractive technologies for energy transition metals (ETM)? The mining sector's footprint directly translates into pressure exerted on the host context. The final question in this set is: how much of this pressure can be alleviated by developing alternatives to mining? These questions connect the mining sector with the rest of the supply chain, with mine sites being source points from which metals enter the economy.

The second set of questions relate to the host context and its response to mining. Characteristics of the operating context can signal specific factors of vulnerability which heighten the risk of negative impacts in these locations. How do mining footprints intersect with elements of the operating context, such as pre-existing land uses, human settlements, ecosystems, or water resources? In other words, which pressure points are most significant? Is a mining region at risk because of limited water resources, or because of vulnerable remote communities? In some cases, the host environment throws up constraints to mining development. Pebble in Alaska and Reko Diq in Pakistan are examples of projects that have been halted because of anticipated impacts on First Nation peoples and security risks, respectively. Despite being two of the largest copper deposits in the world, these projects faced loss of investor confidence, and ultimately, divestment. How common are these situations, and are they becoming more frequent? And to what extent will these ESG concerns affect global supply and slow the energy transition? Interdisciplinary research is in a prime position to find answers to these complex questions. The next section reviews the latest advances in relevant fields.

3. Contemporary research landscape

3.1. Established research: supply-demand outlook

The Material Flow Analysis (MFA) literature pre-dates the rise of ESG. This large body of work analyses the social metabolism, quantifying rates of material use, and tracking losses and inefficiencies through the value chain. Supply and demand outlooks are performed for a wide range of materials at a variety of scales. Global metal demand forecasts model future societal needs and are regularly updated to account for evolving consumption trends. Global demand for metals is expected to increase significantly in the coming decades (Elshkaki et al., 2018) due to the build-up of global material stocks (Krausmann et al., 2017) and the transition to low-carbon energy systems (Mudd, 2020; Weng et al., 2016). Watari et al. (2021a) estimate that the decarbonization of energy and transport sectors will increase metal production and associated resource extraction by more than a factor of 7 by 2050 relative to 2015 levels. The International Energy Agency anticipates the energy sector to become a primary consumer of metals as clean energy technologies are deployed (Iea, 2021).

Supply risk assessments are a subfield in MFA that evaluate whether supply can meet global demand. Achzet and Helbig (2013) reviewed supply risk assessment methods and their scope. These methods combine proxies for macro-economic factors that could constrain supply. They typically assess the supply risk of a commodity based on the geographic distribution of resources. Geopolitics, and concentration of production or resources in a limited number of countries and companies are prominent supply risk factors (Ciacci et al., 2016). Political, security and regulatory risk in jurisdictions hosting large resources is another key consideration. Supply risk assessments also account for geological linkages, namely when two or more metals are found in the same orebody. These linkages increase the supply risk for specialty metals exclusively mined as by-products of major metals, because their extraction is dependent on another commodity's demand (Mudd, 2020). This is the case for metals such as indium and rhenium (Werner et al., 2017).

Materials recovered through recycling are alternative supply sources that reduce the need for mining. The mining sector is the input flow to a large societal system of metal flows and stocks, within which circular flows reduce the need for external input (i.e. mineral resources) and unwanted outputs (i.e. waste disposal). From this perspective, the need for mining and associated impacts is re-evaluated in light of the potential for recycling, and other circular flows (Ciacci et al., 2020). The goal of these analyses is to identify system improvements that will lead to more sustainable resource consumption, where societal well-being is decoupled from the impacts of raw material extraction (Krausmann et al., 2017). The projected demand for energy transition metals (ETM) appears incompatible with the decoupling concept, and recycling flows can only partially offset the need for these metals (Watari et al., 2021a). Technical challenges are another constraint to increasing recycling rates. For example, the complexity of end-of-life products makes metals like copper harder to separate and recycle (e.g. Loibl and Tercero Espinoza, 2021). Mining is expected to remain a primary source of metal supply in the near to medium-term future.

3.2. Emerging research: ESG risks in mining as a source of supply risk

Emerging research provides new perspective on supply risk by focusing on the mining lifecycle, and linked to the ESG discourse (e.g. Jowitt et al., 2020; Valenta et al., 2019; Mudd and Jowitt, 2018). In this literature, the mining system at the source of supply is central to the analysis. This sits in contrast to conventional supply risk assessments. Source risk assessments move from the national level resource estimates to regional and mine site level data and consider local ESG risk dynamics around mining projects as important dimensions of analysis (Mudd, 2020; Watari et al., 2020).

Decades of environmental and social science research have helped characterise risk dynamics around mining projects. Mining activities generate social and environmental risk through emissions (dust, noise, vibrations) (Csavina et al., 2012), consumption and degradation or contamination of local natural resources (water, timber, land) (Thomashausen et al., 2018), and socio-economic and demographic changes such as unmanaged population in-migration (Bainton et al., 2017), displacement and resettlement (Owen and Kemp, 2015), unequal distribution of mining benefits and increased livelihood dependency on these benefits (Bebbington et al., 2008). The mining project is part of a complex relationships network between state, corporations, communities, and the natural environment (Ballard and Banks, 2003). This network enables risks to rebound towards the mining project (Kemp et al., 2016). Occasionally, stakeholder action against mining results in added costs and penalties, production disruption or project cancellation, thereby disrupting supply (Franks et al., 2014). The emerging concepts of source risks and ESG risks in mining build on this understanding of local risk dynamics.

Conflict studies illustrate what happens when source risks materialise. Mining-related conflicts have been on the rise in recent years (Andrews et al., 2017). Researchers have used large datasets to examine patterns in mine-community conflict (e.g. Temper et al., 2020; Hatayama and Tahara, 2018; Andrews et al., 2017). Examples of successful mobilisation against mining development are frequent, with project cancellation occurring in 11% of cases recorded in the Environmental Justice Atlas from 1970 to 2020 (Scheidel et al., 2020). These instances show ways in which dynamic ESG risks arise from the interaction between mining projects and the host environment. In some cases, ESG risk events escalate to the point of violent conflict. The mining sector registers the highest number and the most violent conflicts of all economic sectors (Scheidel et al., 2020).

Several decades of satellite imaging now allow visualising the evolving intersection between mining projects and their host environment (e.g. Ang et al., 2021; Bebbington et al., 2018; Lechner et al., 2019). Mapping the evolution of the mine footprint over time sheds new light on how mining developments exert pressure on the local context via land use competition. New spatial datasets are being developed to locate and quantify mine footprint at global scale. The Fineprint project produced a dataset of 21,000 polygons delineating mining boundaries (6000 active mine sites, 57,277 km^2) (Maus et al., 2020). Werner et al. (2020)'s work on a set of 259 mines provides additional granularity by distinguishing between specific mine features, including open cut pits, water storage ponds, milling infrastructure, waste rock dumps, and tailings storage facilities. This work correlates a mine's land footprint and its cumulative production volume to estimate the extent of future mine area based on expected production. Waste storage is confirmed as constituting the majority of the mine land footprint, a source of social risk and a driver of physical and economic displacement (Owen and Kemp, 2019). These findings have implications for how ESG risks in mining can be managed.

3.3. Experimental research: complex orebodies

The availability of geo-localised mining data has enabled the development of experimental frameworks for the assessment of ESG risks in mining. Several recent studies have used spatial tools to analyse how mining developments overlay with specific environmental risks, including water and climate risks (Northey et al., 2017), and biodiversity conservation (Luckeneder et al., 2021), (Sonter et al., 2020). This research stream experiments with the idea of "situated risks" (Owen et al., 2020). Situated ESG risks are defined by the context in which mining takes place in that pre-existing risk factors create specific risk conditions for the developer, whose projects and practices then drive these risks up or down. High-resolution non-mining spatial datasets serve as proxies for factors contributing to social risk, such as the presence of human settlements or agricultural land uses in direct proximity to the mining project (e.g. Cuba et al., 2014). Situated governance risks relate to political, regulatory and permitting conditions within the country or state where the project is located.

Research on situated risks quantifies a project's risk exposure based on its location. Lèbre et al. (2020) developed a framework compiling spatial datasets into a set of situated ESG risk dimensions, see Fig. 1. In this framework, a high score in any dimension drives up both the likelihood and the severity of the consequences of a detrimental event with consequences potentially affecting the developer, local people, and the environment. The cumulation of several risks in the same location creates complexity for the developer, measured by summing the ESG risk dimensions. In this sense, "complex orebodies" face multiple geological, technical and situated ESG risks that constrain their development (Valenta et al., 2019). When a commodity is sourced from complex

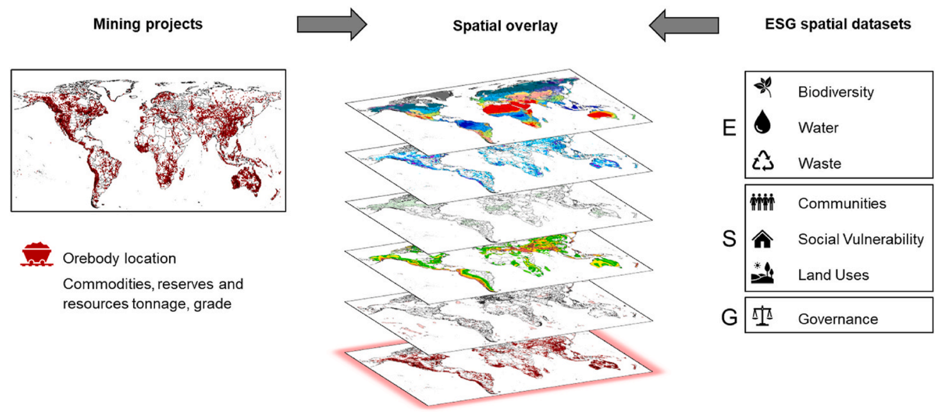

Fig. 1. Situated ESG risk framework (adapted from Lèbre et al., 2020).

orebodies, the risk of supply disruption is heightened.

ESG and the concept of situated risks are useful frames of reference for categorising and comprehending the complexity of mining development. The use of proxies for mining-relevant ESG risk factors is valuable given the low disclosure of site-level information in the global mining industry. This approach has served to de-centre complexity from the exclusively geological read, and in doing so created new ways of thinking about complex orebodies. The situated risk framework offers a process of sense-checking where additional due diligence is needed in assessing the possible intersection between resource projects and their host environment. A challenge going forward is ground truthing global-level findings with project-level observations, ultimately feeding back these observations to the global scale.

3.4. Research in resources policy and corporate governance

The literature reviewed above has conceptualised and analysed different overlapping risks – supply risks, source risks, situated risks, through different system lenses - social metabolism, supply chains, complex orebodies. Research in resources policy and corporate governance studies other man-made systems that determine the way these risks are managed by governments and industry. Governments exercise influence on industry practices via systems of laws, policies, regulations, taxation, and permitting processes. Recent works evaluate these systems in light of specific national and regional contexts. Paredes and Rivera (2017), for instance, examines mineral taxation in Chile, and Yıldız and Kural (2020) the permitting process in Turkey. Researchers also review existing schemes, guidelines, standards and tools and evaluate their potential to influence better social and environmental outcomes in mining (e.g. Kemp et al., 2021; Burritt and Christ, 2021; Sauer, 2021). Watari et al. (2021b) examine the role independent third-party auditing as a way to ensure the credibility of certification schemes in the mining industry. Research is yet to critically assess the effects of responsible sourcing initiatives and ethical minerals schemes in improving industry performance.

Corporate governance is the system by which an organisation is controlled and operates. Researchers explore organisational processes that manage ESG risks in the mining industry. For instance, Aaen et al. (2021) propose a site evaluation tool for exploration companies to assess the social context early on – before a major investment – and make decisions on whether to proceed or not. The tool includes a screening process with identified social thresholds and social 'no-go' factors. Aaen et al. (2021) define social no-go factors as "expected adverse social impact imposed […] on local communities that violates human rights and for which no effective mitigation measures can be determined". Aaen et al. recommend that involuntary resettlement is one such factor, arguing that orebodies located underneath human settlements should not be mined. Adopting an early screen that includes a broad set of no-go criteria across security, social, environmental and geological dimensions would allow mine developers to lower their exposure to risks that they are unable to manage. Calls for a moratorium on all deep-sea mining activities are an example of a 'no-go' decision on a specific supply source (Shukman, 2021).

4. A future facing research agenda

Contemporary research provides a basis from which to re-think the way risks and impacts associated with resource projects are analysed, and the standing of different disciplines within that analysis. This includes a stock of interdisciplinary methods applied at a variety of scales, seeking to de-centre conventional knowledge boundaries and established industry-centric norms around risk definition and risk mitigation. Moving forward, there are several challenges to address.

4.1. Data challenges

1. *Blind spots.* Industrial mining activity data is incomplete, and completeness varies significantly between countries. Some key supplier countries have low rates and standards of disclosure, such as Indonesia. Geolocated project data covers only about 10% of nickel production in the country (S&P Global, 2021; Usgs, 2020). For artisanal and small-scale mining, which is often not captured by global assessments due to its informal, and sometimes illegal character, major data and knowledge gaps exist. This is concerning given the important role the small sector plays in supplying cobalt and tantalum and its increasing recognition as a livelihood activity in the global south (Hilson and Mcquilken, 2014). Data for specialty metals exclusively mined as by-products, such as indium and rhenium, is also scarce (Werner et al., 2018; Mudd, 2020).
2. *Granularity.* Global datasets lack granularity. While global assessments are informative about general trends, they do not accurately represent local conditions around extractive sites. Analyses focusing on smaller scales, e.g. national or subnational, can make use of more detailed data and provide insights from specific mining locations (e.g. Cole and Broadhurst, 2020; Cuba et al., 2014). Global assessments can help identify regions and thematic questions and drivers requiring greater policy attention.
3. *Ground truthing.* Direct access to data from mining locations is necessary to ground truth risk assessments. External visibility over local risk dynamics in mining locations is generally limited due to the remoteness of resource extraction (Bainton et al., 2020). This imposes heightened costs in terms of time and financial resources. Determining where the ground truthing begins (e.g. validating baseline conditions versus assessing risk interactions) and how these findings contribute to improving the resolution of global scale datasets are important considerations.

4.2. Methodological challenges

4. *Mining systems.* Global assessments of the mining industry's footprint should integrate characteristics of the local context with characteristics of the operations and the operator into local mining systems. Global supply originates from multiple mining systems that form as many supply source points. Operational characteristics intersect with the external context such as, for example, the economic importance of the operation for the region, the number of employees, the mining method (e.g. open cut or underground), or energy and water uses.
5. *Expanded footprint.* Spatial assessments of mining sector's footprint need to account for changes happening beyond local mining systems. Mining activities and associated processing, transport and energy infrastructure induce changes in the host environment that can expand well beyond the local scale. For example, the use of desalinated water in mining operations transfers some socioenvironmental impacts to coastal regions (Odell, 2021). Other changes are indirectly triggered by mining activities, for example when transport corridors enable agriculture expansion (Bebbington et al., 2018).
6. *The mine lifecycle.* Mining projects generate different risks depending on the development stage. Risk assessments should consider cumulative risks over the mine lifecycle, from orebody discovery to final closure. Closures represent major events that often negatively impact the workforce, communities, and the environment, and risk dynamics associated with mine closure need to be studied at both local and regional scales. This could include retrospective studies of mining regions having reached resource depletion, and risk assessments of regions currently dependent on commodities such as thermal coal, whose demand is predicted to decline as the energy transition progresses.
7. *Likelihood versus consequence.* In analysing ESG risks in mining, there is a clear distinction to be made between latent risks and materialised events. Mechanisms that turn one into the other remain uncertain, and the result of complex risk interactions. Developing an understanding of these mechanisms and their root causes may mean to go back to traditional risk measurements: where risk equals the anticipated consequence of an event, multiplied by that event's likelihood of occurrence.
8. *Risk to whom?* Risk directionality and rebound dynamics within the mining system are another significant element to the measurement of risk. Risk directionality has implications for mineral supply (Kemp et al., 2016). If risk is primarily directed towards the external context (in other words, it is externalised), then supply disruption is unlikely, whereas social and environmental impacts embedded in supply are high. Risk rebound dynamics redirect risk towards the project and can affect production, and at a larger scale, supply.

5. Conclusion: what's in the special issue

In the context of climate change, the deployment of clean energy technologies imposes an urgent and unprecedented global demand for metallic minerals. Important questions are being raised around supply risk and the social and environmental implications of the intensification of extractive activities. This special issue aims to stimulate discussion and debate about demand projections for energy transition metals (ETM), recycling potential, supply risks and ESG factors in mining, disruption events at mine sites and no-go factors that could inhibit the commissioning of projects and the flow of metals into the global economy. Invited authors will approach these questions from a diversity of angles, from papers synthesizing the state of play, to more targeted discussion about specific commodities, geographic regions, or risk dimensions. The special issue promotes interdisciplinary studies that take a systems approach focused broadly on these following topics:

- the relationship between situational and technical complexity, commodity prices and project development;
- the relationship between mining project disruption and supply risk; the dynamics of mineral supply chains, linking mining production with global metal demand;
- the relationship between inbound risk (risk to project) and outbound risk (risk to people and environment);
- new risk assessment and modelling methods, or perspectives on existing methods that enhance our understanding of their scope and potential;
- spatial and temporal approaches to analysing situated risk factors at various scales;
- critical analysis of national policies or global initiatives in relation to the complexity challenge;
- case studies of complex orebody developments, including corporate and stakeholder responses to risk;
- the emergence of discourses that critique or support the complex orebodies view.

More generally, this special issue aims to profile research that rethinks existing approaches, methods and findings. We have encouraged authors to think of specific ways to address the challenges identified in section 4. The potential impact of advances in this area is significant, given the projected commodity demand over the coming decades and the local conditions associated with their extraction.

Acknowledgements

The authors are grateful for the strategic funds received from The University of Queensland (UQ) in support of the Sustainable Minerals Institute's (SMI) cross-disciplinary research on “complex orebodies”. The authors would also like to acknowledge funding from the Australian Research Council (grant id: DE220101129).

References

Aaen, S.B., Hansen, A.M., Kladis, A., 2021. Social no-go factors in mine site selection. Extr. Ind. Soc. 8, 100896.
Achzet, B., Helbig, C., 2013. How to evaluate raw material supply risks—an overview. Resour. Pol. 38, 435–447.
Andrews, T., Elizalde, B., Le Billon, P., Hoon Oh, C., Reyes, D., Thomson, I., 2017. The Rise in Conflict Associated with Mining Operations: what Lies beneath? Canadian International Resources and Development Institute (Cirdi).
Ang, M.L.E., Arts, D., Crawford, D., Labatos Jr., B.V., Ngo, K.D., Owen, J.R., Gibbins, C., Lechner, A.M., 2021. Socio-environmental land cover time-series analysis of mining landscapes using Google Earth Engine and web-based mapping. Rem. Sens. Appl.: Soc. Environ. 21, 100458.
Bainton, N., Vivoda, V., Kemp, D., Owen, J., Keenan, J., 2017. Project-Induced In-Migration and Large-Scale Mining: A Scoping Study. *University of Queensland, Centre for Social Responsibility in Mining.* St Lucia, Queensland, Australia.
Bainton, N., Owen, J.R., Kemp, D., 2020. Invisibility and the extractive-pandemic nexus. Extr. Ind. Soc. 7, 841–843.
Bainton, N., Kemp, D., Lèbre, E., Owen, J.R., Marston, G., 2021. The energy-extractives nexus and the just transition. Sustain. Dev. 29, 624–634.
Ballard, C., Banks, G., 2003. Resource wars: the anthropology of mining. Annu. Rev. Anthropol. 32, 287–313.
Bebbington, A., Hinojosa, L., Bebbington, D.H., Burneo, M.L., Warnaars, X., 2008. Contention and ambiguity: mining and the possibilities of development. Dev. Change 39, 887–914.
Bebbington, A.J., Humphreys Bebbington, D., Sauls, L.A., Rogan, J., Agrawal, S., Gamboa, C., Imhof, A., Johnson, K., Rosa, H., Royo, A., Toumbourou, T., Verdum, R., 2018. Resource extraction and infrastructure threaten forest cover and community rights. Proc. Natl. Acad. Sci. Unit. States Am. 115, 13164–13173.
Bhrrc, 2020. Transition Minerals Tracker - Tracking the Human Rights Implications of the Mineral Boom Powering the Transition to a Low-Carbon Economy. Business & Human Rights Resource Centre.
Burritt, R.L., Christ, K.L., 2021. Full cost accounting: a missing consideration in global tailings dam management. J. Clean. Prod. 321, 129016.
Campbell, R., Tivey, J., Wright, O., 2021. Mining & Metals 2021: Esg Momentum Reaching a Crescendo in a Resilient Market. White & Case.
Ciacci, L., Nuss, P., Reck, B.K., Werner, T., Graedel, T., 2016. Metal criticality determination for Australia, the Us, and the planet—comparing 2008 and 2012 results. Resources 5, 29.
Ciacci, L., Fishman, T., Elshkaki, A., Graedel, T.E., Vassura, I., Passarini, F., 2020. Exploring future copper demand, recycling and associated greenhouse gas emissions in the Eu-28. Global Environ. Change 63, 102093.
Cole, M.J., Broadhurst, J.L., 2020. Mapping and classification of mining host communities: a case study of South Africa. Extr. Ind. Soc. 7, 954–964.

Csavina, J., Field, J., Taylor, M.P., Gao, S., Landázuri, A., Betterton, E.A., Sáez, A.E., 2012. A review on the importance of metals and metalloids in atmospheric dust and aerosol from mining operations. Sci. Total Environ. 433, 58–73.
Cuba, N., Bebbington, A., Rogan, J., Millones, M., 2014. Extractive industries, livelihoods and natural resource competition: mapping overlapping claims in Peru and Ghana. Appl. Geogr. 54, 250–261.
Denina, C., Reid, H., 2021. Big Miners Reconsider Congo, Zambia Risks as Copper Price Surges. Reuter. October 14th.
Elshkaki, A., Graedel, T.E., Ciacci, L., Reck, B.K., 2018. Resource demand scenarios for the major metals. Environ. Sci. Technol. 52, 2491–2497.
Evans, X., Mahoney, P., Ratcliffe, M., Stanway, G., 2021. State of Play: Ecosystem.
Franks, D.M., Davis, R., Bebbington, A.J., Ali, S.H., Kemp, D., Scurrah, M., 2014. Conflict translates environmental and social risk into business costs. Proc. Natl. Acad. Sci. Unit. States Am. 111, 7576–7581.
Global, S.&P., 2021. S&P Capital Iq Pro. Thomson Reuters, New York.
Gri, 2020. Carrots & Sticks - sustainability reporting policy: global trends in disclosure as the Esg agenda goes mainstream. In: Global Reporting Initiative (Gri). the University of Stellenbosch Business School (Usb), the Un Environment Programme (Unep).
Hansen, A.M., Johnstone, R.L., 2019. In the Shadow of the Mountain: assessing early impacts on community development from two mining prospects in South Greenland. Extr. Ind. Soc. 6, 480–488.
Hatayama, H., Tahara, K., 2018. Adopting an objective approach to criticality assessment: learning from the past. Resour. Pol. 55, 96–102.
Hibbard, W.R., 1968. Mineral resources: challenge or threat? Science 160, 143–149.
Hilson, G., Mcquilken, J., 2014. Four decades of support for artisanal and small-scale mining in sub-Saharan Africa: a critical review. Extr. Ind. Soc. 1, 104–118.
Iea, 2021. The Role of Critical Minerals in Clean Energy Transitions - World Energy Outlook Special Report. International Energy Agency, Paris, France.
Jowitt, S.M., Mudd, G.M., Thompson, J.F.H., 2020. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. Commun. Earth Environ. 1, 13.
Kemp, D., Worden, S., Owen, J.R., 2016. Differentiated social risk: rebound dynamics and sustainability performance in mining. Resour. Pol. 50, 19–26.
Kemp, D., Owen, J.R., Lèbre, É., 2021. Tailings Facility Failures in the Global Mining Industry: Will a 'transparency Turn' Drive Change? n/a.
Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., Jackson, T., 2017. Material flow accounting: measuring global material use for sustainable development. Annu. Rev. Environ. Resour. 42, 647–675.
Kung, A., Svobodova, K., Lèbre, E., Valenta, R., Kemp, D., Owen, J.R., 2021. Governing deep sea mining in the face of uncertainty. J. Environ. Manag. 279, 111593.
Lèbre, É., Stringer, M., Svobodova, K., Owen, J.R., Kemp, D., Côte, C., Arratia-Solar, A., Valenta, R.K., 2020. The social and environmental complexities of extracting energy transition metals. Nat. Commun. 11, 4823.
Lechner, A.M., Owen, J., Ang, M.L.E., Edraki, M., Che Awang, N.A., Kemp, D., 2019. Historical socio-environmental assessment of resource development footprints using remote sensing. Rem. Sens. Appl.: Soc. Environ. 15, 100236.
Loibl, A., Tercero Espinoza, L.A., 2021. Current challenges in copper recycling: aligning insights from material flow analysis with technological research developments and industry issues in Europe and North America. Resour. Conserv. Recycl. 169, 105462.
Luckeneder, S., Giljum, S., Schaffartzik, A., Maus, V., Tost, M., 2021. Surge in global metal mining threatens vulnerable ecosystems. Global Environ. Change 69, 102303.
Maus, V., Giljum, S., Gutschlhofer, J., Da Silva, D.M., Probst, M., Gass, S.L.B., Luckeneder, S., Lieber, M., Mccallum, I., 2020. A global-scale data set of mining areas. Sci. Data 7, 289.
Mudd, G.M., 2020. Metals and Elements Needed to Support Future Energy Systems. Future Energy, pp. 711–726.
Mudd, G.M., Jowitt, S.M., 2018. Growing global copper resources, reserves and production: discovery is not the only control on supply. Econ. Geol. 113 (6), 1235–1267.
Northey, S.A., Mudd, G.M., Werner, T.T., Jowitt, S.M., Haque, N., Yellishetty, M., Weng, Z., 2017. The exposure of global base metal resources to water criticality, scarcity and climate change. Global Environ. Change 44, 109–124.
Odell, S.D., 2021. Desalination in Chile's mining regions: global drivers and local impacts of a technological fix to hydrosocial conflict. J. Clean. Prod. 323, 129104.
Okamura, K., 2019. Interdisciplinarity revisited: evidence for research impact and dynamism. Palgrave Commun. 5, 141.
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., 2019. Displaced by Mine Waste: the Social Consequences of Industrial Risk-Taking. The Extractive Industries and Society.
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
Paredes, D., Rivera, N.M., 2017. Mineral taxes and the local public goods provision in mining communities. Resour. Pol. 53, 328–339.
Sauer, P.C., 2021. The complementing role of sustainability standards in managing international and multi-tiered mineral supply chains. Resour. Conserv. Recycl. 174, 105747.
Scheidel, A., Del Bene, D., Liu, J., Navas, G., Mingorría, S., Demaria, F., Avila, S., Roy, B., Ertör, I., Temper, L., Martínez-Alier, J., 2020. Environmental conflicts and defenders: a global overview. Global Environ. Change 63, 102104.
Shukman, D., 2021. Companies Back Moratorium on Deep Sea Mining. Bbc News, 3rd April 2021.
Sonter, L.J., Dade, M.C., Watson, J.E.M., Valenta, R.K., 2020. Renewable energy production will exacerbate mining threats to biodiversity. Nat. Commun. 11, 4174.
Temper, L., Avila, S., Del Bene, D., Gobby, J., Kosoy, N., Le Billon, P., Martinez-Alier, J., Perkins, P., Roy, B., Scheidel, A., 2020. Movements shaping climate futures: a systematic mapping of protests against fossil fuel and low-carbon energy projects. Environ. Res. Lett. 15, 123004.
Thomashausen, S., Maennling, N., Mebratu-Tsegaye, T., 2018. A comparative overview of legal frameworks governing water use and waste water discharge in the mining sector. Resour. Pol. 55, 143–151.
Unep, 2020. Sustainability Reporting in the Mining Sector: Current Status and Future Trends. United Nations Environmental Programme, Nairobi, Kenya.
Unpri, 2019. What Is Responsible Investment? : Un Principles for Responsible Investment.
Usgs, 2020. Mineral Commodity Summaries 2020. U.S. Geological Survey, Reston, Va, Usa.
Valenta, R., Kemp, D., Owen, J., Corder, G., Lèbre, É., 2019. Re-thinking complex orebodies: consequences for the future world supply of copper. J. Clean. Prod. 220, 816–826.
Watari, T., Nansai, K., Nakajima, K., 2020. Review of critical metal dynamics to 2050 for 48 elements. Resour. Conserv. Recycl. 155, 104669.
Watari, T., Nansai, K., Nakajima, K., 2021a. Major metals demand, supply, and environmental impacts to 2100: a critical review. Resour. Conserv. Recycl. 164, 105107.
Watari, T., Nansai, K., Nakajima, K., Giurco, D., 2021b. Sustainable energy transitions require enhanced resource governance. J. Clean. Prod., 127698
Weng, Z., Haque, N., Mudd, G.M., Jowitt, S.M., 2016. Assessing the energy requirements and global warming potential of the production of rare earth elements. J. Clean. Prod. 139, 1282–1297.
Werner, T., Mudd, G.M., Jowitt, S.M., 2017. The world's by-product and critical metal resources part Iii: a global assessment of indium. Ore Geol. Rev. 86, 939–956.
Werner, T.T., Ciacci, L., Mudd, G.M., Reck, B.K., Northey, S.A., 2018. Looking down under for a circular economy of indium. Environ. Sci. Technol. 52, 2055–2062.
Werner, T.T., Mudd, G.M., Schipper, A.M., Huijbregts, M.A.J., Taneja, L., Northey, S.A., 2020. Global-scale remote sensing of mine areas and analysis of factors explaining their extent. Global Environ. Change 60, 102007.
Yıldız, T.D., Kural, O., 2020. The effects of the mining operation activities permit process on the mining sector in Turkey. Resour. Pol. 69, 101868.