ESG mapping of the Australian mining sector – The state of play on mobilising spatial datasets for decision making

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Highlights

- ESG mapping analyses and compares extractive locations across large scales
- The paper critically reviews 32 spatial ESG datasets available at the scale of Australia
- It identifies steps to using ESG mapping as a decision-support tool and provides two proof-of-concept applications
- One application tests the overlap between land tenure and mining project delays
- The second application aggregates ESG datasets into a composite measure of vulnerability

Abstract

The global energy transition will drive increased demand for a broad range of mined minerals. Australia is well positioned to support the global energy transition, given its mature mining sector and rich and diverse mineral resources. The potential growth in the mining sector represents an economic opportunity, however, navigating the associated environmental, social, and governance (ESG) risks remains a challenge. A step towards improved ESG credentials across the Australian mining sector is for mine developers, regulators, communities, investors and other industry stakeholders to be capable of integrating diverse types of ESG data into decision-making processes. This paper evaluates how ESG mapping, a research technique that mobilises spatial data to analyse and compare extractive locations across large scales in terms of factors relevant to mining and exploration, can be applied at the scale of Australia. The paper critically reviews 32 spatial ESG datasets available at national scale across six main themes: people, land uses, water resources, extreme events, nature conservation, and governance. The paper then provides two proof-of-concept applications of ESG mapping to the Australian mining context and draws on these applications to lay out a path forward for this technique to inform decision makers.

1. Introduction

The global energy transition will drive increased demand for mined minerals (IEA, 2023a). At least 34 energy transition minerals (ETMs) are needed in low-carbon energy technologies and infrastructure (Hund et al., 2020; IEA, 2021), for which future demand is projected to exceed current supply. For example, transition-related demand for copper is set to increase by 55% by 2030 (IEA, 2023b) and demand for lithium, a specialty metal needed in batteries, is projected to quadruple by 2050 (IEA, 2023b). In the immediate future, between 196 and 382 new mines are estimated to open by 2030 to meet demand for cobalt, copper, lithium, and nickel (Bingoto et al., 2023). The potential growth in the ETM mining sector represents an economic opportunity for resource-rich countries; however, navigating the associated environmental, social and governance (ESG) risks remains a challenge for government and industry stakeholders and mining-affected communities (IEA, 2023a).

Australia is well positioned to support the global energy transition, given its mature mining sector and abundance of ETMs (Huo and Ampofo, 2023). The country currently produces all 34 ETMs and ranks among the top five producers for 13 ETMs: aluminium, cobalt, iron, lead, lithium, magnesium, manganese, rare earths, silicon, silver, titanium, zinc, and zircon (Hughes et al., 2023). Its exploration budget, the second largest after Canada, has the highest success rate in the world (Schodde, 2023), and is invested in continued expansion of Australia’s resource base (S&P Global, 2024). Australia’s reserves, the part of the resource that has been deemed commercially viable, are also considerable. Australia hosts the world’s largest reserves of nickel, rare earths, lead, zinc, and iron, and the second largest reserves of copper (S&P Global, 2024).

In 2023, the Australian government published a Critical Minerals Strategy (Australian Government, 2023), outlining plans to support mining development through instruments such as loans, award programs, streamlined approval processes, apprenticeship initiatives, and lowering project risk. The strategy also commits to strengthening Australia's ESG credentials, as doing so is seen as a competitive advantage in improving local stakeholder support and securing global market access. To achieve these improvements tractable pathways and explicit commitments are needed (Sinclair and Coe, 2024) as recent publicised events demonstrate room for improvement exists, such as destruction of aboriginal heritage (Wensing, 2020), a tailings dam failure (Hambrett, 2021), and investigations on a culture of sexism across the mining sector (Elizabeth Broderick & Co, 2022).

A step towards improving ESG performance across the Australian mining sector is for mine developers, regulators, investors, communities, and other industry stakeholders to be capable of integrating diverse types of ESG data into decision-making processes. ESG mapping is a research technique that mobilises spatial data to analyse and compare extractive locations across large scales in terms of geographical factors relevant to mining and exploration (Lèbre et al., 2022). It is based on the idea that geography is a central construct in the mine-community-environment interface (Owen and Kemp, 2019), and spatial data can therefore provide information relevant to stakeholders for improved planning and practice, including but not restricted to risk assessment. To date, this approach has been applied at the global scale (e.g. Lèbre et al., 2020, Sonter et al., 2020), with recent national-scale targeted assessments conducted in Canada (Lawley et al., 2022a, focused on nature conservation), Australia (Burton et al., 2024a, 2024b, focused on social data) and South Africa (Cole et al., 2024, focused on mine closure).

This paper is a state of play on applying ESG mapping to the Australian mining and exploration sector. It reviews national-scale datasets available for undertaking spatial analysis, considering the full spectrum of spatial ESG factors. The paper's goal is to establish the foundations: identifying main data gaps and challenges, laying out a pathway forward and making recommendations for future work. In the next section, we set the scene by reviewing past ESG mapping studies and examining their scope. Section 3 consists of a critical review of available ESG spatial datasets and their applicability to the Australian mining context. Sections 4 and 5 then provide two proof-of-concept applications of the ESG mapping approach: Section 4 analyses one ESG dataset's intersection with a mining dataset, while Section 5 provides an example of aggregation of several ESG datasets into a composite measure. It should be noted that these two sections focus on the process of ESG mapping, and that results are only preliminary and thereby included for reference in Appendices (B and C). Finally, Section 6 discusses the path forward to using this approach to inform decision making in mining and exploration.

2. ESG mapping and associated concepts

ESG is an investment acronym that was originally used to capture financially material environmental, social and governance risk factors affecting an asset or a business. With the global growth of responsible investing (PRI, 2024), ESG evolved to not only cover financial risks but also broader sustainability concerns. ESG is now commonly applied across the private sector to evaluate a company's performance in terms of its impacts on society and the environment (GRI, 2024). The ESG sphere has significantly grown in recent years to incorporate a diversity of metrics and standards (e.g. SABS, 2023) to measure, report, and assess this performance.

In the mining sector, risks and impacts often manifest locally and can vary greatly depending on where mine sites are located. Mine planning and practices must adapt to site specificities, and outcomes (positive or negative impacts) are influenced by pre-existing conditions. For instance, reducing freshwater consumption in mining and processing is most critical within areas of high baseline water stress. A company's anti-corruption policy will be most tested when developing projects in jurisdictions with endemic corruption. This location factor has given rise to ESG mapping, an area of research that models the geographic context around mining development as spatial layers of environmental, social, economic, regulatory, and political data (Figure 1, right panel). The analysis of these layers of information does not aim to generate insights on a company's performance or practices, but rather focuses upstream, on evaluating the external pre-existing conditions that need to be considered in developing and operating a mine. ESG mapping studies overlay existing or potential mining and exploration project locations (Figure 1, left panel) with spatial ESG datasets to draw insights from the co-location of ESG factors and projects.

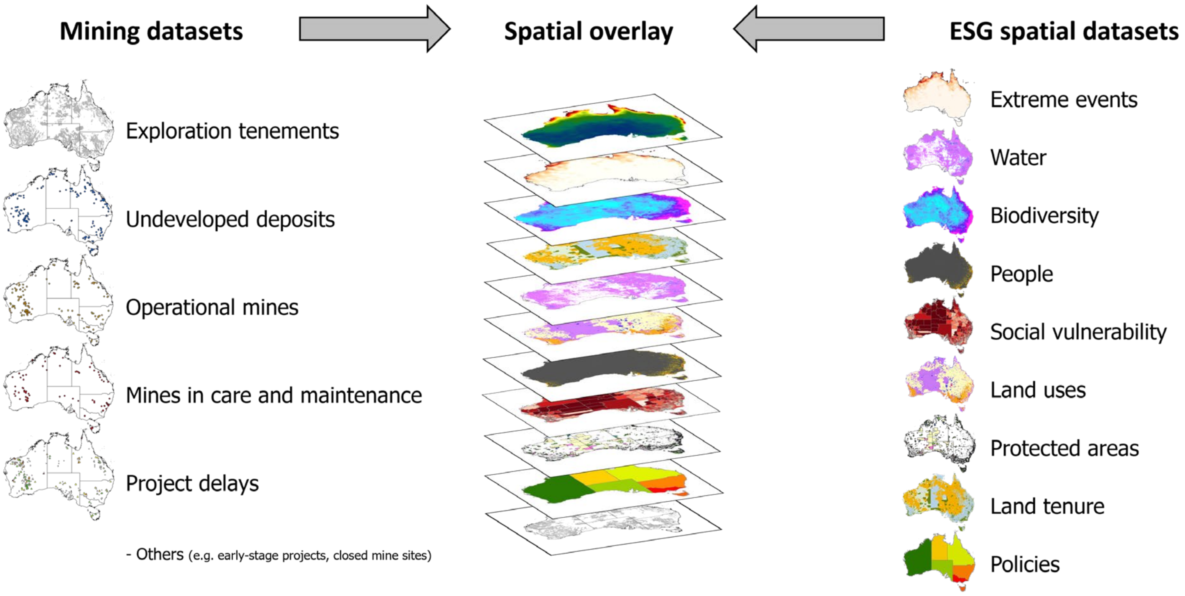


***Figure 1**: Illustrative ESG mapping framework adapted for Australia.*

ESG mapping studies have drawn on the original definition of ESG as financially material risk factors and have often taken this risk orientation. In mining, ESG risks are understood broadly to materialise through a dynamic interface between a mining or exploration project and its host context (Lèbre et al., 2022). Within this interface, risks are multidirectional and can be inbound (i.e., ESG risks to the mining project) or outbound (i.e., risks of mining to community or environment) (Kemp et al., 2016). They can accumulate, transfer, and rebound across mining industry actors. Past work has either taken this broad risk definition (e.g. Lèbre et al., 2020) or emphasized specific directional aspects. For instance, initial works from Valenta et al. (2019) and Lèbre et al. (2019) and more recently Lawley et al. (2024) argued that an accumulation of ESG risk factors can constrain mining development (i.e. a materialisation of inbound risk). Lawley et al. (2024) assessment ranked Australia third in the world in terms of favourable spatial ESG conditions in terms of the risk of natural resource conflicts. Other works have focused on outbound risks, including risks of mining to biodiversity (Luckeneder et al., 2021; Sonter et al., 2020), and to land-connected peoples (Owen et al., 2023).

In other mapping works, ESG is a sub-component of risk. For instance, Northey et al. (2017) frame their study around mining project's 'exposure' to water scarcity and climate change. Bainton et al. (*in review*), Kemp et al. (2021), and Owen et al. (2021) take a 'vulnerability' lens as a sub-component of risk to people (outbound risk). Owen et al. (2021), for instance, use spatial indicators to measure pre-existing levels of social, political, and economic vulnerability in communities facing mining-induced resettlement. Everingham et al. (2022) applied the ESG mapping approach to evaluate the socio-economic 'capacity' of mature mining regions to successfully transition to a post-mining future. Owen et al. (2023) evaluate the institutional 'capacity' of mining jurisdictions to protect the rights of land-connected peoples. Valenta et al. (2019) question the mining industry's 'capacity' and 'capability' to manage and overcome difficult pre-existing ESG conditions.

The above works all apply the ESG mapping approach at a global scale. National-scale studies typically benefit from access to richer and more precise data and analysts are thus able to interrogate the data in more targeted ways. Burton et al. (2024a), for instance, use spatial data to identify socio-economic issues for policy makers and industry to attend to as they seek to scale up Australia's critical minerals sector. Burton et al. (2024b) study the co-occurrence of mineral deposits in Australia and Indigenous peoples' rights in land. In Canada, Lawley et al. (2022b) overlay prospectivity maps with ecosystem service maps to inform natural resources management strategies with the aim of balancing resource exploitation and conservation. Walsh et al. (2020) take an ‘opportunities’ lens, overlaying prospectivity maps with infrastructure data to assess regional economic viability for mineral resource development in Australia, as well as other economic outcomes, such as tax revenue and employment.

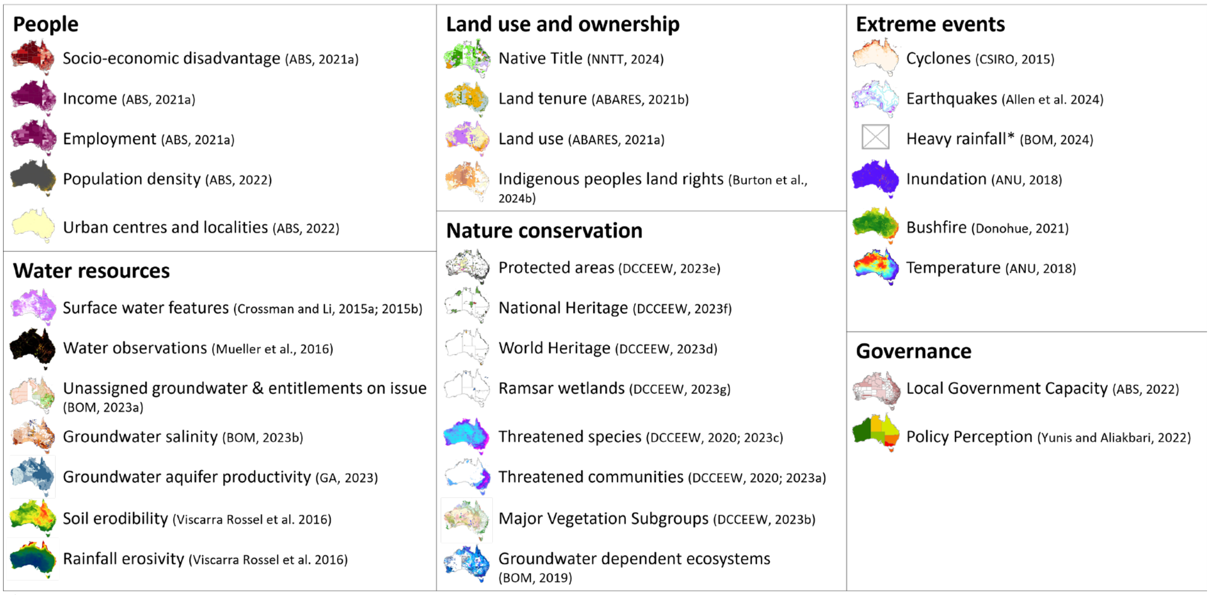
ESG mapping studies have in common that they seek to understand pre-existing contextual factors that play a role in mining development and associated social and environmental outcomes. They are not intended to be predictive, and they focus on understanding latent conditions rather than issues of performance, practice, or impact. Lawley et al. (2024) state that such approach can constitute a pool of knowledge for pre-competitive land-use planning where ESG considerations can be incorporated early on. More broadly, large-scale datasets mobilised in ESG mapping enable comparability across locations based on a wide array of location attributes. They can be used to i) compare exploration projects or mining projects (early stage or operational) against a cohort of peer projects, ii) compare mining asset portfolios to each other, and iii) compare projects or portfolios against global or national averages. They can also be used more broadly to identify areas within a territory that warrant further investigation, which would then mobilise more precise data and ground truthing. Because of their scale, these datasets are typically not suitable for Environmental and Social Impact Assessments (ESIA), which rely on local data collection and aim to predict future impacts.

The national scale is pertinent as significant decisions, such as the implementation of Australia’s Critical Minerals Strategy, are made at this scale. As technology improves, increasingly trusted, high-resolution datasets are available at this scale across Australia (Geoscience Australia, 2024). Companies can use national ESG mapping to identify potential showstoppers early in the process before significant investments are made, and evaluate the resources and capabilities that might be needed to enter a certain area. ESG mapping can help policymakers and regulators better understand their territory’s specificities and complexities and guide the development of adequate incentives or safeguards where needed. Mapping also provides regional and national context for communities considering resource projects in their area. For Australia, ESG mapping can facilitate a national conversation on the benefits and risks associated with critical mineral development considering concurrent economic, social, and environmental objectives.

3. Review of spatial ESG datasets available for Australia

In this section, we critically examine national-scale spatial ESG datasets available to inform the Australian mining sector and its stakeholders. Different users of the data – industry, policy makers, civil society groups or local communities, planning agencies and State and local government – will have different interests and questions around vulnerability, capacity, capability, or risk exposure, and different views on risk directionality (inbound or outbound). For the purpose of this review, as much as possible, we keep a broad definition of who the end user may be. We focus on how existing spatial datasets can contribute to generating knowledge about the diversity of geographic contexts around the Australian mining sector, and how this knowledge may be mobilised to ultimately mitigate ESG risk (as broadly defined in Section 2) and enhance positive outcomes for all stakeholders.

The list of 32 datasets visualised in Figure 2 (see Appendix A for details) was generated through a desktop review followed by consultations with subject matter experts. The desktop review focused on six major ESG themes identified in previous global-scale mapping works (Lèbre et al., 2020; Owen et al., 2020). These themes – ‘people’, ‘land use and ownership’, ‘extreme events’, ‘water resources’, ‘nature conservation’, and ‘governance’ – capture well-researched patterns of interaction between mining or exploration projects and their geographic context (e.g. Kemp et al., 2010; Owen and Kemp, 2015; Owen and Kemp, 2017; Ang et al., 2023; Bebbington et al., 2018; Sonter et al., 2018) and are further explained in this section. Following the desktop review, a two-day workshop was organised, gathering experts across these six themes. The workshop discussed 1) the datasets’ relevance to inform mining and exploration stakeholders, 2) their readiness for use, i.e. whether they can be mobilised through no or little conversion or transformation, and 3) the quality of data, including precautions and limitations for use. This consultation with experts led to some datasets being excluded and others added, resulting in a consolidated list of datasets. Workshop participants were later invited to review and contribute to this paper.



* = dataset not readily accessible as spatial layer

***Figure 2**: Spatial datasets available for Australia across six ESG themes. See Appendix A for details.*

3.1. People

For this first theme, The Australian Bureau of Statistics (ABS) provides a rich diversity of datasets about the social, cultural, and economic characteristics of the communities living nearby mining and exploration projects. This data has direct relevance for developers gathering a social knowledge base (Owen and Kemp, 2019) to understand the context they are entering, and use this knowledge in operational-level decision-making to ultimately mitigate risk (both to people and to projects). Data from the ABS is collected through the national census every five years and is compiled at different scales, from finest Statistical Area 1 (SA1) level to Local Government Area (LGA) level. This results in relatively low spatial resolution in remote areas where LGAs and SA1s are large (up to 250,000 km^2 for the largest SA1). Burton et al. (2024a) also point to inaccuracies in places with existing Fly-in-fly-out (FIFO) operations. The ABS provides composite measures that combine several variables from the census, facilitating interpretation and examination of multi-faceted socio-economic factors. For instance, the Index of Relative Socio-economic Disadvantage (IRSD) (ABS, 2021a) is made up of 15 variables for income, education, and employment, and provides a multi-dimensional picture of pre-existing levels of vulnerability amongst the local population (ABS, 2013), which has implications for community engagement, benefit sharing, and policies aiming to install social safeguards.

Employment data helps understand the level of economic diversity, identify the presence of a skilled local workforce, and anticipate local procurement opportunities. For instance, such data could help identify opportunities to revive declining mining economies by supporting new developments nearby existing mining towns. Population density and Urban Centres and Localities are other datasets from the ABS (2022), provided at a spatial resolution of 1 km. These can be used as indicators of remoteness and to evaluate a project's proximity to the nearest community (proximity being associated with health and safety risks, and displacement and resettlement risks).

'People' data for Australia is generally well suited, in terms of relevance and readiness for use, for ESG mapping. However, caution should be exercised around interpretation, especially when applying them as risk measures. For most 'people' variables, a high or low score often cannot be directly translated into a quantitative estimation of a singular risk (or opportunity) for a mining stakeholder. For instance, on the one hand, low population density (remoteness) is a measure of vulnerability, i.e. a component of risk to people, while under certain conditions it can also be seen as an opportunity for a mine to make a positive contribution to economic development. On the other hand, high population densities indicate challenges of a different nature, such as land use competition.

3.2. Land use and ownership

Land use and land tenure data form essential parts of a developer's social knowledge base and have important implications for Free, Prior and Informed Consent (FPIC) (Owen and Kemp, 2014). Mining and exploration activities rely on land access, and competing uses or interests over the land present risks (including potential showstoppers for a project) and opportunities. FPIC introduces heightened social performance requirements (Owen and Kemp, 2014), and 'land' data can help a developer evaluate whether it has the resources and capabilities needed to meet these requirements. The Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), a division of the Department of Agriculture, Fisheries and Forestry, provides maps of land use (ABARES, 2021a) and land tenure (ABARES, 2021b). These maps have high spatial resolutions but the information they display may be outdated, with land tenure being from 2016. In addition to the ABARES data, the National Native Title Tribunal (NNTT) maintains a diversity of maps related to Indigenous peoples land (NNTT, 2024). These maps are high-resolution and recent (2024), although the dynamic situation around native title in Australia means latest changes may not be reflected. Because the number of native title claims is growing, areas with no data do not indicate an absence of Indigenous interests in the land. Burton et al. (2024c) have significantly progressed the integration of NNTT and ABARES data into a national map of Indigenous peoples' land rights.

'Land' data for Australia has clear relevance to ESG mapping, although some data quality issues remain. However, there are challenges associated with readiness for use and interpretation. While the ABARES provides definitions for each category of land use and tenure, the information does not allow ranking these categories in terms of risks or opportunities in a mining context. There is little information about the commercial value of the land or about land use intensity and exclusivity (i.e. whether multiple land uses can overlap). ABS is working on consolidating land use, tenure and value data at national scale, but this initiative appears to be at the experimental stage (ABS, 2021b). On Indigenous peoples' land rights, Burton et al. (2024c) have facilitated interpretation by assembling data into three categories: 1) exclusive rights; 2) co-existing rights and interests; and 3) native title claims (yet to be determined by the court). Interpretation for mining developers remains uncertain, however, as exclusive rights, the strongest form of land title, usually do not cover rights to the subsurface (this varies across States).

3.3. Extreme events

This theme captures the risk of extreme climatic and seismic events, which generate costs to business (e.g. greater infrastructure design requirements for impacts mitigation, damage to infrastructure or production stoppages) as well as costs to local stakeholders and the environment. They are measures of operational risk, i.e. risk that can materialise throughout the life of mine, rather than development risk (constraining initial mine development). They are also measures of legacy risk, i.e. risk that befall local stakeholders after mining has ceased (Bulovic et al., 2024). We reviewed data for earthquakes (Allen et al., 2024), cyclones (CSIRO, 2015), extreme rainfall (BOM, 2024), extreme temperatures (ANU, 2018), floods (ANU, 2018), and bushfire risk (Donohue, 2021). Seismicity has relatively low relevance in the Australian context, however it is not negligible. Except for mine sites that are near the coastline, cyclones tend to impact mines indirectly by interrupting ore shipments. Extreme rainfall events can cause disruptions, costs, and downstream pollution, through flooding of mine voids and waste containment failures (WISE, 2024). Risk management uses extreme events data and mitigates risks through engineering design requirements and active water management.

The Australian Bureau of Meteorology (BOM) is the primary source of climate data nationally, from which most information on climate-related natural hazards are derived. The BOM generates a range of spatial datasets, including those on extreme rainfall in the form of rainfall percentile maps and engineering design rainfalls (BOM, 2024). Several design rainfall datasets are produced to capture the magnitude of events of numerous frequencies and durations, from those that may occur a few times a year to extremely rare events (e.g. 1 in 2000 Annual Exceedance Probability). However, interpreting extreme rainfall data in terms of flood risk are not necessarily straightforward, as a location's susceptibility to flooding is also linked to catchment topography, antecedent soil moisture, land use, etc. Historical satellite-derived information on the location and frequency of flooding is available from the annual inundation dataset (ANU, 2018).

In general, data quality across this theme is fair, but some regions can suffer from gaps or uncertainties due to a lack of monitoring data. Data access can be a constraint for BOM's engineering design rainfall datasets which are provided by region-of-interest and need to be stitched together to produce a national map.

3.4. Water resources

Water is a theme relevant to mining and exploration in several important ways. Mineral processing and other site activities require large volumes of water and mining developments in some locations are constrained by scarce water resources. In other locations, orebodies intersect productive aquifers and mine pits require dewatering, treatment, or disposal of large volumes of water, which can affect the feasibility of mining. In Australia, governance of water resources (consumption and discharge) is controlled by State and Territory governments, who set limits on total extraction and define the rights of water users. While some surface and ground water systems have unassigned water available for new developments, others are fully allocated, and new users must obtain water entitlement through the local water market. Companies can access relevant information through the BOM's Water Market Dashboard (BOM, 2024), although this information is not readily available as a national map. Spatial data on water supply schemes (management areas for surface water) in particular, are missing as a national map product. Groundwater management area maps are available via the BOM (BOM, 2023a) and provide relevant information on groundwater resources including the total market volume and the percentage of unassigned water, which help predict potential availability constraints and conflicts between users. GA's Groundwater aquifer map (Geoscience Australia, 2023) ranks main aquifers according to their productivity and provides a national overview of Australia's hydrogeological units.

The viability of resource extraction also depends on the feasibility of diverting or mining underneath a surface water body. Such proposals can generate significant community scrutiny and require regulatory approval. Geoscience Australia's (GA) high-resolution surface water feature maps (Crossman and Li, 2015a, b) and water observations from space (Mueller et al., 2016) allow assessing these potential challenges and anticipate where diversion might be required. Finally, land disturbance caused by mining activities can lead to increased stormwater runoff, erosion, export of sediments, and degraded water quality (McIntyre et al., 2016) generating impacts on the environment. In Australia, regulatory frameworks impose strict conditions on the containment and controlled release of mine-affected water, and compliance costs will impact on a project's feasibility. Erosion datasets produced by CSIRO (Viscarra Rossel et al., 2016) are relevant to evaluate the conditions that can influence the magnitude of soil loss. However, erosion risk is largely dictated by changes to topography induced by mining activities, and erosion datasets are only relevant to understand the erosive power of rainfall and intrinsic soil properties that are beyond the mine's control. BOM's Australian Groundwater Insight provides a national map of groundwater salinity (BOM, 2019a) which is a key consideration for water quality for use in mineral processing or disposal to stream when the mine is in surplus.

3.5. Nature conservation

Mining and exploration activities creates a variety and varying scales of impacts on the environment including biodiversity loss and habitat destruction. The Australian Government's Department of Climate Change, Energy, the Environment and Water (DCCEEW) hosts a data portal with several high-resolution and regularly updated spatial datasets relevant to nature conservation. These include spatial distributions of threatened species and ecological communities (DCCEEW, 2020, 2023a, c), locations of protected areas (DCCEEW 2023c), as well as world heritage and national heritage areas (DCCEEW, 2023d, f). These datasets show facets of biodiversity regulated by current national environmental legislation. They have a range of implications for mining developers, from monitoring and surveying costs, additional works in environmental impacts assessments, to permitting delays and potentially project cancellation. These datasets, however, represent only a small part of the nature conservation picture for Australia.

Other facets of biodiversity are not regulated and many currently do not have national scale datasets to represent them. These facets are important for conservation efforts and considerations around the risks mining can pose to nature conservation. They include, but are not limited to, biodiversity hotspots, habitat corridors, landscape connectivity, ecosystem services, and ecosystem intactness or irreplaceability. Notable national-scale maps include groundwater-dependent ecosystems maps provided by BOM (2019b) and the Ramsar wetland list (DCCEEW, 2023g) which identify sensitive receptors that are most vulnerable to withdrawal or contamination of water resources, however these maps are incomplete (see Appendix A for details). A landscape connectivity model could be assembled to understand how a piece of land dedicated to exploration or mining contributes to landscape fragmentation within a specific regional setting. The National Vegetation Information System extant vegetation map produced by DCCEEW (2023b) could be used as a first pass to understand natural habitat distribution.

Overall, a diversity of data is available for this theme, however many datasets are sub-national, and would require consolidation into a national map. Another limitation is that ‘no data’ areas on a map do not necessarily signify an absence of threatened species (for instance) and the resulting uncertainty of whether or not a species does occur can also be considered a risk to mining development (Irvine-Broque and Dempsey 2023). The various facets of biodiversity would benefit from being integrated into one meaningful layer that addresses a particular conservation challenge.

3.6. Governance

Governance is an overarching theme that connects with all previous themes and greatly influences mining and exploration practices and outcomes. Governance of mineral resources in Australia primarily happens at the State and Territory level, which have the power to grant mineral rights and are responsible for developing, implementing, and enforcing mining legislation within their jurisdiction. States and Territories have their own environmental and social impact assessment requirements, and varying processes for local stakeholders to voice concerns or objections. Royalties are also decided at the State and Territory level. Relevant governance measures for ESG mapping therefore require ranking States and Territory in terms of the quality of their mining regulations and the strength of social and environmental safeguards. Unfortunately, only one such measure was found, the Policy Perception Index (PPI), which is a global dataset developed by the Fraser Institute and based on mining company surveys (Yunis and Aliakbari, 2022). PPI scores are based on perceptions of professionals about the attractiveness of a jurisdiction for mining investments, and they only provide a narrow view on governance. The Resource Governance Index (NRGI, 2021) provides a broader view but only assesses Western Australia. Other measures may be found dispersed across various academic publications. Sinclair and Coe (2024), for instance, compared Australia’s mainland States and Territory in terms of their critical mineral strategies. This comparison however does not allow for a straightforward ranking of jurisdictions.

Local governance could be inferred from an LGA’s population count (dataset from ABS, 2022) with low population counts associated with limited local governance capacity (Burton et al., 2024a). For mining developers and regulators, this constitutes an opportunity to draw services, infrastructure, and economic activity to an otherwise under-serviced area. Strong multi-stakeholder governance mechanisms such as those in Central Queensland, Hunter Valley and Pilbara mining regions are important local governance aspects, although not available as spatial data. Legal agreements between mining companies, Native Title holders and State governments are equally important local governance instruments. These agreements determine the responsibilities of each party, such as companies providing local jobs or services, or governments building and maintaining shared infrastructure. While some of these agreements can be geolocated (NNTT, 2024), their content, and the details of their implementation, are typically not publicly available.

3.7. Main findings from the review

This review identified a broad range of spatial ESG datasets available to provide relevant information about the geographic context around mining and exploration in Australia. Gaps were noted throughout, ranging in sizes, from major gaps in measures of governance, to smaller gaps on surface water availability and some measures of biodiversity. People and land data suffer from other intangible gaps because of their qualitative nature that does not lend itself easily to spatial observation or quantification. Data access issues were also noted, e.g., rainfall data, although most datasets are publicly available. Accuracy issues are another challenge, and data quality limits usability to some extent. Accuracy of national scale data is a consistent challenge that is not specific to Australia, and such data typically should not be used directly to make local decisions, such as proceeding or not with a project in a specific location. This has been noted in Section 2 where we discuss limits to scope for large-scale mapping studies (e.g. not suitable for ESIA). Local decisions should be supported by ground truthing and data validation.

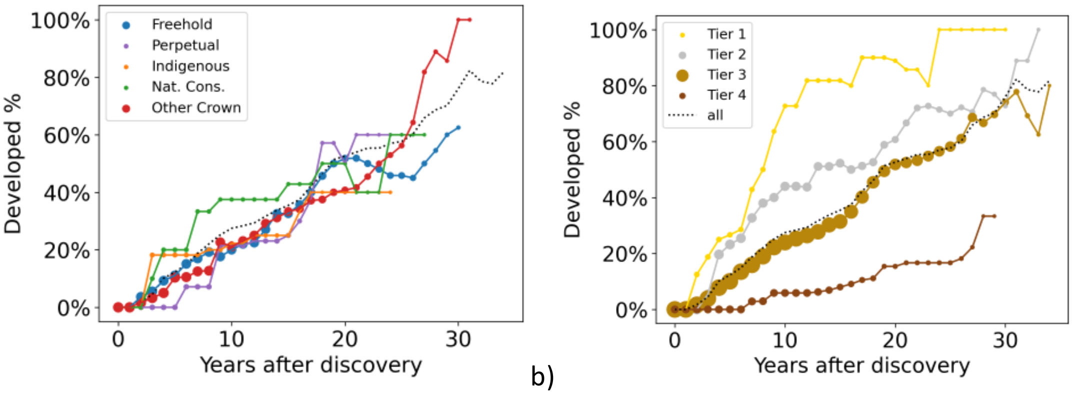
This review also identified further work needed around data interpretation. Spatial ESG datasets are not designed specifically for the mining sector, and their meaning and implications for developers and other stakeholders are often not straightforward. The ABS provides clear guidance on how politicians, private sector, and researchers may want to use the Index of Relative Socio-economic Disadvantage (see ABS, 2013). Similar guidelines could be developed on how the IRSD and other datasets can be applied in a mining context. Providing guidance on ESG mapping includes clarifying what spatial data can and cannot show. Further analysis of the data and how it intersects with exploration and mining datasets will contribute to developing such guidance. In the next section, we provide such analysis for the land tenure dataset and test its overlap with mining development delays. This is to test the dataset’s implications in terms of future “risk to project” (inbound risk).

Finally, because of the great diversity and nature of spatial ESG data for Australia, there are inherent difficulties in translating this breadth of data into clear messages that would ultimately support decision making. Aggregation and consolidation of datasets is likely to be needed, both within themes and across themes, i.e. combining social, environmental and governance datasets together to answer specific questions or test a hypothesis. Burton et al. (2024c) is an example of such consolidation work on Indigenous peoples land, which reconciles some of the definitional differences across Australian States and Territory. The benefits and challenges of aggregation are explored further in Section 5.

4. Analysing one ESG dataset and its intersection with a mining dataset

In our review of existing ESG datasets for Australia, the land tenure dataset (ABARES, 2021b) was highlighted as one that has embedded legal implications for the mining sector regarding land access. In particular, the freehold land title implies exclusive proprietary rights (Burton et al., 2024b), which can potentially be exercised against mining acquisition. In this section, we test whether land tenure as defined in the ABARES dataset has had any apparent effect on past mining development and draw implications for future developments. To do so, we overlay the land tenure dataset with 289 geolocated records of mining project delays (Ewers et al., 2002), and assess whether there is any statistical correlation between a specific land tenure type and delay length. For added perspective, we compare the results with a parallel analysis examining the correlation between deposit quality (tier) and delay length. See Appendix B for analyses of other datasets.

Figure 3a compares subsets of mining projects falling in a particular land tenure type, and Figure 3b compares the same projects but this time organised by deposit quality (with tier 1 having the highest economic potential). Subsets whose curve sits above the black dashed line (representing the trend across all 289 projects) have shorter delays than average, while subsets sitting below the line are progressing slower. The size of each point is proportional to the number of projects having the same deposit discovery year and falling under the same tenure or tier category (years with fewer than five deposits were excluded from the analysis).



a) b)

Figure 3*: Results of spatial overlay for mining project development times. Fraction developed since discovery by a) land tenure type; b) deposit quality by Tier. The Tier definition follows that of MinEx Consulting where Tier 1 deposits are 'company making' large, long life and low cost with a net present-day value (NPV) of >$1000 m USD, Tier 2 are 'significant' with NPV of $200-1000 m USD, Tier 3 are small marginal deposits with NPV of $0-$200 m USD, Tier 4 are of minimal value. Nat. Cons.: nature conservation reserves.*

From this analysis, we find little evidence that land tenure contributes to systemic delays. The development curves in Figure 3a were compared using a chi-squared test. At a family-wise significance level of α=0.05, there is no clear difference between the curves for the different land tenure types in Figure 3a. Freehold land does not show any statistically significant difference from other land tenure types. Instead, economic considerations (the deposit's tier, Figure 3b) have a stronger correlation. For the same family-wise significance level (α=0.05), the chi-squared test indicates that the different tiers have distinct patterns of development, with Tier 1 deposits developing faster than the other tiers and Tier 4 deposits developing at a slower rate.

Land tenure may affect development in other ways than by delaying projects. For instance, it could have an effect on exploration by constraining land access, which would result in reduced deposit discovery rates. Strongest forms of land tenure (e.g. freehold) could also lead to some projects being permanently stalled, rather than delayed. In Appendix B, we provide a preliminary analysis that overlays land tenure types (and other ESG datasets) with exploration tenements and stalled projects (undeveloped deposits). Freehold non-Indigenous land and nature conversation reserves host a larger proportion of stalled projects. Lower levels of exploration activity are registered on freehold Indigenous land, potentially explaining why mining activities appear to be less frequent under this type of land tenure. This indicates that land tenure may play different roles at different stages of mining developments and stresses the importance of considering these different stages when undertaking ESG mapping more broadly. A more in-depth analysis would be needed to understand these multiple influences and confirm their statistical significance.

Overall, the influence of economic factors on past development appears to be stronger than the influence of land tenure. This is not a surprising finding, and economic factors are known to be key determinants while land tenure is merely one spatial ESG factor among others. However, it is possible that spatial ESG factors have more influence cumulatively than individually. Valenta et al. (2019) hypothesized that ESG factors co-existing in the same location create ‘complexity’ for developers by interacting with and reinforcing each other. Future research in this space should 1) select ESG dataset candidates that potentially represent risks to development and perform individual analyses for these datasets, and 2) perform analyses for various combinations of these datasets. Another possibility is that land tenure and other land ownership factors constrain development in ways that are not comprehensible only through spatial observation. The full picture on understanding what constrains mining development is likely made of a mix of interconnected spatial and non-spatial factors. ESG mapping only captures some pre-existing geographic conditions and does not capture performance and practices that also influence outcomes.

This example stresses the need for prior analysis before interpreting any spatial dataset as a measure of risk or other proxy. Interpretation of what different spatial datasets mean in the Australian mining context is a key step in mobilising these datasets to inform decision makers. Furthermore, the land tenure example shows the relevance of investigating other dimensions than risk to business. Mixed findings around freehold land tenure pose the question of risk to landowners and developers.

5. Aggregating ESG datasets into a composite measure to support decision making

Given the richness and heterogeneity of spatial ESG data available for Australia, aggregation is likely to be a necessary step to generate condensed and digestible information for mining stakeholders. Aggregation of multiple datasets into composite measures supports decision making by summarising complex multi-dimensional realities. In this section, we provide four main steps to follow when undertaking aggregation of spatial ESG datasets, drawing on OECD guidelines (Nardo et al., 2008). We use the example of context vulnerability to illustrate these different steps (preliminary results from this example in Appendix C).

5.1. Aggregate around a specific problem

While a composite measure is easier to handle than a series of separate datasets, its meaning can be dubious. Aggregation takes the user away from the original meaning and intended purpose of individual datasets and, to be effective, it must generate a new meaning and purpose. The new composite measure needs to demonstrate fitness for its intended use. Therefore, when handling heterogenous ESG data, it is advised to first articulate a clear question or problem with which to interrogate the data, and then carefully select datasets (5.2) and an aggregation method (5.3) with the view of answering that question.

Drawing on previous ESG mapping work (Kemp et al., 2021; Owen et al., 2021), we use the example of context vulnerability, namely the sensitivity and adaptive capacity of the local context as it experiences mining-induced changes (Turner et al., 2003). Vulnerability is a component of outbound risk to people and environment as described in Section 2. Taking a vulnerability perspective recognises that mining activities sometimes generate hazards, and certain local factors can contribute to exacerbating the resulting social or environmental impacts. In this example, the questions that set the direction for the aggregation exercise are: should mining development occur, what are the local factors of vulnerability to consider to ensure effective mitigation of negative impacts and enhancement of positive outcomes? And where are the most vulnerable areas in Australia, according to these factors?

5.2. Dataset selection

Taking the vulnerability example, several of the datasets listed in Figure 2 can be used as measures of vulnerability. The presence of threatened species (DCCEEW, 2020, 2023a, 2023c) and water-dependent ecosystems (BOM, 2019) are suitable indicators for environmental vulnerability, as they signal a sensitivity of the natural environment to mining-induced pollution and degrading water quality. Remoteness (ABS, 2022) and the Index of Relative Socio-economic Disadvantage (IRSD) (ABS, 2021a) are two measures of social and economic vulnerability (Constantin et al., 2015). Erosivity and erodibility (Viscarra Rossel et al., 2016) are physical vulnerability factors that, when interacting with mining activities (notably excavation and waste storage), may exacerbate soil and water contamination. Mining activities' high water consumption may further stress already scarce resources, thus low water entitlement volumes (BOM, 2023b) could be used as a proxy for groundwater resource scarcity and constitute another measure of vulnerability. Surface water features (Crossman and Li, 2015a, 2015b) or productive aquifers (Geoscience Australia, 2023) can also be considered as vulnerability factors, as their presence exacerbates the risk to water quality.

In selecting datasets to build an aggregated picture of vulnerability, there is a risk of leaving out important dimensions either because they are not measurable spatially, or because data is not available. It is important to acknowledge any relevant information missing from a composite measure and ensure that recommendations based on the measure include this information in other ways. In the vulnerability example, a missing dimension is a dataset that captures social and cultural vulnerabilities associated with Indigenous Peoples, who have strong ties to the land and are thus sensitive to mining-induced changes of that land. Burton et al.'s Indigenous people land layer (2024c) could potentially be used for that purpose but would require ranking the different land categories (see 3.2) in terms of relative vulnerability, which is not straightforward. On the one hand, co-existing rights and native title claims yet to be determined by the court (categories 2 and 3) can be seen as more vulnerable as they have lower legal protection. Furthermore, exclusive land rights (category 1) may capture areas that have historically been the most intact and therefore are most vulnerable to land degradation induced by mining.

Ranking and weighting, i.e. assigning relative value or preference to a 'variable' (here an ESG dataset, or categories within a dataset) are key features of aggregation methods. The Indigenous peoples land example shows how these features can be susceptible to subjectivity and arbitrariness. Aggregation exercises therefore should start with defining objectives and end users and undertaking multi-stakeholder engagement (Nardo et al., 2008) across all four steps summarised in this section. One key is to ensure maximum transparency around the choices of both methods and underlying data, which happens at the results visualisation step (5.4).

5.3. Choice of aggregation method

There are multiple means of data aggregation with varying benefits. Here we present Pareto ranking, a multicriteria optimisation method designed to balance multiple potentially conflicting criteria and diverse stakeholder priorities. Thus it is well-suited for ESG mapping. For example, Walsh et al. (2024)

demonstrated how Pareto rankings could be used in early-stage exploration in Australia to identify regions that perform best under competing measures (economic value, mineral potential, and water resources). Compared to other aggregation methods (Wierzbicki, 1982; Brown, 1990) that focus on identifying single solution and typically blind to other high-ranking alternatives, Pareto rankings also identify nearby alternative solutions that may better match stakeholder preferences.

In applying the Pareto ranking method to the vulnerability example, however, we faced an issue as the method identifies ‘best’ options, i.e. least vulnerable areas. The Pareto optimisation would result in identification of least vulnerable areas according to most variables, but these areas could still exhibit high vulnerability across a few variables that would be at risk of being hidden by aggregation. Hence, instead a ‘reverse’ Pareto ranking can be applied to aggregate the datasets and identify most vulnerable areas, which has less consequential trade-offs (i.e. areas identified as most vulnerable could exhibit a few low-vulnerability features).

5.4. Visualisation of results

While aggregation into a spatial composite measure allows comparing locations or projects effectively, it can draw decision makers to simplistic conclusions. Providing a disaggregated visualisation of results alongside the aggregated score, such as the spider chart in Figure 4b next to the aggregated heat map in Figure 4a, helps observe variations across individual components and identify potential trade-offs. It also reminds the user of dimensions captured (and those not captured) by the composite measure and ensures transparency. Noting that in the vulnerability example, socio-economic disadvantage is already a composite measure (aggregating 15 variables), and a disaggregated visualisation of the IRSD index may be warranted for further analysis focused on social and economic vulnerability.

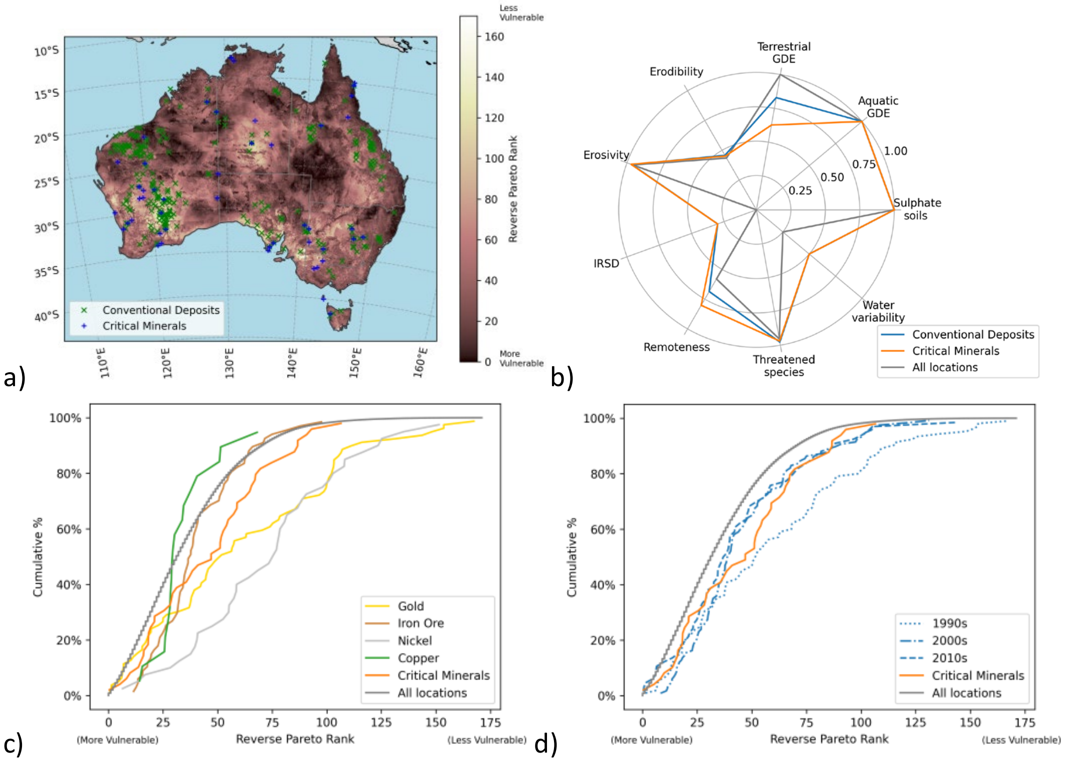


***Figure 4**: Comparison of locational ESG vulnerability: a) reverse Pareto ranking of all points across Australia with locations of conventional and critical mineral deposits; and b) spider chart with*

normalized median scores for each ESG dataset. Cumulative distribution plots show the reverse pareto rankings for c) projects based on the primary metal and e) the decade of discovery (deposits after Ewers et al., 2002).

Figures 4c and 4d allow comparing cohorts of mining projects between themselves and against the national average (grey line). Figure 4c classifies projects according to their primary commodity, while Figure 4d classifies projects according to the deposit discovery year. This shows how the Pareto Ranking approach can mobilise different project attributes for comparison. In Figure 4c, nickel and gold projects appear to be in less vulnerable areas than the other cohorts. Critical Minerals projects from the 2024 Australian Critical Minerals Prospectus (ATIC, 2024) are the next best performing cohort and show lower vulnerability levels than would be expected from a purely random sample of locations within Australia.

6. Path forward and recommendations

This paper's objective is to set the foundations for gathering and utilising spatial ESG data to support decision making around future mining developments in Australia. We aimed to lay out a path forward and make recommendations for future work. After presenting the ESG mapping approach and what it has to offer (Section 2), we critically examined a diversity of spatial datasets that can be mobilised to better understand the ESG context around mining locations in Australia (Section 3). The identified datasets are a representative list of best available and ready-to-use datasets covering six key dimensions of relevance to mining and exploration. Section 3 examines opportunities in mobilising these datasets as well as gaps and data limitations. It captures some of the rich discussions held with subject matter experts and summarises the collective knowledge base.

In Section 4, we analysed an ESG dataset (land tenure) and how it overlaps a dataset of mine development delays. In doing so, we tested a hypothesis that specific types of land rights act as constraints to development, i.e. generating risk to business. Evidence of such influence would be of interest to the industry, government and communities. We found mixed evidence of land tenure influencing development outcomes, and this example shows the importance of verifying assumptions about the implications a particular spatial ESG factor may have on mining development. The analysis also pointed to the need to explore potential influences at different stages of the mine life cycle, from exploration and permitting, to operation and closure.

In Section 5, we discussed the benefits and risks of aggregation in ESG mapping and defined key steps to follow while undertaking such analysis, using context vulnerability as an example. We demonstrate a method through which spatial ESG data can be aggregated to answer questions about pre-existing conditions that developers should be mindful of when considering a location to invest in.

Based on this work, our recommendations are fourfold. First, further work is needed on interpretating available spatial data and drawing implications for different mining stakeholders. Analysis expanding on Section 4 will need to verify historical influences of certain factors, both individually and as a group (observing potential cumulative effects). Figure 4d also shows the possibility of tracking trends over time, which would have value to connect past conditions with current and future challenges. To consolidate the foundations for ESG mapping, we recommend deep technical dives into key themes (e.g. water, biodiversity, people) as well as cross-disciplinary work to test combinations of datasets across themes.

Secondly, the development of use cases and concrete ESG mapping applications requires stakeholder engagement. In section 5, we saw that a preliminary step of aggregation is to identify end users and involve them along the process, from agreeing on the question or problem and defining the objectives of aggregation, to selecting ESG measures and choosing the aggregation strategy. This involvement helps reduce subjectivity and maximise public acceptability. Stakeholder engagement will likely result in a diversity of use cases that go beyond the risk-to-business question. While this question is of high interest to industry, there are other ways to interrogate the data, as we show in section 5, and ESG mapping has value that extends beyond risk and industry-centric perspectives.

Thirdly, ESG mapping is a decision-support tool, but the difficult task of making decisions remains with the user. For instance, ESG mapping helps identify vulnerable communities in areas subject to mining development, but it does not prescribe solutions to address these issues. This broad recommendation reflects the capabilities and limitations of ESG mapping: 1) ESG mapping provides spatial information, but real-life decisions must incorporate both spatial and non-spatial information. 2) ESG mapping is suited for large-scale analyses comparing multiple exploration or mining locations, but any insights generated at national scale need to be verified with local data when focusing on a specific location.

Finally, to fully make use of the rich spatial data available for Australia, future work could aim to simplify data accessibility, e.g. by creating a single data portal, and usability, notably by publishing guidelines and case examples on how data might be used. Such work could eventually become a public resource for all mining stakeholders. Examples like those shown in Sections 4 and 5 can help construct or underpin narratives for lay or literate audiences, facilitate communication, capture interest, and raise awareness. As Australia scales up its mining sector to position itself as a key supplier of energy transition minerals, decision makers will need to be diligent about factors that influence developmental outcomes as well as social and environmental outcomes. ESG mapping can contribute to a pool of knowledge available upstream of decision making, with the goal to mitigate risks and enhance opportunities for all mining stakeholders.

7. Conclusion

ESG data use at different stages of decision making has become common practice across all economic sectors. Deloitte estimate that 83% of investors incorporate ESG data into fundamental analysis (Deloitte, 2024). The Australian mining sector is no exception to this trend, as shown by the recent revision of the Australasian Joint Ore Reserves Committee's (JORC) code, which recognises that ESG factors play a role in a deposit's economic viability, and requires these factors be reported at different stages of resource development (JORC, 2024). However, ESG as a concept has recently become increasingly contentious and politicised (Edmans, 2023). On the one hand, opponents to the concept are asking for a blanket rejection of ESG data use in business and investment decision making. Advocates, on the other hand, sometimes go too far in their use of ESG data by 1) over-relying on poor quality data, 2) applying the concept as an aggregated single measure without a clear understanding of its subcomponents, and 3) assuming causal relationships (e.g. that better ESG performance leads to better financial performance) when there sometimes is no evidence to support it. These may be teething issues, as the broad-scale application of ESG data in decision making remains relatively recent, with most of the growth witnessed in the past five years (Deloitte, 2024). Nevertheless, in this context, it is ever more critical to use ESG data, including spatial data, cautiously and rigorously.

In this paper, we set the foundations for good practice in the use of spatial ESG data, focusing on the Australian mining sector. Our paper reviews available national-scale datasets, considering gaps and limitations, and lays out a path forward for using this type of data in decision making. It highlights the need to verify assumptions when interpreting a particular ESG factor and lists the risks and opportunities of aggregating data into composite measures. Further work is required, notably deep dives into key ESG themes, and cross-disciplinary work looking at connections between themes. We recommend the engagement of stakeholders in future work and stress the importance of transparency to ensure public acceptability.

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Appendix A: List of available ESG datasets for Australia

Category	Subcategory	Indicator	Dataset name/s	Source	Usage notes and limitations
Extreme events	Earthquakes	Peak Ground Acceleration	10% in 50 year seismic hazard map	Allen et al., 2024	
	Cyclones	Cyclone Intensity and Frequency	Australian Region Cyclone Intensity and Frequency Index - CAMRIS	CSIRO, 2015	
	Rainfall	High rainfall	Rainfall percentile maps (monthly to annual)	BOM, 2024	Data not readily accessible- needs to be downloaded across multiple regions and manually stitched together.
			IFD (intensity-frequency-duration) information for very frequent to rare design rainfalls	BOM, 2024	
		Inundation	Inundation (annual maximum)	ANU, 2018	Raw data available annually (2000 to present) needs to be aggregated to a representative long-term value.
	Temperature	No. Hot days >35°C per year	Hot Days	ANU, 2018	
	Fire	Bushfire risk	Fuel load and bushfire risk Index	Donohue, 2021	Data currently not available for download. Updated fire risk dataset in progress by CSIRO.
Water resources	Surface water	Surface water features	National Surface Water Information	Crossman and Li, 2015	Stream order not available.
		Surface water observations	Water observations from space	Mueller et al., 2016	
	Erosion & water quality	R-factor (rainfall erosivity)	Maps of Australian soil loss by water erosion derived using the RUSLE	Viscarra Rossel, 2016	Pre-existing conditions only, does not measure erosion risk of mined material.
		K-factor (soil erodibility)			
	Groundwater	Unassigned groundwater (percent average)	Groundwater management areas (GMA)	BOM, 2023	
		Entitlement on issue (volume of water)	Groundwater management areas (GMA)	BOM, 2023	
		Groundwater average salinity	Australian Groundwater Insight	BOM, 2019a	
		Aquifer productivity	Groundwater aquifers	Geoscience Australia, 2023	

Nature conservation	Biodiversity values	Threatened species richness, number of threatened communities	Species and Communities of National Environmental Significance (Species Richness)	DCCEEW, 2020	Areas with no data do not indicate an absence of threatened biodiversity.
		Threatened species habitats	Species of National Environmental Significance Distributions	DCCEEW, 2023c	
		Threatened Ecological Communities	Ecological Communities of National Environmental Significance Distributions	DCCEEW, 2023a	
		Ramsar wetlands	Ramsar Wetlands of Australia	DCCEEW, 2023g	Only captures wetlands of international importance.
		Land cover	Australia - Present Major Vegetation Subgroups - NVIS Version 6.0 (Albers 100m analysis product)	DCEEW, 2023b	Data discrepancies across state borders.
		Groundwater Dependent Ecosystems	Groundwater Dependent Ecosystems – Aquatic and Terrestrial (two datasets)	BOM, 2019b	Areas with no data haven't been surveyed. Varying levels of accuracy due to different survey methods.
	Protected areas	Protected area boundaries	Collaborative Australian Protected Areas Database (CAPAD) 2022 – Terrestrial, Indigenous Protected Areas (IPA)	DCCEEW, 2023e	
		World Heritage	Australia World Heritage Areas	DCCEEW, 2023d	
		National Heritage	National Heritage Areas	DCCEEW, 2023f	
People	Socio-economic disadvantage	Socio-economic disadvantage	Index of Relative Socio-economic Disadvantage (IRSD)	ABS, 2021a	Recommend disaggregating to assess index' individual components. Recommend using LGA level (rather than Statistical Area 1) data to connect remote areas with nearest mining hubs (see Burton et al., 2024a). Depending on usage, spatial and temporal resolution (updated every 5 years) can be a limitation.
	Income	Populations access to economic resources	Index of Economic Resources (IEO)		
	Employment	Proportion of people with high qualifications and/or highly skilled jobs	Index of Education and Occupation (IEO)		

	Demography	Population density	Australian population grid 2022	ABS, 2022	
			Urban Centres and Localities		
Land use and land ownership	Land ownership	Land tenure	Land tenure of Australia 2010–11 to 2015–16	ABARES, 2021b	Outdated.
		Indigenous peoples	Indigenous peoples' land rights	Burton et al. (2024b)	Provide download instructions and code to assemble maps from different sources.
		Native Title	National Native Title Tribunal Data (Native Title Claims and Determinations, Indigenous Land Use Agreements, Future acts)	NNTT, 2024	Areas with no data do not indicate an absence of Indigenous interests in the land.
	Land use	Human land use	Catchment scale land use of Australia – Update December 2020	ABARES, 2021a	
Governance	Local government	Local Government population	Population estimates by Local Government Area 2022	ABS, 2022	
	State government	Policies	Policy Perceptions Index (Fraser Institute)	Yunis and Aliakbari, 2022	

Appendix B: Analysis of ESG datasets and how they intersect with exploration and mining datasets

This appendix presents a preliminary analysis of five ESG datasets that have potential embedded legal implications regarding land access and permitting and that span across the three ESG pillars: the land tenure dataset (ABARES, 2021b) for 'S', three protected area datasets (DCCEEW, 2023d, e, f) for 'E', and the Policy Perception Index (Yunis and Aliakbari, 2022) for state-level governance ('G').

We overlay these five datasets with three mining datasets: a consolidated national map of exploration tenements (Supplementary Figure S1a), 192 undeveloped deposits with demonstrated economic resources (Figure S1b), and 289 records of mining project delays (Figure S1c). The undeveloped deposits and project delays datasets exhibit two types of development constraints that may have distinct sets of causes. With exploration tenements, we are interested in testing whether their spatial distribution tends to prefer or avoid certain types of land, or certain jurisdictions. In addition to these three datasets, we reviewed records of 80 projects in care and maintenance (Figure S1d) from the S&P Global database (2024) and checked for any disclosed causes of care and maintenance. This last step does not mobilise spatial ESG datasets and was meant to use another type of data (corporate disclosures) to check for overall influence of ESG factors (as opposed to only spatial ESG factors) in project constraints. Together, these four mining datasets represent different types of constraints that may occur at different phases of the mine life cycle – exploration, study (scoping, pre-feasibility, or feasibility), and operational phase.

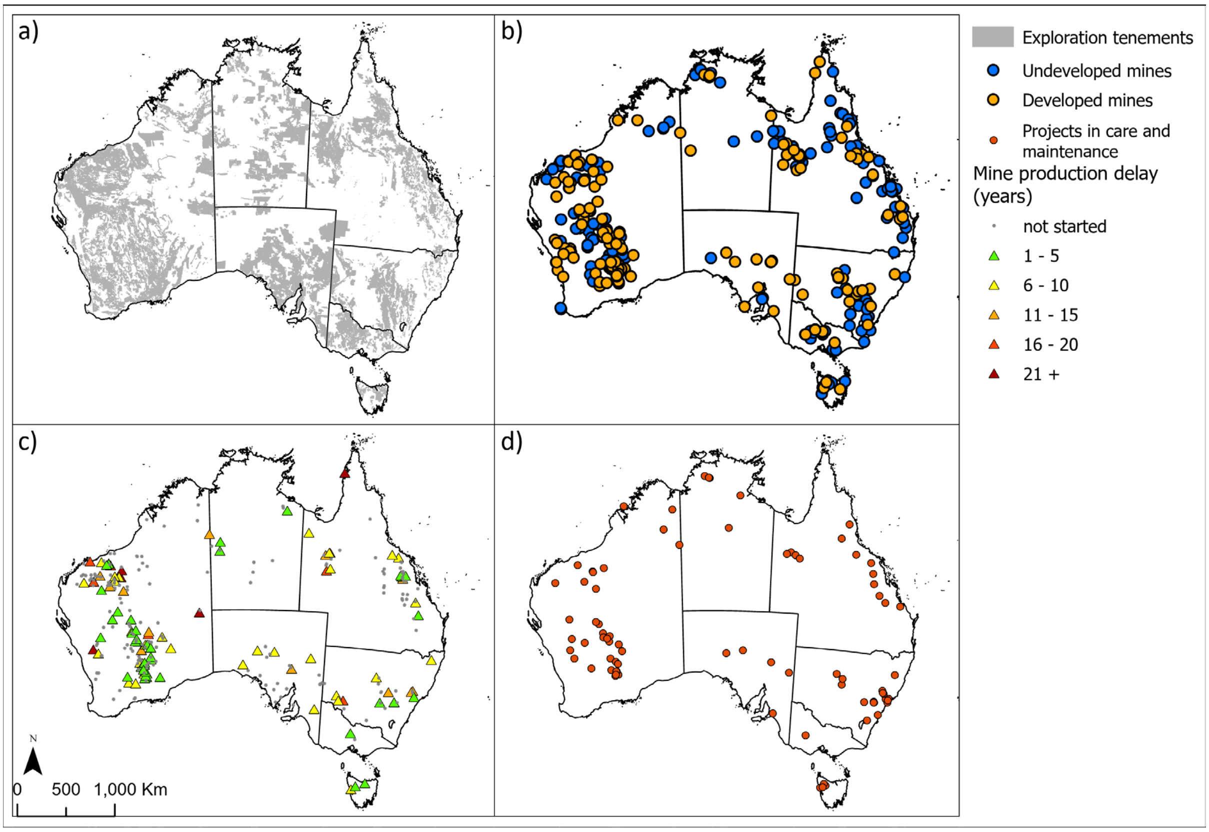


***Figure S1**: Mining datasets for Australia. a) exploration tenements (DEM, 2020; Department of Regional NSW, 2023; DER, 2023; DJSIR, 2024; DMIRS, 2023; GSNSW, 2023; MRT, 2023; STRIKE, 2023), b) undeveloped deposits and developed mines (Geoscience Australia OZ MIN Mineral Deposits Database, Ewers et al., 2002), c) project delays (Ewers et al., 2002) and d) projects in care and maintenance (S&P Global, 2024). Note: to enable comparison, undeveloped deposits were analysed side by side with developed mines.*

Figure S2 compares the frequency of delays among subsets of mining projects subject to particular ESG factors to be compared with the delays in all the mining projects (the dashed black line in each figure). Subsets above the black dashed line have shorter delays than the national average, while subsets below the line are progressing slower. The world and national heritage datasets do not appear in Figure S2d because the number of projects falling in these areas was too small to be analysed through this method.

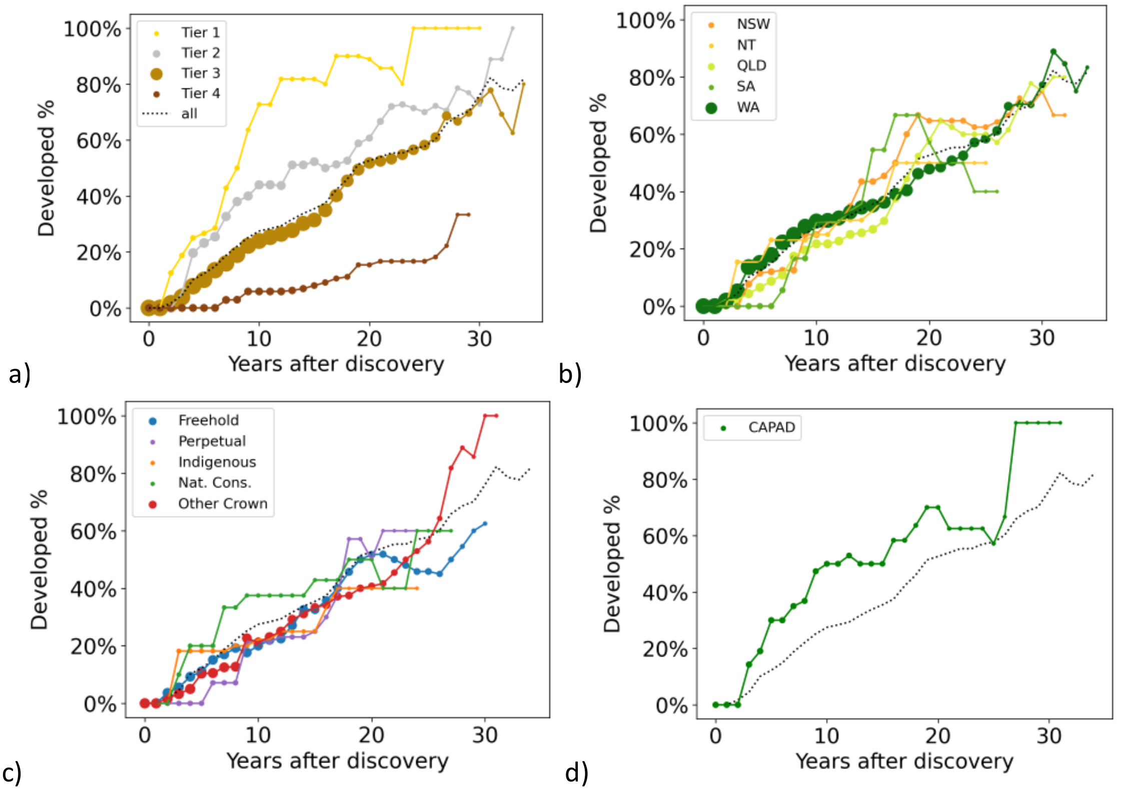
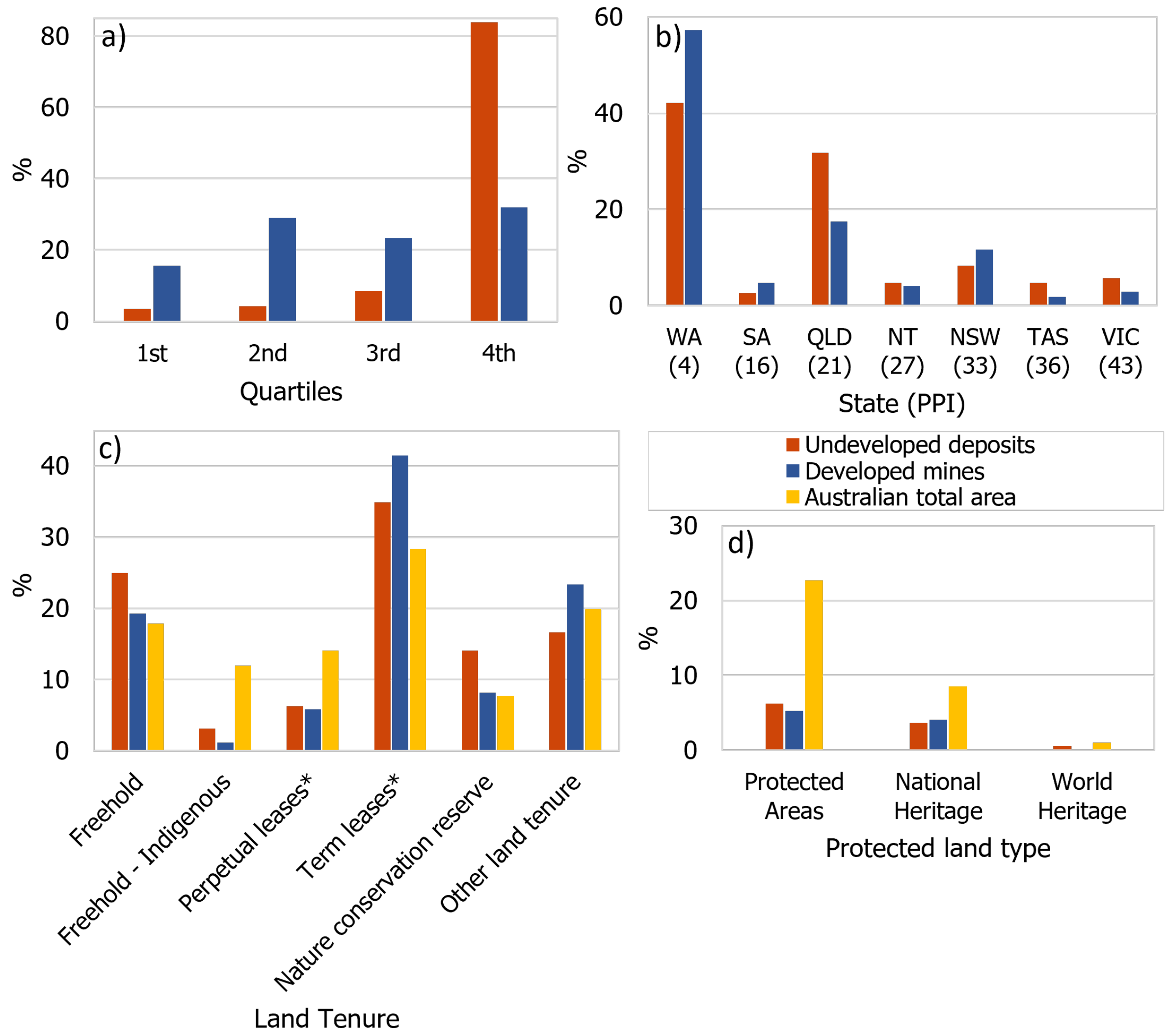


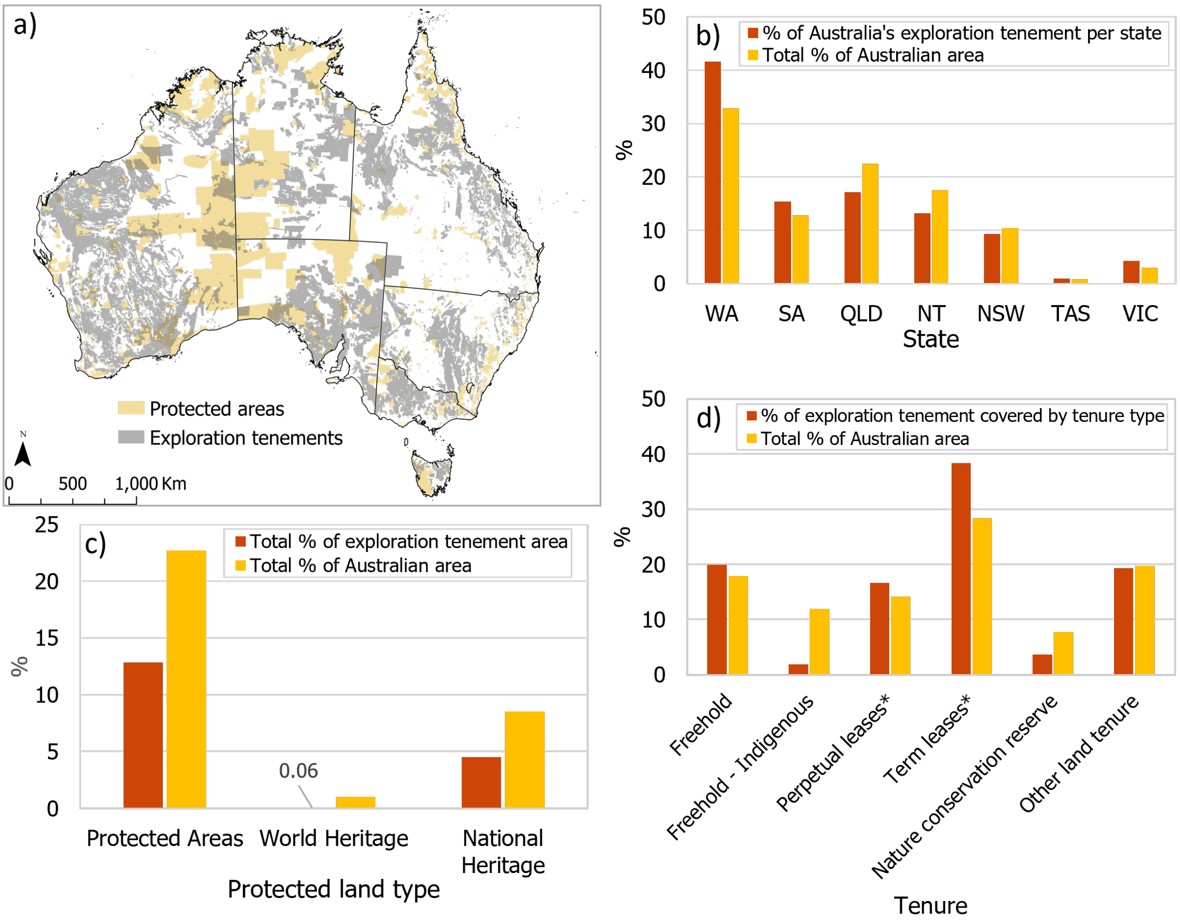
***Figure S2**: Results of spatial overlay for mining project development times. Fraction developed since discovery by a) deposit quality listed by Tier; b) State; c) tenure type; and d) protected areas (CAPAD). The size of each point is indicative of the number of deposits for each year in each category, years with fewer than five deposits were excluded from the analysis. Colours in Figure 5b correspond to PPI State ranks, Western Australia having the most favourable rank.*



^= Gold copper, nickel, iron and zinc reserves (S&P Global 2024). Australian reserves used, except for zinc (global) due to smaller sample size (n < 20) in Australia.

*Perpetual leases = Pastoral perpetual lease + other perpetual lease. Term leases = Pastoral term lease + other term lease.

Figure S3*: Results of spatial overlay for undeveloped deposits versus developed mines in Australia. Panel of 4 graphs. Histograms for a) deposit size by quartiles of reserves, b) state (ordered by decreasing PPI score, with global rank listed in brackets), c) tenure type and d) protected land type. Thresholds for reserves quartiles were calculated using Australian reserves (S&P Global, 2024) for the 5 most common commodities (Gold, Copper, Nickel, Iron and Zinc) across the undeveloped and developed datasets, except Zinc for which quartiles were calculated through global reserves (S&P Global, 2024) due to smaller sample size in Australia (n <20).*



*Perpetual leases = Pastoral perpetual lease + Other perpetual lease. Term leases = Pastoral term lease + Other term lease.

***Figure S4**: Results of spatial overlay for exploration tenements across Australia with a) showing avoidance of some exploration in protected areas. Histograms showing exploration in b) states (ordered by decreasing PPI score), c) protected land types and d) tenure type.*

The analysis of the four mining datasets returned contrasting results. For the project delays dataset, we find little evidence that particular ESG factors are attributable to significant systemic delays. Interestingly, the perceived quality of mining policies in a State (represented by the PPI, Figure S2b) plays no discernible role in project delays. Instead, economic considerations (the deposit's tier, Figure S2a) appear to have a much larger impact. This is in keeping with patterns of delay observed in global datasets (Schodde, 2017). Similar observations can be made for the undeveloped deposits dataset (Figure S3), where potential trends are harder to observe compared to the clear influence of deposit size (Figure S3a). Undeveloped deposits are small compared to developed mines, indicating that economic factors may have been the primary reason for halting development. Land tenure types and protected land types appear to have some effects, although they tend to affect undeveloped deposits and developed mines equally, except for freehold land and nature conversation reserves which host a larger proportion of undeveloped deposits. Somewhat clearer trends can be observed for exploration tenements (Figure S4), which tend to partly avoid protected areas and certain types of land tenure, namely freehold Indigenous land, and nature conservation reserves. Lower levels of exploration could partly explain why mining activities appear to be less frequent in freehold Indigenous land (Figure S3c) and protected areas (Figure S3d). The PPI does not seem to play any significant role in outcomes in Figures S3 and S4, except for a slight advantage in high PPI States, Western Australia and South Australia (there are fewer undeveloped deposits and larger areas for exploration claims in these two States).

The examination of corporate disclosures for projects in care and maintenance uncovered a range of ESG and economic causes. Data, however, is scant. Of the 80 project records examined, only 24 records contained relevant disclosures regarding factors contributing to their placement under care and maintenance. Economic factors, primarily falling currency exchange rates and metal prices, were listed as contributing factors for 17 of these projects. ESG factors were reported to be responsible for the care and maintenance status of 12 projects. Listed ESG factors (spatial and non-spatial) include flooding, pollution events, fatal accidents, worker strikes, and governance (permitting hurdles). ESG factors sometimes contribute alongside economic factors. Because of poor disclosure quality, we are unable to ascertain whether the listed issues are the sole contributors, and, when there is more than one issue listed, which is making the largest contribution. Overall, analysing these disclosures we found that ESG factors can be causes of care and maintenance, but most of these factors are non-spatial. This indicate that operational projects can face ESG constraints that are either internal (connected to operator’s own practices) or external (linked to contextual pre-existing factors).

Appendix C: Aggregation of ESG datasets into a composite measure – application to a case example

Supplementary Figure S5 shows an example of aggregating a selection of spatial datasets to explore the question of local context vulnerability. For this illustrative example, we analyse the 52 future projects listed in the 2024 Australian Critical Minerals Prospectus (ATIC, 2024) and compare them to the operational projects and undeveloped deposits from more conventional mineral systems (Ewers et al., 2002) in terms of their location in vulnerable contexts. The ATIC projects have been identified by the Australian Government as high-quality investment-ready projects "that have significant potential to address anticipated production shortfalls" (ATIC, 2024, p5). Given the increased emphasis on critical mineral production, and the novel geological context of some of these projects, it is worthwhile considering how their ESG context compare to more conventional mineral production.

In Figure S5a, we map the Reverse Pareto Rankings (RPR) across Australia for the nine datasets that are potential candidates to represent context vulnerability. In Figure S5c, we compare the distribution of the RPR for the conventional deposits and the critical mineral locations to the distribution for Australia as a whole. Notably, both sets of deposits show lower vulnerability levels than would be expected from a purely random sample of locations within Australia.

To better understand which factors contribute to the Pareto rankings, we calculate the median values for the three sets of point locations (conventional projects, critical mineral projects and the random set) and scale them according to

$$s = \frac{V_{med}^{*} - V_{worst}}{V_{best} - V_{worst}}$$

where V_{best} and V_{worst} correspond to value extremes for each ESG dataset, while V_{med}^{*} represents the median value for the individual cohort. As illustrated in Figure S5b, the median values for the conventional and critical mineral projects are better than or equal to the median values across all Australia in every dataset considered except for Terrestrial Groundwater-Dependent Ecosystems.

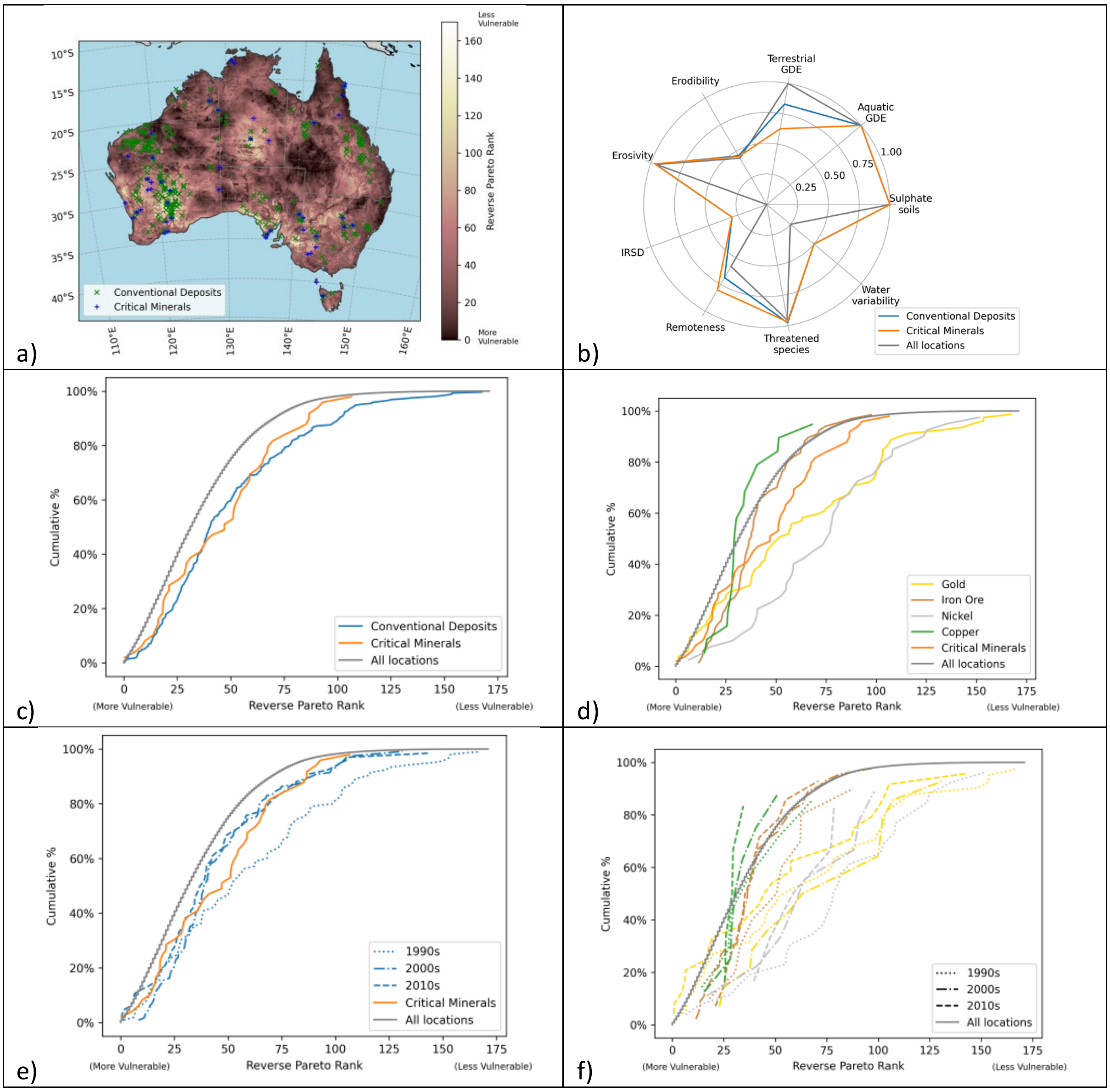


***Figure S5**: Comparison of locational ESG vulnerability: a) Reverse Pareto Ranking of all points across Australia highlighting conventional and critical mineral projects; and b) normalized median scores for each ESG dataset. The lower four cumulative distribution plots show the reverse pareto rankings for c) the historical and critical mineral projects; d) projects based on the primary metal; e) the decade of discovery; and f) primary metals and the decade of discovery combined. Cumulative distributions for all locations across Australia are included for comparison in each plot.*

In the Reverse Pareto Rankings (RPR) in Figures S5d, e, and f, deposit locations are organised by primary metal commodity and decade of discovery. Overall, Australian gold and nickel deposits and mines tend to occur in less vulnerable regions than copper and iron ore projects (Figure S5d). Figure S5e compares trends across all deposits discovered in different decades. The plot shows that the measures of ESG vulnerability are typically greater at the locations found in the 2000s and 2010s compared to those discovered in the 1990s. More recent discoveries also tend to be located in more vulnerable regions when considering individual minerals. This is most clearly demonstrated in Figure S5f which shows RPR by primary commodity and discovery decade. Overall, ESG vulnerability within each commodity tends to be greater at deposit locations discovered in the 2010s than those discovered in the 2000s, which are in turn at more vulnerable locations than those discovered in the 1990s. Conversely, Figure S5e shows the distribution of RPR for *all* mining projects, where little change between the 2000s and 2010s can be observed. This apparent contradiction between Figures S5e and S5f can be attributed to the change in demand for different commodities - with an increase in the proportion of iron ore and gold deposits, and a decrease in the proportion of nickel and copper deposits discovered over the same period.

We emphasize that these findings are limited to the ESG datasets selected for this analysis, and changes to the distributions reflect the overall performance of a cohort, rather than that of individual projects. Nevertheless, the analysis shows how such ESG datasets can serve as a means of tracking trends in the industry over time and across commodity type.