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Comparative capacity of global mining regions to transition to a post-mining future

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ABSTRACT

This paper focuses on the ability of regions where mining is concentrated to adapt to closure given the regional assets and the complexities of their association with declining production of various commodities. We propose a conceptual framework to examine the relative capacity of global regions to transition and prosper post-mining by analysing contextual factors and characterising the mining footprint in the regions. Public sources of geo-locatable data are used to define and locate mining regions in transition and to assess the interacting mining and contextual factors that enable or constrain their capacity to transition. The data-driven examination illuminates the comparative capacity of global regions confronting the challenge of mine closure. It engages with themes from regional studies, mine closure and transition studies to consider multidimensional aspects of regional transition.

1. Introduction

Changes in global commodity markets are reshaping the mining sector and are having profound societal consequences. Exploration investments are taking mineral exploitation to new regions. At the same time, mature mining regions – those hosting large, long-established mines in the USA, Europe and South Africa, for instance – are inevitably coming closer to resource depletion. This evolution is accelerated by the continuous increase in society's material requirements, given global population growth. In addition, recent trends, such as climate change mitigation and growing environmental awareness, are prompting a decline in thermal coal production and increased production of energy transition minerals and metals (Skorczkowski et al., 2020). As market demand for commodities changes, there will be a period of structural adjustment. Central to managing the consequences of this global adjustment are the mining regions that host resource operations.

Around 1000 mines worldwide are reported to be facing closure within the next 10 years (S&P Global, 2020). In mining regions where imminent closures are clustered, their impact presents significant socio-economic and environmental risks. These regions vividly illustrate the dynamics of the radical transformations of an industrial transition and are, therefore, the focus of this paper's assessment of regional adaptive capacity. As Haggerty et al. (2014) and Marot and Harfst (2021) note, many mining regions continue to lag socially and economically decades after mining has ceased, while others demonstrate greater resilience to closure-related changes and are able to transition more smoothly and successfully.

The research literature highlights the absence of a consistent definition of a mining region and of the factors that influence a region's resilience against the decline of a major economic sector, such as mining. This paper pioneers new methods in the definition and analysis of mining regions in transition. Our purpose is to examine the complexity of factors shaping the relative capacity of global mining regions to transition to sustainable post-mining futures by:

(i) locating mining regions on a global scale;
(ii) identifying configurations of contextual factors and mining characteristics likely to pose managerial and governance challenges to transition capacity;
(iii) using a solid and repeatable combination of quantitative measures to assess these factors; and

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(iv) developing and applying a rigorous data-driven framework that enables global comparisons of how regions might fare in their respective transition journeys.

Our work builds upon a broad range of theoretical approaches from disciplines as diverse as economic geography, regional studies, management studies, sociology and ecology that have been used to explain aspects of the inherently multi-dimensional sustainability transition (Markard et al., 2012). While there is increasing interest in theory of regional resilience and capabilities that equip regions to diversify and transition (Boschma 2015, 2017), the reviews by Strambo et al. (2019) and Aung and Strambo (2020) suggest some significant gaps in the literature about closure transitions and the associated factors. This research focusses on the less explored issue of how the unique factors characterising socio-economic, environmental, governance and remoteness dimensions combine (or re-combine) in a regional context to respond to market forces, environmental imperatives and lifecycle changes. We seek to stimulate dialogue about these issues through a global scan that employs a systematic and clearly defined methodology. We also provide a useful diagnostic tool for regional communities, governments and responsible mining companies to use in planning mine closure transition options.

The paper is ordered as follows: Section 2 reviews recent literature to highlight relevant developments in 'regional' research. Our explicit focus is to demonstrate the value of emerging definitional constructs of 'regions' for understanding the placement, concentration and implications of global trends, such as the energy transition. In Section 3 we draw on recent literature to establish a foundation for identifying regional-scale administrative jurisdictions globally and, from this set, arrive at a working set of 'mining regions in transition'. We develop a multi-dimensional analytical framework for examining levels of congruence between contextual and mining footprint characteristics of the regions and the scale of challenges each region might expect to face as it transitions to a sustainable post-mining economy. In Section 4 our findings are discussed in light of potential rapid switch scenarios. Conclusions are drawn in the final section.

2. Literature review

The capacity of global mining regions to transition to sustainable post-mining futures is complex and multifaceted. Our research draws from two key themes across the literature to address the current knowledge gap: definitions of regions and mining regions, and regional industrial transitions including mine closure processes and adaptive capacity.

2.1. Mining regions

The research literature is replete with definitions of a *region*. Common characteristics used to define regions include geographic location, population density, type of land use and built environment, climate, geophysical characteristics, administrative boundaries, and cultural identity. Definitions are driven by the purpose of the work. For example, a recent transitioning regional economies study by Australia's Productivity Commission (2017) defines regions based on contained and cohesive networks of trade. This pattern of definition by purpose is repeated in planning (Park et al., 2019; Rega et al., 2020), governance (Endl et al., 2018) and demography (Segers et al., 2020; Stas et al., 2020). Multidisciplinary definitions have likewise formed around a given purpose. Many of the characteristics highlighted in the studies by the Regional Australia Institute (2017), Chen (2016) and Debnath and Ray (2019) are relevant to identifying global mining regions and foregrounding some of the opportunities and constraints they may face in the closure transition. However, the spatial boundaries of regions in many of these examples were not considered pertinent nor are they comparable since they do not relate to a geo-locatable area.

Characteristics of *mining* regions most commonly featured in the research literature are the dependencies that form around a narrow economic base, disparity in wages between mining employees and workers in other industries, widespread modification of the local landscape, and a distinct mining identity (Boldy et al., 2021; Fleming-Munoz et al., 2020; Marais et al., 2017; Svobodova et al., 2021). This literature also notes that globally, a majority of mining regions are isolated and sparsely populated with unbalanced demographic profiles (Carson et al., 2020). These characteristics evolve over time. A recent study of the Schefferville region in Canada (Rodon et al., 2021) finds that mining regions are increasingly influenced by global commodity and supply chains, and use long distance commuting and flexible workforces, and even remote administrative and labour arrangements.

For purposes of understanding mining regions in transition, the existence of a definable 'mining region' is necessary as is understanding of mining lifecycles. Extraction of non-renewable resources means various stages with transition to eventual mine closure being inevitable. Scholars note the significant impact of lifecycle transitions upon the future of those regions and, particularly, closure (Ackermann et al., 2018; Forget and Rossi, 2021). The term 'mining region in transition' can have contrasting meanings and different terms may be used to refer to areas with mining activity at similar stages of the mine lifecycle (Hansen and Coenen, 2015). A *mining region in transition to closure* has implications of scale, temporal and spatial features. For comparative purposes, other desirable features include standardised distinguishing characteristics and boundaries that are coterminous with administrative boundaries and mining regulation jurisdictions. Consequently, our study adopts a definition that offers an extended, future-focussed, process perspective. The definition is: mining regions that have a significant proportion of closed mines and of mines approaching closure, and that also host significant mineral reserves and resources. This definition allowed us to identify influential factors from past experiences and future plans, since there are neither simple nor internationally agreed environmental, socio-economic or governance factors that affect closure transitions in mining regions (Forget and Rossi, 2021). The lack of agreed factors confounds conceptual and comparative assessment. In addition, the nature and management of socio-economic transition challenges at regional scale are yet to be rigorously investigated in the mine closure literature.

2.2. Regional transitions

Transition studies generally examine systemic and structural changes and their impacts on regional dynamics in the lead up to, or directly in the wake of, major market restructures (e.g. Boschma, 2018; Johnstone and Hielscher, 2017; Panetti 1981). Agriculture and manufacturing feature strongly as examples of large-scale market restructures in which the capacity of local and regional centres to adapt is assessed. Mine closure (or abandonment) is another persistent theme in the history of industrial transitions. How regions manage benefits and adverse impacts from mining at the closure phase of the mining lifecycle presents particular challenges (Poruschi and Measham, 2018; Sincovitch et al., 2018). Bebbington et al. (2008) argue that the contribution of mining to regional development is contentious and ambiguous at best. Its contribution fluctuates across the mining lifecycle. During mine construction, there is considerable pressure on labour and housing markets. At the tail end of the lifecycle, declining production levels and the prospect of permanent or temporary closure can increase unemployment rates, produce housing market gluts (Marais et al., 2017; Measham et al., 2019), reveal unrehabilitated environments and create challenges for infrastructure, services and local authorities (Wirth et al., 2012). The academic literature on mine closure is predominantly concerned with mine rehabilitation planning (Hendrychová et al., 2020), decommissioning of plants (Veselov et al., 2019) and defining completion criteria as an environmental management challenge (Manero et al., 2020). Scholars have typically examined these issues from the vantage point of individual mining assets (Perez-Sindin and Van Assche 2020; Skoczkowski et al., 2020). This approach, however, is ineffective when dealing with post-mining transitions in regions with multiple operations (Franks et al., 2010), as it does not consider cumulative impacts.

An emerging body of scholarship frames these challenges as multi-dimensional and positions the phenomenon at a regional scale (Arratia-Solar et al., 2022; Johnstone and Hielscher, 2017; Lechner et al., 2019; McCrea et al., 2019). This scholarship seeks to facilitate comparisons across multiple regions and commodities (Werner et al., 2020). Separately, Amirshenava and Osanloo (2018) and Ackerman et al. (2018) have established distinct multi-dimensional indicators related to the process of transitioning through and beyond mine closure. Support for conceptualising these issues at the regional scale is similarly compelling. Van Druten and Bekker (2017) connect several of these indicators to the long tail of impacts that stem from poorly managed legacy mining operations. We build on this line of enquiry by examining the multiple contextual dimensions of mine closure at the regional scale as a specific example of an industrial transition and assess the relevance of these dimensions to capacity to adapt.

The notion of regional adaptive capacity (Cole, 2013; Productivity Commission, 2017) has attracted interest as a measure of resilience and response to a shock or significant change (Robinson and Carson, 2016). Capacity to transition and resilience – in the sense of adaptation and adaptability as described by Boschma (2015) – both imply the ability to not only maintain but also improve conditions (Dutra et al., 2015). This assertion is made insofar as robust capacity ensures institutions function effectively, utilise the constellation of available resources and optimise new growth trajectories in response to unanticipated developments (Panetti et al., 2018). The concept holds that individuals, organisations and regions have characteristics that enable them to persevere, respond, renew, recover and even prosper, when encountering adversity or dramatic changes (Linnenluecke, 2017). Capacity of a region operates within an overarching set of constraints and opportunities placed by environmental, institutional and socio-economic conditions (e.g. Haasnoot et al., 2013; Lima et al., 2016). These factors may enable or constrain execution of transition strategies and implementation pathways. Australian research identifies the main factors shaping relative adaptive capacity of a region as human and social capital (e.g. education, skills level and community cohesion) as well as degree of remoteness and accessibility of infrastructure and services (Productivity Commission, 2017). Other researchers similarly note the contribution of social capital to adaptive capacity (Leys and Vanclay, 2011; Panetti et al., 2018). Techno-industrial diversity is regarded as more central to adaptive capacity than industry specialisation, though there is discussion about the relative benefits of related, versus unrelated, variety of industries and skills (Boschma 2015, 2017). A compelling stream of research portrays transitions resulting from sectoral change as influenced by multidimensional patterns in surrounding contexts rather than coupled dynamics or single factors (Bergek et al., 2015; Boschma et al., 2017). Bergek et al. (2015) further highlight the significance of spatial dimensions and system boundaries (see also characterisation of transition processes as place-dependant, Hansen and Coenen, 2015).

Greater resilience to fluctuations and transitions in extractive industries has been associated with many variables relevant to mine closure, including decreasing dependence on an extractive industry by developing viable alternative industries over time (Measham et al., 2019). Yet it has been argued that lack of clarity about this capacity and how it is assessed hamper attempts to maintain or improve the transition experience (Linnenluecke, 2017; Svobodova et al., 2020). Our research builds on these insights from mine closure studies and transition studies about salient mining and contextual influences. It takes a multi-dimensional approach and shifts the focus from management options of a single mine site to the complex process of human-nature interactions in mining regions as a whole.

3. Methods and analytical framework

The methodological approach consisted of three main steps. First, a working definition of a mining region was used to identify and locate mining regions around the world. Second, an additional selection procedure was applied to show those mining regions predictably confronting mine closure impacts. We refer to these regions as mining regions in transition (MRITs). Third, a framework was developed and applied to analyse and compare the capacity of MRITs to adroitly manage this process of transition.

3.1. Identification of mining regions

A region considered to be a ‘mining region’ typically spans several (often small) communities and hosts multiple mines that may operate asynchronously, for different durations, under different companies and potentially extract different commodities at different scales (as is evident in studies by Carson et al., 2020; Plummer and Tonts, 2013; Ryser et al., 2014; Sandlos and Keeling, 2016). For our purposes, mining regions are defined as regions administered by a single government entity and hosting at least three operating and/or closed mines within 50 km of each other. Taken together, these two criteria – minimum number of mines and maximum distance between them – capture localities where large-scale mines do not exist in isolation and where mines’ socio-economic areas of influence overlap. Based on this definition, a total of 554 mining regions were identified. Fig. 1 shows the global distribution of these regions.

Mines within 50 km of each other can be considered as constituting an economic cluster, meaning they are interacting with the local economy as well as with each other (e.g. Sonter et al., 2020). To identify mining regions, we combined two sets of global data: S&P Global Market Intelligence database (the S&P database) and the Database of Global Administrative Areas (GADM). The S&P database facilitated the location of global mining activities other than quarrying. This database is one of the most comprehensive and up-to-date repositories of mining data (Lèbre et al., 2020). As of June 2020, the S&P database contained a dataset of 8555 mining operations listed as either operating or closed, with geo-located XY coordinates (S&P Global 2020). Concurrently, GADM delineated the administrative boundaries of mining regions (GADM, 2021). We adopted sub-country and sub-province administrative levels as representative of administrative regions with consistent regulation and functional systems of governance. A dataset of 16,171 administrative regions was identified from the GADM database.

3.2. Identification of mining regions in transition

Using the S&P database, we identified a subset of 46 regions as MRITs that have a significant scale of mining operations and a significant proportion of closed mines and/or mines approaching the end of their economic lives. We did not aim to comprehensively account for all mining regions in transition globally. Our aim was to select relevant candidates for further analysis in terms of their capacity to successfully transition to viable post-mining alternatives. Applying a combination of indicators and their thresholds, MRITs were defined as regions with:

(i) a percentage of closed mines equal to or above 20 percent, which corresponds to the median value across the 554 mining regions;
(ii) a percentage of mines with projected closure dates within the next decade equal to or above 13 percent, which corresponds to the average value across the 554 mining regions; and
(iii) a sum of ore reserves and resources of all mines equal to or above 278.9 million tonnes, which corresponds the median value across the 554 mining regions.

A high proportion of closed mines indicates a mature mining region where a regional transition to closure is plausibly under way. A high

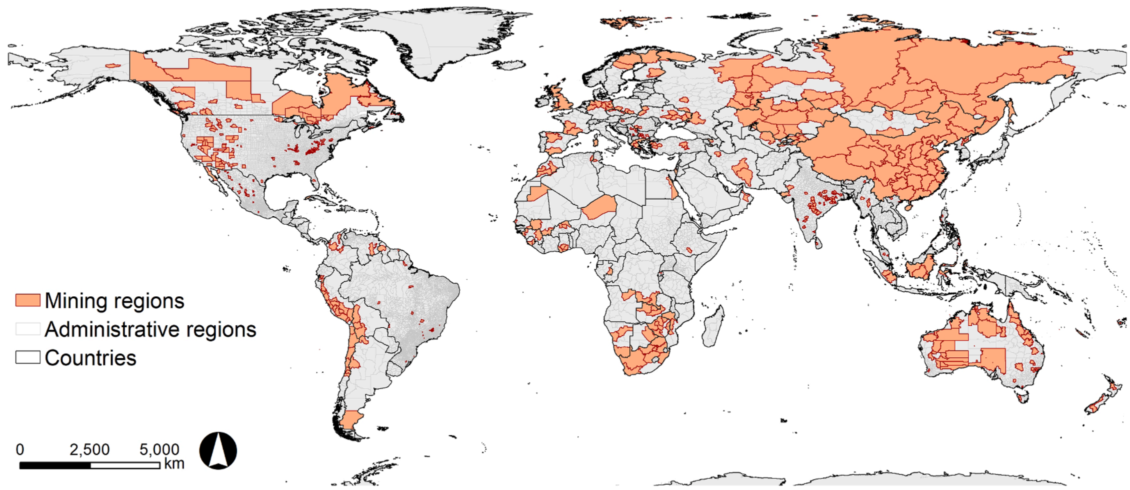

Fig. 1. Global distribution of 554 mining regions.

proportion of mines scheduled for closure similarly indicates that preparations for closure are progressing and that there are more closures to come. The scale of mining operations, which we approximated here by the sum of reserves and resources in the region, is another key factor to consider. When mining is a prominent economic driver, regions with larger scales of mining will provide different insights about the capacity needed to transition. Such regions are likely to require more resources, technical capability and higher levels of coordination to manage their transition. By using median and average values as the thresholds, we selected representative candidates of global mining regions based on shared rather than extreme values.

3.3. *Assessment of the regional capacity to transition*

We understand the regional capacity to transition to be dynamic and multidimensional. Transition capacity depends on the ability to harness, adapt or re-configure regional assets and to cultivate new competencies that enable a region to survive and prosper after mining activities cease (Boschma et al., 2017). Our approach aligned with previous work that recognises the role of the geographic context in development transitions especially related to mining (Brunsdon and Comber, 2020; Hansen and Coenen, 2015). Previous studies have used publicly available, global metrics to characterise the context in which mining takes place and deduce social and environmental implications (e.g. Lèbre et al., 2020; Svobodova et al., 2019; Valenta et al., 2019).

To assess the capacity of MRITs, we focussed on the interaction of factors characterising the socio-economic, environmental, governance and remoteness dimensions within a region's mining footprint (Fig. 2). Collectively we called these four dimensions sustainability dimensions. While characteristics of mining footprints will determine the scale of potential impacts across a region, the context shows vulnerabilities and strengths across sustainability dimensions (Worrall et al., 2009). For example, a region with favourable contextual factors in sustainability dimensions and a contained mining footprint would be considered to have a relatively strong capacity to transition. By contrast, a region with favourable context but challenging mining footprints, or vice versa, would have a lower relative capacity to transition. A mining region with less favourable context and an extensive mining footprint would be regarded as having the lowest capacity to transition.

3.3.1. *Context*

To better understand how context affects the capacity to transition,

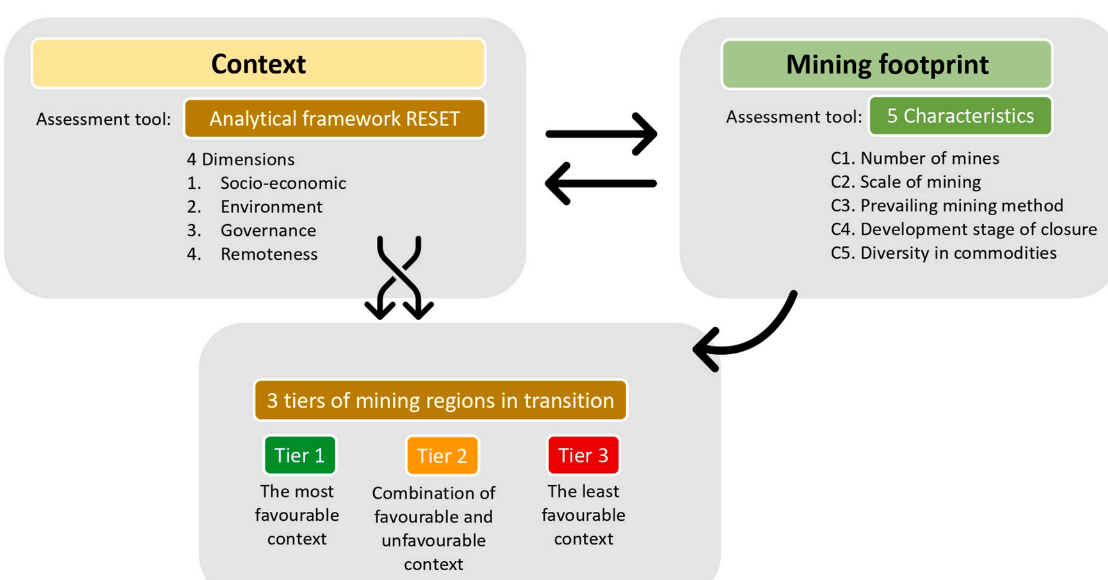

Fig. 2. A theoretical framework of the regional capacity to transition.

we designed an analytical framework, RESET (Regional Economic, Social and Environmental Transition). The core of RESET consists of four dimensions: socio-economic, environment, governance and remoteness as shown in Table 1. For our study, each dimension is composed of one or two contextual factors, which are quantified using a single measure or a combination of measures. Where possible, the framework used fine-grained measures allowing for the observation of sub-national variations. This is the case for measures used in the environmental and remoteness dimensions. Due to the general coarseness of global social, economic and governance data, however, the remaining dimensions of RESET were populated using national measures.

The socio-economic dimension broadly describes the interaction between national scale human development and mining dependence scores. Higher levels of human development indicate an improved ability to withstand economic changes, as more material and human resources are available to recombine and mobilise post-mine alternatives. Dependence on mining implies a lack of economic diversity, which will magnify the socio-economic impact of mine closures.

The environmental dimension comprises water risk and cumulative human modification measures. Water is widely regarded as the most essential natural resource (Vörösmarty et al., 2010) and in mining regions, water is shared between resource developers and other users. Region-wide mine closures can significantly shift water security, water management and consumption patterns across the region (Fraser and Kunz, 2018). Human modification is understood as the spatial extent and intensity of human activities that create constraints for land-use alternatives (Theobald et al., 2020). While low levels of land modification indicate a stable and healthy natural environment in the region, high levels of land modification are associated with stressed natural environments with greater ravages of human degradation to be addressed. High water risks and land modification can significantly limit post-mining land use, regional biodiversity and ecosystem services (Kunz, 2020). Low levels, however, do not guarantee the quality of the undisturbed territory or its suitability for other purposes.

Table 1
RESET: an analytical framework to assess the context of mining regions in transition. The framework consists of four dimensions and six contextual factors that influence transition capacity of the region. For each factor, measures, their scores and thresholds were used to form binary groups of MRITs with favourable and less favourable classification.

Dimensions	Contextual factors	Measures	Threshold group Range of scores	Context classification
Socio-economic	Level of development	UNDP's Human Development Index (HDI); (UNDP, 2018)	Less developed 0 - 0.699	Less favourable
			Developed 0.7 – 1	Favourable
	Dependence on Mining	ICMM's mining contribution index (MCI); (ICMM, 2018)	dependent over 60	Less favourable
			Less dependent 0 - 59	Favourable
Environment	Risks to regulation, quality and quantity of water	Aqueduct Water Risk Atlas – composite water risks at catchment level (Aqueduct, 2019)	Low risk 0 - 2	Favourable
			High risk 3 - 5	Less favourable
	Extent of modification of natural environment	Cumulative Global Human Modification (GHM); (Kennedy et al., 2019)	Low modification 0 - 0.1	Favourable
			High modification 0.11 - 1	Less favourable
Governance	Quality of national governance and regulation	Composite Worldwide Governance Indicators (WGI); (WGI, 2019)	Less satisfactory Less than 60.29	Less favourable
			Satisfactory Over 60.30	Favourable
Remoteness	Population density	2015 residential population density (CIESIN, 2018)	Rural 150 inhabitants/km^2 and less	Less favourable
			Urban Over 150 inhabitants/km^2	Favourable

The quality of governance in a country is indicative of the presence of institutional safeguards that protect people and the environment. Whether mining development activities translate into broad economic and social benefits in mining regions depends on the quality of their regulation (ICMM, 2019). Regime factors can facilitate, limit or prevent transitions from occurring (Murphy, 2015; Panetti et al., 2018). Critically, governance determines the rigorous systems required for effective mine closure are in place, including strategic planning well in advance of closure, and substantial resources being available (Gregory, 2021; Hoogstraaten et al., 2020; Normann, 2019).

The remoteness dimension captures isolation from economic centres and infrastructure (Owen et al., 2022). The size and density of a region's population interact with its economic, social and political organisation, its environmental endowments, transport and communication links and distances to influence development prospects. Urbanised regions provide more propitious contexts compared with remote regions that have lower population densities (Monosky and Keeling, 2021). Regions with higher population density and sizeable population centres benefit from greater resource availability, including critical infrastructure and public services (Cattaneoet al., 2021). These factors are important for understanding what residual human, physical and economic resources might be available to a region as it begins to chart an alternative post-mining future (Carson et al., 2021; Plummer and Tonts, 2013).

For each measure used to quantify dimensions and contextual factors in RESET, we define a threshold score that makes a binary separation between 'regions with favourable scores' and 'regions with less favourable scores' for each factor (see Context classification in Table 1). Based on the assigned score for each contextual factor and our thresholds, all 46 MRITs were classified into one of three tiers. The MRITs have varying degrees and combinations of favourable conditions for transition as described below and illustrated in the Supplementary Material. The classification accounts for both the magnitude of the constraining factors and their co-occurrence within a region.

Tier 1 represents regions with the most favourable context across socio-economic, environmental and governance dimensions. These regions have contextual factors and available assets to facilitate closure adaptation and, therefore, have a stronger capacity to transition than MRITs from other tiers. Conversely, regions in Tier 3 exhibit the highest proportion of unfavourable contextual factors. Tier 3 MRITs are the most constrained in their transition capacity. Tier 2 regions sit between the other tiers and have combinations of factors that, as they co-evolve, will support or impede sustainability transitions.

The global distribution of regions in Tiers 1–3 is shown in Fig. 3. Tier 1 contains 12 MRITs located in Canada (5 regions), the USA (3 regions), Australia (3 regions), and Sweden (1 region). The 27 MRITs of Tier 2 are dispersed across Australia (6 regions), New Zealand (1 region), the USA (4 regions), Latin America (10 regions), and Europe (6 regions). The seven Tier 3 MRITs are located primarily in Africa (4 in South Africa and 1 each in Democratic Republic of Congo and Guinea), with one in South America (Bolivia).

3.3.2. Mining footprint

The mining footprint of MRITs is measured using five characteristics. The characteristics are: C1. number of mines in a region, C2. scale of mining (sum of reserves and resources), C3. prevailing mining methods

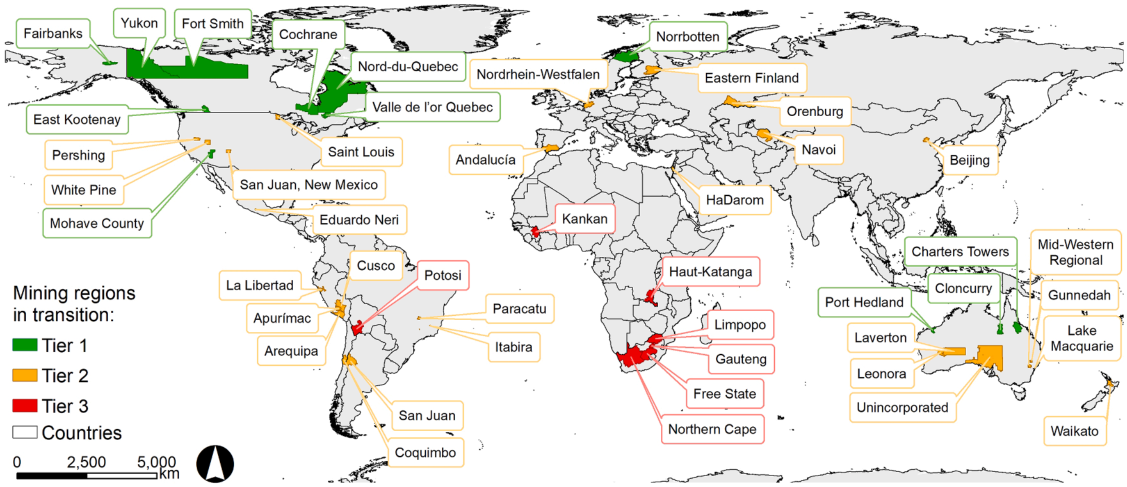

Fig. 3. Global distribution of MRITs in three tiers of capacity to transition. Each region is labelled with the name recorded in the GADM database and coloured in accordance with its associated tier.

in each region's mines, C4. stage of closure, and C5. diversity in commodities. The rationale for each is described below.

C1. More mines bring greater potential for cumulative socio-economic and environmental impacts from multiple mine closures within the same timeframe, the mitigation of which requires significant co-operation, planning and resourcing at the regional level (Porter et al., 2013; Svobodova et al., 2021).

C2. Larger socio-economic impacts are expected from the closure of large-scale mines compared with small mines due to greater employment displacement and the flow-on effects to procurement of local goods and services and indirect impacts on other local businesses (Fleming-Muñoz et al., 2020). Larger mines also generate more waste and surface disruption, which may increase negative impacts (Forget and Rossi, 2021).

C3. The mining method influences the level of environmental and social impacts and the nature of rehabilitation required prior to closure and relinquishment (Williams, 2017). In general, open-pit mines are more challenging to rehabilitate than underground mines due to the existence of large final voids, the size and extent of waste dumps that require re-contouring and revegetation, and the potential for acid mine drainage.

C4. Regions where high numbers of mines have been closed and are closing, face bigger challenges associated with mine closure than those with more distant or dispersed closure dates, especially if closure is premature or unplanned (Laurence, 2011; Vivoda et al., 2019).

C5. Regions with closed and closing mines producing the same commodity will face bigger challenges associated with their transition than those with more diversified mining and economic bases. As Watkins (1963) explains, when a single commodity dominates the major economic flows in the region, the regional focus on the commodity can distort development pathways. It can also impede a region's economic viability once the resource stock is depleted. Issues associated with the primary commodity shape regional policy and decision-making, tie social and economic activities to the dominant one, influence new initiatives, and compound problems.

Considering interactions between contextual factors and characteristics of mining footprints allowed us to compare transition capacity across three tiers of MRITs. Though we portray the tiers generically, they are inevitably heterogenous. The lines of demarcation, while not arbitrary, could conceivably be determined by an alternative rationale. Additionally, our analysis and designation of tiers does not predetermine the destiny of regions. Rather, it identifies the relative capacity of MRITs as the basis for identifying factors that may warrant more strategic attention through the process of transition.

There are limitations to our analysis, including the above-mentioned coarseness of global social, economic and governance data. A lack of comparable data about crucial regional variations precluded a nuanced understanding of these sustainability dimensions. Regional variations include the proportion of Indigenous population and FIFO population; technological sophistication of mining methods; and percentages of regional production, government revenue and employment attributable to mining. Furthermore, our source of data on global mining activities, the S&P database, has limitations as it builds on varying disclosure standards in different jurisdictions and reporting companies. These disclosure differences may affect the coverage, completeness and reliability of disclosures. In our calculations of mining footprints, we considered closed and closing mines with equal importance due to the lack of data on the specific phase of mine closure, rehabilitation and relinquishment.

Descriptive statistics and details on contextual factors and mining footprint characteristics in all 46 MRITs are outlined in Supplementary Material and viewable in the supplementary Interactive Map Data (.kmz format).

4. Findings: capacity of regions to transition

This section presents the contextual and mining footprint characteristics for the three tiers of MRITs, recognising that transitions do not follow a simple, linear path but can be considered a complex interaction of connected patterns, as demonstrated by de Haan and Rotmans (2011). Although the regions exhibit some common patterns across the tiers, they possess key differences with respect to sustainability dimensions and mining experience that influence their capacity to transition. The specific details provided in Supplementary Material are summarised below.

4.1. Context

The majority of MRITs are found in countries with high human development scores (Fig. 4a). All 39 regions in Tiers 1 and 2 are in developed countries, whereas all seven Tier 3 regions are in less developed countries, with Bolivia and the Democratic Republic of Congo having noticeably lower human development scores. On average, Tier 1 regions are in countries that are less economically dependent on mining than the other two tiers (Fig. 4b), with only three Australian regions

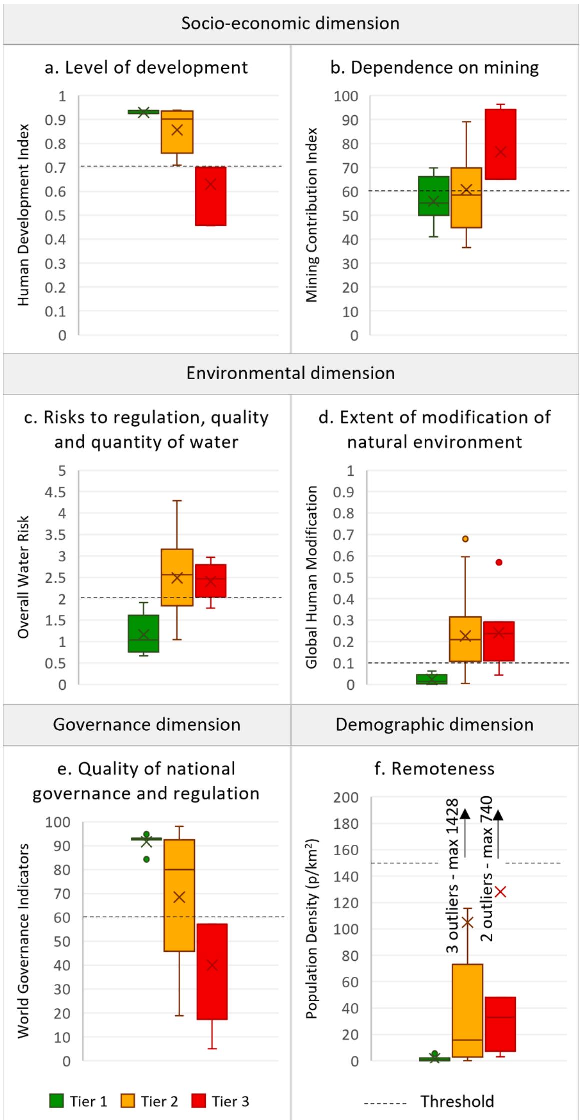

Fig. 4. Distribution of contextual factors across three tiers of MRITs.[11]

(Charters Towers, Cloncurry and Port Headland) being ranked as highly dependent. In contrast, all Tier 3 regions are in countries with high or very high economic dependence on mining.

In terms of environmental context (Figs. 4c, d), while Tier 1 regions have low water risk and human modification scores, Tiers 2 and 3 show varying constraints on these measures. Twenty Tier 2 and six Tier 3 regions have highly modified natural environments, and 21 Tier 2 and six Tier 3 regions have high water risk scores. Four regions show medium-to-high risk scores in both environmental categories: Beijing region in China; Gunnedah and Lake Macquarie regions in New South Wales, Australia; and Nordrhein-Westfalen in Germany. While these four Tier 2 regions are the most constrained from an environmental perspective, they are endowed with favourable factors in the social-economic and governance dimensions of RESET.

Governance is identified as having a key role in sustainability transitions (Markard et al., 2012). All Tier 1 regions have satisfactory scores relating to the quality of national governance and regulation whereas all Tier 3 regions are in jurisdictions with less satisfactory governance (Fig. 4e). Tier 3 regions with the lowest governance scores are Kankan (Guinea), Potosí (Bolivia) and Haut-Katanga (Democratic Republic of Congo). Across the 27 Tier 2 regions, governance quality is a differentiating factor. Sixteen of the regions are in countries with sound governance, while national governance scores for the remaining regions are less satisfactory.

A common pattern associated with remoteness was found across the three tiers of MRITs (Fig. 4f). All but five MRITs are rural regions, with population densities below 150 residents/km^2. Tier 1 regions have the lowest population densities with the average regional maximum being seven residents/km^2. Tier 2 and Tier 3 regions, on the other hand, show higher diversity of population numbers across the regions, with regional averages ranging between 0.5 and 1428 residents/km^2 (Tier 2) and from three up to 740 residents/km^2 (Tier 3).

4.2. Mining footprint

Across the sample of MRITs, Tier 3 regions have significantly more mines (an average of 33 compared with 10 each in Tiers 1 and 2; Fig. 5a) and larger mines (an average of seven compared with two in Tiers 1 and 2; Fig. 5b). There are, however, outliers such as the Tier 2 Mid-Western region in New South Wales, Australia, where 75% of the mines are large and the Tier 1 region East Kootenay in British Columbia, with 67% of large mines. Amongst Tier 3 regions, the South African regions are notable, having between 35 and 56 mines – the highest number of any MRIT. Limpopo, with 20 large mines, is an example of the relevance of mine size in this tier. Tier 3 regions also have the highest number of open-pit mines. This characteristic further contributes to the cumulative challenges faced by this group of regions (Figs. 5c, 5d).

On average, Tier 1 regions have a higher percentage of closed mines (45%) than the other two tiers (Fig. 5e). Tier 3 regions have the highest average percentage of mines scheduled to close within 10 years (30%) (Fig. 5f), suggesting imminent closure transitions for different reasons. Regions with more than half their mines scheduled to close in the next decade include, for example, the Tier 1 region of Valle de l'Or Québec in Canada (55% of mines scheduled to close); Tier 2 regions, such as San Juan, Argentina (75% of mines), Itabira in Brazil (60%), White Pine in Nevada, USA (50%); and the Tier 3 region of Kankan in Guinea (57%).

Gold is the most common commodity in the MRITs with seven Tier 1 regions, 12 Tier 2 and three Tier 3 regions specialising in gold. Tier 2 shows the highest degree of commodity specialisation (Fig. 5). Also, in Tier 2 regions, copper and coal are produced in five and six regions respectively, while iron ore dominates in three regions (Fig. 5h). In Tiers 1 and 3, a single commodity focus outside of gold is less common. Regions that specialise in mining, especially of single commodities, may have related industries like processing, power generation and manufacturing, but struggle to rejuvenate, recombine and re-orientate their human, institutional and other resources to alternative, sustainable industries and livelihoods (as elaborated in Boschma, 2015).

4.3. Configurations of contextual factors and mining footprint characteristics

The configuration of socio-economic, environmental, governance and remoteness factors, together with the aggregate mining footprint, influences a region's capacity to transition to closure. Tier 1 regions have the most favourable context across socio-economic, environmental and governance dimensions. Remoteness and, in the case of three of the regions, dependence on mining, are their only unfavourable contextual factors. Mining footprints add unfavourable characteristics which, when combined with less favourable contextual factors, could indicate potential constraints on a region's capacity to transition.

Overall, favourable conditions in Tier 1 suggests that significant assets could be mobilised to support transition. This assertion needs to be weighed against the high proportion of closed mines and a relatively high degree of commodity specialisation in these regions. Tier 2 regions have the most diverse combinations of contextual factors and mining footprint characteristics. Their capacity to transition to a positive post-mining future will therefore vary considerably and is more ambiguous. Regions in Tier 3 have the least favourable contexts. Their

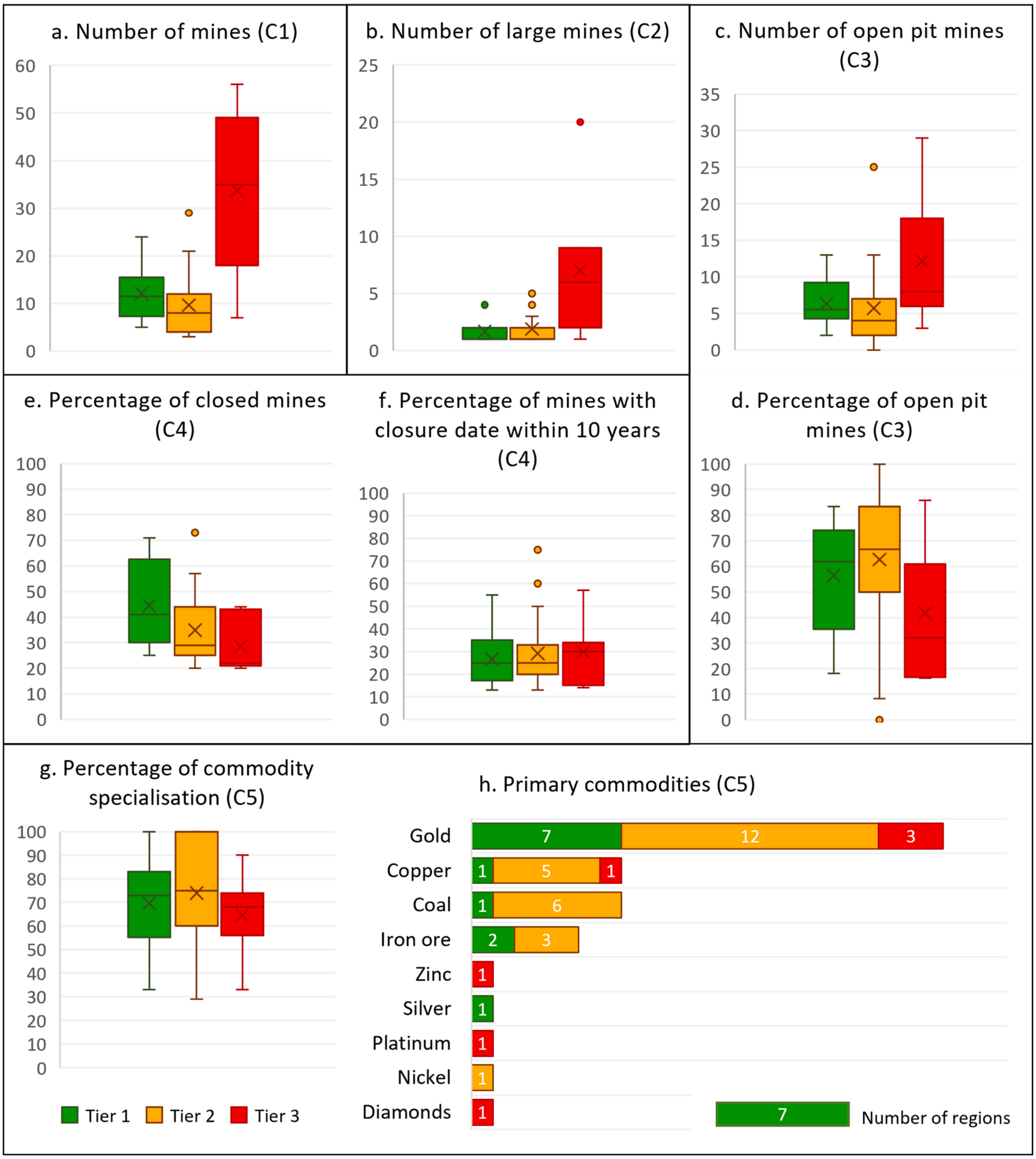

Fig. 5. Scale and character of mining footprint affecting transition capacity of MRITs; comparison across tiers.

cumulative mining footprint characteristics, particularly having the highest number of mines and the highest number of large and open-pit mines, are negative attributes. With such unfavourable conditions, even with some potentially favourable contextual factors, indications are that Tier 3 regions face major constraints.

5. Discussion

Regions are not equally equipped to make sustainability transitions since such transitions entail a far-reaching re-configuration of intertwined, regional factors and characteristics into a new socio-economic system (Boschma et al., 2017; Markard et al., 2012; Truffer et al., 2015). We argue that greater understanding of regional capacity to transition can help avoid predictable decline when a mining-dependent region loses its primary economic sector. In developing policies and carrying out mine closure planning, regulators and mining companies cannot afford to ignore the regional factors and characteristics that influence transition capacity (Bergek et al., 2015; Hoogstraaten et al., 2020). This discussion is structured around our sustainability-informed analytical framework and focuses on the interplay between contextual factors and the overall mining footprint in the different geographical milieus of the 46 regions.

5.1. Regional context

Our study highlights the links between level of development and dependence on mining, with vulnerability to closure shocks and human development implications being more acute in less developed, more dependent Tier 3 regions. All Tier 3 regions are dependent on mining

[1] Box plot diagrams present data in quartiles. The height of the box indicates the spread and distortion in the data. The lines extending from the boxes (whiskers) indicate range of the data from minimum to maximum values. Individual points show outliers. Lines across the plot indicate median (middle) values. The cross shows a mean value.

compared with about half the Tier 2 regions. Tier 1 regions are the least depende nt of the MRITs, with three quarters of them outside the dependence threshold. As the regions were selected as having extensive mining activity, the degree of dependence will be crucial to determining diversification strategies and transition pathways (Coenen et al., 2015; Hötte, 2020). Dependence can also constrain their progress against the United Nations' Sustainable Development Goals. One factor that we did not test is the extent to which individual regions depend on other mining regions, such as for materials, labour or the supply of energy (Svobodova et al., 2020). These sub-national dependencies are likely to further highlight the importance of policy coordination between regions. This also suggests that national governments will need to adopt novel multi-scalar approaches to managing transition pathways, acknowledging that in some circumstances this could include concurrent periods of growth and decline across their mining sectors.

Globally, MRITs are spread across different climatic, vegetation and land-use zones and across heterogeneous landscapes. Our findings highlight the relevance of a regional perspective on vital natural resources like water and the natural environment. Tier 2 and Tier 3 regions have significantly higher water risks than Tier 1 regions. Water impacts will limit the range of potential post-mining land use options, particularly in terms of regional biodiversity, ecosystem services and local livelihoods (Kunz, 2020). Further investigation is required to understand how a region's available water assets can be optimised to support future development options. Regional advantages in terms of natural resource endowments must be safeguarded and supplemented by value creation processes if sustainable alternative industries are to eventuate, as Hansen and Coenen (2015) note is argued by many authors.

The generally robust governance procedures and practices of Tier 1 regions enhance their potential to harness suitable planning, human and financial resources for regional transitions. Nevertheless, these favourable contextual factors may be subject to regional policies and priorities and to distribution idiosyncrasies in each context. Planners will need to pay close attention to equity issues, including ensuring benefits and opportunities are widespread and are not limited to a specific sector nor small, elite groups (Wilson et al., 2018).

The relevance of the remoteness dimension is evident in research showing that regions with higher regional populations, denser settlement patterns and functioning social capital, benefit from the availability of enabling infrastructure and public services found in sizeable urban centres (Hansen and Coenen, 2015). Such regions have more favourable transition prospects than those in more remote and sparsely settled areas (de Krom, 2017). In addition, closure transitions in urban areas attract more media and political scrutiny than rural regions, putting regulators and proponents under pressure to deliver beneficial post-closure outcomes (Wanrooij, 2021). In this regard, the evidence of remoteness in terms of population density reinforced existing knowledge that mining and, consequently, mine closure, poses greatest challenges for sparsely populated regions remote from major population and economic centres (Marais et al., 2017, 2021).

Evidence about contextual factors raises awareness of assets and challenges likely to be prominent in different tiers of regions as well as the influence of various factors on post-mining development (Fig. 4). As the Productivity Commission (2017) notes of its relative adaptive capacity index, no single representation can capture the unique attributes of each region nor all the pertinent constraints and enabling factors. Nevertheless, this research shows four regional context dimensions that interact with specific mining footprint characteristics which contribute to the complexity of regional capacity to transition.

5.2. Mining footprint

The industrial history and footprint of the pre-existing industry are additional parameters within which transitions will proceed (Boschma, 2015). Our study investigated five key inter-related mining footprint characteristics (Fig. 5). From a mine closure perspective, the socio-economic challenges facing regions with mines producing the same commodity exceed those of regions with more diversified mining and economic bases (especially if closure is early or unplanned). In 22 of the 46 MRITs, gold mining prevails across closed and closing mines. Methods for mining gold combined with other socio-economic and environmental factors pose technical and environmental challenges that may be beyond the governance capacity of those regions. Consequently, there is a case for collaboration and knowledge sharing amongst gold miners, and also copper miners, coal miners and iron ore miners as these are primary commodities in multiple MRITs.

When considering the mining footprint, the location of mines is relevant since close clustering means that there is greater potential for cumulative socio-economic and environmental impacts from multiple mine closures within the same timeframe. The mitigation of these impacts requires co-operation, planning and resourcing at the regional level (Porter et al., 2013). Tier 3 regions have significantly more mines and more large mines than Tiers 1 and 2. Regions with many mines are more likely to have less economic diversity than regions with fewer mines. In terms of size, it is notable that the average percentage of large mines in the 554 mining regions is 16%. Twenty-seven MRITs have above this global average. More significant economic impacts are expected from the closure of large mines compared with small mines due to the broad-based economic displacement effect, as well as greater accumulated waste and more surface disruption, which may increase negative outcomes.

Mining and rehabilitation practices are important considerations in closure planning and prospects for resilience during the closure transition since long-term compromise of ecosystems is common in mining regions (Lechner et al., 2017). Open-pit mines are more challenging to rehabilitate than underground mines due to their size and the extent of waste (Williams, 2017). In this respect, Tier 2 regions have the highest average percentage of open-pit mines, but Tier 3 regions have the highest absolute number of open-pit mines. While strip mining (e.g. in open-cut coal or bauxite mining) is conducive to progressive rehabilitation, open-pit mining of metal orebodies is not, as the entire void needs to remain open for mining to occur. Remediating these pits, in particular, will take significant effort to complete.

6. Conclusion

Mining regions face an uncertain future largely due to reverberations of global developments, including changes in the supply and demand for commodities to support continuous population growth, growing economies and climate change mitigation efforts. These trends, and the resources drawn upon to mitigate them, will have profound implications for mining regions. Just as the operational stage of the mining lifecycle is largely shaped by an 'accident' of geology converging with technological capacity and market demand, a region's post-mining future will be shaped by a suite of factors, including environmental, remoteness, economic and political dimensions.

Our proposition is that four sustainability dimensions and five mining footprint characteristics combine and interact to influence a region's capacity to transition to a positive post-mining future. We have demonstrated that some regions have conditions more favourable to harnessing available resources than others. We have also explained how to consider these conditions in relative terms. A structured understanding of regional capacity to transition can help avoid predictable decline when a mining-dependent region loses its primary economic sector. In developing policies and carrying out mine closure planning, regulators and mining companies cannot afford to be blind to the regional characteristics that influence transition capacity.

This paper has presented a pioneering approach to the study of mining regions with an explicit focus on the challenges associated with a post-mining transition. This study's approach to global scale reporting makes three contributions to scholarship. It:

(i) provides a framework for an integrated understanding of comparative regional capacity to transition;
(ii) identifies configurations of contextual factors and mining characteristics likely to pose managerial and governance challenges; and
(iii) develops a reasoned definitional construct and applyies a rigorous, data-driven method.

The parameters and limitations of this study suggest opportunities for future research. Where this macro study relied on global data, national studies (in countries with comprehensive data at regional and jurisdictional levels), would allow equally rigorous investigation of spatial implications and finer-grained insights about relevant factors. There is potential to vary the measures used and scale examined to suit particular research questions, regions and phenomena of interest. Future research could pursue differences between Tier 1 and Tier 2 regions within the same national context (e.g. Australia or USA); or patterns associated with additional factors, such as trends in population, residential location or income over the past decade. Similarly, differences in mining footprint could be explored between predominantly open-cut and underground operations, and contrasting options for regions currently producing hydrocarbons, critical minerals and precious metals. A particularly valuable extension would be to undertake a fine-detailed scan prior to longitudinal and qualitative investigation of the impact of intraregional differences in local demography, economy and settlement history, since there is potential for great diversity in contextual factors even within a region. Consideration of these issues and planning based on assessment of assets could fuel the community participation advocated as essential to positive post-mining outcomes (Everingham et al., 2020; Gregory, 2021; Syahrir et al., 2021) and help avoid chaotic, unplanned and traumatic processes of mine closure and community adjustment. As a result, policies and closure strategies might be more effective and appropriate to particular social, cultural, and economic circumstances.

A global scan identifying regions likely to face similar transition challenges and work with similar resources and constraints is no substitute for in-depth understanding of specific transition contexts as is provided by the diverse, rich case studies now emerging (e.g. Fernández-Vázquez, 2022; Gregory, 2021; Holcombe, 2020; Rodon et al., 2021; Syahrir et al., 2021). It nevertheless serves as a caution against the idea that selected case studies will provide a formula for transitioning successfully in any regional context. For instance, Tier 1 regions may be blessed with positive natural resources, infrastructure and human capital, however, these positive factors may well be eroded in a poorly or hastily managed transition process. Some regions are dealt a better hand than others, but these are not rigid determinants and skilful playing of a bad hand may still have broad and lasting positive effects. We conclude that understanding and cultivating a favourable political, economic, socio-cultural and governance context is as important as technical understanding in ensuring a resilient regional post-mining transition.

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Supplementary materials

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