Manero, A., Standish, R., & Young, R. (2021). Mine completion criteria defined by best-practice: A global meta-analysis and Western Australian case studies. Journal of Environmental Management, 282, 1-12. https://doi.org/10.1016/j.jenvman.2020.111912

Mine completion criteria defined by best-practice: a global meta-analysis and Western Australia case studies

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Abstract:

In many mining-intensive areas around the world, knowledge-sharing among companies is critical to advance best-practices in mine rehabilitation and closure. The academic literature documents innovative, best-practices, yet these are often not open access. Published mine closure plans provide relevant examples of standards accepted by regulators, however, regulations vary with jurisdiction and can change over time, limiting the utility of these plans. There is, therefore, a need for greater transparency and accessibility of practical knowledge to inform the definition of achievable completion criteria. The purpose of this study is to provide an overview of best-practices for the purpose of defining mine completion criteria. The methods comprise: i) a qualitative meta-analysis of the global peer-reviewed literature; and ii) three in-depth case studies in Western Australia. The research identifies ten key best-practices that could be potentially applied by mining proponents to guide the definition of successful completion criteria. These include: *multiple references*, *monitoring and corrective actions*, *science-informed completion criteria, holistic rehabilitation, dynamic targets, leading indicators, integration of rehabilitation with mine operations, innovation-guided completion criteria, specific objectives and indicators* and *risk-based completion criteria.* These best-practices are further examined through recent mine rehabilitation and closure programs of mid-to-large mining operators in Western Australia. Our findings provide the first comprehensive review of best-practices towards the definition of mine completion criteria, which are relevant to industries requiring rehabilitation of disturbed lands across Australian and international jurisdictions.

Keywords: closure planning; ecological restoration; mine closure; mine reclamation; mine rehabilitation.

1. *Introduction*

Mining is a highly disruptive activity, often resulting in severely modified natural and social environments. For this reason, companies in mining jurisdictions across the world - e.g. Brazil (Sánchez et al. 2014), Canada (AANDC 2013), Australia and New Zealand (ANZMEC & MCA 2000) - are required to return used mine sites to a state that is safe, stable, non-polluting and supportive of an agreed post-mining land use (ICMM 2019). Mining companies, government agencies and the public have long recognized the need to consider criteria to determine when rehabilitation is complete (Gardner & Bell 2007), and ultimately, when the mine is ready for relinquishment (Morrison et al. 2005). Such criteria may refer to ecosystem health, soil, water, flora, fauna and social factors (Blommerde et al. 2015). A frequent goal in mine rehabilitation is reinstatement of pre-mining land uses and native ecosystems (Rosa et al. 2018), although full recovery is difficult and often incompatible with the disruptions caused by mining operations (Doley & Audet 2016; Gillespie et al. 2015; Rosa et al. 2018). In these cases, the goal might be to repurpose the mine for another land-use such as agriculture. Regardless of the goal, for mine sites to be successfully closed and rehabilitated, it is critical that realistic and measurable criteria are defined and agreed upon (Blanchette et al. 2016).

Completion (or closure) criteria are defined as rehabilitation performance objectives that provide an indication of mine rehabilitation success and the likelihood that the site has reached its agreed closure state (i.e. rehabilitation objective) (LPSDP 2016). Official guidelines across the world prescribe how completion criteria should be defined, such as being specific, measurable, achievable, relevant and time-bound - commonly referred to as S.M.A.R.T. (APEC 2018; Environment Canada 2009; Gann et al. 2019; Heikkinen et al. 2008; ICMM 2019; Sánchez et al. 2014; South African Government 2015). Despite the available guidance, completion criteria around the world are often ambiguous or ill-defined, thus resulting in unclear standards for regulators and unrealistic expectations among stakeholder communities (Holmes et al. 2015). Observations in Australia point at frequent confusion between objectives and criteria, which results in the definition of arbitrary, irrelevant targets (Fawcett & Laurencont 2019).

Nation and region-wide legal frameworks must be applicable to a wide range of environments (e.g. different bioregions and extractive processes), which means they are often too broad to provide detailed guidance to specific mine sites (Blommerde et al. 2015). Such challenges in the definition of mine completion criteria are not limited to Australia, but common across many mining jurisdictions worldwide (Holmes et al. 2015). In the European Union, companies and local regulators often find it problematic to determine when closure can be deemed achieved, because the EU's Mine Waste Directive is vague and open to interpretation (Blommerde et al. 2015). Similarly, in Canada, inadequate financial mechanisms and the lack of criteria for determining whether reclamation objectives have been met result in very few sites being relinquished (Blommerde et al. 2015; Holmes et al. 2015). Absence of clear closure targets is also a problem in Brazil, where it contributes to rehabilitation failure (de Jesus & Sánchez 2013).

Difficulties in the definition and agreement of mine completion criteria are regarded as one of, if not the most critical factor impeding closed sites from being relinquished (Butler & Bentel 2011; Murphy & Heyes 2016). Lack of adequate rehabilitation and closure is a major issue, as mine sites that do not transition into their agreed post-mining land uses, typically enter 'care-and-maintenance' mode or become abandoned (Ashby et al. 2016; Mitchell et al. 2019). It is estimated that there are millions of abandoned, orphaned or derelict mine features across with world, with approximately 600,000+ in the USA; 50,000 in Australia; 11,700 in the UK, 10,100 in Canada and 8,000 in South Africa (Unger et al. 2012; Worrall et al. 2009). When left unmitigated, negative mining legacies may result in risks to humans and the environment, as well as damage to the reputation of industry and governments (Unger 2017).

In Australia, loose regulatory frameworks have given rise to a high level of company self-regulation and varying quality of rehabilitation works (Erskine & Fletcher 2013). Mining proponents often resort to their own internal procedures or other similar mine sites to inform the definition of completion criteria (Young et al. 2019). Despite industry's "self-reliance" as a source of guidance, in practice, there appear to be only a few Australian sites achieving successful rehabilitation and closure (Lamb et al. 2015), and even fewer of examples of relinquishment (Tiemann et al. 2019). It is understood that poor rehabilitation outcomes are relatively common, yet underreported in the literature (Lamb et al. 2015).

Although numerous mine sites have been rehabilitated without clear closure criteria or achieving less than desirable environmental outcome, they are still used by proponents as examples to inform future rehabilitation plans (Hernandez-Santin et al. 2020). For instance, in Western Australia, the Department of Mines, Industry Regulation and Safety maintains a public record of over 500 approved mine closure plans (DMIRS 2019a). However, such plans do not necessarily reflect all requirements set by regulators and typically lack the detail required to understand the science guiding the definition of completion criteria.

Much of the knowledge on mine rehabilitation and closure remains lost in the grey literature, including internal documents or compliance reports (Hernandez-Santin et al. 2020). Indeed, academic publication is often a low priority for companies, and disclosure of innovative approaches can be discouraged or barred by corporate or government policies (Hernandez-Santin et al. 2020). Nonetheless, a growing body of literature is dedicated to documenting and sharing industries' best-practices and successes (see Table S1 in supplementary materials). The majority of these studies are strongly focused on narrow rehabilitation aspects and geographic scopes (e.g. revegetation in Western Australia's south west region), which hinders the process of learning from and replicating best-practices.

The aim of this study was to conduct a synthetic review of best-practices that can inform the definition of industry-standard mine completion criteria, in a manner that is relevant to a variety of mining environments and jurisdictions worldwide. The research was conducted in two steps: i) a qualitative meta-analysis of the academic literature addressing definition of mine completion criteria and ii) three in-depth case studies illustrating current best-practices by leading mine operators in Western Australia.

To the authors' knowledge this is the first comprehensive study addressing best-practices in the definition of mine completion criteria. The results present evidence that can be used by mining practitioners and regulators around the world to improve the definition of mine completion criteria, thus facilitating more sites to advance towards closure and relinquishment.

2. *Materials and Methods*

2.1. *Meta-analysis*

The systematic review of the global literature on mine completion criteria was done in the form of a qualitative meta-analysis, whose aim was to aggregate findings and identify commonalities across primary studies (Levitt 2018). Qualitative meta-analyses are also referred to as meta-synthesis, given the process is typically more interpretive than aggregative, as opposed to meta-analysis in quantitative research (Timulak 2014).

The methodological steps of the literature review are described below. A summary overview of the five steps of the article search and selection process is presented in Figure 1.

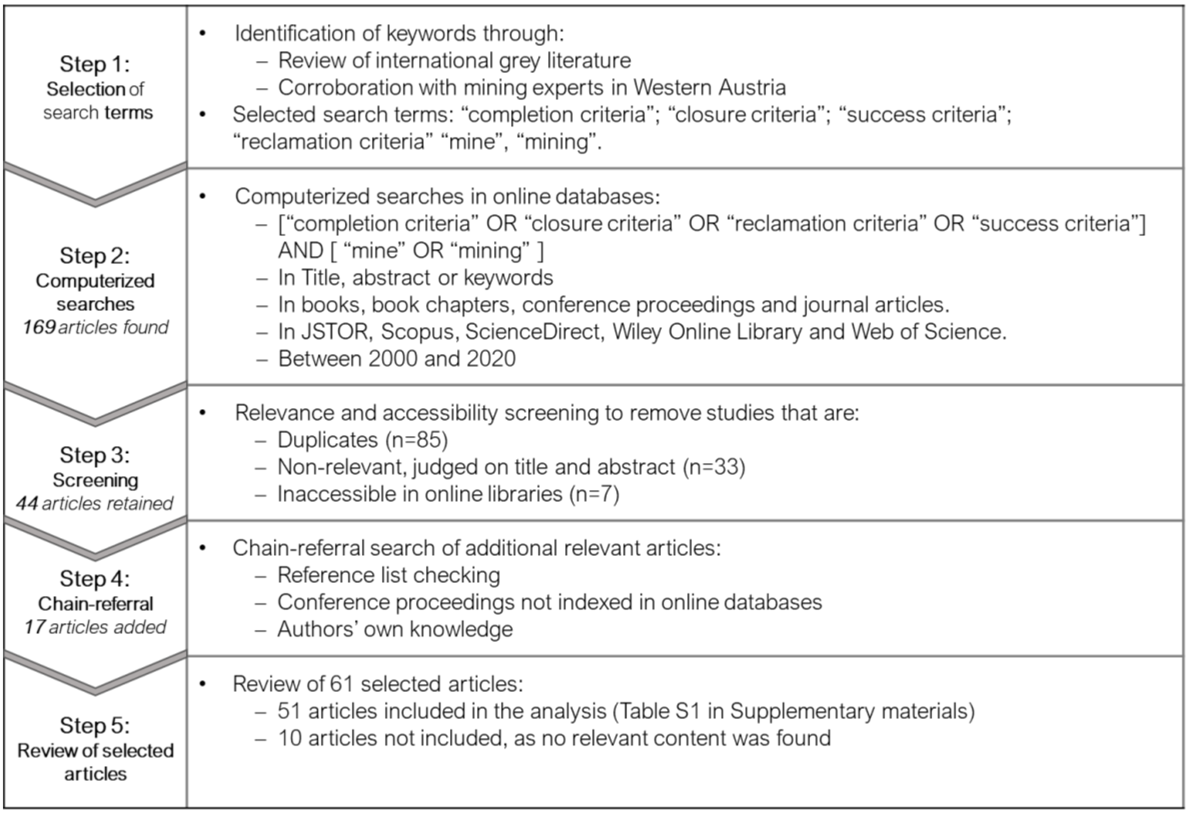

Figure 1. Overview summary of the literature search and article selection process

Search terms were initially informed through review of the international grey literature (i.e. mine rehabilitation and closure guidelines and company reports), and then corroborated with mining experts in Western Australia (comprising practitioners, regulators, researchers and consultants). Details of the grey literature review and stakeholder consultation process can be found in Young et al. (2019). Hence, the terms included in the search were: "completion criteria"; "closure criteria"; "success criteria"; "reclamation criteria" – in combination with "mine" or "mining".

Secondly, we completed a series of computerized searches of online databases: JSTOR, ScienceDirect, Scopus, Web of Science and Wiley Online Library. Terms were searched in titles, abstracts and keywords. To ensure a minimum quality standard (Levitt 2018), the search was limited to research published in English language, in books, book chapters, conferences proceedings and journal articles. Only studies in or after the year 2000 were included, to capture recent advances in best-practices. A total of 169 articles were identified.

Thirdly, papers that would or could not be reviewed were excluded, i.e. duplicates (n=85), not fitted to our research question (e.g. data mining) (n=33) or inaccessible through online libraries (n=7). Where possible (n=1), a copy of the study was requested from the corresponding author, but no answer was received. Consequently, 44 studies were retained for the meta-data analysis.

Additional studies (n=17) were identified through a process of chain-referral (Britton et al. 2020), were relevant papers were identified through reference list checking and the authors' own knowledge. These included, among others, peer-reviewed proceeding of the *Mine Closure* conference series, which is not indexed in the online databases. Inclusion of new articles was stopped as the process reached the point of data saturation, where new data repeated themes identified hitherto (Saunders et al. 2018).

Finally, selected studies (n=61) were reviewed to identify best-practices in the definition on mine completion criteria. Common themes (i.e. groups of similar best-practices) were identified through the qualitative analysis method 'thematic mapping'. In particular, *in-vivo* coding technique was used, where conceptual categories of a word of phrase express the meaning of the information coded under that category in a concise way (Thornberg & Charmaz 2014). The meta-data were coded into researcher-defied categories using NVivo software (Sotiriadou et al. 2014). A comprehensive summary of identified best-practices, sorted into common themes, is presented in Table S1, in the Supplementary Materials. The analysis comprises 51 studies, as the rest (n=10) were found to contain no relevant information regarding best-practices in the definition of mine completion criteria.

2.2. Case studies

Case studies were selected to represent the diversity of mining activities in Western Australia including bioregion and commodity, e.g., iron ore, bauxite (Young et al. 2019). The Pilbara region was prioritized given the significant impact of iron ore mining on its social and natural environments and the capacity for the industry to set standards of best-practice rehabilitation. Thus, BHP provided a case study of their Goldsworthy Northern Areas. The second case study was provided by Mount Gibson Iron, showcasing the capacity of a medium-sized company to achieve success in the state's mid-west bioregion. The third case study was provided by Alcoa of Australia on their experience achieving success with mine rehabilitation, closure and relinquishment in jarrah forest. To our knowledge, Alcoa is the only company in the state, and one of only a few in Australia, to have achieved relinquishment. With the exception of the state's extensive gold mining operations, for which we were unable to recruit a case study, the three case studies broadly represent the state-of-the-art with regards to the development of completion criteria for mine rehabilitation and closure in Western Australia.

Research for each of the three case studies in this paper was split into two phases, carried out between April and July 2019. Firstly, a document review was completed, primarily involving company reports, such as mine closure plans. Second, semi-structured interviews were conducted in person with expert staff in mine rehabilitation and closure planning. The aim of the interview was to fill knowledge gaps evident after the document review or to provide more detail on specific topics.

The semi-structured interviews were carried out following a pre-defined interview guide, comprising a list of topics to cover and a series of open-ended questions (Ayres 2008). A copy of the interview guide is provided in the supplementary materials (Table S2).

Alcoa

Alcoa of Australia has mined bauxite in the northern jarrah forest since 1963 and has practiced mine site rehabilitation since 1996 (Koch 2007a). The company started mining operations at Jarrahdale, 60 km south-east of Perth, and have progressively moved further south to the mines currently in operation at Huntly and Willowdale. The mines fall within the Peel and South-West regions, where the climate is Mediterranean, with dry, hot summer, and wet, cool winters (Young et al. 2019). The region is characterized by its rich biodiversity, comprising 780 native plant species, 235 terrestrial vertebrate species and tens of thousands of invertebrate species (Grant & Koch 2007).

Mine rehabilitation activities occur concurrently within the forest, with the first efforts involving planting exotic pine trees into topsoil over an unripped mine pit (Koch 2007a). Nowadays, approximately 550 ha of forest is cleared, mined and rehabilitated each year (Koch 2007a). The goal is to establish a self-sustaining jarrah forest ecosystem, capable of supporting conservation and recreational forest values and uses (Gardner & Bell 2007; Rosa et al. 2020). In 2005, 17 years after the Jarrahdale mine ceased operations and four years after mine rehabilitation was completed, Alcoa successfully relinquished the first 975 ha parcel of rehabilitated jarrah forest (~25% of the Jarrahdale mine) to the state government for the purposes of biodiversity conservation, timber, water management, and public recreation (Grant & Koch 2007). Alcoa continues to refine its best practice mine rehabilitation through an active research program and adaptive management (Alcoa 2019; Daws et al. 2019; Richardson et al. 2019; Standish et al. 2018).

BHP Billiton

BHP Billiton is the world's largest mining company, by market capitalization (PWC 2019) and one of the top three producers of iron ore in Western Australia, particularly in the Pilbara region (DMIRS 2019b). The Pilbara's iron ore accounts for 78% of the Western Australia's value of minerals (DMIRS 2019b) and 16% of global iron ore production (Shackelford et al. 2018). BHP Billiton's Goldsworthy Northern Areas (GNA) mining hub is located 178km east of Port Hedland (on the north coast of the Pilbara region) and comprises eight separate mines sites. The GNA was in operation between 1992 and 2014, with progressive rehabilitation starting in 1995. The Cattle Gorge mine had its rehabilitation program finalized in 2016, thus constituting the most recent example of rehabilitation in BHP's GNA mining hub.

The Pilbara region has a semi-arid climate with irregular and intense rainfall events, mainly associated with tropical summer storms (Sudmeyer 2016), which makes timing of vegetation re-establishment critical for rehabilitation success (Muñoz-Rojas et al. 2016). The Pilbara is home to an estimated 1,800 flora species (Shackelford et al. 2018) and hundreds of fauna communities, including Ghost Bats (*Macroderma gigas*), whose roosts are particularly susceptible to mining disturbances (Armstrong 2010). Across the eight mines in the GNA hub, the disturbed area covers 230 ha, comprising perennial hummock grasses, woody shrubs and sparse trees (Shackelford et al. 2018). The GNA mining leases (established in 1964) overlay pastoral leases and, in accordance with stakeholder consultation, the proposed post-mining land use is 'low-intensity grazing'.

Mount Gibson Iron

Mount Gibson Iron is a Perth-based independent iron ore producer established in 1996. Tallering Peak was the company's first mine, located 175 km northeast of Geraldton and approximately 500 km northeast of Perth. Mining operations at Tallering Peak commenced in 2004 and ceased in 2014, with the rehabilitation of the final site completed in 2015 (Mount Gibson Iron 2020). At the time of writing, the company was progressing mine closure to achieve site relinquishment.

During operations, the Tallering Peak Iron Ore mine site consisted of three open pits and three waste dumps, with a total area of disturbance close to 400 ha. The area is characterized by its semi-arid climate and native shrubland (e.g. *Acacia* shrubs) communities. The mining tenements overlay the long-established pastoral leases of Wandina and Tallering Pastoral Stations. Pre-mining land use was low-intensity grazing of rangeland goats, and thus, post-mining land use was agreed to be returned to pastoral activities. This was decided through a stakeholder consultation process involving regulators, local councils, residents and the mine site's current pastoral lease holder.

3. Results

3.1. Meta-analysis

We identified ten best-practices in the definition of completion criteria, as detailed below.

Multiple types of references

The use of multiple types of references to set completion criteria was the most common best-practice, appearing in 24 of 61 studies. It is recognized that in highly-altered mining landscapes, it can be unfeasible to restore pre-mining ecosystems (Lamb et al. 2015), although this is still the most prevalent closure goal in Australia (Meney & Pantelic 2019; Rosa et al. 2020) and elsewhere, e.g. the USA (Krzyszowska Waitkus 2018). In some cases, it has been reported that mines without an analogue reference have embarked on rehabilitation with no reference at all (Morrison et al. 2005). In response to the difficulties in developing achievable completion criteria based on pre-disturbance conditions alone, a growing number of studies are incorporating a range of alternative references to inform targets. Multiple references may be used to generate a 'modelled' benchmark (Bollhofer et al. 2014) or 'conceptual aspirational model' (Neldner & Ngugi 2014a).

Possible references that may be used in combination with pre-disturbance or analogue sites include: alterative land uses (Brooks 2000; Coppin 2013; Rosa et al. 2020), industry-leading rehabilitation practices (Coppin 2013; Erskine & Fletcher 2013; Nichols et al. 2005), monitoring data (Jones et al. 2008), nearby undisturbed sites (Coppin 2013; Hernandez-Santin et al. 2020; Morrison et al. 2005; Neldner & Ngugi 2014a; Ritchie & Krauss 2012; Thompson & Thompson 2004), 'novel' ecosystems (Doley & Audet 2016; Erskine & Fletcher 2013; Gillespie et al. 2015), science-informed expected vegetation growth trajectories (Blanchette et al. 2016; Ngugi et al. 2015; Osborne & Brearley 2000; Whiteside et al. 2020), stakeholders' and right holders' expectations (Doley & Audet 2016; Jones et al. 2008; Lamb et al. 2015; Nichols et al. 2005; Rosa et al. 2018; Simth & Nichols 2011). Although *nearby undisturbed sites* do not reflect changes resulting from mining, they remain a valuable reference as they may reveal external impacts occurring over the life-of-mine, such as fire, climate change or colonization by invasive species, which would be absent in pre-mining (baseline) conditions. Importantly, references based on new data, such as monitoring or expected trends, should be supported by well-defined monitoring programs and research program, as explained in the sections below.

Monitoring and corrective actions

The second most common best-practice identified (n=21) was *monitoring and corrective actions*, whereby the definition of completion criteria should be accompanied by regular and targeted monitoring of rehabilitation progress (Koch & Ward 2005). Easily measured indicators are recommended (Ludwig et al. 2003) to detect and document successional states (Craig et al. 2015; Morrison et al. 2005), through which the rehabilitated landscape will transition over the life-of-mine. It is advised that monitoring should be more frequent in early stages of rehabilitation and post-disturbances (Hernandez-Santin et al. 2020), and even expand into the long-term after decommissioning (Jones et al. 2008; Nichols et al. 2005).

Most notably, monitoring data should be analyzed to understand if rehabilitation goals have been met or are on track to being met, thus providing the managers with the information needed to make timely decisions (Lacy et al. 2008; Stedille et al. 2020). When a risk of non-compliance is detected, interim completion criteria based on trajectory may act as 'trigger levels' (Nichols et al. 2005) to determine the need and extent of rehabilitation rework, i.e. 'corrective or remedial actions' (Fawcett & Laurencont 2019; Nichols et al. 2005; Simth & Nichols 2011) or 'adaptive contingent management' (Blommerde et al. 2015).

In Canada (Holmes et al. 2015) and Australia (Ngugi et al. 2015), monitoring has been proposed as a suitable diagnosis tool forming part of the assessment protocol for seeking relinquishment. Furthermore, monitoring also plays a critical role in building a knowledge to inform how different early restoration practices may be associated with future trends, ecosystem resilience and functionality (Gillespie et al. 2015; Grant 2006a; Grant & Koch 2007; Thompson & Thompson 2004).

Scientific research to understand rehabilitation trends and inform achievable criteria

In highly disturbed mining landscapes, it is often not know if, when or how ecosystems will recover (Hernandez-Santin et al. 2020; Meney & Pantelic 2019), or if they will do according to entrenched assumptions (Cristescu et al. 2013). Such rehabilitation uncertainties make it difficult to define *achievable criteria*, particularly in early stages of the life-of-mine – as it is typically required by regulators (DMP & EPA 2015; Sánchez et al. 2014; South African Government 2015). At the same time, it is recognized that rehabilitation success is heavily dependent on the degree of understanding and its application to rehabilitation processes (Meney & Pantelic 2019), e.g. linking environmental variables and vegetation recovery (Burke 2018). Thus, the use of scientific research to understand rehabilitation trends and inform achievable criteria was the third most found best-practice in the literature (n=20).

To overcome the knowledge gap, over the last few decades, a number of mining practitioners and academics have been doing scientific research to better understand the drivers of rehabilitation success. This is because long-term monitoring and research programs provide closure planners with greater certainty of what recovery trends can be expected over the life-of-mine and post closure (Koch 2007b), and what are (likely) achievable mine completion criteria (Nichols et al. 2005; Simth & Nichols 2011; Whiteside et al. 2020). The continual advancement of research and development is considered as a critical pathway to improve mine closure, as certain rehabilitation challenges can be addressed specifically by targeted research (Lamb et al. 2015).

For instance, enhanced rehabilitation outcomes could be possible through a better modelling and understanding of how spatial patters determine composition, function, resilience or structure of future flora populations (Miller et al. 2010; Ngugi et al. 2015; Nichols et al. 2005; Norman et al. 2006). As an example, Alcoa's 40+ years research programs in their bauxite mines in Western Australia's South West have shown how nitrogen fertilizer significantly increased exotic species richness, density, and cover (Norman et al. 2006); and how different prescribed burning regimes may result in better integration of the restored forest with the surrounding plant community (Grant 2003; Grant & Loneragan 2003; Grant et al. 2007; Morley et al. 2004).

Holistic rehabilitation measures

Rehabilitation success has been traditionally judged upon a suite of ecological (e.g. Muñoz-Rojas (2018); Turner et al. (2017)) or geo-physical factors (e.g. Emmerton et al. (2018); Hancock et al. (2019). However, because certain rehabilitation factors influence others (Amoah et al. 2011), is increasingly recognized that mine completion criteria should reflect the interlinkages and complexities associated with multiple factors. It is collectively – not individually – that critical factors will reflect rehabilitation success in a more accurate way (Doley & Audet 2016; Jones et al. 2008). Completion criteria should consider potential cumulative effects from neighboring mines (de Jesus & Sánchez 2013), as well as changes in ecological processes over the life-of-mine (Craig et al. 2015). Thus, the use of *holistic rehabilitation* criteria was adopted or recommended by 20 out of the 61 studies analyzed.

In the reviewed studies, Landscape function analysis (LFA) were often proposed as a useful method for assessing and monitoring mine site rehabilitation, which focusses spatial processes and uses filed indicators to generate indices that reflect the functional status of the rehabilitated landscape (Bao et al. 2014; Doley & Audet 2016; Gillespie et al. 2015; Grant & Loneragan 2003; Morrison et al. 2005; Tongway & Ludwig 2006). Similarly, ecosystem function analysis (EFA), which comprises LFA, erosion, habitat complexity and vegetation – can be used to inform fauna and flora rehabilitation criteria (Lacy et al. 2008; Lamb et al. 2015; Nichols et al. 2005; Tongway & Ludwig 2006). While LFE and EFA are common, these indices are qualitative measures, and detailed quantitative studies would be required to measure specific ecological functions such as carbon storage and litter decomposition. Other proposed multi-factor assessment tools include 'habitat complexity indices' (Ludwig et al. 2003), 'habitat suitability models' (Nelson et al. 2005), 'ecosystem services' (Coppin 2013; Rosa et al. 2018), 'five-star scale' (Hernandez-Santin et al. 2020) and 'spiderweb-like diagrams' (Neldner & Ngugi 2014b; Ngugi et al. 2015).

Dynamic targets

Long-term monitoring has revealed in many mine sites that rehabilitation may transition through multiple states, before reaching the state deemed suitable for closure. It is, therefore, critical that completion criteria are defined on the basis of successive 'conceptual' stages (Blommerde et al. 2015) and targets are regularly reviewed, as more monitoring data become available (Coppin 2013). The use of *dynamic targets* in the definition of completion criteria is prescribed by a growing number of studies (n=16).

The 'state-and-transition succession model', developed for jarrah forest restoration by Grant (2006a), is used to identify desired and deviated successional states, which then informs the risk of not meeting completion criteria. Several later studies (Craig et al. 2015; Doley & Audet 2016; Hernandez-Santin et al. 2020; Koch 2007b; Morrison et al. 2005; Nichols et al. 2005) have endorsed the 'state-and-transition succession model' as a valuable tool to inform rehabilitation practices and definition of achievable completion criteria.

Leading indicators

Because ecological restoration is an inherently slow process, many ecological completion criteria, such as vegetation density (Ngugi et al. 2015) or fauna return (Cristescu et al. 2013), may take decades before they reach their target levels, when they can be evaluated. These so-called 'lagging' indicators contrast with 'leading' indicators, which can be measures in early phases of rehabilitation, as an indication of future rehabilitation outcomes (LPSDP 2016). In addition to frequently used performance-based criteria, it is also possible to define 'prescriptive' criteria based on actions that have been carried out, such as construction or protection of fauna habitat features (Gardner & Bell 2007; Nichols et al. 2005). In our meta-analysis, *leading indicators* were presented in 15 studies, as an effective tool to define mine completion criteria and timeframes for relinquishment (Lamb et al. 2015).

Leading indicators of vegetation rehabilitation criteria may include microbes (Blanchette et al. 2016); Na, Al, pH (Di Carlo et al. 2020); legume density, topsoil cover, ripping depth (Grant 2006b) and lines (Ludwig et al. 2003); tree height and spacing of trees at planting (Koch & Ward 2005); species composition (Ngugi et al. 2015) and diversity (Nichols et al. 2005) in the seed mix; species abundance distribution and taxonomy group (Stedille et al. 2020). Notably, orchids may signal mycorrhizal fungi recovery (Collins et al. 2005), which, in turn, can be used as indicators for plant–nutrient relations (Ludwig et al. 2003). Flora variables are also critical to develop 'leading' indicators of fauna recolonization, given the difficulty in measuring mobile fauna.. Examples include species richness in food trees favored by koalas (*Phascolarctos cinereus*) (Cristescu et al. 2013), canopy characteristics supporting squirrel population (Nelson et al. 2005) and vegetation structural characteristics correlated with the overall avian community (Craig et al. 2015). Importantly, such fauna 'leading' indicators need to be based on corroborated science evidence - not commonplace assumptions (Craig et al. 2015; Cristescu et al. 2013).

Integration of rehabilitation with mine operations

A key success factor in mine rehabilitation and closure is the timely integration of rehabilitation and ecosystem restoration with life-of-mine planning and operation (Amoah et al. 2011; de Jesus & Sánchez 2013; Doley & Audet 2016; Nichols et al. 2005; Szwedzicki 2001). Thus, closure objectives and completion criteria should be defined early in the life-of-mine, e.g. during the design or conceptual stages (Coppin 2013; Fawcett & Laurencont 2019; Jones et al. 2008). Once defined, completion criteria should be used throughout the life-of-mine (Holmes et al. 2015) to guide progressive rehabilitation and continuous improvement (Meney & Pantelic 2019; Morrison et al. 2005). In Australia, it is advised that regulators require greater degree of progressive rehabilitation, which should be explicitly included into the business accounting practices (Lamb et al. 2015). A total of 12 studies were found that highlight the importance of setting completion criteria on the basis that progressive rehabilitation is carried out as an integral part of the overall mining process.

Innovation (not regulation) to guide definition of completion criteria

While mine rehabilitation and closure regulations tend to be broad and conservative (Blommerde et al. 2015; Lamb et al. 2015), a number of recent studies (n=11) relied on science and innovation to guide the definition of completion criteria. In an exemplary case of mine site rehabilitation, Alcoa (has a longstanding commitment to keep a high level of environmental and restoration performance, ahead of any legislative requirements (see *Alcoa* in-depth case study in Section 3.2) (Gardner & Bell 2007; Grant & Koch 2007). In the USA (Nelson et al. 2005) and Australia (Richardson et al. 2019), the use of laser technologies is becoming more widespread to record vegetation data and estimate restoration attributes. Similarly, Unmanned Aerial Vehicles (Fletcher & Erskine 2013; Johansen et al. 2019) and object-based image analysis (Bao et al. 2014; Whiteside et al. 2020) allow improved monitoring and performance evaluation, compared to conventional on-ground data gathering. Other innovative practices used in the definition of completion criteria are Geographic Positioning Systems readings to determine pre-mining radiological conditions (Bollhofer et al. 2014), Geographic Information System (GIS) to collect and manage bond release data (Krzyszowska Waitkus 2018) and genetic management and integration of the plant *Banksia attenuata* (Ritchie & Krauss 2012).

Specific objectives and indicators to accompany completion criteria

One of the difficulties in consistent definition of completion criteria is the confusion and misuse of key terms such as criteria, attributes, objectives, 'sub-objectives', goals, indicators and parameters (Coppin 2013; Fawcett & Laurencont 2019; Meney & Pantelic 2019; Worrall et al. 2009). In the meta-analysis, nine studies were found that express the need for completion croetia to be accomapied by performance indictors, under the overach of closure objectives.

As prescribed by the Australian federal and state governments (Blommerde et al. 2015), it is critical that mine rehabilitation and closure planning clearly distinguish between: i) closure objectives, as the required outcomes that guide overall rehabilitation principles (Fawcett & Laurencont 2019; Lamb et al. 2015); ii) completion criteria, as agreed standards or levels of performance that indicate rehibition success (Manero et al., 2020); and iii) performance indicators, which provide measures of change in completion criteria (Szwedzicki 2001). In addition, some comapies like Alcoa set their own itnernal objectives to be used in self-certification (Grant & Koch 2007; Nichols et al. 2005).

Risk-based definition of completion criteria

Building on the concept of *dynamic targets*, whreby compeltion criteria should be regulary reviwed and updated based on evolving rehbialtion cirusmtamnces, it is essential that risk is taken into account as ciritcal factor in the definition and monitoirng of completion crieria (Coppin 2013). Understing risk posed by each rehabiation-related facotrs, allows targered planning and execution of rebiaation and closre tasks (Jones et al. 2008). The use of risk evalaution in the defintiono of compltion reria was found in seven studies.

While all facets of rehabilitation are important, it is increasignly recognized that not all closure outcomes and completion criteria entail the same level of precision for the success of rehabilitation (Meney & Pantelic 2019). Thus, risk-based multi-criteria analysis (Hutchison et al. 2011) and 'three-tier hiearchy' (Jones et al. 2008) have been proposed as valuable tools in mine closure planning and the definition of compeltion criteria. The criticality of closure outcomes and completion criteria may depend, for instance, on their relevance for the local community or their ability to support certain priority wildlife species (Lamb et al. 2015). Importantly, risk-based approaches for rehabilitation and closure planning should be tailored to each site, and even to each domain or feature within the same site (Meney & Pantelic 2019), e.g. open voids, tailings, waste rock landforms and infrastrucure. Risk-based methods for definition of completion criteria may inform the selection of the most appropite rehabilitation methods (Meney & Pantelic 2019), as well as serve to identify residual risks resutling in potentail rehabilitation failure (Simth & Nichols 2011).

3.2. Case studies

Alcoa

Mine rehabilitation occurs in tandem with mining operations at Alcoa bauxite mines in the northern jarrah forest (i.e., rehabilitation is progressive). Since the 1990s, the restoration objective has been to return a self-sustaining jarrah forest ecosystem with associated water, timber, recreation and conservation values (Gardner 2001). The completion criteria associated with these objectives are based on five key principles that are reviewed periodically: land use, integrated landscape, sustainable forest growth and management, resilience to disturbances such as drought and fire, and integrated management (Young et al. 2019). Alcoa's commitment to success has been motivated by recognition of the remarkably diverse jarrah forest ecosystem and the desire to maintain its unique cultural and environmental values for the people of Perth (Grant & Gardner 2005). Significantly, Alcoa's internal standards of mine rehabilitation exceed regulatory requirements (Grant & Gardner 2005). This is becausee Alcoa has consistently endeavoured to maintn itsef as an idutry leadr, whose research and knowladge serve to infrom regulatory changes and set high indsutry standards (Gardner & Bell 2007).

Completion criteria for jarrah forest rehabilitation have been developed and refined through five decades of research and practice. Example completion criteria include a minimum density of legumes established at nine months and plant species richness within the range of reference forest at 12 years and older (Young et al. 2019). To achieve these criteria, research has revealed the benefits of: ripping the pit floor to alleviate soil compaction, using fresh topsoil, and among other lessons, refining amounts of P-fertiliser to achieve high species richness in the understorey without compromising growth of the dominant trees. In practice, regular monitoring is used to identify whether completion criteria have been met or will likely to be met in time (Figure 2). Alcoa use leading indicators to highlight whether intervention is needed to achieve key completion criteria. For example, density of jarrah nine months after the onset of rehabiliation is a leading indicator of forest development and may trigger reseeding or thinning to obtain optimal density of jarrah (Figure 2).

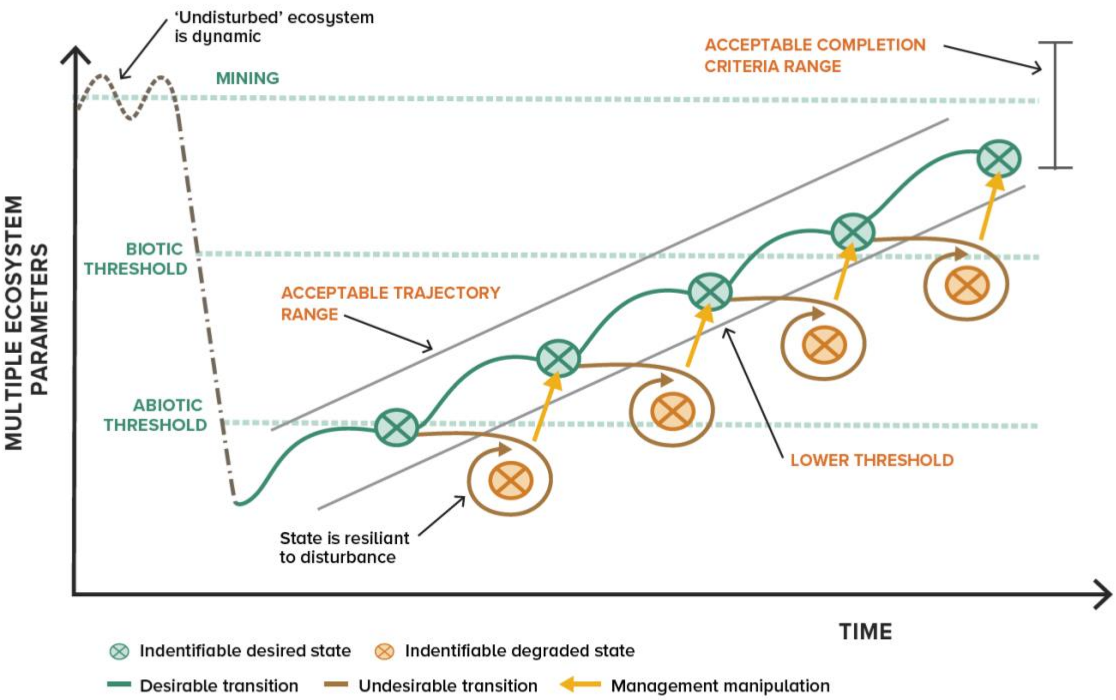

Figure 2 Regular monitoring of Alcoa's rehabilited jarrah forest is used to identify the likelihood of achieving time-bound completion criteria and the ultimate restoration objective. Deviated states (in brown) trigger intervention to promote rehabilitation along the desirable trajectory (in green). Adapted from Grant (2006a) and reproduced here with permission from Young et al. (2019).

BHP Billiton

Completion criteria at the GNA mine sites were guided by the company's 'outcome-based' hierarchy, which underpins BHP Billiton's closure and rehabilitation planning. The hierarchy clearly distinguishes between four echelons: *vision, objective, guiding principles* and *completion criteria* (BHP Billiton Iron Ore 2017b). The *vision* responds to corporate values to create enduring, positive legacies for stakeholders and local communities. For each specific mine site, the vision is aligned with the post-mining land use, which is agreed based on social, environmental, legal and technical factors. In accordance with state regulations (DMP 2016), the closure *objective* is to 'develop a safe, stable, non-polluting and sustainable landscape that is consistent with key stakeholder agreed social and environmental values and aligned with creating optimal business value' (BHP Billiton Iron Ore 2017a p. 21) for the site to be safe, stable, non-polluting, capable of sustaining closure goals principles set in accordance with the state regulatory guidelines, mandating that rehabilitated mine sites reach a state that is safe, stable, non-polluting/non-contaminating, and capable of sustaining the agreed postmining land use (DMP 2016). BHP Billiton's guiding closure principles, for iron ore operations in the Pilbara region, are defined for 11 aspects, such as safety, landforms, water and ecosystem sustainability. For each of these, a *guiding principle* outlines what the company commits to achieve at closure, e.g. 'Ecosystem Sustainability: Areas demonstrated to be sustainable, resilient, and capable of meeting objectives relating to agreed final land use in terms of flora, vegetation, fauna, and surface and groundwater hydrology' (BHP Billiton Iron Ore 2017a p. 22). Finally, *completion criteria* are used as the measures against which progress towards *guiding principles* can be assessed. For example, a *completion criterion* relative to ecosystem sustainability was 'vegetation survival over one or more seasons of low rainfall'. For more accurate assessment, numeric targets could be included specifying the required level of vegetation survival (e.g. percentage or revegetated area).

Another crucial factor contributing to BHP Billiton's GNA rehabilitation success is the use of research and regular monitoring to inform dynamic revegetation objectives and the adjustment of appropriate ecological restoration techniques (i.e. *corrective actions*) (Shackelford et al. 2018). This is part of the company's adaptive management approach, whereby specific mine closure plans are updated to account for closure risk, liability, innovations and stakeholder requirements (BHP Billiton Iron Ore 2017a). Thus, knowledge gaps at each site, and within domains of a site, are identified and research programs are prioritized, according to the risk of not meeting rehabilitation requirements (Young et al. 2019).

BHP Billiton's seed research program is an illustrative example of innovation and adaptive management, towards ecological restoration that is able to comply with highly demanding completion criteria. In semi-arid regions like the Pilbara, revegetation of woody species in is typically quick and successful, often leading to undesired over-abundance in rehabilitated areas (Golos et al. 2016; Morrison et al. 2005). Consequentially, to improve vegetation outcomes to better match the surrounding (analogue) sites, BHP Billiton modified the germinable fraction of physically dormant seed in the seed mix, and reduced seed being sown (Shackelford et al. 2018). Moreover, research and monitoring at the BHP Billiton Pilbara sites, identified innovative ways to improve management of seed storage and growth media, as well as new technologies for seed enhancement (Erickson et al. 2017). In recognition of very wide range in seed longevity across species and through industry-research collaborations, BHP Billiton developed an effective, structured seed collection and storage programs, resulting in the ability to keep high-quality stocks that are sufficient to supply seeds over a 3-5 years period of future (Erickson et al. 2017). Further, the adoption of innovative 'flash flamming' processes proved successful in the removal of unwanted seed appendages, while seed-enhancement technologies (priming, pelleting, and coating) improved germination (Erickson et al. 2019). Nevertheless, an important challenges remains to increase the precision of seeding rates and placement in the field, to ensure that success of seed collection, storage and enhanced are not in vain (Erickson et al. 2019).

Mount Gibson

Progressive rehabilitation of the Tallering Peak mine site was conducted in accordance with the long-term goal 'to re-establish productive land surface that required minimal ongoing maintenance and management (i.e. stable and safe)' (Young et al. 2019). Accordingly, revegetation of disturbed areas was carried out with a self-sustaining system of native species, with similar diversity, density and cover to the pre-mined ecosystem. Given the various stages of progressive rehabilitation across multiple domains within the mine site, the age of restored vegetation ranged from two to 12 years old, at the time of writing. Furthermore, when no longer required, infrastructure associated with mine operations was progressively decommissioned, thus facilitating timely rehabilitation and reducing the site's long-term liability. Because of the varying characters and their stages of progressive rehabilitation across the mine site, closure objectives and completion criteria were tailored to each mine domain, distinguishing, for example, between open pits, infrastructure and waste dumps. Examples of closure objectives, completion criteria and monitoring protocols can be found in the publicly available Tallering Peak mine closure plan (Mount Gibson Iron 2016).

The final version of the mine closure plan (Mount Gibson Iron 2016), together with the 2016 Annual Environmental Report (DMIRS 2016), demonstrates that, after 10 years of progressive rehabilitation, 98% of the site area had been successfully rehabilitated. A comparison of before and after rehabilitation conditions (2012-2018) is depicted in Figure 3. In 2016, 23 out of 26 completion criteria had achieved 100% progress, while only three (relinquishment, fencing and stakeholder consultation) required further action. However, after finals reports were drafted, in 2017, a 160-day dry spell affected the revegetation in the two younger waste landforms, thus resulting in reduced plant richness and density. Consequently, at the time when the site was being assessed for relinquishment in late 2017, the completion criterion for vegetation cover had fallen below its agreed target of 75% of the man recorded for analogue sites. Such fallback prevented the mine from successful relinquishment, despite the vegetation cover criterion having been met in 2016 and similar drops in vegetation indicators in the analogue site due to the drought conditions. In personal consultation with closure planning personnel, a desire was expressed that, instead of a sequence of "tick boxes", rehabilitation success would be assessed on a holistic basis, taking into account the overall state of the site, for example, through Landscape Function Analysis.

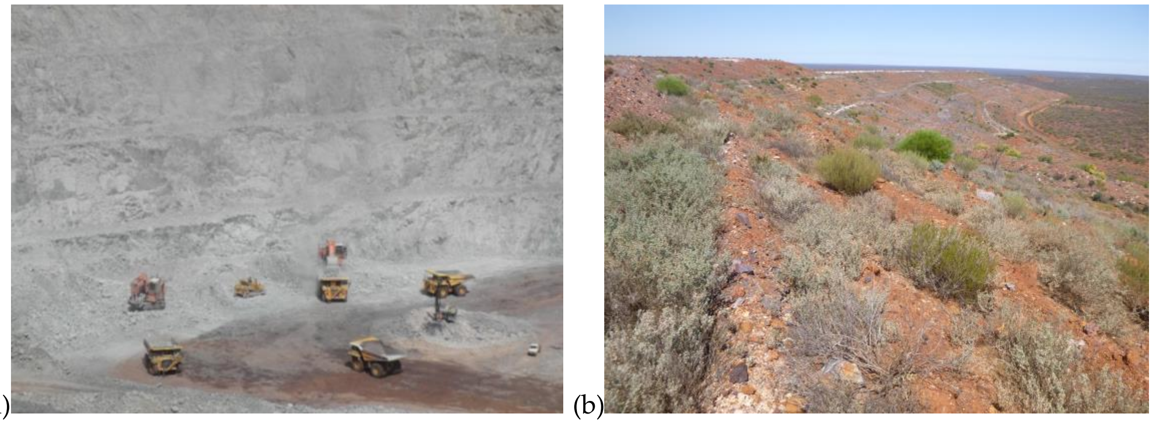
(a) (b)

Figure 3 Tallering Peak waste dumps in 2012 (a) and 2018 (b). Source: Courtesy of Mount Gibson Iron

4. *Discussion and conclusion*

Defining achievable, demonstrable mine completion criteria is crucial for rehabilitation and closure success, yet the widespread practice of setting aspirational, unrealistic targets contributes to many mines becoming abandoned (Unger et al. 2020). Across the world, legislative requirements are defined to be relevant across the entire jurisdiction they cover, which, in turn, renders them vague and impractical for application at the level of specific mine sites. Thus, mining proponents often resort to comparable examples of past rehabilitation to guide their own goals, which results in a perpetuation of past failures and slow innovation (Hernandez-Santin et al. 2020). A growing body of academic literature presents novel advances in the definition of mine completion criteria, although these are very rarely consulted by mining proponents, because the knowledge reported tends to be highly specialized and can be difficult to interpret and transfer (Young et al. 2019). To bridge the current gap between scholarly innovation and advances in practice, in this study, we report on ten research-informed best-practices in the definition of mine completion criteria, and we put them into context through three recent examples of mine rehabilitation. We do this through a systematic meta-analysis of the global, peer-reviewed academic literature, followed by primary investigation of three rehabilitation case studies of mid-to-large size mining companies in Western Australia.

Through thematic analysis of 51 studies, we identify the following 10 best-practices for the definition of mine completion criteria (number relevant studies are in parentheses):

- Use of *multiple references* - such as modelled benchmark or novel ecosystems - to inform the definition realistic, achievable targets (n=24);
- Incorporation of *monitoring and corrective actions* to track rehabilitation progress and regularly update completion criteria and rehabilitation practices though 'adaptive management' (n=21);
- Use of *scientific research to predict attainable future rehabilitation outcomes*, which can be used to define achievable criteria (n=20);
- Assessment of *rehabilitation success in a holistic manner,* as opposed to a suite of disconnected criteria (n=20);
- Definition of *dynamic targets,* which reflect the multiple successional states rehabilitation will evolve trough over the life-of-mine (n=16);
- Use of *leading indicators* as 'proxies' for rehabilitation outcomes that are difficult or measure, or can only be assessed in the very long-term (n=15);
- *Integration of mine rehabilitation with operations*, to allow progressive rehabilitation and promote synergies between concurrent mining tasks (n=11);

- Unequivocal *distinction between objectives, criteria and indicators*, to accurately define, measure and demonstrate rehabilitation success (n=9);
- *Risk-based definition of completion criteria,* to inform the prioritization of rehabilitation tasks and, thus, minimize likelihood of rehabilitation failure (n=7).

It is critical to note that the above best-practices are often inter-related. For example, effective *leading indicators* cannot be defined without a solid scientific basis obtained through careful observation (*monitoring*) of rehabilitation trends and/or results of reach trials. Similarly, completion criteria based on *dynamic targets* should be set considering the evolving and *interconnected nature of rehabilitation and mining operations*, as well the changes reflected in on-the-ground data collected through regular *monitoring*.

In addition to the 10 best-practices identified in the meta-analysis, we commend the clear distinction between the terms *reclamation* and *rehabilitation*, which are often used interchangeably across the mining industry, in Australia and internationally. Inconsistencies in the definition and application of the terminology hampers the effective interpretation and communication of closure goals, while generating uncertainty for mining proponents, regulators and the research community (Cross et al. 2018). Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed (Gann et al. 2019; SERA 2017). Mine rehabilitation is a broader term, encompassing a suite of multiple activities (e.g. construction of landforms or establishment of sustainable ecosystems), aiming at returning the disturbed land to a safe, stable, non-polluting/non-contaminating state that is ecologically sustainable and self-supportive of its agreed post-mining land use (DMP & EPA 2015; LPSDP 2016). While we acknowledge the sometimes inaccurate use of *restoration* and *rehabilitation*, in the results Section 3.1, we have maintained the original term used in the cited sources, to ensure validity and transparency of the meta-analysis.

Our case studies illustrate notable rehabilitation achievements across three diverse locations in Western Australia, by Alcoa, BHP Billiton and Mt Gibson mining companies. Alcoa illustrate how their commitment to scientific research has allowed the company to achieve world-class rehabilitation outcomes (Gardner & Bell 2007). Alcoa's success demonstrates the corporate and environmental benefits of innovation-driven rehabilitation – a stark contrast with commonplace habits of short-term cost cutting and avoidance of rehabilitation trials, observed elsewhere across the global mining industry (Unger 2017). Like Alcoa, BHP Billiton's rehabilitation success is also strongly reliant on research of ecological restoration and adaptive management. For large, international operators like Alcoa and BHP Billiton, leading (rather than following) high industry standards allows them to stay ahead of regulatory requirements. Industry leadership represents a key advantage when operating across multiple geographies, particularly given the current lack of inter-state or international agreement for the definition of completion criteria (Blommerde et al. 2015). The mid-size operator, Mount Gibson Iron, highlighted the practical importance of considering rehabilitation success in a holistic manner. Despite completion criteria having been met at the time of reporting, slight shortfalls at the time of regulatory evaluation prevented the mine from progressing towards relinquishment. Arguably, rehabilitation standards should be kept high as a safeguard for the environment and post-mining land users. Even so, a more flexible, holistic approach could contribute to more mines being closed and relinquished – instead of adding to the tens of thousands of legacy sites in Australia and worldwide (Unger 2017; Worrall et al. 2009).

Our summary of best-practices and practical learnings may serve mining proponents, consultants and researchers as a catalogue of potentially beneficial approaches, which should be carefully evaluated and adapted to the specific circumstances of each mine site. We encourage future researchers to investigate exemplary case-studies of completion criteria definition across diverse geographies with high mining footprints, such as China, Russia, the USA, India and South Africa, among many others (ICMM 2018). Tailored investigations could add deeper insights into the best-practices relative to different mining processes (e.g. open pit vs. surface mining), as well as certain aspects requiring critical attention, such as tailing dams or acid and metalliferous drainage. We also encourage a culture of sharing data and knowledge, to drive future innovation, which could be favored by cooperative, long-term research projects like the CRC for Transformations in Mining Economies (University of Queensland 2020). While our analysis identified a suite of best-practices, we have not assessed which are more effective of impactful. Hence, a quantitative meta-analysis may help to identify relative contributions of success factors, e.g. investment in research and development, holistic approach by proponents and regulators or access to a public knowledge bank.

Given the shared challenges in the definition of completion criteria across major mining jurisdictions worldwide (Holmes et al. 2015), we envisage our findings to be valuable at the international level. Further, we propose that future revisions of international guidelines for the definition of completion criteria – e.g. AANDC (2013); ANZMEC and MCA (2000); APEC (2018); ICMM (2019); Sánchez et al. (2014) – take into account demonstrated, best-practices. Importantly, the current lack of internationally agreed standards for the definition of mine completion criteria calls for a collaborative, multi-lateral effort to improve worldwide rehabilitation and closure outcomes.

Acknowledgments: The authors of this paper and the Western Australian Biodiversity Science Institute (WABSI) would like to thank Mount Gibson Iron, Alcoa, and BHP for their time and effort towards this project and their openness in sharing information. The report was commissioned by WABSI and funding for this project was received from WABSI; Department of Mines, Industry Regulation and Safety (DMIRS); Department of Water and Environmental Regulation (DWER); Alcoa; BHP; Hanson Heidelberg Cement; IGO; Iluka; Rio Tinto; Roy Hill and South32. In kind support was provided by Curtin University, the Department of Biodiversity Conservation and Attractions, Murdoch University and the University of Western Australia for the authors' time. Renee Young was supported by the Australian Research Council Centre for Mine Site Restoration (ICI150100041) funded by the Australian Government. The authors acknowledge the work done by Emma Stock in the original development of the BHP Billiton case study.

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