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Review

Overlooked and undervalued: the neglected role of fauna and a global bias in ecological restoration assessments

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Abstract. Globally increasing rates of mine site discontinuations are resulting in the need for immediate implementation of effective conservation and management strategies. Surveying vegetation structure is a common method of assessing restoration success; however, responses of fauna to mine site restoration remain largely overlooked and understudied despite their importance within ecosystems as ecological engineers, pollinators, and restoration facilitators. Here we review the current state of the use of fauna in assessments of mine site restoration success globally, and address biases or shortcomings that indicate the assessment approach may undershoot closure and restoration success. We identified just 101 peer-reviewed publications or book chapters over a 49-year period that assess responses of fauna to mine site restoration globally. Most studies originate in Australia, with an emphasis on just one company. Assessments favour general species diversity and richness, with a particular focus on invertebrate responses to mine site restoration. Noteworthy issues included biases towards origin of study, study type, and target taxa. Further searches of the grey literature relating to fauna monitoring in mine site restoration, which was far more difficult to access, yielded six monitoring/guidance documents, three conference proceedings, two book chapters without empirical data, and a bulletin. As with peer-reviewed publications, grey literature focussed on invertebrate responses to restoration, or mentioned fauna only at the most basic level. We emphasise the need for global re-evaluation of regulatory standards to address these major limitations in assessing the capacity of the mining industry to comprehensively and representatively restore faunal communities after mining.

Additional keywords: mine, rehabilitation

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Introduction

Habitat destruction and fragmentation are primary drivers of biodiversity loss and extinctions worldwide, and the effects of these are being increasingly exacerbated through human activities such as mining, agriculture, forestry and urbanisation (Fahrig 1997; Lande 1998; Tilman *et al.* 2001; Cristescu *et al.* 2012). While the physical environmental footprint of mining operations is <1% of terrestrial landscape areas, and relatively concentrated in comparison to other industries, e.g. agriculture and urbanisation, which account for 70% and 3% of global land disturbances, respectively (Hodges 1995; Bridge 2004; McKinney 2006), mining often has a substantial local, and often regional, environmental impact (Salomons 1995; Rybicka 1996). Activities from mining can fundamentally alter relatively intact and undisturbed habitats into inhospitable land matrices, and can create serious environmental pollution issues such as tailings leakage, dust, and hydrological change (Salomons 1995; Bian *et al.* 2009). Though mining activities impact a small terrestrial footprint, 75% of active sites are situated on land considered to be of high conservation value (Miranda *et al.* 2003; Bridge 2004). Hence, although environmental impacts of mineral extraction may be restricted in spatial extent, they are intensely disruptive to ecosystems that are often uncommon and fragile. The resultant alteration and degradation from mining activities present some of the most difficult landscapes to restore. As such, lessons learned from the restoration of mine sites may be transferrable to land restoration practices in other areas of high conservation value that have suffered other forms of degrading processes.

Many different environmental components (e.g. soil, plants, microorganisms, and fauna) require study in assessments of ecosystem health and functionality (Duffy 2003); yet restoration monitoring is typically restricted to plant communities and vegetation structure, which remain a key priority in assessing postmining restoration success (Ruiz-Jaen and Mitchell Aide 2005; Koch *et al.* 2010). Majer (1989) highlights this issue; however, the disparity between fauna and plant studies remains a key issue. This is despite fauna being essential to restoration success, and playing critical roles in the provision of numerous essential ecosystem functions, such as seed dispersal, pollination, nutrient cycling, and soil formation (Majer 1989; Lavelle *et al.* 2006; Mace *et al.* 2012). Importantly, fauna, due to their mobility, often rely on spatial scales far greater than plants, and hence are often dependant on habitats and resources that occur both within and outside the restoration patch. However, responses of fauna are often overlooked in favour of standardised vegetation surveys, which typically can be achieved rapidly and follow established principles (Ruiz-Jaen and Mitchell Aide 2005). Fauna are often assumed to return to predisturbance diversity and abundances following the return of vegetation (Block *et al.* 2001; Cristescu *et al.* 2012) through what is commonly referred to as the 'Field of Dreams' Hypothesis ('build it and they will come': Palmer *et al.* 1997). In practice, recovering animal biodiversity and community structure are some of the most difficult components to understand, achieve, and assess following the restoration of degraded sites (Cristescu *et al.* 2012; Perring *et al.* 2015).

Faunal responses to mine site restoration require study across a wide range of habitats and climatic regions to maximise biodiversity outcomes. Biases to certain regions or mineral extraction types limit our ability to inform on best practices for restoring ecosystem function by preconditioning our expectations to outcomes that may be unique to some places or disturbance patterns. Surface (e.g. strip mining, open pit, and quarry) and subsurface (underground) mining have varying levels of physical environmental impact (Dudka and Adriano 1997). Underground mining can have significant impacts on subsurface hydrology and soil structure (Altun *et al.* 2010); however, the above-ground impact (other than infrastructure and tailings or waste rock dumps) of underground mining is of a lower magnitude by comparison to the often very large terrestrial footprints of surface mining (Lin *et al.* 2005). Hence, conclusions drawn from sites of only one extraction type may not be best suited to inform restoration practices for other mining techniques.

Faunal responses to mine site restoration also require studies across varying climatic regions. Many of the world's 35 global biodiversity hotspots are situated within the tropics (Mittermeier *et al.* 2011). These regions contain higher proportions of endemic species than areas outside the hotspots (Myers *et al.* 2000). Endemic species, by virtue of occupying one or few specialised habitats, are likely to be affected more severely by habitat fragmentation and loss than generalist species, increasing the difficulty associated with restoring biodiversity values and potentially ecosystem functioning (Ewers and Didham 2006). Furthermore, while iron ore extraction from ultramafic soils takes place in biodiverse landscapes in, for example, Brazil, New Caledonia and Australia, it seems unlikely that the best practices of ecological restoration developed in Australia, with its unique flora and fauna and ancient, arid landscapes (Hopper and Gioia 2004; Hopper 2009), would translate well to the different tropical ecosystems of an island in the Pacific, or the rainforests of South America to improve restoration practices and biodiversity conservation.

Although a higher focus is being placed on fauna assessments in restoration in recent years (Majer 2009), of the limited studies that assess animal responses to restoration (particularly in relation to mine site restoration), there is a strong emphasis evident towards the use of certain taxa as biological indicators (bioindicators); for example, ants and birds, both of which typically can be easily surveyed with minimal time and financial investments (Majer 1983; Andersen *et al.* 2003; Nichols and Nichols 2003; Gould and Mackey 2015). The use of bioindicators has remained a favoured method of assessing environmental health, since the introduction of the concept by Hall and Grinnell (1919). While invertebrates are highly important in ecosystems, and can provide essential information in assessments of environmental health (Majer *et al.* 2007), basing restoration practices on responses of only ants and common bioindicators may under-represent other groups or negatively affect overall ecosystem development. For restoration efforts to be effective for all faunal groups, assessments for restoration success must be derived from a wider range of fauna, and from their role in the ecosystem, rather than ease of survey effort.

Studies assessing faunal responses to restoration typically favour assessments of species richness and abundance, likely due to reliability and ease of implementation. However, species diversity assessments have several limitations, namely that there is a high probability of missing rare, cryptic, migratory, or seasonally active species, and in the potential for species diversity to be altered through the detection of invasive or cosmopolitan species (Hejda *et al.* 2009; Chiarucci *et al.* 2011). Fauna that are capable of dispersing large distances may present a false representation of utilisation of restoration areas, as these areas may only be used opportunistically or transiently and incapable of supporting resident fauna communities in the long term. Isolated assessments of species presence or absence, or diversity, may therefore provide relatively little information as to the functional success of restoration. Studies based primarily on presence or absence do not allow for evaluation of resource use and use of wider restoration landscapes, and hence provide an inaccurate assessment of restoration trajectory and success. Integrative ecological and behavioural studies remain an emerging branch of conservation biology, and might provide an increased understanding of what constitutes a return to a fully restored site. Globally, little is known of how human disturbances alter the behaviour and ecology of fauna that persist in disturbed landscapes, such as postmining environments. Ecological and behavioural studies require significant time investment, and often have higher associated risks and costs than more general species diversity assessments, in terms of the ease of data collection. However, studies of ecology are essential, as behavioural characteristics are the most flexible of faunal adaptations to their environment, and have differing responses to environmental changes (Wolf and Weissing 2012).

This review assesses the current state of knowledge of the use of fauna in assessments of mine site restoration success. While Cristescu *et al.* (2012) published a review on the use of fauna in assessments of mining restoration success (termed rehabilitation), they primarily assessed the empirical data on faunal recolonisation of mine sites within Australia, whereas we identify and address any potential biases or patterns within literature assessing faunal responses to mine site restoration on a global scale. Specifically, we assess patterns in origin and year of study, targeted taxa, study type (i.e. presence or absence, or species diversity and abundances), and terminology use. We also seek to extend a similar interrogation to the grey literature surrounding faunal monitoring in mine site restoration. Understanding and addressing the current knowledge gaps in mine site restoration literature allows for the identification of areas requiring an increased study focus, and is integral to implementing the 'International Standards for the Practice of Ecological Restoration' (McDonald *et al.* 2016).

Methods

We compiled a comprehensive database of peer-reviewed literature composed of studies relating to any use of fauna (invertebrate or vertebrate) in assessments of mining restoration success. Studies were not limited to those using the terminology 'restoration', but included those describing attempted return of vegetation (unassisted natural regeneration or otherwise) following cessation of mining. Mining restoration literature encompasses a wide range of terminologies for describing various restoration practices (Kaźmierczak *et al.* 2017; Cross *et al.* 2018). For the purposes of this review, we use 'restoration' (adopted terminology in McDonald *et al.* 2016), which we define as 'the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed' (Clewell *et al.* 2004; McDonald *et al.* 2016). Literature assessing faunal responses to mining without reference to any form of restoration were discounted. We used three databases to interrogate the literature: Google Scholar, Web of Science (all databases, 1950–2018), and Scopus (all documents including secondary documents, all years; last searched November 2018). Additional sources were gleaned from bibliographies in the published literature.

Search terms comprised any combination of 'Australasia', 'Africa', 'North America', 'South America', 'Asia', or 'Europe', AND/OR 'animal', 'fauna', 'bird', 'reptile', 'mammal', 'vertebrate', or 'invertebrate' AND 'response', or 'behaviour' AND 'mine', or 'mining' AND 'restoration', 'rehabilitation', 'reclamation', 'recultivation', 'afforestation', or 'regeneration'. Publications were compiled into a database and sorted based on date of publication, country of origin, target taxa, type of mineral mined, terminology used, and key search terms. The literature comprised 101 publications (references used in analyses but not cited in text are summarised in Table S1). As postmining recovery may not be fully represented in the primary literature, we extracted the grey literature from searches and compiled these into a separate database. Grey literature included unpublished data, articles without empirical data, governmental reports, conference proceedings, and bulletins (summarised in Tables S1, S2 available as Supplementary Material). Analyses were designed to assess the current state of research in assessments of faunal responses to mining restoration, and identify potential knowledge gaps or biases. Although our aim was to interrogate the grey literature in a similar fashion to the peer-reviewed work, our analyses were insupportable due to the paucity of accessible or relevant data.

First, we identified the number of studies from each individual mine site, allowing for the detection of any potential overlaps or biases to particular sites and type of mineral mined. We then grouped studies based on country of origin and year of publication. Third, we identified the main terminology (the primary term used if multiple terms were present) to assess whether there was a standardised approach to terminology. Lastly, we investigated correlations between location, date of publication, and type of study, with use of particular taxa and type of mineral operation. We identified the following seven variables: (1) mineral type: coal (including publications listing the term 'lignite'), bauxite, sand, bentonite, gold, iron ore, limestone, tin, uranium, peat, multiple (polymetallic mines, or mines where two or more mineral types were listed), and not stated; (2) taxon group: vertebrate, invertebrate, or both; (3) target clade: Mammalia, Aves, Reptilia, Amphibia, Insecta, Clitellata (a taxon of annelid worm), or multiple targets; (4) main terminology; (5) date of publication; (6) country of origin; and (7) study type: ecology (pollination, density/biomass, predation), presence/absence, or population abundance of fauna species, and translocations.

Pearson's Chi-square tests were undertaken to compare differences between all categorical variables. All statistical analyses were conducted in the *R* 3.4.4 statistical environment (R Core Team 2016), implemented using RStudio (RStudio Inc., Boston, United States, 2018). The results from literature searches have been visualised in a PRISMA 2009 flow diagram (Fig. S1, Supplementary Material).

Results

Searches of peer-reviewed, published literature yielded a total of 101 publications from 10 different mineral type operations. Grey literature searches yielded just 12 readily accessible documents, eight of which made direct reference to fauna or fauna monitoring in restoration landscapes. Of the published literature, six studies were based at mines extracting multiple minerals, and five studies did not state the mineral type. Studies predominantly focused on bauxite ($n = 34$), coal ($n = 26$), and mineral sand mines ($n = 19$). Two studies each were from limestone, uranium, gold, and peat mines/quarries, and one each from bentonite, iron ore, and tin mines. Many of these minerals are typically extracted through surface mining, with the exception of coal and gold (both surface and subsurface mining), and uranium (subsurface mining). Terminology varied considerably between publications, with a total of seven different terms used: 'rehabilitation', 'restoration', 'regeneration', 'reclamation', 'recultivation', 'revegetation', and 'afforestation'. Of the 101 publications, 73 used a single terminology to describe restoration activity and 28 mixed terms within the same publication. The countries of origin comprised 14 countries (Australia, United States, Germany, Brazil, Hungary, Spain, South Africa, New Zealand, Czech Republic, United Kingdom, Canada, Colombia, Indonesia, and Italy), two of which are listed in the top five mineral-producing (by metric ton) countries (Fig. S2*a*, *b*, Supplementary Material). Indonesia, Colombia, Brazil, and Australia are listed in the top five megadiverse countries, ranked 1 to 4, respectively (Fig. S2*c*).

Invertebrate responses to mining restoration were assessed in 60 publications; 39 publications assessed vertebrate responses, and two papers assessed both invertebrate and vertebrate responses. Invertebrate studies favoured assessments for insects (90%), and vertebrate studies typically favoured assessments of birds (46%). Studies were significantly more likely to involve assessments for species diversity and abundance (75%, $\chi^2 = 309.5$, $P < 0.001$) compared with those including ecology (including pollination, density/biomass, and predation studies; 18%), presence, absence or population abundance of individual species (6%), or translocations (1%).

Terminology

'Rehabilitation' was the most commonly used main term (primary terminology used within the publication; $n = 47$), followed by 'restoration' ($n = 21$), 'regeneration' ($n = 10$), 'reclamation' ($n = 8$), 'recultivation' ($n = 7$), 'revegetation' ($n = 4$), and 'afforestation' ($n = 3$). The main terminology of one study (either 'restoration' or 'reclamation') could not be ascertained with certainty (Table S3, Supplementary Material**)**. Use of terminology appeared to be, in part, associated with publication date. While 'rehabilitation' had been in consistent use across the range of publication dates (1978 to 2017), 'restoration' appeared to be the favoured term within the last decade. Other terminologies do not appear to be in widespread use. European studies had the widest range of terminology (all terminologies apart from 'regeneration': Table 1). The use of 'afforestation' and 'recultivation' were exclusively restricted to European studies, and 'reclamation' was limited primarily to European and North American studies, with one use in an Australasian study.

Origin and date of study

Studies of fauna in mining restoration were significantly more likely to originate within Australasia than any other region (59%, $\chi^2 = 293.41$, $P < 0.001$). While there is a major Australian bias in the literature, 28 of the 60 Australian studies arise from a single organisation: Alcoa of Australia (hereafter Alcoa), which has extensively reported the role of fauna in the restoration of its bauxite operations in the jarrah forests of south-west Australia. These reports account for 82% of studies of bauxite mines globally ($n = 28$ of 34), and this pattern is the global norm: many studies within mineral categories result from a single mine site. All eight studies within South Africa are from the same locality (Richards Bay), with similar trends among other countries including Germany ($n = 2$ of 7, Berzdorf lignite mining district, eastern Germany), Czech Republic ($n = 3$ of 3, north/north-west Bohemia), Hungary ($n = 3$ of 3, Pécs, southern Hungary), and New Zealand ($n = 2$ of 2, Wangaloa coal mine, Otago). Publication output increased over time; however, study focus appeared to shift from invertebrate to vertebrate species within the last decade (Fig. 1). It is noteworthy that output between any given time bracket is not high within this research area, with a peak rate of less than two papers published annually in the years between 2001 and 2010 (Fig. 1).

Table 1. Use of terminology across literature by region

Region	Terminology	No. of uses
Africa	Rehabilitation	7
	Regeneration	1
Asia	Restoration	1
Australasia	Rehabilitation	34
	Restoration	13
	Regeneration	8
	Revegetation	2
	Reclamation	1
Europe	Recultivation	7
	Restoration	3
	Reclamation	3
	Afforestation	2
	Revegetation	1
	Rehabilitation	1
North America	Reclamation	5
	Restoration	2
	Revegetation	1
	Regeneration	1
South America	Rehabilitation	3
	Restoration	2

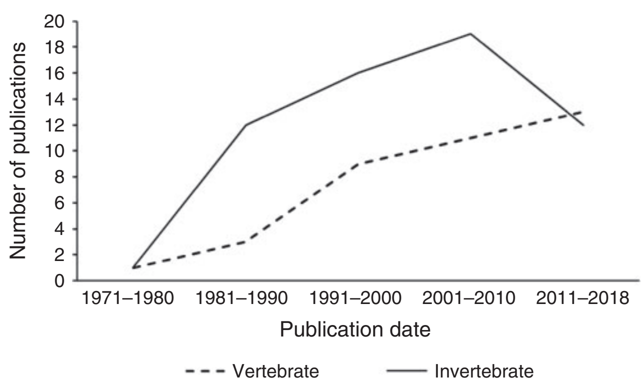

Fig. 1. Publication output for vertebrate and invertebrate responses to mine site restoration studies.

Invertebrate responses

Invertebrate responses to mine site restoration were reported in 60 publications (comprising over half (59%) of the literature). Invertebrate studies included species from three phyla (Arthropoda, Annelida, and Mollusca), with a particular focus on the Arthropoda (Insecta; $n = 54$ of 60). Excluding those assessing multiple groups, studies primarily assessed responses of the Formicidae (ants; $n = 19$), followed by the Coleoptera (beetles; $n = 7$), Collembola (springtails; $n = 4$), Araneae (spiders; $n = 3$), Diplopoda (millipedes; $n = 2$), Lepidoptera (butterflies; $n = 2$), Oligochaeta (earthworms; $n = 2$), and

Table 2. Summary of target class by mineral type and region for invertebrate studies
Numbers in parentheses denote number of studies for each target or mineral type

Region	Target	Mineral type
Africa	Multiple invertebrates (2)	Multiple minerals
	Coleoptera (2)	Sand (1), not stated (1)
	Diplopoda (2)	Multiple minerals
Australasia	Formicidae (14)	Bauxite (5), coal (2), sand (4), uranium (2), iron ore (1)
	Multiple invertebrates (6)	Bauxite (3), coal (1), sand (2)
	Coleoptera (2)	Peat (1), coal (1)
	Araneae (2)	Bauxite
	Collembola (2)	Bauxite
	Hemiptera (1)	Bauxite
Europe	Multiple invertebrates (8)	Coal (6), limestone (2)
	Coleoptera (3)	Coal
	Formicidae (2)	Coal (1), not stated (1)
	Collembola (1)	Coal
	Oligochaeta (1)	Coal
North America	Multiple invertebrates (3)	Bentonite (1), peat (1), coal (1)
	Lepidoptera (2)	Coal
	Oligochaeta (1)	Bauxite
South America	Formicidae (3)	Bauxite (1), coal (1), gold (1)
	Collembola (1)	Sand

Hemiptera (true bugs; $n = 1$). Twenty studies did not have a focal group and assessed general species diversity and richness for multiple groups. Studies within Australasia and Europe had the widest range of targeted taxa (Table 2). Excluding assessments for multiple invertebrate groups, ants were the most commonly assessed group across almost all mineral types ($\chi^2 = 49.6$, $P < 0.001$). Of the eight stated mineral operation types (excluding sites listed as 'multiple minerals', or 'not stated'), only three had studies examining more than one invertebrate class (bauxite, coal, and sand mines).

Vertebrate responses

Studies of vertebrate responses to mining restoration comprised less than half of the total number of publications ($n = 39$ of 101, discounting two studies that assessed both invertebrate and vertebrate responses). Studies significantly favoured the use of birds (45%, $\chi^2 = 19.846$, $P < 0.001$) followed by reptiles (18%, $n = 7$), mammals (18%, $n = 7$), and amphibians (3%, $n = 1$). Seven studies assessed responses of multiple groups. Of the 39 vertebrate studies only 12 had specific target species, with the other 27 assessing general species diversity and richness. Vertebrate studies primarily originated from Australasia ($n = 30$), with just three based in each of Europe and North America, and one each in South America, Africa, and Asia. Studies originating outside of Australasia almost exclusively assessed responses of birds, with the exception of three studies (one each in North America, Europe, and Africa) that targeted a combination of mammal, reptile, and amphibian species (Table 3). The type of mineral extracted at sites assessing vertebrate responses to mine site restoration appears to be associated with the region of study. Studies of vertebrate responses at bauxite and sand mines occur exclusively within Australasia, whereas those at coal mines are based either in North America or Europe (Table 3).

Discussion

Studies of faunal responses to mine site restoration are lacking globally, and we found over a 49-year period just 101 peer-reviewed publications reporting on fauna as part of mining restoration activities, with over half from Australia. We interpret this number as 'lacking' because 46 of the 101 studies originated from either the same mining site, or the same locality within a country. Furthermore, as a very rough guide, as of October 2018, Google Scholar reports ~24 000 papers reporting on 'vegetation' AND 'ecological restoration' AND 'mining' in the same period since 1971. Studies of faunal responses to mine site restoration favoured assessments for general species diversity and abundances of invertebrate species. There is a noticeable lack of studies that assess the behaviour and ecology of fauna, particularly of vertebrate species.

Study origin

Australia is at the forefront of mining restoration initiatives, as one of the few countries with widespread legislation (complemented by non-compliance penalties) aimed at mine closure (Gilbert 2000; Clark and Clark 2005; Cristescu *et al.* 2012). This is reflected in the number of studies reporting faunal responses to mine site restoration originating within Australia. Australia's high activity within the mining restoration field likely results from the increased availability of funding that mineral extraction companies are required to provide for ecological restoration following mine site discontinuation, in order to obtain closure (Clark and Clark 2005). While a leader in restoration research, a recent report identified ~60 000 mine sites across Australia as abandoned (Campbell *et al.* 2017), of which the number confirmed as restored and officially closed could be as low as 21 (Western Australia: unknown; South Australia: 18 sites; New South Wales, Victoria, and Tasmania: one site each; Queensland and Northern Territory: no confirmed sites:

Table 3. Summary of target taxa by mineral type and continent for vertebrate studies
Numbers in parentheses denote number of studies for each target or mineral type

Region	Class	Target	Mineral type
Australasia	Aves	Cockatoo (*Calyptorhynchus* sp.) (2)	Multiple minerals (1), bauxite (1)
		Multiple targets (10)	Bauxite (8), sand (2)
	Mammalia	Swamp wallaby (*Wallabia bicolor*) (1)	Sand
		Koala (*Phascolarctos cinereus*) (1)	Sand
		Mouse (*Mus* sp.) (1)	Sand
		Multiple targets (2)	Sand
		Bat (Chiroptera sp.) (1)	Bauxite
	Reptilia	South-western crevice skink (*Egernia napoleonis*) (1)	Bauxite
		Bearded dragon (*Pogona minor*) (2)	Bauxite (1), not stated (1)
		Multiple targets (4)	Bauxite (1), sand (3)
	Amphibia	Multiple targets (1)	Sand
	Mammalia, Reptilia	Multiple targets (2)	Bauxite (1), gold (1)
	Mammalia, Reptilia, Amphibia	Multiple targets (1)	Bauxite
	Reptilia, Amphibia	Multiple targets (1)	Bauxite
North America	Aves	Greater sage-grouse (*Centrocercus urophasianus*) (1)	Coal
		Multiple targets (1)	Coal
	Amphibia, Reptilia	Multiple targets (1)	Coal
South America	Aves	Multiple targets (1)	Not stated
Europe	Aves	Ring-necked pheasant (*Phasianus colchicus*), European nightjar (*Caprimulgus europaeus*), and yellowhammer (*Emberiza citronella*) (1)	Coal
		Common quail (*Coturnix coturnix*) (1)	Coal
	Amphibia, Reptilia	Multiple targets (1)	Coal
Asia	Aves	Multiple targets (1)	Tin
Africa	Mammalia	Multiple targets (1)	Not stated

Campbell *et al.* 2017). It is apparent that restoration research focused on reinstatement of fauna after mining is still lacking within Australia. Outside Australia, global mine abandonment numbers are largely either unknown or under-reported. Among countries with (soundly estimated) abandonment figures, high numbers are common, with at least 5000 mine sites in South Africa and 10 000 in Canada identified as abandoned (Cowan *et al.* 2010; Milaras *et al.* 2014), many unlikely to have any substantial ecological management effort that would achieve restoration as defined by McDonald *et al.* (2016).

Rates of mine site cessations and abandonments are cumulatively growing worldwide; however, legislation relating to mine site closure is lacking in most countries (Clark and Clark 2005). Within developed nations, only four countries have widespread legislation relating to mine abandonment (Australia, Japan, Ireland and the United Kingdom), and two have legislation in select states (Canada and the United States: Clark and Clark 2005). Even fewer have legislation for bonding procedures (monetary bond to ensure sites are appropriately restored: Clark and Clark 2005). Just 11 developing countries have complete legislation relating to mine site closure (Clark and Clark 2005), none of which appear in our search results. Globally, Australia appears to be one of the leaders in this space, largely due to comprehensive legislation, although this clearly is not the only motivator as, of the three other developed regions with widespread legislated restoration requirements, we found just one publication relating to faunal responses to mine site restoration (from the United Kingdom). While closure legislation is an essential component in the regulation of mining activities, legislated financial support of restoration activities and research is equally critical.

While much of the literature originates from Australia, almost half of these are from a single organisation: Alcoa's bauxite mining operations in south-west Australia. Not only does this organisation account for a significant proportion of Australian studies, but almost all studies from bauxite mines globally – a mining practice with large surface impacts. These studies originate in a unique ecological region, and a biodiversity hotspot that has been isolated from the rest of the world for a substantial period (Hopper and Gioia 2004). It is highly likely that patterns seen from these studies in the south-west Australian biodiversity hotspot may not provide an accurate representation of faunal responses to mine site restoration in other understudied regions. While it is unlikely that a single, standardised approach to fauna restoration in mining could be implemented globally, due to the ecological diversity of habitats, until legislative requirements and funding increase globally, the diversity of responses by faunal communities to mine site restoration will remain obscure.

Invertebrate responses

Invertebrate species are most commonly studied in assessments of faunal responses to mine site restoration success, and have been studied across a wide diversity of mineral extraction operations. Invertebrates are exceptionally diverse and abundant and typically respond rapidly and with high sensitivity to habitat disturbance, providing an ideal study group for monitoring environmental change and habitat health (Waltz and Covington 2004; Gerlach *et al.* 2013). Among the mining restoration literature involving studies of particular invertebrate groups, there is a strong focus on assessing diversity and abundances of ant species. Ants have been used extensively as bioindicators in a range of studies, across many habitat types and land uses (Hoffmann and Andersen 2003), including savannahs (Majer 1984*b*; Andersen 1991; Cross *et al.* 2016*a*), coastal environments (Majer and Brown 1986; Cross *et al.* 2016*b*), woodlands and forests (Andersen 1991; Vanderwoude *et al.* 1997), including rainforest (King *et al.* 1998). Ants are an obvious study group of choice, occurring in exceptional abundances in all but three regions (Iceland, Greenland and Antarctica: Hölldobler and Wilson 1990).

Ant community dynamics and responses to disturbances are well studied, and sampling can be performed with ease, rapidity, and at comparatively low cost (Majer 1983; Andersen 1986). One of the few drawbacks in their use stems from difficulties in taxonomy, with many species yet to be described and named (Gerlach *et al.* 2013). Their widespread use across the mining literature is therefore unsurprising. While ants are the most commonly targeted group, general species diversity assessments for multiple groups (no specific targets) are equally common. General diversity assessments may present further issues, in that they do not account for varying ecologies of species, and identification tends to be broader (Chiarucci *et al.* 2011). Species diversity and richness assessments are one of the most straightforward and reliable forms of data collection, especially when targeting fauna present in large numbers (Gerlach *et al.* 2013), likely accounting for the significant bias towards this form of assessment over all other study types.

Vertebrate responses

Vertebrates are less frequently studied in assessments of mine site restoration, and are generally considered to be less effective for use as bioindicators of habitat health than invertebrates (Landres *et al.* 1988; Bisevac and Majer 1999*a*; Gerlach *et al.* 2013). Unlike invertebrates, many species of which occur in high numbers across many habitats, vertebrates can be cryptic, often present in far fewer numbers, and move over greater spatial scales, considerably increasing detection difficulty (Oliver *et al.* 2009). Few studies assess behavioural and ecological responses of vertebrate fauna, particularly apex predators, to mine site restoration. Behavioural studies can be particularly costly (especially in the initial set-up stage); however, they can also provide extremely successful measures for assessments of the interactions of fauna with their surrounding habitat (Silveira *et al.* 2003).

Assessments of vertebrate responses to mine site restoration favour avian fauna. This is particularly evident in studies originating outside of Australasia, two-thirds of which assess responses of birds. Birds are relatively easy to detect and identify, have a stabilised taxonomy, often can be common and widespread, and their environmental interactions are well studied, providing an excellent faunal group for use in studies of ecosystem health (Jordano 1982). However, birds may not accurately represent restoration use, as their great mobility may allow for easier recolonisation than other fauna groups. Second to birds, there are relatively substantial numbers of mammal-focused studies, particularly of charismatic mammals and those that have threatened conservation status. Australia is a land of lizards, and has extremely high rates of endemism (93% endemism: Chapman 2009), yet despite being one of the few countries to assess responses of non-avian taxa, there are surprisingly few reptilian studies. Reptiles are experiencing global declines (Böhm *et al.* 2013), yet they are often overlooked, with few studies examining their response to habitat restoration (Munro *et al.* 2007; Todd *et al.* 2010). Reptiles can provide information on thermal environments (e.g. whether restoration areas have higher associated thermal costs than reference habitats), which other groups, such as birds, may not. Hence, extrapolating responses of birds to poikilothermic fauna is potentially problematic.

Ecosystem function

Research is lacking into ecosystem functionality in terms of assessing interactions of fauna with mine site restoration areas. In many ecosystems, functionality is in some way related to faunal interactions, and loss of biodiversity can greatly impact on ecosystem services (Naeem *et al.* 1994), yet 81% of studies identified in this review of mine site restoration measure species diversity, abundance, presence, or infer absence. While providing important ecological data, these studies have several drawbacks, and may not provide data on whole ecosystem functionality or be appropriate measures for determining whether a site has been effectively restored. By performing only these assessments, there is a significant chance of missing rare and cryptic species, or in incidental captures of animals moving through the site but not inhabiting the area. This may be particularly problematic in terms of achieving outcomes for mining restoration, as it may provide a false community representation and appear as though a habitat is restored when, in fact, that system may only be in use opportunistically, or not even in use at all.

Moreover, only so much may be learnt from assessing faunal biodiversity. Key ecosystem functions can result or fail as a result of altered animal behaviour and movement patterns (Fahrig 2007; Tarszisz *et al.* 2018), ecological energetics (Tomlinson *et al.* 2014), or nutritional physiology (Birnie-Gauvin *et al.* 2017). This can result in cryptic disruptions to key services such as insect pollination (e.g. Tomlinson *et al.* 2018) that are not apparent from other studies of pollinator communities such as birds (e.g. Frick *et al.* 2014). Although there is some evidence that successful mine site restoration is constrained by limited natural recruitment (Koch 2007; James *et al.* 2011), the role of fauna-mediated pollination and seed dispersal is understudied. Herbivory is a critical plant/animal interaction that has long hampered the restoration of discontinued mining areas, yet has been rarely studied (Keesing and Wratten 1998; Koch *et al.* 2004; Parsons *et al.* 2007). These dynamic interactions are important to restoration research, yet fauna are studied only in the context of ecological restoration at a restricted level.

Grey literature and issues with its use

While it is possible that information and data surrounding faunal responses to mine site restoration exist within the grey literature, we found little empirical data or relevant information within the few that were readily accessible. Accessible grey literature largely comprises premining surveys for fauna species within and around potential new mine sites, conservation and management strategies for rare and threatened species during the life of the mining operation, conference proceedings, or book chapters without empirical data. There is a noticeable dearth of grey literature directly referencing either short- or long-term monitoring of fauna in restoration landscapes, or methods for assessing faunal responses. However, as with published literature, the marginal volume of grey literature to which we could gain access did not discuss fauna in detail, and did not discuss whole animal community return, or return of fully functioning ecosystems. We found eight articles directly referencing fauna in restoration landscapes: three conference proceedings or presentations, three book chapters, and two monitoring plans or guidance documents. Grey literature comprised discussion of the role or return of fauna in mine site restoration (Nawrot and Klimstra 1989; Majer 1997, 1998; Moloney *et al.* 1998), a monitoring plan for the conservation of rare and threatened fauna (Nickel and Claremont 2015), an assessment of nest translocations for bird species in restoration (termed reclamation) sites (McKee 2007), a guidance document describing techniques for promoting fauna return to rehabilitating sites (Brennan *et al.* 2005), and a book chapter referencing published studies of vertebrate colonisation of rehabilitating sites at Alcoa (Tibbett 2015). Other resources do recognise the effects of mining on fauna, but this is limited to simple statements on the need for returning habitat components that promote faunal recolonisation; for example, habitat corridors (McLaughlin 2012), monitoring plans for threatened species or management of feral species (without reference to restoration) (Guinea 2007; Weipa 2015; Knuckey 2018) or simply recognition that fauna play important roles in ecosystems and are often overlooked in restoration monitoring (Glenn *et al.* 2014).

Our biggest challenge in extending our analyses to the grey literature was that resources tend to be largely inaccessible, and often unreliable (Farace and Schöpfel 2010; Corlett 2011). Information and data in unpublished reports and documents are often accessible only within governmental departments and specific regions or countries, and not by the scientific community (Corlett 2011). This has likely resulted in a significant proportion of information within grey literature being overlooked during the development of new conservation and management plans, restoration strategies, and mine site closure policies. It also allows for large, multinational companies to apply different standards in different countries depending on the local legislative and regulatory structures and departments. In order to advance the field of mine site restoration and develop targeted and effective fauna conservation and management strategies, data from these grey literature sources must be peer reviewed, published, and accessible.

Conclusions and future research

The most obvious pattern that has emerged from our review of the literature on responses of fauna to mine site restoration is the overwhelming number of Australian studies contrasted by the surprising dearth of literature for the remainder of the world. This has likely resulted from Australia having both the legislative structure, and financial incentives and capacity for research. To gain an increased understanding of how restoration is impacting ecosystem functioning across a wide range of ecosystems, research must be expanded to a more global level, and encompass a wide range of habitats with varying types of mineral extraction. Not only will this help to account for differences between habitats and ecosystems, but also for the likelihood of varying environmental impact resulting from different mining techniques. Another major limitation is the restricted focus on assessments of behaviour and ecological interactions and functional capacity. Studies of species richness rarely offer insight into the critical ecosystem functions provided by animals. An increased focus must be placed on assessments for ecology and behavioural responses of animals to habitat change and restoration, with an increased emphasis on vertebrate animals within these systems. However, there needs to be a global realisation that mining regulatory systems need to place an emphasis on assessing fauna at multiple taxonomic and functional levels, to ensure that restoration after mining returns an ecosystem to a level of ecological resilience and capacity that matches the local reference ecosystem.

Glossary

Mine discontinuation or abandonment: termination of active mining, ownership of land is retained but site is inactive.

Mine closure: ‘a whole-of-mine-life process, which typically culminates in tenement relinquishment. It includes decommissioning and restoration’ (DMP and EPA 2015).

Conflicts of interest

The authors declare no conflicts of interest.

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