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ARTICLE

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An approach to defining and achieving restoration targets for a threatened plant community

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Abstract

Connecting scientific research and government policy is essential for achieving objectives in sustaining biodiversity in an economic context. Our approach to connecting theoretical ecology, applied ecology, and policy was devised using principles of restoration ecology and the requisite methodology to restore biodiverse ecosystems. Using a threatened ecological community (TEC) with >120 plant species, we posit our approach as a guide for interpreting and achieving regulatory compliance (i.e., government conditions) enacted to manage or offset environmental impacts of development. We inform the scientific approach necessary to delivering outcomes appropriate to policy intent and biodiverse restoration through theoretical and applied research into the ecological restoration of the highly endemic flora of banded ironstone formations of the Mid West of Western Australia. Our approach (1) defines scale-appropriate restoration targets that meet regulatory compliance (e.g., Government of Western Australia Ministerial Conditions); (2) determines the optimal method to return individual plant species to the restoration landscape; (3) develops a conceptual model for our system, based on existing restoration frameworks, to optimize and facilitate the pathway to the restoration of a vegetation community (e.g., TEC) using diverse research approaches; and (4) develops an assessment protocol to compare restoration achievements against the expected regulatory outcomes using our experimental restoration trials as a test example. Our approach systematically addressed the complex challenges in setting and achieving restoration targets for an entire vegetation community, a first for a semiarid environment. We interpret our approach as an industry application relevant to policy- or regulator-mediated mine restoration programs that seek to return biodiverse species assemblages at landscape scales.

KEYWORDS

banded iron formation, emergence, germination, threatened ecological community, vegetation composition

INTRODUCTION

Ecological restoration should be a joint venture between theoretical ecology, applied ecology, and policy (Lindenmayer, 2020; Perring et al., 2015, 2018; Suding, 2011; Wainwright et al., 2018). The success of ecological restoration is dependent on the dynamics of this joint venture and is ever more urgent, with mounting pressures from global environmental changes (Cardinale et al., 2012). Global change has led to a proposal for global action and the proclamation from the United Nations General Assembly to "position ecosystem restoration as a major solution to meeting global development goals and national priorities" (UNEP, 2019). While the conservation of intact ecosystems remains the primary strategy for protecting biodiversity (Jones et al., 2018), ecological restoration clearly paves the way forward for mitigating environmental impacts and meeting shared conservation and economic goals (Strassburg et al., 2019). Despite this, the application of ecological theory and restoration practices to biodiverse ecosystems within complex and sophisticated regulatory and policy frameworks remains unusual and tests the current scientific understanding of natural systems (Baker & Eckerberg, 2016; Stevens & Dixon, 2017).

Restoration that is grounded in ecological theory provides the advantage of demanding the definition of key terms important to the restoration context and identifying mechanistic processes central to restoration outcomes (Lindenmayer, 2020; Perring et al., 2015; Török & Helm, 2017). The definition of points of reference, for example, is often not well described or understood in (m)any restoration projects in terms of either scale-appropriate data capture (EPA, 2004; Legendre & Legendre, 1998) or statistical analysis of community composition (Chiarucci et al., 2003). For projects aiming to restore predisturbance landscapes attributes, the definition of a point of reference, including attributes such as community composition, structure, and function, must be characterized (Carrick & Forsythe, 2020; Erskine et al., 2019; Zobel et al., 1998) and measured at an appropriate scale (Török & Helm, 2017). This enables the development of suitable completion criteria for a corresponding restoration site (Erskine et al., 2019; Gann et al., 2019; Manero et al., 2020; Miller et al., 2017). Typically, points of reference are defined from mature-phase extant vegetation, but there may exist greater biodiversity and functionality among successional, ruderal, or ephemeral species in the ecosystem that emerge following specific events or conditions. These species also contribute to ecosystem richness, function, and resilience and, therefore, should be included in restoration completion criteria (Pärtel et al., 2011).

Beyond defining a point of reference, the restoration of specific vegetation communities requires the integration of ecological theory that addresses mechanistic processes (Lindenmayer, 2020; Miller et al., 2017; Perring et al., 2015; Wainwright et al., 2018). These include but are not restricted to community assembly processes, the development of sustainable populations, plant/seed performance and their interactions with landform/substrate functionality, and environmental changes to guarantee the establishment and function of restoration (Lindenmayer, 2020; Wainwright et al., 2018). Invariably, relationships between a vegetation point of reference and its landscape attributes should be recreated to improve the likelihood of restoration success. Landscape attributes include vegetation responses to the physical, chemical, and hydrological properties of likely, or possible, reconstruction substrates, as well as the role of landform structure and topography (Erskine et al., 2019; Miller et al., 2017; Muñoz-Rojas, 2018). Recognition of integrating research on the functional complexity of ecosystem operations with optimization of restoration practices is becoming more common (Sinclair et al., 2018; Wainwright et al., 2018); however, new disturbances (e.g., mining) continue to emerge in new areas where we have not yet developed an understanding of complex biotic–abiotic interactions (Stevens & Dixon, 2017).

Building on theoretical ecology, applied ecology puts theory into practice. Restoration practices require the application of a toolbox of methods to return species at a site, since species differ in their capacity for restoration, and necessary approaches may be species-specific and as varied as the species diversity of a given ecosystem (Gann et al., 2019; Miller et al., 2017; Perring et al., 2015). Approaches to the establishment (return) of species must operate within the practical boundaries of the availability, quality, and suitability of source material (Basey et al., 2015; Broadhurst et al., 2016; Buisson et al., 2017; Merritt & Dixon, 2011). Hence, the relevance of assembling a knowledge base of species recruitment dynamics (Bell et al., 1993), propagation capacity (Beyl & Trigiano, 2015; Bunn et al., 2011), germination biology (Turner et al., 2013), and horticultural practices (Beyl & Trigiano, 2015) becomes apparent when optimizing for species return. The restoration toolbox, therefore, includes selecting from among many options to ensure that the chosen method maximizes the number of plants established, is the most cost-effective option, and improves restoration success.

The third aspect of this ecological restoration joint venture is applying ecological approaches to meet policy settings. Policy guides decision-making processes and any regulatory conditions that accompany a decision. Where regulatory approval to disturb a site is contingent on a commitment to restore specific values, the meeting of restoration targets that satisfy these specific values is inherent (Commonwealth of Australia, 2012). These policy-driven regulatory conditions can demand high achievement standards, particularly when state-listed species or ecological communities may be impacted (Commonwealth of Australia, 2012). It is also becoming increasingly common for these conditions to mandate a numerical target with a relevant ecosystem attribute (e.g., "achieve ≥70% of original species richness") (Government of Western Australia, 2009) or ecosystem function (e.g., "establish a new self-sustaining population") (Government of Western Australia, 2017). These legal requirements alone do not guarantee success, but the regulatory and public attention applied to these cases encourages a high level of scientific and technological investment. The challenges to restoration involve both landscape (e.g., isolation, geomorphology, threats) and local (e.g., availability of resources, ecological interactions) factors, which have only gradually begun to be considered in restoration programs that need to be conducted within a framework of regulation and policy. Establishing new industry benchmarks to meet policy expectations will provide confidence that conservation and mining can co-occur with the highest standard of restoration being achieved.

We explore the challenges of determining targets and approaches to restoring a biodiverse plant community at an iron ore mine in the semiarid Mid West region of Western Australia. Regulatory conditions on approved mining activities meant that the company was required to restore a listed threatened ecology community (TEC). The premise of our approach was based on well-known, detailed restoration standards and frameworks (Gann et al., 2019; Manero et al., 2020; Miller et al., 2017) that guided defining targets, implementing science-based restoration practice, and monitoring against targets/completion criteria for the company responsible for delivering the restoration of the TEC. We developed four specific aims: (1) define ecologically realistic and scale-appropriate targets; (2) identify an optimal approach to return the required species from the species pool; (3) optimize and facilitate the pathway for restoration; and (4) develop a protocol to assess the achievement of targets—in this case a return of ≥70% flora and vegetation composition. To accomplish these aims we (1) developed a protocol/method for defining scale-appropriate targets; (2) described the optimal approach to returning each TEC species; (3) developed a conceptual model, based on existing restoration frameworks, that uses a variety of research approaches necessary for restoration success beyond a basic method for direct species return; and (4) conducted a precursive assessment of our experimental TEC restoration against defined outcomes to provide a working example of the assessment protocol that was developed.

METHODS

Mine site and policy background

Western Australia (WA) is a global leader in mining activities, particularly iron ore mining, where it accounts for 38% of global production (valued at AUD63 billion in 2017) (Government of Western Australia, 2018). The Koolanooka iron ore mine site, operated by Sinosteel Midwest Corporation, is located south-east of Geraldton in WA (29°11′ S 116°12′ E). Mining operations relevant to this study involved the recommencement of open-pit activities following five previous mining campaigns that started in 1966 as Australia's first iron ore export operations. Mining and rehabilitation procedures involved clearing vegetation, removing and stockpiling topsoil, mining underlying banded iron formation (BIF) ore and separating it from the waste rock, placing the waste rock (a rock–soil matrix) as an engineered landform nearby, and finally replacing the stockpiled topsoil on the surface of the new landform. Through these mining activities, approval to clear a 4.46-ha area of the state listed TEC of the Koolanooka System, was granted.

Approval to impact a state-listed TEC involved a high level of regulatory compliance (i.e., Ministerial Conditions), which included an adjacent 7-ha area to be restored to a specific state under an offset clause (Government of Western Australia, 2009). First, these Ministerial Conditions required that "The proponent shall ensure that mining and mining related activities of this proposal shall not cause the loss of or adverse impacts on any native flora, including the Threatened Ecological Community (TEC), outside areas approved to be cleared of vegetation" (Government of Western Australia, 2009). Second, that "flora and vegetation are re-established with not less than 70 percent composition (not including weed species) of the known original species diversity" (Government of Western Australia, 2009). Achievement of this was expected by the company within 5 years of cessation of mining (Government of Western Australia, 2009). Industry benchmarks for species richness in ecological restoration have been established by several mining companies operating in WA (e.g., Hanson Construction Materials for Banksia Woodland and Alcoa for Jarrah Forest), which notably use different extraction techniques (strip mining compared to open pit) in a higher rainfall zone (Stevens & Dixon, 2017). However, to our knowledge there is no precedent for restoring a defined plant community to meet regulatory targets. Despite iron ore mining operations in WA since the 1960s (Stevens & Dixon, 2017), these Ministerial Conditions represented a significant scientific and practical challenge.

Aim 1: Defining ecologically realistic and scale-appropriate targets

Existing knowledge of original species diversity

The Ministerial Conditions provided high-level goals to establish ≥70% of the original species diversity, but it lacked detailed information to guide the achievement of this goal. For instance, there were no measurable assessment criteria, such as quantification of the original species diversity. Furthermore, previous vegetation survey and mapping recognized a varying number (2–31) of unique communities and a species list that differed 10-fold in size (Table 1). The Ministerial Conditions only referred to two of these studies (ATA Environmental, 2004; Ecologia Environment, 2008) when identifying vegetation community targets. The sampling approach, floristic and spatial resolution, and extent of all of these surveys differed, and none aimed to identify restoration targets, and none matched the scale of the area to be restored under the offset clause (i.e., 7 ha) (Table 1). This demonstrated the scale dependency of surveys and lack of consistency to identify suitable restoration targets for the TEC. Complicating matters was the lack of preimpact data on species composition or richness, and the restoration site was not the same as the cleared site. Hence, we needed to develop an approach to defining the level of species diversity and composition, in a manner appropriate for the scale of the restoration site (7 ha).

Approach to identifying scale-appropriate targets

We selected an area of natural, undisturbed vegetation as a reference community that was on a similar landform, within the mapped TEC boundary and adjacent to the area identified to be restored. To match the scale of the area to be restored under the Ministerial Condition offset clause, we identified a 7-ha area within this reference community to establish the species richness target. Within this 7-ha area (i.e., the reference site), we conducted vegetation surveys in 10 randomly placed 20 × 20 m plots (TEC1-10) (Figure 1), and then searched the entire remaining area to record any additional species that were not identified within the survey plots (TEC-walk) (Figure 1). Several species in our surveys could not be identified to species level, and we did not include multiple subspecies in determining the species pool.

We developed two extensive species lists because no preimpact data were available, and we needed to acknowledge the close association of adjacent vegetation communities to the TEC and the detection of these species in the restoration site. The first list was a TEC species pool, which included species from the TEC defined in Meissner and Caruso (2008). The second list was a supplementary species pool, which included species from adjacent vegetation that was strongly associated with the BIF landform (the Koolanooka Range). For the TEC species pool list, we combined data from our vegetation surveys (TEC1-10 and TEC-walk surveys in 7 ha) (Figure 1) with the previous (or historic) vegetation surveys in the TEC (shown in Figure 1 as TEC11-20 surveys) (Meissner & Caruso, 2008; Maia, 2010). For the supplementary species pool list, we collated data from only previous (or historic) surveys located in adjacent vegetation (SUPP1-15 surveys) (Figure 1) (ATA Environmental, 2004; Maia, 2010; Meissner & Caruso, 2008).

In summary, the number of species within the 7-ha reference site was compiled as the baseline for the ≥70% species composition target from the scale-appropriate surveys (i.e., 10 plots from TEC1-10 and TEC-walk) for a restored 7-ha area. Species from these surveys, together

TABLE 1 Previous (historic) vegetation surveys are summarized by the survey year; number of replicates, size and type of field method employed (m: meters); total area surveyed (m^2); number of plant associations/communities defined; species richness (number of species); and estimated number of species required to meet a ≥70% target richness for restoration based on each survey outcome

Vegetation survey	Field method	Total area (m^2)	Defined plant communities	Species richness	Target for ≥70% richness
Hamilton-Brown (2000)	11, 10 × 10 m plots	1100	5 Associations[a]	67	47
ATA Environmental (2004)[b]	>31, 50 m transects	Unspecified	31 Communities	207	145
Meissner and Caruso (2008)	50, 20 × 20 m plots	20,000	6 Communities	217	152
Ecologia Environment (2008)[b]	2 relevés	Unspecified	2 Communities	47	33
Maia (2010)	10, 20 × 20 m plots	4000	3 Communities	96	67

[a]An association is defined as a climax community of which the dominant stratum has a qualitatively uniform floristic composition and which exhibits uniform structure as a whole (ESCAVI, 2003).
[b]Indicates the surveys referred to in the Ministerial Condition (Government of Western Australia, 2009).

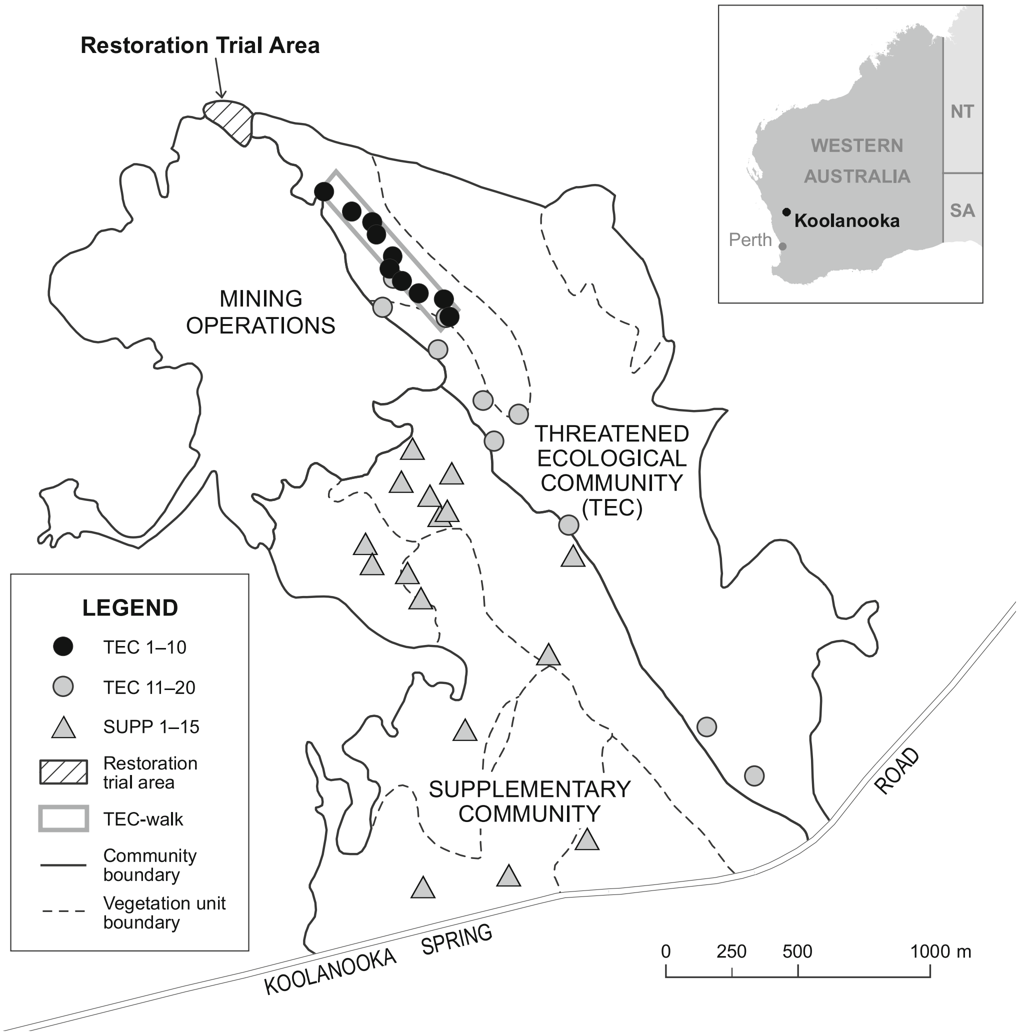

FIGURE 1 Location of Koolanooka System, a banded iron formation (BIF), within Western Australia (inset) and position of its mining operation footprint, experimental restoration trial area (0.86 ha); threatened ecological community (TEC); supplementary community strongly associated with BIF landform; appropriately scaled (7 ha) vegetation surveys from our study (TEC1-10; TEC-walk: gray rectangle); and previous (or historic) vegetation surveys (TEC11-20; SUPP1-15; ATA Environmental, 2004; Maia, 2010; Meissner & Caruso, 2008). Specific vegetation unit boundaries within each community were derived from ATA Environmental (2004). See Appendix S1: Table S1 for further study area information

with previous surveys (TEC11-20), were used to make the TEC species pool list (total of 20 plots).

We analyzed the species composition of the TEC species pool list and used this as a proxy for ecosystem function (Carrick & Forsythe, 2020) to restore a diverse representation of the functional groups in the TEC vegetation. We ranked species according to their frequency of occurrence so we could quantify community composition, which was calculated as the percentage of the total number of plots in which a species was found. The species identified in the 20 plots (TEC1-20) were classified as very common (present in 11–20 plots or >50% of surveys), common (present in 2–10 plots or 10%–50% of surveys), or uncommon (present in 1 plot or <1%–10% of surveys). Species that were only found on the 7 ha walk (TEC-walk) were considered infrequent.

We used the frequency of occurrence in the 7-ha reference site, described previously, to identify species that were a priority for restoration. The criterion we used was to include all of the very common species (i.e., 19 species), most of the common species (i.e., at least 70% of these 42 species), some of the uncommon species (i.e., 20%), and some of the infrequent species (i.e., 20%) in selecting species for return.

Experimental restoration trials for this project were undertaken on 0.86 ha within the 7-ha area to be restored

(Figure 1). Therefore, the scale-appropriate target for the experimental trial area (i.e., our working example) was adjusted and defined as ≥70% of the number of TEC species expected to be contained within an area of 0.86 ha. We interpolated a target species richness for this smaller area from a species-area accumulation curve (Appendix S1: Figure S1) obtained from the plot and walk surveys in the reference site described earlier (i.e., TEC1-10 plots: 400 m^2 each and the TEC-walk: 7 ha).

The approaches to defining and quantifying scale-appropriate targets (i.e., species richness, frequency of occurrence, restoration priority rank), as described earlier, provided the evaluation criteria for the protocol used to assess achievement of the ≥70% species composition target.

Aim 2: Approach to identifying optimal method of return

For each species in the TEC species pool, we compiled any available data on key traits, including growth form (tree, shrub, annual herb); ecological life-history strategy (annual, long-lived perennial, disturbance perennial); ecological amplitude (widespread, restricted); regeneration strategy (soil seedbank, canopy seedbank, vegetative); species-specific restoration approach (topsoil seedbank, collected seed, cuttings); and a target range of densities (and the number of individuals for the area). Data were sourced from published and unpublished material (e.g., Western Australian Herbarium, 1998–2018) or experimentally determined. These key traits helped identify the most likely source of material and the capacity for these species to be restored at levels that would meet restoration targets.

We investigated the most cost-effective method of returning TEC species. The return options included natural dispersal, the topsoil seedbank, collected and direct sown seed, and planted tubestock (seedlings or cuttings). To assess natural dispersal, we installed experimental plots without seed or topsoil addition and monitored species emergence.

A prerestoration analysis of the topsoil seedbank identified species present in the TEC topsoil, which had been stripped and stockpiled. We sampled 0.14 m^3 of stockpiled topsoil and assessed seedling emergence ex situ. Topsoil samples were spread across 140 trays to a depth of 1 cm (∼1 L topsoil/tray) over 2 cm of clean sterile sand. Half of the trays were treated with aerosol smoke to stimulate germination (Dixon et al., 1995). All trays were placed in a glasshouse under ambient winter/spring conditions, irrigated, and monitored for emergence (Perth, WA in 2012). In addition, stockpiled topsoil was spread in situ across 216 m^2 to a depth of approximately 10 cm and monitored for emergence (half the area included a mix with waste rock in 2012–2013) (see Merino-Martín, Commander, et al. [2017] for details).

Available seed was collected from the TEC and the seed quality, presence of dormancy, and germination were assessed. Dormant seeds were treated to overcome dormancy and improve germination (e.g., hot water for physical dormancy) (Commander et al., 2020). Seed quality and ex situ germination testing enabled the estimation of appropriate seeding rates (Erickson et al., 2017). Small-scale seed broadcast trials were conducted in situ to determine which species could be returned from directly sown seed and to further adjust seeding rates to optimize species and plant densities. For species with low seed numbers or no seed at all, we propagated tubestock (from seed or plant cuttings), planted them in situ, and monitored for growth and survival.

This research culminated in the installation of one large field trial in the restoration site, in which we returned stockpiled topsoil, sowed a biodiverse seed mix, and planted tubestock to experimentally determine the practicality of scaling up restoration activities, from small-scale (i.e., 1–5 m^2) to larger-scale (i.e., >300 m^2) field trials.

Aim 3: Optimizing and facilitating restoration pathways

We used the framework of biophysical research themes outlined in Miller et al. (2017) to develop a conceptual model that would potentially optimize and facilitate restoration pathways for our study system. The objective for developing this conceptual model was to provide a pathway or research agenda that could be used by applied researchers to guide their investigations, as recommended by Miller et al. (2017), into improving seedling establishment and survival, beyond identifying the optimal method of species return (i.e., AIM 2), by examining key environmental and ecological features of plant establishment. The conceptual model outlines investigations into the biotic features, abiotic features, and biotic–abiotic interactions, under five knowledge-gap themes from Miller et al. (2017) (seed biology, ecophysiology, demography, soil science, and ecohydrology) that we identify as important to understand in our system. It needed to encompass a research agenda that would theoretically maximize seedling recruitment and plant establishment in the long term, that is, research questions were based on those outlined in Themes 3 and 4 in Miller et al. (2017), to be relevant for achieving the restoration target of this study (i.e., establish ≥70% of the original species diversity). We discuss the implications of bridging these knowledge gaps through an extensive research agenda, but specific results from the experiments are not presented in their entirety; however, we refer to some that have been published.

Aim 4: Determining the achievement of targets

We developed a protocol to assess the achievement of restoration targets, ≥70% flora and vegetation composition, and demonstrate its use by testing our restoration trial (0.86 ha) 20 months after installation, for example. We consider this early-phase monitoring, but a longer period following installation was beyond the program timeframe. We quantified the species richness, abundance, and composition of the restoration trial area and "evaluated" it against the reference site. We assessed the number of target TEC species returned to site, by which method of return, and the number of non-TEC species returned to site. Overall species richness was assessed by identifying the species returned and their abundance in experimental plots (direct seeded, tubestock, and topsoil) and outside these plots through a survey walk of the entire area (natural dispersal, topsoil). We determined the species composition by examining their frequencies (i.e., at the experimental plot level, excluding tubestock plots of five species; $n = 36$ plots of 8×5 m) and the different life forms (i.e., grass, herb, shrub, tree) and compared them to the reference site (TEC1-9; $n = 9$ plots of 20×20 m; no data collected for TEC10). We used non-metric multidimensional scaling (with Bray Curtis similarity using square-root-transformed data), analysis of similarities (ANOSIM), and Simper in Primer (Clarke et al., 2006) to compare the similarity and dissimilarity between reference and restoration trial sites.

RESULTS

Aim 1: Scale-appropriate targets

In total, 120 species were identified across both species pools (i.e., TEC and supplementary), and 102 of these species were identified as the TEC species pool (Table 2). Our scale-appropriate surveys identified 80 TEC species in the 7-ha reference site: 66 from the plots (TEC1-10) and 14 from the TEC-walk. The remaining 22 TEC species were identified from the previous (or historic) survey campaigns (TEC11-20 in Figure 1). An additional 18 associated species made up the supplementary species pool (SUPP1-15 in Figure 1 and Table 2). A complete list of the TEC species pool and supplementary species pool can be found at https://doi.org/10.26182/ph8n-yv07.

For the working example, we determined the scale-appropriate number of species for 0.86 ha restoration trial area to be 67 species. Therefore, ≥47 species were required in the experimental trial area to achieve ≥70% species richness target (i.e., our example target to test the achievement protocols of Aim 4) (Table 2).

Aim 2: Optimal method of species return

We found 62 species from the TEC species pool that could be returned by at least one method from natural dispersal, topsoil seedbank, emergence of sown seed, or survival of planted tubestock (see https://doi.org/10.26182/ph8n-yv07 for details) (Commander, Golos, Elliott, et al., 2017).

In situ and ex situ analysis of seedling emergence from topsoil found 32 species, including 7 not identified in the TEC species pool, that emerged from either the topsoil seedbank or dispersed seed (Table 2). The topsoil seedbank was expected to provide at least 12 species identified in the TEC species pool (15%) for which no seed or cuttings were available, as well as supplementing 14 species in the TEC species pool that were identified to be returned from seeding or planting.

Resource availability (collected seeds, plant material for cuttings) restricted the number of species for the restoration trial (Table 2). Seed was collected from 46 species, 26 of which were not found in the topsoil seedbank. Improved germination was achieved for 19 species, with up to 14 times higher germination after pretreatments under ex situ conditions (Golos, Commander, Fontaine, et al., 2016). Only 25 species from the target TEC species pool could be used for direct seeding in situ. Due to insufficient seed quantity, 13 species (5 species also not found in the topsoil seedbank) were selected for propagation via tubestock (10 from cuttings, 1 from seed, and 2 from both). Also, owing to difficulties in sourcing plant material and the slow growth rates of some species propagated from cuttings, only 10 species had sufficient tubestock numbers of suitable quality at the time of planting (Table 2).

In summary, a total of 40 TEC and supplementary species pool species were returned (Table 2). The largest contributor was the topsoil seedbank or dispersal of seed, compared to direct seeding or tubestock planting (Table 2). The contribution from the topsoil or seed dispersal was greater (33 species) than the maximum observed from the ex situ topsoil seedbank analysis (26 species) (Table 2), while 64% of directly seeded species (16 species) and 70% of planted species (7 species) successfully established (Table 2). We detected 42 unidentified species in the restoration trial area that may have been TEC species (Table 2).

TABLE 2 Summary of results for scale-appropriate target setting (AIM 1); method of return (AIM 2); and precursory achievement of ≥70% target species richness (AIM 4 – working example only)

		AIM 1		AIM 2						AIM 4	
				Actual species returned and methods(s)[a]							
		Target species ≥70% return		Topsoil/dispersal		Sowed seed		Tubestock			
Species frequency	**Species pool**	**7 ha**	**0.86 ha**	**Analysis[b]**	**Returned**	**Sowed**	**Returned**	**Planted**	**Returned**	**Total no. species returned**	**Target species returned (%)**
Source community											
Threatened Ecological Community (TEC)[c]											
Very common (>50%)	19	19	16	9	10	8	6	4	3	13	81.3
Common (10%–50%)	42	29	24	10	14	12	6	3	3	17	70.8
Uncommon (1%–10%)	27	5	4	6	7	5	4	2	1	8	200.0[d]
Infrequent (TEC-walk only)	14	3	3	1	1	0	0	1	0	1	33.3
TEC species pool	102	...	...	...	...	...	...	...	...	39	83.0
Associated communities[e]											
Supplementary pool	18	NA	NA	0	1	...	...	...	...	1	...
Total species pool	120	56	47	26	33	25	16	10	7	40	85.1
Unidentified species (UIS)	...	...	...	...	...	...	...	...	...	42[UIS]	...
Absent from vegetation surveys											
Topsoil initial analysis[b]	NA	NA	NA	7	6	3	...	...	...	6	...
Topsoil monitoring[f]	NA	NA	NA	...	13	...	...	...	...	13	...
Grand total	120	56	47	32	52	28	16	10	7	101[UIS]	...

Notes: Species pool: number of species required from each frequency group (i.e., very common [>50% of surveys], common [10%–50% of surveys], uncommon [1%–10% of surveys], infrequent [only in 7 ha TEC-walk]) or alternate species sources (i.e., supplementary species pool, topsoil), that were prioritized for return from the TEC species pool; target species: scale-appropriate target of TEC species for ministerial condition offset clause (7 ha) and our illustrative working example (experimental restoration trial: 0.86 ha); actual species returned and method(s): method selected for species return (installation June 2015) itemized by anticipated number of species from topsoil seedbank/dispersal, sown or planted, and actual number returned (see https://doi.org/10.26182/ph8n-yv07 for details); total species returned: total number of unique species returned to site; percentage of target species returned in working example: calculated against 0.86-ha scale, from species pools of TEC and associated communities (i.e., supplementary); unidentified species (UIS): number of unidentified species at last monitoring (February 2017); absent from vegetation surveys: cryptic TEC species returned in experimental restoration trial (i.e., found in TEC topsoil). Numbers with superscripted UIS may include unidentified TEC species. Nonapplicable estimates to ≥70% target setting (NA).

[a]Some species were returned via multiple methods (see https://doi.org/10.26182/ph8n-yv07 for details).

[b]Prerestoration topsoil seedbank analysis (Merino-Martín et al., 2014).

[c]TEC species pool: species from specific TEC vegetation units (TEC1-10 and TEC-walk from this study; TEC11-20 from Meissner & Caruso [2008] and Maia [2010]; see Figure 1 and Appendix S1: Table S1 for details).

[d]This percentage represents an overachievement of intended ≥70% return for a 0.86-ha target.

[e]Associated communities (supplementary species pool): species from adjacent vegetation units strongly associated with banded ironstone formation (BIF) landform (SUPP1-15 in Figure 1 from Meissner & Caruso [2008], Maia [2010], and ATA Environmental [2004]; see Appendix S1: Table S1 for details).

[f]In situ installation and monitoring of stockpiled topsoil (Merino-Martín, Commander, et al., 2017).

Aim 3: Optimizing and facilitating restoration pathways

Our conceptual model for optimizing and facilitating restoration pathways is presented in Figure 2 and spans the multiple biotic and abiotic disciplines and their interactions, considered important for TEC restoration. This conceptual model identified key ecological questions under five knowledge-gap themes of understanding the role of seed biology (e.g., seeds in their environment), ecophysiology (e.g., environmental influence on plant performance), demography (e.g., disturbance response), soil science (e.g., altered properties in restored soils), and ecohydrology (e.g., water retention and flow properties) to improve plant establishment and survival in TEC restoration (Figure 2). These key ecological issues were developed into a research agenda (Appendix S1: Table S2) that investigates plant performance and survival responses to different landform components (topography, soil moisture dynamics) and integrated restoration techniques (topsoil use, ripping the landform surface, irrigation, seed enhancement). Appendix S1: Table S2 outlines the research agenda developed from the conceptual model and details the research discipline, question, and approach we proposed for each knowledge-gap theme to assist in the achievement of restoration targets.

Aim 4: Precursory assessment of achievement of targets

A total of 101 putative native species (59 identified + 42 unidentified) were returned to the 0.86-ha restoration trial site 20 months after installation, of which 40 identified species were confirmed as being from the TEC and supplementary species pools (Table 2). Using this restoration trial site as a working example of how to assess achievement of targets, it represented 60% of the target TEC species richness for the trial area (i.e., our precursive assessment of target achievement). Nineteen local native species emerged on site that were not identified from the TEC species pool or associated supplementary species pool (Table 2). These species were mostly annual or perennial herbs (14 species) or shrubs (4 species), which are generalist ephemerals of disturbed areas (e.g., Chenopodiaceae). The 42 unidentified species could feasibly include a similar or greater proportion of the TEC species pool, but this can be confirmed only with additional monitoring.

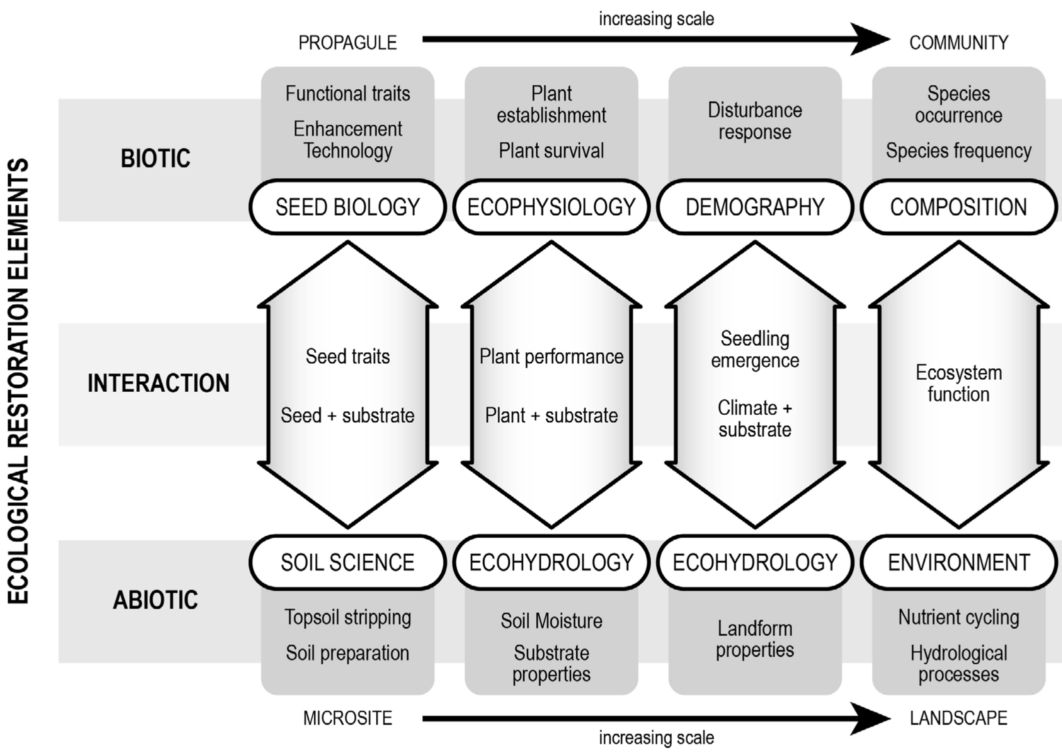

FIGURE 2 Conceptual model for optimizing and facilitating restoration pathways, for the threatened ecological community (TEC), was based on the framework of biophysical research themes outlined in Miller et al. (2017). The model encompasses multiple scales (e.g., propagule to community level) using biotic features, abiotic features, and biotic–abiotic interactions to improve restoration success under five knowledge-gap themes (seed biology, ecophysiology, demography, soil science, and ecohydrology). As a consequence, improved restoration leads to more tangible, functional interactions of biodiverse restoration with the surrounding landscape and vegetation communities at an ecosystem level (i.e., last column; Theme 5 in Miller et al. [2017])

Ordination of species community data indicates a clear difference in composition between plots of the restored trial area and reference site (Figure 3), confirmed by ANOSIM (Global $R = 0.976$; $p < 0.001$; Adonis: $F = 17.378$; $\Pr[>F] = 0.001$). Mean similarity within Simper analysis showed that this pattern was largely driven by the presence of several Chenopodiaceae species (*Atriplex* sp., *Maireana* sp., *Salsola australis*) and *Grevillea obliquistigma* in the restored trial area and their absence, or much reduced frequency, in the reference site. These taxa cumulatively account for 48.3% of the average dissimilarity between the restored trial area and reference site compositions (see Appendix S1: Table S3 for details).

There were no major differences in life form composition (trees, shrubs, and herbs) of the restoration trial area compared to the reference site, except for grasses, which were underrepresented in TEC species returned to the restoration area (1 vs. 10 species, respectively) (Figure 4). However, there were many unidentified grasses at the time of monitoring. A greater proportion of shrubs and herbs were in the restoration trial area compared with the reference site (Figure 4). Herbaceous species in the restoration trial area were predominantly non-TEC (74%) rather than TEC (26%–28%) species, with the non-TEC species likely to have returned from the topsoil seedbank or through dispersal. Orchids, ferns, and arboreal hemiparasites were not found in the restoration trial area, although they only accounted for four species in the reference site.

DISCUSSION

Connecting scientific research and government policy is essential for sustaining biodiversity conservation and the economy (Strassburg et al., 2019). We demonstrate that a joint venture among theoretical ecology, applied ecology, and policy can provide an approach to interpreting

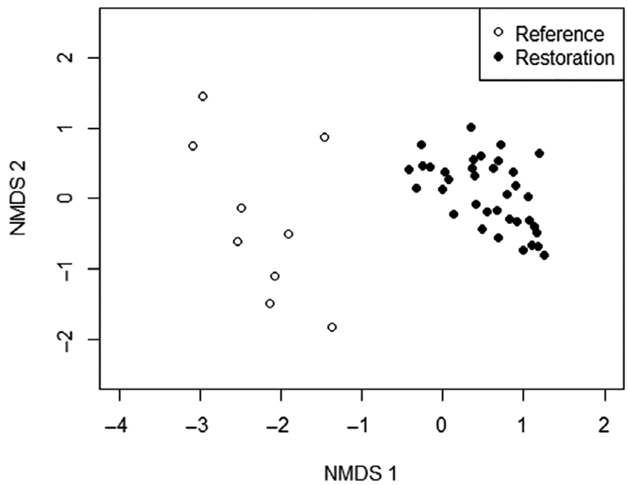

FIGURE 3 Nonmetric multidimensional scaling (2D stress = 0.12) of species community data, of restoration trial plots (closed circles), and reference site plots (open circles; threatened ecological community [TEC] survey plots TEC1-9; TEC10 plot data unavailable)

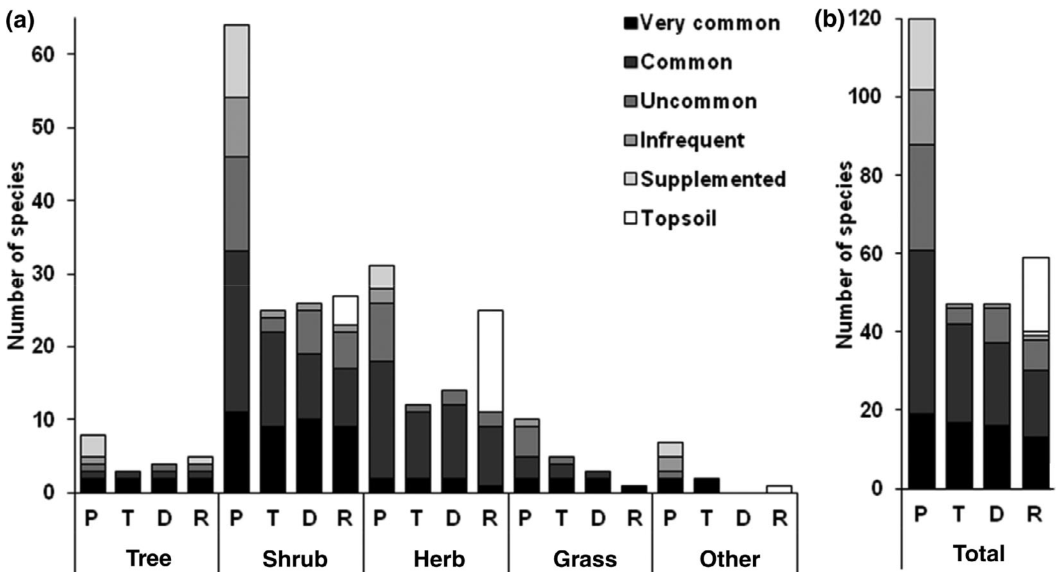

FIGURE 4 Distribution of species (a) by life form (tree, shrub, grass [annual or perennial], herb [annual or perennial], other [aerial hemiparasite, fern, orchid or climber]) and (b) overall total, at each stage of project according to frequency of occurrence of TEC species pool (i.e., very common [>50% of surveys], common [10%–50% of surveys], uncommon [1%–10% of surveys], infrequent [only in 7-ha walk]) or alternate species sources (i.e., supplementary species pool, topsoil). Project stages included AIM 1 (P)—identified TEC species pool from surveys; (T)—planned return of species target based on survey frequency data and adjusted for reduced area (7 ha vs. 0.86 ha) of restoration; AIM 2 (D)—species delivered (i.e., seed, tubestock), and AIM 4 (R)—species returned after 20 months

regulatory requirements and informing the scientific process necessary for delivering outcomes in line with policy intent and biodiversity restoration. Our approach can be used in other plant communities or other highly disturbed landscapes, like abandoned agricultural areas, because it can apply to systems that require a course of action that defines targets from a policy statement, outlines the implementation of restoration practices and evaluates restoration outcomes against targets. The premise of our approach was to define scale-appropriate restoration targets (AIM 1) that met regulatory compliance (e.g., Government of Western Australia Ministerial Conditions), identify and optimize approaches to the ecological restoration of a vegetation community (e.g., TEC) using diverse research approaches (AIMs 2 and 3), and then develop an assessment protocol to compare restoration achievements against the expected regulatory outcomes (AIM 4). We believe our approach, summarized in Figure 5, outlines a new industry benchmark in setting scale-appropriate restoration targets from regulatory conditions (AIM 1) for an entire vegetation community in a semiarid environment, and has global applications for approaches to systematically addressing the complex theoretical, practical, and regulatory challenges for achieving biodiversity restoration.

To our knowledge, this project is the first to use theoretical ecology and a scale-appropriate approach to setting species richness and compositional targets to achieve regulatory compliance (i.e., a Ministerial Condition of ≥70% return) for semiarid plant community restoration (Figure 5). Our challenges were developing completion criteria that met legally binding compliance conditions and a lack of knowledge for restoring a unique vegetation community (e.g., TEC), let alone the site-specific and climatic challenges inherent in restoring reclaimed mining substrates. A lack of precedent necessitated investment in research that highlighted the importance of understanding ecological scale (spatial and temporal) as it related to setting and achieving restoration targets. In particular, we observed the complications imparted by temporal scales to setting and achieving targets, and we discussed these issues with the intent to draw attention to their vital consideration during the process and offer potential avenues of resolution.

Ecologically realistic and scale-appropriate targets

Scale-appropriate approaches can properly address regulatory compliance and evaluate restoration outcomes (Chiarucci et al., 2003; Török & Helm, 2017). Our development of scale-appropriate points of reference (spatial scale), strategically combined with previous (or historic) information (access to temporal scale), characterized the target and provided the details for developing the evaluation criteria that would assess regulatory compliance (Figure 5). In addition, we used scale-appropriate frequency of occurrence to strategically restore species at compositions representative of the point of reference, thereby directly connecting restoration ecology with community ecology (Lindenmayer, 2020; Zobel et al., 1998). The implementation of comparative spatial scales that define points of reference and restoration targets were grounded in ecological theory (Török & Helm, 2017). However, the limited incorporation of temporal scales in this study raised questions regarding the suitable capture of cryptic species diversity and how this impacted target setting and, in addition, the capacity to reconcile the time difference between reference (often mature-phase or advanced) and restoration (often early-phase or young) sites and how this impacted the assessment of achieving targets.

This unidentified, but ecologically relevant and functionally cryptic or "dark diversity," component (Pärtel et al., 2011) presents several obstacles to restoration. The first obstacle is defining it in the reference community and, in this way, accurately setting the restoration target. Second is the added complexity of being able to source and appropriately return cryptic species in restoration. Third is knowing how to assess the successful establishment of cryptic species, post restoration. One approach to overcoming these obstacles would be to assess the topsoil seedbank prior to or in parallel with aboveground vegetation surveys to capture cryptic species (e.g., specialist, ephemeral). Consideration of the seasonal timing of surveys or having multiple surveys is another approach that would improve the availability of morphological characters required for identification (e.g., season specific like flowers/fruits or maturity related like seedling/juvenile stages) or timing (e.g., annuals) or targeted surveys around a natural recruitment event (e.g., fire or highly variable rainfall patterns) (Elliott et al., 2019; Miller et al., 2019). Here we attempted to accommodate cryptic diversity using three different survey campaigns and a prerestoration topsoil analysis, but this still fell short. In the end, only regular and long-term monitoring will capture cryptic diversity before and after restoration. Thus, the appropriate inclusion, acknowledgment, or consideration of dark diversity is required to account for cryptic species in setting and achieving restoration targets of vegetation communities.

Reconciling time differences between the points of reference and restoration depends on maturity or successional state of both communities; however, it is critical that an improvement in the capacity for realistic timeframes be accommodated in melding theoretical, practical, and policy demands in restoration (Perring

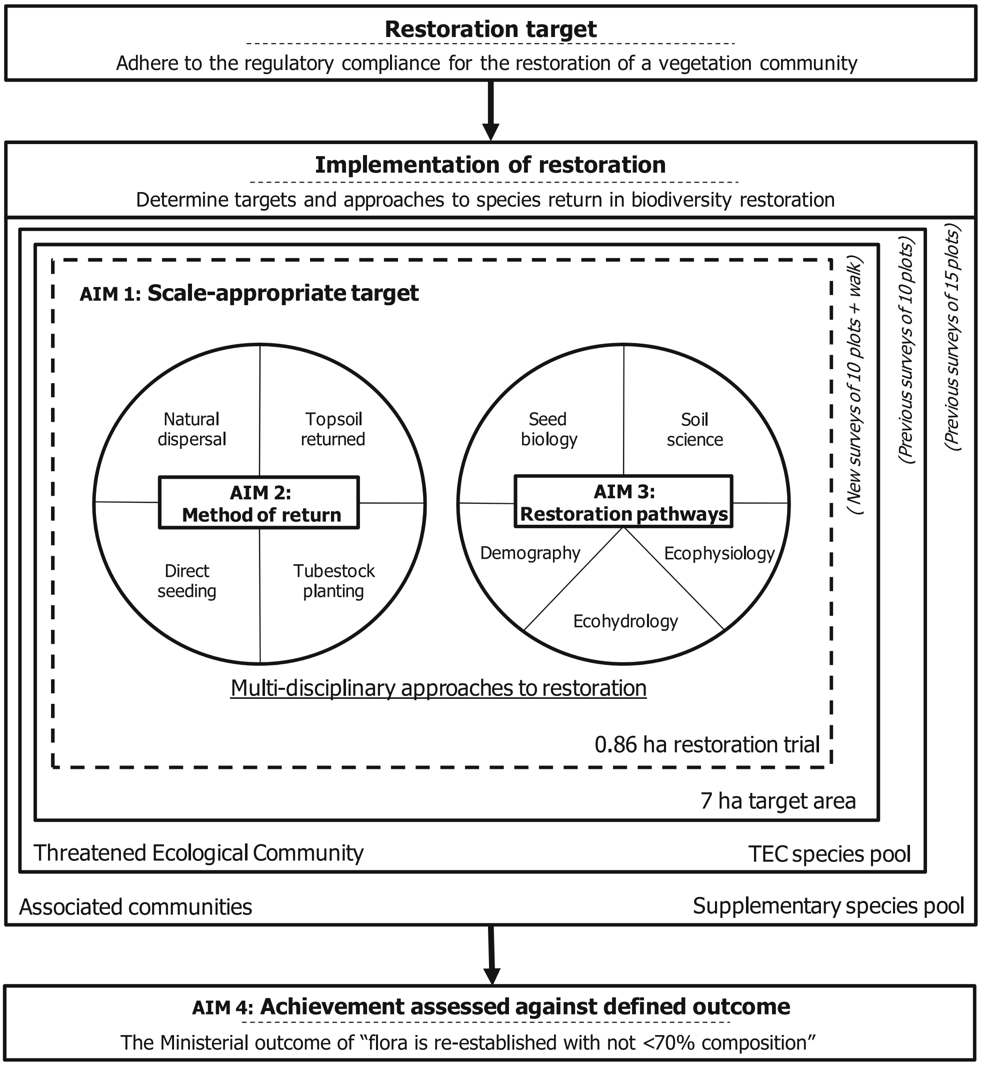

FIGURE 5 Overall conceptual model of our approach that determined targets and species return for restoration of threatened ecological community (TEC) and used to meet ministerial objectives (≥70% return). The principle of our approach was based on existing restoration standards and frameworks (Gann et al., 2019; Manero et al., 2020; Miller et al., 2017). It begins with a restoration target (specific to restoration project) and progresses to implementation of restoration that encompasses three aims. AIM 1: define ecologically realistic and scale-appropriate approaches to setting species richness and compositional targets (full extent, 7 ha, or smaller trial area, 0.86 ha) and the identification of the source species pools for restoration (TEC species pool or supplementary species pool), as represented by nested boxes. Survey sources used for each nested box for this study are in italics. AIM 2: identify optimal approaches to directly return TEC species, as represented by circle on left. AIM 3: optimize and facilitate pathways for restoration, as represented by circle on right. The model concludes with an assessment of restoration against the defined outcome (AIM 4) (Government of Western Australia, 2009)

et al., 2015; Wainwright et al., 2018). A 10-year synthesis of semiarid restoration found restoration age and climate were important for understanding the drivers of similarity (i.e., restoration success) between reference and restoration sites (Shackelford et al., 2018). However, it was recommended that targeted research on recruitment limitations and variable environments be done to improve strategies and understand trajectories (Erskine et al., 2019; Shackelford et al., 2018). Trajectory assessments of the developing community could be an option for estimating the progression of a restoration community over a longer period (>5 years) and connect a 5-year expectation of achieving regulatory compliance to the demands of decadal progression for ecological restoration.

Research investment in expanding the theoretical understanding of ecological processes involved in community or population trajectories would benefit environmental policy by providing measurable, interim criteria on a more flexible temporal scale without compromising the expected restoration outcome of having functional vegetation communities that take time to develop (Lindenmayer, 2020; Sinclair et al., 2018; Wainwright et al., 2018). Project funding constraints often dictate monitoring timeframes, and regulatory compliance that stipulate short timeframes may be imposed to ensure biodiversity is returned while mines are still operational, with resources and personnel to support activities. Even in broader terms, the timing of monitoring, assessment, and any regulatory consequences—such as tenure relinquishment, direction for follow-up works or research, penalties for poor outcomes, or timely input for subsequent approvals—may also not match common restoration outcomes and could benefit from trajectory assessments of restoration targets. This will be particularly important as regulatory compliance becomes more complex, with conditions requiring evidence of self-sustainability now being considered (Government of Western Australia, 2017).

Optimal approach for species return

Our approach utilized species-specific biology, assessed site-specific sourcing opportunities (natural dispersal [Zobel et al., 1998], topsoil [Golos, Dixon, et al., 2016], seed availability for collection [Buisson et al., 2017]), and researched the ease or possibility of establishment from sown seed or tubestock (Figure 5). In our study, limitations on seed and tubestock resources meant that topsoil was the greatest source of species return, but we recognized the implications for a species richness target that was based only on aboveground vegetation surveys and a single, small-scale ex situ topsoil assessment that restrained cryptic species identification. The acknowledgment of topsoil seedbank analysis limitations (e.g., issues of low seed density) (Golos, Dixon, et al., 2016), improved understanding of in situ and ex situ topsoil seedbank processes (Golos & Dixon, 2014; Golos, Dixon, et al., 2016), and amendments to the identification process for emergent species (e.g., develop seedling photo library from seed) would enhance species return from this primary source for restoration (Hall et al., 2010).

Without understanding the biology, sourcing, or establishment capability of the species of interest there are significant limitations on their return in restoration (Erskine et al., 2019; Miller et al., 2017). The alternative to this has been to implement so-called best practice, whereby outcomes are limited by current knowledge of restoration resources, strategies, or practices that are potentially derived from other ecological systems or locations (Gann et al., 2019). For our unique and complex biodiverse TEC, there was an inadequate knowledge base and many unresolved solutions to proceed with best practice, with substantial consequences for not meeting restoration targets if researched solutions to restore these species were not found. Besides the obvious key seed-specific traits or horticultural propagation technique that require classification and quantification, knowledge of species growth form, ecological strategy, distribution, and regeneration strategy can greatly guide the decision-making processes for determining the most appropriate method to return species in restoration (Lindenmayer, 2020; Wainwright et al., 2018).

Optimizing and facilitating restoration pathways

We tested the research framework outlined in Miller et al. (2017) and demonstrated its intended application of assisting in the identification of specific research needs with a focus on practical priority for the system in question. For our system, we showed that addressing five knowledge gaps (i.e., seed biology, ecophysiology, demography, soil science and ecohydrology) to better understand the mechanisms driving restoration (Lindenmayer, 2020; Miller et al., 2017; Suding, 2011) was fundamental to determining the influence of site and climate conditions on restoration outcomes, such as plant diversity, establishment success, plant performance, and microsite characteristics (Figure 2 and Appendix S1: Table S2). For example, moving beyond understanding the mechanisms for germination (Commander, Golos, Miller, et al., 2017) we showed that soil chemical and physical properties influenced soil hydrology and, consequently, seedling emergence under the stress of water availability (Merino-Martín, Courtauld, et al., 2017). In understanding interactions among different substrate types, we extended the use of topsoil coverage by mixing through waste rock to create a soil composite with similar seedling emergence performance as standard topsoil (Golos et al., 2021; Merino-Martín, Commander, et al., 2017). Finally, monitoring plant performance (e.g., plant stress) (Golos, Commander, Elliott, et al., 2016; Lambers et al., 2008) or indicators of soil function (e.g., soil respiration) (Muñoz-Rojas, 2018) across seasonal stresses demonstrated the response of restoration to environmental factors and might provide the proxy for interim trajectory assessments of restoration, particularly when vegetation is immature or not yet able to recruit. In summary, these theoretical and practical approaches to optimizing and facilitating the pathway for restoration can be informative in improving restoration activities, establishing benchmarks of success, or identifying opportunities to further our understanding of the biotic–abiotic dynamics of restoration if they are planned alongside research on direct species return (e.g., AIM 2) (Figure 5) (Commander, Golos, Elliott, et al., 2017).

Assessment of achievement of targets

Scale-appropriate approaches provided the details for developing the evaluation criteria and are critical for the assessment of achieving the target (i.e., ≥70% flora and vegetation composition). We demonstrated this by testing our restoration trial (0.86 ha), 20 months after installation, as an example. In this example, the assessment found that the restoration trial achieved 60% total species richness and a <52% composition similarity compared to the reference site. Despite our restoration trial not setting out to achieve the aforementioned restoration target, it did highlight several potential bottlenecks for restoration not achieving the targets. First, resolving species identification (42 unidentified species) with ongoing surveys would increase recorded species return and, therefore, potentially achieve the target within the 5-year regulatory timeframe (20 months was too short). Second, the dissimilarity between reference and restoration sites was driven by a cryptic species group of annual and perennial herbs that were not observed in the reference. They functionally represent an important seasonal component or common disturbance opportunist that is more associated with mining disturbances (i.e., colonizing mining landforms) rather than the surrounding natural vegetation (Golos & Dixon, 2014; Golos, Dixon, et al., 2016) and does not add to the permanent structure of these communities. An alteration to the community definition in the restoration guideline that specifically includes the perennial species would be beneficial for returning the permanent structural features of these shrubland or woodland communities.

Setting aside the challenging issues of recognizing and quantifying dark diversity (Pärtel et al., 2011), our precursory example shows that >40% of the known TEC flora was missing, including many groups and life forms (Figure 4). This raises the question of whether we can determine that the structure or ecological function performed by the missing flora is represented by other species. The absence of >40% of the TEC species could place the long-term success of restoration efforts at risk, owing to a potential compromise in capacity to function normally or respond to change (Hooper et al., 2005; Perring et al., 2015; Sinclair et al., 2018). It is generally accepted that there is a positive relationship between species composition and ecosystem function, although the significance of the relationship can vary depending on the type of ecosystem and which ecosystem function is examined (i.e., soil structure) (Carrick & Forsythe, 2020 and references within). Therefore, it is important for other measures of ecosystem function (e.g., soil science theme, as illustrated in Figure 2), including the well-known proxy of species composition (Carrick & Forsythe, 2020), to be incorporated into restoration targets. From the current policy point of view, regulatory compliance set biodiversity targets (from a species richness and composition aspect) but did not specifically define or set any targets around ecological function. We might be able to restore a vegetation community that looks like the target (richness and composition) but does it function in the same way. Only time will tell. A way forward is to perhaps include components of functionality in restoration targets or success criteria; however, this requires that scientists continue to collaborate with regulatory bodies to establish the format and expectation of these more complex targets.

CONCLUSION

We highlighted the need for science to feed into regulatory-body and mining-industry decisions and practices for successful restoration and conservation outcomes to be achieved. First, a regulatory target necessitates the development of appropriate methods to define it, and additional guidance is needed on how to go about defining targets. Second, the regulatory timeframes that require species return within 5 years are conceivably achievable; however, these timeframes may not always be long enough to compare a restored community against mature points of reference. Hence, restoration targets could include trajectory assessments that track the successional transition of restoration through time or are compared to recently disturbed reference communities (e.g., 5 years following a fire). Alternatively, there could be provisions that ensure that the restored area will be monitored until it reaches a mature state, with targets that need to be met at regular intervals to ensure that the trajectory will likely reach that of the reference, and if not, then intervention and adaptive management will occur. Third, restoration science needs to push the boundaries of reconstructing vegetation communities beyond extant species richness and composition by engaging in the challenge of capturing cryptic or dark diversity, developing vegetation community trajectory models specifically for restoration, incorporating plant functional performance in restoration assessment criteria and focusing on establishing ecological interactions and functionality to ensure sustainability of restoration.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Elliott et al., 2021) are available from The University of Western Australia's repository: https://doi.org/10.26182/ph8n-yv07.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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