Strategic adaptive management planning—Restoring a desert ecosystem by managing introduced species and native herbivores and reintroducing mammals

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Abstract
Arid rangelands are degraded worldwide, suffering vegetation transformation, soil erosion, introductions, and extinctions. Wild deserts is restoring a desert ecosystem in Sturt National Park, New South Wales, Australia (35,000 ha), eradicating or controlling introduced animals, managing native herbivores, and reintroducing regionally extinct mammals. We describe a Strategic Adaptive Management Plan for restoration of this desert ecosystem, including a vision, model of ecosystem processes, stakeholder input, a hierarchy of objectives linked to triggers and their management actions, producing outcomes and outputs. Our management treatments included two “no restoration” areas and three “restoration” areas. The latter include two exclosures (each 2,000 ha), free of introduced animals (foxes, cats, rabbits), with previously abundant kangaroos removed and regionally extinct mammals to be reintroduced. The third management treatment is a Wild Training Zone (10,400 ha), with introduced animals and kangaroos managed at low levels, using innovative methods, improving survivorship and avoidance behavior of reintroduced mammals to introduced predators. These measures will allow populations of threatened animals to establish, initially in the exclosures, then the Wild Training Zone and potentially more widely. Our strategic adaptive management planning approach is generic and implementable for any natural resource management project, providing explicit steps and processes that track and report transparently on outcomes, fostering learning by doing.

KEYWORDS
feral animal control, governance, regionally extinct mammals, restoration targets, strategic adaptive management
1 | INTRODUCTION

Conservation managers need to continually determine if biodiversity goals are met by management (Parrish, Braun, & Unnasch, 2003), but tracking effectiveness of such natural resource management, including restoration of ecosystems, is challenging. In many protected areas of the world, there are significant deficiencies in management (Leverington, Costa, Pavese, Lisle, & Hockings, 2010), with many conservation management initiatives (e.g., restoration) inadequately tracked (Ferraro & Pattanayak, 2006). Major conservation projects often lack clear goals, with monitoring poorly aligned to assess success or failure, particularly over the long term (Ewen & Armstrong, 2007), including inadequate indicators (Read, Kovac, & Fetchen, 2005). This makes it difficult for managers, stakeholders, and communities to assess effectiveness. For example, a review of the management of six national parks in Canada and South Africa found inadequate monitoring of biodiversity indicators, essential in demonstrating effectiveness in protecting ecological integrity (Timko & Innes, 2009). Monitoring needs to be clearly linked to goals or objectives, aligned with a future ecosystem state, within budget constraints, but importantly testing management effectiveness for biodiversity outcomes (Bal, Tulloch, Addison, McDonald-Madden, & Rhodes, 2018). Often goals are too broad, allowing interpretations of different applicable management actions and monitoring. This ambiguity can produce management actions and monitoring which may not achieve goals of a project.

Conservation management is complex, incorporating ecosystem dynamics and socioeconomic drivers (Folke, Hahn, Olsson, & Norberg, 2005). Adaptive management is a way of improving effectiveness of management actions, based on learning by doing (sensu Walters, 1986; Lee, 1993, Williams, 2011). It promotes decision-making, involving an assessment of the problem, designing and implementing actions, monitoring and evaluating outcomes and adjusting management where necessary (Williams, Szaro, & Shapiro, 2009). In addition, adaptive management also often includes social objectives and learning over short to long time scales (Fabricius & Cundill, 2014; McLoughlin & Thoms, 2015; Pahl-Wostl, 2009): the doing (single-loop), challenging the status quo and exploring innovation (double-loop) and altering governance arrangements (triple-loop). Without social objectives, success of projects may be constrained (Schwartz et al., 2018). Adaptive management incorporates a range of approaches or tools from experimental knowledge and observation through to experimentation (Armitage, Marschke, & Plummer, 2008; Keith, Martin, McDonald-Madden, & Walters, 2011; Kingsford, Biggs, & Pollard, 2011; Stem, Margoluis, Salafsky, & Brown, 2005). Despite increased uptake, there remain considerable opportunities to improve practical implementation of adaptive management (Keith et al., 2011; Westgate, Likens, & Lindenmayer, 2013).

Different adaptive management frameworks for conservation that can be applied to a range of ecosystems and their threats differ primarily in terminology and emphases. They commonly include analyses of the context, some captured in a conceptual model of threats and other factors, which drives development of goals or objectives, followed by actions, triggered by thresholds, with monitoring informing on effectiveness in achieving biodiversity or social outcomes related to objectives (Schwartz et al., 2018). Open Standards for the Practice of Conservation is a popular structured approach involving these components and development of if-then hypotheses linking objectives to actions (result chains) for achieving conservation targets (Carr et al., 2017; Margoluis et al., 2013; Schwartz et al., 2012; Schwartz et al., 2018). Strategic Adaptive Management follows a similar logic structure but incorporates an explicit hierarchy of objectives (embedded result chains), linking broad objectives to progressively finer-scale objectives, with the finest scale articulating the targets or management actions, triggered by thresholds, with monitoring of management effectiveness informing learning (Biggs & Rogers, 2003; Kingsford et al., 2011; Roux & Foxcroft, 2011).

Large areas of the world’s rangelands are degraded by changes in plant composition, (such as decreased vegetation cover, shrub encroachment), nutrient loss, increasing soil erosion and salinization (D’Odorico, Bhattachan, Davis, & Runyan, 2013) and loss of functional species (Chillo & Ojeda, 2012). Such impacts can reduce resilience to environmental variability (Fenshaw, Wang, & Kilgour, 2015; Healy, Tulloch, & Fenshaw, 2020; Letnic, 2000; Milton, du Plessis, & Siegfried, 1994), although some impacts may be reversible (Silcock & Fenshaw, 2019). Legacies of pastoral degradation (Eldridge & James, 2009; Fenshaw et al., 2015; Letnic, 2000; Tiver & Andrew, 1997), including impacts of artificial watering points (Healy et al., 2020; James, Landsberg, & Morton, 1999), compounded by introduced species, particularly rabbits *Oryctolagus cuniculus*, red foxes *Vulpes vulpes*, and feral cats *Felis catus*, have resulted in local mammal extinctions (Woinarski et al., 2011). This has disrupted trophic networks (Morris & Letnic, 2017) and degraded ecosystems.

Restoration of these landscapes for native biota (including regionally extinct species (Moseby et al., 2011)) and their ecological processes is becoming increasingly popular, allowing ecosystems to persist and evolve. We demonstrate the use of Strategic Adaptive
Management for the restoration of a desert ecosystem in semiarid Australia, the Wild Deserts project (35,000 ha of Sturt National Park in northwest New South Wales [NSW], Figure 1, Pedler et al., 2018). This approach focuses on using different management treatments and monitoring management actions, with triggers, to determine if outcomes and outputs are achieved. This paper deals with the overarching framework, supported by a separate more detailed operational plan. To illustrate our approach in practice, we develop three objectives down to their finest level, at the operational plan level, where they can become management actions, with triggers and predicted outcomes informed by monitoring and outputs with timelines.

2 | STRATEGIC ADAPTIVE MANAGEMENT PLAN

Our Strategic Adaptive Management plan includes setting a desired future state, captured by a vision, which leads to specification of high-level objectives, informed by the context and stakeholders (Figure 2). Resources, which may need to be acquired (new), provide the impetus for planning and identifying management options, but may need approvals and conditions (Figure 2, Pedler et al., 2018). Low-level objectives then provide the template for identifying triggers for management actions which are then monitored and analyzed, resulting in outputs but ultimately also the conservation, social and educational outcomes (Figure 2). There are also important feedbacks, providing learning and changing objectives up to the vision if necessary (Kingsford et al., 2011, Figure 2).

2.1 | Desired future state

Setting the desired ecosystem state has three components: (a) a vision, influenced by context (Figure 2) and involving development of key attributes (Table S1); (b) a conceptual framework or understanding; and (c) an objectives' hierarchy (Table S1).

2.1.1 | Context and vision

The Wild Deserts' project is bounded on the northern and western sides by the dingo fence, which aims to exclude dingoes Canis familiaris from NSW, to protect...
domestic livestock. Wild Deserts occupies the traditional land of the Wongkumara and Maljangapa Aboriginal people, developed for grazing sheep and cattle in the early 19th century, before becoming a national park in 1972. Degradation by overgrazing during and since pastoral use was substantial. For the restoration, we aim to eradicate and control introduced animals, manage native herbivores, remove artificial waters and reintroduce seven regionally extinct mammals (Figure 1). The project is funded by the NSW Government (AUD 8.5 million over 10 years) and other sources, involving close collaboration with the NSW National Parks and Wildlife Service.

Our vision included our contractual goal (reintroduction of regionally extinct mammals), plus the restoration of the functionality and composition of the desert ecosystem, using science and incorporating effective partnerships (Table S1). It was influenced by the legal, social, policy and economic context and involved meetings and submission of plans and strategies and other communications with stakeholders (see Pedler et al., 2018). These included our main funder and regulator (NSW Government, Department of Planning, Industry and Environment, particularly National Parks and Wildlife Service) and traditional owners, other funders, neighbors, other scientists and the public.

The key attributes comprised six statements of the social–ecological system that captured the main ecological processes and social structures. We defined these attributes or statements to express the “requisite simplicity” of a complex social–ecological system (Holling, 2001; Stirzaker, Biggs, Roux, & Cilliers, 2010). They include causes, mechanisms, effects, and social causes of degradation that guide setting of ecological and social objectives representing the desired future state (Table S1).

2.1.2 Conceptual framework—Desert ecosystems

Conceptual frameworks summarize understanding of ecosystem functions and dynamics, capturing the main cause and effect relationships and predicted transitions among states. Constructing these frameworks helps to identify uncertainties and guide development of key hypotheses to be tested with experiments or monitoring.

Central to our conceptual framework is episodic rainfall, which drives much of primary production and vital rates of plants and animals in desert ecosystems (Whitford & Duval, 2019). In Australia, this creates temporally variable patches of high productivity, mediated by topographic heterogeneity (Morton et al., 2011). Perennial plants and lichen crusts bind surface soils and, with other plants, cycle nutrients and provide food and shelter for invertebrate and vertebrate consumers. Ephemeral plants exploit flushes of water availability, persisting through droughts in long-lived seedbanks (Capon & Brock, 2006). Morphological, physiological, and phenological traits of the biota reflect selection pressures associated with diurnally high temperatures, and deprivation of water and nutrients. For example in Australia, many vertebrate and invertebrate fauna are nocturnally active (Read & Moseby, 2001), sheltering from high temperatures in burrows or under shrubs. Fossorial mammals engineer soil structure and provide regeneration niches for plants (James & Eldridge, 2007; Read, Carter,
Moseby, & Greenville, 2008) and shelter for a range of species (Read et al., 2008), while predators and the availability of plant biomass regulate populations of herbivores and granivores (Dickman, Mahon, Masters, & Gibson, 1999; Letnic & Dickman, 2010; Letnic, Felt, & Forsyth, 2018).

Aboriginal communities occupied the region for tens of thousands of years, subsisting on a range of native animal and plant species. With European colonization, introduced species have dramatically degraded composition and ecological processes in Australia’s desert ecosystems. Artificial watering points have also allowed large populations of livestock (feral herbivores) and wild large native herbivores (kangaroos), contributing to overgrazing (Healy et al., 2020; James et al., 1999; Letnic et al., 2015). Rabbits have suppressed long-lived woody plants, decreasing ground cover, increasing soil erosion and altering vegetation structure (Cooke & Soriguer, 2017). Rabbits have also facilitated increased populations of introduced predators (i.e., foxes and cats, Pech, Sinclair, Newsome, & Catling, 1992). Exclusion of dingoes, the top predator, has benefited introduced mesopredators, exacerbating predation pressure on critical weight range mammals (Letnic et al., 2018; Letnic, Ritchie, & Dickman, 2012). It has also led to increased populations of large native herbivores, further damaging soils and vegetation (Rees, Kingsford, & Letnic, 2017). Australian desert ecosystems have dramatically changed, with the extinction and endangerment of many native mammal species, shifting the structure and composition of vegetation (Silcock & Fensham, 2019; Woinarski, Burbidge, & Harrison, 2015).

Much of the degradation is irreversible, given extinction of species (Woinarski et al., 2015), extirpation of long-lived plants and changes to soil structure and function. However, partial restoration is possible by mitigating threats including, removing introduced animals and artificial watering points, reducing populations of native herbivores and reintroducing regionally extinct species (Moseby, Hill, & Read, 2009; Silcock & Fensham, 2019). These measures can improve the composition and functionality of the desert ecosystem, restoring vegetation composition and cover, and increasing abundances and diversity of some fungal, invertebrate, small mammal, reptile, frog and bird populations (Contos & Letnic, 2019; Moseby et al., 2009; Rees, Kingsford, & Letnic, 2019).

2.1.3 Objectives’ hierarchy

We developed an explicit objectives’ hierarchy (see Rogers & Biggs, 1999), guided by our vision (level 1, Figure 3), supporting increasingly broad-scale objectives for Wild Deserts (Levels 2 and 3, Figure 3), spanning partnerships, the ecosystem, resources, planning and communication (Level 2, Figure 3). Accomplishment of broad objectives (Levels 1–3) is dependent on achievement of fine-scale objectives or actions (Levels ≥4); these fine-scale objectives change more frequently as they achieve their outcomes and outputs (Figure 2). Level 3 social objectives focus on the types of partnerships, necessary financial, infrastructure and human resources, required planning processes, internal governance and types of transparent communication (Level 3, Figure 3). Level 3 ecosystem objectives relate to restoration (Figure 3), including our contracted task: to successfully establish seven regionally extinct mammal species (Figures 1 and 3). We also specify objectives related to the management of introduced animal and plant species (Figure 3), with species’ specific lower level objectives linked to triggers, management actions, outcomes, outputs and time lines, informed by monitoring (Figure 2).

Management of kangaroo populations is also a key objective, given they can sometimes reach high densities in the absence of dingoes (Table 1, Rees et al., 2017). Our remaining ecosystem objectives focus on indicators that track key changes in ecosystem composition and functionality (Table 1). We expect a range of other biodiversity objectives (in addition to the seven reintroduced mammal species, introduced species and kangaroos) and ecosystem processes to respond to management actions (Table 1).

3 MANAGEMENT ACTIONS AND TRIGGERS

Implementation of the new management strategy began with an establishment phase that required establishment of staff and accommodation, planning approvals, fence construction and eradication of feral animals (Figures 2 and 3, Pedler et al., 2018). To restore the ecosystem and learn about the relative effects of different management actions, we established five management treatments (Figure 1). We posed testable predictions of changes in biodiversity composition and processes (Figure 4), as a result of our management actions and triggers, based on current conceptual understanding of ecological interactions in these ecosystems. Our management actions were implemented in three management treatments (within the two exclosures (Thipa and Mingku, see Pedler et al., 2018 for selection process) and the Wild Training Zone, Figures 1 and 4), where we controlled introduced animals, managed kangaroos, and will reintroduce regionally extinct species. The establishment of two exclosures allows us to introduce regionally extinct species (in addition to the seven reintroduced mammal species, introduced species and kangaroos) and ecosystem processes to respond to management actions (Table 1).
species at different times and sequences to tease out cause and effect relationships. It also offers opportunities to explore effectiveness of minor fencing options (e.g., use of electric hot-wires). The remaining two “no restoration” treatments provide a baseline or control. They include control areas in Sturt National Park and South Australia in similar habitats (Figure 1), providing a means of measuring progress towards management goals in the three management treatments (Figure 4).

The “no restoration” management treatment in New South Wales includes high numbers of kangaroos, when productivity is high (up to 90 individuals km\(^{-2}\) (Pedler, Read, Moseby, Kingsford, & West, in press) cf. 0.07–0.61 individuals km\(^{-2}\) (Caughley, Grigg, Caughley, & Hill, 1980)), given the scarcity of dingoes (Figure 1), exerting pressure on vegetation (Figure 4a). This grazing pressure likely reduces habitat and food availability for invertebrates, reptiles, and granivorous birds (Rees et al., 2017). There are also introduced animals, including foxes and cats which prey on a range of animals. Rabbits further increase grazing pressure and support fox and populations (Pedler et al., 2016). In South Australia, “no restoration” management areas support high densities of dingoes which suppress kangaroos, emus and foxes, artificial watering points and cattle (outside Sturt National Park, Figure 1).

Removal of introduced animals and large herbivores (kangaroos and emus) from the exclosure management treatments (Exclosure [Thipa] and Exclosure [Mingku], Figure 4b) is predicted to increase ground cover (particularly perennial grasses), allowing recruitment of long-lived perennial plants and increasing seed resources, benefiting granivorous and insectivorous birds and mammals (Figure 4a, Table 1). Further, reintroduction of regionally extinct mammals (e.g., bilbies) is expected to play an important functional role, because these animals
Table 1  Main groups of organisms and processes targeted for Strategic Adaptive Management in the Wild Deserts’ project and their functional role, reflected in biodiversity outcomes, linked to our monitoring (Table S1), and identified as indicators predicted to change with our management in the restoration of this desert ecosystem. Refer to Table 2 for detailed objectives and triggers for management actions, leading to biodiversity outcomes and outputs provided for three groups: feral cats, kangaroos, and bilbies.

| Group                              | Name                                      | Functional role                                                                                      | Biodiversity outcomes                                                                 |
|------------------------------------|-------------------------------------------|------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Introduced species for eradication/suppression | Grazers—rabbit, goat *Capra hircus*, pig *Sus scrofa* | Responsible for deleterious ecosystem degradation in Australia’s arid zone. Impact on perennial plant recruitment and survival, vegetation structure, ground cover, soil erosion and compete with native herbivores, support elevated introduced predator populations. Goats browse native vegetation and pigs disturb soils and vegetation. Burrows create refuges for other native/introduced species | Total eradication from exclosures, suppression within Wild Training Zone. Improved vegetation communities and soil condition and increases in native animals. |
| Predators—fox, cat, dingo          |                                           | Foxes and cats prey on small mammals, birds, reptiles and invertebrates. Dingos impact negatively on neighboring livestock | No foxes within the exclosures and wild training zone. No cats within the exclosures and <0.3 km$^{-2}$ within the Wild Training Zone. Improved vegetation communities and soil condition and increase in native animals. |
| Native herbivores for population management | Macropods: Red kangaroo *Macropus rufus*, Western grey *Macropus fuliginosus* | Large macropods are significant grazers in the ecosystem, with high densities negatively affecting vegetation condition, ground cover, soil erosion, and animal welfare. | Removal of macropods from both exclosures and maintain macropod densities at ≤2 km$^{-2}$ within Wild Training Zone. Improved vegetation and soil condition and increases in native animals. |
| Regionally extinct native mammals for reintroduction | Bandicoots: Greater bilby *Macrotais lagotis*, Western barred bandicoot *Peramelesguni*, Golden bandicoot *Isodon auratus* | Increase soil health, through mycorrhizal fungal associations, turnover, and mixing of nutrients, resulting from diggings which trap organic matter, increase water infiltration, providing opportunities for establishment of nutrients and plants which can improve seedling germination and establishment. Bilbies create burrows providing refuges for other animals. All three species prey on invertebrates, some reptiles and amphibians. They are also prey for western quolls and owls. | Successful establishment in exclosures, and then into Wild Training Zone and beyond. |
| Burrowing bettong *Bettongia lesueur* |                                           | Creation of underground refuges via warrens providing thermal protection for a range of species. They graze on Chenopod species and perennial seedlings and may deplete the seed bank. | Option to allow reintroduction in one of two exclosures, or just in Wild Training Zone. Density to remain at less than 0.3 per hectare based on overpopulation issues elsewhere (Moseby, Lollback, & Lynch, 2018). |
| Greater stick-nest rat *Leporillus conditor* |                                           | Nests provide habitat for invertebrates and small mammals/reptiles. They graze on Chenopod and succulent species. Prey items for western quolls and aerial predators | Successful establishment in exclosures, allowing beyond the fence opportunities. |

(Continues)
Predicted changes in our five management treatments, capturing key processes among different organisms (arrows denote direct effects with relative width the strength of the effects) and their predicted effects, representing different stages of restoration of a desert ecosystem, following reintroduction of regionally extinct mammals (Table S2, dashed lines), removal of artificial waters and removal and control of introduced animals (rabbits, foxes, cats, black) where local rainfall is the key driver: (a) “no restoration” areas (C1 and C2); (b) the exclosures (E[T] and E[M]); and (c) the Wild Training Zone (see Figure 1).
Some perennial plant, reptile, and bird species in the formerly degraded ecosystem, may decline with improved vegetation structure and coverage, increased specialist grazers, predators, and competition (Read & Cunningham, 2010, Figure 4b). Our third management treatment aims to establish and maintain regionally extinct mammals within our Wild Training Zone, with low numbers of introduced predators, already present and native predators (Figures 1 and 4c), enclosed by a fence linking the two exclosures and the dingo fence (Figure 1). We aim to promote establishment of regionally extinct native mammals through in-situ predator exposure, facilitating improved survival and increased predator awareness and ultimately coexistence with low densities of introduced predators (Moseby, Letnic, Blumstein, & West, 2019; Ross, Letnic, Blumstein, & Moseby, 2019; West, Letnic, Blumstein, & Moseby, 2018). We expect changes in functionality and composition in the Wild Training Zone to be similar, but less marked than in the exclosures and likely more similar to our control no restoration sites in South Australia where dingoes suppress introduced predators and kangaroos (Figure 4c). These predictions are outlined in the finer levels of the objectives, triggers, management actions and expected biodiversity outcomes and outputs, as well as timelines (Figure 2, Table 2).

In our adaptive management system, our Level 3 objectives (Figure 2) are connected to fine-scale objectives (Levels 4–6, Figure 2). To illustrate this connectivity from broad objectives to management actions, their triggers and adaptive learning from monitoring outcomes, we detail the links between the broad scale objectives (Figure 4) and management objectives (Levels 4–6) for three groups (Table 2, Figures 2 and S1). These span the major ecological management challenges for restoring this ecosystem, including management of feral cats, kangaroos, and reintroduction of bilbies. Other objectives leading to a range of biodiversity and social outcomes (see Table 1, Figure 3) follow a similar structural and detailed pattern but are not replicated here.

For feral cats (under introduced mammal species, Level 3, Figure 3), the Level 4 objective relates to the broad objective to manage feral cats (Table 2, Figure S1). This leads to the specific Level 5 objectives (management actions, with triggers), relevant to the three management treatments (two exclosures and Wild Training Zone). Eradication of cats from the exclosures was achieved in 2018 by eradicating rabbits, requiring no other lethal control (Table 2). Once the exclosures were closed, we used repeated spoor tracking in sandy substrates, camera traps, and spotlight surveys to confirm that no cats were present. We also operated four Felixer grooming traps in non-lethal mode (currently only legally permitted in NSW) with audio lures and cameras (Read et al., 2019) and detected no cats. Ongoing surveillance focuses on ensuring the fence is secure to any incursions, with removal of cats if this occurs (Table 2, Figure S1). Adaptive management will involve learning where incursions occur and improving fencing if required. For our Wild Training Zone, we will reduce feral cats to a threshold density or trigger (initially forecast at <0.3 km⁻², Figures 1 and 4, Table 2) to allow regionally extinct native mammals to persist in the presence of low level feral cat predation (Moseby et al., 2019; Ross et al., 2019; West et al., 2018). Adaptive management experiments will enable testing to identify the most effective combination of Felixer grooming traps and other modes of control (e.g., poisonous prey, Read, Peacock, Wayne, & Moseby, 2015), supported by similar monitoring and improving understanding of feral cat behavior Table 2, Figure S1).

For kangaroo management, the Level 3 objective specifies the need to manage kangaroo populations (Figure 4), while the Level 4 objective specifies management of overabundant kangaroos (Table 2). Management actions follow as Level 5 objectives, related to the three management treatments (Figure 1), with their triggers (supported by monitoring) (Table 2). Before construction of exclosure fences, extremely dry conditions caused significant mortality of kangaroos across Sturt National Park, a reduction to <1% of densities before fence construction (<90 individuals km⁻², Pedler et al., in press). We used water to attract seven kangaroos out of the exclosures, using one way gates in 2018. Finally, under strict government and animal welfare protocols, 11 individuals were euthanized, leaving the enclosure free of macropods, essential given its lack of permanent water. For the Wild Training Zone, we aim to control numbers of kangaroos with a trigger for densities >2 individuals km⁻² (Table 2), similar to densities where dingoes are present (Caughley et al., 1980). We are experimenting with different methods to manage these densities, including using one way gates and watering troughs, with lethal control if necessary (Table 2, Figure S1, Pedler et al., in press).

Bilbies are planned as the first reintroduced species to be established (Level 4 objective, Table 2). As ecosystem engineers, they can benefit other species (James & Eldridge, 2007). We developed two Level 5 objectives, related to bilby populations in the exclosures and Wild Training Zone, with Level 6 objectives detailing our management actions and the triggers (supported by monitoring data) for those actions (Table 2, Figure S1). The translocation plan is completed with a release planned for spring 2020 or autumn 2021, depending on conditions. We will use adaptive management to learn about
**Table 2** Detailed fine-scale objectives (Levels 4–6 including management actions) and their triggers, outcomes and outputs, linked to broad objectives (Levels 1–3, Figure 3), for management of three groups, feral cats, kangaroos, and bilbies. Triggers and outcomes are informed by monitoring detailed for each.

| Species          | Level 4 objectives                      | Level 5 objectives                      | Level 6 objectives                      | Triggers                                                                 | Management action                                                                 | Outcomes                             | Outputs*                      | Timeline                  |
|------------------|----------------------------------------|----------------------------------------|----------------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------|------------------------------|---------------------------|
| Feral cats       | To manage feral cat populations         | To manage cats in exclosures           | To remove all cats from the two exclosures | Completion of the fenced exclosures                                      | Cat removal techniques by removal of rabbit prey, shooting and trapping—determined by intensive and comprehensive surveillance during eradication phase, extensive repeat track surveys, spotlight surveys, camera traps and routine surveys of fence. | No cats present                     | Report to the NSW Government | February 2019              |
|                  |                                        |                                        |                                        | Weekly fence patrol to detect potential entry points for cats, particularly at potential vulnerable points: Floppy top shape, holes in foot netting and gate latching and also impacts on reintroduced species in relation to carcass detection. Fence patrol also checks for cat tracks within exclosures. | Cat removal techniques by shooting and trapping—determined by comprehensive annual surveys, tracks per km, spotlight surveys, camera traps and routine surveys of fence. | No cat incursions detected          | Quarterly reporting to NSW Government | 2019-long-term             |
|                  |                                        |                                        |                                        | Exceedance of threshold, determined from data on spotlight surveys, track counts, camera traps, and routine surveys of fence. Increase feral cat control if >60% of released reintroduced species predated by feral cats. | Reduction in cat densities ≤0.3 km⁻² or lower, using Felixer grooming traps and targeted baits and other controls—determined by comprehensive annual surveys, tracks per km, spotlight surveys, camera traps and routine surveys of fence. | Feral cat densities ≤0.3 km⁻² or lower | Quarterly reporting to NSW Government | 2019-long-term             |
| Kangaroos        | To manage over abundant macropods       | To remove all macropods from the two exclosures | To use one-way gates and water troughs to attract out | Near completion of the fenced exclosures. | Trapping and tracking feral cats in the Wild Training Zone. | Understanding impacts and behavior of feral cats on areas used by tracking areas used, permeability of dingo fence to cats, diet in relation to prey availability and cat size and sex. | Quarterly reporting to NSW Government | 2021–2026 (subject to funding) |

*NSW = New South Wales
| Species                  | Level 4 objectives | Level 5 objectives | Level 6 objectives | Triggers                                                                 | Management action                                                                 | Outcomes                                                                 | Outputs*                        | Timeline          |
|-------------------------|--------------------|--------------------|--------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------|---------------------------------|-------------------|
|                         |                    |                    |                    | To use lethal control to reduce density if other methods fail             | Implement macropod removal techniques—determined by spotlight and diurnal surveys, tracks per km and camera trap surveys. | Remaining macropods removed from the two exclosures.                        | Macropod and Emu Management Plan | Oct–Nov 2018       |
| Macropods               |                    |                    |                    | Some macropods remain within exclosures once fence completed—determined by spotlight and diurnal surveys, tracks per km and camera trap surveys. | Establish and service water troughs, turning them off when heavy rainfall creates temporary natural surface water sources. Monitored during spotlight and other surveys of the Wild Training Zone and water use monitored with camera traps. | Health and condition of kangaroos.                                       | Macropod and Emu management plan | Ongoing            |
|                         |                    |                    |                    | To maintain and sustain macropod densities at \( \leq 2 \text{ km}^{-2} \) in the Wild Training Zone | To provide water troughs when necessary                                       | Macropod and Emu management plan                                             | Ongoing                         |                   |
|                         |                    |                    |                    | Water provided in warm season months (Nov–Mar), when no temporary natural surface water exists. | Establish and service water troughs, turning them off when heavy rainfall creates temporary natural surface water sources. Monitored during spotlight and other surveys of the Wild Training Zone and water use monitored with camera traps. | Macropod and Emu management plan                                             | Ongoing                         |                   |
|                         |                    |                    |                    | To use one-way gates to reduce density                                    | Macropod density >2 \( \text{ km}^{-2} \) in the Wild Training Zone.           | Macropod density is reduced \( \leq 2 \text{ km}^{-2} \). Sustainable densities of macropods managed at a level which reduces their welfare and impacts on the ecosystem. | Macropod and Emu management plan                                             | Ongoing                         |                   |
|                         |                    |                    |                    | Macropod density index data continuously >2 \( \text{ km}^{-2} \) over three successive counts and provision of water/food attractants at one-way gates have failed to reduce densities below the threshold over a 1-month period. | Establish three permanent one-way gates allowing exit from the Wild Training Zone. Another seven temporary one-way gates opened if macropod density exceeds 2 \( \text{ km}^{-2} \) over three successive counts. Determined from spotlight and diurnal surveys, tracks per km, camera trap surveys and macropods not exiting through permanent one-way gates. | Macropod density is reduced \( \leq 2 \text{ km}^{-2} \). Sustainable densities of macropods managed at a level which reduces their welfare and impacts on the ecosystem. | Macropod and Emu management plan                                             | Ongoing                         |                   |
| Bilbies                 | To reintroduce      | To establish self- | To complete an      | Identification of potential timing for reintroduction.                      | Implement lethal macropod removal techniques—determined by spotlight and diurnal surveys, tracks per km and camera trap surveys. | Macropod density reduced \( \leq 2 \text{ km}^{-2} \). Sustainable densities of macropods managed at a level which reduces their welfare and impacts on the ecosystem. | Macropod and Emu Management Plan                                                                 | If required |                   |
|                         | bilbies             | sustaining         | approved            | plan                                                                         | plan for approval                                                              | plan for bilbies Berns                                                                 |                                 |                   |
|                         |                    | populations of    | translocation       | Draft translocation plan for approval.                                      | Approved plan                                                                  | Translocation plan for bilbies                                                 |                                 |                   |
|                         |                    | bilbies in         | plan               |                                                                             |                                                                                  | (Continues)                                                                  |                                 |                   |
| Species | Level 4 objectives | Level 5 objectives | Level 6 objectives | Triggers | Management action | Outcomes | Outputs \(^a\) | Timeline |
|---------|--------------------|--------------------|--------------------|----------|--------------------|----------|---------------|---------|
| To obtain bilbies from two translocation sites and release them | Sufficient rain for invertebrate and vegetation response to enable reintroduction. | Implement translocations from translocation sites. Organize transport, health checks and attach transmitters. Release bilbies. | Successful arrival and release of translocated bilbies. | Quarterly reporting to NSW Government | Spring 2020 or Autumn 2021 |
| To establish widespread populations of bilbies | Widespread sign of range extension with >50% of suitable habitat occupied. | Radiotracking, tracks per km, mark-recapture trapping, spotlight surveys, and camera traps. | Densities of 0.1–0.16 bilbies ha\(^{-1}\); >40% of release animals survived for 3 months, body condition stabilized over 0–12 months. | Quarterly reporting to NSW Government | Ongoing |
| To ensure bilbies are breeding successfully | Evidence of breeding. | Trapping at 3, 6, and 12 month intervals and identification of pouch young—tracks per km, mark-recapture, spotlight surveys, and camera traps. | Presence of pouch young and young at foot and F1 individuals recruited to the population. | Quarterly reporting to NSW Government | Dependent on release time |
| To ensure genetic diversity and limited inbreeding | Monitoring of genetic diversity | Selection of genetically diverse source populations determined by heterozygosity, inbreeding coefficients, release group size and release group sex ratio. Determine genetic diversity of founding individuals by taking ear biopsy from all released animals and comparing between genetic diversity indices 8 years’ post-release to pre-release values. | Heterozygosity maintained and inbreeding depression not detected. | Translocation plan |
| To establish self-sustaining population of bilbies in the Wild Training Zone | To release bilbies to the Wild Training Zone from the two exclosures | Cat densities <0.3 ha\(^{-1}\) and no foxes present; sufficient bilbies within the exclosures for release; and sufficient vegetation and invertebrate resources in the Wild Training Zone. | Release of bilbies through one-way gates in the exclosures or direct translocation—feral cat density determined by tracks per km, mark-recapture via trapping, spotlight surveys and camera trap surveys. | Successful release of bilbies from exclosures into the Wild Training Zone via direct release or one-way gates from the exclosures. | Quarterly reporting to NSW Government | 2022 |
| To establish widespread populations of bilbies | Widespread sign of range extension with >50% of suitable habitat occupied | Radiotracking, tracks per km, mark-recapture trapping, spotlight surveys, and camera traps. | Densities of 0.1 ha\(^{-1}\); >40% of release animals survived for 3 months, body condition stabilized over 0–12 months. | Quarterly reporting to NSW Government | Ongoing—Dependent on reintroduction timing |
| Species | Level 4 objectives | Level 5 objectives | Level 6 objectives | Triggers | Management action | Outcomes | Outputs* | Timeline |
|---------|-------------------|-------------------|-------------------|----------|-------------------|---------|----------|----------|
|         |                   |                   |                   | Evidence of breeding | Trapping at 3, 6, and 12 month intervals and identification of pouch young—tracks per km, mark-recapture, spotlight surveys, and camera traps. | Presence of pouch young and young at foot and F1 individuals recruited to the population. | Quarterly reporting to NSW Government | Ongoing—Reintroduction timing |
| To ensure bilbies are breeding successfully |                   |                   |                   |          |                   |         |          |          |
| To ensure genetic diversity and limited inbreeding | Monitoring of genetic diversity | Selection of genetically diverse source populations determined by heterozygosity, inbreeding coefficients, release group size and release group sex ratio. | Heterozygosity maintained and inbreeding depression not detected. | Translocation plan | Dependent on reintroduction timing |
|         |                   |                   |                   |          |                   |         |          |          |
| To reduce prey naivete of bilbies to cats | Bilbies established and cat densities <0.3 ha⁻¹ | Determine anti-predator responses of bilbies to cats by measuring flight initiation distances, responses to cat odor at burrows and food trays, handling behavior and personality (docility vs. boldness). | Improved anti-predator responses of bilbies to feral cats in founding and F1 individuals. | Quarterly reporting to NSW Government | Dependent on reintroduction timing and funding |

*Environmental data are publicly available for NSW government projects, under the NSW open data policy https://data.nsw.gov.au/nsw-government-open-data-policy, as well as our reporting to Government, results will also be written up in the scientific literature.
success of reintroductions in the different management treatments.

4 | OUTCOMES, OUTPUTS, AND TIMELINES

Learning during the establishment phase has primarily focused on organization and planning and building of an effective introduced animal-proof fence (Pedler et al., 2018, Figure 3), rather than ecosystem restoration, a pattern reflected in many projects (Fabricius & Cundill, 2014). We have learnt about planning processes (Pedler et al., 2018), communicated widely (Figure 3), with many of our current outcomes related to infrastructure establishment, with outputs including a Macropod and Emu Management Plan, a Bilby Translocation Plan (Table 2), a research strategy, an Ecological Health Monitoring Framework and a communications strategy (Figure 3). This establishment phase was essential and critical. It also included the design of our management treatments, aimed at learning about cause and effect relationships, supported by monitoring (Figures 1 and 4, Tables 1, 2, and S2). Data are regularly reported to the NSW Government but we also endeavor to publish our learnings in the scientific literature, as outlined in our Research Strategy (Table 2).

The two exclosures have allowed learning, including optimizing techniques for eradication of introduced species (rabbits, cats, and foxes), removal of kangaroos (one-way gates) and fence construction (Tables 1 and 2, Pedler et al., 2018). They also provide flexibility for future trialing of different groups of species and sources of animals and phased reintroductions for herbivores, such as burrowing bettongs given vulnerability for overpopulation (Moseby et al., 2018) and native predators (crested mulgara and Western quoll, Figure 1). More specific outcomes, outputs, and timelines are provided for our three examples for managing feral cats and kangaroos and reintroduction of bilbies (Table 2).

We have also established predictions for other biodiversity objectives supported by our monitoring program to promote learning (Tables 1, 2, and S2). This is essential to evaluate our management outcomes, critical for achieving our vision supported by its hierarchy of objectives (Figure 3, Kingsford et al., 2011; Roux & Foxcroft, 2011). Data collection at ecological monitoring sites is linked to triggers for management actions (Tables 1 and 2). Each management treatment area has seven monitoring sites, consisting of two 1 ha plots on the two main structural systems (dune and swale). In each plot, mammals, reptiles, and frogs are surveyed annually using dry pitfall traps, invertebrates with wet and dry pitfall traps, vegetation quadrats, and drone imagery for each plot, soil sampling, refuges (burrows), invertebrate structures, and separate 1 km bird transects (Table S2). In addition, there is regular monitoring of kangaroos and introduced animals in management treatments (spoor tracking, camera traps, Felixer traps, and spotlight surveys, see Tables 2 and S2).

5 | CONCLUSIONS

Ecosystem restoration necessarily occurs over long periods of time, requiring considerable investment. Strategic Adaptive Management offers an explicit process for transparently detailing objectives which drive management actions, linked to triggers, for biodiversity and social outcomes and outputs with timelines (Figure 2). Our vision provides a focus for Wild Deserts, supported by a hierarchy of objectives (Figures 3 and S1), linked to management actions and triggers, with explicit measurable biodiversity outcomes, outputs, and timelines (Figure 2, Table 2). Our management treatment design, supported by a rigorous monitoring program, can improve our understanding of cause and effect relationships, across a range of indicators in the ecosystem. This probing of uncertainties with monitoring and other scientific investigations potentially provides considerable opportunity to improve management. Close coupling of management and research (a hallmark of adaptive management) strengthens our capacity to learn from management successes and failures, and adapt where necessary.

Such adaptive management is applicable to any ecosystem restoration and other natural resource management projects. Adaptive management is underpinned by learning, stimulated through improvements in current practices, changing practices and fundamentally challenging governance (Fabricius & Cundill, 2014; McLoughlin & Thoms, 2015; Pahl-Wostl, Nilsson, Gupta, & Tockner, 2011). This project can provide learning across each area. In this paper, we demonstrate how we are applying the Strategic Adaptive Management approach to achieving three major objectives and measuring our progress, exemplifying the approach we are implementing across our full range of our social–ecological objectives (Figure 3). It also provides a practical example of implementation of adaptive management (Fabricius & Cundill, 2014), broadly applicable to improved transparent and accountable conservation management.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Richard Kingsford organized the structure of and the manuscript and wrote it, with detailed contributions on objectives from Rebecca West and Reece Pedler. All authors are in involved in our Strategic Adaptive Management approach and its implementation, including developing the vision and design of our exclosures and Wild Training Zone. All authors contributed to reviews of the manuscript.

ETHICS STATEMENT
Adaptive management, monitoring and research are carried out under Wildlife License SL101862 and UNSW Animal Care and Ethics License ACEC 20/21B.

DATA AVAILABILITY STATEMENT
This paper details the framework that we are using and did not use any data and so this is not applicable.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of this article.

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