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CONTRIBUTED PAPERS

Effects of different management strategies on long-term trends of Australian threatened and near-threatened mammals

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Abstract

Monitoring is critical to assess management effectiveness, but broadscale systematic assessments of monitoring to evaluate and improve recovery efforts are lacking. We compiled 1808 time series from 71 threatened and near-threatened terrestrial and volant mammal species and subspecies in Australia (48% of all threatened mammal taxa) to compare relative trends of populations subject to different management strategies. We adapted the Living Planet Index to develop the Threatened Species Index for Australian Mammals and track aggregate trends for all sampled threatened mammal populations and for small (<35 g), medium (35–5500 g), and large mammals (>5500 g) from 2000 to 2017. Unmanaged populations (42 taxa) declined by 63% on average; unmanaged small mammals exhibited the greatest declines (96%). Populations of 17 taxa in havens (islands and fenced areas that excluded or eliminated introduced red foxes [*Vulpes vulpes*] and domestic cats [*Felis catus*]) increased by 680%. Outside havens, populations undergoing sustained predator baiting initially declined by 75% but subsequently increased to 47% of their abundance in 2000. At sites where predators were not excluded or baited but other actions (e.g., fire management, introduced herbivore control) occurred, populations of small and medium mammals declined faster, but large mammals declined more slowly, than unmanaged populations. Only 13% of taxa had data for both unmanaged and managed populations; index comparisons for this subset showed that taxa with populations increasing inside havens declined outside havens but taxa with populations subject to predator baiting outside havens declined more slowly than populations with no management and then increased, whereas unmanaged populations continued to decline. More comprehensive and improved monitoring (particularly encompassing poorly represented management actions and taxonomic groups like bats and small mammals) is required to understand whether and where management has worked. Improved implementation of management for threats other than predation is critical to recover Australia's threatened mammals.

KEYWORDS

biodiversity conservation, invasive predator control, Living Planet Index, long-term ecological monitoring, management effectiveness, population trends, predator-free havens, threatened species

Efectos de diferentes estrategias de manejo sobre las tendencias a largo plazo de los mamíferos amenazados y casi amenazados de Australia

Resumen: El monitoreo es fundamental para evaluar la efectividad del manejo, aunque faltan evaluaciones sistemáticas y a gran escala de este monitoreo para evaluar y mejorar

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los esfuerzos de recuperación. Compilamos 1,808 series temporales de 71 especies y subespecies de mamíferos terrestres y voladores amenazadas y casi amenazadas en Australia (48% de todos los taxones de mamíferos amenazados) para comparar las tendencias relativas de las poblaciones sujetas a diferentes estrategias de manejo. Adaptamos el Índice Planeta Vivo para desarrollar el Índice de Especies Amenazadas para los Mamíferos Australianos y así rastrear las tendencias agregadas de todas las poblaciones muestreadas de mamíferos amenazados y de los mamíferos pequeños (<35 g), medianos (35–5,500 g) y grandes (>5,500 g) entre 2000 y 2017. Las poblaciones sin manejo (42 taxones) declinaron en un 63% en promedio; los mamíferos pequeños sin manejo exhibieron las declinaciones más marcadas (96%). Las poblaciones de 17 taxones incrementaron 680% en los refugios (islas o áreas encercadas que excluían o eliminaban al zorro rojo [*Vulpes vulpes*] y al gato doméstico [*Felis catus*], especies introducidas) Afuera de los refugios, las poblaciones sometidas al cebado constante de los depredadores en un inicio declinaron en un 75% pero después incrementaron al 47% de su abundancia para el 2000. En los sitios en donde los depredadores no fueron excluidos o cebados sino sometidos a otras acciones (manejo del fuego, control de herbívoros introducidos), las poblaciones de los mamíferos pequeños y medianos declinaron más rápido, pero los mamíferos grandes declinaron de manera más lenta que las poblaciones sin manejo. Sólo el 13% de los taxones contaron con datos para sus poblaciones con y sin manejo; las comparaciones entre índices para este subconjunto mostraron que los taxones con poblaciones en incremento dentro de los refugios declinaron afuera de éstos, pero los taxones con poblaciones sujetas al cebado de depredadores afuera de los refugios declinaron más lentamente que las poblaciones sin manejo y después incrementaron, mientras que las poblaciones sin manejo continuaron su declinación. Se requiere un monitoreo más completo y mejorado (particularmente el que engloba las acciones de manejo mal representadas y los grupos taxonómicos como los murciélagos y los mamíferos pequeños) para entender si ha funcionado el manejo y en dónde. La implementación mejorada del manejo para las amenazas distintas a la depredación es fundamental para recuperar a los mamíferos amenazados de Australia.

PALABRAS CLAVE
conservación de la biodiversidad, control de depredadores invasores, especie amenazada, efectividad de manejo, Índice Planeta Vivo, monitoreo ecológico a largo plazo, refugios libres de depredadores, tendencias poblacionales

【摘要】
监测对于评估保护管理有效性至关重要, 但目前仍缺乏对监测的大尺度系统评估, 以评价和提高恢复工作。本研究整理了澳大利亚71种受威胁或近危的陆生及飞行野生哺乳动物物种和亚种(占所有受威胁哺乳动物的48%)的1808个时间序列, 以比较受到不同管理策略影响的种群的相对趋势。我们基于"地球生命力指数(Living Planet Index)"开发了"澳大利亚哺乳动物受威胁物种指数", 并追踪了2000-2017年所有采样的受威胁哺乳动物种群以及小型(<35克)、中型(35-5500克)和大型哺乳动物(>5500克)的总体趋势。结果表明, 未受到管理的种群(42个类群)数量平均减少了63%;未受到管理的小型哺乳动物种群数量下降幅度最大(96%)。17个在避难所(驱除或消灭了外来赤狐[*Vulpes vulpe*]及家猫[*Felis catus*]的岛屿和围栏区)中生活的类群种群数量增加了680%。在避难所外, 受到持续捕食者诱捕管理的种群最初数量下降了75%, 但随后增加到2000年种群数量的47%。在没有驱除或诱捕捕食者, 但采取了其它行动(如火灾管理、引入食草动物控制)的位点, 小型和中型哺乳动物种群比没有受到管理的种群下降得更快, 但大型哺乳动物相比下降得更慢。只有13%的类群同时有未受到管理种群和受到管理种群的数据, 这部分数据的指数比较显示, 在避难所内种群增加的类群在避难所外种群有所下降, 但在避难所外受到捕食者诱捕的种群比没有管理的种群下降更慢且随后种群数量增加, 而未受到管理的种群则持续下降。未来还需要更全面和更好的监测工作(特别是纳入没有得到充分代表的管理行动及类群, 如蝙蝠和小型哺乳动物), 以了解管理的有效性以及有效的区域。进一步落实对捕食以

外威胁的管理措施, 对于澳大利亚受威胁哺乳动物恢复至关重要。【翻译:胡怡思;审校:聂永刚】

关键词: 生物多样性保护, 地球生命力指数(Living Planet Index), 入侵捕食者控制, 受威胁物种, 种群趋势, 管理有效性, 长期生态监测, 无捕食者避难所

INTRODUCTION

Evidence-based management of species at risk of extinction is central to curbing biodiversity loss (Bolam et al., 2021). Fully assessing the need for and direction and effectiveness of management interventions requires information on species' population trajectories (Balmford et al., 2005), an understanding of species' threats (Tulloch et al., 2015), and information on where and how alternative management interventions have been applied (Garnett et al., 2019). However, few studies link conservation efforts to measurable biodiversity outcomes informed by population change over time (Possingham & Gerber, 2017). Greater accountability of conservation efforts and evaluation of management effectiveness is essential to identify and focus on successful interventions, making future allocation of limited conservation resources more efficient (Ferraro & Pattanayak, 2006).

Mammals are arguably the best studied and funded taxonomic group globally (Davies et al., 2018; Laycock et al., 2011). Despite this, one quarter of the world's mammals remain threatened with extinction (IUCN, 2019), and losses of phylogenetic diversity are disproportionally large in mammals relative to species that have recently gone extinct in other taxonomic groups (Davis et al., 2018). In a sample of 173 species of large mammals on 6 continents, most lost more than 80% of their geographic range over the last century (Ceballos & Ehrlich, 2002), implying extensive population declines. Invasive mammalian predators, especially red fox (*Vulpes vulpes*) and domestic cat (*Felis catus*), are one of the strongest influences on mammal declines; they are linked to at least 45 (56%) of the approximately 80 extinctions of mammals since 1500 (Doherty et al., 2016). Their influence is particularly strong in Australia (Woinarski et al., 2019), where ground-dwelling mammals in the critical weight range of 35–5500 g are particularly prone to decline and extinction (Burbidge et al., 2008).

Management efforts to mitigate mammal species declines range from actions undertaken at scales of hundreds to thousands of square kilometers (e.g., aerial prescribed burns [Radford, Woolley, Corey, et al., 2020], baiting of invasive predators [Moseby et al., 2021]) to those undertaken at relatively small scales (e.g., widlife tunnels [van der Ree et al., 2009]). Localized action includes the Australian network of havens (islands without introduced predators and intensively managed mainland areas with predator-proof fencing), which has mostly been used for reintroduction of predator-susceptible mammals extirpated across most of their former range (Legge, Woinarski, et al., 2018). At least some management actions, including predator baiting (Kinnear et al., 2010; Moseby et al., 2021; Sharp et al., 2015) and safe havens (Kanowski et al., 2018; Moseby et al., 2009), can lead to large local population increases of mammals. However, management evaluations tend to focus on species-level outcomes of localized management programs (e.g., Comer et al., 2020; Wayne et al., 2017), and national-scale outcomes of management strategies across multiple species remain poorly resolved.

To address this gap, we modeled and compared aggregate trends in threatened and near-threatened mammals in Australia undergoing different conservation management regimes to evaluate broad patterns in species decline or recovery that might provide insights into the efficacy of species recovery efforts. We focused on the Australian continent and its islands because one third of the world's mammal extinctions have occurred here since 1500 (IUCN, 2019) and many species continue to decline. The main driver of Australian mammal extinctions has been introduced predators, and these extinctions have been compounded by habitat degradation and introduced herbivores (Fisher et al., 2003; Woinarski et al., 2015).

Following the methodology of the threatened species index for Australia's birds (Bayraktarov et al.,), we collated long-term monitoring data from multiple data custodians to develop the first national Threatened Species Index for Australian Mammals, representing the average aggregated trend estimate for all mammal populations and defined subsets. We added an additional element not included in the bird index by eliciting information from data custodians about conservation management at sites where mammals were monitored. This allowed us to separate all data into sites with no known targeted management, management in havens, and management outside havens ("beyond the fence" [Hayward et al., 2012]), including either sustained invasive predator management or management of other threats (e.g., invasive herbivores, changed fire regimes, and weeds). We interrogated trends to ask whether the average abundance of imperiled mammal populations changed between 2000 and 2017 in managed compared with unmanaged sites and whether subgroups of mammals (small, medium, and large) exhibited different aggregate trends.

METHODS

Data collation

Before this study, no centralized repository of threatened mammal monitoring data in Australia existed. Nation-wide systematic monitoring of threatened species was limited and uncollated, with monitoring conducted by many disparate government and nongovernment bodies, researchers, citizen science groups, and individuals (Scheele et al., 2019). From 2018 to 2020, we conducted a nation-wide collation of monitoring data sets that contained abundance data on threatened and near-threatened Australian mammals collected repeatedly at one or more survey sites over time (i.e., a time series) for any 2 consecutive or nonconsecutive years up to and including 2017. Any mammals listed, as of March 2020, under the Australian Environment Protection and Biodiversity Conservation (EPBC) Act 1999 (vulnerable, endangered, or critically endangered) or on the International Union for the Conservation of Nature (IUCN) Red List (near threatened, vulnerable, endangered, or critically endangered) (IUCN, 2019) were candidates for inclusion (149 listed species or subspecies).

We contacted 208 potential data contributors regarding 637 possible monitoring data sets for inclusion. Nine potential custodians (4%) did not respond. Another 44 custodians had threatened mammal data but either did not have time or capacity to provide their data sets within the time allotted for data collation or data were not yet eligible for our analysis because data sets did not have at least 2 data points prior to 2017 or did not meeting other inclusion criteria. Our criteria for verifying the suitability of each time series were time series derived from standardized monitoring that was repeated with consistent effort over time for the same species and site; data could be converted into either an absolute or relative measure of abundance over time (Bayraktarov et al., 2021); and, unpublished data set trends produced for each population were approved by custodians. Trends from 127 eligible data sets were sent to data custodians (human ethics approval number 2018001572 by University of Queensland), who were requested to confirm that trends produced for their individual data sets (which often included >1 species) met expectations based on their knowledge of the monitored populations.

We received feedback for 74% of the data sets following custodian consultation and rejected 25 data sets (83 time series) because single-species trends produced with the data were unreliable (usually due to inconsistent or uncertain sampling effort or changes in monitoring protocol over time). We compiled all eligible time series into a single data set in the Threatened Species Index for Australia (TSX) database (TSX, 2020).

In the feedback surveys, we also asked custodians to confirm whether and what kind of threat management was applied at the sites where the mammals were monitored. Due to the lack of replicates for some management strategies and co-occurrence of multiple management actions at many sites, we aggregated these categories into 4 levels of threat management: no known targeted management (other than broad national and jurisdictional policies, such as native vegetation legislation that protects habitats); invasive predator-free havens (islands where invasive predators, i.e., cats and foxes, were never present or had been eliminated and fenced reserves where these predators are actively excluded); sustained predator baiting outside havens (alongside which other actions such as fire management might also occur); and management of threats other than predators (control of invasive herbivores such as European rabbits [*Oryctolagus cuniculus*], cattle [*Bos taurus*], and goats [*Capra hircus*]; weed management; ecological fire management) outside predator-free havens.

Data collation resulted in a database containing 1859 time series on 76 threatened and near-threatened terrestrial mammals from 90 dedicated monitoring programs (Appendices S1–S3). Time series came from 14 broad monitoring protocols. Some protocols were used simultaneously to maximize detection; hence, the sum is >1859. Protocols included cage or box trapping (n = 647), spotlighting (n = 537), daytime population counts and searches (n = 301), ultrasonic detection of bats (n = 96), nest-box monitoring (n = 75), remote digital camera monitoring (n = 67), scat searches (n = 55), track-based monitoring (n = 52), stag watching (observing a hollow-bearing tree at dusk to count arboreal mammals that emerge) (n = 21), genetic sampling (e.g., hair tubes followed by DNA analysis) (n = 13), aerial surveys (n = 6), pitfall trapping (n = 5), call playback (n = 4), and thermal imagery (n = 2). We excluded marine mammals (51 time series for 5 species) because this sample size was judged unrepresentative of marine mammals and their threats generally.

To explore how successful management interventions had been for different mammal groups, we allocated each mammal in the database to a body mass category: small (<35 g), medium (35−5500 g), and large (>5500 g). Bats were allocated to a separate category (Allek et al., 2018). Thresholds for each category were drawn from the extensive literature on threats to Australian mammals that shows differences in species extinction rates and threats driving extinctions for mammals in the critical weight range (35−5500 g), for which declines have been driven predominantly by the invasive predators fox and cat (Burbidge & McKenzie, 1989).

Calculation of multitaxon trends

The final data set in the 2020 Threatened Species Index for Australian Mammals used for analysis comprised 71 terrestrial and volant mammal taxa (n = 1808 time series). Of these taxa, 54 were listed as threatened under national legislation, 5 were not nationally listed but were listed as threatened on the IUCN Red List, and 12 were not nationally listed but listed as near threatened on the IUCN Red List (Appendices S1 & S2). We ran composite trend analyses for these 71 taxa to derive the Threatened Species Index for Australian Mammals (hereafter the index). We applied the Living Planet Index (LPI) method (Collen et al., 2009; Loh et al., 2005; McRae et al., 2017) with the rlpi 0.1.0 package in R 3.8.3 (R Core Team, 2020) to produce a national-scale multitaxon trend from 2000 to 2017. We chose the baseline year of 2000 after assessing data availability to maximize time-series length and the number of time series available for analysis. Prior to 2000, availability of monitoring data for most mammals (especially small and large bodied) was limited (Appendices S4–S7). Although it is well known that Australian mammal populations fluctuate widely in response to resource availability and disturbance events (Bennison et al., 2018), our 17-year time frame is considered long enough to infer directional trends among the noise generated by population oscillations (Greenville et al., 2017).

The LPI method follows a 2-step process to build an aggregate trend from a large data set of time series across different sites and species within each data subset. First, it aggregates all the time series for a single taxon (a species or subspecies) into one trend line with generalized additive modeling. Second, all single-taxon trend lines are aggregated into a final overall index with geometric averaging of trends. Following Collen et al. (2009), we used a bootstrap resampling technique to generate confidence bounds around the multitaxon composite (treating each taxon as an independent unit) and taking the central 9500 of 10,000 iterations. These confidence bounds indicate the heterogeneity among single-taxon trends relative to the baseline year used to build the composite.

For each population subset undergoing different management regimes described above, we calculated an overall national index and separate indices for the 3 body mass categories and bats. We calculated subtrends of the overall trend if data for at least 2 taxa were available (list of taxa, threat status, invasive predator susceptibility [Radford et al., 2018], and representation in each management grouping is in Appendix S2). Because naturally occurring taxa in havens might have a more stable trajectory than reintroduced predator-susceptible populations (Radford et al., 2018), we disaggregated the haven data into populations translocated into havens (10 taxa) and populations that naturally occurred in a haven (8 taxa) and reran the index for these populations and for reintroductions or translocations of 3 taxa outside havens. We also undertook paired index comparisons to evaluate management effectiveness. We created subsets from the overall data set that included taxa that had populations subject to the following management strategies: inside havens versus outside havens but undergoing sustained predator baiting (4 taxa); outside havens undergoing sustained predator baiting versus outside havens not undergoing predator baiting (5 taxa); and outside havens undergoing nonpredator-focused management versus outside havens not being managed (7 taxa).

We evaluated data availability and quality for each body mass and management combination of mammal taxa to investigate possible bias in the representativeness of taxa in the index and potential differences in data suitability for trend analyses, measured through time-series length (period between first year of repeated measure and last year for each time series; may include data gaps) or time-series sample years (number of years with a value in a time series). We conducted 2-way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) post hoc tests to evaluate effects of body mass and management category on time-series length and time-series sample years. To verify whether trends in any management grouping were driven by species' extinction risk characteristics, we also conducted 2-way ANOVAs to evaluate the effect of threat status and body size on species representation in management groupings (no management, haven management, or nonhaven management). Normality checks and Levene's test were carried out and assumptions were met.

We conducted sensitivity analyses that built taxon leverage plots to investigate the marginal contribution of each taxon trend (marginal contribution = index value − taxon leverage value) on the index (Appendices S8 - S10). The leverage value for each taxon was the value of the index when recalculated after removal of each single taxon. The results from these sensitivity analyses indicated whether a taxon's trend had a positive (values > 0) or negative (values < 0) effect on the composite index. This determined whether trends from particular taxa were driving the overall index and whether the aggregate trend was driven by a few outlier series (Leung et al., 2020).

RESULTS

Trends in threatened mammal populations

Populations of 71 threatened mammal taxa from 1808 time series monitored across Australia between 2000 and 2017 declined on average by 35% (i.e., index value in 2017 was 0.65 relative to a baseline of 1 in 2000) (Table 1; Figure 1a; Appendix S11a). Overall change in aggregate abundance was highly variable among species and populations undergoing different forms of management. The average abundance of populations in predator-free havens (17 taxa at 31 sites) increased by 680% (Figure 1d). Taxa that naturally occur in havens increased at approximately half the rate of reintroduced populations (29% per year vs. 56% per year, respectively) (Appendix S11b). In comparison, populations undergoing sustained predator baiting outside predator-free havens declined by 53% (9 taxa) (Figure 1e), which was 10–27% less severe than declines in populations that were either not managed at all (63% decline, 42 taxa) (Figure 1b) or outside predator-free havens with management but without sustained predator baiting (80% decline, 20 taxa) (Figure 1f; Table 1).

In addition to differences in overall decline, taxa with different management regimes outside havens declined at different rates (Figures 1 & 2). For taxa undergoing sustained predator baiting, we observed a severe initial decline in aggregate abundance between 2000 and 2005 (to 35% of baseline abundance). Taxon leverage plots indicated that the short-term decline was driven predominantly by western ringtail possum (*Pseudocheirus occidentalis*) population declines in the Jarrah (*Eucalyptus marginata*) forests of southwestern Australia; removing this species from the data set resulted in the index declining at a much slower rate (Appendix S10e). On average, populations with sustained predator baiting increased between 2010 and 2017 (low of 0.25 in 2010 to 0.47 in 2015).

When divided into body mass categories, small mammals showed the largest overall decline (99%, 7 taxa), medium-sized mammals and bats also declined (19%, n = 56 taxa and 35%, n = 4 taxa, respectively), and large mammals increased (11%, 8 taxa) on average between 2000 and 2017 (Table 1). All body mass categories of threatened mammals at sites with no known management declined between 2000 and 2017 (Figure 2), with small mammals again showing the largest overall and between-year change in aggregate abundance (96% decline over 17 years, average 5.6% per year). Populations of medium and large mammals inside predator-free havens increased (average increases of 635% and 393%, respectively), whereas mammal populations in all body mass categories managed outside havens declined

TABLE 1 Overall and average between-year change in average population abundance for groupings of threatened Australian mammals across all sites and for sites with different management types

Species grouping*	Management type	No. of taxa	No. of sites (time series)	Overall change in aggregate population abundance between 2000 and 2017 (%)	Average between-year percent change in aggregate population abundance 2000–2017 (SE)	Adjusted overall change between 2000 and 2017 (%) from leverage analysis removing outlier taxa: Minimum	Adjusted overall change between 2000 and 2017 (%) from leverage analysis removing outlier taxa: Maximum
All species	All sites	71	1808	–35	–2.03 (1.22)	–31	–12
	No known management	42	1545	–63	–3.73 (0.97)	–61	–46
	any management	40	263	+8	0.54 (2.48)	–3	+57
	Predator-free havens	17	31	+680	40.02 (19.54)	+493	+1775
	Nonhaven management	28	232	–74	–4.34 (1.77)	–75	–56
	Sustained predator baiting outside havens	9	73	–53	–3.14 (2.41)	–67	–18
	Management excluding predator exclusion or baiting	20	159	–80	–4.73 (2.39)	–86	–66
<35 g	All sites	7	174	–99	–5.81 (1.57)	–98	–92
	No known management	5	113	–96	–5.63 (2.12)	–95	–82
	Any or nonhaven management	3	61	–98	–5.79 (2.13)	–99	–85
35–5500 g	All sites	56	1388	–19	–1.13 (1.52)	–25	3
	No known management	34	1200	–55	–3.22 (1.28)	–58	–36
	Any management	31	188	+40	2.21 (3.02)	–3	+111
	Predator-free havens	15	27	+635	37.38 (19.30)	+345	+2151
	Nonhaven management	19	161	–74	–4.35 (2.26)	–82	–63
	Sustained predator baiting outside havens	8	72	–18	–1.07 (2.95)	–41	+5
	Management excluding predator exclusion or baiting	12	89	–71	–7.07 (5.56)	–83	–58
>5500 g	All sites	8	246	+11	0.63 (3.62)	–33	+127
	No known management	3	232	–61	–3.81 (0.56)	–73	–43
	Any management	6	14	+48	2.84 (5.61)	–15	+273
	Predator-free havens	2	4	+393	23.13 (38.54)	+155	+2382
	Nonhaven management	5	10	–47	–2.74 (3.67)	–80	+270
	Management excluding predator exclusion or baiting	5	9	–45	–2.66 (3.71)	–80	+270
Bats	All sites (no management)	4	206	–35	–2.08 (3.41)	–57	–22

*See Appendices S8–10 for the full list of taxa in each grouping and for minimum and maximum bounds in average population abundance change. No species <35 g were monitored in predator-free havens, so all managed sites for this category of mammals were outside havens. No managed bat populations were represented in the data set. All trends calculated from reference baseline year of 2000 except for mammals of 35–5500 g subject to management other than predator exclusion or baiting or both for which reference year is 2007 due to no monitoring prior to this date.

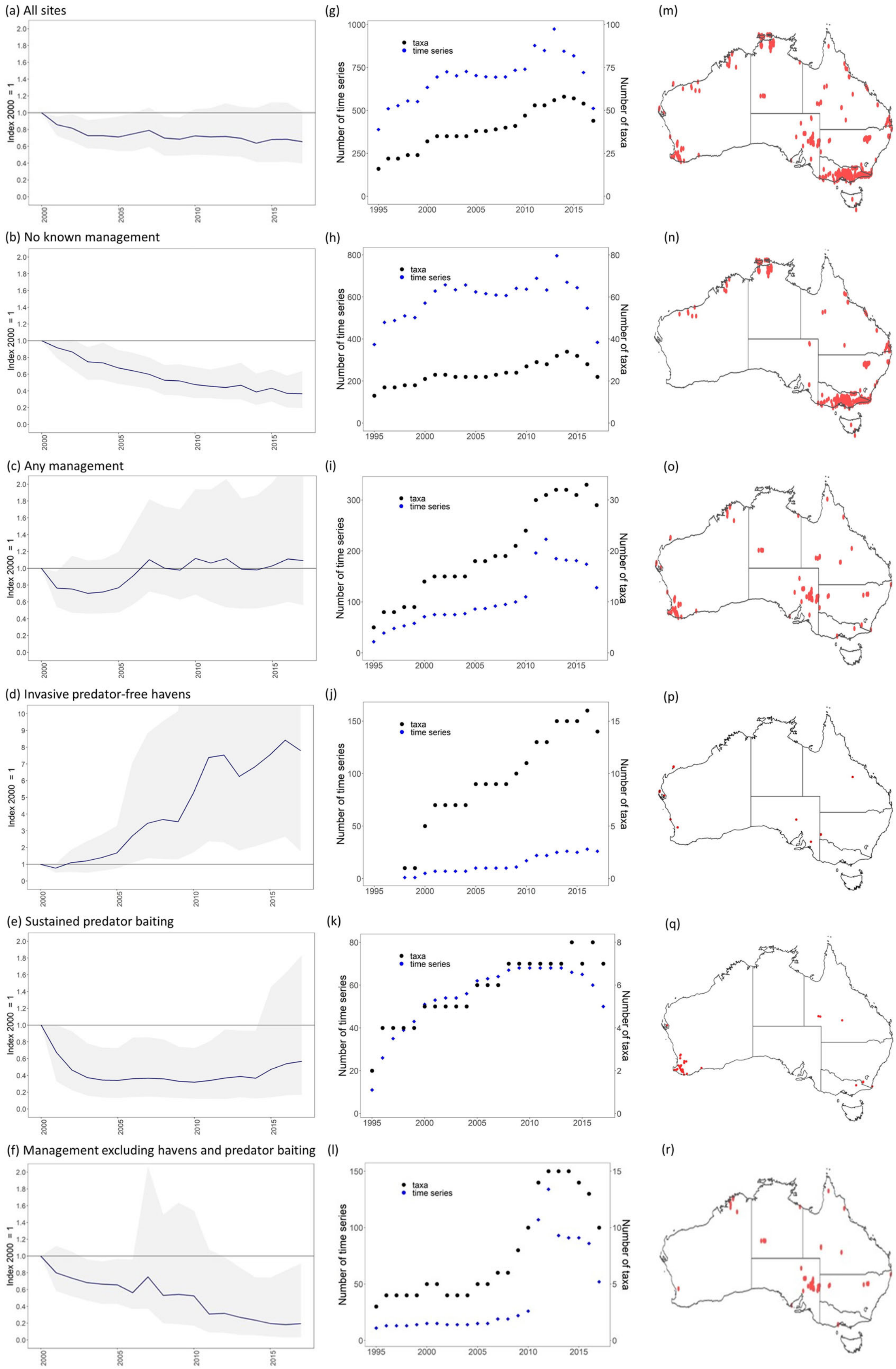

FIGURE 1 Threatened Species Index for Australian Mammals trends and data availability for different management types based on data from (a) all sites where threatened and near-threatened mammals were monitored from 2000 to 2017 and subsets of sites (b) with no known targeted management actions, (c) with any management, (d) where invasive predators are completely excluded (e.g., fenced areas or islands), (e) outside predator-free havens with sustained predator baiting, and (f) with other management actions outside predator-free havens but excluding sustained predator baiting (blue line, composite multitaxon index; gray shading, heterogeneity among single-taxon trends). Dot plots (g–l) show the number of taxa (black circles) and number of time series (blue diamonds) available to

(Continues)

FIGURE 1 (Continued)
calculate the index for each year by management type. Data availability is shown prior to 2000 to indicate the low levels of data availability for most management categories before this time. Maps (m–r) indicate where threatened mammal monitoring data, by management type, were recorded

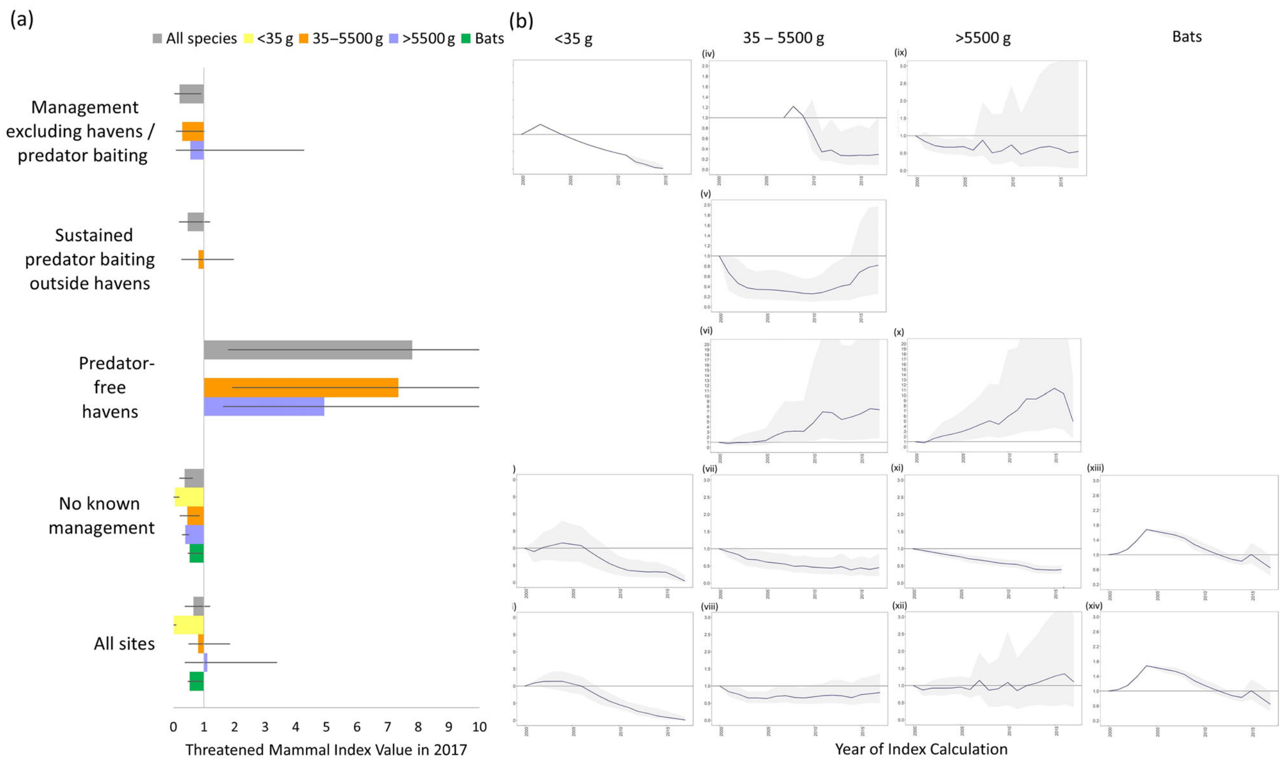

FIGURE 2 Threatened Species Index for Australian Mammals results for all species and populations in 4 body mass categories subjected to different management regimes from 2000 to 2017: (a) overall change in average abundance of mammal populations between 2000 and 2017 by management type and body mass category, (b) trends for all mammal body mass categories and management types (i–xiv, trends over time for each body mass by management type subset; blue line, composite multitaxon index; gray shading, heterogeneity among single-taxon trends; blank area, insufficient data to create a trendline for that body mass and management type combination). The list of species in each grouping is in Appendix S2, and the minimum and maximum bounds of values in 2017 are in Appendix S11

(average declines for small, medium, and large mammals of 98%, 74%, and 47%, respectively) (Table 1). Only large mammals had greater overall declines in unmanaged populations compared with populations managed outside havens (61% vs. 47%) (Table 1; Figure 2). For medium-sized mammals, we were able to compare nonhaven management categories, and, similar to the pattern for all species combined, populations undergoing sustained predator baiting declined at a slower average annual rate (1.1% annually, 18% over 17 years) than populations undergoing other forms of management outside havens (7.1% annually, 71% over 11 years) (baseline for this trend was 2007 due to limited data availability prior to this date) (Table 1; Figure 2; Appendices S1 & S2).

Considering only taxa monitored with and without a given management strategy showed patterns similar to the trends with all data (Figure 3; Appendix S11b). Taxa with populations increasing inside havens declined outside havens by 26% even when managed through sustained predator baiting (4 taxa) (Figure 3a,b) (identities of taxa in Appendix S2). Taxa with populations that were subject to predator baiting declined at a slower rate than populations with no management, then increased to 74% of their baseline abundance, whereas unmanaged populations continued declining to 10% of their baseline (5 taxa) (Figure 3c,d). Taxa with populations monitored in locations with management focused on threats other than predators and without management showed concurrent severe declines of 89% and 82% (7 taxa) (Figure 3e,f).

Taxon leverage plots indicated that removal of outliers from management and body mass groupings rarely changed the direction of the aggregate trend, but in several cases it affected the magnitude of change (Appendices S8–S10). Unmanaged populations declined at similar rates with and without exclusion of outlier species (indicated by the marginal contribution of any individual taxon being small for most taxa and relatively small heterogeneity around the index) (Figure 1b). Some species had more influence on the index than others. For example, 3 taxa drove the steep increase in aggregate abundance of populations inside havens: the Shark Bay bandicoot (*Perameles bougainville*) (island populations in Western Australia's Shark Bay World Heritage Area and a mainland population in South

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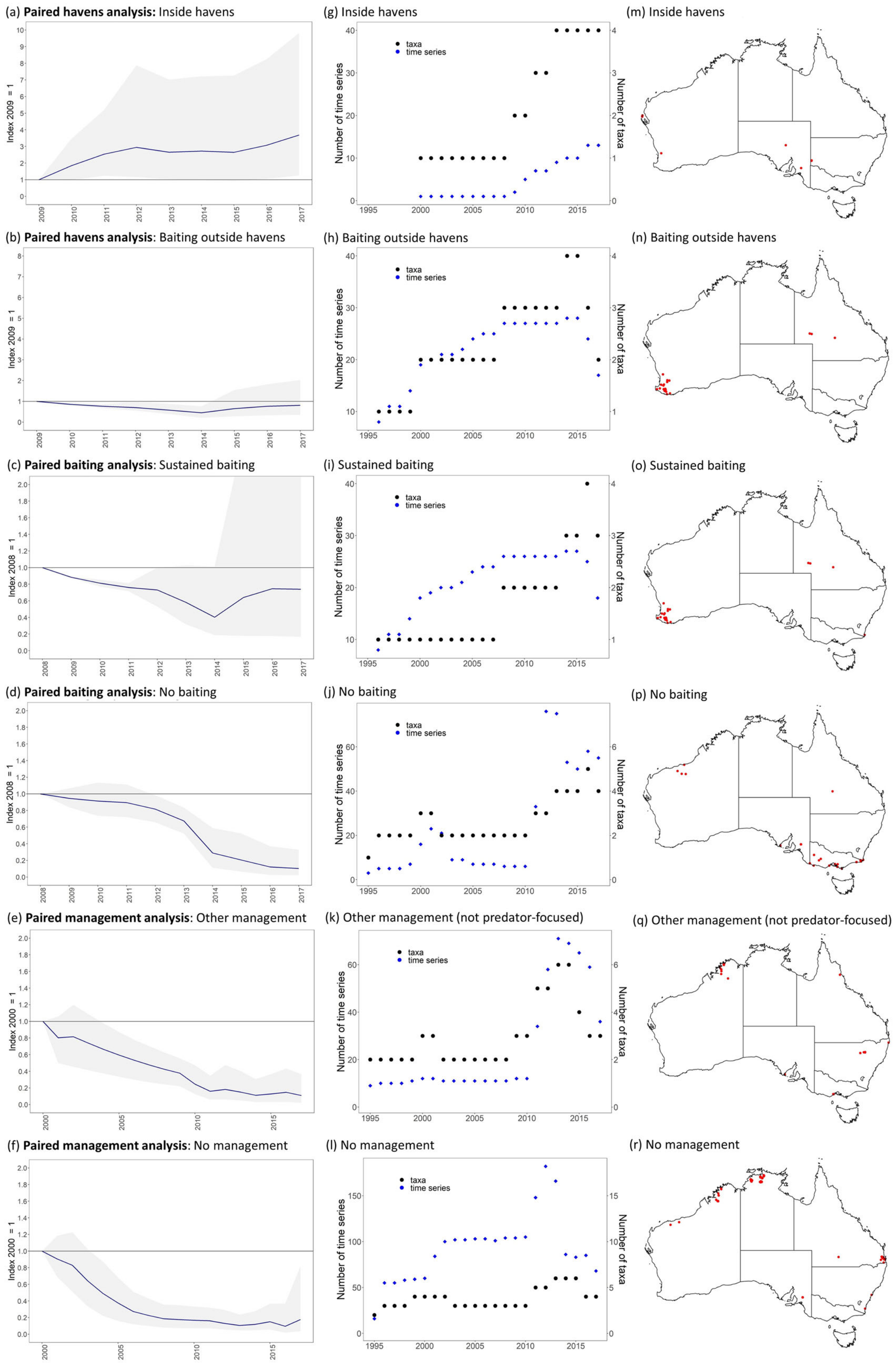

FIGURE 3 Threatened Species Index for Australian Mammals trends and data availability for different paired analyses where only time series for taxa that had populations with and without a given management action were included in the aggregate index. The index was calculated using data from (a–b) taxa with populations being monitored inside and outside havens from 2009 to 2017, (c–d) taxa with populations being monitored with and without sustained baiting from 2008 to 2017, and (e–f) taxa with populations being monitored in locations with nonpredator-focused management and without management from 2000 to 2017 (blue line, composite multitaxon index; gray shading heterogeneity among single-taxon trends). Dot plots (g–l) show the number of taxa (black circles) and number

(Continues)

FIGURE 3 (Continued)
of time series (blue diamonds) available to calculate the index each year. Maps (m–r) indicate where threatened mammal monitoring data were recorded. See Appendix S2 for the species in each grouping and Appendix S11 for index details

Australia's Arid Recovery reserve), plains mouse (*Pseudomys australis*) (Arid Recovery reserve), and bridled nailtail wallaby (*Onychogalea fraenata*) (Australian Wildlife Conservancy's Scotia Wildlife Sanctuary). Other species (e.g., greater stick-nest rat [*Leporillus conditor*], Arid Recovery reserve) declined and therefore had a negative influence on the index. This led to very wide bounds around the index for haven populations (179–2905% increase between 2000 and 2017) (Figure 1d). There were similarly wide bounds around the index for managed populations outside havens but not undergoing sustained baiting (Figure 1f), driven by positive effects of taxa with relatively stable populations or slow rates of decline (e.g., yellow-footed rock-wallaby [*Petrogale xanthopus*]) and negative effects of taxa with steep declines (e.g., woylie [*Bettongia penicillata*] in southwestern Australia). Populations of most taxa with sustained baiting changed in similar ways over time (Appendices S8 & S10e). However, variability around this index increased (Figure 1e) because some populations (in particular, the bridled nailtail wallaby, western ringtail possum, and woylie) negatively influenced the index, whereas others (e.g., greater bilby [*Macrotis lagotis*], mountain pygmy possum [*Burramys parvus*]) had a positive effect (Appendix S8).

Monitoring data availability and species representation

Data on threatened mammal trends across Australia were uneven across management categories (Table 1; Appendices S1 & S2); 85.8% of time series were from sites with no known management from 2000 to 2017. Of the remaining time series, 1.7% ($n = 31$) were from invasive predator-free safe havens; 12.8% ($n = 232$) from nonhaven management; 4.0% ($n = 73$) were undergoing sustained invasive predator baiting; and 8.8% ($n = 159$) had other management strategies, including intermittent predator control, weed control, intermittent or sustained fire management, and control of invasive herbivores (e.g., feral goat, pig [*Sus scrofa*], or cattle). Most mammal taxa (62 of the 71 species and subspecies, 87.3%) lacked monitoring data for both unmanaged and managed sites (Appendices S1 & S2), and 85% (60) had data for only one management grouping (no management 33, nonhaven management 14, haven management 13 taxa). Unmanaged sites included 59% ($n = 42$) of the species in the index, and managed sites included 56% ($n = 40$) of index species (predator-free safe havens 24%, sustained predator baiting 13%, management of other threats 28%). Only 4 taxa were monitored inside and outside of havens (greater bilby, numbat [*Myrmecobius fasciatus*], woylie, bridled nailtail wallaby), and 3 had monitoring data from reintroductions or translocations outside havens (New Holland mouse [*Pseudomys novaehollandiae*], bridled nailtail wallaby, woylie). Only one small mammal, the New Holland mouse, had data across 2 management categories: no management and management of threats other than predators (Appendix S2).

Data from threatened mammal populations were biased toward certain body mass groupings, but there was no significant effect of body mass or conservation status on species representation in different management types (Appendix S12). Medium-sized mammals were overrepresented relative to their proportion of Australian mammal taxa listed as threatened or near threatened (79% of species in index vs. 68% of threatened mammals across Australia). Small mammals and bats were underrepresented (10% and 6% of species in index vs. 22% and 12% of threatened mammals, respectively). Over one half of Australia's threatened medium and large mammal taxa (55% and 53%, respectively) were represented in our index in at least one management type, compared with only 21% of small mammal and bat taxa (Figure 4a). For no management and havens, representation of bats, small mammals, and large mammals was lower than medium mammals relative to the numbers of species listed in each body mass category (Table 1; Appendix S2), reflecting that most havens have been purposed for conserving predator-susceptible medium-sized mammals.

Time series varied in their length and sampling completeness between management types (Appendix S12). A statistically significant interaction existed between the effects of body mass class and management type (no management, haven or nonhaven management) on time-series length ($F_{3,2} = 14.13$, $p < 0.01$) and time-series sample years ($F_{3,2} = 20.27$, $p < 0.01$). Small mammals and bats had significantly shorter time series than medium and large mammals (Figure 4b). Sites with predator control outside safe havens had the longest time series on average (15.3 years [SD 8.4]), and sites undergoing fire and herbivore management the shortest (6.0 years [3.0]). The average number of sampled years was significantly lower for small mammals and bats compared with medium and large mammals (Figure 4c).

DISCUSSION

Trends in the abundance of species populations are essential measures of the state of biodiversity (Santini et al., 2017) and enable recovery actions to be improved or enacted prior to species being lost irrevocably. Our study presents the first national-scale analysis of long-term aggregate trends in 48% of Australia's threatened mammal species. We found that Australian mammal populations declined on average by 35% across all sites and by 61% at sites without conservation management over almost 2 decades, averaging a 2.1% and 3.6% decline, respectively, each year. This proportional loss is an underestimate because we did not include in our analyses 2 mammal species that became extinct from 2000 to 2017 (Woinarski, 2018). We track threatened species trends, and many species

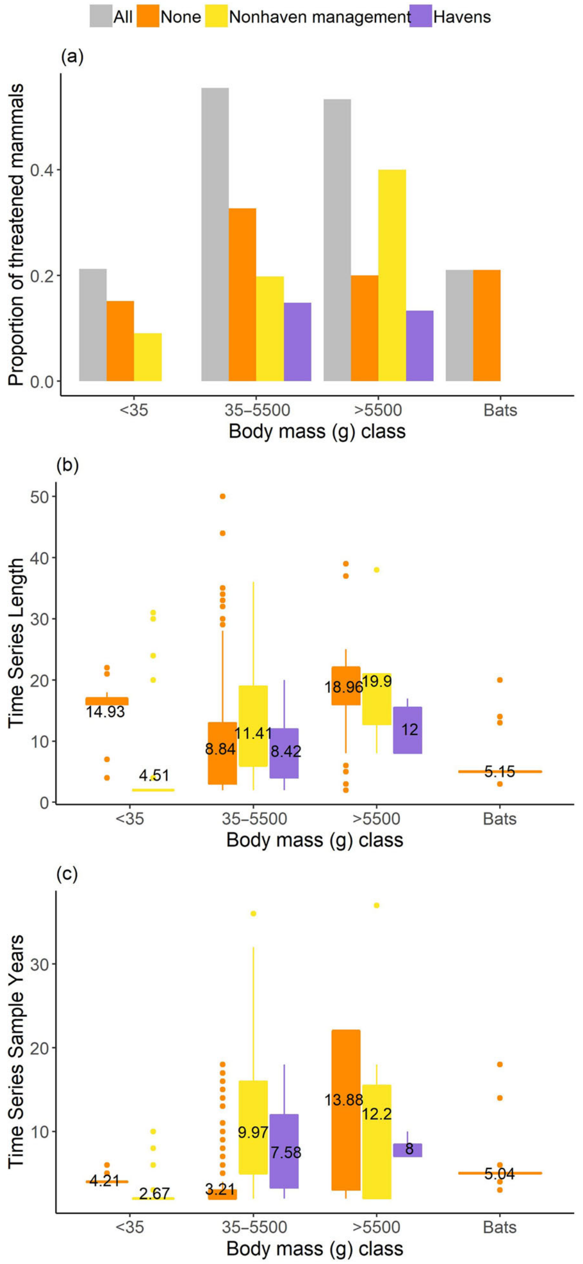

FIGURE 4 Data availability for informing the Threatened Species Index for Australian Mammals: (a) proportion of mammals listed as threatened or near threatened Australia-wide from each body mass category that is in the index database grouped by body mass and management combination, (b) distribution of time-series length relative to body mass class and management type, and (c) distribution of time-series sample years relative to body mass class and management type (numbers associated with bars, average for each body mass and management combination; bars, 25th to 75th percentiles; whiskers, 95% confidence interval; dots, points outlying 95% confidence interval) (see also Appendix S11)

listed as threatened were listed because monitoring showed a marked decline. Still, the decline we measured was much steeper than the global 1.13% annual average decline of terrestrial species estimated by the LPI (McRae et al., 2017). Declines occurred across all body mass categories and continued through a large La Niña event (2010–2012) and associated resource pulse when above average rainfall led to short-term increases in the abundance of many vertebrate populations (Greenville et al., 2018; Moseby et al., 2018). Of particular concern is the staggering 99% decline of small mammal populations and the fact that small and medium mammals undergoing nonpredator-related conservation management outside of havens had greater average declines than those with no known management. Also of concern is that most (86%) of our data were sourced from sites undergoing no conservation management, indicating that many threats and species are largely unmanaged.

Our finding of a 40% increase per year for populations in havens supports local-scale findings that eliminating invasive predators from islands and fenced areas can prevent likely extinction and allow for reintroductions of some vertebrate populations following extirpation (Monks et al., 2014; Smith et al., 2020). Around one half of Australia's threatened mammal species are highly to extremely susceptible to invasive predators (Radford et al., 2018). Havens will deliver local benefits to these species and, for some, are currently the only effective strategy for securing populations from predator impacts. However, havens cover <0.05% of Australia's land surface (Legge, Woinarski, et al., 2018) and contain only 58% of the mammal species that are extremely or highly susceptible to invasive predators (Legge, Woinarski, et al., 2018; Ringma et al., 2018), and the current haven network encompasses only a very small proportion of the former range of many predator-susceptible species. Fenced havens are mostly small (median size 4 km^2 in Australia), and there is some evidence from established havens that the almost 700% population increase observed in this study is not sustainable, with some havens having reached population carrying capacities for certain mammals (Moseby et al., 2018). There have been attempts to reintroduce overabundant populations to locations outside haven boundaries, but these are often unsuccessful (Hayward et al., 2012; Moseby & Hill, 2011). Our results indicate that strategic addition of species and locations to the existing haven network will help protect predator-susceptible taxa from extinction. Even so, havens do not protect most of Australia's threatened mammals from current and emerging threats such as habitat loss, climate change, and extreme events, such as drought and wildfires (Bino et al., 2021; Ratnayake et al., 2019; Ward et al., 2020), that are likely to exacerbate declining trajectories outside havens and require proactive policy changes in addition to local actions.

In addition to the positive effects of havens, our results provide evidence that sustained predator baiting can, in some contexts, maintain populations of species that are highly predator susceptible outside havens. This is not the case for "extremely predator-susceptible" species, which cannot survive outside predator-free zones (Radford et al., 2018). Our paired comparisons of trends for taxa with populations undergoing predator baiting and also inside havens showed overall declines outside havens compared with increases inside (Figure 3). However, comparisons of trends for highly predator-susceptible taxa with populations outside havens that were undergoing predator baiting and not being managed showed only a 26% overall decline for baited populations compared with a 90% decline when unmanaged. Our results suggest that sustained predator baiting outside havens has substantially slowed rates of threatened mammal decline and even led to population increases in some (but not all) predator-susceptible mammals (Figures 2 & 3; Appendices S2 & S3).

Initial declines of baited mammal populations were relatively consistent across all taxa (Figure 1), indicating that early management was insufficient to protect populations from invasive predators. The most severe declines were for the western ringtail possum. This species continues to decline and is also affected by drought, severe fire, and logging, requiring a landscape-scale multipronged approach to manage all threats (W. Geary, personal communication). The recent improved trajectory of mammals subject to sustained predator baiting may be due to adjusted predator control strategies, from targeting a single predator to landscape-scale multispecies management controlling foxes and cats and managing interacting processes like fire (e.g., Comer et al., 2020). Success stories for haven and sustained baiting populations must be viewed in the context of historical trends. Many taxa had already declined to very low numbers prior to the time our monitoring took place. Because our baseline of 2000 is recent and arbitrary (based on data availability), we remain cautious about making broad conclusions about taxon recovery due to any one management regime, lest inferences be susceptible to the shifting baselines syndrome (Mehrabi & Naidoo, 2022).

In addition to managing impacts of cats and foxes, improved effectiveness of other management actions is critical to recovering declining Australian mammals, particularly species for which invasive predators are not the main threat. The 80% decline for taxa outside havens with management of threats other than predators indicates that on average management actions in the >99% of Australia outside havens may be failing to maintain elements of the biodiversity (particularly small mammals) that they were intended to protect. It is concerning that the paired analysis indicated greater declines in populations at sites with management of threats other than predators relative to populations at sites without management (Figure 3e,f). It is also concerning that most threatened species monitoring data came from unmanaged populations—this may be indicative of the low level of conservation management across much of Australia. Nonpredator-focused efforts to recover mammals outside havens have been successful for certain populations, as indicated by index confidence intervals >0 for large mammals (Figure 2), but it was not possible to evaluate which management aspects were effective given low sample sizes. We recommend further studies to explore drivers of success and failure, which will help enhance management and plan future recovery actions (e.g., Radford, Woolley, Corey, et al., 2020).

That managed taxa outside havens sometimes had steeper declines than unmanaged populations could be because selected actions provided little control of the threats they targeted. Steeper declines in managed species may be due to selection bias in the set of sites and species being managed and monitored. If management focuses on sites where a species is locally abundant, monitoring is more likely to commence near a population peak than a trough and ensuing time series more likely to show populations declining than increasing (Fournier et al., 2019). Site selection criteria were not available for most time series. We recommend this be reported in future monitoring evaluations. Steeper declines could also be due to the limited set of management actions other than introduced predator control noted by data custodians (introduced herbivore control, ecological fire management, weed control, reintroductions). This does not represent the full range of actions underway to recover threatened mammals. Notably, ecosystem restoration is increasingly seen as central to conserving biodiversity because habitat loss is the major driver of species extinctions (Maxwell et al., 2016). Habitat restoration was rarely noted as management by data custodians. If populations categorized as not managed in our database were in habitats that had been restored prior to monitoring (and therefore not identified as currently managed), this might explain why unmanaged populations were faring slightly better at a national scale than those with some targeted management.

Unmanaged populations of mammals may be in marginal areas where many threats associated with human activities are not as intense as other more productive areas or declines occurred in the past and populations have now stabilized. Alternatively, declines in managed populations outside havens might be due to interacting threats, such as livestock grazing (Legge et al., 2019), or processes, such as drought or disease (e.g., Radford, Woolley, et al., 2020; Tulloch et al., 2020), resulting in perverse outcomes, including possible cascading declines due to worsening of co-occurring threats after one was mitigated (Geary et al., 2019). To halt and reverse declines in already managed populations, an overarching strategy for investment in all priority threats is required, which takes into account likely threat interactions, management effectiveness, and costs (Chadès et al., 2015).

Some recent studies have suggested that the LPI is susceptible to outlier trends (e.g., Leung et al., 2020), but our leverage analyses indicated that trends for broad management categories were relatively robust to the exclusion of outliers. Although the total aggregated change over time was altered when certain taxa with extreme positive or negative trends were excluded from the index, the direction of change (and ranking of effectiveness) of different management strategies for recovering populations was not (Table 1). Populations in predator-free havens still had the most positive change over time, sustained predator baiting outside reserves resulted in less decline than nonpredator-related management, and populations of medium-sized mammals undergoing nonpredator-related management sometimes had steeper declines than those with no known management. Although our results showed that the magnitude of the trend is sensitive to extreme outliers and species vary in their individual responses to threats and their management, the patterns we found are useful for understanding relative effectiveness of different management strategies and for highlighting the dire nature of declines for some taxa such as small mammals, which, even when outliers were excluded, showed declines of between 82% and 99% over 17 years. Our analyses support recent sensitivity analyses of the LPI, indicating that the true population trends for species not included in such analyses may be worse than suspected (Murali et al., 2022).

Our index provides a foundation from which many enhancements can be developed to increase its robustness, comprehensiveness, and utility for measuring management effectiveness. It highlights the importance of continued and strengthened monitoring programs to track and report on the effectiveness of threatened species recovery efforts. We could locate no monitoring data for 52% of threatened mammal species. Many taxa were represented by only a few years of data (Figure 4), data on nonpredator-related management actions were limited, and only 13% of taxa had data available for both unmanaged and managed sites that would enable paired comparisons. Despite hundreds of mammal translocations and reintroductions outside havens having been conducted over past decades (Palmer et al., 2020), we were able to access reintroduction monitoring data for only 3 species (*B. penicillata*, *O. fraenata*, *P. novaehollandiae*). None of these species have extreme predator susceptibility, so the trend for these species is not representative of reintroductions in general, which have variable success across mammals but have always failed for extremely susceptible species (Radford et al., 2018).

Paired evaluations of treated and nontreated sites allow stronger inferences to be made about management effectiveness (Legge, Robinson, et al., 2018). Many subindex trends are uncertain because they were based on fewer than 7 taxa (e.g., all large mammal management groupings), which is the recommended minimum number of taxa needed for aggregate trends (Bayraktarov et al., 2021). Many species were monitored in only a single location across their range. For taxa with very small ranges such as the Barrow Island boodie (*Bettongia lesueur*) (Barrow and Boodie Islands subspecies), this might be sufficient to characterize trends across the entire taxon, but for other wide-ranging species this is unlikely to be adequate for describing variation in trajectories across the species. For example, the spotted-tailed quoll (*Dasyurus maculatus*) occurs in disjunct populations across over 20,000 km^2 of the Australian east coast across 4 biomes. Some biomes (such as the central arid rangelands that make up 70% of the continent) were very poorly represented across all taxa. Varied survey effort within and across taxa biased our results to the most-studied locations and taxa, but also meant that we were unable to disaggregate trends further into biome- or region-specific management evaluations. This is an important area of future research. Investigators could also explore different approaches for aggregating or disaggregating data for wide-ranging taxa into multiple time series per taxa, and these might be included in the index to represent biome-specific variability over time. More targeted monitoring of small mammals and bats is also needed to address taxonomic bias. With more targeted monitoring, data aggregation and synthesis of trends across species can be conducted at finer spatial scales and for finer management categorizations to improve future decision-making (Loh et al., 2005).

Our conclusion that populations of threatened Australian mammals have declined by 35% over the period 2000–2017 parallels a similar trend (44% decline, 2000–2016) from comparable analyses of threatened Australian birds (Bayraktarov et al., 2021). That mammal decline is less steep than that of birds is due largely to increases of some predator-susceptible mammals that are intensively managed in havens; without such successes, the rate of mammal decline would be worse than that of birds. Given biases in favor of conservation efforts toward mammals and birds (Walsh et al., 2013), this suggests that rapid and ongoing declines are likely to be occurring across Australian threatened species generally.

Although we discovered substantial positive responses to localized management of threats to mammals, national-scale recovery of Australia's threatened mammals is unlikely without increased investment in threatened species conservation and enforcement of legislation to protect habitat from loss (Wintle et al., 2019). Although policy commitments and targeted management have fostered significant conservation achievements, we found that management evaluation is critical to assess intervention effectiveness. We evaluated threatened species conservation efforts at a national and continental scale; such efforts are lacking across most of the world. The message is clear: future biodiversity action needs to be scaled up to avert additional extinctions.

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SUPPORTING INFORMATION

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

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