Beyond total area protected: A new set of metrics to measure progress in building a robust protected area estate

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A R T I C L E   I N F O

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A B S T R A C T

With protected areas identified as the primary tool to halt the loss of biodiversity, the Convention on Biological Diversity has set targets for protected area expansion. Increasingly, concerns are being raised that target-driven growth, where targets focus largely on quantity (total area protected) rather than quality, may fail to achieve their intended biodiversity outcomes. Therefore, it is important to assess whether growth in area protected is translating into a more robust system of protected areas that better safeguard biodiversity. In this study, we propose a set of seven indicators, drawing on the body of evidence for the elements of protected area design and management associated with better biodiversity outcomes. Many of the features of effective design and management interact with one another, making it essential to use a suite of indicators and consider progress relative to trends across all of these indicators. We implemented the proposed indicators for the Australian National Reserve System, which has undergone significant growth over the past two decades. Our findings demonstrate that relying on trends in total area protected can obscure negative trends in other important indicators which suggest many protected areas in Australia are under increasing pressure. Meanwhile, the level of resourcing for management has not kept pace with increases in total area protected and has certainly not scaled with changes in pressures on protected areas. It is important that the global conservation community strive for a more nuanced set of indicators for conservation progress to identify whether growth in area protected has, or has not, translated into a more robust and effective system of protected areas. Given that most of the indicators we propose can be populated with existing data, we believe this approach could be achievable for protected areas globally.

1. Introduction

Protected areas (PAs) are the major conservation strategy to address ongoing habitat loss and continued declines in biodiversity (Tittensor et al., 2014). The Convention on Biological Diversity (CBD) has set targets for PA expansion, using growth in area protected as the key indicator of progress towards achieving this conservation objective (Convention on Biological Diversity, 2010). Since these global targets were established in 1996, they have been the catalyst for significant increases, with near exponential growth in both the number of PAs and the area under protection (Watson et al., 2014). This expansion has been heralded as a major conservation success, being one of the only CBD indicators demonstrating progress (Tittensor et al., 2014).

Nonetheless, there are risks associated with target-driven growth in PAs, namely that policy-driven targets that focus on quantity rather than quality can fail to achieve their intended biodiversity outcomes (Collen and Nicholson, 2014; Svancara et al., 2005). As such, concerns are growing that the CBD targets may be generating perverse outcomes by catalysing growth in PAs that have little value for biodiversity as countries race to meet area targets (Barnes, 2015; Barnes et al., 2018; Watson et al., 2016). To guard against poor or inefficient conservation outcomes from PA growth, it is essential to be able to evaluate whether growth has strengthened the capacity of PA networks to conserve biodiversity over time (Watson et al., 2016).

Simple metrics, such as the total area protected, are too insensitive to capture progress because they only reveal net growth, rather than tracking gains and losses (Cook et al., 2017; Lewis et al., 2019). An even greater limitation of using total area protected is that all gains in area are assumed to contribute equally to biodiversity conservation, despite volumes of evidence to the contrary (e.g., Edgar et al., 2014; Gaston et al., 2008; Geldmann et al., 2013). In recognition of this fact, Aichi Target 11 highlights the need for protected areas to be ecologically representative, connected and effectively and equitably managed (Convention on Biological Diversity, 2010). Metrics for measuring progress in representation (Butchart et al., 2016) and connectivity (Santini et al., 2016) exist, although there is no consensus about how...
Parties to the CBD should measure progress toward these goals (Watson et al., 2016). A critical gap remains in providing metrics for the effectiveness of PA networks that genuinely track progress toward addressing ongoing habitat loss and continued declines in biodiversity (Watson et al., 2016).

Ideally, estimates of the ecological effectiveness of PAs are derived from impact evaluations that assess whether PAs reduce habitat and biodiversity loss relative to unprotected areas (e.g., Edgar et al., 2014; Geldmann et al., 2013). However, currently this is not feasible at the scale required to judge progress toward conservation targets. Nevertheless, there is a growing evidence base on the structures of PA networks (e.g., design and management features) that lead to better outcomes for biodiversity (reviewed in Barnes et al., 2017). There is an opportunity to use this evidence base to develop a more detailed set of indicators that can assess how growth in area protected has contributed to the capacity of PA networks to protect biodiversity (Barnes, 2015; Collen and Nicholson, 2014; Watson et al., 2016). Assessing the structure of robust PA networks can draw on both the attributes of effective individual PAs (e.g., Edgar et al., 2014; Geldmann et al., 2013; Laurence et al., 2012) and how PAs networks function collectively to protect biodiversity (e.g., Margules and Pressey, 2000). Indicators should also be designed so that they account for change over time (hereafter PA dynamics) to assess whether changes constitute progress in improving the capacity of PA networks to conserve biodiversity (Roberts et al., 2018).

The local scale drivers of biodiversity outcomes in terrestrial PAs relate to elements of design (e.g., size, shape, level of protection) and management (e.g., resources and governance) (Barnes et al., 2017; Edgar et al., 2014). Given the evidence that design factors are pivotal to the ability of PAs to achieve the best long-term outcomes for biodiversity, this makes them valuable, yet currently neglected indicators of progress in building robust systems of PAs. The challenges of data collection at a global scale make it highly desirable that any proposed indicators can, at least initially, be populated using existing data. Therefore, our objective was to develop and test an efficient set of indicators that can track PA dynamics and reveal progress in building robust systems of PAs. Using the key features of effective PA design and management to drive biodiversity outcomes, as identified by literature reviews (Barnes et al., 2017) and meta-analyses (Edgar et al., 2014; Geldmann et al., 2013), here we identify simple metrics that can be aggregated for portfolios of PAs to assess trends in the structure of PA systems. Specifically, we examined the size, shape, level of protection and compatibility of the matrix around PAs as elements related to effective design, and the level of human pressure surrounding PAs and expenditure as elements of PA management. Ideally, metrics of robust PA systems should include trends in representation, connectivity and management effectiveness (including threat mitigation). Appropriate metrics for representation (e.g., Butchart et al., 2016) and connectivity (e.g., Santini et al., 2016) have been addressed elsewhere. While metrics for management effectiveness have been proposed (e.g., Leverington et al., 2010), they do not yet have sufficient data available to broadly address trends, and the level of resourcing has been identified as a valuable proxy for management (Watson et al., 2014).

In interpreting progress relative to the indicators, it is important to consider the impact of the legacy of PA declaration that anchors the ability to effect change. This requires consideration of the theoretically desirable trend in indicators given the particular starting point, to judge progress towards a more robust network. Given the significant problems with using the World Database on Protected Areas (WDPA) to track change in the global protected area estate (Lewis et al., 2019; Thomas et al., 2014; Visconti et al., 2013), we illustrate the application of the indicators for the Australian National Reserve System (NRS), which has more than doubled in size since Australia became signatory to CBD in 1996 (Cook et al., 2017b). We then present the desirable and actual progress achieved by Australia for each of the proposed indicators to assess progress. Our aim is to provide a platform for discussion about a more nuanced set of indicators, which are essential to assess global progress toward positive biodiversity outcomes from PAs.

2. Material and methods

2.1. The Collaborative Australian Protected Areas Database

The Collaborative Australian Protected Areas Database (CAPAD) is used by the Australian Government to report progress toward meeting CBD protected area targets. All government jurisdictions (i.e., six states, two territory and one federal government) contribute spatially explicit data on their PAs to CAPAD biennially. CAPAD includes nine time steps between 1997 and 2014, providing longitudinal data of change in the NRS over a 17 year period. This dataset suffers from many of the same deficiencies as the WDPA, in relation to boundaries, date of designation, IUCN designation and reporting changes not reflected on the ground (Cook et al., 2017b). To prepare the data for analysis, we conducted a wide range of data quality checks to verify and correct these errors for all years (Appendix A, see also Cook et al., 2017b).

2.2. Indicators of protected area network design

2.2.1. Total area protected

While total area protected can be a broad indicator of progress towards area-based targets, there is growing evidence for the downsizing and degazettement of PAs (Symes et al., 2016), and the fact that total area metrics can obscure these losses (Cook et al., 2017b; Lewis et al., 2019). Therefore, total area protected should be reported as both area gained and lost. Ideally, progress in this indicator should show steady growth in area (ensuring for example that resources for management can keep pace with growth), with no losses in area (Fig. 1A).

To assess the total area protected and lost from the Australian NRS during the study period, the area (km²) of every polygon in the CAPAD dataset was calculated for every time period. Areas gained (increases to existing areas or new PAs) and lost (downsizes or degazettements) in each time step were identified, and the area (km²) of every polygon calculated (see Cook et al., 2017b for detailed methods).

2.2.2. Protected area size

If a PA is too small to meet the ecological needs of species then it is unlikely to maintain the biodiversity it was designed to protect, or support the ecological and evolutionary processes that enable persistence (Gaston et al., 2008). While the minimum size for a PA depends on the species it supports (Clements et al., 2018), there is evidence that larger PAs tend to provide better outcomes for biodiversity (Edgar et al., 2014; Geldmann et al., 2013), are more resistant to land use change (Maierano et al., 2008) and are less costly to manage per unit area (Armstrong et al., 2011) relative to smaller PAs. We use the distribution of sizes of PAs as an indicator of progress for this design element.

While larger PAs will be important for large, far-ranging species (Woodroffe and Ginsberg, 1998), ideally there should be a distribution of size classes that recognise that smaller PAs may be essential for conserving critical components of biodiversity (such as highly threatened species or areas with high endemism) in highly fragmented landscapes, which are vulnerable to continued habitat loss (Tulloch et al., 2016). We suggest that ideally the size class distribution would include the spectrum of size classes, with a higher proportion of PAs in the moderate to large size classes (Fig. 1B). While the ideal scenario is likely to be country specific, Australia has many small PAs, so progress in this indicator would be demonstrated by higher growth in larger size classes relative to smaller size classes, adding more large PAs or enlarging existing PAs.

We calculated the size class distribution of Australian PAs in two ways. First, we assigned each PA to a size class using a log scale (< 1;
For each time step, we calculated the proportion of PAs in each size class (Fig. 1B). Using these data we then calculated a PA size (PAS) index (Fig. 1C) that provides a metric for the change in the proportion of PAs in each size class, weighted by the size of PAs based on their size category (Eq. (1)). This PAS index is comparable to the IUCN Red List Index (Butchart et al., 2007).
The PAS index for time step $t$ is:

$$\text{PAS}_t = 1 - \frac{\sum_{\text{pa}} W_{c}(t,\text{pa})}{W_{c}^{\text{N}}}, \quad (1)$$

where $\text{pa}$ is each PA in the time step $t$, $W$ is the weight applied to each PA size category, $W_{c}$ is the weighting for category $c$, $W_{c}$ is the maximum category weight given to the smallest size class ($W_{c} < 1 \text{km}^2 = 5$), and $N$ is the total number of PAs. As with the Red List Index, we used a five category weighting system, with scores ranging from 0 (largest size class) to 5 (smallest size class). The weighting is applied based on the rationale and evidence that larger PAs are more effective than small ones (e.g., Edgar et al., 2014).

### 2.2.3. Protected area shape

Edge effects have a range of negative consequences for the capacity of a PA to conserve biodiversity, such as increasing exposure to pollutants, resource exploitation, invasion and disease transfer (Ewers and Didham, 2007; Laurance, 1991). It is generally accepted that a more compact shape minimises the perimeter to area ratio and limits the impact of edge effects on PAs leading to better biodiversity outcomes (Barnes et al., 2017). Ideally the mean perimeter to area ratio should decrease over time as more compact areas are added or the shape of existing PAs is improved through strategic addition and preventing fragmentation (Fig. 1D).

We calculated the perimeter to area ratio (km$^2$/km$^2$) for all PAs in each time period using the ‘calculate geometry’ function in ArcMap (Version 10.3). We then calculated the mean perimeter to area ratio ($\pm$ standard error) in each time step to evaluate the change in the exposure to edge effects across the PA system over time.

### 2.3. Indicators of pressures on protected areas

#### 2.3.1. Landscape context

The connectivity versus isolation of PAs, (i.e., the degree to which individual PAs are physically or functionally connected to other PAs, or suitable habitat), is an important element of effective PA design to support ecological and evolutionary processes (Hansen and DeFries, 2007). While connectivity measures based on species’ dispersal capability (e.g., Santini et al., 2016) and resistance to species movement (i.e., landscape permeability; Rae, 2006) exist, they are currently difficult to populate at broad scales. We propose a proxy measure for isolation of PAs that also captures important information about the landscape context of PAs to indicate the pressure they are under from edge effects: matrix compatibility, measured as the proportion of PA perimeter exposed to incompatible (e.g., agricultural, urban etc.) land use. Ideally, the proportion of PAs surrounded by incompatible land uses should decline over time (Fig. 1E) due to new PAs being more strategically placed and restoration targeted to provide buffers for PAs.

To determine the proportion of each PA surrounded by incompatible land use in each time step, the ‘Polygon Neighbour tool’ in ArcMap (Version 10.3) was used to calculate the length of PA perimeter (km) adjoining different land uses. The proportion of perimeter adjoining incompatible (e.g., agricultural, mining, and residential and commercial infrastructure) versus compatible land uses (e.g., native vegetation with or without minimal use, such as stock routes) (see Appendix B for land use classes). In this case a comparatively strict categorisation of compatibility was used. Continuous rather than binary measures of matrix compatibility could in future accommodate a more nuanced and context specific assessment of compatibility. Land use data were derived from Australian Land Use and Management Classification Data for 2001-02 (Version 3), 2005-06 (Version 4) and 2010–2011 (Versions 5), compiled by the Australian Bureau of Agricultural and Resource Economics and Sciences.

#### 2.3.2. Human population pressure

Human population pressure on PAs has consistently been found to have negative impacts on the effectiveness of PAs to protect habitat (Geldmann et al., 2013). The human population density surrounding PAs has been shown to be an important indicator of the human pressure on PAs (Geldmann et al., 2014). There is no agreed value for how best to estimate human population density. We selected mean population density with 10 km of each PA as a measure of human population density. While iconic PAs may draw visitors from further away, this will not be the case for the vast majority of PAs, so we aimed to measure pressure from the local population. Mean population density will tend to increase with human population growth, and a decline in this metric may indicate PAs are being placed in areas under less pressure from human populations (Fig. 1F). Therefore, trends associated with this metric should be considered in relation to trends in PA size (Figs. 1B, C), the level of protection from human impacts (Fig. 1G) and the resources for management (Fig. 1H).

We calculated the population density with a 10 km buffer of each PA using the ZonalStat by Polygon tool in ArcMap. Population density was estimated from the 2006 Australian Census data (collected every 10 years by the Australian Bureau of Statistics), which provides the number of people per km$^2$ across Australia. We selected census data from 2006 as it fell within the middle of our study period, and using population data from a single year prevented the metric being impacted by population growth. We calculated the mean population density surrounding each PA ($\pm$ standard error) for each time step.

### 2.4. Indicators of management response

#### 2.4.1. Level of protection

The IUCN recognises PAs with a range of different objectives, which permit more or less high-impact human activity, through a classification system (Dudley, 2008). More strictly protected categories (e.g., Categories I & II) provide higher protection for biodiversity by excluding higher impact human activities, like resource exploitation, permitted within other IUCN categories (e.g., Category V & VI) (Bradshaw et al., 2015), and have been directly linked with better biodiversity outcomes in PAs (Edgar et al., 2014). The proportion of the total area protected within different IUCN categories therefore provides some indication of the pressure PAs are under from human activities, and the costs associated with managing associated infrastructure (e.g., visitor facilities). Ideally, the proportion with stricter protection would increase over time to approximately two thirds to accommodate PAs with multiple objectives, such as Indigenous PAs, which are typically lower protection categories (Fig. 1G).

For each time step, we calculated the proportion of the PA system (by area) within each IUCN category. The calculations were made at the level of polygon, rather than PA, to capture special protection zones...
within some PAs (Appendix A). Calculations were made for each IUCN category, then aggregated to the commonly used grouping (sensu Joppa and Pfaff, 2009) reflecting higher protection (Categories I and II) and weaker protection (Categories III, IV, V, VI) for biodiversity.

2.4.2. Resources for management

Adequate resourcing for PA management has consistently been identified as a primary driver of outcomes within PAs (e.g., Leverington et al., 2010; Waldron et al., 2013). Globally, assessments have identified significant variation in the level of resources for conservation activities, with major shortfalls when assessed against the funding needed (Balmford et al., 2003). Data on the level of resourcing for PAs are notoriously difficult to obtain (Waldron et al., 2013), and there is little guidance about what types of costs (see Cook et al., 2017a; Iacona et al., 2018) should be included (e.g., overheads versus direct management costs). Determining the resources required for “effective” management is likewise problematic. Resources for management should be calculated as the funding per unit area, to account for costs scaling with the area. Funding per unit area should at a minimum keep pace with economic inflation where resources are sufficient to meet operational requirements. Ideally, resources would scale with management need, which could be assessed in relation to the pressures on PAs (e.g., Section 2.3).

We based our estimates for the funding for PA management in Australia on data compiled by the World Wildlife Fund, sourced directly from relevant government agencies responsible for management (Taylor et al., 2014). Data were only available for four of the relevant time periods. We divided the total funding by the total area protected in each time step to determine the funding per unit area ($/km²). The average annual rate of inflation in Australia averaged 2.6% (Consumer Price Index; Australian Bureau of Statistics (ABS, 2017) across the study period. We doubled this rate (5%; Fig. 1H) to achieve modest growth in real funding beyond that of keeping up with inflation. Values in Australian dollars were converted into US dollars, which are frequently used as a global standard, using on historical exchange rates for the relevant periods.

2.5. Data analyses

To evaluate trends in indicators we used a range of models depending on the properties and distributions of the variable being modelled, all with the indicator metric as the dependent variable and time period as the explanatory factor. Linear regression was used to assess whether there has been a change in the PAS index, landscape context and resources for management over time. A negative binomial generalised linear model with a log link function was used to evaluate trend in PA shape and human population pressure over time.

3. Results

3.1. Indicators of protected area network design

3.1.1. Total area protected

The Australian NRS has more than doubled in area since 1997, with losses in area of around 13,000 km² (Cook et al., 2017b; Fig. 2). Gains have been somewhat episodic rather than steady, with largest gains occurring towards the end of the study period.

3.1.2. Size distribution of protected areas

There has been little if any progress in shifting the size distribution of Australian protected areas over the 17 year study period, with the majority continuing to be in the smallest size class (<1 km²) and 80% less than 10 km² (Fig. 3A). The PAS index also reflects a lack of the desired trend towards larger PAs (Fig. 1C), with the index value consistently remaining below a value of 0.45 (Fig. 3B) and no significant difference between time periods ($R^2 = 0.32$; $\beta = 0.57$; $df = 1,7$; $p = 0.11$).

3.1.3. Protected area shape

We found no evidence of the desired decrease in perimeter to area ratio (Fig. 1D). Instead, the perimeter to area ratio of PAs appears to have increased significantly over time ($\chi^2 = 50,787.80$; $df = 1$; $p < 0.001$; Fig. 4), suggesting greater exposure to edge effects.

3.1.4. Matrix compatibility

While it is desirable that strategic growth in PAs would prevent isolation of natural areas by incompatible land use (Fig. 1E), we found no evidence that this has occurred during the study period. Instead, we observed a small but significant increase in the mean proportion of PA
boundaries that are adjoining incompatible land uses \( R^2 = 0.01; \beta = 0.09; \text{df} = 1,57814; p < 0.001; \text{Fig. 5} \), suggesting new areas tend to be more isolated and/or existing PAs are becoming increasingly isolated through continued land-use change.

3.1.5. Human population pressure on protected areas

There has been a significant increase in the human population density surrounding Australian PAs during the study period \( \chi^2 = 8,322,245.80; \text{df} = 1; p < 0.001; \text{Fig. 6} \). This increase \( \mu = 2.8\% \text{ per annum; Fig. 6} \) is commensurate with the average population growth within Australia \( \mu = 3.0\% \text{ per annum; Australian Bureau of Statistics (ABS, 2017)} \) over the study period.

3.2. Indicators of protected area network management response

3.2.1. Level of protection for biodiversity

Australian PAs were mostly in the higher protection IUCN categories at the beginning of the study period; however, the majority of growth in new area has occurred in categories offering lower protection to biodiversity \( \text{Fig. 7} \). While changes in the balance of different protection levels initially followed a desirable trend \( \text{Fig. 1G} \), the rapid growth in lower protection categories has significantly reduced the proportion of the PA estate offering strong protection to biodiversity \( \text{Fig. 7} \).

3.2.2. Resources for protected area management

Limited accessible data on the funding for PA management meant we could only estimate trends for half the survey period. The level of funding per km\(^2\) was variable during this time \( \text{Fig. 8} \) with no significant trend \( R^2 = 0.13; \beta = -44.10; \text{df} = 1,4; p = 0.56 \). Failing to keep pace with inflation \( \text{e.g., Fig. 1H} \) means an effective decline in funding due to increases in salary and operational costs. Global estimates of funding for conservation management from 2002 \( \text{Balmford et al., 2003} \) suggests Australia was ahead of much of the rest of the world. However, the level of resourcing per unit area in 2012 was approximately half the 2004 value, adjusted for inflation, over the period \( \text{Fig. 8} \).
4. Discussion

It is increasingly clear that no single metric can provide an adequate measure of conservation progress (Collen and Nicholson, 2014; Roberts et al., 2018). Our data reinforce concerns that relying on the total area protected alone can obscure important trends that may impact the capacity of PAs to support biodiversity (Barnes, 2015). Activity does not necessarily translate into progress building a robust PA system, and without strategic growth, it is possible that the world will meet the 17% coverage target for terrestrial PA but fail to achieve the desired biodiversity outcomes (Watson et al., 2016). We show that using indicators based on the drivers of biodiversity outcomes in PAs, including key elements of both effective design and management, can provide a more nuanced and complete assessment of how growth in area influences the overall capacity of PAs to deliver positive outcomes for biodiversity. These results should encourage the global community to move beyond total area to reporting progress against measures of the capacity of PAs to conserve biodiversity.

Australia provides a valuable case study with which to evaluate PA dynamics. While the area protected has more than doubled over the past 17 years, despite some losses (Fig. 2), this growth has not always been associated with desirable trends (e.g., Fig. 1) in indicators of robust design (Figs. 3–4), pressures on PAs (Figs. 5–6) or management responses (Figs. 7–8). These trends highlight the importance of considering a wider set of metrics when assessing progress, especially given that many of the different elements of PA design and management can interact to impact the capacity of the system to provide positive outcomes for biodiversity. This makes it particularly important to consider trends in a single indicator relative to changes in the others.

4.1. Interpreting indicators of effective protected area design and management

Globally, the vast majority of PAs are small (Gaston et al., 2008), and these areas can be important for conserving important natural features (Tulloch et al., 2016). The prominence of small PAs (e.g.,
80% < 10 km$^2$; Fig. 3A) can partly be explained by necessity, given representation targets within highly fragmented bioregions can often only be reached by adding small PAs. However, where the majority of PAs are small, it is important to consider whether they are likely to be able to maintain adequate populations of important species (Clements et al., 2018; Gaston et al., 2008) or support ecosystem level processes (Peres, 2005) and therefore sustainably achieve conservation objectives. In situations where most PAs are small, connectivity becomes increasingly important to facilitate the metapopulation dynamics that enable species to persist long-term (Hanski, 1998).

A further challenge for small PAs is that they are highly susceptible to the pressures associated with edge effects (Woodroffe and Ginsberg, 1998), which have increased over time in Australian PAs as indicated by the higher perimeter to area ratio overall (Fig. 4). In fragmented landscapes, edge effects may be exacerbated by land use change leading to greater pressure from threatening processes around PAs (Laurance, 1991). This is indeed the pattern we observed, with mostly small PAs (Fig. 3), and a trend towards higher exposure to edge effects (Fig. 4) and land uses around PAs contributing to lower matrix compatibility (Fig. 5). Add to this increasing pressure from human populations surrounding PAs (Fig. 6), and small PAs are likely to be suffering from greater internal and external pressures per unit area relative to larger PAs. Small PAs tend to be more costly to manage per unit area relative to larger ones (Armsworth et al., 2011), so increasing pressures from outside PAs are likely to further compound the costs of managing the average PA. This would support the case for a higher level of resourcing per unit area over time, although this was not the trend we observed (Fig. 8) suggesting deteriorating capacity to address the increasing pressures.

One way in which internal pressures on PAs could be mitigated is by offering higher levels of protection for biodiversity from human activities, as indicated by IUCN categories. Stricter protection has been associated with better outcomes for biodiversity (Barnes et al., 2017; Edgar et al., 2014), and may reduce the impact from pressures such as visitation, which is not encouraged within IUCN Category I PAs (Dudley, 2008). Therefore, a situation where pressures outside PAs are
increasing might be offset to some degree through trends towards higher levels of protection from internal pressures. However, this was not observed within the Australian NRS, where strict protection for biodiversity was reduced from 77% to 42% of the area protected (Fig. 7). In interpreting trends in the level of protection for PAs it is important to remember that biodiversity protection is not the only objective of PAs, many of which have important cultural and social objectives as well (Dudley, 2008). This is particularly the case for Indigenous Protected Areas and other multi-use PAs that promote sustainable use of natural resources (Category V & VI). In many cases, the involvement of local communities can have positive effects on PAs and communities (Corrigan et al., 2018). Yet with biodiversity protection the primary objective of PAs (Dudley, 2008) and the evidence for the negative impacts human populations can have on the biodiversity outcomes for PAs (Geldmann et al., 2013), the combination of lower levels of protection (Fig. 7), higher human population pressure (Fig. 6) and a decrease in matrix compatibility surrounding PAs over time (Fig. 5) could mean areas are more vulnerable to degradation, and therefore make effective management even more critical.

Many of the drivers of biodiversity outcomes in PAs have the potential to influence the costs of management (Barnes et al., 2017; Watson et al., 2016), making it desirable that resources should scale with both area and the pressures on PAs to ensure they can meet management needs. The mismatch we observed between spending (Fig. 8) and the resources required for management in PAs is common globally (Balmford et al., 2003). Australia is among the top 40 underfunded countries for biodiversity conservation (Waldron et al., 2013) and yet is in the top 10% of countries in terms of per capita GDP (2017 statistics, https://data.worldbank.org), which highlights another critical risk that area funding for the PA estate could be met without achieving biodiversity goals (Watson et al., 2014). Ensuring countries meet the Aichi Target 11 for management effectiveness evaluation of PAs could help to assess this risk. We were not able to include indicators for management effectiveness due to a lack of available data, yet the trends we observed suggest these data may be essential to inform how resourcing can be better matched to changes in the pressures on PAs.

Given the use of targets and indicators have the potential to drive perverse outcomes (Barnes et al., 2018; Fukuda-Parr, 2014), it is important to consider how the indicators we propose might drive change. Striving to improve trends in indicators of PA size or pressures in isolation of other indicators could see investment in large but residual reserves (Devillers et al., 2015). It is therefore critical that PA planning still be done within a systematic planning framework, that prioritise principles of comprehensive, adequate and representative reserves (Margules and Pressey, 2000). Therefore, the indicators we propose would help drive investment that promotes the best outcomes within the inevitable restrictions on designing the ideal PA system.

5. Conclusion

Taken together, the indicators of effective PA design and management can be used to highlight where rapid growth in area may not have translated into a strengthening of the capacity to protect biodiversity long-term, providing a more nuanced assessment of conservation progress. By considering the indicators collectively, and the ways in which they interact with or magnify one another, it is possible to identify if PAs are on average under more or less pressure and the degree to which they may be able to deliver positive biodiversity outcomes. We would not advocate that countries reflexively avoid adding new PAs if these areas contribute to undesirable trends in some indicators. Countries will need to formulate desired trends in indicators in the context of current and historical development of their PA networks. While there is a risk that if governments focus on improvements in a single indicator this could compromise outcomes in other indicators, this should not prevent transparent reporting on changes in PA networks, particularly where PA dynamics reveal that additional management responses may be required to protect biodiversity. Therefore, the focus on reporting change across the suite of indicators could drive positive changes for existing PAs. For example, an increase in pressures on PAs supports an argument for additional management resources, raising the levels of protection for sensitive area or restoring habitat adjacent to and connectivity among PAs. While ideally progress building robust PAs would be judged by evaluating population trends for biodiversity (e.g., Geldmann et al., 2013), the indicators we propose provide a major step forward for a more detailed and transparent assessment of progress in building robust PAs beyond total area protected.

One of the great benefits of the indicators we propose is that most can be populated using existing global datasets. There is a clear need to reduce the errors within the World Database on Protected Areas (International Union for the Conservation of Nature (IUCN), United Nations Environment Program - World Conservation Monitoring Centre (UNEP-WCMC, 2016) to improve the accuracy of trend assessments,
and several authors provide guidance on how this could be achieved (Lewis et al., 2019; Thomas et al., 2014; Visconti et al., 2013). Global spatial layers for population density and land use change exist (Geldmann et al., 2014), providing data for the majority of PAs. The PADDDTracker Database currently has over 3700 records of losses in area protected (World Wildlife Fund (WWF), 2018), but this is likely to be a significant underestimate of losses in regions with no comprehensive PADDD assessments. Data on funding for PA management are currently not available, although Waldron et al. (2013) were able to source country-level spending on biodiversity conservation, which includes spending on PAs and other conservation activities.

To facilitate global reporting on a broader set of indicators, the revised conservation targets could encourage signatory countries to report against indicators of effective PA design and management. This would require the development of explicit methodologies to ensure data are comparable, which could facilitate a more detailed discussion about whether the set of indicators should be expanded, such as through the addition of social indicators, and how indicators can most effectively be measured. Nevertheless, the current challenges to reporting on all of the indicators we propose should not prevent the conservation community striving to entrench a more meaningful set of indicators of PA dynamics. We hope that by outlining a set of indicators that address important elements of PA design, pressures and management responses in advance of the development of the post-2020 CBD targets, we will stimulate broader reflection on how to more effectively measure conservation progress.

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### Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.j gloenvcha.2019.101963.

### References


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