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SUPPLEMENT ARTICLE

Planning for the future: Incorporating global and local data to prioritize coral reef conservation

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Abstract

1. It is necessary, yet challenging, to manage coral reefs to simultaneously address a suite of global and local stressors that act over the short and long term. Therefore, managers need practical guidance on prioritizing the locations and types of conservation that most efficiently address their goals using limited resources.
2. This study is one of the first examples of a vulnerability assessment for coral reefs that uses downscaled global climate change projections and local anthropogenic stress data to prioritize coral reef locations for conservation investment. Vulnerability was separated into manageable and unmanageable components (bleaching likelihood and local anthropogenic stressors, respectively), and the highest priority was given to places with low levels of unmanageable threats and high levels of manageable threats. Following prioritization, resilience characteristics were derived from standard reef monitoring data and used to identify the specific conservation strategies most likely to succeed given local ecological conditions and threats.
3. Using Indonesian coral reefs as a case study, 9.1% of total coral reef area was identified as of high conservation priority, including parts of Raja Ampat, Sulawesi, and Sumatra that are not currently included in marine protected areas (MPAs).
4. Existing MPAs tend to be located in areas less threatened by local-scale anthropogenic activities, which has implications for both the implementation costs and the likely impact of conservation investment. This approach employs common and publicly available data and can therefore be replicated wherever managers face the familiar challenge of allocating limited conservation resources in the face of rapid global change and uncertainty.

KEYWORDS

climate change, decision science, exposure, Indonesia, marine protected area, prioritization, resilience, vulnerability

1 | INTRODUCTION

Rapidly increasing concentrations of atmospheric CO_2 have created global-scale threats to the future of coral reefs, including ocean warming and acidification (Graham et al., 2008; Hoegh-Guldberg et al., 2007). Climate impacts are typically modelled at a global scale by combining predicted future climate, under a range of IPCC-generated scenarios, with expected impacts on corals. For example, species distribution models predict that there will be at least a 43% decrease in available coral habitat in the next century (Freeman, Kleypas, & Miller, 2013). By incorporating additional variables that affect ocean temperature, such as currents, wind speed, and UV radiation, models offer more region-specific predictions (Maina, Venus, McClanahan, & Ateweberhan, 2008), and these models are frequently updated as better and finer- scale data become available (van Hooidonk, Maynard, Manzello, & Planes, 2014). For example, recent models incorporate both temperature and acidification impacts, and move beyond bleaching to add sub-lethal impacts to corals (e.g. changes in calcification and growth rates) (Wolff et al., 2015).

At the same time, reefs are negatively affected by local-scale anthropogenic activities, including overfishing and destructive fishing,

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pollution, and sedimentation (Burke et al., 2012). Given the suite of global and local threats to reefs, managers seeking efficient use of limited conservation resources need relevant information and guidance on how to prioritize local conservation actions through the lens of global climate change (Aswani et al., 2015). Marine spatial planners recognizing this need are increasingly incorporating climate change, but balancing conservation plans for local and global threats remains a major challenge (Game, Watts, Wooldridge, & Possingham, 2008; Gurney, Melbourne-Thomas, Geronimo, Aliño, & Johnson, 2013; McLeod et al., 2012). Species distribution models are the most common way that climate change is incorporated into marine spatial planning (Jones, Watson, Possingham, & Klein, 2016), although these complex models are still frequently excluded in favour of combining simpler data such as habitat maps, expert opinion, and landscape-level processes like connectivity (Tulloch et al., 2016). Further, as climate change models become more refined and available at smaller spatial scales, scientists should update and revise previous conservation guidance based on the best available data. Previous vulnerability assessments for reefs in the Coral Triangle have used historical temperature data or modelled projections at large (e.g. 1° or 70 km grids) spatial scales (Heron et al., 2012; McLeod et al., 2010; Peñaflor, Skirving, Strong, Heron, & David, 2009). This paper expands on existing guidance by using the latest downscaled projections (van Hooidonk et al., 2016), not historical data, and by incorporating the projected threat of climate change impacts, local anthropogenic threats, and local ecological resilience to prioritize actions where climate impacts will be minimal and local efforts will have the greatest impact.

Conservation prioritization schemes can be broadly summarized as either proactive and risk tolerant (highest vulnerability) or reactive and risk averse (lowest vulnerability) (Boon & Beger, 2016; Hoffmann et al., 2006; Tulloch et al., 2015). Vulnerability has two primary components: exposure and resilience, where resilience is composed of sensitivity and adaptive capacity (Smith et al., 2010). However, defining vulnerability for coral reefs is complicated because the first vulnerability component, exposure, is made up of both local, manageable threats and global, unmanageable threats; and the second component, resilience, depends on a suite of local ecosystem characteristics. In this paper, exposure is explicitly separated into distinct manageable and unmanageable components, and combined with ecological resilience, in order to develop a framework for prioritizing coral reef conservation.

Orthogonal to prioritizing locations with high or low vulnerability, vulnerability itself can be evaluated using current ecosystem condition, climate projections, or local anthropogenic impact. A vulnerability assessment based solely on ecological condition means focusing on the healthiest, least affected, and most irreplaceable wilderness areas regardless of local or global human impacts. Such remote areas often contain different communities and species from even the best protected reserves (Graham & McClanahan, 2013) and are targeted because they contain specific habitats, high biodiversity, or species of particular concern (Hughes, Bellwood, & Connolly, 2002; Roberts et al., 2002). A vulnerability assessment based on climate impacts means focusing on areas that have the most favourable climate futures, regardless of local anthropogenic stress or ecosystem condition (Graham et al., 2008). Finally, a vulnerability assessment based on local anthropogenic threats means employing decision science to allocate scarce conservation resources where they will have the greatest impact on manageable threats and focusing on places that are most likely to be lost without an intervention (Pressey & Bottrill, 2008; Pressey, Watts, & Barrett, 2004; Wilson, McBride, Bode, & Possingham, 2006).

This study's primary objective is to prioritize local conservation actions within the context of global climate change, providing guidance to managers on where and what type of conservation actions are the most efficient use of conservation resources. To that end, this prioritization gives highest priority to places facing the greatest *manageable* (local) threats and the least *unmanageable* (global) threats. Specifically, reefs that will be most affected by bleaching are given a lower priority for local conservation, because local conservation actions cannot reduce coral bleaching. Instead, locations with actual manageable impacts that can be mitigated by local conservation actions are identified as priorities. This approach provides an alternative to current approaches that generally prioritize areas that are in good condition or where protection would have the lowest cost. For example, the global trend in marine protected areas is biased toward 'residual' placement, where minimizing cost (economic or social) takes priority over explicitly reducing vulnerability (Devillers et al., 2014). Proponents of the 'residual reserve' approach argue that protecting remote or uninhabited locations minimizes the social and economic costs of protection, and that such locations might serve as an insurance policy against future climate change (Devillers et al., 2014). In contrast, the prioritization criteria presented here direct resources towards places with impacts that managers can reduce, thereby making the most efficient use of conservation investments.

This prioritization was applied to a case study of Indonesia's MPAs (Box) to: (1) evaluate how well existing MPAs account for climate change; (2) determine whether existing MPAs tend toward any particular prioritization strategy; and (3) identify new priority areas for different types of conservation investment based on resilience potential. Finally, the analysis was conducted in an accessible way using global and public data that are available at a management-relevant spatial scale to facilitate reef managers conducting a prioritization analysis for their own regions and goals.

Conservation in Indonesia as a proxy for global management of coral reefs for climate change

Throughout this paper, the term 'conservation activities' refers inclusively to all actions intended to protect, restore, or conserve coral reefs, including, but not limited to, marine protected areas (MPAs). While MPAs are not always effective, particularly where capacity shortfalls lead to weak enforcement and compliance (Gill et al., 2017; Pollnac et al., 2010), they are the most widely implemented approach to marine conservation, particularly for coastal ecosystems such as coral reefs. It is far more straightforward to find comprehensive and reliable information on MPA boundaries and area than, for example, data on fishing gear restrictions, restoration projects, or ridge-to-reef style management initiatives to reduce runoff on coral reefs (Marine Conservation Institute, 2016; Wood, 2007). Therefore, in this study, MPAs are used to quantitatively examine to what extent existing conservation efforts account for exposure to climate change and are prioritized for the most efficient use of conservation resources.

In terms of addressing climate resilience, coral reefs inside MPAs often have better capacity to recover more quickly from disturbances like bleaching (Mellin, MacNeil, Cheal, Emslie, & Caley, 2016; Wilson et al., 2012) or flooding (Olds et al., 2014) if there is higher herbivore biomass and therefore higher coral recruitment (Mumby et al., 2007; Olds et al., 2014). But the presence of an MPA alone does not confer climate resilience (Graham, Jennings, MacNeil, Mouillot, & Wilson, 2015; Graham et al., 2008). Instead, environmental factors beyond the influence of MPA status may be stronger drivers of resilience and recovery rates, such as bleaching severity (McClanahan, 2008), reef depth, nutrients, or structural complexity (Graham et al., 2015), or initial cover and hardiness of the coral community (Darling, McClanahan, & Côté, 2013). Nevertheless, MPAs remain the most common tool to protect coral reefs and are therefore an informative lens through which to examine conservation effort.

Specifically, MPAs in Indonesia are the focus of this analysis. Indonesia is a relevant and useful case study because the country has an extensive reef system, a large population with a high dependency on reefs, and climate projections that are representative of coral reefs globally. Indonesia has 51 000 km^2 of coral reef, more than any other country in the world (Spalding, Ravilious, & Green, 2001), and 25% of its population lives within 10 km of the coastline (Burke et? al., 2012). Furthermore, the average projected year of the onset of annual severe bleaching (ASB) is similar in Indonesia and globally (2044 and 2043, respectively), and the variation in the projected year of onset of ASB is similar in Indonesia and globally (82 and 83 years, respectively) (van Hooidonk et al., 2014). In other words, locations that are relative climate refugia within Indonesia are also absolute refugia for the planet. Thus, Indonesia-focused conservation prioritization based on climate projections can be meaningfully extrapolated to reefs in the rest of the world.

2 | METHODS

This paper has three main components. First, to establish relative conservation priorities; global and local threats were defined for all coral reefs in Indonesia. Then, the vulnerabilities to each of these threats were combined and assigned priorities according to a matrix that weights the threat of bleaching more heavily. Finally, once relative priorities were assigned for all of Indonesia, a case study of South-west Maluku reefs was conducted to identify appropriate types of conservation activities based on specific resilience characteristics.

2.1 | Global threats: Coral bleaching projections

The latest statistically downscaled climate models were used to assess spatial variation in the onset of annual severe bleaching (ASB) conditions in Indonesia, where ASB is defined as a decade in which every year is projected to have more than 8 degree heating weeks (van Hooidonk et al., 2014). These models are at the smallest spatial scale currently available: 4 km grids compared with 1° × 1° (approximately 70 km) grids used in earlier models and vulnerability assessments (Beger et al., 2013). Locations were defined as having relatively early, average, or late onset of ASB relative to other reefs in the region. In Indonesia, the mean year of onset of ASB is 2044 (± 10 years SE) (van Hooidonk et al., 2014). Therefore, 'early' reefs are projected to experience the onset of ASB before 2034 (2044–10 years), 'average' reefs between 2034 and 2054 (2044 ± 10 years), and 'late' reefs in 2055 or later (2044 + 10 years). Sea surface temperature (SST) data for global climate models (GCMs) were obtained from the CMIP5 for the RCP8.5 and RCP4.5 scenarios (Moss et al., 2010). These experiments statistically downscaled model outputs from 33 GCMs for RCP8.5 and 35 GCMs for RCP4.5 to a 4 × 4 km Pathfinder grid (for detailed downscaling methods see van Hooidonk et al. (2014)). Data are publicly available from NOAA Coral Reef Watch [https://coralreefwatch.noaa.gov/climate/projections/downscaled_bleaching_4km/index.php].

2.2 | Manageable threats: Local-scale anthropogenic activities

To quantify local anthropogenic impacts, integrated local threat (ILT), a combined measure of overfishing, destructive fishing, watershed based pollution, marine pollution, and coastal development, was mapped (Burke et al., 2012). Reefs were defined as having Low, Medium, High, or Very High ILT based thresholds developed from observed impacts to reefs. Reef locations were resampled from the original 500-m resolution using the maximum pixel value within each 4-km pixel.

To establish conservation priorities, a matrix of combined vulnerability to global and local threats (ASB onset and ILT, respectively) was created (Figure 1). Unlike a straightforward vulnerability assessment, this matrix explicitly displays priorities based on high levels of local anthropogenic threats and low levels of global threats (i.e. later than average onset of ASB). In reflection of the severity of climate threat to coral reefs, we make explicit our value judgment that climate projections should receive more weight than local anthropogenic threat (Game, Kareiva, & Possingham, 2013). In other words, major bleaching events can swamp any benefits of low local impacts. Therefore, the matrix is not symmetrical; for example, any location with later than average onset of ASB is a High or Very High priority, regardless of ILT. In contrast, even locations with the highest ILT can only be a Medium priority if they are projected to experience ASB earlier than average. Such an asymmetrical prioritization reflects the numerous recent examples of major bleaching events in MPAs and other well-managed systems (Graham et al., 2008, 2015; Hughes et al., 2017) and the very real likelihood that even places with very low levels of local human impacts can be decimated by climate change. This matrix could be adjusted to reflect different objectives, such as protecting locations that are climate refugia, more ecologically pristine, socio-economically important, or with low implementation and management costs. The matrix was used to assign relative conservation priorities of Low, Medium, High, or Very High to all 12 035 4-km reef pixels in Indonesia based on each pixel's individual category of ASB and ILT.

Onset of ASB	Anthropogenic Threats: Low	Medium	High	Very High
Early	Low	Low	Medium	Medium
Average	Medium	Medium	High	High
Late	High	Very High	Very High	Very High

FIGURE 1 Conservation prioritization matrix developed to most efficiently use conservation resources by targeting areas with maximum manageable threats (anthropogenic threats measured as ILT (Burke et al., 2012)) and minimum unmanageable threats (bleaching from global climate change measured as projected onset of ASB (van Hooidonk et al., 2014))

2.3 | Case study of MPAs in Indonesia

To examine the extent to which Indonesia's current conservation investment accounts for climate change and makes the most efficient use of conservation investments (i.e. prioritizing areas with manageable local impacts), and to identify priority locations for investing in specific management actions, results of the prioritization matrix were compared with existing MPA boundaries in Indonesia. Coral reef pixels were defined as inside or outside MPAs using maximum area rules, where boundary pixels count as inside an MPA if greater than 50% of pixel area is inside the MPA. Proportions of reef area inside and outside MPAs were compared for each conservation priority category, projected onset of ASB, and ILT level.

2.4 | Using ecological resilience to inform management actions in South-west Maluku

The prioritization matrix was applied to South-west Maluku, Indonesia, which is part of a region the Ministry of Marine Affairs has identified as a national priority for fisheries production and ocean conservation (Watloly, 2010). After sites in South-west Maluku were assigned priorities based on the local and global threat matrix, specific conservation actions that would be appropriate for each location were identified based on type and degree of local threat, degree of global threat (projected onset of ASB), and specific dimensions of reef resilience (Table 1). To quantify reef resilience to bleaching, this study used standard reef monitoring data so that the approach could be easily replicated in any region where managers are interested in combining data from global modelling and local ecological monitoring to prioritize conservation actions.

Seven resilience characteristics (italicized below) that promote resistance to and recovery from bleaching events were measured. *Herbivorous fish biomass* indicates the potential speed at which reefs can recover following disturbances (Maynard et al., 2012; Olds et al., 2014), or at least how slowly reefs will degrade (Edwards et al., 2011). *Macroalgal cover* can increase rapidly to prevent coral recovery after disturbance (Wilson et al., 2012), typically as a result of low grazing rates and/or high nutrient load. *Crustose coralline algae (CCA) cover* promotes coral settlement and is often the inverse of turf or fleshy macroalgae (Smith et al., 2016), such that high CCA cover is an indicator of abundant substrate for coral settlement. *Hard coral cover* before disturbance is an important indicator of recovery (Graham et al., 2015), although it might not affect the rate of decline, only the duration (Edwards et al., 2011). *Coral diversity* promotes resilience, perhaps because it increases the likelihood of having stress-tolerant taxa (McClanahan, Maina, & Muthiga, 2011; but see Darling et al., 2013). Therefore, to also capture the relative cover of taxa with varying resistances to bleaching (Darling et al., 2013; Furby, Bouwmeester, & Berumen, 2013; Marshall & Baird, 2000; Maynard et al., 2012; van Woesik, Sakai, Ganase, & Loya, 2011; Wilson et al., 2012), this study measured *coral community susceptibility to bleaching* with a new metric (described below). Finally, *temperature variability* may allow corals to adapt or acclimate to elevated temperatures (Ateweberhan & McClanahan, 2010; Donner, 2011; Maina et al., 2008; Maynard et al., 2012; McClanahan, 2008; Oliver & Palumbi, 2011; but see Mellin et al., 2016). These seven factors were selected based on available evidence and data, but the framework can be adjusted as new data become available to accommodate additional factors that either confer resilience, such as connectivity and dispersal (Maynard et al., 2015; McLeod, Salm, Green, & Almany, 2009; Olds et al., 2014; Sale et al., 2005), or that indicate a system likely to be resilient, such as structural complexity (Graham et al., 2015), density of juvenile corals (Graham et al., 2015; Mumby & Harborne, 2010; Olds et al., 2014), or response to past bleaching (Logan, Dunne, Eakin, & Donner, 2014; Middlebrook, Hoegh-Guldberg, & Leggat, 2008; Wilson et al., 2012;).

Herbivore biomass, macroalgae cover, CCA cover, coral cover and coral diversity were measured at 30 sites in South-west Maluku in November 2015 on three 50 m transects at 10 m depth, following standard reef monitoring protocols (Ahmadia, Wilson, & Green, 2013). Fish biomass was calculated using *a* and *b* values from Indonesia when available, and otherwise from nearby bioregions (Froese & Pauly, 2016). For 29 species for which *a-b* values were unavailable, the genus mean was used, and for three species for which genus *a-b* were unavailable, the family mean was used. Coral diversity was calculated as the inverse Simpson index. A new metric of coral community bleaching sensitivity was developed: for each hard coral genus in the Sunda Banda Arc, a bleaching sensitivity score was assigned based on a literature review of past bleaching responses, then multiplied by taxa-specific percentage cover to get a single site-level measure of coral community bleaching sensitivity (Table S1, Supporting information). Temperature variability is the standard deviation of warm season sea surface temperature (SST) from 1982 to 2012 from NOAA Pathfinder Version 5.2, where warm season is the three months that centre on the month with the maximum monthly mean SST (Casey, Brandon, Cornillon, & Evans, 2010; Maynard et al., 2015).

Indicators were normalized to a scale of 0 to 1, such that a score of 1 represents the highest value in the study region (e.g. higher coral cover and lower macroalgae cover both yield a higher score). One drawback of normalizing these data is giving uneven weight to relative changes in each metric. For example, the highest coral cover was 87%. The effect of normalizing this metric is that each 1% change in coral cover equates to a 0.011 change on the normalized scale. In contrast,

TABLE 1 Criteria, rationale, and descriptions of management actions to n = 30 sites in South-west Maluku, Indonesia (after Maynard et al., 2015). The number of sites matching each criterion is listed in parentheses. Management actions are not intended to be exhaustive

Management action	Criteria	Rationale	Examples of management action
Conservation	Very high resilience potential (6) ***OR*** Relatively favourable bleaching projections (1)	It is difficult to build intrinsic resilience to climate change, so sites with the highest relative likelihood of surviving, recovering from, or avoiding bleaching are high conservation priorities regardless of local impacts.	Marine protected areas, including no-take zones and other actions described below.
Fishery management and enforcement	High/very high resilience potential and high fishing pressure (4) ***OR*** Medium/low herbivore biomass and high fishing pressure (9) ***OR*** Both (5)	Managing fisheries is an effective approach where there is high fishing pressure and where the ecosystem is likely to be responsive to fishery improvements.	Increased enforcement, marine protected areas, seasonal or temporary closures, size/catch/bag limits, monitoring fish populations.
Development [managing impacts from]	Very high resilience potential and the highest category of coastal development threat (high or medium) (1)	Managing land-based threats is an effective approach where there are existing impacts from development and where the ecosystem is likely to survive or recover from bleaching.	Property development guidelines, zoning, terrestrial parks, investment in waste management infrastructure, boating and tourism restrictions.
Bleaching monitoring and supporting recovery	Medium/low bleaching resistance, medium/low herbivore biomass, and high/very high coral cover (4)	Conservation strategies focused on bleaching mitigation is appropriate at sites with a lot to lose from bleaching (e.g. abundant but susceptible coral taxa) and limited herbivory to promote post-bleaching recovery.	Increased monitoring during warm seasons, shading or other cooling measures, supporting recovery processes using any of the other actions described in this table.
Reef restoration	Medium/low coral cover or coral diversity, high/very high herbivore biomass, and the lowest category of integrated local threat (low or medium) (7)	Active reef restoration is (1) necessary where there is low coral cover/diversity, and (2) most likely to succeed where there are minimal ongoing local threats and high herbivory.	Artificial reef installation, priority coral nursery and transplantation areas, post transplantation monitoring, moorings and no-anchor zones.

the maximum macroalgal cover was 52.3%, so a 1% change in macroalgae cover equates to a 0.019 change on the normalized scale. While weighting changes in algal cover twice as much as changes in coral cover may not be ecologically correct, it is unclear what a correct balance would be. In fact, normalizing to actual data from the study location turns these data into relative metrics that are appropriate to the local context: given the maximum recorded coral and algal covers, it is reasonable to consider cover of 43.5% (coral) and 26.15% (macroalgae) as 50% changes, or 0.5 on the normalized scale. Further, normalizing provides the benefit of allowing comparison across different metrics, for example percentage cover, grams per square metre, and degrees Celsius.

The seven normalized indicators were combined into a single resilience score for each site as the mean of all seven indicators. Many of these indicators are correlated or causal: herbivore biomass and macroalgal cover are likely to be related; coral cover and coral diversity might correlate; cover of benthic groups (corals, macroalgae, and CCA) must, mathematically speaking, be inversely related. Counting each metric separately could overweight some aspects of resilience (e.g. higher score for both high coral cover and low macroalgal cover, when in reality these two metrics likely reflect the same ecological processes). However, it is no simple task to quantitatively weight the potential interactions among, or relative importance of, metrics. For example, the relative weights offered by McClanahan et al. (2012) are based on expert knowledge, not quantitative data. Nonetheless, total resilience was calculated as both a weighted and unweighted average, using the weights proposed by McClanahan et al. (2012). Weighting per their framework, and weighting using a theoretical and implausibly extreme variance among metrics, made no qualitative difference to the relative scores of each site. Therefore, for transparency and parsimony, total resilience was calculated as a simple arithmetic mean. Individual resilience metrics were also used to inform specific management actions appropriate for each site (Table 1).

Based on its total resilience score, each site was assigned to one of four relative resilience categories: Low (more than 1 SD below the mean), Medium (within 1 SD below the mean), High (within 1 SD above the mean) and Very High (more than 1 SD above the mean) (Maynard et al., 2015). These scores are relative within the study area, to focus on prioritization within a confined geopolitical context, and do not allow for direct comparisons with other locations. Finally, the climate projections, local anthropogenic threats, and resilience scores were combined to identify the most appropriate management actions for each site: spatially constrained conservation (MPAs), fishery management and enforcement, managing impacts from development, bleaching monitoring, and reef restoration (Table 1) after Maynard et al. (2015). Because specific sites and boundaries have yet to be established, this is an opportune time to provide decision-makers with practical guidance.

3 | RESULTS

3.1 | Spatial distribution of global (ASB) and local (ILT) stressors

On average, Indonesia's reef will begin experiencing annual severe bleaching in 2044 ± 10 years (SE). Of the 12 035 coral reef pixels in Indonesia, 8.3% are projected to begin experiencing ASB before 2034 and 9.2% after 2054. Locations with earlier predicted ASB are in southern Indonesia, along East and West Nusa Tenggara and South-west Maluku, and locations with later predicted onset of ASB are largely in central Sulawesi and Raja Ampat (Figure 2).

Most reefs in Indonesia are rated as having High (29.5%) or Very High (26.6%) ILT; reefs with low ILT are relatively rare (5.4%) and are located only in the remotest parts of Indonesia (e.g. in the Bird's Head Seascape and in remote island areas south east of Wakatobi National Park) (Figure 3). The remaining 38.5% of coral reefs are rated as Medium ILT (Figure 4a).

Based on the prioritization matrix, projected ASB and ILT were combined to code each 4-km coral reef pixel as Low, Medium, High, or Very High conservation priorities (Figure 1). This prioritization resulted in identifying 9.1% of Indonesia's coral reefs as Very High conservation priorities. Most reefs are either High (44.6%) or Medium (43.8%) priorities, and only 2.5% are Low priorities (Figure 4b). There are three clusters of coral reefs that are nearly homogeneously Very High conservation priorities: central Sulawesi, Raja Ampat, and parts of Cenderawasih Bay (Figure 5). However, most of Indonesia has considerable spatial heterogeneity in the distribution of conservation priorities.

3.2 | How existing MPAs align with this prioritization scheme

The placement of existing MPAs in Indonesia in general does not match the prioritization scheme. The distribution of conservation priorities inside MPAs is slightly right-skewed with an over-representation of lower priority locations inside MPAs (Figure 4b), suggesting that either past MPA planning has not followed a prioritization strategy based on climate projections and local threats, or that MPAs have effectively reduced local threats. The distributions of conservation priorities for all reefs and for reefs outside MPAs are nearly identical (Figure 4b). More than half of the coral reefs in Indonesia that are not currently in MPAs are either High or Very High (47.9 and 8.9%, respectively) priorities, including locations along the west coast of Sumatra, Sulawesi, and in Raja Ampat. These locations are priorities for establishing MPAs to reduce local threats efficiently within the context of global climate change.

The tendency for MPAs to protect reefs that are lower conservation priorities is driven by patterns of ILT, not by patterns of bleaching projections. Nearly one-third (29.8%) of coral reefs outside MPAs face Very High local anthropogenic threats compared with 16.4% of reefs inside MPAs, though the data do not distinguish whether this is a result of past successes in MPAs reducing local threats or an indication that MPAs have been established in less-threatened areas. In contrast, the proportions of MPA reefs with relatively late and relatively early bleaching projections (9.8% and 8.3%, respectively) are virtually identical to the proportions of non-MPA reefs (9.0% and 8.3%, respectively), suggesting that MPAs for coral reefs planning has not taken into account climate change projections. Central Sulawesi stands out as having a high concentration of reefs with relatively late projected ASB that are not currently protected with MPAs.

3.3 | Conservation actions identified for South-west Maluku, Indonesia

Raw resilience scores for the 30 sites in South-west Maluku range from 0.44–0.64 (Table 2). Sites in this region are most variable in coral diversity (range of inverse Simpon's Index from 0.16 to 0.70) and more similar in macroalgae cover (13.0 ± 2.2%), temperature variability (0.4 ± 0.1°C), and coral community bleaching resilience (2.8 ± 0.07 on a scale of 1–5) (Figure S1). Ecological resilience is approximately normally distributed within the Inner Band Arc: n = 6 sites have Low, n = 8 have Medium, n = 10 have High, and n = 6 sites have Very High resilience. There is spatial autocorrelation in resilience potential, with many sites having similar resilience scores to neighbouring sites (Figure 6). However, several exceptions where nearby sites have very different resilience scores suggest ecological patterns that may complicate conservation strategies. For example, a site on southern Romang Island (Romang 2) has the lowest resilience score of all sites in South-west Maluku, while the site with the third highest resilience score (Mitan Island) is located only 2 km away (Figure 6b, Table 2). These sites face identical levels of local anthropogenic threats (overall ILT score = High) but have very different scores for each of the seven resilience metrics (Table 2).

Each of the five potential management strategies was recommended for one or more sites in South-west Maluku. The most common recommended conservation action was fisheries management and enforcement of fishing regulations, with nearly half the sites (n = 14 of 30) meeting the criteria. Fewer than one-third of the sites are good candidates for establishing an MPA. Most sites (n = 24 out of 30) meet the criteria for at least one type of conservation action, and n = 11 sites meet the criteria for more than one conservation action (Table 1). Similar to the spatial patterns in resilience scores, there is broad spatial autocorrelation in suggested management actions such that spatially proximal sites are generally candidates for similar actions (Figure 7a, c, d). However, there are several cases where neighbouring sites have notably different recommended conservation action. For example, three sites on the western tip of Leti Island less than 5 km apart (Moa 1, Moa 2, and Moa 3) are all candidates for fisheries management. However, only the two outer sites, Moa 1 and 3, also meet the criteria for establishing an MPA; Moa 2, in the middle, does not. Establishing two separate MPAs at only the outer sites could lead to complicated regulations and enforcement and would contradict general MPA design principles of larger and less fragmented protected areas (McLeod et al., 2009), yet if the entire region were made an MPA, expectations should be adjusted, since establishing an MPA at Moa 2 might have limited ecological impact. In such cases where the prioritization results are impractical or conflict with best practices, managers might choose to incorporate additional factors into their prioritization. In this example, local community

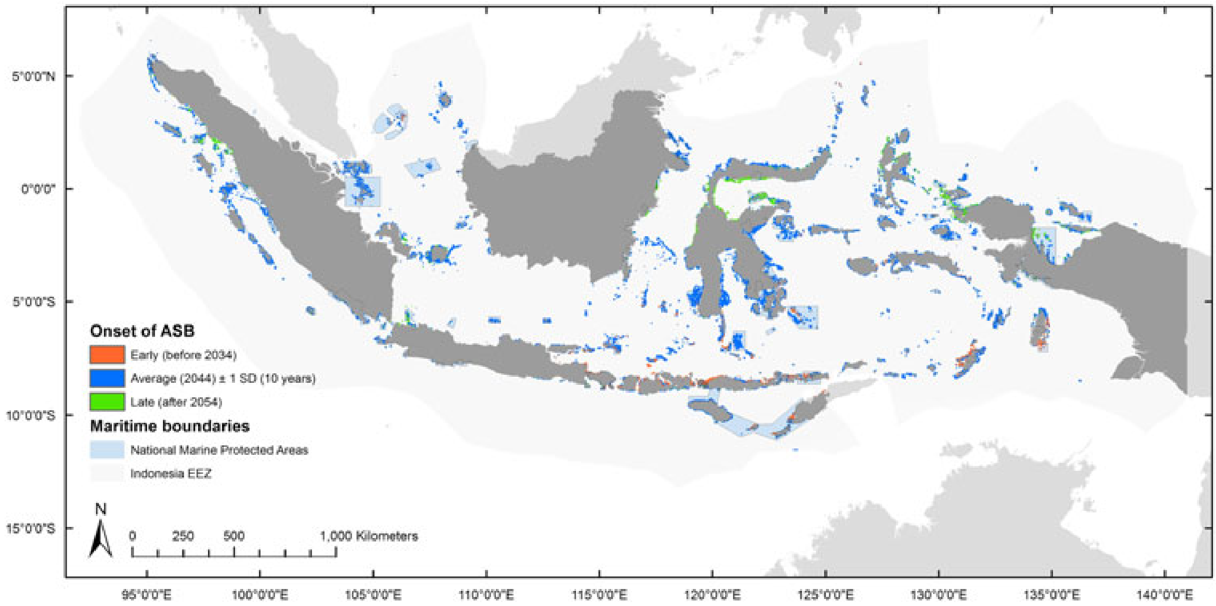

FIGURE 2 Projected year of the onset of annual severe bleaching under RCP8.5 for coral reefs in Indonesia (van Hooidonk et al., 2014)

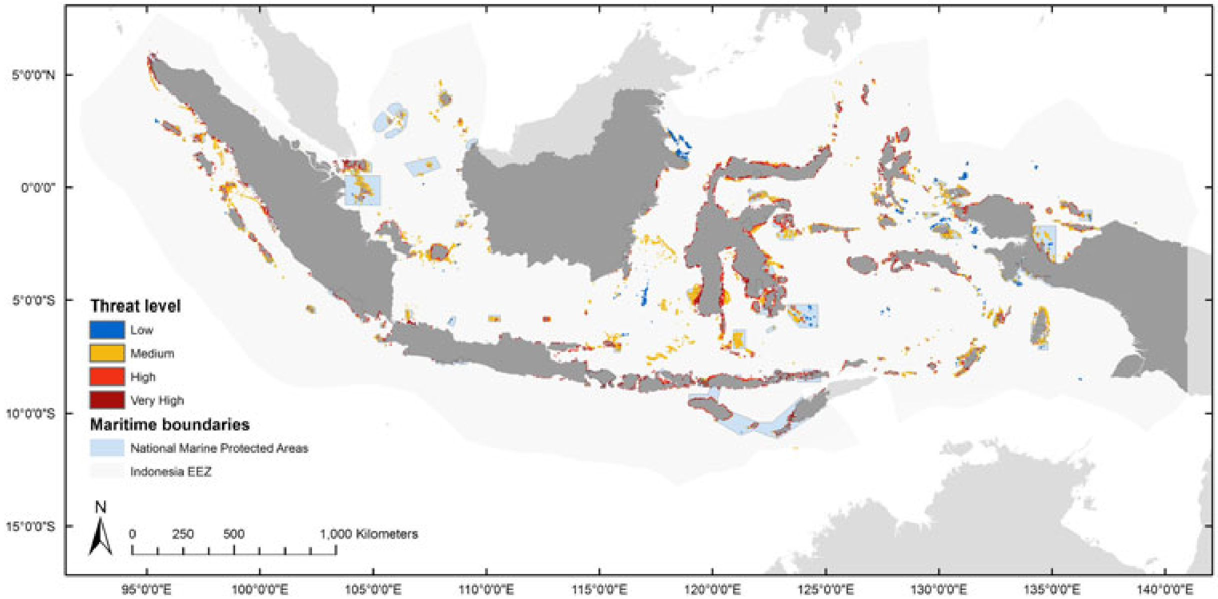

FIGURE 3 Local anthropogenic threats to coral reefs in Indonesia based on the integrated local threat measure from Burke et al. (2012)

support or existing social structures conducive to conservation could lead to a clear choice between one large and two small MPAs. This is one example of how mapping ecological resilience and management recommendations at a small spatial scale can help managers make informed decisions for more effective and efficient conservation, and highlights opportunities to incorporate additional social and economic factors into conservation prioritization.

4 | DISCUSSION

Examining the challenge of allocating limited conservation resources to manage local threats to coral reefs in the context of vulnerability to global climate change highlights potential synergies and tradeoffs in conservation strategies. By comparing global and local threats, this study presented one way that managers can prioritize areas where local conservation actions will have the greatest impact given the overarching threat of coral bleaching. Further, a case study of MPAs in Indonesia demonstrated how to develop a set of relevant conservation strategies by combining projected global climate stress, local anthropogenic impacts, and seven dimensions of resilience. The dominant pattern was positive spatial autocorrelation, although multiple cases of high spatial variability in reef condition and anthropogenic stress were revealed, in some cases highlighting neighbouring sites with disparate resilience and recommended management actions. In cases of high heterogeneity, maximizing conservation output may require management at the scale of individual reefs or villages nested within a broader regional management plan (Christie, White, & Deguit, 2002).

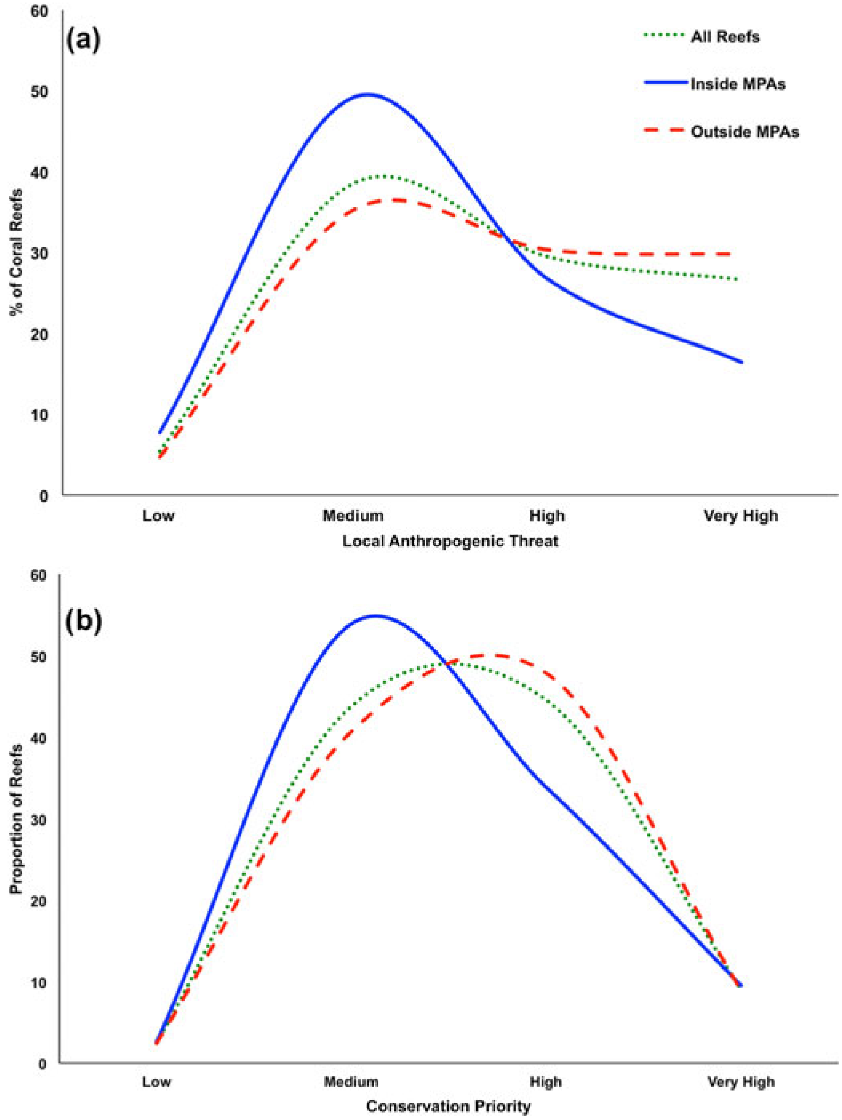

FIGURE 4 Distribution of Indonesia's coral reefs inside and outside existing MPAs that are classified as **(a)** each category of local anthropogenic threat, and **(b)** relative conservation priorities

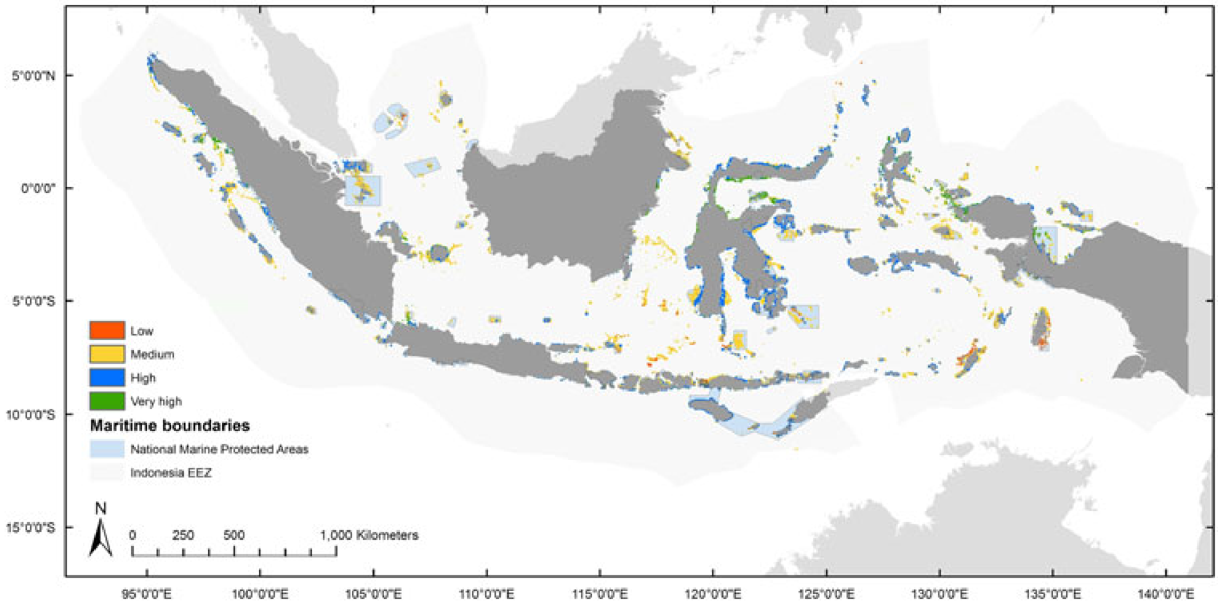

FIGURE 5 Combined vulnerabilities resulting in relative conservation priorities for coral reefs in Indonesia. Priorities based on maximizing manageable vulnerabilities and minimizing unmanageable vulnerabilities as in Figure 1

TABLE 2 The distribution of normalized and raw resilience score (RS) and seven environmental resilience indicators (herbivore biomass (HB), macroalgae (MA), crustose coralline algae (CCA), coral cover (CR), coral diversity (CD), coral community bleaching susceptibility (RT) and temperature variability (TV)) for n = 30 sites in South-west Maluku, Indonesia, ranked in descending order. Coloured cells denote relative classifications: green = very high, yellow = high, orange = medium, red = low

Site	Rank	Norm RS	Raw RS	HB	MA	CCA	CR	CD	RT	TV
Spooky Moa (Moa 3)	1	1.00	0.64	0.11	0.90	1.00	0.32	0.65	0.66	0.85
Moa 1	2	0.99	0.64	0.14	0.95	0.69	0.42	0.67	0.70	0.86
Mitan	3	0.99	0.63	0.52	0.95	0.04	0.60	1.00	0.62	0.69
Luang Barat 3	4	0.99	0.63	0.14	0.88	0.45	0.51	0.82	0.73	0.89
Jagotutun (Magic Corner)	5	0.98	0.63	1.00	0.94	0.31	0.18	0.36	0.81	0.80
Desa Wasarili	6	0.98	0.63	0.09	0.90	0.04	1.00	0.81	0.74	0.82
Amortaun	7	0.96	0.61	0.50	0.98	0.16	0.37	0.69	0.74	0.83
Luang Barat 1	8	0.95	0.61	0.15	0.91	0.65	0.33	0.61	0.74	0.90
Sermata 3	9	0.95	0.61	0.13	1.00	0.00	0.86	0.64	0.77	0.87
Sermata 1	10	0.93	0.60	0.48	0.94	0.02	0.43	0.70	0.74	0.87
Moa 2	11	0.92	0.59	0.10	0.86	0.18	0.52	0.86	0.72	0.86
Wetar 2	12	0.90	0.58	0.28	0.95	0.35	0.25	0.54	0.82	0.84
Pulau Dawelor	13	0.89	0.57	0.30	0.86	0.38	0.29	0.57	0.62	0.97
Wetar 1	14	0.89	0.57	0.33	0.98	0.15	0.26	0.58	0.83	0.86
Wetar 3	15	0.89	0.57	0.25	0.83	0.29	0.29	0.58	1.00	0.75
Leti 1	16	0.88	0.56	0.11	0.95	0.00	0.54	0.82	0.75	0.79
Luang Barat 2	17	0.87	0.55	0.28	0.86	0.07	0.41	0.70	0.66	0.90
Masela 1	18	0.84	0.54	0.11	0.86	0.00	0.48	0.50	0.80	1.00
Masela 3	19	0.83	0.53	0.09	0.85	0.00	0.66	0.23	0.89	0.99
Grouper Fate	20	0.83	0.53	0.30	0.93	0.18	0.31	0.54	0.69	0.75
Leti 2	21	0.82	0.53	0.13	0.91	0.00	0.44	0.79	0.62	0.79
Masela 2	22	0.82	0.52	0.08	0.76	0.00	0.56	0.51	0.75	1.00
Schooling Paradise (Kisar 3)	23	0.80	0.51	0.39	0.88	0.02	0.28	0.47	0.68	0.86
Wallderful (Kisar 2)	24	0.77	0.49	0.03	0.94	0.05	0.38	0.58	0.67	0.80
Sermata 2	25	0.76	0.49	0.25	0.85	0.02	0.27	0.53	0.69	0.82
Sea Mount	26	0.76	0.49	0.20	0.94	0.04	0.21	0.27	0.84	0.91
Leti 3	27	0.74	0.47	0.05	0.96	0.04	0.33	0.62	0.49	0.81
Romang 1	28	0.73	0.47	0.11	0.93	0.02	0.32	0.36	0.79	0.75
Soft Coral Valley (Kisar 1)	29	0.68	0.44	0.08	0.88	0.13	0.17	0.26	0.68	0.86
Romang 2	30	0.65	0.42	0.21	0.80	0.05	0.21	0.34	0.66	0.67

In contrast, neighbouring sites that meet criteria for the same conservation action could be considered higher priority, because their proximity might reduce financial, social, or political costs to implement regional conservation plans.

This prioritization is based on the argument that there is greater potential for management to make a difference – for conservation investments to actually reduce threats – in areas with relatively late projected onset of ASB and medium to high local anthropogenic threats. Local management cannot prevent impacts from global climate change; severe bleaching events can decimate even the healthiest reefs (Obura & Mangubhai, 2011). Therefore, when the primary goal is long-term benefits, local conservation action in areas likely to avoid bleaching (later onset of ASB) should be prioritized as a stop-gap to ensure that reefs persist until ocean temperatures stabilize (Kennedy et al., 2013). Where the goal is the most efficient use of conservation investment, reefs with more manageable (local) threats should be prioritized (Boon & Beger, 2016; Bottrill et al., 2008; Game et al., 2008; Pressey & Bottrill, 2008). Conservationists cannot ignore either local or global threats, so prioritizing local actions informed by global climate projections will help managers make the most efficient conservation decisions.

These results are a starting point, and there is no one-size-fits-all approach to conservation prioritization (Game et al., 2008; and see debate among Bottrill et al., 2008; Jachowski & Kesler, 2009; Parr et al., 2009). While managers inevitably prioritize whenever they make decisions about where to engage in conservation activities, it is unrealistic to suggest that they prioritize based solely on ecological and climatological criteria. It is impractical and unethical to 'write off' degraded locations likely to experience ASB earlier than average when those locations have social value or high reliance on reefs for food and livelihoods. Further, management decisions operate within finite geopolitical and social boundaries, so decision-makers can only set relative priorities within their management purviews. Regions with uniformly early projections for ASB may not be appropriate for more conventional conservation activities, such as MPAs, reef restoration, or fishing regulations, which are unlikely to succeed and are therefore

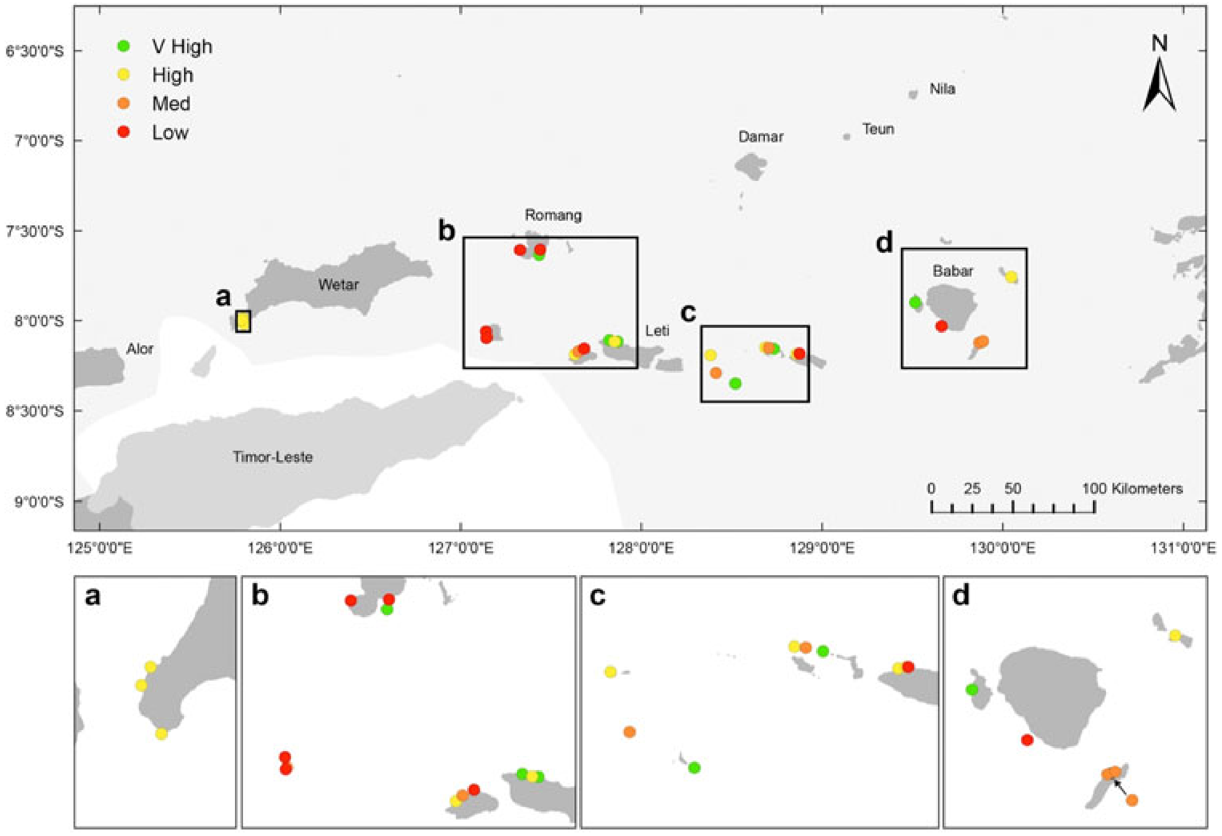

FIGURE 6 Relative resilience potential of *n* = 30 sites in South-west Maluku, Indonesia based on seven resilience metrics (Table 2). Insets **(a-d)** show finer spatial scales

an inefficient use of limited capital. However, such locations could be priorities for human-focused conservation, such as supporting community capacity to adapt to climate change. While prioritization theory is appealing, we acknowledge the necessity of balancing ideal priorities with pragmatism (Pressey and Bottrill's (2008) 'informed opportunism') and encourage managers to look for 'win-win' areas that emerge as conservation priorities regardless of strategy (Boon & Beger, 2016).

Furthermore, our results indicate that reef managers will increasingly need to implement a diverse portfolio of approaches to reef conservation in the future, and our framework can help managers prioritize specific actions to fit into their marine spatial planning. We found the need for five distinct management actions in our case study of South-west Maluku, Indonesia, and many sites emerged as candidates for more than one action (e.g. MPAs combined with reef restoration). MPAs, despite being the most common conservation tool for coral reefs, were not the most common recommended strategy for this region. This disparity highlights the need for conservation decision-makers to first clarify what threats exist to be managed before investing in conservation strategies.

We see multiple strengths to our approach. It is easily replicable because the climate and ILT data used here are both publicly available on a global scale, and some form of reef monitoring is typically conducted when designating conservation zones. For example, the resilience indicators could be adjusted for coral life forms instead of genera to accommodate available monitoring data. Furthermore, our resilience table (Table 2) can be easily modified to accommodate new data as they become available or as management goals change. For example, future analyses might add factors that provide resilience to ocean acidification, storms, or sea-level rise (Pendleton et al., 2016). This work may also be seen as a starting point for managers to assign ranks based on manageable and unmanageable threats before incorporating additional socio-economic priorities, such as reliance on fishing as a primary source of protein or income. Importantly, our approach does not require 'heavy' computational and modelling skills; anyone who can work in Excel can repeat this exercise. While in many cases complex models support decision-making, in other situations where computational and other resources are lacking and /or prohibitive, this 'lighter' approach could bridge the gap and make conservation prioritization more accessible (Holden & Ellner, 2016).

These data on climate projections, local threats, and ecological resilience could also be used in more formal spatial planning (e.g. Marxan), following the same prioritization framework that separates exposure into manageable and unmanageable components. Other considerations such as equity, local enabling conditions, and marine resource dependence of local communities could be incorporated into management decisions as costs or constraints. For example, our findings that existing MPAs in Indonesia are biased toward areas with fewer local anthropogenic threats suggest that MPAs are being placed where there is less dependence upon the ocean, and subsequently lower social costs to implementation (Ban & Klein, 2009; Devillers et al., 2014). However, the lower cost of implementation might be outweighed by the lower enforcement costs when protected areas are located close to higher population densities (Beger, Harborne, Dacles, Solandt, & Ledesma, 2004; Kritzer, 2004). A limitation of our

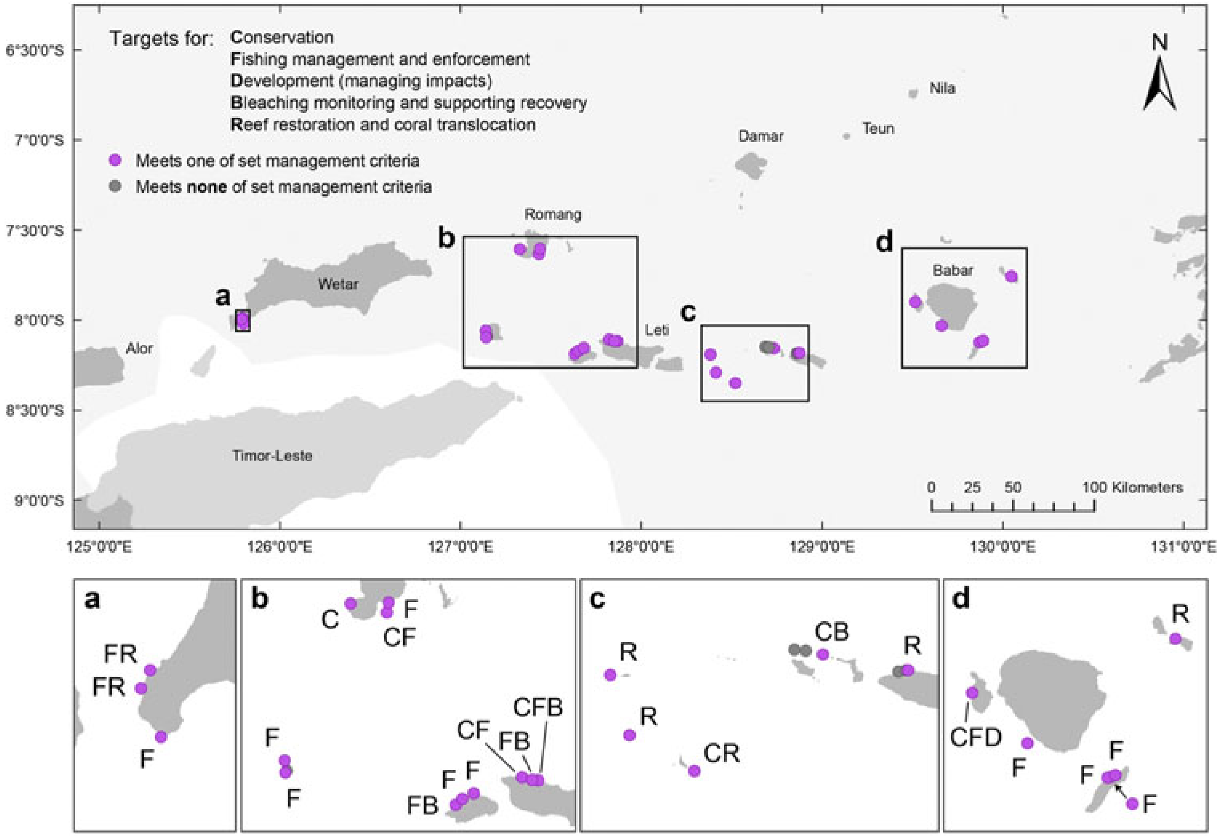

FIGURE 7 Management actions for n = 30 sites in South-west Maluku, Indonesia, based on types of threats and sources of resilience (Figures 2 and 3, Table 2). Purple sites are priorities for at least one management action; grey sites are not priority locations for any management action. Abbreviations and descriptions for each management action in Table 1. Insets (a-d) show finder spatial scales

approach is that we do not address issues of complementarity or connectivity: areas are prioritized based on their intrinsic characteristics, not in the more realistic context of a network where individual locations might benefit each other (Pressey, Humphries, Margules, Vane-Wright, & Williams, 1993). Next steps in developing this approach include incorporating connectivity into this study's definition of priority management areas (Maynard et al., 2015).

While the global scope of these data begs for a global examination of management strategies, such an application would likely reveal heterogeneity in the distribution of reef vulnerability to both climate change and local human activities and resulting inequity in the international distribution of conservation priorities (Pendleton et al., 2016; van Hooidonk et al., 2016). Therefore, we urge careful consideration of the consequences of applying this framework at a global scale. Even though 'conservation triage' is increasingly promoted as a strategy for prioritizing limited resources to address increasing pressures on natural systems (Bottrill et al., 2008; Wilson & Law, 2016), global scale triage (Wilson et al., 2006) based solely on ecological features such as biodiversity (Roberts et al., 2002) and endemism (Hughes et al., 2002) has the pitfall of overlooking regions with social, economic, or cultural value. Given the importance of reefs for food security, it is neither practical nor ethical to 'write off' large regions of the world's reefs. To account for this possibility, goals beyond ecosystem health and biodiversity can be incorporated into prioritizations, such as the social impacts of climate change (Cinner et al., 2016) and ecosystem functions that directly support human communities.

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DISCLOSURE/CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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