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Comprehensive Assessment of Risk to Ecosystems (CARE): A cumulative ecosystem risk assessment tool

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A B S T R A C T

Unassessed marine ecosystems are often unmanaged marine ecosystems. Several risk assessment methods exist that can provide a scientific basis for siting interventions and guiding management actions, but these methods focus mainly on single species and evaluate only the impacts of fishing in detail. We present a new ecosystem risk assessment model, the Comprehensive Assessment of Risk to Ecosystems (CARE), which allows analysts to consider the cumulative impact of multiple threats, interactions among threats that may result in synergistic or antagonistic impacts, and the impacts of a suite of threats on whole-ecosystem productivity and functioning, as well as on ecosystem services. CARE can be completed very rapidly, and uses local and expert knowledge where data are lacking. It can be applied to virtually any system, and can be modified as knowledge is gained or to better match different site characteristics. Two case studies are provided to illustrate how CARE can be applied. These CARE analyses suggest that in Karimunjawa, Indonesia activities other than fishing should be addressed to ensure that a fisheries intervention will achieve desired outcomes. Conversely in Cantilan, Philippines a well-designed and implemented fishery intervention could address all of the most important system threats.

1. Introduction

1.1. Ecosystem risk assessment—existing tools, uses, and challenges

Failure to assess the impacts of human activities on ocean ecosystems can impair the capacity of these systems to produce the goods and services people value. Understanding risks is also important for siting management interventions when capacity and resources are limited: for example, improving fisheries management will not result in higher yields or better fishing revenues if other impacts are limiting the production of fish biomass. Without an accurate assessment of the full suite of risks facing a system, managers may spend valuable time and resources attempting to control the wrong drivers of system change. For instance, after four decades of concerted efforts to protect and restore the Great Barrier Reef, recent research suggests that a failure to accurately assess and prioritize the different factors impacting this system has been a main reason for its continued decline (Kearney and Farebrother, 2014). Furthermore, recent research suggests that the potential impact of various risks on the achievement of project objectives has not been given sufficient attention by most conservation organizations (Game et al., 2013).

A variety of methods have been developed to assess the status of fisheries and the ecosystems on which they depend, and to model the predicted impacts of various stressors that affect those systems. Recently, methods to assess risks to marine ecosystems, even when data are limited, have been developed (Hobday et al., 2011; Miriam et al., 2015; Patrick et al., 2009; Samhouri and Levin, 2012; Sharp et al., 2014). Data-limited fisheries are those that lack sufficient scientific data to conduct the complex assessments traditionally used to inform fisheries management decisions (Honey et al., 2010). Data-limited fisheries present a variety of challenges for sustainable management, and it is often necessary to use novel or specialized methods to assess stock and ecosystem health and functioning before implementing management changes (Fujita et al., 2013).

Ecological Risk Assessment (ERA) is a process that involves scoring the impacts of various stressors on a set of system characteristics. For example, the Ecological Risk Assessment for the Effects of Fishing (ERAEF) developed by Australia's Commonwealth Scientific and Industrial Research Organisation in 2007 is a seminal example that uses a hierarchical process to estimate the risk to a species, habitat, or community from fishing activities (Hobday et al.,

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2011, 2007). ERAEF starts with a largely qualitative scoping exercise conducted to collect information on known attributes of the species, habitat or communities, followed by a qualitative assessment of the scale and intensity of threats along with the likely consequences for the species or system, and a semi-quantitative Productivity Susceptibility Analysis that uses scores on attributes associated with productivity and susceptibility to fishing to estimate overall vulnerability of the species, habitat, or community to a given fishery. Finally, a fully quantitative system model is recommended when sufficient data become available (Hobday et al., 2011). Other authors and organizations have since built on this method, and modified it for application to a variety of settings. For example, the National Oceanic and Atmospheric Administration (NOAA) developed a PSA tool to estimate stock vulnerability (NOAA Fisheries Toolbox: Productivity and Susceptibility Analysis (PSA), 2010; Patrick et al., 2009). The Natural Capital Project has developed a Habitat Risk Assessment model as part of their InVEST suite of modeling tools (Sharp et al., 2014). Samhouri and Levin (2012) developed an assessment of ecosystem risk from land- and sea- based impacts, which mirrors the PSA process, but compares the exposure of a population to any activity, and the sensitivity of the population to that activity, given a particular level of exposure.

More recently, the Department of Fisheries and Oceans of Canada commissioned the development of an ERA tool (called the Ecological Risk Assessment Framework or ERAF) to analyze risks facing their system of Marine Protected Areas (MPAs) (Department of Fisheries and Oceans, 2012; Miriam et al., 2015). This model follows the ERAEF framework and builds on other existing tools, examining the risk to a system from multiple threats, related to both fishing and non-fishing activities. However, rather than using the standard PSA approach, which calculates risk in terms of Euclidean distances from the origin of a graph for which species productivity and susceptibility represent the X and Y axes (Hobday et al., 2011; Patrick et al., 2009), the ERAF calculates risk as the product of the exposure to a threat, and the likely response to that exposure (Miriam et al., 2015). Because of this change, the resulting risk scores more accurately represent the potential impact of a given threat on a system, making them more appropriate for comparison with risk scores from other threats, or at other sites (Miriam et al., 2015).

These ERA tools represent remarkable progress in ecosystem risk assessment. However they all have certain limitations that will be important to overcome to fully characterize risk and thus provide good guidance for risk management. Specifically:

- most of these tools model only the impacts of fishing without quantitatively considering other threats that may face a marine system;
- none of these tools assess the synergistic or antagonistic effects that different threats acting on a system may have on each other;
- ecosystem productivity and functioning are substantially simplified to just a handful of representative factors, such as key population abundance or spatial habitat extent, and do not incorporate new findings on attributes of ecosystems associated with recovery or resilience;
- there are currently no tools designed to evaluate risk in relation to differential ecosystem service provision in data-limited systems, which will be especially important when considering siting of spatial management measures such as exclusive fishing territories and marine protected areas;
- all existing ecosystem risk assessment tools require significant time (several days) and capacity (expert knowledge and access to primary literature) to complete, limiting their feasibility where capacity is low.

1.2. Comprehensive Assessment of Risk to Ecosystems (CARE)

We developed the Comprehensive Assessment of Risk to Ecosystems (CARE) method to address these issues. This tool can be used to rapidly rank the threats facing a system or a species to aid in the selection of sites for fishery reform interventions and guide threat reduction strategies in data-limited systems. The CARE model draws from other ERA methods, and from recent research on cumulative impact assessment, ecosystem resilience, and ecosystem service assessment (Barbier et al., 2011; Halpern et al., 2008; Keith et al., 2013; Link, 2005) to add value to the existing ecosystem risk assessment tools in a number of important ways. First, CARE can be used to assess risk from any number of threats to a given ecosystem. Second, CARE allows the analyst to assess the *interactions* (synergistic or antagonistic) of multiple threats with each other. Third, CARE assesses risk to the entire ecosystem through use of a more comprehensive suite of attributes that characterize system health and functioning as described by intrinsic system recovery potential (e.g., "regeneration time" and "connectivity") and resistance to impact (e.g., "removability of system components" and "functional redundancy and diversity"). Fourth, CARE includes a module designed to quantify risk to the production of ecosystem services in both data-rich and data-limited settings. Finally, CARE can be implemented in the field, relying largely on local and expert knowledge when data are limited, and completion of a CARE analysis by system experts can take as little as 1–2 h. CARE generates risk values for each threat as it impacts each "target" (valued components of the system selected for analysis), ecosystem service production, and the ecosystem as a whole.

CARE can be used to evaluate risks facing a single site, to compare multiple sites for the suitability or necessity of different management options, or to evaluate the effects of a proposed management action aimed at reducing one or more risks. This method can help users identify which threats are the most important at a given site and for a given target, and therefore where limited management resources should be targeted. It can also help to identify where different management approaches might be most appropriate. For example, if a site is particularly at risk from fishing, but proves to be more resilient to the impacts of non-fishing threats such as coastal development or nearby aquaculture, a well designed and implemented fishery improvement project would be expected to result in significant improvements in fishery outcomes. Alternatively, if a site is at risk from a larger variety of non-fishing threats, policies aimed at reducing the most important threats might be a more appropriate approach. Furthermore, because CARE also results in scores for various ecosystem services at a site, it can be helpful for planning uses that are consistent with optimizing the value of ecosystem services. CARE can be applied to any spatially-explicit system, and can be adapted to better fit individual system characteristics.

We have applied CARE to sites in a variety of countries around the world to inform management strategy decisions. Here we briefly present our methods in designing CARE, along with example applications and results from two case study sites: Cantilan, the Philippines and Karimunjawa, Indonesia. Supplementary Appendix B provides greater detail on the design of the CARE model.

2. Methods

CARE, consistent with other ERA methods, guides users through evaluation of the potential impact of all natural and anthropogenic "threat" activities present in a system on a selection of "targets" (ecosystems and/or species) that are valued by the user. To maximize its usefulness in the field, and minimize time requirements for analysis, the complete CARE analysis of a given target is completed

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in a single-phase, on a single Excel worksheet, rather than through a hierarchical process (as with the ERAEF or ERAF). We recommend conducting this analysis using a group of experts (including individuals familiar with the sites being evaluated) to draw on different levels of experience and different kinds of expertise.

Risk scores in other tools are calculated as Euclidean distances from the origin of a graph where productivity and susceptibility scores constitute the X and Y axes, respectively (e.g., Hobday et al., 2011; Patrick et al., 2009; Sharp et al., 2014). Risk in CARE is calculated as the product of an Exposure score (the extent to which the target is exposed to a threat, and the potential effect of that exposure, based on considerations such as spatial scale, frequency, and intensity of the threat, given the "worst case scenario") and a Response score (the likely response of the target to the impact, based on factors thought to contribute to system vulnerability and to recovery time, such as species diversity and functional redundancy), following the methods of Miriam et al. (2015). One of the most important outcomes of the CARE analysis is the rank order of threats facing the system under analysis. The multiplicative approach is therefore more appropriate than the Euclidean distance approach for our purposes because it results in similar risk scores for threats with different intensity and impact characteristics, but that would result in the same potential consequences. The Euclidean distance approach would estimate different levels of risk from such threats. To adapt the example given in Miriam et al. (2015), using the multiplicative calculation, a threat that has the potential to impact 40% of a system (Exposure), and is likely to reduce system functioning by 50% (given system resistance and recovery abilities) in all areas encountered (Response), would receive a risk score of 20%. A second threat that impacts only 20% of a system (Exposure), but that is likely to reduce system functioning by 100% (i.e., complete destruction) in all areas impacted, would also receive a risk score of 20% through the multiplicative model. The Euclidean distance calculation, on the other hand, would generate risk scores of ~100% and 64% for these two threats, respectively.

CARE also includes a way to score the interactions of multiple system threats, to estimate the degree of synergy between them and thus characterize the cumulative impact of threats more accurately. Exposure, Response, and Risk scores – adjusted for uncertainty and synergies between threats – are computed in a single spreadsheet for each target evaluated, and aggregated in a separate tab if multiple targets are assessed (See Supplementary Appendix A). CARE can be applied to any system, and can be adapted or amended as knowledge is gained or to better match different site characteristics.

2.1. Scoping

The first step when applying CARE is to select a site, and identify a target or targets within that site that users value. Targets can include any valued species, including fisheries targets, keystone species, engineer species, charismatic species, or any other species users wish to assess, and all ecosystem types, identified by the dominant habitat type (e.g., coral reef, seagrass, mangrove), within the site. A CARE worksheet must be completed for each target identified in the Scoping phase, and thus the goal should be to identify the smallest number of targets that can be considered representative of the system under analysis, as determined by expert opinion. At a minimum, the predominant ecosystem, or the most vulnerable ecosystem within the focal site should be selected as a target for evaluation.

Threats can include any natural or anthropogenic processes or activity that system experts suspect might pose a risk to any of the valued targets (e.g., fishing, coastal development, typhoons). Supplementary Appendix B provides guidance on how to identify threats and targets. Each threat is evaluated in a separate field on a single spreadsheet for each target under evaluation (Supplementary Appendix A).

The CARE Scoping process relies on users to judge which threat activities will actually impact their focal target(s), and include only these in the risk analysis. CARE is intended to be completed by experienced site managers or other individuals who are familiar with the history and present state of the site, such that they have a sufficient understanding of the existing system threats. It is also recommended that users consult with other local experts and system stakeholders to develop a comprehensive list of threats.

2.2. Base risk scores

We have developed guidelines based on the ERAEF (Hobday et al., 2011) and the ERAF (Miriam et al., 2015) to qualitatively calculate the potential threat impact severity (or "Risk") for each target, where an "Exposure" score is combined with a "Consequence" score. However, we have replaced the "Consequence" section with a "Response" section, comprised of attributes that characterize a target's intrinsic ability to resist and recovery from impact, rather than the consequence of a specific threat. Furthermore, we have modified the scoring process with reference to Halpern et al. (2007) to make it more explicit and transparent, and more appropriate for comparing and combining a variety of threats in addition to fishing. The Halpern et al. (2007) method for calculating the cumulative impact of multiple stressors involves qualitative analysis of each threat-target pair over a suite of five "vulnerability criteria": (1) the spatial scale at which the threat acts within the site (including both direct and indirect impacts), (2) the frequency with which it acts, (3) the intensity (based on number of trophic levels impacted), (4) the resistance of the target to impact, and (5) the recovery time needed to transition to a desired state after impact. CARE adapts this method by combining the first three of these vulnerability criteria (scale, frequency, and intensity) into an Exposure score, and the latter two (resistance and recovery) into a Response score. These two values are multiplied to result in a Base Threat Risk Score for a given target (c) from a given threat (t).

$$BaseRisk_{ct} = BaseResponse_c \times BaseExposure_t \quad (1)$$

2.2.1. Response

CARE combines a Recovery score and a Resistance score – two of the five vulnerability criteria, as adapted from Halpern et al. (2007) to generate a Base Response score, which represents the target ecosystem's or species' intrinsic productivity and vulnerability. This calculation is done once for each target being assessed. Recovery attributes measure the intrinsic productivity of the given target as it presents in the site under evaluation. Resistance attributes describe the target's intrinsic vulnerability and capacity to resist or avoid harm. Users assign each attribute a score using a 1–3 (low to high risk) scale, and following guidance provided in the model (Supplementary Appendix A). These attributes capture the inherent vulnerability/resilience of the target to any given threat, and are scored based on life history parameters such as growth rate, natural mortality, and behavioral patterns for the species, and on biophysical characteristics such as contiguity, the frequency of natural disturbance, and community diversity and complexity for the ecosystems (see Tables 1 and 2 for full list of Response attributes for target ecosystems and species, respectively, and their associated scoring metrics). These attributes can be modified as knowledge is gained to better represent the factors that control species or system productivity and vulnerability. In addition, attributes can be added or subtracted to better match the assessment to the specific characteristics of any given site.

Table 1
CARE model ecosystem Response attributes—Users use the qualitative guidance provided to assign scores, ranging between 1 and 3, for the intrinsic recovery and resistance potential of each target ecosystem. If attributes are deemed unnecessary for a given system they may be assigned an NA score.

Recovery Attributes	Low (1)	Moderate (2)	High (3)
Frequency of Natural Disturbance	Daily to weekly	Several times per year	Annually or less often
Regeneration time (informed by natural mortality and recruitment rates of substratum, reefs, etc.)	Less than 1 yr	1–10 yrs	More than 10 yrs
Connectivity (of biogenic habitat)	many high quality adjacent patches of similar habitat are within the dispersal range of the biogenic organisms	few or low quality adjacent patches of similar habitat are within the dispersal range of the biogenic organisms	no adjacent patches of similar habitat are within the dispersal range of the biogenic organisms
Habitat Type Contiguity	All endemic habitat types/areas are represented (relative to reference or historical site); no habitat types have been removed or highly degraded.	Some endemic habitat types/areas degraded or missing (relative to reference or historical site)	Many endemic habitat types/areas degraded or missing (relative to reference or historical site)
Biological productivity	High biological productivity (based on light, nutrients, etc.)	Medium biological productivity (based on light, nutrients, etc.)	Low biological productivity (based on light, nutrients, etc.)
Substrate integrity	In tact	somewhat broken up	highly broken up
Water Residence Time	Low	Medium	High
Species Richness	>300	50–300	<50
Abundance of ecosystem engineer species	High relative to healthy/reference site, or historical baseline	Medium relative to healthy/reference site, or historical baseline	Low relative to healthy/reference site, or historical baseline
Abundance of predators	High relative to healthy/reference site, or historical baseline	Medium relative to healthy/reference site, or historical baseline	Low relative to healthy/reference site, or historical baseline
Abundance of grazers	High relative to healthy/reference site, or historical baseline	Medium relative to healthy/reference site, or historical baseline	Low relative to healthy/reference site, or historical baseline
Recovery Score			
Resistance Attributes	**Low (1)**	**Moderate (2)**	**High (3)**
Geographic concentration of the habitat substrate	biogenic habitat is distributed in >50% of site	biogenic habitat is distributed in 25% to 50% of site	biogenic habitat is distributed in <25% of site
Relief	High relief (>1.0 m), rugged surface structure (cracks, crevices, overhangs, large boulders, rock walls); >10° slope	Low relief (<1.0 m), rough surface structure (rubble, small boulders, rock edges); 1–10° slope	No relief, smooth simple surface structure (mounds, undulations, ripples); <1° slope
Removability of substratum (Threat specific)	Immovable (bedrock and boulders >3 m)	<6 cm (transferable)	6 cm–3 m (removable)
Removability/mortality of fauna/flora	Low, robust or small (<5 cm), smooth or flexible, OR robust or deep burrowing	Erect or medium sized (but <30 cm), moderately rugose or inflexible, OR moderately robust or shallow burrowing	Tall, delicate or large (>30 cm high), rugose or inflexible, OR delicate or shallow burrowing
Habitat-forming species resilience	High	Medium	Low
Proximity to invasive species sources	Known invasive species sources (e.g., boats, aquaculture) not present in immediate site vicinity	Known invasive species sources present in immediate site vicinity, but relatively far away	Known invasive species sources present in immediate site vicinity, and relatively near
Current status of system or proxy (listing status, fishable biomass, etc.)	Healthy; Low concern; >0.50 unfished biomass (for coral reefs)	Threatened or of concern; 0.30-0.50 unfished biomass (for coral reefs)	Not Healthy; Endangered; <0.30 unfished biomass (for coral reefs)
Nutrients	Not modified relative to healthy/reference site or historical baseline	Somewhat modified relative to healthy/reference site or historical baseline	Highly modified relative to healthy/reference site or historical baseline
Salinity	Not modified relative to healthy/reference site or historical baseline	Somewhat modified relative to healthy/reference site or historical baseline	Highly modified relative to healthy/reference site or historical baseline
Sedimentation	Not modified relative to healthy/reference site or historical baseline	Somewhat modified relative to healthy/reference site or historical baseline	Highly modified relative to healthy/reference site or historical baseline
pH (acidity)	Not modified relative to healthy/reference site or historical baseline	Somewhat modified relative to healthy/reference site or historical baseline	Highly modified relative to healthy/reference site or historical baseline
Herbivory	Not modified relative to healthy/reference site or historical baseline	Somewhat modified relative to healthy/reference site or historical baseline	Highly modified relative to healthy/reference site or historical baseline
Water Residence Time	Not modified relative to healthy/reference site or historical baseline	Somewhat modified relative to healthy/reference site or historical baseline	Highly modified relative to healthy/reference site or historical baseline
Functional diversity	Many different kinds of functional types (e.g., resource use types, disturbance response types) relative to historical baseline, or healthy reference site	Medium amount of different kinds of functional types (e.g., resource use types, disturbance response types) relative to historical baseline, or healthy reference site	Few different kinds of functional types (e.g., resource use types, disturbance response types) relative to historical baseline, or healthy reference site

Table 1 (*Continued*)

Recovery Score Resistance Attributes	Low (1)	Moderate (2)	High (3)
Functional redundancy	Many species carry out similar functional roles within functional groups	Medium number of species carry out similar functional roles	Low number of species carry out similar functional roles
Functional Complementarity	High functional complementarity between species (e.g., in resource use, body size, stature, trophic status, phenology) relative to healthy/reference site, or historical baseline	Medium functional complementarity between species (e.g., in resource use, body size, stature, trophic status, phenology) relative to healthy/reference site, or historical baseline	Low functional complementarity between species (e.g., in resource use, body size, stature, trophic status, phenology) relative to healthy/reference site, or historical baseline
Structural complexity	High complexity of substrate architecture relative to healthy/reference site, or historical baseline	Medium complexity of substrate architecture relative to healthy/reference site, or historical baseline	Low complexity of substrate architecture relative to healthy/reference site, or historical baseline
Foodweb structure	many steps in the food web with "pyramid" shape- highly abundant primary producers but with levels that reach all the way to top predators	medium length food web with few top predators; somewhat simplified	simplified foodweb with few steps, no top predators; system composed mostly of small things with fast growth rates
Species Diversity (flora and fauna)	Not modified relative to healthy/reference site or historical baseline	Somewhat modified relative to healthy/reference site or historical baseline	Highly modified relative to healthy/reference site or historical baseline
Resistance Score			
Ecosystem Response Score:			

2.2.2. Exposure

CARE incorporates the three remaining "vulnerability criteria", adapted from Halpern et al. (2007) to calculate an Exposure score for each threat as it impacts the target under analysis. These are: (1) the spatial scale at which the threat acts within the site, (2) the frequency with which it acts, (3) and the intensity, or number of trophic levels impacted. Users score each of these criteria on a 0–4 (no impact to extreme impact) scale, considering the threat's direct impact on the target under analysis. These scores, and the accompanying guidance, were designed based on the ERAF model so that a score of 0 represents no impact or interaction between the threat and target whatsoever, while a score of 4 represents the most extreme case possible of the given vulnerability criteria (i.e., impacting the entire site, impacting the entire community, continually occurring, etc.). While the Response section of CARE uses a three category scoring system, this five category system allows for more precision when scoring each attribute. This is important because each threat's Exposure score is based on just three attributes, rather than on the combination of many attribute scores, as in the Response section (18 and 30 attributes are combined for the Species and Ecosystem Response scores, respectively). Users may have to "round" some answers up or down when scores are based on just three categories. For example, if they believe biological productivity in their system is "medium-high" they will have to choose either "medium" or "high" when assigning a score. This imprecision is more likely to even out when a large number of attribute scores are averaged to create the overall Response score (Supplementary Appendix C, Section C.1). However, for the Exposure scores to be reasonably accurate, each of the three attribute scores of which they are comprised must be as precise as possible (Table 3). CARE then combines these three scores to generate the Base Exposure score.

2.2.3. Conversion to indices

The Base Exposure and Base Response scores they are converted to indices (the product of the scores is divided by the maximum possible value (9 for Response and 64 for Exposure), and then multiplied by 10 to allow for a wider range of possible Risk scores) to make them comparable (e.g. Table B.4).

$$BaseResponse_c = \left(\frac{AvgRecovery_c \times AvgResistance_c}{9}\right) \times 10 \tag{2}$$

$$BaseExposure_t = \left(\frac{Scale_t \times Frequency_t \times Intensity_t}{64}\right) \times 10 \tag{3}$$

2.2.4. Additional threat modifications

Next, the effects of other threats present in the system on the "focal threat" (the threat for which a Base Risk Score has just been calculated) are assessed. Here our method differs from the ERAEF, the ERAF, and all other similar existing risk assessments. Other ERAs include methods to calculate cumulative threat impact scores after individual scores have been determined (Hobday et al., 2011; Miriam et al., 2015; Patrick et al., 2009). However, because many threats do in fact interact (Crain et al., 2008) CARE allows users to evaluate the potential synergistic or antagonistic effects of the other present threats in the system and use them to modify individual threat impact scores before they are combined into a cumulative score. Expert judgment is used because data are generally lacking on the effects of threats on each other. For example, if a system is affected by both nutrification (large increases in nutrient loading) and intensive fishing of grazing fish, the analyst may conclude that nutrification exacerbates the effects of fishing on the system, because it provides fleshy macroalgae with a competitive advantage over other types of algae in nutrient-limited systems such as coral reefs. Similarly, the analyst may conclude that the removal of large numbers of grazing fish likely exacerbates the impact of nutrification, because it removes an important check on the growth of fleshy macroalgae. Threats can also *reduce* the impacts of other threats on a target; for example, seaweed aquaculture might reduce the effects of fishing on a target species or on a coral reef by reducing nearshore area available for fishing, if there is little potential for the intensification of fishing effort in remaining areas.

To quantify these potential synergistic or antagonistic interaction effects, CARE includes guidance for scoring an "Additional Threat Modification (ATM) Factor" for each of the five vulnerability criteria in each threat-target pair analysis. The ATM Factor is a value falling between −1 and 1, by increments of 0.25. This value is a numerical representation of the degree to which the impact of the focal threat, and the target's response to that impact, may be changed by other threats in the system (see Table 4 for scoring metric). This modification value must be considered separately for each of the five vulnerability criteria, as the interaction effects on each may not be to the same degree, or in the same direction. For example, seaweed aquaculture might slightly reduce the Scale of

Table 2
CARE model species Response attributes—Users use the qualitative guidance provided to assign scores, ranging between 1 and 3, for the intrinsic recovery and resistance potential of each target species. If attributes are deemed unnecessary for a given system they may be assigned an NA score.

Recovery Attributes	Low (1)	Moderate (2)	High (3)
r (population growth)	>0.5	0.5–0.16 (mid-point 0.10)	<0.16
Max size	<60 cm	60–150 cm (mid-point 105)	>150 cm
von Bertalanffy growth coefficient (k)	>0.25	0.15-0.25 (mid-point 0.20)	<0.15
Estimated natural mortality (M)	>0.40	0.20-0.40 (mid-point 0.30)	<0.20
Measured fecundity, or Life history strategy	Fish: >10e4 (10,000) offspring produced by one female in one year; Non-Fish: High relative to similar species	Fish: 10e3–10e4 (1000–10,000) offspring produced by one female in one year; Non-Fish: Medium relative to similar species	Fish: <10e3 (1000) offspring produced by one female in one year; Non-Fish: Low relative to similar species
Breeding/Reproductive strategy	Internal fertilization and parental care	Internal fertilization or parental care but not both	External fertilization and no parental care
Recruitment Pattern	highly frequent recruitment success (>75% of year classes are successful)	moderately frequent recruitment success (between 10% and 75% of year classes are successful)	infrequent recruitment success (<10% of year classes are successful)
Average age at maturity	<2 yrs	2–4 yrs (mid-point 3.0)	>4 yrs
Mean trophic level	<2.5	2.5–3.5 (mid-point 3)	>3.5
Connectivity (population dispersal/mobility and presence of essential habitat)	many high quality adjacent patches of similar habitat are within the dispersal/mobility range of the species	few or medium quality adjacent patches of similar habitat are within the dispersal/mobility range of the species	zero or only poor quality adjacent patches of similar habitat are within the dispersal/mobility range of the species
Frequency of natural disturbance	Daily to weekly	Several times per year	Annually or less often
Recovery Score			
Resistance Attributes	**Low (1)**	**Moderate (2)**	**High (3)**
Geographic concentration	species is distributed in >50% of its total range	species is distributed in 25% to 50% of its total range	species is distributed in <25% of its total range
Biomass of spawners (SSB) or other proxies (e.g., Listing Status)	B is >40% of B0 (or max observed from time series of biomass estimates); Low concern	B is between 25% and 40% of B0 (or max observed from times series); Threatened or of concern	B is <25% of B0 (or max observed); Endangered
Schooling/Aggregation	Behavioral/physiological response reduces impact	Behavioral/physiological response does not change impact	Behavioral/physiological response increases impact
Morphology affecting mortality from Threats	species morphology results in low susceptibility to mortality from Threats	species morphology results in moderate susceptibility to mortality from Threats	species morphology results in high susceptibility to mortality from Threats
habitat specificity	Low habitat specificity (species are generalist and can thrive in many different habitats)	Moderate habitat specificity (species can thrive in a few habitats)	High habitat specificity (highly specialized species that thrive in only one type of habitat are impacted)
diet specificity	Low diet specificity	Moderate diet specificity	High diet specificity
Proximity to invasive species sources	Known invasive species sources not present in immediate site vicinity	Known invasive species sources present in immediate site vicinity, but relatively far away	Known invasive species sources present in immediate site vicinity, and relatively near
Resistance Score			
Species Response Score:			

Table 3
CARE model Exposure scoring guide—Users use the qualitative guidance provided to assign scores, ranging between 0 and 4, for the scale, frequency, and intensity of each threat as it impacts each target.

Scoring	0	1	2	3	4
Scale	No threat	Single restricted location in site or species range within site	Few restricted locations in site or species range within site	Affecting large percent of site or species range within site, but not whole site/range	Widespread, throughout site or species range within site
Frequency	Never occurs	Rare	Occasional, reasonably often	Frequent, regular	Persistent, continual
Intensity	No impact OR beneficial effect	For ecosystems: affects one or more species only (no cascading effects); For species: low intensity/severity	For ecosystems: affects multiple species within one trophic level; For species: moderate intensity/severity	For ecosystems: affects multiple species in multiple trophic levels; For species: high intensity/severity	For ecosystems: affects entire community, cascading effects; For species: very high intensity/severity

fishing, as discussed above, but it may simultaneously increase the Recovery Time for a given system because removal of the seaweed may reduce breeding or nursery habitat for fish. Users select ATM

Table 4
CARE additional threat modification scoring guide—Users use guidance provided to assign Additional Threat Modification values, ranging between −1 and 1, to quantify the impact of additional system threats on the focal threat's scale, frequency, and intensity with relation to the target, and the target's resistance and recovery time with relation to the focal threat.

Additional Threat Modification Score	For given Vulnerability Criteria:	Overall Effect
−1	Additional Threat causes an Extreme reduction in Focal Threat score	reduction
−0.75	Additional Threat causes a Large reduction in Focal Threat score	reduction
−0.5	Additional Threat causes a Moderate reduction in Focal Threat score	reduction
−0.25	Additional Threat causes a Slight reduction in Focal Threat score	reduction
0	Additional Threat has no impact on Focal Threat score	none
0.25	Additional Threat causes a Slight increase in Focal Threat score	increase
0.5	Additional Threat causes a Moderate increase in Focal Threat score	increase
0.75	Additional Threat causes a Large increase in Focal Threat score	increase
1	Additional Threat causes an Extreme increase in Focal Threat score	increase

values based on expert knowledge and reference to peer-reviewed literature, where available.

Users assign an ATM Factor for each additional threat in the system to each of the three attributes that combine to generate the focal threat's Base Exposure score (Scale, Frequency, and Intensity), and then to each of the two Base Response vulnerability criteria (Recovery and Resistance), as calculated in the Response section. These values are then combined with the Base scores for each vulnerability criteria to generate Adjusted Exposure and Response scores. The adjusted vulnerability criteria calculations are bounded in CARE because the base scoring metrics for each of the vulnerability criteria were designed so that the lowest scores (i.e., a score of 1 for Response criteria or 0 for Exposure criteria) represent the complete absence of impact (e.g., "habitat has not been modified relative to historic baseline;" "threat does not occur within site"), and the highest scores (i.e., a score of 3 for Response criteria or 4 for Exposure criteria) represent the maximum degree of impact possible (e.g., "habitat has been highly modified relative to historic baseline;" "threat impacts *entire* site"). Consequently, these scores cannot go above or below the values regardless of the magnitude or number of modifications by other system threats. These adjusted scores are normalized through the same process applied to the base scores, and then combined to generate an adjusted risk score that captures the synergistic or antagonistic effects that all system threats have on each other.

$$AdjustedRisk_{ct} = AdjExposure_{ct} \times AdjResponse_{ct} \quad (4)$$

$$AdjExposure_t = \left(\frac{(Scale_t + sum(ScaleATMs_{ct})) \times (Frequency_t + sum(FrequencyATMs_{ct})) \times (Intensity_t + sum(IntensityATMs_{ct}))}{64} \right) \times 10 \quad (5)$$

$$AdjResponse_c = \left(\frac{(AvgRecovery_c + sum(RecoveryATMs_{ct})) \times (AvgResistance_c + sum(ResistanceATMs_{ct}))}{9} \right) \times 10 \quad (6)$$

This process is repeated with each threat in the system treated as the focal threat, such that all possible combinations of threats are accounted for, and an adjusted risk score is calculated for each system threat as it impacts the target under analysis (see Tables B.6 and B.7 for example application of the additional threat modification process). An examination of the value of including ATMs in a CARE analysis given the additional time they add to the process is presented in Supplementary Appendix C, Section C.2). As the impacts and interactions of a given set of threats may be significantly different from one system to another (for example, moderate increases in nutrients may actually increase system productivity in some cases, potentially increasing system recovery potential), CARE relies on the knowledge of local experts who understand the specific processes of the system under evaluation to quantify the impacts of these threat interactions. However, it should be noted that each ATM factor scored creates the potential for adding uncertainty. CARE incorporates user uncertainty into the calculations by increasing risk scores when uncertainty is higher (see Section 2.2.4), which is consistent with the precautionary principle. This process, however, necessarily increases the chance of scoring a threat as "high risk" for a system when it is in fact not an important threat (i.e., a "false positive" risk score). Users can decrease this possibility by applying ATM Factors only when they are reasonably confident about the existence of that interaction effect.

2.2.5. Uncertainty

CARE accounts for uncertainty through a method adapted from the approaches presented in the ERAEF, the InVEST HRA, and the ERAF (Hobday et al., 2011; Miriam et al., 2015; Sharp et al., 2014). Uncertainty is recorded qualitatively (i.e., "low", "moderate", "very high", etc.) for each of the base scores given for each attribute in the Response section, for each vulnerability criteria in the Exposure section, and for the ATM factors (combined for each vulnerability criteria). These qualitative scores are converted into numerical values, which are then combined into a single uncertainty factor between 0 and 1 (see Table 5 for the uncertainty scoring metric). This uncertainty factor is multiplied by the adjusted risk score, and then this value is added to the adjusted risk score to determine a final adjusted risk score that has been proportionally increased relative to the amount of uncertainty present. Uncertainty factors are reported in the results tables generated by CARE (Supplementary Appendix A and Tables 6–9) so that users can understand what percentage of the final risk score results from the inclusion of uncertainty in the calculations. For example, an uncertainty factor of 0.75 in the results table indicates that the final individual risk score has been increased by 75% from the adjusted risk score (which is the base risk score, adjusted for inclusion of the ATMs, as described above). Cumulative risk scores also report both the pre-and post-uncertainty scores (which are simple sums of their respective individual risk scores). This method of including the uncertainty directly in the calculations, so that increased uncertainty increases the risk score, facilitates precautionary approaches to risk assessment (Hobday et al., 2011). The maximum possible increase due to uncertainty is a doubling of the risk score (i.e., a 100% increase). See Table B.9 for an example application.

Although this method of eliciting qualitative uncertainty values from the experts who are themselves providing the information under evaluation has been called into question, and a more objective method of calculating uncertainty has been developed by Teck et al. (2010), we feel that the above approach is more appropriate for the type of analysis for which CARE was designed. it is necessary for all of the calculations to be self-contained, rather than require further analysis by an objective party (as in the Teck et al. method) because CARE was designed to be a simple to use, rapid tool which

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Table 5
CARE Uncertainty Scoring Metric—Users use guidance provided to assign qualitative uncertainty categories to each scale, frequency, intensity, resistance, and recovery score assigned to a given threat-target pair, as well as to additional threat modification values. CARE then translates these qualitative categories into numerical values. .

Uncertainty	Auto-generated Score
Very Low: established, substantial empirical data exists for the target area; consensus between experts with extensive personal experience.	0
Low: empirical data exists, but may have limited coverage or corroboration, or be deemed somewhat less reliable for another reason; experts have direct personal experience, but may disagree on some points.	0.025
Moderate: some empirical data exists for target site, but may be based on similar taxa, life history stage, or location; estimates with high variation and limited confidence; experts have some personal experience, but disagree on some key points.	0.05
High: very little empirical data exists for target site; values based on general literature review from wide range of species or regions; experts have limited personal experience and/or strongly disagree on key points.	0.075
Very High: no empirical data exists; no confidence in estimates or suitable substitute values; no expert consensus.	0.1

Table 6
Individual Risk Scores for each system threat as it impacts each valued target (ecosystems and species) resulting from CARE analysis of Cantilan, The Philippines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Threat-Target Pair	Target Response Score	Threat Exposure Score	Base Risk Score	Adjusted Risk Score	Uncertainty Factor (max =1)	Final Individual Risk Score
Fishing-Reef	4.92	5.63	27.66	69.85	0.75	122.23
Fishing-Seagrass	5.18	2.81	14.58	44.43	0.75	77.76
Fishing-Beaches	4.17	0.00	0.00	0.00	0.75	0.00
Fishing-Streamlined spinefoot	3.43	5.63	19.32	43.71	0.70	74.11
Fishing-Yellowtail fusilier	4.38	5.63	24.62	52.53	0.70	89.06
Fishing-Daisy parrotfish	3.64	5.63	20.45	45.44	0.70	77.05
Fishing-Octopus cyanea	3.50	4.22	14.77	24.12	0.72	41.55
Fishing-Brown surgeonfish	4.24	5.63	23.86	50.64	0.70	85.85
Total for Fishing:			**79.17**	**165.81**		**281.77**
Illegal Fishing-Reef	4.92	3.75	18.44	41.43	0.75	72.50
Illegal Fishing-Seagrass	5.18	0.31	1.62	3.79	0.75	6.64
Illegal Fishing-Beaches	4.17	0.00	0.00	0.00	0.75	0.00
Illegal Fishing-Streamlined spinefoot	3.43	3.75	12.88	29.14	0.70	49.41
Illegal Fishing-Yellowtail fusilier	4.38	3.75	16.41	35.02	0.70	59.37
Illegal Fishing-Daisy parrotfish	3.64	3.75	13.64	30.30	0.70	51.36
Illegal Fishing-Octopus cyanea	3.50	3.75	13.13	26.80	0.72	46.17
Illegal Fishing-Brown surgeonfish	4.24	3.75	15.91	33.76	0.70	57.24
Total for Illegal Fishing:			**56.06**	**121.26**		**206.32**
Mining-Reef	4.92	1.25	6.15	8.63	0.83	15.76
Mining-Seagrass	5.18	1.25	6.48	8.79	0.83	16.04
Mining-Beaches	4.17	0.00	0.00	0.00	0.83	0.00
Mining-Streamlined spinefoot	3.43	0.00	0.00	0.00	0.77	0.00
Mining-Yellowtail fusilier	4.38	0.00	0.00	0.00	0.77	0.00
Mining-Daisy parrotfish	3.64	0.00	0.00	0.00	0.77	0.00
Mining-Octopus cyanea	3.50	0.00	0.00	0.00	0.80	0.00
Mining-Brown surgeonfish	4.24	0.00	0.00	0.00	0.77	0.00
Total for Mining:			**0.00**	**0.00**		**0.00**
Typhoons-Reef	4.92	2.50	12.29	30.59	0.75	53.54
Typhoons-Seagrass	5.18	2.50	12.96	31.91	0.75	55.84
Typhoons-Beaches	4.17	1.88	7.82	15.69	0.75	27.45
Typhoons-Streamlined spinefoot	3.43	0.63	2.15	5.38	0.70	9.12
Typhoons-Yellowtail fusilier	4.38	2.50	10.94	25.86	0.70	43.84
Typhoons-Daisy parrotfish	3.64	2.50	9.09	22.37	0.70	37.93
Typhoons-Octopus cyanea	3.50	2.50	8.75	19.79	0.72	34.10
Typhoons-Brown surgeonfish	4.24	2.50	10.61	24.93	0.70	42.27
Total for Typhoons:			**30.93**	**73.40**		**124.99**
Climate Change-Reef	4.92	10.00	49.18	73.25	0.83	133.67
Climate Change-Seagrass	5.18	7.50	38.88	51.32	0.83	93.65
Climate Change-Beaches	4.17	7.50	31.27	31.27	0.83	57.08
Climate Change-Streamlined spinefoot	3.43	5.00	17.17	25.51	0.77	45.16
Climate Change-Yellowtail fusilier	4.38	5.00	21.89	30.91	0.77	54.73
Climate Change-Daisy parrotfish	3.64	5.00	18.18	26.52	0.77	46.94
Climate Change-Octopus cyanea	3.50	5.00	17.51	22.22	0.80	39.95
Climate Change-Brown surgeonfish	4.24	5.00	21.21	29.55	0.77	52.31
Total for Climate Change:			**74.75**	**105.16**		**186.78**

managers and policy makers can utilize without assistance or feedback from the designers. Furthermore, a similar method to the one presented here is used to capture uncertainty in a variety of previous risk assessment tools (including the PSA, ERAEF, and ERAF – Patrick et al., 2009; Hobday et al., 2011; Miriam et al., 2015), and has proved useful. Our approach builds on these previous methods by quantifying the uncertainty categories, and providing additional scoring guidance for increased clarity and transparency.

$$FinalAdjustedRisk_{ct} = AdjustedRisk_{ct} + (UncertaintyFactor_{ct} \times AdjustedRisk_{ct})$$

The final adjusted risk scores for all the threats facing a given site can be compared with each other to identify the threat or threats that are most responsible for driving system change.

2.3. Cumulative risk scores

CARE differs from other ERAs in that it allows for the estimation of the risk posed by the cumulative effects of all the threats being evaluated. Combining different types of threats (e.g., fishing, mining, climate change) into a single risk value is a challenge that most other risk assessment methods have avoided by focusing in detail only on the impacts of fishing. Of course, in reality, multiple threats are often present, so cumulative impacts are real and

Table 7
Cumulative Risk Scores for each valued target (ecosystems and species), as well as Ecosystem Service Provision Scores for each valued ecosystem, resulting from CARE analysis of Cantilan, The Philippines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Target	Cumulative Adjusted Risk Score	Cumulative Adjusted Risk Score w/ Uncertainty
Coral Reef Ecosystem	223.75	397.70
Seagrass Ecosystem	140.24	249.93
Beach Ecosystem	46.96	84.53
Siganus argenteus (Streamlined spinefoot)	103.74	177.80
Caesio cuning (Yellowtail fusilier)	144.32	247.01
Chlorurus sordidus (Daisy Parrotfish)	124.63	213.29
Octopus cyanea (Octopus)	92.94	161.77
Acanthurus nigrofuscus (Brown surgeon fish)	138.87	237.66
	Ecosystem Service Provision Score (1 – 3)	
Reef Ecosystem		2.16
Seagrass Ecosystem		2.11
Beach Ecosystem		2.08

Table 8
Individual Risk Scores for each system threat as it impacts each valued target (ecosystems and species) resulting from CARE analysis of Karimunjawa, Indonesia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Threat-Target Pair	Target Response Score	Threat Exposure Score	Base Score	Adjusted Score	Uncertainty Score (max =1)	Score w/ Uncertainty
Fishing-Reef	3.91	4.22	16.51	81.25	0.78	144.22
Fishing-Seagrass	4.21	2.81	11.84	60.94	0.78	108.16
Fishing-Mangroves	3.27	0.00	0.00	0.00	0.78	0.00
Fishing-Beaches	4.17	1.41	5.86	19.16	0.78	34.01
Fishing-Yellowtail fusilier	4.38	4.22	18.47	74.21	0.62	120.25
Fishing-Blue-barred parrotfish	3.94	4.22	16.62	69.42	0.62	112.49
Fishing-Bumphead parrotfish	6.31	4.22	26.63	81.25	0.62	131.66
Fishing-Squaretail coralgrouper	4.71	4.22	19.89	76.33	0.62	123.68
Total for Fishing:			**81.61**	**301.20**		**488.08**
Illegal Fishing-Reef	3.91	3.75	14.67	25.78	0.78	45.76
Illegal Fishing-Seagrass	4.21	1.88	7.89	16.11	0.78	28.60
Illegal Fishing-Mangroves	3.27	0.00	0.00	0.00	0.78	0.00
Illegal Fishing-Beaches	4.17	0.00	0.00	0.00	0.78	0.00
Illegal Fishing-Yellowtail fusilier	4.38	2.50	10.94	14.98	0.62	24.28
Illegal Fishing-Blue-barred parrotfish	3.94	3.75	14.77	22.03	0.62	35.69
Illegal Fishing-Bumphead parrotfish	6.31	3.75	23.67	25.78	0.62	41.78
Illegal Fishing-Squaretail coralgrouper	4.71	3.75	17.68	24.22	0.62	39.25
Total for Illegal Fishing:			**67.07**	**87.01**		**141.00**
Coastal Development- Reefs	3.91	7.50	29.35	87.50	0.85	161.88
Coastal Development-Seagrasses	4.21	10.00	42.11	100.00	0.85	185.00
Coastal Development-Mangroves	3.27	5.63	18.38	31.36	0.85	58.03
Coastal Development-Beaches	4.17	7.50	31.27	46.59	0.85	86.19
Coastal Development-Yellowtail fusilier	4.38	5.63	24.62	59.94	0.70	101.62
Coastal Development-Blue-barred parrotfish	3.94	5.63	22.16	56.07	0.70	95.06
Coastal Development-Bumphead parrotfish	6.31	5.63	35.51	65.63	0.70	111.26
Coastal Development-Squaretail coralgrouper	4.71	5.63	26.52	61.65	0.70	104.52
Total for Coastal Development:			**108.81**	**243.28**		**412.46**
Seaweed Mariculture- Reefs	3.91	3.75	14.67	40.63	0.78	72.11
Seaweed Mariculture-Seagrasses	4.21	5.00	21.05	50.00	0.78	88.75
Seaweed Mariculture-Mangroves	3.27	1.25	4.08	12.87	0.78	22.84
Seaweed Mariculture-Beaches	4.17	0.00	0.00	0.00	0.78	0.00
Seaweed Mariculture-Yellowtail fusilier	4.38	2.50	10.94	28.13	0.62	45.58
Seaweed Mariculture-Blue-barred parrotfish	3.94	2.50	9.85	27.06	0.62	43.85
Seaweed Mariculture-Bumphead parrotfish	6.31	2.50	15.78	28.13	0.62	45.58
Seaweed Mariculture-Squaretail coralgrouper	4.71	2.50	11.78	28.13	0.62	45.58
Total for Seaweed Mariculture:			**48.36**	**111.43**		**180.57**
Grouper Aquaculture - Reefs	3.91	3.75	14.67	40.63	0.85	75.16
Grouper Aquaculture -Seagrasses	4.21	3.75	15.79	40.63	0.85	75.16
Grouper Aquaculture -Mangroves	3.27	0.63	2.04	5.30	0.85	9.81
Grouper Aquaculture -Beaches	4.17	0.00	0.00	0.00	0.85	0.00
Grouper Aquaculture -Yellowtail fusilier	4.38	3.75	16.41	38.16	0.70	64.70
Grouper Aquaculture -Blue-barred parrotfish	3.94	3.75	14.77	35.70	0.70	60.53
Grouper Aquaculture -Bumphead parrotfish	6.31	3.75	23.67	40.63	0.70	68.88
Grouper Aquaculture -Squaretail coralgrouper	4.71	5.00	23.57	46.97	0.70	79.63
Total for Grouper Aquaculture:			**78.43**	**161.46**		**273.75**
Climate Change- Reefs	3.91	10.00	39.13	89.47	0.85	165.53
Climate Change-Seagrasses	4.21	7.50	31.58	75.00	0.85	138.75
Climate Change-Mangroves	3.27	7.50	24.51	45.16	0.85	83.54
Climate Change-Beaches	4.17	7.50	31.27	49.63	0.85	91.82
Climate Change-Yellowtail fusilier	4.38	5.00	21.89	45.66	0.70	77.42
Climate Change-Blue-barred parrotfish	3.94	5.00	19.70	42.72	0.70	72.43
Climate Change-Bumphead parrotfish	6.31	5.00	31.57	50.00	0.70	84.77
Climate Change-Squaretail coralgrouper	4.71	7.50	35.35	70.45	0.70	119.45
Total for Climate Change:			**108.50**	**208.84**		**354.08**

should be accounted for in evaluating risk to ecosystems. The calculation of combined impacts of a variety of disparate threats on a given target is possible in CARE because each of the threat-target impact components have been converted to dimensionless factors (i.e., the five vulnerability criteria) following the method of Halpern et al. (2007). This enables users of CARE to compare different sites to each other based on relative risk scores, which are based on expert knowledge specific to the system. While the actual consequences

Table 9
Cumulative Risk Scores for each valued target (ecosystems and species), as well as Ecosystem Service Provision scores for each target ecosystem, resulting from CARE analysis of Karimunjawa, Indonesia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Target	Cumulative Adjusted Risk Score	Cumulative Adjusted Risk Score w/ Uncertainty
Coral Reef Ecosystem	365.25	664.65
Seagrass Ecosystem	342.68	624.42
Mangrove Ecosystem	94.69	174.22
Beach Ecosystem	115.38	212.02
Caesio cuning (Yellowtail fusilier)	261.08	433.85
Scarus ghobban (Blue-barred parrotfish)	252.99	420.05
Bolbometopon muricatum (Bumphead parrotfish)	291.41	483.93
Plectropomus areolatus (Squaretail coralgrouper)	307.74	512.11
	Ecosystem Service Provision Score (1 – 3)	
Reef Ecosystem		2.42
Seagrass Ecosystem		2.26
Mangrove Ecosystem		2.46
Beach Ecosystem		2.54

of the different threats evaluated may be completely different (e.g., the consequences of climate change vs. the consequences of fishing), the relative potential for these impacts to occur, and relative negative impact that can be expected, based on threat exposure and system response, can be compared.

A variety of methods have been proposed for the calculation of cumulative risk to a system from multiple threats (Folt et al., 1999). CARE uses the "simple additive" model (Folt et al., 1999), simply summing the final adjusted risk scores for each threat to generate a cumulative adjusted risk score for a given target ecosystem or species. This method was chosen as the default for the CARE method calculations (Supplementary Appendix A) because recent research shows that many threat interactions are additive (Crain et al., 2008). However if users have additional data or information about their system that supports the use of a different model for calculating cumulative impacts (e.g., comparative, multiplicative) they can easily adjust the CARE model equations as appropriate.

$$CumulativeAdjustedRisk_c = \sum_{c=1}^{n} FinalAdjustedRisk_{ct} \quad (8)$$

The cumulative adjusted risk score can be compared with the cumulative adjusted risk scores for other targets within the site (i.e., other ecosystems or species), or with corresponding scores for other sites under analysis to help managers make more informed management siting decisions.

It should be noted that when using the simple additive model, sites facing more threats will likely have higher Cumulative Risk Scores than sites facing fewer threats, regardless of individual threat severity. Furthermore, the potential for user error and bias towards false positives may also increase as the number of threats under consideration increases. Rather than being a shortcoming of the model, however, we believe this reflects reality, as overall risk would be expected to increase with the number of threats generally (Crain et al., 2008). Furthermore, this feature comports with the precautionary principle, as the more threats that are present, the higher the uncertainty around potential impacts and interactions, and thus the higher the risk score should be.

2.3.1. Risk score interpretation

Individual threat risk scores from CARE range between 0 and 200 (or 0 and 100 without uncertainty), while cumulative risk scores range between 0 and the number of threats present in the site multiplied by 100. CARE does not specify a particular risk score cutoff value above which threats should be considered "more important" than others, but instead utilizes a continuous green, yellow, red (low, moderate, high) color coding scheme to help users interpret the scores generated by the model (Supplementary Appendix A). This color coding allows users to more easily compare all scores, both within and across sites, as they relate to each other. However, the level of risk that is acceptable in a given site is subjective, and depends on the specific values, concerns, risk tolerance, and objectives of the managers and stakeholders who will be impacted by system changes. It is often impossible to avoid impacts all together when using natural resources, and there may be trade-offs that must be made between biophysical and socioeconomic benefits and user-defined goals. Users should weigh all of these factors when deciding which threats must be addressed and which do not require immediate attention.

2.4. Risk to ecosystem service provision

In addition to the Exposure-Response Analyses detailed above, CARE also includes optional worksheets to help users quantify the ecosystem service provision of the different habitat types within their sites (Supplementary Appendix A). This analysis can be considered as an additional axis, the results of which can be compared with the Exposure, Response, Individual, and Cumulative Risk scores for each ecosystem in order to get a fuller picture of what might be lost if threats are not addressed. Attributes that control the provision of ecosystem services in different types of habitats were compiled with reference to Barbier et al. (2011), and 1–3, "low to high" scoring metrics were developed for each attribute. These attributes relate to system characteristics such as reef distance from shore and number of endemic species, as well as the degree of modification, relative to a historical baseline or healthy/reference site, of processes like the nutrient cycling regime and the abundance of predators. Each attribute is labeled with the ecosystem services associated with these characteristics or processes, based on our literature review, so that users can identify which services are provided by which ecosystems. For more detail on the attributes and scoring metric used in the Risk to Ecosystem Service Provision module see Supplementary Appendix D.

The results of the ecosystem service assessments can be used to compare the relative ecosystem service productivity of different habitat types within a given site, or between separate sites. Scores from this component can also be compared with risk scores generated through the Ecosystem Risk Assessments to identify where a system with high ecosystem service provision is also at high risk. This assessment process is unique to CARE, and we anticipate its use to inform marine spatial planning (e.g., zonation) or site selection for different management options such as Territorial Use Rights for Fishing reserves, MPAs, or tourism by elucidating the services provided and the risk to those services. However, completion of these worksheets is not necessary for completion of the CARE model if time and resources are limited.

3. Case studies: Cantilan, Philippines and Karimunjawa, Indonesia

We applied CARE to two case studies to evaluate its usefulness and help to inform management actions in these sites. Here we briefly present the results of these analyses as a means of demonstrating the types of information that can be generated through the CARE model. (See Supplementary Appendices E–G for a full account of the inputs and methods behind these results).

3.1. Cantilan, the Philippines

Cantilan is a small municipality in the northeastern part of the island of Mindanao in the Philippines. Overfishing is a pervasive problem throughout the Philippines, and most nearshore areas are overexploited (Gomez et al., 1994; Pauly et al., 1989). Ayoke Island, just east of the main land in Lanuza Bay, suffers from overfishing, but it has a fairly well-managed MPA and many of the social and institutional conditions that would be conducive to the improvement of fishery management (Personal Communication, Sarah Poon, 2013). However, a handful of activities both within and around this site present potential threats to ecological health and functioning in this area. Fishery management, regardless of the quality of design or management implementation, can only address the threats associated with (legal and illegal) fishing and marine resource use. We applied CARE to determine whether non-fishing threats are likely to undermine the ability of fishery management to restore overfished stocks at this site.

3.1.1. Cantilan results summary

Three target ecosystems were identified through a review of relevant literature as well as interviews with locals and experts: coral reefs, seagrass beds, and beaches. There are also five species that are especially valuable to the fisheries in Cantilan and/or considered to be “at risk”, which were identified as targets for analysis: the Streamlined spinefoot (*Siganus argenteus*), the Yellowtail fusilier (*Caesio cuning*), the Daisy parrotfish (*Chlorurus sordidus*), Cyane’s octopus (*Octopus cyanea*), and the Brown surgeonfish (*Acanthurus nigrofuscus*). Five activities were identified that may impact these target species and ecosystems: legal fishing, illegal fishing, mining, typhoons, and climate change.

Table 6 shows the complete suite of individual threat risk scores calculated using CARE for each threat facing the system at Cantilan. The “Base Risk Score” column in Table 6 contains the score that results from combination of the unmodified Exposure and Response scores. The “Adjusted Risk Scores” are the result of modifying the base risk scores to account for the ATMs (which can either increase or decrease the base risk score, as described above), and the “Final Individual Risk Score” is a result of increasing the adjusted risk scores by the proportion dictated by the “Uncertainty Factor,” which is also reported in the results tables.

Table 7 shows the cumulative risk scores for each target in the Cantilan site. Scores in these tables are color-coded using a green – yellow – red (low, moderate, high) gradient scheme. Table 7 also contains ecosystem service provision scores for each target ecosystem in the Cantilan site. These range from 1 to 3, and are color-coded using a red-yellow-green color scheme (opposite to the Risk scores). The complete CARE analysis and scores for Cantilan can be found in Supplementary Appendices E and F.

CARE suggests that legal fishing, climate change, and illegal fishing (in this order) are the most important threats facing the targets evaluated in this site (Tables 6 and 7). Legal fishing is the largest threat to most of the target species in Cantilan, while climate change may pose the greatest risk to the evaluated ecosystems. Furthermore, the cumulative risk scores from CARE show that the coral reefs are the most threatened ecosystem evaluated, followed by seagrasses, and then beaches. The Yellowtail fusilier and the Brown surgeonfish receive higher cumulative risk scores than the other three target species evaluated. These scores probably reflect the fact that the reef systems are targeted more directly by fishers in Cantilan, and reefs in general are more vulnerable to many of the pressures of climate change than are seagrass beds and beaches. The species that have been identified as highest risk are larger, longer lived, and slower growing than the other three, and are also more dependent on the fragile reefs, and thus more vulnerable to the threats that negatively impact the reef system at this site. Finally, ecosystem service provision scores for the three evaluated ecosystems reveal the reefs as a slightly higher producer of ecosystem services than the seagrasses and beaches. Together, these results imply that coral reefs in Cantilan should potentially warrant more attention than the seagrass and beach ecosystems because they are at much higher risk, and they produce more ecosystem services.

All of this implies that this site has a high recovery potential through implementation of improved fishery management. Better fishery management could adequately reduce pressure from legal fishing, and potentially eliminate the threat of illegal fishing. This would greatly reduce risk to most of the evaluated targets in this site and leave only climate change as a significant concern, especially for the Brown surgeonfish. Furthermore, control of these other threats could allow the system and this species to recover sufficiently that they might more easily withstand the stressors associated with climate change (Nystrom et al., 2000; Peachey, 2005; Pörtner et al., 2005). This analysis suggests that Cantilan is an excellent candidate for the implementation of fishery management improvement projects.

3.2. Karimunjawa, Indonesia

Karimunjawa National Park, located 80 km northwest of the island of Java in central Indonesia, was established as a national marine park in 1986. The park is managed through a network of zones designated for different uses, including protection zones, rehabilitation zones, tourism zones, and “core” no-take zones in addition to open access fishing areas. Although overfishing is a concern within the park, with some species that used to be market staples now in decline, the park has a relatively high capacity for management and enforcement of fishing regulations (Personal Communication, Erica Martling, 2013). However, despite its designation as a National Park, the area is subject to a variety of potential threat activities that must be considered when evaluating the potential efficacy of improved fishery management. Inhabitants of the park and fishers from other areas intermingle throughout the fishing zones, and therefore a network of fishing territories and marine reserves throughout the park might be the most appropriate fisheries management option (Personal Communication, Erica Martling, 2013). For this reason our CARE analysis of this site was carried out with regards to the park as a whole, rather than to a smaller section of the park.

3.2.1. Karimunjawa methods and results summary

Four target ecosystems were identified: coral reefs, seagrass beds, mangroves, and beaches in the scoping phase of the CARE analysis. Four valued species were also identified: the Bumphead parrotfish (*Scarus perrico*), the Yellowtail fusilier (*Caesio cuning*), the Blue-barred parrotfish (*Scarus ghobban*), and the Squaretail coralgrouper (*Plectropomus areolatus*). Seven threats were identified as potentially impacting one or more of these targets: legal fishing, illegal fishing, coastal development (including tourism), seaweed mariculture, grouper aquaculture, and climate change.

Table 8 shows the complete suite of individual threat risk scores calculated with CARE for Karimunjawa. Table 9 contains the cumulative risk scores for each target in Karimunjawa, as well as the ecosystem service provision scores for each target ecosystem. As with the Cantilan results above, scores in these two tables are color-coded from green to red (lowest to highest risk). The complete CARE analysis and results for Karimunjawa can be found in Supplementary Appendices E and G.

Tables 8 and 9 show that, unlike in Cantilan, CARE analysis of Karimunjawa reveals a variety of significant threats, many of which have very similar risk scores (implying equal importance in this site). If legal and illegal fishing were controlled through implementation of an effective fisheries management regime, all species and ecosystem targets in this site would still face substantial pressures from coastal development and climate change. Furthermore, seaweed mariculture and grouper aquaculture present significant risks to many of the target species (especially the Squaretail coralgrouper) as well as to the reef and seagrass ecosystems. In fact, these two threats are on par with climate change in risk to seagrass habitats.

These results indicate that at this site, comprehensive threat reduction may be necessary to ensure that fishery management improvement projects are successful. Large differences between base and adjusted threat risk scores imply that the additional threat modifications are important in this analysis (see Supplementary Appendices E and G). Also, as this analysis was carried out at the scale of the park as a whole, some of these threats may be more or less important at a finer spatial scale. Careful siting within the park could further reduce some of these non-fishing threats.

Ecosystem service provision scores (ranging between 1 and 3) for Karimunjawa can also be found in Table 9. All four systems evaluated have higher ecosystem service provision scores than do the corresponding ecosystems evaluated in Cantilan (Table 7). These results reveal that the reef and seagrass ecosystems, which generated the two highest cumulative risk scores, also have relatively high ecosystem service provision scores, implying that damage to these systems could result in high losses to valuable services. On a more positive note, the beach and mangrove ecosystems have the two highest ecosystem service provision scores, and these systems face relatively low risks. Through proactive management and policy decisions, these habitats could likely be safeguarded against some of their main stressors, which come from coastal development and climate change.

3.3. Case study conclusions

These two case studies illustrate how CARE can inform threat reduction strategies and management siting decisions. In Karimunjawa, activities other than fishing pose significant threats to the ongoing health and functioning of the valued ecosystems and species. These threats should be addressed in to ensure that a fisheries intervention will achieve desired outcomes. Conversely in Cantilan a well-designed and implemented fishery intervention could address all of the most important system threats and is unlikely to be undermined by non-fishing impacts.

These results also support our hypothesis that the CARE analysis could be applied to only the dominant habitat type at a site, rather than all ecosystems and valued species present, and still provide the necessary information to provide useful guidance. This option may be preferable to managers working with especially limited capacity or on extremely limited timelines, as analysis of just one target per site will be significantly quicker than analysis of many targets. If the CARE analysis had been applied to only the most dominant habitat types – in both of these cases, the coral reef systems – the analyses would have resulted in nearly identical rank orders of important system threats as were revealed through analysis of the full suites of targets presented above. Furthermore, assessing only the coral reef ecosystems in both Cantilan and Karimunjawa would have revealed a higher cumulative risk score in the latter site, just as completion of CARE for these larger lists of targets has shown. This information may be useful if managers are deciding between the two locations for the siting of a spatially explicit management intervention, such as a Marine Protected Area. However, it is important to note that interpretation of the CARE results should be sensitive to the resolution at which the model was applied. That is to say, if only one ecosystem is evaluated, users must keep this in mind when making decisions about the management of other system targets. Thus, to capture all the potential target-specific impacts, we recommend applying the CARE model to as many valued system targets as time and resources will allow.

4. Discussion and conclusions

Ecological Risk Assessment (ERA) can be used in a variety of different ways to facilitate marine resource conservation and management. Understanding the factors that could lead to project failure allows implementing organizations to prioritize and preemptively address them with threat reduction strategies or avoid them through site selection. Recent research indicates that many conservation projects fail to consider such factors, and that this could prevent or delay the achievement of goals (Game et al., 2013). ERA can provide a scientific basis for successfully siting resource management interventions (Fletcher, 2005; Halpern et al., 2008; Hobday et al., 2011; Levin et al., 2009; Miriam et al., 2015; Tallis et al., 2010). For example, in areas where the pressures associated with fishing present the highest risks, MPAs or other restricted use areas can be implemented to allow for system recovery. In areas that face multiple other non-fishing threats, such as land-based pollution or coastal development, ERA using CARE can help to identify the most important among these pressures, and to better understand both the sources of these threats and the specific system components that are most vulnerable to them, thus allowing managers to make well-informed decisions about management siting and the allocation of resources for threat reduction. Spatially-explicit fishery management measures, such as TURF reserves or other cooperative-style systems, can be sited in areas least impacted by non-fishing threats, so that efforts to restore stocks and ecosystems will not be undermined by factors that are out of the control of system managers. Furthermore, distorted perceptions of threat importance that may create resistance to addressing truly important threats can be adjusted by using CARE in a participatory way that allows stakeholders to consider other viewpoints and data to systematically co-create understanding about the relative importance of threats.

Several methods for evaluating risks to single species exist, and many also attempt to characterize risks to species communities or critical habitats, generally by evaluating simplified proxies for habitat health (e.g., spatial extent) (Hobday et al., 2011; Miriam et al., 2015; Patrick et al., 2009; Sharp et al., 2014; Zhou and Griffiths, 2008). CARE replicates many of the features of existing methods, including assessment of the likelihood of exposure and the severity of the potential response of the species or system and the quantification of uncertainty around user scores. CARE builds on these methods by allowing analysts to investigate multiple threats to multiple ecosystem types, capture interactions between threats, and describe potential impacts of threats on ecosystem services. CARE also incorporates recent research on ecosystem attributes

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(Barbier et al., 2011; Fujita et al., 2012; Halpern et al., 2008; Keith et al., 2013; Link, 2005) associated with resilience to better characterize ecosystem response to threats. Finally, the streamlined, one-step CARE format makes this tool more appropriate for rapid site selection than some of the longer, hierarchical ERA methods (ERAEF, ERAF), as well as more accessible to scientists and managers operating with limited time, resources, and capacity.

CARE could potentially also be used in the design of management measures for the maintenance or recovery of a diverse array of ecosystem goods and services. Ecosystem service provision is not equal across all systems, or even across similar systems with slightly different characteristics (Arkema et al., 2013; Koch et al., 2009; Shepard et al., 2011). Protection and restoration efforts targeted at systems that produce especially high levels of ecosystem services, and that also face high risks of degradation, could prove to be an especially efficient use of resources because of the significant financial and environmental benefits potentially provided by these systems (Arkema et al., 2013; Barbier et al., 2011; Costanza et al., 1997). CARE is unique among ERA tools in that it has been designed to quantify both the relative risk(s) facing a system, and the relative provision of ecosystem services by that system. Thus, application of CARE could improve MPA siting decisions by revealing which of multiple high-risk areas under consideration for new MPAs are the strongest providers of ecosystem services, and therefore where it may be most efficient to focus protection efforts. Conversely, a CARE analysis could identify areas of high ecosystem service provision, where the risks are relatively low. Such areas could feasibly be opened up to a well-managed fishery, or to other sustainable marine resource uses (e.g., tourism), with minimal concern over the negative impacts of external stressors. Finally, managers could choose not to focus protection or restoration efforts in areas that produce low levels of ecosystem services, as such efforts may not ultimately be cost-effective.

In addition to helping managers select the best sites for a particular project, CARE can inform project design and implementation by identifying which of the specific characteristics of a given threat-target pair (which of the descriptive attributes) are driving high risk scores. Results of individual modules can also inform threat reduction efforts, and help managers target limited resources. For example, scores from the Recovery and Resistance modules can identify systems that are intrinsically more resilient or more vulnerable than other systems, implying differential needs for management intervention. Managers can tailor protection and restoration efforts to the specific system attributes that are most in need. For example, if high risk scores for a particularly delicate coral reef ecosystem are driven primarily by the physical impacts of a fishery (i.e., from corals coming into contact with fishing gears or boats), as opposed to the actual removal of species, then gear restrictions, spatial closures, or fishermen education programs could be implemented to significantly reduce these impacts. Similarly, results from the various attributes that comprise the Exposure scores – attributes that characterize Scale, Frequency, and Intensity of threats – identify which aspects of the important threats are driving high risk scores. For example, shipping lanes could be moved to reduce the scale of the overlap of a shipping operation with a vulnerable system. Individual Threat Risk scores and Cumulative Target Risk scores generated by CARE can be compared within and across sites to determine which interventions will be most effective in which areas. This information can be useful in designing regulations, as well as directing often-limited monitoring and enforcement resources. Thus, CARE can inform marine resource management decisions that allow communities to sustainably achieve both conservation and economic goals.

The results of a CARE analysis can also help users understand how to increase system resilience in the face of climate change. Systems under chronic stress are less likely to recover from acute stress events, such as those that are likely to accompany climate change (e.g., higher sea surface temperatures, more frequent storms, new disease pathogens) (Grimsditch and Salm, 2006; Nystrom et al., 2000). Therefore, identifying and reducing controllable threats (e.g., fishing, pollution, aquaculture, etc.) that are having a significant impact on system health may improve resilience to future system pressures. Furthermore, synergies between certain anthropogenic stressors such as fishing and pollution are likely to exacerbate climate change impacts (Peachey, 2005; Pörtner et al., 2005). It may be possible to design new regulations explicitly to address specific aspects of threats (e.g., certain fishing gears) that are most likely to exacerbate the effects of climate change (Cinner et al., 2009). Results from CARE can help to elucidate these threat relationships so that managers can implement targeted reforms. In addition, system vulnerability and resilience to climate change is not likely to be spatially homogeneous, and may depend on the existence of unaffected refugia (Grimsditch and Salm, 2006; McClanahan et al., 2002; McLeod and Salm, 2006; West and Salm, 2003). Understanding the spatial relationship of ecosystems of differing vulnerabilities to various types of existing threats can help managers identify the best areas to protect in order to safeguard such climate change refugia (McClanahan et al., 2008).

There are important caveats that must be considered when making decisions based on the results of CARE analysis. First, the validity and reliability of the results depend on expert knowledge, data quality and availability, as well as on the consistency of users in scoring attributes of ecosystem productivity and resilience, and of threat intensity and scale. We have attempted to craft scoring metrics that allow for accurate results with extremely limited data. However, more and better information on which to base these assessments will always lead to more reliable results. When using the model to compare different sites for selection of different management options, we recommend that at least one person participate in model scoring for all sites. This will help safeguard against different interpretations of the scoring metrics, and against different user biases confounding results. Second, users should keep in mind that the CARE model results, as is the case with all existing risk analyses, reveal only the relative risk of harm to ecosystem or species health from the set of threats facing a given system. These results do not inform what the actual impacts of these threats will be. Although it is possible, through examination of the scores for individual attributes, to identify specific system characteristics that are more likely to be damaged, or that are sources of weakness against a specific threat, this should not be confused with a prediction of the real-world system changes. Third, CARE is temporally static, and the results may therefore become outdated or irrelevant if the system undergoes a relevant change, such as a new management measure that changes the scale, frequency, or intensity of one or more system threats. We recommend that the CARE analysis be completed before and after such changes come into effect to help users get a sense of how the change in question will impact relative risk.

Fourth, as discussed above, the inclusion of the ATM factors, while an important advance in the computation of cumulative risk, also creates additional and significant opportunities for user error which could skew the final risk scores. Each ATM scored can potentially alter resulting risk scores in either the positive or negative direction. In addition, as the CARE uncertainty scoring process generates only higher risk scores (creating more precaution where uncertainty is greater), and each ATM scored is accompanied by an additional uncertainty factor, inclusion of ATMs can increase the chance of scoring threats as high risk when they are in fact low risk. For both of these reasons ATMs should only be applied when users are relatively confident about the nature of the threat interaction in question. The impact of both the ATMs and the uncertainty factors are reported in the results tables generated by CARE so that users

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can understand how much the final risk scores have been altered by these components of the analysis. Users should pay close attention to all of this information when making management decisions based on the results of a CARE analysis. If, for example, the greatest contribution to the final risk score comes from the uncertainty factor, than management resources might be best used to increase understanding of the relationships between system components rather than directly addressing the threats evaluated. Finally, while our method of transforming threat characteristics into dimensionless index scores allows users to combine and compare threat impacts from different types of threats, it should be noted that the actual consequences of disparate threats that receive the same risk score will not necessarily be the same. For example, if the threat of fishing receives a threat score of 60 for a site, and climate change also receives a threat score of 60 for that same site, it should not be assumed that the two threats will have the same practical outcomes (i.e., fish removed, storms increased). Furthermore, although the cumulative risk score for this site (if it faced no other threats) as calculated with the simple additive model would be 120, this does not mean that the real-world consequence of both threats happening at once would be a simple doubling of the effects of one of the threats, for example, twice as many fish removed.

Failure to assess risks to ecosystems can impede effective marine resource conservation and management. Poor siting of spatially-explicit management efforts could lead to wasting resources in a sub-optimal area. Unforeseen, and therefore unmitigated, external threats could undermine any potential benefits of an intervention. Thus, the need for reliable, accessible tools to help managers understand risks to ecosystems that support fisheries, tourism, and many other goods and services will grow as momentum toward improving marine resource conservation and management increases. CARE is one such tool that can be used to provide a scientific basis for ecosystem management, even when data are scarce.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2016.09.017.

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