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Generating actionable data for evidence-based conservation: The global center of marine biodiversity as a case study

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ABSTRACT

Sufficiently rigorous monitoring and evaluation can assess the effectiveness of management actions to conserve natural resources. However, costs of monitoring can be high in relation to program budgets, so it is critical to design monitoring efforts to ensure a high return on investment. To assess the relative contribution of different monitoring strategies to yield information for management decisions, we examine the evolution of a multi-year monitoring program across several MPAs in West Papua, Indonesia. Three monitoring strategies were implemented: external expert, science practitioner, and community monitoring staff. We place the monitoring objectives in a decision science framework, with six explicit fundamental objectives for monitoring to evaluate performance of marine protected areas. We examine each strategy in light of the six objectives to evaluate: 1) power to detect change, 2) extent of local capacity development, and 3) cost effectiveness. Over time, costs were reduced and scientific value increased through clear communication of science objectives, outcome-driven experimental design, adequately resourced monitoring programs, and a long-term view that anticipates phasing out outside consultants and transitioning monitoring responsibilities fully to locally-based staff. Investments to develop capacity of staff living locally to perform data management, analysis, interpretation, and science communication proved the most cost-effective approach in the long-term. With many globally important ecosystems in developing countries, developing local scientific capacity for the full cycle of monitoring is key to informed decision-making and ensuring long-term sustainability of efforts to conserve biodiversity.

1. Introduction

Over the past two decades, scholars and practitioners have called for a shift towards evidence-based conservation to ensure management interventions are effective and have the desired impact (Ferraro and Pattanayak, 2006; Sutherland et al., 2004). Yet the long-standing need for adequate human and financial resources (Gill et al., 2017) poses significant barriers to developing a systematic and scientifically-defensible foundation of evidence that can inform adaptive management, policy, and strategic planning (Cook et al., 2016). Consequently, a substantial disconnect exists between scholarly discussion and on-ground practice in both developed and developing countries. Long-term efforts to standardize best practices in conservation (e.g., the Conservation Measures Partnership) have transformed conservation planning and implementation (Stem et al., 2005), but real examples of adaptive management remain rare (Cook et al., 2016), with

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Box 1
Monitoring strategies in the BHS.

Depending on the goals and priorities, different monitoring strategies were employed, with different tradeoffs around statistical power to detect change, local capacity development, cost, and timing (Fig. 1).

External expert: Bringing in an external expert with high capacity (in the form of an external consultant) provided results with good power (i.e. many species identified and higher precision in differentiating sites) on a short time frame, but costs were fixed and local capacity development (and therefore sustainability) limited.

Science practitioners: NGO monitoring staff trained in Indonesian universities had a good science foundation, and with support, now contribute in the international science community. This strategy is likely more sustainable than an external expert-led model, and further develops Indonesian capacity, but with less local capacity the risk remains that staff may leave and/or program priorities shift.

Community monitoring staff: Training Papuan citizens with commercial fishing experience and who could read and write focused on adding basic science skills (e.g. interpreting a graph, working with Excel, basic ecological theories), as their species identification and biomass estimation skills were often exceptional. This approach has resulted in relatively stable local monitoring staff.

monitoring practices on the ground frequently inadequate to support real-time decision-making at multiple spatial scales (from local to global) by the necessary array of actors (e.g., conservation managers, policy makers, funders).

Because ecological monitoring can be expensive, particularly in remote locations, and in extreme cases can equal or surpass the cost of other management objectives (e.g. planning, decision making, operations, community engagement, enforcement) combined (Howe and Milner-Gulland, 2012), trade-offs in resource allocation among objectives are common in diverse programs. In this context, it is crucial to be both clear about the full array of monitoring objectives (Houk and van Woesik, 2013) and their relative priorities, as well as to maximize the utility of the information generated for management and decision making as a result of monitoring (Hauser et al., 2006; McDonald-Madden et al., 2009; Possingham et al., 2012). If monitoring data collected are insufficient to detect ecological change or to evaluate the effectiveness of interventions, then these efforts might be considered a waste of resources (Legg and Nagy, 2006).

For at-risk ecosystems such as coral reefs, delayed information to inform management could be devastating (Possingham et al., 2012), resulting in missed opportunities to address emerging threats, adapt management that is ineffective, and allocate resources where they can maximize outcomes. In developing countries, home to many globally important and imperiled ecosystems, monitoring requires capacity that might not be commonly available. Tradeoffs might exist between developing long-term capacity for monitoring, and ensuring near-term monitoring rigor (Burton, 2012; Houk and van Woesik, 2013). However, the importance of local staff capacity for providing scientific support is increasingly recognized as critical for ensuring the long-term sustainability of monitoring efforts (McLeod et al., 2015; Şekercioğlu, 2012). Therefore, importing external capacity risks compromising sustainability in exchange for this short-term information gain (Danielsen et al., 2005). While monitoring almost always has multiple implicit objectives, and the goals of monitoring programs are rarely clearly articulated (Possingham et al., 2012), a well-designed program can also yield unintended consequences or benefits not originally anticipated (Edwards et al., 2010).

Efforts to develop capacity for monitoring generally occur through a combination of training local community members or in-country non-governmental organizations (NGOs), university, or government technical staff who have had relevant formal education to conduct monitoring activities (Danielsen et al., 2003). The critical role of local communities in resource management has long been recognized (Johannes, 1998a). Locally-led monitoring encompasses a range of approaches, and can be defined as local residents directly involved in data collection, regardless of their formal education (Danielsen et al., 2005); hereafter "community monitoring staff". At the same time, monitoring requires a high level of knowledge (e.g. of scientific monitoring design and protocols or computer literacy) and skills (e.g. species identification or data management). Consequently, potential tradeoffs frequently result in emphasis being placed either on capacity development, with the hypothesis that it will have greater long-term sustainability, or on information gain (i.e. scientific rigor) to ensure that the data will be useful in supporting planning, management and policy decisions. Many communities may trust the data more if they are directly involved in collecting it, and therefore may be more likely to make management decisions (Obura et al., 2002). If developing community monitoring capacity can simultaneously empower local communities and meet scientific monitoring needs, it would have greater benefit overall for improving natural resource governance (Danielsen et al., 2009; Holck, 2008).

1.1. *This study: evaluating tradeoffs among monitoring objectives*

To understand tradeoffs among monitoring objectives, we used a case study of an ecological performance measurement program, defined as the process of measuring progress towards a specified project, program, or policy objectives, including desired levels of activities, outputs, and outcomes (Mascia et al., 2014). Different monitoring and training approaches were implemented with varying emphasis placed on rigor and capacity development by different stakeholders, which resulted in multiple distinct strategies. This allows us to evaluate the benefits of monitoring against multiple management objectives common to many monitoring programs (Box 1; Ahmadia et al., 2015). We used a decision theoretic framework and applied a strategy evaluation to evaluate the relative costs and benefits of each monitoring strategy. We hypothesize that over time it becomes more cost-effective to base a monitoring program on locally-based science practitioners and community monitoring staff, but this results in a longer time to achieve sufficient power to detect change, which is often critical to trigger a management intervention (Fig. 1).

We tested this hypothesis with data from Raja Ampat, part of the Bird's Head Seascape (BHS) in West Papua, Indonesia, considered the global epicenter of marine biodiversity (Allen, 2008; Veron et al., 2009). Since 2007, a consortium of conservation actors in the BHS has worked towards protecting and sustaining the marine resources on which local communities depend (Mangubhai et al., 2012; Supplementary material). Their approach assumes that investing in improved community engagement and better governance of marine protected areas (MPAs) will result in more positive ecological and social outcomes across the Seascape. A monitoring program was designed to measure ecological conditions within MPAs over time, as indicators of management performance, with standardized core monitoring protocols. Monitoring efforts are intended to meet two strategic goals: (i) gain information to support and guide management decisions, and (ii) improve the capacity of local community monitoring staff to monitor MPA conditions. Implicit in this design are two hypotheses: (i) higher quality information that meets global standards for rigor will be more likely to be used for adaptive decision-making to support the overall

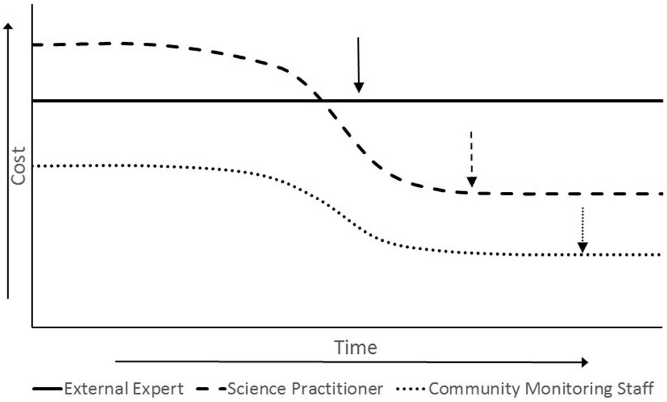

Fig. 1. A conceptual illustration of hypothesized tradeoffs with different monitoring strategies. Arrows indicate time to detect a change with each strategy. External expert has fixed costs and early power to detect change. Monitoring based on science practitioners and community monitoring staff takes longer to detect change, but ultimately is more cost effective, plus long-term datasets are in general quite valuable, even if less rigorous.

marine resource management goal; and (ii) improved local monitoring capacity will result in greater engagement of local communities, and thus better governance of marine resources in the long-term.

2. Methods

2.1. *Study area and Bird's Head Seascape monitoring program*

From its inception in 2007, the BHS monitoring program had multiple goals, with an ~10-year time horizon and 3-year funding cycles associated with opportunities for evaluation and adaptation, as well as a planned progression in program's primary focus and priorities (see Appendix A for further details). Priorities included informing conservation planning efforts (Grantham et al., 2013; Mangubhai et al., 2015), developing Indonesian and community monitoring and scientific capacity, and establishing baselines for monitoring performance of the MPAs, with a focus on the delineation of no-take zones within the MPAs (Table A1). Reliable data were required to plan conservation investments and shape adaptive management, in order to measure performance towards specified targets and goals and to influence local, regional and national policy (Huffard et al., 2012a, 2012b). As a result, a variety of monitoring systems were developed, tested, and implemented across the Seascape, i.e. resource use patterns (Mous et al., 2005), community perception monitoring (Widodo et al., 2010), social impacts and marine resource governance monitoring (Glew et al., 2012), ecological monitoring of coral reef and fish communities (Wilson and Green, 2009), and the population trends of charismatic species (e.g., nesting leatherback, green and loggerhead turtles) (Mangubhai et al., 2012). Here, we focus on ecological monitoring of coral reef fish communities in 6 MPAs in the BHS (Fig. 2; Raja Ampat Islands MPA was not part of the monitoring program).

2.2. *Objectives and evaluation of monitoring strategies*

To evaluate the overarching goals of evaluating conservation performance to gain information to support and guide management decisions, and improving the capacity of local staff to monitor MPA conditions, while ensuring that the monitoring strategy was cost effective, we identified six explicit, measurable and time-bound objectives:

A. Baseline monitoring information exists.
B. **Sufficient power** (defined in Section 2.2.1) is achieved within five years.
C. Minimize time lag (number of years of surveys) before 'sufficient power' exists.
D. **Sufficient capacity** (defined in Section 2.2.2) is achieved within five years.
E. Minimize time lag (number of years of surveys) before 'sufficient capacity' exists.
F. **Cost of Information** (**cost efficiency**): Maximize cost-effective information gain by **minimizing** the cost of sufficient power.

We evaluate the performance of three alternative strategies (Box 1) against each of these six objectives, and present the findings as a consequence table (Gregory et al., 2012). In so doing, we are able to qualitatively explore short- and long-term tradeoffs around 1) power to detect change, 2) capacity, and 3) costs and cost effectiveness of monitoring programs. All analysis was conducted using R, Version 2.15.0 (R Core Team, 2016).

2.2.1. *Power to detect change (Objectives A, B, & C)*

The original BHS monitoring plan was MPA-specific for the first several years of the program. Standardized protocols for ecological monitoring (Wilson and Green, 2009) and Excel-based data entry spreadsheets were developed with the intention that they be used consistently at each MPA, but these were modified by field teams in several sites (due to logistics, technology, and limited staff capacity in data management and monitoring protocols at this stage). In addition, variation in sampling led to spatial and temporal inconsistencies in the data, limiting comparability. Data at some sites also exhibited observer bias, data fragmentation, inadequate sample sizes, and experimental design not integrated across multiple sites, and so were not able to be used despite collection.

In 2012, an evaluation of the ability of data from individual MPAs to synthesize information at the Seascape level and contribute to regional analyses led to a major overhaul and re-design to create a more streamlined region-based monitoring program. Existing coral reef health monitoring protocols were updated (Ahmadia et al., 2013), standard Access databases developed to support Seascape-wide analyses, and the monitoring approach re-designed to be more streamlined (see Section 2.2.3). Statistical analyses were conducted to update the sampling design to include enough sites to detect changes in the condition of coral reefs over time (Ahmadia et al., 2015).

Sites are included in performance evaluations (i.e. were useable; Glew et al., 2015a) if repeat surveys were conducted and included in the master database. Sites meeting this standard are used for performance evaluation to facilitate adaptive management (Fig. 2). A site was considered to have a baseline (Objective A) if any sampling data are available within two years of establishment of the MPA, where the establishment phase is the window between legal declaration of the MPA (2007–2009) and the enforcement of marine resource rules, which typically occurs within two years (Glew et al., 2012). Thus, in this case, we define a site with a baseline as any site with sampling data in any year prior to 2012.

We estimated information utility, or benefit, using a statistical power analysis of fish biomass data collected in six BHS MPAs. The analysis was performed using power.t.test in the R base stats package (R Core Team, 2016). Fish biomass served as a proxy for fish community health and fishery potential. Each sampling event (consisting of five 50 m transect swims at depth of 8–12 m) was treated as a replicate. Only fish > 10 cm contributed to biomass calculations, and only data that were properly entered into the master database (see considerations above) were considered for this analysis. Variation in sample size was a result of data management challenged, observer bias etc., rather than design per se as the program was originally designed with even sampling. We calculated power in 2010, 2012, and 2014 (once in each phase of the program to date, or each time a full sampling cycle was completed). Data were right-skewed so log transformations were performed to satisfy normality before conducting power analysis.

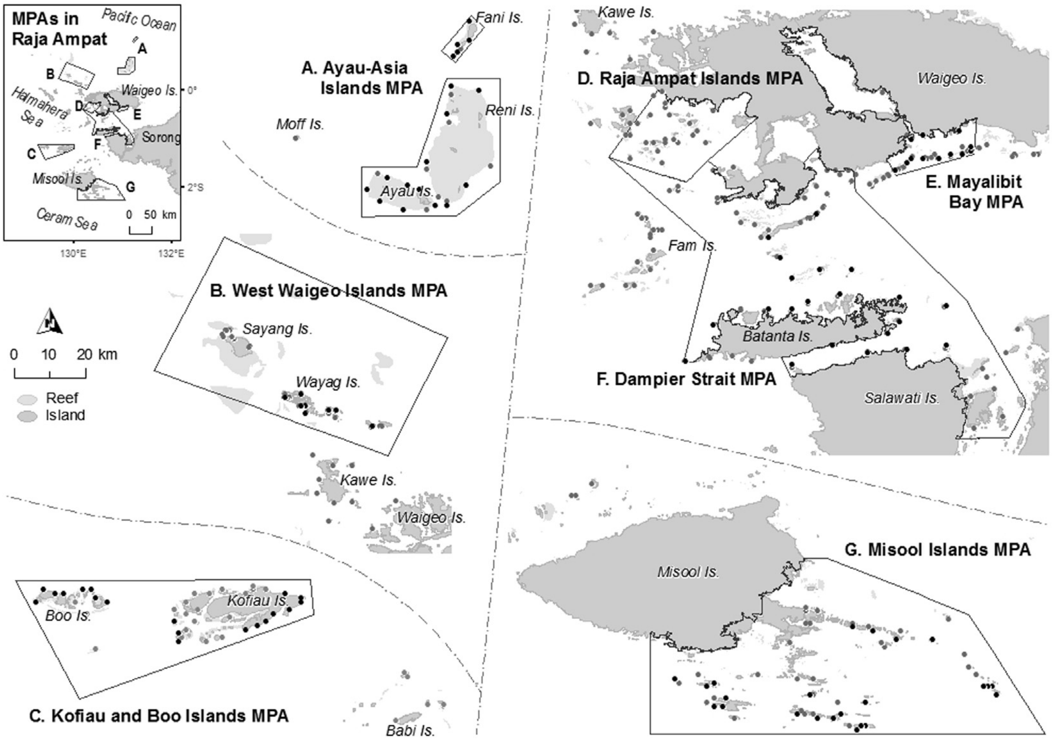

Fig. 2. Marine Protected Areas (MPAs) and monitoring sites in the Raja Ampat MPA Network, part of the Bird's Head Seascape in West Papua, Indonesia. Monitoring sites were either used for performance measurement (black) or not (grey) (see Section 2.2.1).

Sufficient power for performance evaluation of MPAs is defined as: an 80% likelihood of detecting a 20% change (i.e., an effect size of 0.20) from baseline in mean fish biomass at $p = 0.05$ power among sites within MPAs between survey periods, a standard threshold for management relevant change (Meador et al., 2008). We calculated power to detect change under each of the three strategies employed in the BHS (‘alternatives’ in decision science terminology Gregory et al., 2012; Runge et al., 2013; Box 1). To calculate cost per unit power per strategy, power was averaged (mean) over all MPAs within each strategy through time.

2.2.2. Capacity (Objectives D & E)

Significant investments were made in developing scientific and monitoring capacity within conservation NGOs, although training approaches were different. Initially, some sites used a consultant skilled in fish identification (i.e. external expert) to collect data, while also focusing on training staff who were community members (i.e. community monitoring staff) to conduct routine, simplified monitoring for an immediate ‘status report’ of the coral reefs in different zones of the MPAs. Many community monitoring staff had little to no prior training in scientific data collection, so training included development of a curriculum “Making the Most of Monitoring” (Huffard, 2012). Other monitoring training was targeted towards Indonesian NGO staff (i.e. science practitioners) with an initial higher capacity, so that they would also have more advanced skills to analyze, interpret, and report on data. **Sufficient capacity** is defined as “the field team as a unit can implement and sustain appropriate MPA performance measurement independently”.

To estimate the impact of training on capacity at different sites, the capacity level of monitoring staff over time was estimated through surveys of the monitoring team conducted in August 2014. Managers were asked to rate the competency of individual monitoring staff over time on a scale of 0 (none), 1 (basic), 2 (intermediate), or 3 (advanced) in the following categories: ability to identify key fisheries species, ability to identify species > 35 cm, ability to identify species < 35 cm, experimental design ability, and reporting ability. Overall scores were normalized, resulting in a comparable continuous scale from 0 to 1 for each monitor for each category. A score of 0 represented no ability or experience necessary to accurately monitor and evaluate, while a 1 represented high ability to accurately monitor in the given category. An average capacity rating was calculated based on the normalized scale across categories over each 3-year grant cycle. As most monitoring staff gained experience in these areas via continued monitoring, capacity ratings were expected to increase over time. Differences in capacity through time and among strategies were tested using a Mann Whitney U test for ordinal non-parametric data (and see Section 4.1 for a discussion of the limitations of this approach).

Later, in preparation for transitioning management of the Raja Ampat MPA network to a Regency government unit (*Unit Pelaksana Teknis Daerah*) a Monitoring and Evaluation Capacity Scorecard was developed to document the ability of Indonesian institutions to design, implement and sustain appropriate marine protected area monitoring and evaluation systems in the BHS (Glew et al., 2015b; Table A2). A focus group including representatives from ecological field teams, monitoring leads, and external scientists developed criteria for four levels (Novice, Basic, Proficient, and Expert) and ten technical competencies associated with well-designed monitoring (e.g. research design, data analysis and interpretation) (Table A2). The scorecard is designed to score organizations, not individuals, and generates scores for each functional role (e.g., monitoring lead, field coordinator, data analysis lead) (Glew et al., 2015b).

2.2.3. Costs and cost-effectiveness

In general, sufficient funding for the monitoring program was included within the overall BHS program. Revision and evaluation of the monitoring program occurs every three years. When the overall monitoring design was streamlined, the goals were to minimize additional field monitoring costs while providing data that could be used both for performance measurement and impact evaluation. This is possible because depending upon the scale of monitoring and research

Box 2
Impact Evaluation and the cost of monitoring programs.

Due to a shared interest in understanding the intended and unintended impacts attributable to MPA establishment in the BHS, the ecological monitoring re-design laid the foundation for impact evaluation as well as continuing to enable the existing performance measurement system that aligns closely with the interest of managers and decision makers for local-scale adaptive management (Ahmadia et al., 2015). An impact evaluation approach requires more sophisticated statistical analyses to control for observable bias in the placement or outcomes of MPAs (Sekhon, 2009). Frequently, this approach is beyond the capacity of a typical monitoring team (in both developed and developing countries), so costs for the postdoctoral scientists necessary to provide statistical support were not included in cost analysis here. It is worth noting however, that while impact evaluation is more costly, it also results in far greater understanding of the causal impacts of conservation actions.

design, the same indicators can be used for different monitoring intents (e.g. ambient monitoring, performance measurement, and impact evaluation; Mascia et al., 2014). The existing coral reef health monitoring program was adapted to align with the design requirements of impact evaluation to allow for causal inference (Box 2, Rosenbaum, 2010; Sekhon, 2009). This included modifying sampling strategies and monitoring comparison sites outside MPAs (Ahmadia et al., 2015). MPAs were monitored less frequently, but in a more coordinated manner across sites, such that overall in-field monitoring costs were lower.

Monitoring costs (*C*) for each grant cycle were calculated from monitoring work plans and budgets provided for each MPA. Costs associated with monitoring were categorized into supplies (*s*), fuel (*f*), food (*h*), wages (*w*), and other (*o*), which consisted of miscellaneous supplies, park fees, and logistics. Cost in a given year (*t*) is equal to the sum of the components,

$$C_t = \sum s + f + h + w + o$$

To calculate the cost of monitoring individual sites within an MPA the total cost of monitoring for each MPA was divided by the number of sites monitored.

Complete budget data for all MPAs (Fig. 2) were available for 2015, 2016, and 2017. 2012 budget data were available for the MPAs Ayau-Asia, Dampier Strait, Wayag-Sayang, and Mayalibit Bay (Fig. 2). The cost of monitoring for 2014 was determined by applying the mean rate of inflation in Indonesia per annum (mean = 5.5%; The World Bank, 2015) to the cost of FY 2012 such that,

$$C_n = C_t\,(1 + i)^n$$

where: C_n is the total inflated cost in year *n*, C_t is the base estimated cost in year *t* (in this case 2012), i = mean Indonesian inflation rate, and *n* is the difference between the base year (*t*) and the calculation year. Costs for earlier years were estimated by discounting the cost of FY 2012 by the rate of inflation, such that years became negative, i.e.

$$C_n = C_t\,(1 + i)^{-n}$$

The cost of staff time, *w*, was estimated based on the skill level and commensurate pay rate per unit time (wage) of individuals who undertook monitoring each year. The mean wage across all skill levels was applied to calculate the total cost of wages for monitoring in a given year. Each strategy includes program management and fundraising by expatriate staff, but as this is equivalent among strategies, these were not included in calculations of program cost. The cost of other elements (supplies *s*, fuel *f*, food *h* and other *o*) was taken directly from program budgets, and was assumed to have indexed with inflation.

The cost for sufficient power (see Section 2.2.1) was calculated for each MPA and by strategy by dividing the total cost of monitoring in a given year by the power to detect change. A Mann-Whitney *U* test was used to determine test for significant differences in the cost of power.

3. Results

We evaluated the three strategies (Box 1) against six objectives (Section 2). We describe the findings for each objective and then present the findings as a consequence table to highlight synergies and trade-offs among strategies, as well as relative strengths and weaknesses.

3.1. Power to detect change (including baseline)

Baseline data were available for all (100%) of sites where an external expert conducted monitoring, but not all sites now included in the regional monitoring program were sampled. Under the science practitioner strategy 71% of sites have a baseline, and power remained relatively stable (Table 1, Fig. 3). Under the community monitoring staff strategy 57% of sites have a baseline, and power increased gradually through time (Table 1, Fig. 3).

3.2. Capacity

Training efforts and on-the-ground practice resulted in improved monitoring ability, both in data collection and more advanced skills of study design and reporting (Fig. 4). Monitoring teams using science practitioners can now independently organize and monitor reef health and resource use. Capacity ratings for data collection significantly increased over time for science practitioners (Fig. 4; Data Collection: from a median of 0.67 in 2008 to 1.0 in 2014, Mann-Whitney *U* test, $W = 30, p < 0.01\ \alpha = 0.05$) and community monitoring staff (Fig. 4; from a median of 0.47 = in 2008 to 0.67 in 2014, Mann-Whitney *U* test, $W = 0, p \leq 0.001\ \alpha = 0.05$) and sufficient capacity (see Section 2.2.2) was reached after 3–4 years. External experts, by design, met all criteria, and capacity remained constant. Science practitioners did increase capacity in advanced skills, and overall have very high scores

Table 1
Fish monitoring sites with available baseline data (as defined in Section 2.2.1) and proportion of the total number of sites used for performance measurement in the most recent evaluation of MPAs in the region (Glew et al., 2015a). Values were extracted from the master database.

MPA	# sites with baseline	# sites for performance measurement	Proportion of sites with baseline
Ayau-Asia	16	18	0.89
Kofiau and Pulau Boo	16	19	0.84
South East Misool	14	24	0.58
Dampier Strait	16	18	0.89
Mayalibit Bay	5	13	0.38
Wayag-Sayang (Kawe)	1	9	0.11

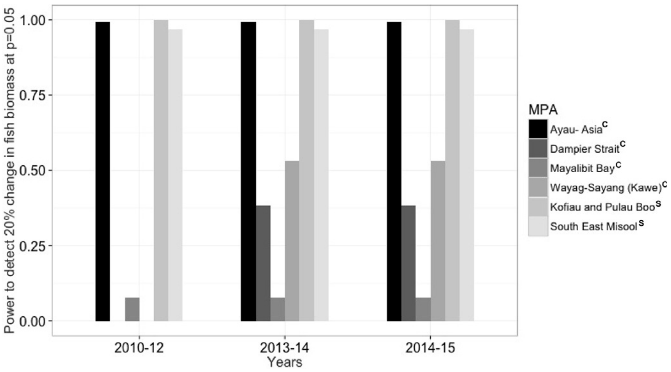

Fig. 3. Power to detect a 20% change in fish biomass at $p = 0.05$ by strategy across all MPAs where community monitoring staff (CMS); and science practitioner (SP) strategies were applied through time. Colors indicate MPAs, and the strategy employed in each MPA is indicated by either a superscript C (CMS) or S (SP) beside the legend.

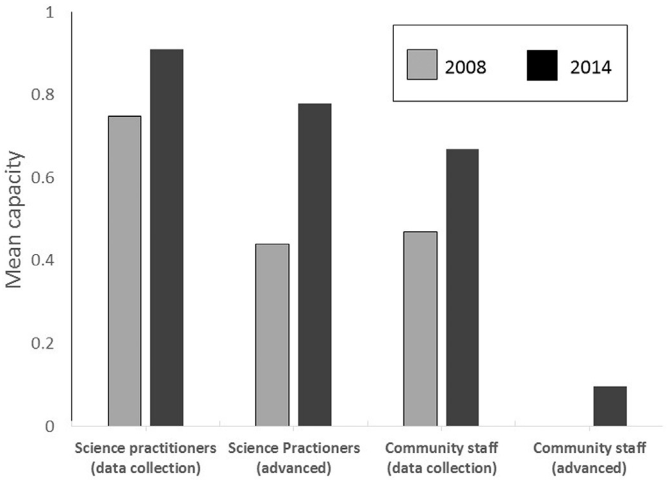

Fig. 4. Average normalized capacity score over time by strategy and by skillset (data collection and advanced skills of design/reporting).

in capacity, but this change was not significant (Fig. 4; Advanced: Mann-Whitney U test, $W = 224$, $p = 0.02$). Community monitoring staff improved advanced capacity significantly, but overall, their scores do not yet meet the standard for independent data management (Fig. 4; Advanced: Mann-Whitney U test, $W = 16$, $p = 0.03$).

3.3. Costs and cost-effectiveness

Consolidating the BHS monitoring plan from MPA-specific to region-wide efforts resulted in significant reductions in the cost of achieving sufficient power (defined in Section 2.2.1; Fig. 5, A1). In 2009–11, community monitoring was significantly less cost efficient than both science practitioner and expert strategies, which were similar (Figs. 3, 5, Mann Whitney U test, $W = 20$, $p = 0.04$, $\alpha = 0.05$). By 2012–14 the cost efficiency of all strategies was similar (Figs. 3, 5, Mann Whitney U test, $W = 12$, $p = 0.12$, $\alpha = 0.05$). While the total monitoring budget remained approximately the same (an average monitoring budget of ~USD $9000–20,000 for each MPA, depending on MPA size, heterogeneity, and distance from Sorong), the cost per unit power for external expert and science practitioner strategies increased slowly through time due to inflation (i.e. cost efficiency decreased; Fig. 5). Initially, the science practitioner strategy is the most cost-efficient approach, although overall power is lower that the expert strategy (Figs. 4, 5). However, for community monitoring staff, where cost efficiency is initially low, with a high cost per unit power, it transitioned over several years to become the most cost-efficient strategy (Fig. 5). Inflation in West Papua is higher than the national average (L. Katz, *pers. comm.*), but results are qualitatively identical when run with a 10% inflation rate.

One of the drivers of the initially high cost of sufficient power with community monitoring staff is that some MPAs had only 4 or 5 sites monitored and/or recoverable from the master database for analysis, which resulted in very low power, so high cost per unit power and low cost efficiency. However, even excluding these from the analysis, the cost of power in FY 2015–2017 is still significantly less than both earlier phases ($p = 0.01$, $\alpha = 0.05$ and $p = 0.04$, $\alpha = 0.05$, respectively). In fact, parallel efforts were ongoing, with increased power to detect change driven by an improvement in sampling design, and increased competency of the monitoring team driven by training and capacity development efforts.

3.4. Consequences

All strategies met standards for power and capacity before the end of the 10-year program (Table 2), but there is no ideal strategy that performed best across all objectives. The external expert strategy provides sufficient power and capacity relatively quickly and is more cost effective initially, but quickly becomes less cost effective and leaves no legacy of local capacity. In contrast, science practitioner and

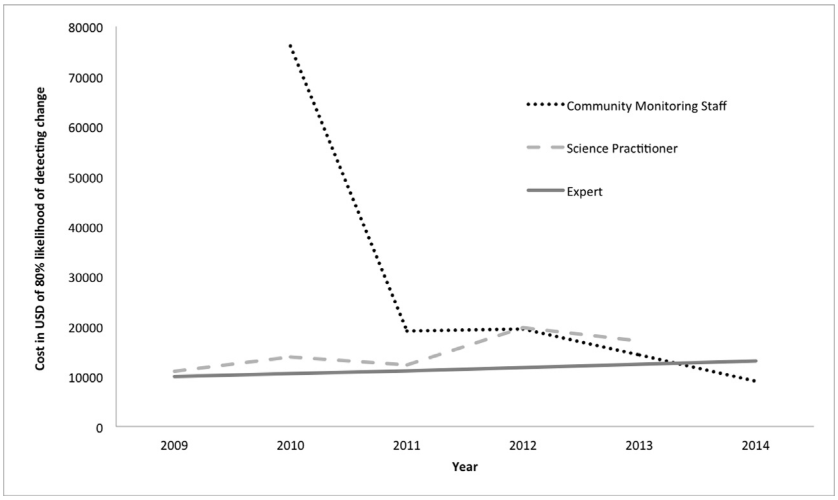

Fig. 5. Ratio of cost in USD for an 80% likelihood (power) to detect a 20% change in fish biomass at $p = 0.05$ power (i.e. sufficient power as defined in Section 2.2.1) in a sample (averaged over all MPAs) for each of three strategies through time (dotted line = external expert, dashed line = science practitioner, solid line = community monitoring staff).

Table 2

	I: External expert	II: Science practitioners	III: Community monitoring staff
A. Baseline	100%	71%	57%
B. Sufficient power	Yes	Yes	Yes
C. Minimise time lag of sufficient power	0	3	5
D. Sufficient capacity	Yes	Yes	Yes
E. Minimise time lag for sufficient capacity	0	3	4
F. Cost efficiency of information (2010)	High	Med	Low
F. Cost efficiency of information (2014)	Low	Med	High

Consequence analysis strategy evaluation table showing the performance of each strategy (column labels) against each of the six objectives (A-F, row labels, described in full in Section 2.2). Shading indicates that a strategy has met an objective criteria (dark grey) or not (white), while grey indicates partial fulfillment. For objectives that are directional (i.e. *minimize*) rather than target based, dark indicates the best strategy, grey intermediate, and white lowest. Note cost efficiency of information (Objective F) assessments for both 2010 and 2014.

community monitoring staff strategies increase in power through time, with community monitoring staff ultimately most cost effective, while delivering a legacy of on-ground capacity, although capacity development has also come at the cost of a robust baseline at some sites.

4. Discussion

The goal of most monitoring programs is to explicitly link the data generated to conservation action, environmental policies, or decision-making. Different monitoring strategies have different tradeoffs in reaching that goal (Table 2). We find that expert assessment has clear benefits, including ensuring that baseline data of sufficient quality are collected, but also the disadvantage of being costly. In contrast, much of the data collected in the initial phase by community monitoring staff as they were still developing data collection and management skills was too simple, biased, or variable to be used, with the distinct disadvantage of not having a baseline prior to the establishment of management.

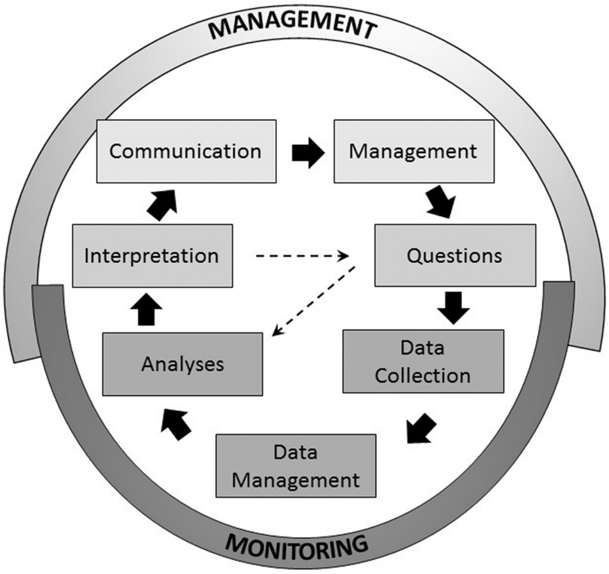

Fig. 6. The “full cycle of monitoring” (originally in Ahmadia et al., 2013).

Baselines, unlike other monitoring data, are a special case with high value of information, because they are a time sensitive requirement; only a one-off opportunity to collect baseline data exists. For long-term sustainability, however, building local capacity in the communities where natural resource management is occurring (i.e. community monitoring staff strategy) is more cost-efficient, with the added benefit of being more likely to be financially and socially sustainable due to the lower continuing cost and higher local benefits. The BHS monitoring program evolved to be more cost-effective by clarifying shared objectives and better understanding tradeoffs in 1) power to detect change, 2) capacity, and 3) costs and cost effectiveness with different monitoring strategies. Perhaps the most interesting finding (Table 2) is that a combined strategy would result in no criteria that have not been met, meaning a rare “win-win” situation can be achieved. Monitoring programs globally could benefit from adapting strategies to incorporate these considerations.

4.1. Power to detect change

A greater focus on monitoring objectives, the statistical implications of sampling design, and power analysis has resulted in a more reliable methodological design with adequate sampling (Legg and Nagy, 2006; Burton, 2012) and increased information benefit from locally-based ecological monitoring. Additional mechanisms used to ensure monitoring is sufficient to detect state changes include:

1. Aligning the monitoring strategy to expectations for the data (Possingham et al., 2012);
2. Explicitly examining the cost effectiveness of survey design, including a priori power analyses and a plan for adaptively evaluating and improving implementation and power (Legg and Nagy, 2006);
3. Allocating sufficient resources towards data management and analysis, as a disproportionate effort is often put into data collection (Caughlan and Oakley, 2001); and
4. Regular review of the monitoring program (Kleiman et al., 2000), including early and frequent data analysis, which can detect problems with data quality or design criteria as well as meet programmatic needs for current information.

We found the first rounds of locally-collected monitoring data had low accuracy and precision, complicaing the process of detecting true population trends, as in other studies (Burton, 2012; Leopold et al., 2009). This meant that it was initially inadequate for decision-making to determine if a management intervention was required (e.g., declines in fish biomass shown through monitoring is critical for local enforcement teams to help them prioritize where to invest patrol time and resources). Data at some sites also exhibited observer bias, data fragmentation, inadequate sample sizes, and experimental design not integrated across multiple sites. These challenges were addressed through improving experimental design and further strengthening capacity for monitoring and planning, with inaccuracies addressed through extensive training and feedback to help standardize the data, following existing best practices (Conrad & Hilchey 2011; Mumby et al., 1995; Uychiaoco et al., 2005).

The main implication of this finding is that community monitoring staff did deliver high quality data after a delay period, in this case ~3–4 years, after which they had similar capacity to other strategies. While initially this is insufficient for program evaluation and decision support, by accounting for the delay, data can be transformed to evidence much earlier in the process.

4.2. Capacity

In developing countries without a strong history of formal MPA management, and with limited higher education institutions that can teach the full-range of scientific skills necessary to support well-designed ecological monitoring efforts, many locally-recruited staff members lack skills for the "full cycle of monitoring" (Fig. 6) upon hiring. Locally-based monitoring may yield less accurate and less precise data, but it is also usually less expensive, and can help local stakeholders better understand their resources (Burton, 2012; Holck, 2008; Uychiaoco et al., 2005) and build scientific capacity within a community (Danielsen et al., 2005). Indeed, the case for data-less marine resource management has been made convincingly (Johannes, 1998b). In a potential positive feedback loop, developing capacity has the ability to strengthen and improve locally-based monitoring (Seak et al., 2011). Less tangible benefits might include building social capital, citizen inclusion in local initiatives, and improved collaboration between the community, government, and NGOs (Andrianandrasana et al., 2005; Conrad & Hilchey 2011). Locally-based monitoring can lead to additionality by empowering stakeholders through increased local participation in management decisions (Danielsen et al., 2005; Fraser et al., 2006), resulting in more equitable governance, and a sense of pride in living local heritage (McLeod et al., 2015). To build a competent, sustainable science team, an MPA program must invest in each staff member's skills, learning trajectory, and professional goals with an eye to developing overlap in skills and understanding of different professional skill levels. This can improve programmatic communication and teamwork, as well as buffer programs in developing countries that experience high rates of missed work through poor health of staff or family obligations (C. Huffard, *pers. obs.*).

We recognize that our approach of scoring capacity based upon managers' opinions of competency is subjective. While we made the best use of the available data, a more robust approach would be to use (and keep track of) more objective measures such as standardized tests of species identification, in-situ size estimation, and data handling. In response to this need a Monitoring and Evaluation Capacity Scorecard has now been developed to document the ability of monitoring teams to design, implement and sustain appropriate marine protected area monitoring and evaluation systems in the BHS into the future (Glew et al., 2015b; Table A2). Nonetheless, we are confident that concerted capacity development efforts in the BHS have resulted in highly qualified community monitoring staff in a variety of academic, non-governmental and government organizations.

4.3. Costs and cost-effectiveness

Lower costs help ensure that the benefits received from monitoring efforts are greater than the resources expended. Longer-term resources for adaptive management and decision support can be challenging to maintain, so ensuring low costs and planning for financial sustainability after the initial start-up phase is pivotal to sustainable monitoring and management, although sustainability also depends on the monitoring program's continued usefulness to its managers (Andrianandrasana et al., 2005).

Actions such as planned exit of expatriate science staff from MPA programs can further reduce costs. In West Papua capacity-development efforts were designed with this transition in mind from the beginning, prioritizing teaching the teams to collect, analyze, interpret data independently, and communicate results to stakeholders. It is important to note that while community monitoring staff capacity for data collection is similar to that of science practitioners, they do not possess sufficiently advanced skills to independently manage their monitoring program (Fig. 3). An interesting follow up question would be an assessment of the process and time required for community monitoring staff to gain this ability, as program choices for any monitoring program may be dictated by whether other capacity is available to manage this component of the system. Since here, the science practitioner strategy has similar power as the community monitoring staff strategy (though higher cost per unit power), there will be situations in a broader context where this additional capacity may change the relative benefit, and therefore ideal strategy for supporting evidence based conservation in the global MPA network.

With the planned transition, costs will continue to decrease. Therefore, a similar overall investment, more strategically allocated with deliberate up-front loading, could have mitigated some tradeoffs. Few programs have the option for such staggering, however, and grants are commonly disbursed at a specific total value per annum. Granting agencies, governments, and philanthropists willing to strategically stagger investments could foster more rapid timelines that would provide sufficient information to inform managers, governments, and policy makers, as well as to evaluate their own programs, with no additional overall cost. Across entire portfolios, the annual cost needn't be highly variable, making such strategies feasible with stable annual yields from capital.

4.4. Conclusions and recommendations

The real value of any large investment in monitoring will come from (i) high quality data being used to inform decisions and adaptive management, (ii) increased local capacity resulting in better governance of marine resources, and (iii) the conservation of marine resources. Monitoring data from the BHS even during the early stages was fed directly into community conservation planning processes to try and meet both ecological and socioeconomic objectives for the MPAs (Mangubhai et al., 2015). Where monitoring showed new damage to coral reefs, for example from bomb fishing, local community enforcement teams were alerted so that patrols could focus on those areas. Ultimately, meeting the monitoring objectives is not the final benchmark against which success or failure of a monitoring program will be measured. The true test is whether the hypotheses underpinning these strategic goals can be validated, and whether the information provided does in fact inform decisions by managers, policy makers and others.

We posit that the foundation for a sustainable high capacity local monitoring program that informs conservation action has been laid here. Communicating declining trends in some locations led to increased community education and investment towards training MPA managers (Glew et al., 2015a and G. Ahmadia, *pers. comm.*). In combination with rigorous social impact monitoring (Glew et al., 2012), insights from the BHS have already informed coastal zone planning and resulted in adaptive management, with rezoning of some Papuan MPAs. This research has also shaped efforts to monitor the impact of conservation investments in other geographies (e.g., the Eastern Tropical Pacific Seascape and the Sunda Banda Seascape) and the findings have major implications for increasing the quality and utility for decision making of monitoring data if replicated in other MPA networks. By integrating monitoring strategies, the core tradeoff associated with implementing community monitoring programs where skill development is required can be avoided, decreasing the delay in how soon information can begin to be used to support evidence-based decision making, and the long-term value of all the information is increased.

A more rapidly available evidence base that includes robust pre-establishment baselines will help managers and other decision makers more rapidly respond to threats, avoiding the constant struggle to conduct management and formulate policy 'in the dark' (Cook et al., 2010). Thus, for future monitoring efforts we recommend an integrated, staggered investment strategy to promote cost-efficiency and local capacity, with an early focus on planning, design, and high quality data collection by experts to ensure the high-value baseline data is produced and uncompromised, combined with investment in developing monitoring capacity in local staff over longer time horizons.

Evaluations with other objectives, e.g., establishing comparison sites for impact evaluation, would similarly benefit from an integrated approach. Simultaneously collecting an expert baseline until local capacity meets required standards to collect high quality data, at which point science practitioners or local staff can take over, would have most of the advantages and few of the drawbacks of any single strategy, although the transaction costs of coordination can be high. This integrated strategy is particularly important if there is a limited time to establish a strong baseline (e.g. before management is implemented) against which to measure conservation impact. The long-term cost-efficiency of a locally-based monitoring strategy is sufficiently high to justify initial investment.

An integrated strategy would benefit from increased emphasis on the "full cycle of monitoring" (Fig. 6), which recognizes that to provide scientific support to MPA management, questions must be clear, and monitoring teams need to be able to collect data, perform analyses, and interpret new and existing data to recognize change or lack thereof. This approach requires a breadth of knowledge to identify and test probable drivers and causal links, and then communicate these results to non-scientists and stakeholders to generate and implement informed recommendations about how to mitigate ecosystem declines. While the term "monitoring" is often equated with data collection, we found that (as is frequently the case) more resources needed to be put into clear formulation of questions and objectives on the front end, and also more time and thought put into data management and organization, analysis and synthesis, and interpretation and communication to decision makers on the back end (Caughlan and Oakley, 2001). Developing local scientific capacity for the full cycle of monitoring is key to informed decision-making and ensuring long-term sustainability of efforts to conserve biodiversity.

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Appendix A. The Bird's Head Seascape (BHS) and BHS monitoring program

As the global epicenter of marine biodiversity, the Bird's Head Seascape (BHS) in West Papua, Indonesia, has been identified as the top marine conservation priority region in Indonesia (Veron et al., 2009; Huffard et al., 2012a, 2012b). The BHS is home to > 1,600 species of coral reef fishes (Allen and Erdmann, 2012) and approximately 75% of the world's scleractinian coral species (Veron et al., 2009). At the same time, the waters of the BHS provide critical habitats for globally threatened sea turtles and cetaceans. These natural riches support the livelihoods and food security of > 350,000 people (Mangubhai et al., 2012). The coastal communities of the BHS are highly dependent on marine resources, with marine capture fisheries providing the main source of monetary income for almost a third of households and the majority of dietary protein for 75% of households (Glew et al., 2012).

Over the past decade, national and international conservation efforts to improve fisheries management in the BHS to both sustain the livelihoods of local communities in coastal Papua and conserve its remarkable marine biodiversity resulted in > 3.5 million ha under protection as of 2014, with the 15 marine protected areas (MPAs) representing almost a fifth of Indonesian MPA estate (Mangubhai et al., 2012). A monitoring program was designed with two main objectives: (i) to assess the effectiveness of management interventions, (ii) assess the health of corals and recovery of fish populations inside no-take zones. Monitoring was carried out over several phases (Table 1). With the establishment of new institutions for marine conservation in Papua came new information needs. In preparation for transitioning management of the MPA sub-networks to Regency government units (Unit Pelaksana Teknis Daerah) a Monitoring and Evaluation Capacity Scorecard was developed to document the ability of Indonesian institutions to design, implement and sustain appropriate marine protected area monitoring and evaluation systems in the BHS (Glew et al., 2015a 2015b; Table A2).

Table A1
Phases and relative emphasis for the BHS monitoring program by strategy, where different (SP = science practitioner and CS = community staff).

Years	Main objectives	Focus for capacity development
2005–2008 (Phase 1)	Establish general understanding of community socioeconomic status, and marine ecosystem condition allowing for initial communication and outreach. Coarse data collection for MPA zoning.	Manta tows, perceptions monitoring targeted research exposing monitoring team to a variety of research techniques.
2008–2011 (Phase 2)	CS: Build capacity of the team. Expand team from core group established in Phase I to include community monitoring team members. Community monitoring team members took part in regency-wide science team activities, but also focused on identifying the science needs of their communities (based on the fisheries and resources important to them), and took part in their MPA's community outreach activities. SP: Data collection using Wilson and Green protocol, to establish a baseline for long-term monitoring and select NTZ. Standardized the timing of data collection—noting different times for the MPAs (Oct/Nov = Misool, Mar/Apr = Kofiau). Focus on governance structures at the MPA level, and the management interventions at the management level.	CS: Group trainings including classroom sessions, one-on-one instruction, and field exercises. Taught in-house, with more experienced team members teaching their areas of expertise. SP: Developed sampling strategy for Kofiau and SE Misool MPA. High level staff received advanced training in analysis and publication of data.
2011–2014 (Phase 3)	CS: Collect baseline data. Develop and begin to implement MPA-specific monitoring protocols to address community interests and concerns identified by community monitoring staff. These staff were involved in communicating monitoring results of their home MPAs.	Addition of comparison sites in 2012.

	SP: Modified monitoring to take into account the final zoning configurations, added additional sites to areas where there were insignificant replicates inside and outside MPAs. Establish baseline data 2–3 years before management interventions, so that variability at site is understood.	
2014–2017 (Transition Phase)	Streamline and transition to UNIPA	Many staff transitioned from NGOs to government agency

Table A2

Reference thresholds for adequate capacity. Technical competencies include Knowledge of literature, Selection of research questions, Research design, Data collection methods, Data management methods, Data analysis and interpretation, and Communications. Foundational competencies include Project management, Fundraising, and Pedagogy (from Glew et al., 2015a, 2015b).

Competency levels	
1-Basic	Demonstrates familiarity with concept, but unable to implement
2-Novice	Demonstrates familiarity with concept and ability to implement with assistance from others
3-Proficient	Demonstrates familiarity with concept, and ability to implement independently. Assistance required to apply concept in novel ways (i.e., to innovate)
4-Expert	Demonstrates ability to implement independently, innovate and transfer skills to others.

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