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LETTER

Integration of Indicator Alarm Signals for Ecosystem-Based Fishery Management

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Abstract

We consider the problem of regulating the rate of harvesting a natural resource, taking account of the wider system represented by a set of ecological and economic indicators, given differing stakeholder priorities. This requires objective and transparent decision making to show how indicators impinge on the resulting regulation decision. We offer a new scheme for combining indicators, derived from assessing the suitability of lowering versus not lowering the harvest rate based on indicator values relative to their predefined reference levels. Using the practical example of fisheries management under an "ecosystem approach," we demonstrate how different stakeholder views can be quantitatively represented by weighting sets applied to these comparisons. Using the scheme in an analysis of historical data from the Celtic Sea fisheries, we find great scope for negotiating agreement among disparate stakeholders.

Introduction

Combining information from multiple, and possibly conflicting, ecological, and additional relevant indicators is a general problem for sustainable resource management (Campbell *et al.* 2002), especially relevant for fisheries (Alder *et al.* 2010) as well as other sectors such as forestry (Wolfslehner & Vacik 2011). The problem is amplified when also trying to take account of diverse stakeholder perspectives. Using the example of an Ecosystem Approach to Fisheries Management (EAFM; FAO 2003), we demonstrate a process for combining a wide range of indicators into a tool for quantitatively comparing management options given the different priorities of multiple stakeholder groups. We take the Celtic Sea fisheries (ICES subdivisions VII e-k) as a worked example and test the method with retrospective data, covering ecological (Piet *et al.* 2008) and economic (Ceriola *et al.* 2008) aspects of the fishery system.

Resource management has generally a broad remit, but in fisheries it concentrates on controlling fish harvesting rates. It often can be interpreted as a control system, driven by signals (indicators) and responding to the crossing of preset thresholds (reference levels), alerting to stress on stocks or other aspects of the system. Rice (2003) and Piet & Rice (2004) recognized this as a threshold-response mode of fisheries management, amenable to the Signal Detection Theory (SDT; Egan 1975), used to quantify the probability that an observer (operator) may respond when thresholds are exceeded. We take an analogous approach, similar to receiver–operator characteristics (ROC; Metz 1978; Søreide 2009) to quantify the evidential support behind management of the harvest rate (Φ) via total allowable catch (TAC) setting.

Here we use the term "harvest rate" in its resource management sense, rather than the specific meaning ascribed by fisheries science. Our signal detection approach focuses on the consistency of management decisions with indicator signals relative to their reference values. We aim to reduce a problem of combining multiple indicators, often with incompatible units, to a one-dimensional signal, by analogy with the "smart alarm" found in anesthesiology (Imhoff & Kuhls 2006). We further simplify the problem to two management options, namely *to reduce* or *not reduce* harvest rate, for example, of a particular species in single-species management. We can then calculate one signal, which we term the "Response Support Signal" (RSS), across the complete range of indicators and options. The RSS quantifies the level of evidential support for each of: reduce or not-reduce the harvest rate. The RSS can incorporate indicator signals from all monitored stocks simultaneously, as well as other ecological and economic indicators as required. It could be interpreted as an additional source of information representing the ecosystem and wider fisheries concerns, which can be used to operationalize EAFM. The tool is not intended to dictate a decision to managers; only to structure communication, facilitating discussion between stakeholders in a transparent governance process.

We extend the concept to allow the incorporation of the views of a wide range of stakeholders and broader objectives. We assume a tactical objective for fisheries management under the EAFM: determining which management option is aligned with the information from a set of indicators and supported by stakeholder preferences. Since fisheries management often should meet multiple objectives set by different stakeholders, it will tend to be normative, context-dependent and multidimensional. Generally, indicators are not equally informative and stakeholders may differ in the relative priority they give to each and the consequences of missing targets set for them. We account for this by applying sets of weightings to the indicators, each representing a different "scenario" for management priorities, for example of a particular stakeholder. Scenarios can reflect stakeholder positions on (1) the relative importance of different indicators and (2) the relative costs of maintaining indicator values in relation to thresholds. Choices over these are kept explicit and transparent providing clear separation between normative decisions and objective information. We use this scheme to examine eight illustrative management priority scenarios, contrasting ecological with economic priorities, to demonstrate its potential as a stakeholder engagement tool in which candidate management responses can be compared.

Methods

Historical analysis of management responses in relation to indicators

Fishing time-series were obtained from ICES Advice Reports in an approach similar to Piet & Rice (2004), for nine Celtic Sea stocks. Twenty-one indicators, with their reference levels, were obtained from the literature (Table 1 and Section S1). Complementarity, a measure of mutual information, among indicators was assessed by calculating a similarity matrix based on the proportion of years for which pairs of indicators simultaneously recorded either presence or absence of a warning signal in their time-series (Section S1.2) This showed statistical evidence for mutual dependency only among the individual stocks' safe biological limits (SBL) indicators, even though we may expect some correlation among indicators on theoretical grounds. To avoid mixing and confusing stakeholder priorities among indicators, we do not combine indicators into orthogonal vectors (e.g., PCA), but keep them separate, despite nonzero mutual information. All the indicators and thresholds and our interpretations of them in relation to Φ are presented as an illustration, rather than a definitive statement: the interpretation used in practice will depend on the particular system examined.

We generate a categorical "status signal" from each indicator. Each status signal is formed in two stages: first, an indicator "warning signal" records whether the indicator is within or beyond its threshold reference level; second, the status signal is generated to record whether a (hypothetical) change to Φ would be aligned with that warning signal: meaning reducing Φ when the indicator is beyond the threshold and not doing so when it is within it. Since Φ is usually adjusted for each fish stock separately, a set of indicator–stock combinations is formed, each having a status signal, which takes an annual value specified by the following definitions, analogous to SDT:

Hit $^-$ (H $^-$): Management set a TAC corresponding to a reduced Φ when the indicator was outside the reference point (RP) (warning signal on; Φ reduced).

Hit $^+$ (H $^+$): Management set a TAC corresponding to an increased/maintained Φ when the indicator was within the RP (warning signal off; Φ not reduced).

Miss (M): Management set a TAC corresponding to an increased/maintained Φ when the indicator was outside the RP (warning signal on; Φ not reduced).

False Alarm (FA): Management set a TAC corresponding to a reduced Φ when the indicator was within the RP (warning signal off; Φ reduced).

Table 1 List of indicators used in the study, the time period covered by each indicator, and the source of the time-series

Indicator and region	Region covered	Time-series
Abundance	EVHOE* Celtic Sea	1987-2002
Average weight	Celtic Sea VIIfghj	1987-2003
Catching efficiency	Celtic Sea VIIe-k	2000-2007
Community biomass	Celtic Sea VIIe-k	1991-2005
		Max - 1984-2010
Discard rate	See area covered by stocks, Table S.5	
		Min - 2005-2010
Fishing-in-balance	Celtic Sea VIIf-j	1946-2006
Fuel costs	Mean across EU countries	2000-2008
Inverse fishing pressure	Celtic Sea, VIIe-k	1991-2005
Large fish indicator	Celtic Sea VIIe-h, j	1986-2004
Log relative price index	Celtic Sea VIIf-k	1972-2000
Large species indicator	Celtic Sea VIIe-h, j	1986-2004
Marine trophic index	Celtic Sea and Bay of Biscay	1950-2006
Mean trophic level	Celtic Sea VIIf-k	1946-1998
Pelagic : demersal biomass ratio	Celtic Sea VIIfghj	1987-2003
Revenue per gear type	Celtic Sea VIIe-k	2003-2010
Revenue per unit effort	Celtic Sea VIIe-k	2003-2008
Safe biological limits (SBL)	See area covered by stocks, Table S.5	1953-2011
Size spectrum	Celtic Sea VIIfghj	1987-2003
Spawning stock biomass per recruit	See area covered by stocks, Table S.5	1978-2011
Species evenness	OSPAR Region 3	1984-2007
Species richness	Celtic Sea VIIfghj	1997-2007

From the frequency of H^-, H^+, M, and FA in each stock for each indicator, the true positive rate (TPR) and false positive rate (FPR) were calculated as

$$\text{TPR} = \frac{\text{N}(H^-)}{\text{N}(H^-) + \text{N}(M)}; \text{FPR}\frac{\text{N}(FA)}{\text{N}(H^+) + \text{N}(FA)},$$

where $N(x)$ denotes the frequency of occurrence of *x*.

TPR is plotted against FPR to summarize the degree of congruence (alignment) between decisions and indicator values. Before studying the consequences of our proposed scheme for combining multiple indicators, we examined the degree to which historical fisheries management in the Celtic Sea had aligned with the chosen set of indicators using these plots for the historical data. The information from this suite of indicators was, of course, not available to managers at that time, and there was no requirement for them to take account of it. The aim here was to compare the historical management choices over Φ, with those that might have been taken had the managers been able to use indicators for wider ecosystem and economic objectives.

Presently, management sets TACs of fish stocks, but that is only the means by which Φ is set. Since in fisheries management, Φ is quantified by fishing mortality (F), which in turn is expressed relative to stock numbers, and a proposed TAC is calculated from this, we focus on "F implied by the TAC" (hereafter Ƒ), considering this the

metric of fishery regulation. Note that increased TAC may correspond to reducing Ƒ, given sufficient concomitant increase in stock size (Walters & Martell 2004). Since our interest is in what fisheries managers can practically achieve with the information available to them at the time of decision making, we test our method with the estimates available at the time of decision making, rather than with post hoc refined estimates (commonly calculated in fisheries management) previously used by Piet & Rice (2004). Details describing the data used are provided in Section S1. We generated one ROC plot for each indicator, each data point corresponding to a fish stock (Section S2).

Aggregating among indicators through management priority scenarios

Assuming only a tactical scope of fisheries management, objectives are achieved through an annual regulation of Ƒ by aligning decisions with ecological and fisheries indicators. Note that since fisheries are currently regulated through single stock harvest control rules, we envisage the aggregate of whole-system indicators as providing additional guidance, rather than necessarily replacing single-stock management.

For each year of an indicator time-series, two management options were defined: (1) reduce (**R**) and (2)

not-reduce (**N**) including increase, Ϝ. Referring to the SDT definitions above, only H^- or FA are possible under **R** and only H^+ or M are possible under **N**. Each of these SDT outcomes (H^+, H^-, M, FA) was numerically weighted according to the values in specific scenarios (Figure 1, Table 2). For each year, the weighted SDT outcomes were summed over indicators to produce the aggregate signal. There was one of these for each management option: $\mathbf{A_R}$ for **R** and $\mathbf{A_N}$ for **N**. The RSS was calculated as $\mathbf{A_N} - \mathbf{A_R}$ (Figure 1). A positive RSS indicates evidential support from indicators in aggregate to not-reduce (including increase) Ϝ, whereas a negative RSS indicates evidential support to reduce Ϝ, recalling that RSS is regarded as additional advice applying to all stocks.

Empirical testing of the scenario method

Eight example scenarios were constructed using weighting values chosen for illustration; these are defined in Table 2. In practice, we would expect weightings to be the outcome of stakeholder deliberation and reflect the relative reliability, information content, and importance of different indicators in a particular circumstance, but here they are designed as probes to reveal the behavior of RSS in relation to indicator signals (in our illustrations, integers and constant multiples were used for simplicity only). The SBL indicators, which describe individual stocks by Spawning Stock Biomass and F, are individually included for all stocks in calculating the RSS. The inclusion of all nine SBL indicators in most scenarios is for illustration only, and not intended to prescribe that the status of all species is necessarily important for the management decisions on each individual species; a relevant subselection of SBL indicators could be used. In all the risk-averse scenarios, Misses weigh heavier than False Alarms among all indicators.

Two scenarios, termed "Indicators Equal," demonstrate the difference between risk-neutral and risk-averse weighting, all other things equal. "Ecological" and "Economic" Priority scenarios (both risk averse) give higher weightings to a corresponding subset of indicators, contrasting management priorities. The "SBL Only" scenario reveals the effect of eliminating all but the SBL indicators of fish stocks, conversely the "SBL-Removed" scenario shows the behavior of all the non-SBL indicators. Under the "Cod Priority" scenario, cod SBL was heavily weighted to illustrate a hypothetically strong focus on the status of a single species. Under the "Demersal Priority" scenario, SBL indicators for pelagic stocks (herring, mackerel and horse mackerel) were removed, all others remaining, illustrating the prioritization of demersal over pelagic fish stocks' status. Time-series of the resulting RSS were plotted for each of these eight priority scenarios

and their magnitudes interpreted as indicating the level of evidential support for a management decision.

For each RSS, a binary time-series, which we term the "supported response" **Y**, represents whether or not the RSS supports a reduction in Ϝ. We compared **Y**, calculated for Ecological and Economic Priority scenarios, to historical records of changes in Ϝ (both historical advice and implemented management action) in each fish stock. Comparison was quantified by the proportional number of years of the time-series (available for each stock) in which **Y** aligned with the advised or implemented direction of adjustments, using a binomial test for significance. A similar analysis quantified the level of agreement between the ICES advice and corresponding implemented adjustments in Ϝ (Sections S3 and S4).

Results

Figure 2A illustrates the TPR and FPR of management decisions in three indicators over the set of fish stocks for which SDT analysis was possible (see Figure S3, for complete set). Pooling across years and stocks showed historic management to be independent of indicator alarms (Figure 2B, $\chi^2 = 0.2$, $P > 0.5$). There was a (nonsignificant) higher occurrence of H^+ and M than H^- and FA, reflecting a bias of historical management towards not reducing Ϝ (64% of years).

The most striking feature of the RSS from the eight stakeholder scenarios was that all support a reduction in Ϝ from 1980 onward, especially during 1990–2008 (Figure 3), showing that different weighting scenarios do not necessarily produce radically different results. Based on the pair-wise comparisons of indicators (Figure S1), the median similarity among SBL indicator pairings was 0.78. There was little correlation among other indicators. The Ecological Priority scenario (Figure 3E) showed no conflict with the Economic Priority scenario (Figure 3F), suggesting scope for agreement on Ϝ among stakeholders. The support for decreasing Ϝ was very clear from SBL, aggregated over stocks (Figure 3A), and reinforced by correlation. When SBL was removed from the mix (Figure 3B), a clear direction was much less readily discerned (no special status was accorded SBL indicators in the preceding analysis). Prioritizing cod and demersal stocks (Figure 3G and H, respectively) generated RSS that differed little from those in Figure 3C–F.

Implemented Ϝ changes for cod, whiting, and horse mackerel significantly disagreed with **Y** from Ecological and Economic Priority scenarios (Table 3). The disagreements occur because historical management did not reduce Ϝ when the RSS (unavailable at the time) suggested a decrease, though recall this is only an illustration. **Y**
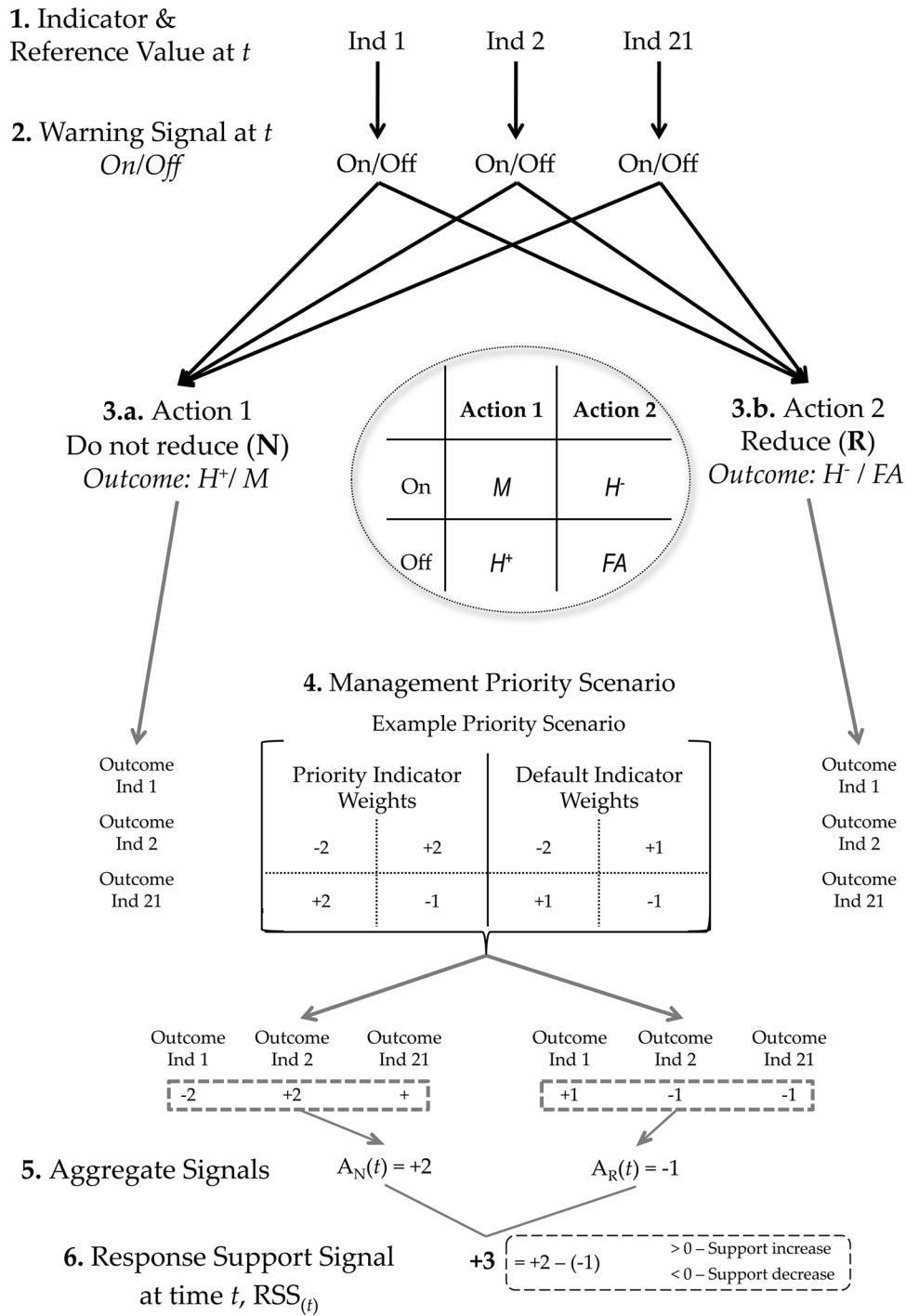
1. Indicator & Reference Value at *t*

Ind 1   Ind 2   Ind 21

2. Warning Signal at *t* *On/Off*

On/Off   On/Off   On/Off

3.a. Action 1 Do not reduce (**N**) Outcome: *H⁺/ M*

	Action 1	Action 2
On	*M*	*H⁻*
Off	*H⁺*	*FA*

3.b. Action 2 Reduce (**R**) Outcome: *H⁻ / FA*

4. Management Priority Scenario

Example Priority Scenario

Outcome Ind 1

Outcome Ind 2

Outcome Ind 21

Priority Indicator Weights		Default Indicator Weights	
-2	+2	-2	+1
+2	-1	+1	-1

Outcome Ind 1

Outcome Ind 2

Outcome Ind 21

Outcome Ind 1   Outcome Ind 2   Outcome Ind 21   Outcome Ind 1   Outcome Ind 2   Outcome Ind 21

| -2 | +2 | + | | +1 | -1 | -1 |

5. Aggregate Signals $A_N(t) = +2$ $A_R(t) = -1$

6. Response Support Signal at time *t*, $RSS_{(t)}$ **+3** $= +2 - (-1)$ $> 0 -$ Support increase $< 0 -$ Support decrease

Figure 1 Signal processing algorithm for calculating the RSS time-series. Each indicator warning signal is 'on' at time t if its value at t exceeds the indicator's reference value; it is 'off' if it does not. The reduce (**R**) and not-reduce (**N**) actions are applied across the time-series for all indicators 1 . . . 21. The indicator warning signal combined with **N** generates either a Hit+ or Miss outcome; if combined with **R** it generates a Hit− or False Alarm outcome at time t. The outcome signal is weighted using a scenario which sets a weighting for the indicator and the outcome value (e.g. weighing Miss > False Alarm) (defined in Table 1). This produces the two aggregate signals $A_N(t)$ **N** and $A_R(t)$ for **R**. RSS(t) is then $A_N(t)$ - $A_R(t)$ and plotted in Figure 3 for each example scenario.

Table 2 Weighting system for the eight priority scenarios

Priority scenario	Weightings	
SBL only, Risk Neutral	1, 1, −1, −1	
SBL removed, Risk Neutral	1, 1, −1, −1	
Indicators Equal, Risk Neutral	1, 1, −1, −1	
Indicators Equal, Risk Averse	1, 1, −2, −1	
Demersal focus (Pelagic SBL removed), Risk Averse	1, 1, −2, −1	
	Priority indicator weights	Default weights
Ecological Priority, Risk Averse	2, 2, −2, −1	1, 1, −2, −1
Economic Priority, Risk Averse	6, 6, −2, −1	1, 1, −2, −1
Cod SBL Priority, Risk Neutral	2, 2, −4, 1	1, 1, −1, −1

Ecological priority indicators: large fish indicator, fishing-in-balance, average weight, size spectrum, large species indicator, species richness, species evenness, pelagic : demersal biomass ratio, mean trophic level, marine trophic index, recruitment/spawning stock biomass, SBL indicators, discard rate, inverse fishing pressure, community biomass, abundance

Economic priority indicators: catching efficiency, log relative price index, revenue per gear type, revenue per unit effort, fuel costs

The Cod SBL scenario uses the Cod SBL indicator as the priority indicator

Values are in order of *H*−, *H*+, *M*, and FA. The first section of the table shows risk weightings applied to all indicators. The second section shows the additional weighting that gives priority of selected indicators over others. The weightings are arbitrary and chosen as an illustration.

from both scenarios agreed more often with the *advised* F changes, showing significant agreement for cod, megrim, sole, plaice, and (for Economic Priority only) herring stocks (Tables S9 and S10).
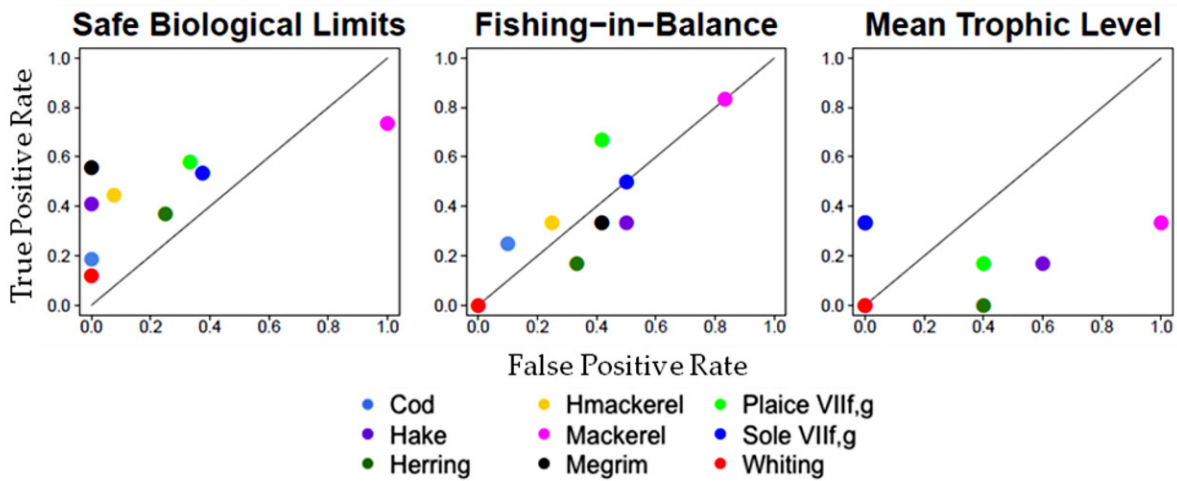
Discussion

Living-resource management needs a scientifically objective means of forming guidance that takes account of (1) multiple and potentially conflicting, but uncertain, indicators and (2) multiple stakeholder interests. The SDT framework offers a practical and effective means of assessing the quantitative usefulness of different indicators in terms of sensitivity and specificity that are most relevant to the practice of fisheries management. Our analysis illustrates a practical and general method for achieving this by calculating an RSS value, which combines both objective indicator information and the expressed preferences of stakeholders, to be used as guidance for managers' decisions. Note that the tool is not necessarily intended to dictate to managers what decision to implement; it aims to structure communication, facilitating discussion between stakeholders in a transparent governance process.

Weightings applied to indicators could reflect their sensitivity and specificity to harvesting, timeliness of response, and the quality and quantity of data used to generate them (this has been quantified in studies such as Houle *et al.* 2012). They could also reflect confidence in identifying appropriate reference values and relative risks of misses. Weightings could also reflect how relevant and

important a stakeholder considers an indicator to be, as this is likely to vary among stakeholders (Rochet & Rice 2005). All these attributes may affect the degree to which different stakeholders place faith in particular indicators, and can all in principle be represented by relative weightings. In the particular EAFM case studied, the set of SBL signals gave the strongest consistent guidance to management (Figure 3A compared to Figure 3B). This should not be interpreted to mean that other indicators were less useful, only that they were less consistent with one another in the particular example studied. Potentially, they could have given a coherent signal that could have influenced management. They remain necessary because they represent aspects of the wider system that must be taken into account in EAFM. In practice, the status of only a subset of species may be considered relevant for a particular management decision; in such a case the relevant subset of SBL indicators could be used.

Quantitative descriptions of stakeholder interests (Duggan *et al.* 2013) and their position on risk (i.e., the relative costs of misses against false alarms) may be used to construct different weighting scenarios for different stakeholder groups, so helping communicate stakeholder priorities and confidence in different indicators. This would be part of a consultation process leading to the explicit and quantitative description of the information most useful in achieving management goals. If combined with a model of the managed system, this process may extend to validating the performance of decision rules using a management strategy evaluation framework (Smith *et al.* 2007). It can also identify how combinations
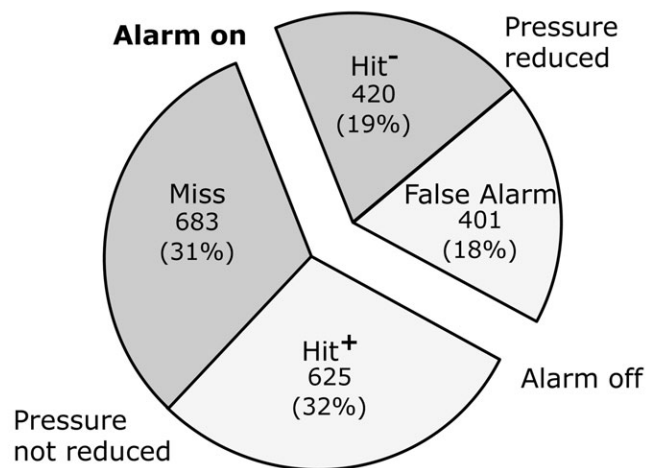
(a)

(b)

Figure 2 (a) Three illustrative ROC plots for indicators as labeled. Each point represents a fish-stock time-series: the further it is to the top left corner of the plot, the more often management action for that stock was appropriate to the indicator signal (in the language of SDT this is positive discrimination). The diagonal line of zero discrimination is shown as a guide: points to the right and below the line show inappropriate responses to the indicator (negative discrimination). (b) Median proportion of Hit−, Hit+, Miss, and False Alarms detected among the indicators, pooling over years and stocks. Dark grey indicates number of times alarms were on and light grey indicate number of times alarms were off. The split indicates whether pressure was reduced (right) or not reduced (left). (The remaining plots are presented in the Supporting Information).

of candidate indicators may improve the guidance for management decisions in an ecosystem approach to resource management.

An operational tool for EAFM requires an increased number of species and the incorporation of "nonfishing values" (Kellner *et al.* 2011, e.g., biodiversity), integrated

so as to flexibly combine economic and other priorities. Our proposal enables this by reducing an inherently multidimensional (and nonscalar) problem to a simple one-dimensional RSS and also explicitly takes account of multiple stakeholder views. The proposed scheme maintains an explicit boundary between scientific and policy
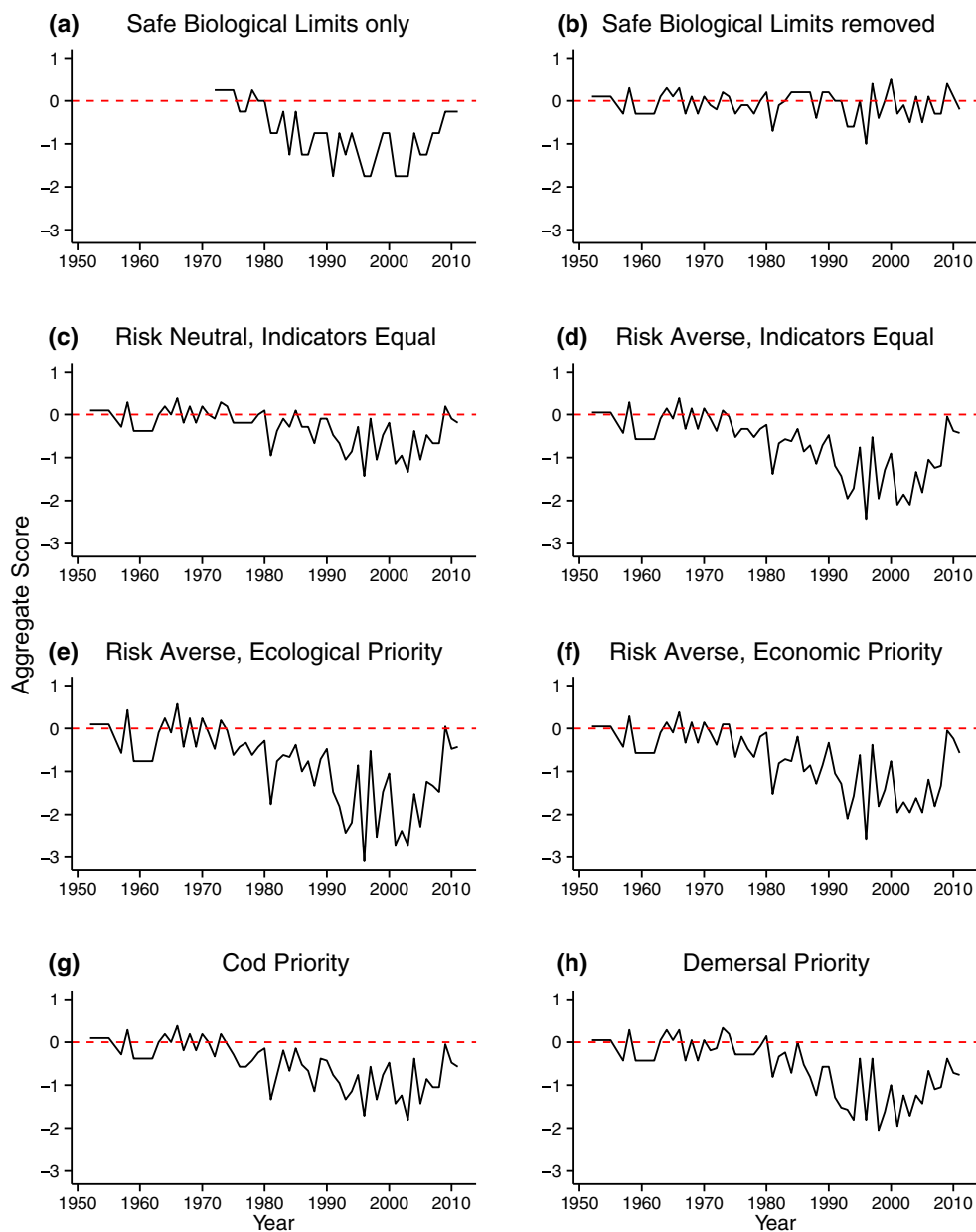
Figure 3 Aggregate alarm signals for eight illustrative priority scenarios defined by outcome weightings (see Table 1). (a) Using only the SBL indicators (with a risk neutral stance), b: excluding SBL indicators (also risk neutral). (c and d) Contrast risk neutral and risk averse stances, respectively (defined in Table 1), aggregating all indicators with equal weight. (e and f) Contrast ecological and economic priority weighting sets, both using a risk averse stance. (g) Cod is assumed the management priority and (h) demersal stocks are assumed the priority (by removing pelagic SBL indicators). Positive scores indicate scope for increasing fishing pressure, negative indicate the need to reduce fishing pressure.

decisions: weightings used to make up the scenarios for calculating RSS are negotiable among stakeholders (Kjærsgaard *et al.* 2007). With this, "transparent" management objectives can be tailored for different ecosystems to reflect agreed priorities, with stakeholder participation (Mackinson *et al.* 2011; Link *et al.* 2012).

We cannot expect all management objectives to be satisfied concurrently: priorities differ and compromises (trade-offs) must be accepted. It may be argued that the ecosystem approach is one of making these normative priorities and compromises explicit (Fenichel *et al.* 2013), rather than implied (as they have been under

Table 3 Binary correlations between the implemented management actions and (A) the ecological priority supported response; or (B) the economic priority supported response

Stock	(A) Implemented vs. ecological RSS			(B) Implemented vs. economic RSS		
	Total (*n*)	Agreement (*x*)	Binomial *P*-value	Total (*n*)	Agreement (*x*)	Binomial *P*-value
Hake	24	9	0.307	24	10	0.541
Cod	19	2	0.001[a]	19	3	0.004[a]
Whiting	19	1	0[a]	19	2	0.001[a]
Megrim	24	8	0.152	24	8	0.152
Plaice VII f,g	24	12	1	24	14	0.541
Sole VII f,g	24	12	1	24	12	1
Herring	24	7	0.064	24	8	0.152
Mackerel	22	16	0.052	22	16	0.052
Horse Mackerel	24	5	0.007[a]	24	5	0.007[a]

n is number of comparable years; *x* is number of agreements. Binomial *P*-values < 0.05 indicate significant correlation of signals.
[a]indicates significant disagreement (there were no significant agreements).

conventional resource management). In practice, fisheries (and other resource) management is frequently expected to prioritize the sustainable harvesting of stocks, setting harvest rates (e.g., fishing quotas) for each stock individually. An ecosystem approach could assess whether these individual stock decisions are congruent with system-wide management objectives. The RSS represents these wider objectives so it applies equally to whichever fish stock is being assessed. This does not imply that single-stock harvest control rules should be replaced by the RSS: the relative weighting of RSS and single stock management remains a normative question of priorities. The suggested framework provides an opportunity to learn from historical data and past experience as well as having the potential to become a useful negotiation and exploration tool, an increasingly important feature in resolving conservation conflicts (Davies *et al.* 2013). Managers could use this information to decide on the compromise solution (Heen *et al.* 2014) to be implemented, a solution for which agreement has been negotiated among stakeholders.

Acknowledgments

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Figure S1: Similarity Matrix shows complementarity among indicators, where similarity between index *i* and *j* is defined as the proportion of years over which *i* and *j* were simultaneously either within or outside their reference levels. Missing data shown as white cells. Note: the expectation for uncorrelated signals is 0.5, so values < 0.5 indicate a tendency to conflict.

Figure S2: The application of the Signal Detection Theory analogy in the evaluation of management advice (adapted from Piet & Rice, 2004).

Figure S3: The plots of TPR and FPR for each stock for each indicator. In each indicator plot each point represents a fish stock time-series. The diagonal line of zero discrimination is shown as a guide: points to the right and below the line show responses inconsistent with the indicator (negative discrimination).

Figure S4: SBL plots prior to 1998 (1987–1997) using available reference points and post 1998 (1998–2011) using official precautionary approach reference points. TPR – True Positive Rate, FPR – False Positive Rate, each data point representing an individual stock.

Figure S5: The number of indicators incorporated into each year of the Response Support Signal.

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