A Method for Implementing Ecosystem Considerations in Forage Fisheries: San Francisco Bay Herring Case Study

J.A. Thayer[a,c], *E. Hazen*[b], *M. García-Reyes*[a], *A. Szoboszlai*[a], *W.J. Sydeman*[a]

[a] Farallon Institute, 101 H Street, Suite Q, Petaluma. CA 94952

[b] NOAA Southwest Fisheries Science Center, Environmental Research Division, 99 Pacific St. Suite 255A, Monterey, CA 93940, USA

[c] Corresponding author email: jthayer@faralloninstitute.org

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Abstract

Ecosystem based fisheries management is a priority nationally and beyond, yet lack of robust approaches has hampered its implementation. Even though forage fishes are critically important in marine ecosystems, few examples of applied ecosystem-based information exist. We created a multi-pronged approach to ecosystem considerations in fisheries management and applied it to the small San Francisco Bay Pacific herring *Clupea pallasii* fishery as a case history for use in other forage fisheries. The first step of our work used environmental parameters and recruitment indices to predict stock status (Sydeman et al. 2018) for use in setting fishing quotas. The second step, herein, was development of a qualitative predator indicator to inform quota setting, which consisted of (1) the status of alternative forage species in the ecosystem, (2) predator population "health" and mortality events. Thisindicator, with "stoplight" management recommendations, is framed in relation to herring population cycles and climatic influences on population dynamics, and can inform potential predator stressors and predation levels on herring. We present a method to apply these metrics to fishing quotas and adjustments, geared toward the annual management cycle and leveraging existing ecosystem status reports. The resulting indicator matrix is flexible to incorporating future environmental and ecosystem change; indeed future research on trophic interactions and climate effects on the herring-based ecosystem is warranted.

Keywords: Clupeid; EBFM; predators; alternative prey; mortality events; qualitative indicators

1. Introduction

Forage fishes and euphausiid crustaceans are important to both fisheries and food web dynamics, and as such have been a primary focus of many developing ecosystem-based fisheries management (EBFM) policies and programs worldwide [1], from the Southern Ocean (e.g., [2]), to temperate upwelling ecosystems such as the Benguela system (e.g., [3]), and the North Pacific [4]. One of the central tenets of EBFM in forage fisheries is to balance the role of forage fish in the ecosystem as prey for marine top predators and as predators of primary and secondary consumers (e.g. of mesozooplankton) with the human food and socioeconomic value of forage fisheries [5]. In practice, EBFM builds upon single-species management strategies that generally do not incorporate ecosystem roles, such as predator-prey interactions and environmental drivers of target fish populations, into a more holistic and comprehensive approach [6,7]. While the call for multi-species approaches to fisheries is not new [8], implementation of EBFM policies has been difficult owing to the complexities of including "ecosystem considerations", generally speaking, into management evaluations [9]. Various ecological indicators have been suggested and used to measure and evaluate fisheries impacts and inform reference levels for management [10-12]. EBFM approaches, however, often default towards contextual background on ecosystem conditions (e.g., [13]), rather than having a direct role in adjusting harvest control rules (i.e., quotas).

In the US, ecosystem considerations are now required for fisheries management (US Ocean Policy statements). To support these policies, the National Oceanic and Atmospheric Administration (NOAA) has developed programs, such as Integrated Ecosystem Assessments (IEAs), in which the physical and biological drivers of fish populations as well as associated ecological and socioeconomic indicators are presented annually to management authorities [14,15]. In the California Current Ecosystem (CCE; US west coast), NOAA partners with the Pacific Fisheries Management Council (PFMC) to implement EBFM using IEA, amongst other tools. The PFMC also has developed Fishery Ecosystem Plans (FEPs[1]), informational documents designed to enhance the Council's species-specific management programs with ecosystem science, and management policies across disparate Fishery Management Plans (FMPs) [16,17], yet they have only begun to be implemented [9,18].

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[1] https://www.pcouncil.org/ecosystem-based-management/fep/ (accessed May 22, 2019)

The State of California also requires ecosystem considerations in FMPs through the Marine Life Management Act (MLMA). In 2012, the California Fish and Game Commission adopted a Forage Species Policy recognizing the importance of forage fish to marine ecosystems[2]. Recently, the California Department of Fish and Wildlife (CDFW) initiated an FMP for Pacific herring (*Clupea pallasii*), which supports a commercial fishery in San Francisco Bay (SFB). This “sac-roe” fishery takes adults as they move into shallow water to spawn in the fall/winter [19]. The FMP does not include the eggs-on-kelp fishery (where no landings have occurred since the 2012-2013 season)[3]. There is a small fresh fish fishery, although any fresh fish catch is counted against the total harvest limits and thus can be considered together with sac-roe landings[3]. Annual landings have ranged up to 11,000 mt since 1980 (although less than 3,500 mt since 2000[4]), compared to biomass estimates of roughly 4,000 to over 100,000 mt [20]. Herring is also an important regional and seasonal forage resource for marine bird, mammal and fish predators [21].

One key goal of the developing FMP is to include environmental and ecosystem considerations in SFB herring management. Various stakeholder groups, including industry and conservation organizations, partnered with CDFW to provide input into the SFB herring FMP process, requesting new science that uses existing data to support the integration of ecosystem considerations into a management framework[3]. This contribution describes the process of developing ecosystem considerations that could be integrated into the FMP for the SFB herring fishery.

2. Ecosystem considerations

Herring is a classic mid-trophic level, planktivorous forage fish, serving as important prey for many upper trophic level predators in the ecosystem. Both herring and herring roe are an important food resource for many large fish, seabirds and marine mammals, including a number of vulnerable or federally listed species such as Steller sea lions, marbled murrelets, and humpback whales (see Table 1). This is especially true in proximity to spawning sites when fish are aggregated. Because herring spawn in winter/spring, they offer a rich food source for predators just emerging from and during winter, when food is often limited and energy costs are

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[2] https://fgc.ca.gov/About/Policies/Fisheries (accessed May 22, 2019)

[3] https://www.wildlife.ca.gov/Fishing/Commercial/Herring/FMP (accessed May 22, 2019)

[4] https://www.st.nmfs.noaa.gov/pls/webpls/MF_ANNUAL_LANDINGS.RESULTS (accessed May 22, 2019)

high, and as predators prepare to migrate or breed [22,23]. Pulsed resource use is important to consumers despite a short duration, and there is a high likelihood of the importance of pulsed resources being severely underestimated due to incorrect scale. This can occur both temporally (if annual or off-season measures are used), and spatially (if summarized over broad areas, or in regions where the resource in question is not concentrated or does not occur). Few studies have focused on the ecology of short-term prey exploitation, but there are some data on their importance positive physiological consequences for predators. Steller sea lions locate their haulouts in winter close to herring spawning locations [22]. Increased body condition as a result of short-term prey consumption has been demonstrated in shorebirds and waterfowl, as well as increased annual survival of migrants (reviewed in 22,24). Migration of scoters (*Melanitta spp.)*, a type of sea duck, is associated with herring spawning events along the U.S. Pacific coast [25,26]. Both predator numerical response [23] and mass gains indicate importance of consuming spawn [25], not only due to high energy content of herring but also because of reduced time spent foraging on this highly concentrated resource ([27]. Winter/spring prey availability is related to pre-breeding female seabird body condition which in turn influences breeding propensity, timing and success [28,29]. The nutritional value, high density, and timing of herring runs indicate seasonally-important opportunities for predators to obtain energy and nutrients relatively easily and quickly.

Inter-annually, herring stocks fluctuate substantially in relation to natural environmental variation as well as human activities [30-33]. The SFB population is currently the southern limit of herring spawning along the US west coast; this population has experienced a marginally significant decline over the past four decades [20].

3. Herring ecosystem matrix

We developed a multi-pronged approach incorporating herring ecosystem indicators directly into management. Previous work summarized our first step, incorporating information on environment and pre-recruits into a model to predict herring spawning stock biomass (SSB), for aiding in setting an annual harvest quota [33]. While there was relatively rich data for predicting biomass in the SFB herring ecosystem, it is data-poor with regards to predator/prey interactions. In step two, the current paper, we leverage existing data summaries to design a simple, low-cost predator ecosystem matrix framework that resulted in a single indicator to account for trophic interactions in adjusting the herring harvest quota when conditions are extreme.

The design of the predator ecosystem matrix herein reflects two particular components: 1) the availability of alternative prey resources for central-northern California herring predators, and 2) characterization of predator population health using a metric sensitive to seasonal and annual changes. This is accomplished by synthesizing 12 component parameters for which data are currently available (abundance/trends of 6 alternative prey species, population size of 1 short-lived predator species, and MMEs for 5 longer-lived marine vertebrates; although the matrix can be easily changed/expanded as additional data become available in the future). Data for these considerations are regularly collected and available from PFMC, US Geological Survey (USGS) and NOAA websites (including the IEA), within the SFB herring managers' quota-setting timeframe (i.e. by September for the October-April spawning/fishing season). The logic underlying the inclusion of these ecosystem considerations is as follows: when alternative prey are less available to predators, herring become even more important to the ecosystem and the predation rate on herring may increase leading to changes in natural mortality. Similarly, when herring predator populations are in decline, management should reduce food stresses on these predators. Thus, our approach would result in more conservative herring harvest controls when alternative prey populations are low and/or when predator populations are below "healthy" reference levels. By the same logic, when herring SSB is high and ecosystem conditions are very good, increasing herring harvest would be considered.

3.1. Selection of predator and alternative forage species

We summarized data on forage and herring predators using a combination of literature review, examination of relevant databases, and discussions with forage and/or predator researchers. When data were sparse, information from neighboring or similar ecosystems was used to provide context. We collated data on predators known to eat herring in the CCE (83 total; 58 whole-fish eating species, and 33 roe-eating species, including 8 that ate both; Table 1), and in California specifically (Table 2). These data were largely gleaned from the California Current Predator Diet Database (CCPDD), which encompasses an extensive literature review of more than 200 papers on ~30 forage species and 120 predators going back 100+ years [21]. We also supplemented with unpublished data on herring consumers from central California.

A)

ancient murrelet
arctic loon
arrowtooth flounder
bat ray
black rockfish
blue shark
Bonaparte's gull
Brandt's cormorant
brown pelican
California gull
California sea lion
Caspian tern
Cassin's auklet
Chinook salmon
chum salmon
coho salmon
common merganser
common murre
copper rockfish
cutthroat trout
Dall’s porpoise
double-crested cormorant
elephant seal
fin whale
glaucous-winged gull
gray smoothhound
gray whale
harbor porpoise
harbor seal
humpback whale
jack mackerel
jumbo squid
long-beaked common dolphin
least tern
lingcod
marbled murrelet
mew gull
Northern fur seal
orca whale
Pacific cod
Pacific hake adult
Pacific hake juvenile
Pacific white-sided dolphin
pelagic cormorant
pigeon guillemot
red-breasted merganser
rhinoceros auklet
sablefish
short-beaked common dolphin
sei whale
shortspine thornyhead
sooty shearwaters
soupfin shark
sperm whale
spiny dogfish
Steller sea lion
Western grebe
Western gull
yelloweye rockfish
yellowtail rockfish

B)

American coot
American widgeon
Barrow's goldeneye
black brant
black scoter
Bonaparte's gull
Brandt's cormorant
bufflehead
canvasback
common goldeneye
common loon
Eurasian wigeon
glaucous-winged gull
greater scaup
harlequin duck
hooded merganser
horned grebe
lesser scaup
long-tailed duck
mallard
mew gull
Northern pintail
oldsquaw
pelagic cormorant
red-breasted merganser
redhead
ring-billed gull
ruddy duck
surf scoter
Western grebe
Western gull
white-fronted goose
white-winged scoter

Table 1. Known predators (8) of adult herring and herring roe from the CCE [21]: A) 59 predators of adult herring, , and B) 33 species of herring egg predators [76,77]; **bold** indicates duplication for 8 species.that consume both eggs and fish.

Herring predator	CCS summer diet[1]	Summer California diet[1]	Winter California diet	GOF (Sep-Dec) diet	GOF (Oct-Mar) diet	GOF-MB (Dec-Mar) diet	GOF (Mar-Apr) diet	Source – Winter diet central California (years)
Chinook salmon	9%	4%	27%	3% (1-5%)	16% (5-27%)	29% (10-49%)	24% (9-39%)	1955 GOF [28]; 1980-86 GOF [29]
humpback whale	~13%	*not summarized* [2]	~19%	~5%		~33% (26-40%)		1920, 1922 MB [78]; 1988, 1990 GOF [79]
common murre	7%	0%	6%		20% (12-28%)		28%	1974-75 MB [38]; 1985-88 coastal GOF only [39]
harbor seal	6%	8%	1%					1968-1973 cenCA [80]; 1991-2 SFB, MB, Elkhorn Slough [81-83]; 2007-8 SFB [84]
rhinoceros auklet [3]	6%	1%	1%					1974-75 MB [38]
California sea lion [3]	4%	1%	< 1%					1998-9 MB [88]; 2009 MB (Thayer et al. unpubl. data)
harbor porpoise	1%	2% [4]	2% [4]					1968-73 cenCA [87]; 1985-6 MB [88]; 1999-2000 MB [89]
Pacific hake	7%	3%						*no winter CA data*

[1] Data from [21]

[2] Some data on humpback summer diet in California was available from the early 1920s but was not summarized, as levels of herring were lower than in winter, which was summarized

[3] Winter data for auklets and sea lions was not available from the GOF, therefore, herring in the diet reported here may be an underestimate compared to sampling the coastal GOF just outside SFB

[4] Data in various studies was presented as all months combined

Table 2. Herring in predator diets, with focus on localized spatio-temporal data surrounding herring spawning in San Francisco Bay (SFB). In central California (cenCA), the Gulf of the Farallones (GOF) is just outside SFB, and Monterey Bay (MB) is roughly 80km south of the GOF. Herring spawn in winter months peaking from December to March. For GOF diet, percentage of herring in the diet is indicated by an average value with range in parentheses if data from more than one study was available. The range is important because averaging dampens extremes and does not reflect prey importance to predators during specific events. Months of available diet were provided in the source column unless diet data was collected in all seasons. Light gray shading denotes related winter data for California. Blank cells indicate no data.

At an inappropriate spatio-temporal scale, importance of a forage resource to predators might be underestimated if not ignored [22]. Notably, predator diet data are extremely limited in winter due to logistical constraints of sampling. For example, herring occur in sea lion diets in central California, although winter diet samples were not relevant for our analysis since foraging did not occur in the Gulf of the Farallones outside SFB. Focused spatio-temporal sampling would likely demonstrate the seasonal importance of herring to central California sea lions, as has been shown for Steller sea lions *Eumetopias jubatus* in Alaska (see [22,34]). The best central California winter diet data on herring comes from Chinook salmon *Oncorhynchus tshawytscha* in the Gulf of the Farallones [35]. Herring comprised ~50% of the diet (by mass) in February-March 1955, higher than the annual mean of 13% [35]. In the early 1980s, herring in winter salmon diet peaked at roughly 20% [36]. Herring are also important to the winter diet of humpback whales *Megaptera novaeangliae* and seabirds such as common murre *Uria aalge* (Table 2). Diet proportion of herring for salmon, humpback whales and murres was between 15-30% on average in the GOF for the winter half of the year (roughly October to April; Table 2).

In terms of annual importance of herring, Chinook salmon diet from 1980-1986 was the only predator data for which we had annual resolution which overlapped with the SFB herring SSB time-series. SFB herring SSB was significantly correlated with the annual proportion of herring in Chinook salmon diet in the GOF ($R^2 = 0.80$, $p = 0.006$; Appendix I).

We could not locate Gulf of the Farallones winter diet data containing herring for other predators. Therefore, predators whose diet contained a high proportion of herring, Chinook salmon, humpback whale and common murre, are used to represent the "predator community" and their overall diet to represent the associated "alternative forage community" (Table 3).

Main alternative prey species comprised at least 5% of the diet in central California for at least one of the three top herring predators for which there was data. Averaging data across space and time reduces resolution and can mask high local diet dependencies [5]; therefore we chose 5% as a cutoff [5]. Main prey species included other small pelagic fishes (northern anchovy (*Engraulis mordax*) and Pacific sardine (*Sardinops sagax*)), invertebrates (krill (Euphausiidae) and market squid (*Doryteuthis opalescens*)), and juvenile groundfish rockfish (*Sebastes* sp.) and hake (*Merluccius productus*)).

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[5] J. Thayer unpublished analysis demonstrated that an initial 50% prey importance in predator diet can be reduced to 5% when averaging over multiple spatio-temporal scales and ontogenies.

		Chinook salmon[1]	Humpback whale	Common murre	Overall average	Overall importance of forage species to herring predators	Generally available in winter?	Forage matrix rows
small pelagics	anchovy	52%	32%	33%	39%	high (3)	yes (1)	4
	sardine [2]	27%	26%	5%	19%	medium (2)	yes (1)	3
juvenile groundfish	hake	0%	0%	7%	2%	low (1)	no (0)	1
	rockfish	14%	0%	34%	16%	medium (2)	no (0)	2
invertebrates	market squid	1%	0%	11%	4%	low (1)	yes (1)	2
	krill	16%	39%	3%	19%	medium (2)	no (0)	3

[1] Adult salmon diet is represented here

[2] Sardine was not averaged between 1965-1987, years it was ecologically absent from the ecosystem (i.e., < 25,000 mt, A. MacCall unpubl. data) and did not occur in any predator diet [21].

Table 3. Chart of alternative prey levels in diet of herring predators for which the most data exists (see Table 2). Other forage species not listed here comprised ≤ 3% on average of the diet of these predators. Other than herring, the forage species encountered most in winter predator diet are anchovy, sardine and squid (from citations in Table 2).

The alternative prey summary resulted in clear delineations between levels of alternative prey importance (Table 3). Different forage taxa are not equally important to predators due to many factors, including ontogeny, spatio-temporal distribution, size, swimming speed, and energetic content. Anchovy was of high importance at almost 40% of herring predator community diet on average. The small, energy-dense anchovy fits the gape of most predators. Anchovy is largely distributed nearshore and concentrated near the top of the water column in schools, available for much if not all of the year [37]. Medium-ranked alternative prey included sardine, krill and juvenile rockfish, at between 15-20% of overall diet on average. Alternative prey species of low importance were market squid and juvenile hake, at less than a mean of 5% of diet overall among top herring predators.

3.2 Algorithm for alternative forage abundance index

We then developed an index of alternative forage species abundance (Table 4). Each forage species was included in this index corresponding to the importance rating in the Table 3 alternative diet summary for the herring predator community,. For example, in Table 3 anchovy was of high importance, resulting in three preliminary rows of anchovy for Table 4 (a "medium" importance prey taxon would get two rows, and a "low" importance taxon only one). An additional row was added for each prey species that occurs specifically in winter diet of predators, since winter overlaps with herring spawning and the fishery. Winter forage species included anchovy, sardine, and market squid [35,35,37,38,39]; other important forage such as pelagic juvenile rockfish and krill are not widely available in winter in central California [40,41]). Anchovy therefore had a total of 4 matrix rows (Table 4). This had the effect of weighting the average of each forage species based on its importance to herring predators in terms of diet proportion and seasonal availability, and allows for easy adjustment of the matrix as additional predator diet data become available.

Information on alternative forage abundance can be obtained from annual central California NOAA fisheries-independent trawl surveys in spring/summer, representing a 26-year time series to date (see [42]). The resulting 5-year synthesis of alternative forage status is available annually to the management community in the California Current IEA (CCIEA) report (see [15]). From a modified 3-year CCIEA quadrant plot for herring (2015-2017; Fig. 1)[6], numeric codes are applied to the Table 4 for each color of the quadrant plot in which each forage species is located: red = 0, yellow = 1, green = 2. To obtain one index value across the whole alternative forage community, the average across all rows is calculated, reflecting current data as well as trends over the previous 2 years. A color key, based on the mean and standard deviation of the index time-series (1992-2017), is then used to interpret the average (Table 4b). For example, in 2017 forage community status was yellow.

In general, the alternative forage index components are taxa that tend to be more abundant in years of warmer or cooler ocean conditions. A timeseries analysis of taxa in the midwater trawls revealed a strong contrast (using PCA analyses) of groundfish, market squid and krill versus clupeids (anchovy and sardine; [42]). With this in mind, our index contains 4 rows for anchovy plus 3 rows for sardine equaling 7 rows for clupeids, which tend to be warmer water species. In contrast, one row for hake, two rows each for rockfish and squid, and 3 rows for krill equals 8 rows representing cooler water species.

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[6] While the CCIEA report is presented to the PFMC in March, a modified version of the central California forage index could be produced as early as September of the preceeding year and could contain the most recent 3 years of data to reflect herring biology (Fig. 1; rather than most recent 5 years as in the current reporting scheme).

A)

Alternative forage type	**Alternative forage species**	**Index status (CCIEA quad plot)**	**Index numeric code**
Small pelagics	anchovy	red	0
	anchovy	red	0
	anchovy	red	0
	anchovy	red	0
	sardine	red	0
	sardine	red	0
	sardine	red	0
Juvenile groundfish	rockfish	green	2
	rockfish	green	2
	hake	yellow	1
Invertebrates	market squid	green	2
	market squid	green	2
	krill	green	2
	krill	green	2
	krill	green	2
Alternative forage index 2017:			**1.1 (average)** **yellow**

B)

Type	**Threshold**	**Status**
Alternative forage index	**> 1.2**	red
	0.8 - 1.2	yellow
	< 0.8	green

Table 4. Alternative forage species abundance index for central California in 2017. A) Weighted influence of each forage species – each species was included in the index corresponding to the importance ranking in Table 3 overall predator diets, with an additional row added if present in winter diet (i.e., anchovy, sardine, market squid). Numeric codes are applied to the matrix for each color of the CCIEA quadrant plot (Fig. 1) in which each forage species is located: red = 0, yellow = 1, green = 2. To obtain one index value across the whole forage community, the average across all rows is calculated in the thick black box at the bottom. B) The color key, derived from the mean and standard deviation of the long-term data (1992-2017) interprets the forage index outcome.

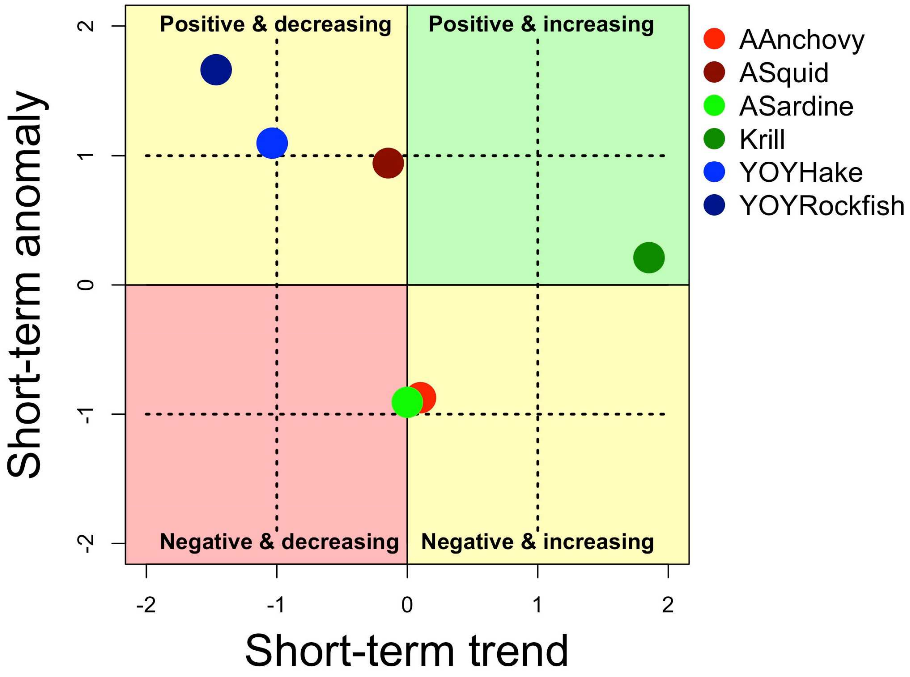

Figure 1. Example of an IEA-style "quad plot" to visualize the status of the central California Current forage community in 2017 over the most recent 3 years given means and trends of CPUE for key forage species for herring predators. Means and trends are from 2015-2017 and normalized relative to the full time series (1990-2017). The position of a point indicates if the recent years of the time series are above or below the long-term average, and if they are increasing or decreasing; quadrants are "stoplight" colored to further indicate the indicator condition. Dashed lines represent ±1.0 s.d. of the full time series.

3.3 Algorithms for predator health indices

There are two primary sources of predator data of interest with respect to SFB herring. First is Chinook salmon escapement (i.e., returns of adults to natal spawning grounds or hatcheries) for the Sacramento River fall run Chinook (SRFC). Chinook are relatively short-lived (generally < 5 years), so their populations may track changes in prey availability more closely than longer-lived species [43]. Pre-season escapement forecasts for the SRFC are available in April each year, including jack (2-yr old male) returns [44,45]. While SRFC ocean abundance estimates, which include ocean fishing mortality, would be a better metric by which to indicate the overall SRFC population status, these estimates are not available in time for herring quota setting in the fall.

The salmon index is scored red if the current season SRFC forecast is below 122,000 fish, the minimum conservation target for hatchery and natural adult escapement (in other words, expert opinion; Table 5;[46]). If SRFC escapement is estimated at 122,000 - 180,000 (the minimum conservation target range; [46]) the index is scored yellow, and if > 180,000 fish the index is scored green. The escapement estimate includes the salmon predicted to be 3 years old in fall of the current year. These thresholds can be re-considered if and when management targets for SRFC change.

The second predator data source is marine bird and mammal mass mortality events (MMEs) which are reported regularly throughout each year. MMEs are easily-observed, generate substantial public interest, and can be a signal of poor population health related to food stress [47-49]. MMEs occur after long-lived marine vertebrates have exhausted their resources to buffer against bad conditions [43], and thus are a more rapid responsive metric than changes in population size. Along the US West Coast, organized beach observing programs that document MMEs have existed for many years [50-52]. In central California these are associated with NOAA, and the Greater Farallones (BeachWatch) and Monterey Bay National Marine Sanctuaries (BeachCOMBERS, see [48]).

The seabird and marine mammal index is based on common murre, rhinoceros auklet, harbor seal, California sea lion, or humpback whale MMEs within central California that are declared, or in progress, at the time of the SFB herring stock review (i.e., in the fall preceding winter herring spawning; Table 5). Information on current mortality events can be found on federal NOAA and USGS websites[7]. The cause of the MME is often listed, if known. Therefore, a fall season containing regional herring predator MMEs for which the cause is emaciation or starvation (for seabirds; or "ecological factors" for marine mammals[8]) receives a status of red (Table 5). MMEs for which the cause is unknown, or the primary cause has been attributed to something other than prey, result in a status of yellow. It is difficult to determine the exact cause of an MME, and so the underlying cause in these cases may still be prey-related. For example, an MME with the primary cause listed as "disease" could have stemmed from lowered predator

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[7] For marine mammals: https://www.fisheries.noaa.gov/national/marine-life-distress/marine-mammal-unusual-mortality-events or https://axiomdatascience.com/maps/#module-metadata/79910598-ec49-11e3-a4d8-00219bfe5678/a4b0bec0-b9be-11e3-835f-00219bfe5678; for seabirds: https://www.usgs.gov/centers/nwhc or https://farallones.noaa.gov/science/beachwatch.html (accessed May 22, 2019)

[8] Since only general causes of marine mammal MMEs are listed on the NOAA website (i.e., "ecological factors" include prey-related causes such as emaciation/starvation), NOAA staff may be contacted for more specific details if desired (current contact is Deborah Fauquier, deborah.fauquier@noaa.gov).

immunity as a result of poor nutrition from food stress [53,54]. If no MME fitting the criteria above is in progress, then the marine bird and mammal index is green.

Finally, the two predator indices are combined into one indicator. Following the precautionary principle, if either contributing predator index is red, the resulting overall predator indicator will be red for that year. In 2017, the SFRC index was yellow and the MME index was green, resulting in an overall predator health index status of yellow.

A)

Predator index	Threshold description	Threshold	Index status
Sacramento Fall Run Chinook salmon escapement	Minimum range for hatchery and natural area adult escapement set by PFMC	< 122,000 fish	red
		122,000 – 180,000 fish	yellow
		> 180,000 fish	green
Seabird or marine mammal mass mortality event	Predator MME (common murre, rhinoceros auklet, harbor seal, CA sea lion, humpback whale, harbor porpoise) within central California (e.g., Sonoma, Marin, San Francisco, San Mateo, Santa Cruz counties) is declared or in progress at the time of SFB herring stock review (i.e., in the fall preceding winter herring spawning)	MME – starvation, emaciation, or “ecological factors”	red
		MME – unk cause or 1° cause is non-prey related	yellow
		No MME	green

Table 5. Ecosystem matrices for SFB herring management focusing on status of predator health in central California, represented by SRFC escapement and MME thresholds.

3.4. Overall ecosystem indicator

The indices for alternative forage and for predators are similarly combined following the precautionary principle to produce an overall herring predator ecosystem indicator (Table 6). The alternative forage portion of the indicator represents effects on a wide herring predator community. The predator indices are narrower in scope (representing roughly 7 out of 83 known herring predators), but can reveal extreme events (i.e., adult mortality). The overall herring predator ecosystem indicator in 2017 was yellow (Table 6).

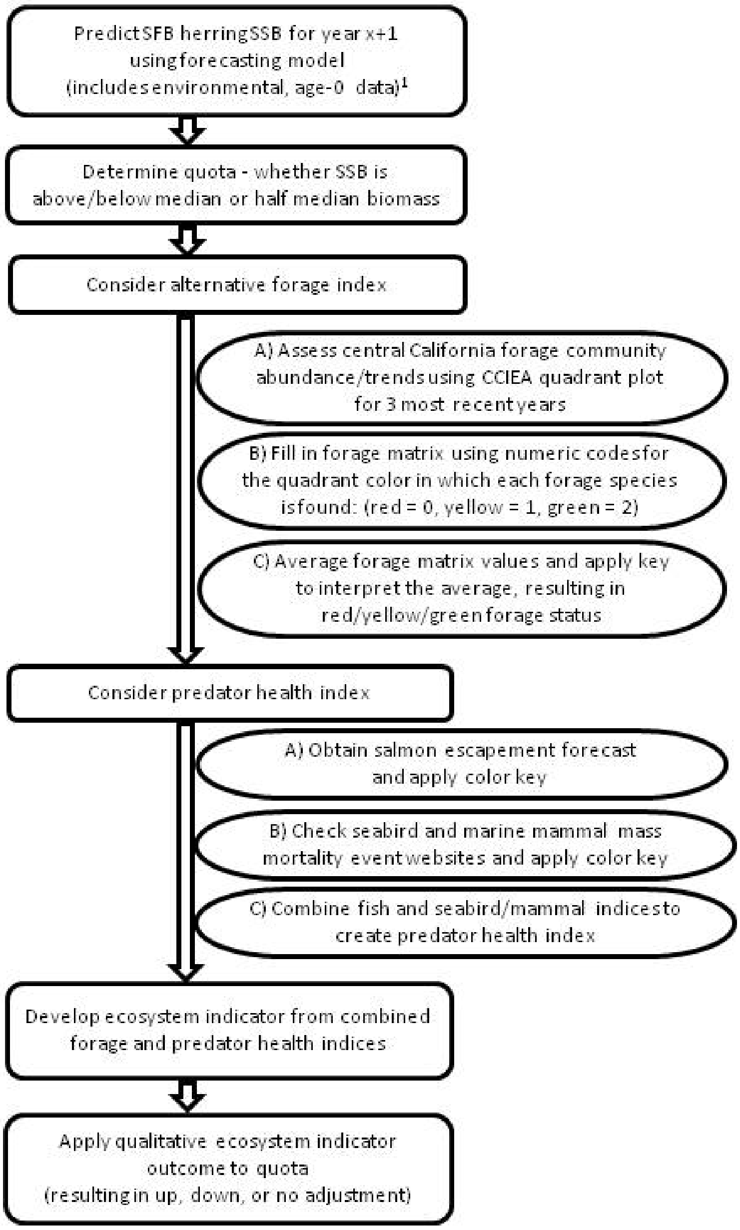
4. Ecosystem indicator application

An outline of steps incorporating ecosystem indicators into SFB herring management is detailed in Figure 2. First, biomass for the coming spawning season is predicted using a model which incorporates environmental variability and a SFB CDFW trawl age-0 index of herring (see [33]; Appendix II). Predicted SSB is then color-coded based on biomass reference points. Given multi-decadal herring population cycles, we used the median SSB of the entire time-series (1979-2017) as a cutoff for defining low versus high biomass (37K mt; Fig. 3). Half of the median defined the threshold for very low biomass (19K mt).

Next, the herring predator ecosystem matrix is populated, first the alternative forage portion and then the predator health indices. From Table 1 herring predators, the importance of herring (Table 2) as well as the abundance and seasonal availability of alternative forage in the diet (Table 3) is assessed. The resulting forage table (Table 4) is populated with data from the CCIEA quadrant plot representing the abundance and trends of each alternative forage species over the most recent 3 years (reflecting herring biology/recruitment time). Predator health is gauged using data on annual population changes of a short-lived fish predator of herring, as well as intra-annual mortality indices for longer-lived marine bird and mammal predators (for which annual population changes may not be a time-sensitive indicator; Table 5). These components are combined into the predator health index, and together with the alternative forage index synthesized into one comprehensive indicator (Table 6). Overall ecosystem indicator status and adjustment recommendations are examined relative to predicted SSB stoplight color-coding from the data-derived biomass reference points (Table 6).

If a quota adjustment is recommended, the amount of quota adjustment should be determined. Lack of information on certain aspects of SFB herring and its food web necessitated development of a qualitative ecosystem indicator. However, while qualitative indicators can be very valuable to translate ecosystem status information to managers from a data-poor system and provide flexibility, they also require some level of expertise to translate these into potential quota adjustments. This approach has been successfully utilized by the North Pacific Fisheries Management Council (NPFMC), with resources to interpret qualitative ecosystem indicators for quota changes [13].

On the other hand, management bodies may need more specific guidance. Our framework is based on the current state of limited data on trophic and climate relationships with SFB herring, but rich quantitative information on alternative forage from the CCIEA and threshold data on predator populations from both CDFW and NOAA. Therefore, in years where the predicted herring SSB is below the low biomass reference point (e.g., < 37K mt), the component indices of our ecosystem indicator could be examined more closely to provide additional information to inform a quantitative quota adjustment. For example, the alterative forage indicator is a numeric average (Table 4a) that may be high or low relative to provided thresholds (Table 4b). This represents prey species in the alternative forage community trending up or down. Similarly for the predator population health indices, predicted SFRC escapement may be high or low relative to conservation goals (Table 5). MMEs may consist of one or many events, include one or multiple species, and be of long or short duration. These additional pieces of information are easily reviewed from the indicator development process above (Sections 3.2, 3.3). In the future, further identification of mechanistic linkages for predator-prey can and should be undertaken to refine the width of uncertainty around each proposed quota adjustment.



[1] Sydeman et al. (2018)

Figure 2. Logic rule for incorporating ecosystem considerations into SFB herring management.

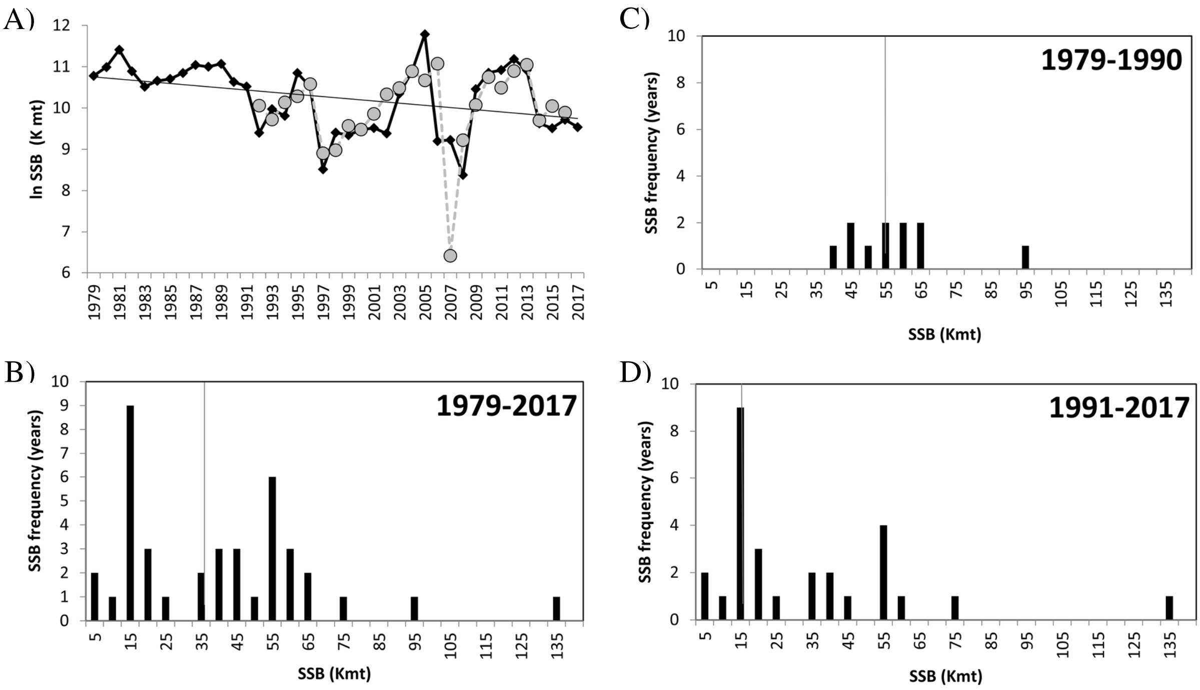


Figure 3. A) Timeseries of SFB herring SSB, observed (solid black line with triangles) vs. predicted (dashed gray line with circles). B) Histogram of observed SSB for the entire study period (1979-2017), as well as C) early (1979-1990) years of data, and D) later years for which SSB could also be predicted (1991-2017). Gray lines in B, C, D denote median SSB for each time-series.

Year	**Alternative forage index** [1]	**Predator health index** [2]	**Overall ecosystem indicator**	**Recommended action**	**Predicted SSB** [3] (Kmt)	**Observed SSB** [3] (Kmt)
1992-1993	yellow	red	red	round down quota	23.3	12.1
1993-1994	yellow	red	red	round down quota	16.6	21.5
1994-1995	yellow	yellow	yellow	caution	25.2	18.2
1995-1996	yellow	red	red	round down quota	29.3	51.4
1996-1997	yellow	yellow	yellow	caution	39.3	37.1
1997-1998	green	yellow	yellow	caution	7.4	5.0
1998-1999	yellow	yellow	yellow	caution	7.9	12.1
1999-2000	yellow	green	yellow	caution	14.3	11.4
2000-2001	yellow	yellow	yellow	caution	13.1	13.0
2001-2002	yellow	green	yellow	caution	19.1	13.6
2002-2003	red	yellow	red	round down quota	30.7	11.9
2003-2004	red	green	red	round down quota	35.7	31.2
2004-2005	green	green	green	static or round up quota	53.6	53.4
2005-2006	yellow	red	red	round down quota	42.9	131.6
2006-2007	yellow	green	yellow	caution	64.4	9.9
2007-2008	yellow	red	red	round down quota	0.6	10.2
2008-2009	green	red	red	round down quota	10.1	4.4
2009-2010	yellow	red	red	round down quota	23.7	34.8
2010-2011	red	yellow	red	round down quota	46.7	51.8
2011-2012	yellow	green	yellow	caution	36.0	55.3
2012-2013	yellow	green	yellow	caution	54.0	72.1
2013-2014	green	red	red	round down quota	63.0	55.0
2014-2015	green	red	red	round down quota	16.3	19.2
2015-2016	yellow	red	red	round down quota	23.2	13.5
2016-2017	red	yellow	red	round down quota	19.8	16.6
2017-2018	green	yellow	yellow	caution	19.1	13.9

[1] Represents broad predator base; warning about poor conditions

[2] Represents narrow predator base; already bad conditions (mass mortality)

[3] SSB is coded green if > 37K mt, yellow if between 19-37K mt, and red if < 19K mt (see text for details)

Table 6. Retrospective status of contributing indices and overall ecosystem indicator for SFB herring. SSB predicted prior to spawning season is presented, as well as observed SSB measured over the course of each spawning season.

5. Ecosystem indicator assessment

5.1 Retrospective analysis

A retrospective analysis was conducted to determine how the ecosystem indicator might have performed in past years where contributing index data was available (1992-2016; Table 6). We evaluated ecosystem indicator status relative to where predicted SSB fell in relation to the data-derived biomass reference points, and secondarily in relation to observed SSB.

For this exercise, we calculated predicted SFB herring SSB for each year using methods of Sydeman et al. (2018; see Appendix II). Predicted SSB ranged from 0.6K - 64.4K mt, with a median of 23.7K mt (Fig. 3a), aligning with our definitions of "very low' in 8 years, "low" in 11 years, and "high" in 7 out of 26 years. Observed SSB during this period ranged from 4.4K - 131.9K mt, with a median of 16.6K mt (Fig. 3a,d). Note that the full time-series of observed SSB data available (1979-2017) revealed decreasing biomass through time (Linear regression, $R^2 = 0.14$, $p = 0.02$), with a much lower median in the later time period used for indicator development (1991-2017; Fig. 3). Predictions performed well overall (observed SSB was similar to predicted in n = 18 years, with a difference of < 10K mt). However, in three instances observed SSB was more than 10K mt different than predictions. There was one observed SSB outlier one order of magnitude higher than any other data point (2005), obviously well outside model bounds, so we knew that prediction for year X+1 (2006) in this instance would not work. This underscores how much we still have to learn about drivers of herring and other small pelagic fish dynamics, and emphasizes the importance of precautionary management.

Overall ecosystem indicator status was yellow in 11 years, red in 14 years, and green in 1 year. Of those years in which predicted SSB was below median biomass and fishery quotas may have been reduced simply due to this reason, an ecosystem indicator status of red supported a further quota reduction a little more than half the time (11 years). The ecosystem indicator suggested caution (yellow) in all remaining years, except 2004-2005 when both the indicator and predicted SSB were green.

As mentioned above, the ecosystem indicator uses data in the summer/fall prior to the winter herring spawning and fishing season when SSB is measured. Therefore the indicator does not describe the effect of herring SSB in the current winter (year X to X+1) on predators, but instead suggests that if herring predators are already stressed in year X (e.g., due to low alternative prey availability), then management should limit additional stressors and similarly that predation mortality on herring spawning concentrations in year X to X+1 could increase. This is a key point, because these elements are not captured by the SSB predictions, hence the importance of our ecosystem indicator to suggest a reduced quota under such conditions. Environmental considerations in the biomass prediction model, together with the ecosystem indicator, thus provide a more holistic view of ecosystem considerations for SFB herring management.

5.2. Indicator sensitivity

We also conducted an assessment of our composite indicator to determine effects of changes in input parameters. A formal sensitivity analysis was not possible, due to the qualitative nature of our index. Therefore, we examined the indicator components, investigating how results might change with different or additional inputs (Appendix III). The additional inputs considered would result in minimal changes to the overall ecosystem indicator, supporting existing results.

There are only a few years that a herring quota reduction would be recommended based on parameters presented (i.e., if predicted SSB was between the upper and lower biomass reference points, and the overall ecosystem indicator recommended a quota reduction; below the lower reference point managers already proposed a low static to zero quota[9]). This indicates that biomass predictions would be sufficient to determine fishing quotas in most scenarios, and only in extreme cases that the predictive biomass model does not incorporate would reductions due to the herring-predator ecosystem indicator potentially be prudent. Our sensitivity assessment would have altered this scenario only in one year, 2002 (Appendix III), when borderline values would have changed the ecosystem indicator ranking from red to yellow, recommending caution rather than a specific quota reduction.

6. Discussion

Ecological indicators have long been suggested as a means to evaluate ecosystem status and inform reference levels for management actions [10,55]. For indicator development, use of existing indices within and among agencies can leverage existing data collection efforts, synthesize across ecosystem components, decrease costs, and ultimately increase the implementation of ecosystem indicators in management. As in the case study for SFB herring, applications of operational indicators and tools will reduce expended effort and duplicity for

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[9] https://www.wildlife.ca.gov/Fishing/Commercial/Herring/FMP (accessed May 22, 2019)

other managed fish stocks. More opportunities exist as CDFW embarks on its updated master plan for state fisheries under the MLMA[10].

Some specific limitations for use of potential indicators include ensuring appropriate spatio-temporal measurements and data availability in the required time frame. Data is needed prior to the stock assessment and quota-setting process, often on an annual schedule (e.g., fall for SFB herring). This constraint underscores the need for researchers to make data available in a reasonable time frame, whether through publication, online databases, interactive tools, or direct communications. This also highlights the need for common indicator frameworks to increase ease of use and broad applicability.

Where data are plentiful, they can be used to quantitatively test relationships. This was possible for SFB herring biomass predictions, examining environmental and recruitment effects relative to the SSB time-series [33]. Data-poor situations, such as the herring-predator ecosystem, however, require a different approach. An example in Australian fisheries management demonstrates the implementation of ecosystem precautions [56]. High risk is assumed in the absence of data or when there is contrary information, a long-held idea in EBFM [6]. This feature provides an incentive to collect data, and avoids improper elimination of any potential ecosystem vulnerability without opportunity to consider it at later stages of an assessment, or at a later time when more data may be collected. Limited data about SFB herring food web linkages necessitated a qualitative red/yellow/green light approach to predator needs in herring quota-setting.

More generally, indicators provide aggregated and simplified information on larger ecosystem processes which involve complex interactions and are often are difficult to measure directly, and therefore can be the subject of intensive debate [57]. In the case of the SFB herring ecosystem, one issue acknowledged about our composite indicator correlation among some variables. For example, taxa in the alternative prey community generally comprise “warm” and “cool” species complexes [42]. Our forage index currently is fairly balanced with regards to each complex, but care should be taken if/when the index is updated with future data.

Wider discussion is also possible in terms of exactly what protections are desired for the ecosystem. For example, if one aspect of the ecosystem is red but others are green, qualitative indicator ranking could be either red as precaution would advise, or yellow to reflect an average

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[10] https://www.wildlife.ca.gov/Conservation/Marine/MLMA/Master-Plan (accessed May 22, 2019)

synthesis of inputs. Economics of the fishery are quantifiable, but ecosystem functioning is more difficult to quantify, and therefore is often overlooked. We argue that this is not prudent, and until more is known, management should err on the side of caution, particularly in the face of increasing climate variability. This should spur more study of the herring ecosystem to try and better understand relationships, yet allow reasonable management to move forward now. Indeed, predator reference points are currently under-represented tactically in EBFM approaches thus developing heuristics to directly inform harvest control rules would improve precautionary management [58].

Insight into indicator performance can be obtained through retrospective analyses. Important factors to consider include species' population cycles, life history, and climate. Population cycles of coastal pelagic species can be more than 50 years [59] and at least several decades for herring [20,60,61]. The relatively short span of our retrospective analysis on SFB herring indicators (Table 6) falls short of an entire population cycle. Considering this, as well as climate conditions during this period, it is not surprising that herring ecosystem indicator status was not green in any of these 25 years. Worldwide, climate change has accelerated since 1991[62]. Herring SSB in the CCS has decreased since the mid to late 1980s, as it has for many other forage species [20]. This decline may be related to the "biotic regime shift" of 1989-90 [63], coupled with increasing marine climate variability (e.g., [64,65]). Herring recruitment is influenced by environmental conditions such as water temperature and upwelling [66]. Recent environmental conditions have been notably variable, including a major and rapid shift between extreme El Niño to La Niña conditions in 1998-99 [67], very delayed upwelling in 2005 [68], record upwelling in 2013 [69], followed by an unprecedented marine heat wave in 2014-15 ("The Blob"; [70,71]) and a severe El Niño event in 2015-16 [72]. Specifically the southern part of the herring range in California, population fluctuations are increasing in frequency ([20]; Fig. 3c,d). This underscores the need for caution.

7. Conclusion

When better data become available, relationships between herring and predators and alternative prey may be quantitatively examined and less precaution may be needed. Indeed, indicators should be adapted and/or replaced periodically. For example, even though indicators are updated annually, the time frame for revisiting Alaskan EBFM indicator structure is every 5 years [13]. A similar approach is recommended for the SFB herring indicators.

In the meantime, qualitative indicators remain very valuable approach for advancing EBFM implementation. They reflect the relative paucity of data on the particular ecosystem, but serve to alert managers to warning signs [13]. The red/yellow/green light approach is easy to understand [73]. This also allows for manager flexibility within quota setting. Additionally, qualitative assessments allow for more rapid integration of new ideas and data and unexpected events in the face of changing ocean conditions [13].

Synthesis of ecosystem considerations into multiple stages of the forage fish management process results in a multi-pronged approach that is robust, straightforward, and easy to interpret. Our example provided an indicator of oceanographic and herring population conditions for stock assessment, and predator and alternative prey considerations in the quota-setting framework. Predators such as marine birds, mammals and predatory fish are increasingly valued by the public, generate economic revenue through commercial exploitation or non-commercial uses (e.g., recreational fishing, ecotourism, whale-watching, etc.), and are acknowledged as an integral part of a functioning ecosystem [74]. Integrating indicators of top predator health and prey needs into forage fish management represents a significant step forward in implementing EBFM.

There is currently considerable stress from climate variability and change on ecosystems worldwide, and particularly upwelling systems such as the CCS. While climate change cannot be directly mitigated, human activities such as fisheries can be better managed, and thus ecosystem approaches and precautionary management are recommended [75].

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Appendix I. Comparison of predator diet to SFB herring SSB

In terms of importance of herring to predators, the only diet data for which we had annual resolution for multiple years which overlapped with the SFB herring SSB timeseries was for Chinook salmon in 1980-1986 (Thayer et al. 2014). SFB herring SSB was significantly correlated with the annual proportion of herring in Chinook salmon diet in the GOF ($R^2 = 0.80$, $p = 0.006$; Figure A1). Unfortunately, fishery-independent trawl data on alternative prey was not available in these years for further comparison.

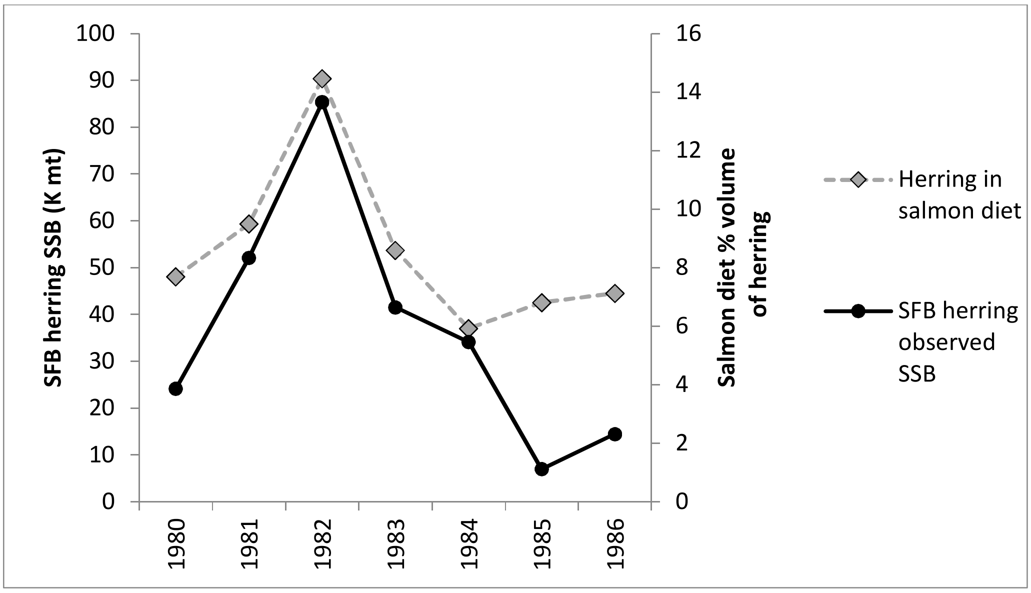

Figure A1. Observed SFB herring SSB and annual proportion of herring in Chinook salmon diet in the Gulf of the Farallones, 1980-1986.

Appendix II. SSB prediction model

We calculated predicted spawning stock biomass (SSB) for San Francisco Bay (SFB) herring for 1991-2016 from the methods outlined in Sydeman et al. (2018), using CDFW SSB measurements based on egg deposition data from all winter months of herring spawning, but excluding any hydroacoustic data. The deposition survey was deemed a better estimate of spawning biomass than hydroacoustic data, which tends to overestimate biomass, with much higher error (Dewees & Leet 2003). A time series model including SSB lagged 1 year, young-of-the-year production (YOY) lagged 3 years, and environmental conditions in the season just prior to spawning explained 74% of the variance in annual biomass (Table A1).

Term	**Coefficient**	**t-stat**	**p-value**
$\mathrm{SSB} = 1 + \mathrm{SSB}_{\mathrm{lag1}} + \mathrm{YOY}_{\mathrm{lag3}} + (\mathrm{FallMOCI}_{\mathrm{lag1}})^2$ $F_{3,20} = 18.5$, p-value < 0.0001, Adjusted $R^2 = 0.74$			
Intercept	15.94	3.19	< 0.01
$\mathrm{SSB}_{\mathrm{lag1}}$	0.34	2.69	0.014
$\mathrm{YOY}_{\mathrm{lag3}}$	0.01	3.00	< 0.01
$(\mathrm{FallMOCI}_{\mathrm{lag1}})^2$	-1.35	-3.26	< 0.01

Table A1. Regression model results and statistics used to predict SFB herring SSB, 1991–2016, following [25]. Lag in years for each term is indicated with subscript. The fall Multivariate Ocean Climate Indicator (MOCI) corresponds to the months October to December.

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Appendix III. Indicator sensitivity assessment

We conducted an assessment of our composite indicator to determine sensitivity to changes in input parameters. A formal sensitivity analysis was not possible, due to the qualitative nature of our index. Therefore, we examined the component parts of the indicator, investigating how results might change with different or additional inputs.

The herring ecosystem indicator is comprised of two main indices, the alternative forage index and the predator health index. The alternative forage index is currently comprised of the abundance/trends of 6 prey species: 2 schooling pelagic fishes, 2 juvenile groundfishes, and 2 invertebrates. The predator index is comprised of the population size of 1 short-lived predatory fish, and mortality events for 6 long-lived marine bird and mammal predators. Thus each main index contains a similar number of component parameters.

For the alternative forage index assessment, we utilized diet data of additional predators of herring from Table 3 (even though the proportion of herring in winter diet of these additional predators is unknown). This would add 2 seabirds, 3 mammals, and 1 predatory fish (Table A2). This would also add 6 additional prey groups that each comprised at least 5% of the average diet in central California for at least one predator (our initial cutoff for consideration), consisting of one offshore pelagic species, one invertebrate taxon at the family level, and 4 benthic taxa (3 grouped at the family level). The new prey taxa would all be categorized as "low" importance, Abundance data on 4 of the 6 new prey is not available from the NMFS midwater trawl, as the additional schooling pelagic species (Pacific saury *Cololabis saira*) occurs offshore beyond the trawl extent, and the remaining species are primarily benthic. Therefore an alternative source of abundance data would be necessary for these 4 species. Octopus and midshipman are encountered in the midwater trawls; however, their abundance levels were lower than those of our main prey species (Ralston et al. 2015), so while raw data are available, they are not summarized in the CCIEA report used to populate the alternative forage index.

The addition of these predators and their diet, or use of different combinations of these predators, would not change the qualitative categories (high/medium/low) of the existing main prey species for the alternative forage index structure. It simply reduced somewhat the average proportion in the diet of each, and therefore also reduced the thresholds between the qualitative categories slightly (Table A2). This exercise confirmed in particular the high importance of anchovy to the alternative forage community for herring predators.

Trial inclusion of octopus and midshipman in the forage index was possible for 22 years (1992-2013), resulting in largely the same alternative forage index scores. The only changes were an increase to a borderline score in one year (2002; red to yellow) and decreases in two years (2004 and 2007; green to yellow and yellow to red, respectively). Variation in both octopus and midshipman abundance is linked to the other "cool" ocean condition species (groundfish, market squid and krill; see Ralston et al. 2015). Therefore, their inclusion in the forage index would result in 10 total index rows for cool water species versus only 7 rows for clupeids (warmer water species), biasing the index away from the single most important alternative prey species, anchovy. Conversely, other species that could not be included due to data limitations, such as saury, have an affinity for warmer water (Tian et al. 2003, Tseng et al. 2014). Thus more data on the quantitative importance of herring to these additional predators, as well as abundance data of these alternative prey species, is needed to establish potential changes to the forage index in the future.

Regarding the predator indices, other short-lived herring predators that occur near SFB include jumbo squid *Dosidicus gigas* (Table 1; salmonids other than Chinook occur further north). While jumbo squid increased in the CCS from 1998-2010 (Field et al. 2013), no time-series of abundance were available that could be examined in relation to the existing Chinook time-series populating the short-lived predator index. While Chinook salmon and other predators included in our index (e.g., humpback whale, seabird populations) are of conservation concern, jumbo squid instead often elicit management concern in terms of their estimated high biomass, rapid growth and voracious consumption of forage and other commercially-important fishes (Field et al. 2013). Therefore, inclusion of jumbo squid in the predator index may not be priority in terms of predator protections.

In terms of the MME index component, seabird MMEs during the time period covered by our retrospective analysis (1992-2017) in central California did not consist of species other than common murre and rhinoceros auklet, which are already contained our index. Marine mammal species with local MMEs, other than what are already contained in our index, consisted of common dolphins, gray whales and sea otters. None of these, however, contain herring in the available diet data (Szoboslai et al 2015, Preti 2019). Therefore, the MME portion of the index would not have changed at all, regardless of consideration of other predators.

Therefore, the additional inputs considered would result in minimal changes to the overall ecosystem indicator. The overall indicator would increase in one year (2002, red to yellow) and decrease in one year (2004, green to yellow, eliminating any green overall indicator ranking from the retrospective time-series). This would have affected potential management decisions in only one year, 2002, when predicted herring SSB was between the upper and lower biomass reference points (Table 6; below the lower reference point managers already proposed a low static to zero quota[11]).

A. III. Citations

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Prey		Chinook salmon[1]	humpback whale	common murre	rhinoceros auklet	harbor seal	California sea lion	harbor porpoise	Pacific hake	Average 3 spp.	Rank 3 spp.	Average 8 spp.	Rank 8 spp.
small pelagics	anchovy	52%	32%	33%	41%	18%	9%	26%	34%	**39%**	high	**31%**	high
	sardine [2]	27%	26%	5%	3%	0%	17%	3%	22%	**19%**	medium	**13%**	medium
	saury (*Cololabis saira*)	0%	0%	0.02%	20%	0%	0%	0%	0%			**3%**	low
juvenile groundfish	hake	0%	0%	7%	0%	2%	14%	4%	0%	**2%**	low	**3%**	low
	rockfish	14%	0%	34%	21%	3%	24%	25%	0%	**16%**	medium	**15%**	medium
invertebrates	market squid	1%	0%	11%	14%	9%	15%	18%	0%	**4%**	low	**9%**	low
	krill	16%	39%	3%	0%	0%	0%	0%	28%	**19%**	medium	**11%**	medium
benthic	cusk eel (*Ophidiidae*)	0%	0%	0.1%	0%	1%	0%	14%	0%			**2%**	low
	midshipman (*Porichthys notatus*)	0%	0%	1%	0%	11%	0%	3%	0%			**2%**	low
	sculpin (*Cottidae*)	0%	0%	0%	0%	11%	0%	0%	0%			**2%**	low
	drum/croaker (*Sciaenidae*)	0%	0%	0%	0%	5%	0%	5%	0%			**1%**	low
	octopus (*Octopodidae*)	0%	0%	0%	0%	7%	5%	0%	0%			**1%**	low

> 39%	**high**	**> 31%**
16-19%	**medium**	**9-15%**
< 5%	**low**	**< 4%**

[1] Adult salmon diet is represented here

[2] Sardine was not averaged between 1965-1987, years it was ecologically absent from the ecosystem (i.e., < 25,000 mt, A. MacCall unpubl. data) and did not occur in any predator diet during that period (Szoboszlai et al. 2015)

Table A2. Assessment of herring predators used to represent the herring predator community, and their diet that was used to develop the alternative forage index, part of the overall herring predator ecosystem index. The first three predators listed were used in the original index development; the last six predators on the right were added for assessment purposes only. Predators were taken from Table 2. The latter six predators were not included in the original index because sufficient winter data on their herring consumption does not exist, although they could potentially be added in the future if more data become available.