The importance of long-term ecological time series for integrated ecosystem assessment and ecosystem-based management

Chris J. Harvey[1], Jennifer L. Fisher[2], Jameal F. Samhouri[1], Gregory D. Williams[3], Tessa B. Francis[4], Kym C. Jacobson[5], Yvonne L. deReynier[6], Mary E. Hunsicker[5] and Newell Garfield[7]

[1]Conservation Biology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Blvd E, Seattle, WA 98112 USA

[2]Cooperative Institute for Marine Resources Studies, Oregon State University, 2030 SE Marine Science Drive, Newport, OR 97365 USA

[3]Pacific States Marine Fisheries Commission, under contract to Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Blvd E, Seattle, WA 98112 USA

[4]Puget Sound Institute, University of Washington-Tacoma, 326 East D St, Tacoma, WA 98421, USA

[5]Fish Ecology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2032 SE OSU Drive, Newport, OR 97365 USA

[6]Sustainable Fisheries Division, West Coast Region, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, WA 98115 USA

[7]Environmental Research Division, Southwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 8901 La Jolla Shores Dr, La Jolla, CA 92037 USA

Abstract

Long-term mechanistic research and monitoring provides integral science support for ecosystem-based management (EBM) of resources, activities and services. Decades of oceanographic and ecological research by Bill Peterson and colleagues along the Newport Hydrographic Line (NH Line) provides essential context for understanding and managing Pacific salmon *Oncorhynchus* spp. and other marine resources in the California Current ecosystem. This research program helped federal scientists convey the significance of the northeast Pacific marine heatwave (2013-2016) to fisheries managers and stakeholders. Particularly illustrative were shifts in the composition of the copepod community, which reflected feeding conditions for Pacific salmon and other consumers. We identify six traits of the dataset produced by Peterson and colleagues that made it especially valuable for informing management: (i) it has generated robust ecosystem indicators; (ii) it is long-term; (iii) it is associated with meaningful ecological mechanisms; (iv) it relates to ecosystem components of high societal value; (v) it can represent processes and lags at meaningful temporal scales; and (vi) it is part of a broader, integrative science effort. This research effort underscores the importance of developing and sustaining long-term mechanistic research and monitoring along the U.S. West Coast and elsewhere in the world.

Keywords

Ecosystem-based fisheries management; ecosystem indicators; California Current Large Marine Ecosystem; copepods; salmon; food web ecology; climate; long-term monitoring

Introduction

The scientific enterprise proceeds in fits and starts, as does the uptake of scientific knowledge in society. Ecosystem science is no exception. Ecosystems are highly complex and inherently difficult to study and understand, which slows delivery of science products and advice to managers. Often, ecosystem research begins or evolves without regular consultation with stakeholders, managers and policymakers, which can lead to divergence between research objectives and societal objectives (Francis et al., 2018; Harvey et al., 2017). In addition, the integration of new ecosystem-scale concepts or paradigms into management systems may be regarded as too risky or beyond the scope of management systems and governance structures. Moreover, the science community, management community, stakeholder community and natural world all act, react and adapt at different speeds. It is no wonder, then, that implementing ecosystem-based management (EBM) of resources and activities remains elusive.

Against the backdrop of these challenges, there is obvious benefit in well-designed, long-term research that couples abiotic with biotic processes, spans multiple trophic levels, relates to species that are valued by people, and is effectively communicated and translated. Long-term monitoring and mechanistic studies are integral elements of EBM worldwide: they provide crucial information on the dynamics of habitat conditions and species status; they enable assessment of ecosystem services as well as impacts of human activities; they help to track performance of management measures; and they define linkages that guide ecosystem modeling (Kaufman et al., 2009). Many EBM implementation frameworks developed in recent years include indicator development and monitoring practices (e.g., Borja et al., 2006; Dunstan et al., 2016; Levin et al., 2009). Some formal EBM arrangements require formal monitoring programs (e.g., Borja et al., 2006; Dunstan et al., 2016; Shephard et al., 2015), and several examples exist wherein long-term and/or comprehensive ecosystem monitoring has informed, improved, or demonstrated the value of ecosystem-level marine resource management (e.g., Brander et al., 2003; Bundy et al., 2017; Gaines et al., 2010; McQuatters-Gollop et al., 2017; Russ et al., 2015).

Successful EBM will fundamentally depend upon robust monitoring—with a keen eye for how monitored components are linked to the broader ecosystem—and effectively communicating findings to management and the public. Bill Peterson was an exemplar of such research and communication, and our objective in this paper is to highlight how the long-term research and monitoring work by Bill and his colleagues has improved the provision of science in support of sustainable management of the California Current ecosystem (CCE). While Bill's work was initially motivated, as for many ecologists, by a fundamental interest in the biology and ecology of his study animals, the sustainability of his research program ultimately was fueled by its usefulness. Our emphasis is on features that have made Bill's efforts, and those like them, so meaningful to management. These features include: a focus on components that meet essential criteria of good ecosystem indicators; maintaining that focus over a long time period; linking the indicators to relevant, meaningful ecological mechanisms; connecting the indicators to species or processes of high societal value; the ability to demonstrate changes and lags at meaningful temporal scales; and the connection of the monitoring work to a larger, integrative science effort. It is our hope that these lessons, highlighted here by the case study of the recent North Pacific marine heatwave, will be valuable for research and management in any marine ecosystem. We further hope to articulate the past and present importance of Bill's work to EBM in the California Current, as incentive to ensure that this type of essential science is sustained in the decades to come.

Background: EBM and IEA

As in other areas of the world, marine resource management agencies in the U.S. have taken steps to implement EBM. For example, NOAA Fisheries, the agency charged with federally managed fisheries in the U.S. under the Magnuson-Stevens Fishery Conservation and Management Act, adopted a formal policy to support ecosystem-based fisheries management (EBFM; NOAA, 2018). In this policy, NOAA defines EBFM as "*a systematic approach to fisheries management in a geographically specified area that contributes to the resilience and sustainability of the ecosystem; recognizes the physical, biological, economic, and social interactions among the affected fishery-related components of the ecosystem, including humans; and seeks to optimize benefits among a diverse set of societal goals*" (NOAA, 2018). NOAA recognizes EBFM as part of a continuum between single-species fishery management and EBM, which spans a range of human use sectors including fisheries (Dolan et al., 2016).

Management at this scale requires complementary science support, but the ecosystem science enterprise itself quickly becomes complicated owing to the number of natural and social science disciplines required, the need to integrate findings across those disciplines, and the task of translating research into products and terms that are meaningful, useful and timely. In recent decades, many decision-support frameworks have been developed to assist with effective information flow in science-stakeholder-management systems (e.g., Borja et al., 2006; Ehler & Douvere, 2009; Kelble et al., 2013; Sainsbury et al., 2014). NOAA Fisheries has adopted the framework of Integrated Ecosystem Assessment (IEA) proposed by Levin et al. (2009) to provide science integration, translation and decision-support for EBM. The IEA framework is an iterative process that begins with identifying EBM goals and objectives, and then moves through steps of monitoring the system, assessing risk and uncertainty, and evaluating potential management strategies designed to achieve the objectives (Fig. 1). This approach is being used in

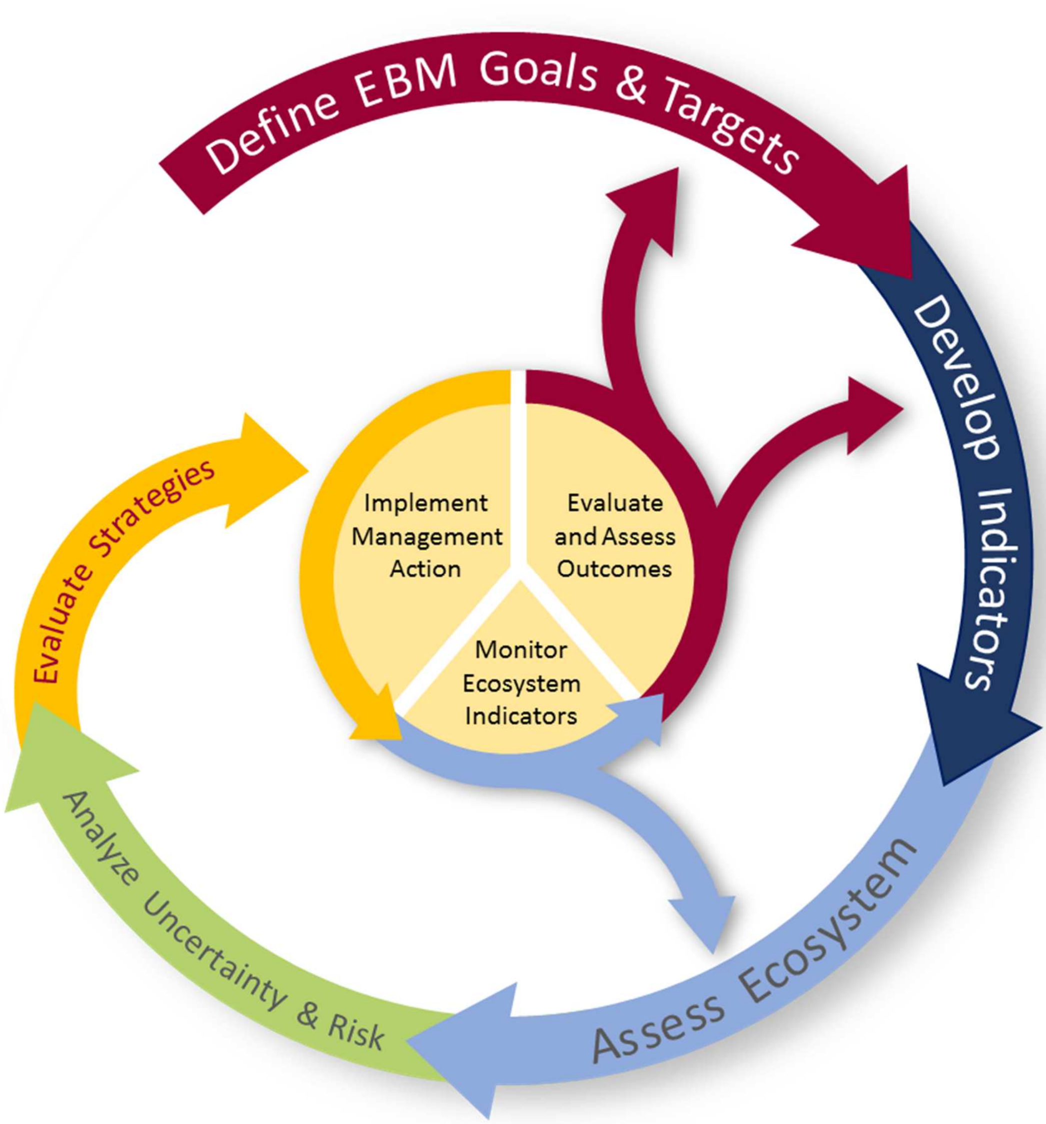

Figure 1. The NOAA Integrated Ecosystem Assessment (IEA) framework, as derived from Levin et al. (2009) and Samhouri et al. (2014).

NOAA-led research programs in Alaska, Hawai'i, the Gulf of Mexico, the Northeast, and the CCE (Samhouri et al., 2014). In the CCE, the California Current Integrated Ecosystem Assessment (CCIEA) team is applying the IEA framework and providing research products to support EBM efforts by a range of end users, in particular the Pacific Fishery Management Council (PFMC), which oversees federally managed fisheries on the West Coast.

The PFMC has well-established responsibilities, outlined by law in the Magnuson-Stevens Act, that center on: (1) providing recommendations to NOAA Fisheries on sustainable harvest of West Coast stocks; (2) ensuring that fishery management plans are consistent with the Magnuson-Stevens Act's ten National Standards, which cover issues such as preventing overfishing, equitable distribution of fishing opportunities and minimizing bycatch [16 U.S.C. § 1851]; and (3) considering effects of fisheries management actions on protected species, habitats, and human wellbeing of coastal communities (deReynier, 2012; see also www.pcouncil.org). While most of the PFMC's work can be characterized as single-species management (sensu Dolan et al., 2016), it is investing greater energy and attention to ecosystem-level considerations, primarily through its Fishery Ecosystem Plan (FEP; PFMC, 2013). The FEP outlines opportunities for bringing integrative ecosystem science into PFMC management processes, and facilitates EBFM through multi-fishery management initiatives.

The PFMC FEP (PFMC 2013, p. 3) also calls for the CCIEA team to provide annual ecosystem status reports (ESRs) that summarize the status and trends of key indicators of physical, ecological, economic and social conditions in the CCE. The ESRs, which represent the "Develop Indicators" and "Assess Ecosystem" steps of the framework in Figure 1, provide the PFMC with context for ecosystem-based decision-making, from local to coastal scales. The CCIEA team has provided ESRs in 2012 and every year since 2014 (Harvey et al., 2018); these

ESRs build on the long tradition of CCE status reporting begun by the California Cooperative Oceanographic and Fisheries Investigations (CalCOFI; http://calcofi.org/ccpublications/ccreports.html) as well as earlier integrated ecosystem assessments by Sydeman and colleagues (Sydeman & Elliott, 2008; Sydeman & Thompson, 2010). ESRs have also been generated for decades by the Alaska Fisheries Science Center for the North Pacific Fishery Management Council, and NOAA has begun developing ESRs for other regions of the U.S. as well (Slater et al., 2017).

As described below, the long-term research conducted by Bill Peterson and his colleagues along the Newport Hydrographic Line off the coast of Oregon has greatly elevated the value of the CCIEA's reporting to the PFMC and other end users. His knowledge of the system's natural history and ability to highlight connections between North Pacific oceanography, zooplankton, salmon and human wellbeing were especially powerful during the unprecedented marine heatwave that arose along the West Coast in 2014.

Connecting science to management: the marine heatwave and the Newport Line

The first two California Current ESRs (NMFS, 2014; PFMC, 2012) enabled the CCIEA team and the PFMC to establish and solidify a partnership. Each report was an opportunity for the CCIEA team to present ecosystem indicator trends compiled from a number of federal, state and tribal monitoring efforts, and to highlight in-depth analyses that accentuated the value of the indicator data. In turn, ESR presentations were opportunities for the PFMC and its advisory bodies to build familiarity with ecosystem indicators and dynamics, make requests, and provide feedback that would help to improve future ESRs.

The actual scientific and management value and resonance of the 2012 and 2014 ESRs was not immediately apparent, however: these first ESRs, which described conditions in the

CCE through 2013, primarily reflected an ecosystem in the midst of several relatively productive years (NMFS, 2014; PFMC, 2012). Climate and physical oceanography indicators revealed strong seasonal upwelling and cooler-than-average ocean temperatures nearly every year from 2008 to 2013. These conditions supported strong productivity at lower and upper trophic levels in much of the ecosystem (Bjorkstedt et al., 2014; Wells et al., 2013), similar to the cool conditions that occurred from late 1998 through the summer of 2002 (Peterson & Schwing 2003). Owing to this relatively productive state, the 2012 and 2014 ESRs may have lacked a clear ecosystem-level narrative that attracted PFMC attention. The ESRs certainly had valuable information related to critically important management topics, such as conditions related to endangered or threatened stocks of Pacific salmon (*Oncorhynchus* spp.) and rebuilding populations of rockfish (*Sebastes* spp.), but the PFMC was well aware of and already deeply engaged in management issues of these stocks and populations.

However, in 2014 the CCE underwent an unprecedented, system-wide change in conditions that had ramifications for all fisheries managed by the PFMC. A major marine heatwave widely referred to as the "Warm Blob," which formed in the North Pacific in 2013 (Bond et al., 2015), pushed warm water onto the shelf off Washington and Oregon in the fall of 2014 and subsequently took hold throughout the CCE (Leising et al., 2015). Numerous effects, ranging from changes in pelagic species composition to food web impacts to reductions in snowpack, became apparent as the heatwave extended through 2015 into the spring/summer of 2016 (e.g., Auth et al., 2018; Harvey et al., 2017; Leising et al., 2015; McClatchie et al., 2016; Peterson et al., 2017; Wells et al., 2017). The CCIEA team had a clear imperative to inform the PFMC of the nature and implications of this event, and an underlying imperative to base their reporting and interpretation on robust science. An essential source of information was the data collected by Bill Peterson and colleagues along the Newport Hydrographic Line (NH Line).

The NH Line is a biological and oceanographic transect located off of Newport, Oregon in the northern California Current (Fig. 2). It consists of 7 stations that extend from 1 to 25 nautical miles (~1-46 km) from shore in depths of 30 to 300 m. The stations have been monitored monthly to twice monthly year-round almost continuously since 1996, largely through the support of competitive grants and funding from the NOAA Northwest Fisheries Science Center. Temperature, salinity, dissolved oxygen, primary production, and aragonite saturation are measured throughout the water column. Surface water is analyzed for nutrients, primary production, phytoplankton species composition and abundance, and harmful algal blooms. Plankton nets are used to collect zooplankton, krill, and larval fish and invertebrates. This sampling regime has yielded understanding of the "heartbeat" of the ocean in this region: how water column properties and the biology of the lower trophic levels change seasonally, interannually, and in response to climatic perturbations (Fisher et al., 2015; Hooff & Peterson, 2006; Keister et al., 2011; Peterson et al., 2014; Peterson et al., 2017; Peterson & Schwing, 2003). Data are available through several platforms, including the Northwest Fisheries Science Center's Ocean Ecosystem Indicators website (https://www.nwfsc.noaa.gov/research/oceanconditions), the CCIEA website (https://www.integratedecosystemassessment.noaa.gov/regions/california-current), and upon request.

In the CCIEA presentation to the PFMC in March 2015, we (CJH and NG) began with information on how the marine heatwave changed physical conditions in the ecosystem so dramatically, as illustrated in maps of sea surface temperatures and time series plots of basin-

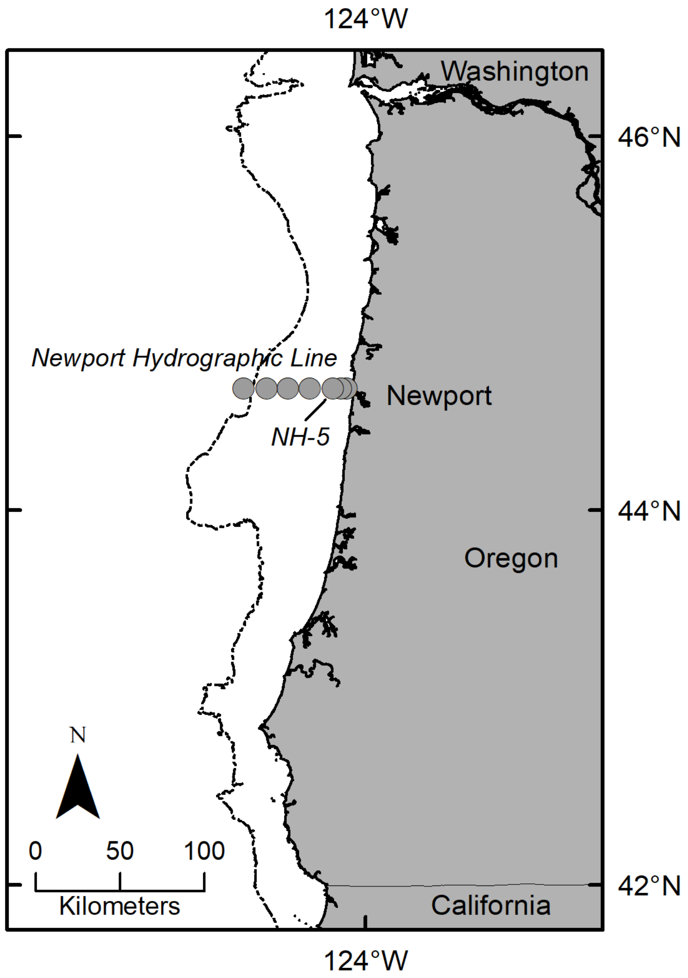

Figure 2. Map of the Newport Hydrographic Line (NH Line) region off of the West Coast of the United States. Sampling stations are indicated by gray circles, including the focal station NH-5, located 5 nautical miles [9.26 km] from shore.

scale ocean drivers like the Pacific Decadal Oscillation (PDO) and an index of the El Niño Southern Oscillation (e.g., Fig. 3a-b). While these plots clearly demonstrated the exceptional physical magnitude of this event (as would be borne out by subsequent research, e.g., DiLorenzo & Mantua, 2016), it was essential that we connect the physical changes to biological or ecological responses that would be meaningful to the PFMC. That connection came primarily in the form of copepod biomass anomalies from the NH Line (Fig. 3c-d). The biweekly time series revealed pronounced shifts in two separate groups of copepods common on the NH Line: a lipid-rich community typified by *Calanus marshallae*, *Pseudocalanus mimus* and *Acartia longiremis*; and a more speciose group of smaller-bodied copepods with lower lipid densities. Biomass anomalies of these two groups have been negatively correlated with one another over the course of the time series (Fig. 3c-d); the lipid-rich “northern” community has been associated with predominance of cooler water masses and negative phases of the PDO (Hooff & Peterson, 2006; Keister et al., 2011; Peterson, 2009), and with more productive feeding conditions for pelagic fishes like Pacific salmon (Burke et al., 2013; Peterson et al., 2014; Peterson & Schwing, 2003). As the marine heatwave moved onto the continental shelf in 2014, northern copepod community biomass rapidly dropped from above average to sharply below the long-term mean (Fig. 3c), while the relatively lipid-poor “southern” copepod community biomass increased from below average to well above average (Fig. 3d). With the influx of warm-water copepods, copepod species richness also increased dramatically (10 species above the long-term mean; data not shown), nearly doubling the number of species observed in previous warm events over the 20-year time series (Peterson et al., 2017).

These changes in the copepod community occurred over the span of weeks, and as later sampling would reveal, the dominance of southern copepods and increased copepod species

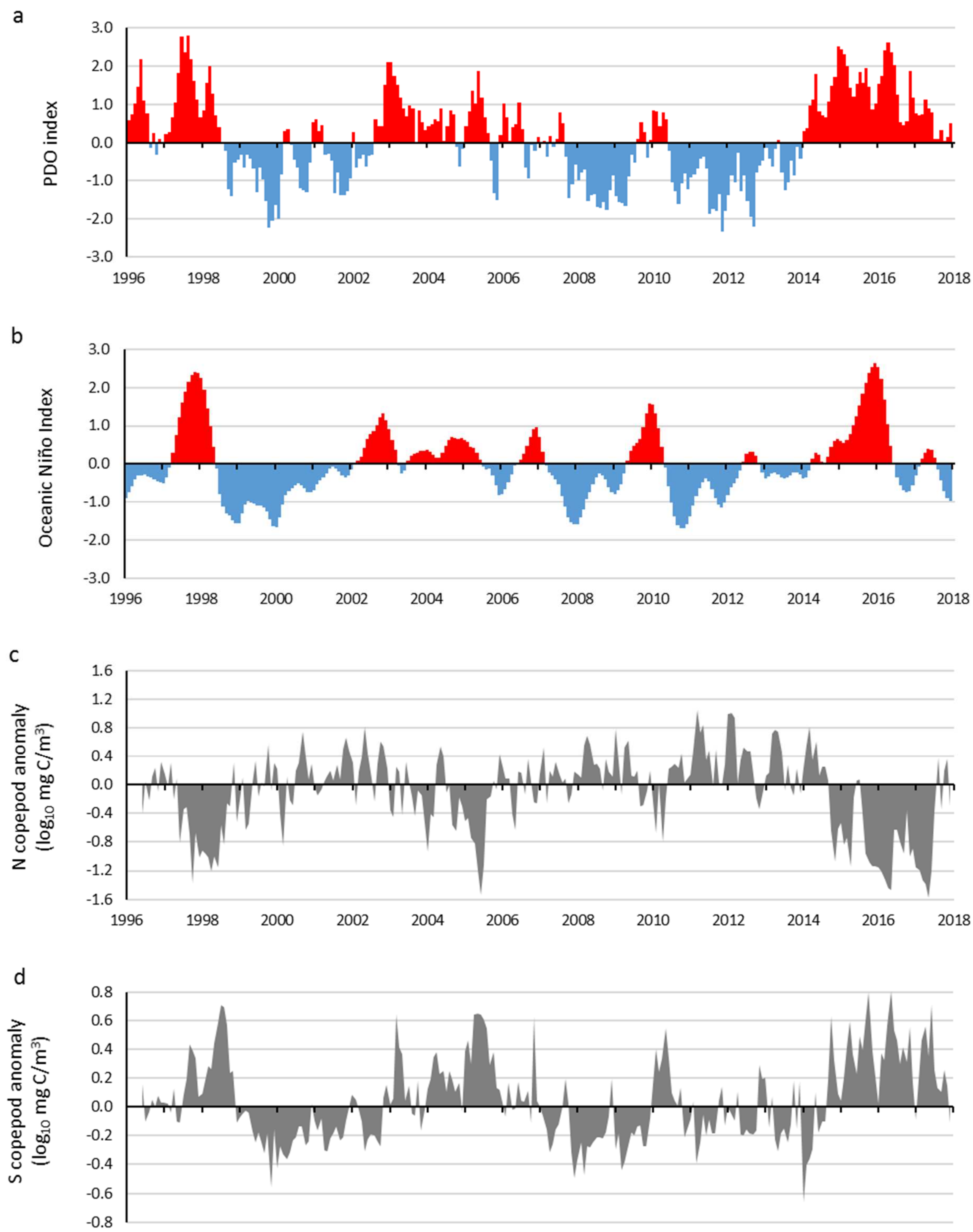

Figure 3. Time series of basin-scale climate drivers and copepod biomass anomalies from station NH-5 along the Newport Line, 1996-2017. (a) Pacific Decadal Oscillation (PDO). (b) Oceanic Niño Index. (c) Northern copepod biomass anomaly. (d) Southern copepod biomass anomaly.

richness along the NH Line would persist well into 2017, even after some basin-scale physical indicators shifted back to near their long-term averages (Fig. 3a-b). The magnitude and duration of the copepod biomass and species richness anomalies were unprecedented in the two decades of sampling along the NH Line (Fig. 3c-d), and supported the conclusion that productivity of coastal waters in the northern CCE was well below average during and after the marine heatwave (Peterson et al., 2017; Wells et al., 2017). This portended strong potential for negative impacts on higher trophic level species under direct purview of the PFMC, a prediction subsequently borne out by recent information on abundance trends of salmon (Jacox et al., 2018) and foraging conditions for seabirds and marine mammals (Jones et al., 2018; McClatchie et al., 2016).

The value of long-term data in science support for EBM

More so than most CCIEA indicators, the rapid shift in the copepod data seemed to resonate with the members of the PFMC in March 2015. The copepod time series has many key characteristics that underlie its resonance and power as a management-relevant ecosystem indicator, and thus increased the impact of the message of this report relative to earlier ESRs. Below, we explore six of those characteristics and attempt to relate them to the decades of careful research that supports them; we propose that these characteristics are critical for any long-term data that are intended to support EBM. They should also have clear relevance in other decision-support contexts within and beyond marine ecosystem management (Friberg et al. 2011; Mirtl et al., 2018; Seddon et al., 2014).

The research focus meets essential criteria of a good ecosystem indicator.

Ecosystem indicators are measurable, tangible proxies for more broadly defined ecosystem attributes, and serve to provide management with information about status and trends in ecosystem condition or management performance (Fulton et al., 2005). For example, one might track a metric like species diversity to represent the resiliency of an ecological community, or toxin loads in fish tissues as an indicator of that species' condition, or the biomass of top predators to indicate the effectiveness of fisheries management or conservation efforts (Fulton et al., 2005; Kershner et al., 2011; Rice & Rochet, 2005). However, in many marine systems, 10s or even 100s of variables are monitored regularly at various spatial and temporal scales, and even more are measured intermittently. This volume of information stands to overwhelm management unless the list of prospective indicators can be reduced to a smaller, high-quality, comprehensive indicator suite. Rice and Rochet (2005) proposed a framework for selecting suites of indicators, including a list of nine essential screening criteria; among those criteria are an indicator's concreteness, its basis in theory, its cost effectiveness, its responsiveness to ecosystem change, and its specificity to the attribute it is intended to represent. Kershner et al. (2011) expanded on the Rice and Rochet (2005) framework and developed a hierarchical, quantitative indicator screening method with 19 criteria related to theoretical considerations, data considerations and more general considerations (e.g., how understandable the indicator is to managers or the public; complementarity of an indicator to an existing indicator suite; etc.).

The CCIEA team adopted the Kershner et al. (2011) indicator screening method to select most of the indicators in their reporting (Levin et al., 2013). Under the general goal of promoting ecological integrity in the CCE, one of the attributes was "community composition," for which the northern copepod biomass anomaly from the NH Line was chosen as a candidate indicator. It was chosen because zooplankton species assemblages often covary with a marine ecosystem's circulation and atmospheric forcing; their short life cycles (on the order of weeks) and close association with water masses give them the potential to respond rapidly to event-scale and seasonal changes in environmental conditions, and thus make them effective sentinel taxa for ecosystem variability (Mackas & Beaugrand, 2010; Mackas et al., 2012). In the CCIEA team's indicator screening process, the northern copepod biomass anomaly was the top-ranked indicator of all 40 indicators considered under ecological integrity, based on both raw and weighted scores (Williams et al., 2013). Notably, it met all of the primary considerations related to theoretical soundness, management relevance, and ecosystem responsiveness; most data considerations associated with concreteness, historical availability, and temporal resolution; and all other considerations related to geographic compatibility, anticipatory qualities, and cost. In more real-world terms, it clearly demonstrated to the PFMC that the marine heatwave had caused major and immediate changes in not just the physical, but also the biological state of the ecosystem (Fig. 3c).

Bill Peterson began studying copepods and other variables along the NH Line in 1969, and established the continuous time series in 1996, well before any of these indicator screening methodologies were published. It is a credit to Bill and his colleagues that they foresaw the robustness of copepods as indicators in support of managing fisheries and broader ocean conservation, and that a quantitative indicator screening framework would affirm that robustness relative to so many other potential indicators.

The research is long term.

The copepod biomass anomaly time series originated in 1969 and has been continuous from 1996 to present, a time period that encompasses considerable climatic and oceanographic variation. Because the sampling frequency since 1996 generally has been biweekly, the long-term data provide ample coverage of processes operating at short- and long-term temporal scales, enabling characterizations of seasonal, annual and decadal processes (Fisher et al., 2015; Francis et al., 2012; Hooff & Peterson, 2006; Keister et al., 2011; Peterson, 2009; Peterson & Schwing, 2003). The time series has thus captured many events, of varying durations and magnitudes, and provides a reasonable sense of the long-term average and variability of copepod community structure and productivity in the region. It therefore enables comparison of copepod responses during the 2014-2016 marine heatwave to responses during other major warming events such as the strong El Niño events of 1997-1998 and 2009-2010 (Peterson et al., 2017). It also allowed the CCIEA team to relate conditions in the marine heatwave to the preceding period in which the northern copepod biomass anomaly was relatively positive for several years (Fig. 3c), making the extent of sudden change clear to the PFMC and other stakeholders.

The copepod time series is also long enough to support advanced time series analyses that help explain changes in ecosystem state. These include multivariate autoregressive models that have quantified relationships between NH Line zooplankton community structure and local, regional and basin-scale forcing (Francis et al., 2012), and analyses identifying potential ecosystem reference points related to threshold relationships between copepods and both natural and anthropogenic forcing (Samhouri et al., 2017). The time series is also being included in analyses to evaluate community-wide responses to large-scale climate perturbations (e.g. marine heatwaves) and to quantify the relative likelihood of the community shifting into a new state as a result of those perturbations, following methods described by Ward et al. (in press) and theory reviewed by Litzow and Hunsicker (2016).

While it is somewhat self-evident that long time series of good indicators are beneficial, we must acknowledge that the foresight to start such data collections, and the resourcefulness to maintain them over multiple decades, are surprisingly rare (Hays et al., 2005; Lindenmayer & Likens, 2009; Lovett et al., 2007; McClatchie et al., 2014). The NH Line is one of three multidecadal time series of processes and variability at the base of the food web in marine waters of the CCE (the others being the CalCOFI transects off southern and central California (McClatchie, 2014) and Line P off of Vancouver Island (e.g., Mackas et al., 2001)). The biweekly-to-monthly sampling frequency of the NH Line provides physical, biogeochemical, biological and ecological information at annual, seasonal and event scales. Additional sampling of zooplankton along the NH Line from 1969-1973, 1977-1978, 1983, and 1990-1992 enable further comparisons over an even longer time span (Fisher et al., 2015; Peterson, 2009). The value and influence of this time series are difficult to overstate. To illustrate, we conducted a Web of Science search (on February 14, 2019) on the terms “copepod*” and “(Newport OR Oregon)” with “Peterson W*” as an author. This generated 43 papers in the primary literature, which had collectively been cited 1550 times in other papers (Fig. 4), including 1387 without self-cites. This contribution to marine ecosystem ecology, and the irreplaceable dataset at its heart, would not have been possible without Bill Peterson’s decades of curiosity and ingenuity, his ability to secure and sometimes cobble together funds, and his dedication and leadership (Gómez-Gutiérrez et al., 2018).

The indicators are associated with relevant, meaningful mechanisms.

The distinctions between the two copepod communities—one made up of large-bodied, lipid-rich boreal species associated with cool water masses, and the other of smaller-bodied, lipid-poor, warm-water species—relate in a straightforward way to mechanisms in life history theory, ocean transport, physiology and trophic ecology. Northern copepods inhabit cool water masses, and therefore need high lipid concentrations in order to undergo diapause and overwinter, while southern copepods are associated with warmer water masses and do not need wax esters for overwintering (Lee et al., 2006). By simultaneously monitoring hydrographic and biological conditions, Bill Peterson and colleagues have been able to link the appearance of each

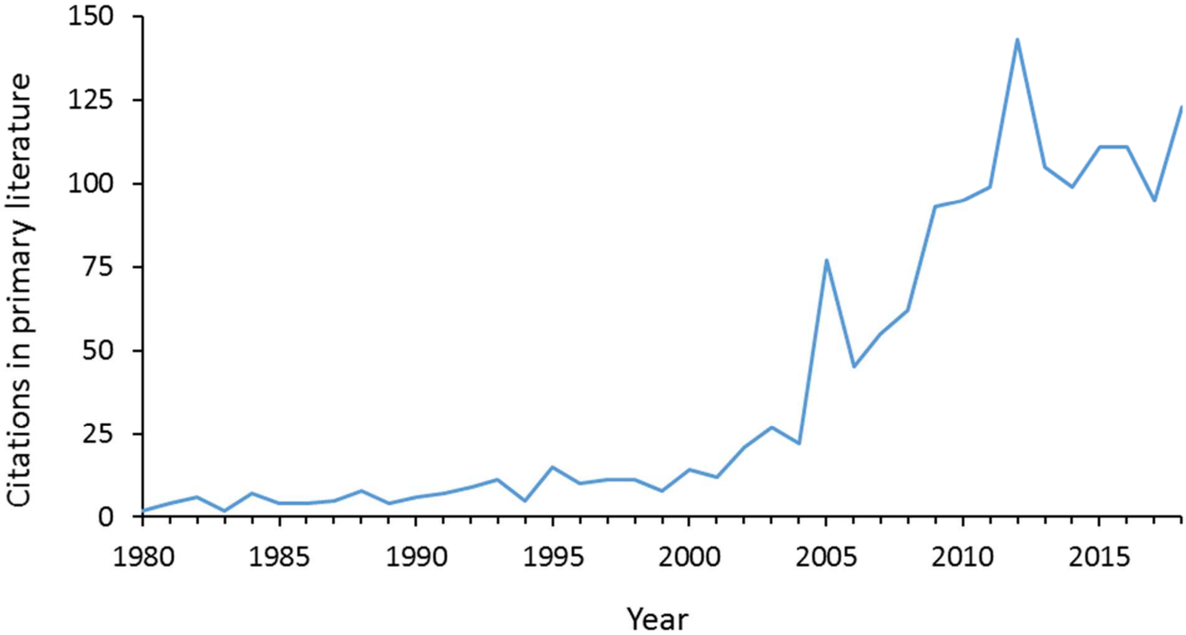

Figure 4. Number of citations per year in the primary literature (1980-2018) of 43 scientific papers published by Bill Peterson and colleagues that included research on copepods off of Oregon. See text for details.

of these species groups with physical mechanisms, namely seasonal, annual and decadal patterns of ocean transport in the CCE (Keister et al., 2011; Mackas et al., 2006; Mackas et al., 2004). From a trophic perspective, the large body sizes, lipid content, and fatty acid composition of northern copepods provide much greater prey quality to their predators (Miller et al., 2017), supporting faster growth in key forage fish such as larval northern anchovy *Engraulis mordax* (Takahashi et al., 2012). This boost in prey quality and system productivity associated with cool water masses is especially beneficial to fishes like juvenile Pacific salmon that have relatively cool optimal temperatures for feeding and growth (e.g., Atcheson et al., 2012).

The mechanisms of physical transport, energy content of northern and southern copepods, and trophic connections to salmon and other fishes have proven easy to convey to a range of audiences, particularly as those audiences have become accustomed to references to the energy-rich northern copepods as “cheeseburgers” and the southern copepods as “celery” in presentations (with Bill’s laughing endorsement). Ease of communication and interpretation for ecosystem information is essential (Baron, 2010; Kershner et al., 2011), given the limited time that ecosystem researchers are likely to have on the crowded agendas of management bodies, and also given the importance of clarity and transparency when communicating with managers, stakeholders and the general public.

The research is related to species or processes of societal value.

The aforementioned ecological mechanisms are all the more meaningful in a management context when they relate to ecosystem components that are highly valued by society. In this case, the copepod data relate to Pacific salmon, which are among the most highly valued and iconic marine species on the West Coast. The northern copepod biomass anomaly is strongly positively correlated to returns of fall Chinook salmon *Oncorhynchus tshawytscha* to the

Columbia River (Fig. 5; Peterson et al., 2014). Columbia River salmon are abundant, support highly valuable fisheries, and rely on habitats that extend into headwater streams of Washington, Oregon, Idaho and British Columbia (PFMC, 2013). They provide irreplaceable cultural value to indigenous communities (e.g., Quaempts et al., 2018). Many of these stocks are federally protected under the Endangered Species Act (PFMC, 2013), and Columbia River salmon as a whole are important components of the food web, including as a seasonal food source for highly endangered Southern Resident killer whales *Orcinus orca* (Hanson et al., 2013). Moreover, consideration of Columbia River salmon production and survival goes into decision-making and tradeoff assessments on water use, river flow management, land use and habitat restoration, management of predator populations, and other human activities that affect many groups of stakeholders (Hand et al., 2018; PFMC, 2013; Ruckelshaus et al., 2002).

Clearly, salmon are high-profile, at-risk species that have wide-ranging intersections with society. This underscores the importance of robust scientific information that can help managers to understand and anticipate the dynamics of the resource. Bill Peterson and his many colleagues recognized that long-term, ecosystem-scale monitoring of oceanography, ecology and natural history—particularly of parsimonious mechanisms and processes related to prey availability, quality and timing—could shed light on present and future salmon population sizes (Burke et al., 2013; Peterson et al., 2014; Peterson & Schwing, 2003; Tucker et al., 2015). The impact of their work to society is demonstrable in their tremendous contributions to the literature (Fig. 4; Gómez-Gutiérrez et al., 2018), and to ecosystem status reports that provide valuable context for salmon management (e.g., Harvey et al., 2018) and the fishing industry (PFMC-CPSAS, 2016; PFMC-SAS, 2016). Their findings may eventually support management directly through incorporation into salmon population models (Burke et al., 2013). Other long-term monitoring

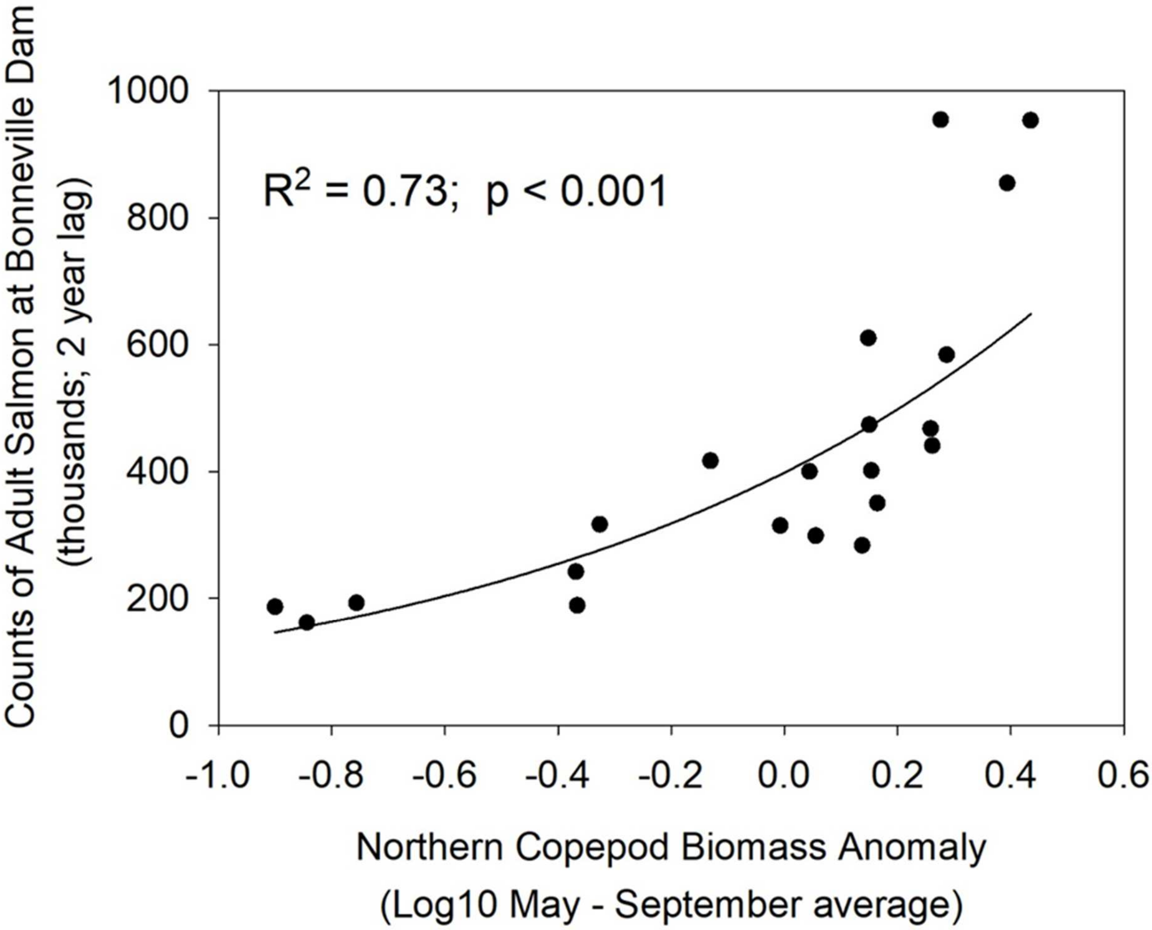

Figure 5. Relationship between fall Chinook salmon returns to Bonneville Dam (lower Columbia River) and the spring/summer northern copepod biomass anomaly during the year of salmon ocean entry, 1996-2016. Dam counts (points) are lagged two years following the year of ocean entry; the line and summary statistics represent the best fit using linear regression.

efforts in the region have shed light on many other ecosystem-scale responses of great societal importance. These include how the marine heatwave contributed to the scale and toxicity of massive harmful algal blooms along the West Coast (McCabe et al., 2016), and how entanglements of humpback whales *Megaptera novaeangliae* in fishing gear increased dramatically during the marine heatwave (NOAA, 2019). Long-term monitoring data are essential for characterizing the frequency, magnitude and duration of ecosystem events and responses. Effective monitoring helps us understand the relative extent of natural and social impacts related to a disturbance; it provides robust data for analyses and models to assess and predict disturbance risk to valued resources and activities; and it allows us to track the progress of management actions taken to control or mitigate disturbance impacts (Kaufman et al., 2009).

The data can demonstrate dynamics at meaningful temporal scales.

The nearly biweekly sampling frequency of the NH Line time series has enabled Bill and colleagues to track not just seasonal and annual changes in physical and biological variables, but also the fine-scale timing of changes, the lags that occur between drivers and responses, and how those lags could extend the ecological effects of climatological or oceanographic events. For example, the regular sampling along the NH Line helped to show that abundance of northern copepods is correlated with the PDO, but that changes in copepod abundance lag behind shifts in the PDO by several months (Hooff & Peterson, 2006; Liu et al., 2015). Similarly, southern copepods can remain significant parts of the community in this region for up to six months following the conclusion of major El Niño events (Peterson & Keister, 2003), and the magnitude and duration of a given copepod anomaly is strongly and positively related to the magnitude and duration of the corresponding El Niño event (Fisher et al., 2015). Identifying the fine-scale timing of transitions in the region supports better understanding of both the physical and biological conditions experienced by pelagic fishes whose life history stages have distinct phenologies, which in turn suggests tailoring specific indicators to particular species of management importance (Peterson et al., 2014).

Descriptions of temporal patterns offer a clear demonstration to stakeholders and managers that even in a dynamic, upwelling-driven system like the CCE, ecosystem processes do not simply switch on and off rapidly in unison; rather, physical, biological and ecological mechanisms can result in lagged responses that affect higher trophic level species and valuable ecosystem services. Thus, even though the copepod community shifted very rapidly at the onset of the marine heatwave in coastal waters, the return of the copepod anomalies to a near-average state was delayed even as prominent basin-scale physical indicators reverted to normal (Fig. 3). Monitoring both abiotic and biotic processes at appropriate scales can help to resolve these lags and lingering effects; doing so should improve our ability to make robust predictions of how perturbations at different temporal scales affect the rest of the system, and communicate those impacts to resource managers and stakeholders.

The time series is part of a larger integrative science effort.

As noted above, the copepod biomass anomaly data (Fig. 3c-d) were the key time series that the CCIEA team presented to the PFMC in March 2015: those “cheeseburger” and “celery” copepods signaled that the marine heatwave was forcing a dramatic decline in prey quality for much of the pelagic food web in the northern CCE. But importantly, many other ecosystem components beside the copepod community are monitored along the NH Line, and in other research and monitoring efforts in the region. For example, the copepod data are part of a larger suite of biophysical ocean indicators that Bill and colleagues have long compiled to generate yearly qualitative predictions of returns of Chinook salmon and coho salmon *Oncorhynchus* *kisutch* to the region. These indicators are derived from basin-scale physical indices, as well as field data collected along the NH Line and on the Juvenile Salmon and Ocean Ecosystem Survey (JSOES) that Bill and colleagues have conducted in the spring for over 20 years off of Washington and Oregon (e.g., Peterson et al., 2010). The suite of indicators includes climate indices and physical data, as well as biological data, all of which can be mechanistically or statistically related to different marine life history stages of salmon to get a general sense of conditions while salmon are at sea. The resulting “stoplight table” (Table 1) is intended to aid managers in decision-making by providing an understandable visual summary of where different indicators for a particular year rank relative to other years across the full time series. The approach has some skill in forecasting if Columbia River and Oregon coastal salmon runs will be above or below average (Peterson et al., 2014); it is also the basis for more robust statistical approaches with even greater predictive skill (Burke et al., 2013). Several groups, such as the PFMC, Washington Department of Fish and Wildlife, and Northwest Power and Conservation Council, request annual updates from these researchers to provide context for a suite of complex management concerns; states, tribes, hatchery managers, academics and the public sector use the results to better understand salmon dynamics and their associated marine environment. While not all salmon populations of the Columbia Basin or the northern CCE will experience identical conditions or respond to them in the same way (Burke et al., 2013), the stoplight table offers valuable guidance for salmon managers and may help identify key indices and mechanisms to explore further.

There is broad consensus that suites of integrated indicators are essential for supporting EBM (e.g., Fulton et al., 2005; Kershner et al., 2011; Rice & Rochet, 2005). Suites of indicators will include some metrics that have high specificity to certain key processes or components,

Table 1. "Stoplight" table summarizing ocean indicator data related to salmon growth and survival. Values are ranks of the indicators for the 21-year time series, color-coded to reflect conditions for salmon (high ranks/green = "good"; intermediate ranks/yellow = "intermediate"; low ranks/red = "poor"). Descriptions of individual indicators and units are in Peterson et al. (2014).

Year

Ecosystem Indicators	*1998*	*'99*	*2000*	*'01*	*'02*	*'03*	*'04*	*'05*	*'06*	*'07*	*'08*	*'09*	*'10*	*'11*	*'12*	*'13*	*'14*	*'15*	*'16*	*'17*	*'18*
PDO (Dec-March)	18	6	3	13	7	20	12	16	14	9	5	1	15	4	2	8	10	21	19	17	11
PDO (May-Sept)	10	4	6	5	11	17	16	18	12	14	2	9	7	3	1	8	19	21	20	15	13
ONI (Avg Jan-June)	20	1	1	7	14	16	15	17	9	12	3	11	18	4	6	8	10	19	21	13	5
Buoy 46050 SST (°C; May-Sept)	16	9	3	4	1	8	21	15	5	17	2	10	7	11	12	13	14	20	18	6	19
Upper 20 m T (°C; Nov-Mar)	20	11	8	10	6	15	16	12	13	5	1	9	17	4	3	7	2	21	19	18	14
Upper 20 m T (°C; May-Sept)	17	12	14	4	1	3	21	19	7	8	2	5	13	10	6	18	20	9	15	11	16
Deep temperature (°C; May-Sept)	21	6	8	4	1	10	12	16	11	5	2	7	14	9	3	15	20	18	13	17	19
Deep salinity (May-Sept)	19	3	9	4	5	16	17	10	7	1	2	14	18	13	12	11	20	15	8	6	6
Copepod species richness anom. (May-Sept)	19	2	1	7	6	14	13	18	15	10	8	9	17	4	5	3	11	20	21	16	12
N. copepod biomass anom. (May-Sept)	19	14	10	11	3	16	13	20	15	12	6	9	8	1	2	4	5	17	21	18	7
S. copepod biomass anom. (May-Sept)	21	2	5	4	3	14	15	20	13	10	1	7	16	9	8	6	11	18	19	17	12
Biological transition (day of year)	18	8	5	7	9	14	13	19	12	2	1	3	16	6	10	4	11	21	21	17	15
Ichthyoplankton biomass (Jan-Mar)	21	12	3	8	10	19	18	15	17	16	2	13	5	14	11	9	20	6	7	1	4
Ichthyoplankton community index (Jan-Mar)	10	13	2	7	5	11	20	18	3	12	1	14	15	8	4	6	9	19	21	17	16
Chinook juv catch (June)	19	4	5	16	8	12	17	20	11	9	1	6	7	15	3	2	10	13	18	21	14
Coho juv catch (June)	19	8	13	6	7	3	16	20	17	5	4	10	11	15	18	1	12	9	14	21	2
Mean of ranks	17.9	7.2	6.0	7.3	6.1	13.0	15.9	17.1	11.3	9.2	2.7	8.6	12.8	8.1	6.6	7.7	12.8	16.7	17.2	14.4	11.6
Rank of the mean rank	21	5	2	6	3	15	17	19	11	10	1	9	13	8	4	7	13	18	20	16	12

while also allowing for multiple, complementary indicators to validate more complex dynamics. Suites of indicators also can cover a wide range of natural system components, human use sectors, and objectives, which is necessary for tracking progress and tradeoffs across multiple goals and objectives in EBM (Kaufman et al., 2009; Singh et al., 2013), and for understanding the potential impacts of emerging ecosystem-scale stressors such as climate change, hypoxia, ocean acidification and harmful algal blooms. The value of such indicator suites will increase as time series grow long enough to robustly explore variation, correlation and nonlinear behavior of indicators within the context of credible mechanistic hypotheses (e.g., Litzow & Hunsicker, 2016; Samhouri et al., 2017).

Synthesis

We have presented six traits of long-term research that enhance its management value, and have illustrated these traits with the case of Bill Peterson's research on copepods and its value to the PFMC and other U.S. West Coast management bodies. These traits are highly consistent and compatible with the theoretical, quantitative and descriptive criteria that distinguish powerful ecosystem indicators (Kershner et al., 2011; Rice & Rochet, 2005). They also parallel the habits of good monitoring programs, which include emphases such as basing the sampling around good, forward-looking hypotheses; maintaining data quality and consistency; and constant interpretation, presentation, review and adaptation of the program as necessary (Lindenmayer & Likens, 2010; Lovett et al., 2007). Maintaining data consistency is a fundamental challenge, particularly at a sampling frequency like that of the NH Line; the pressures of funding, staffing, ship time, and occasional inclement weather and logistical problems are ever-present. Bill's wisdom in the face of this reality was that his team should identify one core station on the transect that they would strive to sample every time that safe conditions allowed, in order to preserve the integrity of the time series; data from that station, NH-5 (Fig. 2) have been the most often used as general indicators of ecosystem condition along the NH Line (e.g., Fig. 3).

As resource management agencies embrace and implement principles of EBM, the value of high-quality long-term monitoring, rooted in mechanistic hypotheses that link species of interest to environmental processes and reference points, will become ever more apparent. NOAA Fisheries recognizes this explicitly in its EBFM policy implementation plan (NOAA, 2016), its stock assessment improvement plan (Lynch et al., 2018), its climate science strategy (Link et al., 2015), and its IEA framework to provide science support for EBM (Levin et al., 2009). The stock assessment improvement plan calls for such monitoring information to be incorporated into single-species stock assessments where possible, provided that the monitoring information provides sufficient additional explanatory power (Lynch et al., 2018). Although NH Line copepod biomass anomaly data have not yet been integrated into any stock assessments that we know of, they show promising correlations with salmon population dynamics in the Columbia River (Burke et al., 2013; Peterson et al., 2014). They have been tested in recruitment models of another key West Coast target species, sablefish *Anoplopoma fimbria* (Tolimieri et al., 2018), and will be tested in other assessments in the future. Even if ecosystem-scale time series data do not improve stock assessment model performance sufficiently enough to be included as assessment parameters (e.g., based upon model selection criteria, or best practices for incorporating environmental parameters as suggested by Basson, 1999), they can still provide the fisheries management decision process with essential ecosystem context (Lynch et al., 2018), such as how environmental variability affects productivity of lower trophic levels (Fig. 3).

While a time series of this enduring importance is not unique at a global scale (e.g., Hays et al., 2005; Klais et al., 2016; Mackas & Beaugrand, 2010; Mackas et al., 2012; McClatchie et al., 2014; Wouters et al., 2015), it is nonetheless special. In this Information Age, there is a tendency to think more toward uses of Big Data, and less toward if and how to collect Big Data to begin with. However, the need for hypothesis-driven monitoring and related research is as real as ever, particularly as new stressors emerge and impose risk, uncertainty and constraint upon management (Lovett et al., 2007), and as baselines that form some basis for management targets continue to shift (McClenachan et al., 2012). Thus, we believe that funding, maintaining and expanding research like that on the NH Line is imperative, and that it should be part of a broader, coordinated regional ecosystem monitoring effort (e.g., Lindenmayer and Likens 2010). Bill was fueled by a deep curiosity in marine systems, a passion for getting his hands wet and dirty, and a conviction to support management and conservation. His example has already inspired the initiation of at least one similar effort—the Trinidad Head hydrographic line, located at 41.06ºN on the US West Coast and sampling biweekly to monthly since late 2007 (Bjorkstedt & Peterson, 2015). Future researchers who follow Bill's lead may wonder whether and how to get started on a long-term monitoring effort, and how to connect it meaningfully to management. We hope that the characteristics of the NH Line research outlined above will provide some guideposts in that endeavor, so that Bill's legacy lives on for decades to come.

Acknowledgments

We thank Brian Burke and two anonymous reviewers for valuable comments on earlier versions of this manuscript. This work was supported in part by funds provided by the NOAA Integrated Ecosystem Assessment (IEA) Program. This manuscript is NOAA IEA program contribution #2019_1.

References

Atcheson, M., Myers, K., Beauchamp, D., Mantua, N., 2012. Bioenergetic response by steelhead to variation in diet, thermal habitat, and climate in the north Pacific Ocean. *Transactions of the American Fisheries Society*, 141, 1081-1096.

Auth, T., Daly, E., Brodeur, R., Fisher, J., 2018. Phenological and distributional shifts in ichthyoplankton associated with recent warming in the northeast Pacific Ocean. *Global Change Biology*, 24, 259-272.

Baron, N., 2010. *Escape from the ivory tower: a guide to making your science matter*. Washington: Island Press.

Basson, M. 1999. The importance of environmental factors in the design of management procedures. *ICES Journal of Marine Science*, 56, 933–942.

Bjorkstedt, E., Peterson, W., 2015. Zooplankton data from high-frequency coastal transects: enriching the contributions of ocean observing systems to ecosystem-based management in the northern California Current. In Y. Liu, H. Kerkering, R. Weisberg (Eds.), *Coastal ocean observing systems* (pp. 119-142). London: Academic Press.

Bjorkstedt, E.P., Goericke, R., McClatchie, S., Weber, E., Watson, W., Lo, N., Peterson, W.T., Brodeur, R.D., Auth, T., Fisher, J., Morgan, C., Peterson, J., Largier, J., Bograd, S.J., Durazo, R., Gaxiola-Castro, G., Lavaniegos, B., Chavez, F.P., Collins, C.A., Hannah, B., Field, J., Sakuma, K., Satterthwaite, W., O'Farrell, M., Hayes, S., Harding, J., Sydeman, W.J., Thompson, S.A., Warzybok, P., Bradley, R., Jahncke, J., Golightly, R.T., Schneider, S.R., Suryan, R.M., Gladics, A.J., Horton, C.A., Kim, S.Y., Melin, S.R., DeLong, R.L., Abell, J., 2012. State of the California Current 2011-2012: Ecosystems Respond to Local Forcing as La Nina Wavers and Wanes. *California Cooperative Oceanic Fisheries Investigations Reports*, 53, 41-76.

Bond, N.A., Cronin, M.F., Freeland, H., Mantua, N., 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, 42, 3414-3420.

Borja, A., Galparsoro, I., Solaun, O., Muxika, I., Tello, E.M., Uriarte, A., Valencia, V., 2006. The European Water Framework Directive and the DPSIR, a methodological approach to assess the risk of failing to achieve good ecological status. *Estuarine Coastal and Shelf Science*, 66, 84-96.

Brander, K.M., Dickson, R.R., Edwards, M., 2003. Use of Continuous Plankton Recorder information in support of marine management: applications in fisheries, environmental protection, and in the study of ecosystem response to environmental change. *Progress in Oceanography*, 58, 175-191.

Bundy, A., Chuenpagdee, R., Boldt, J.L., Borges, M.D., Camara, M.L., Coll, M., Diallo, I., Fox, C., Fulton, E.A., Gazihan, A., Jarre, A., Jouffre, D., Kleisner, K.M., Knight, B., Link, J., Matiku, P.P., Masski, H., Moutopoulos, D.K., Piroddi, C., Raid, T., Sobrino, I., Tam, J., Thiao, D., Torres, M.A., Tsagarakis, K., van der Meeren, G.I., Shin, Y.J., 2017. Strong fisheries management and governance positively impact ecosystem status. *Fish and Fisheries*, 18, 412-439.

Burke, B.J., Peterson, W.T., Beckman, B.R., Morgan, C., Daly, E.A., Litz, M., 2013. Multivariate models of adult Pacific salmon returns. *Plos One*, 8, e54134.

deReynier, Y., 2012. Making ecosystem-based management a reality: the Pacific Fishery Management Council and the California Current Integrated Ecosystem Assessment. *California Cooperative Oceanic Fisheries Investigations Reports*, 53, 81-88.

DiLorenzo, E., Mantua, N., 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, 6, 1042-1047.

Dolan, T.E., Patrick, W.S., Link, J.S., 2016. Delineating the continuum of marine ecosystem-based management: a US fisheries reference point perspective. *ICES Journal of Marine Science*, 73, 1042-1050.

Dunstan, P.K., Bax, N.J., Dambacher, J.M., Hayes, K.R., Hedge, P.T., Smith, D.C., Smith, A.D.M., 2016. Using ecologically or biologically significant marine areas (EBSAs) to implement marine spatial planning. *Ocean & Coastal Management*, 121, 116-127.

Ehler, C., Douvere, F., 2009. *Marine spatial planning: a step-by-step approach toward ecosystem-based management*: Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. IOC Manual and Guides, No. 53, IOCAM Dosier No. 6. UNESCO, Paris.

Fisher, J., Peterson, W., Rykaczewski, R.R., 2015. The impact of El Niño events on the pelagic food chain in the northern California Current. *Global Change Biology*, 21, 4401-4414.

Francis, T.B., Levin, P., Punt, A., Kaplan, I., Varney, A., Norman, K., 2018. Linking knowledge to action in ocean ecosystem management: the Ocean Modeling Forum. *Elementa*, in press.

Francis, T.B., Scheuerell, M.D., Brodeur, R.D., Levin, P.S., Ruzicka, J.J., Tolimieri, N., Peterson, W.T., 2012. Climate shifts the interaction web of a marine plankton community. *Global Change Biology*, 18, 2498-2508.

Friberg, N., Bonada, N., Bradley, D.C., Dunbar, M.J., Edwards, F.K., Grey, J., Hayes, R.B., Hildrew, A.G., Lamouroux, N., Trimmer, M., Woodward, G., 2011. Biomonitoring of human impacts in freshwater ecosystems: the good, the bad and the ugly. *Advances in Ecological Research, Vol 44*, 44, 1-68.

Fulton, E.A., Smith, A.D.M., Punt, A.E., 2005. Which ecological indicators can robustly detect effects of fishing? *ICES Journal of Marine Science*, 62, 540-551.

Gaines, S.D., White, C., Carr, M.H., Palumbi, S.R., 2010. Designing marine reserve networks for both conservation and fisheries management. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 18286-18293.

Gómez-Gutiérrez, J., Batchelder, H., Riquelme-Bugueño, R., 2018. William Thornton Peterson, "Bill", 1942-2017: zooplankton, climate change and salmon ecology. *Journal of Plankton Research*, 40, 503-508.

Hand, B., Flint, C., Frissell, C., Muhlfield, C., Devlin, S., Kennedy, B., Crabtree, R., McKee, W., Luikart, G., Stanford, J., 2018. A social-ecological perspective for riverscape management in the Columbia River basin. *Frontiers in Ecology and the Environment*, 16, S23-S33.

Hanson, M., Emmons, C., Ward, E., Nystuen, J., Lammers, M., 2013. Assessing the coastal occurrence of endangered killer whales using autonomous passive acoustic recorders. *Journal of the Acoustical Society of America*, 134, 3486-3495.

Harvey, C., Garfield, N., Williams, G., Andrews, K., Barcelo, C., Barnas, K., Bograd, S., Brodeur, R., Burke, B., Cope, J., deWitt, L., Field, J., Fisher, J., Greene, C., Good, T., Hazen, E., Holland, D., Jacox, M., Kasperski, S., Kim, S., Leising, A., Melin, S., Morgan, C., Munsch, S., Norman, K., Peterson, W.T., Poe, M., Samhouri, J., Schroeder, I., Sydeman, W., Thayer, J., Thompson, A., Tolimieri, N., Varney, A., Wells, B., Williams, T., Zamon, J., 2017. *Ecosystem status report of the California Current for 2017: a summary of ecosystem indicators compiled by the California Current Integrated Ecosystem*

Assessment Team (CCIEA): US Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-139.

Harvey, C., Garfield, T., Williams, G., Tolimieri, N., Hazen, E., (Eds.), 2018. *California Current Integrated Ecosystem Assessment (CCIEA) California Current ecosystem status report, 2018*: Report to the Pacific Fishery Management Council. Available at: https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-publications-reports.

Harvey, C.J., Kelble, C.R., Schwing, F.B., 2017. Implementing "the IEA": using integrated ecosystem assessment frameworks, programs, and applications in support of operationalizing ecosystem-based management. *ICES Journal of Marine Science*, 74, 398-405.

Hays, G.C., Richardson, A.J., Robinson, C., 2005. Climate change and marine plankton. *Trends in Ecology and Evolution*, 20, 337-344.

Hooff, R.C., Peterson, W.T., 2006. Copepod biodiversity as an indicator of changes in ocean and climate conditions of the northern California current ecosystem. *Limnology and Oceanography*, 51, 2607-2620.

Jacox, M.G., Alexander, M.A., Mantua, N.J., Scott, J.D., Hervieux, G., Webb, R.S., Werner, F.E., 2018. Forcing of multiyear extreme ocean temperatures that impacted California Current living marine resources in 2016. *Bulletin of the American Meteorological Society*, 99, S27-S33.

Jones, T., Parrish, J., Peterson, W., Bjorkstedt, E., Bond, N., Ballance, L., Bowes, V., Hipfner, J., Burgess, H., Dolliver, J., Lindquist, K., Lindsey, J., Nevins, H., Robertson, R., Roletto, J., Wilson, L., Joyce, T., Harvey, J., 2018. Massive mortality of a planktivorous seabird in response to a marine heatwave. *Geophysical Research Letters*, 45, 3193-3202.

Kaufman, L., Karrer, L., Peterson, C., 2009. Monitoring and evaluation. In K. McLeod, H. Leslie (Eds.), *Ecosystem-based management for the oceans* (pp. 115-128). Washington, DC: Island Press.

Keister, J., DiLorenzo, E., Morgan, C., Combes, V., Peterson, W., 2011. Copepod species composition is linked to ocean transport in the northern California Current. *Global Change Biology*, 17, 2498-2511.

Kelble, C.R., Loomis, D.K., Lovelace, S., Nuttle, W.K., Ortner, P.B., Fletcher, P., Cook, G.S., Lorenz, J.J., Boyer, J.N., 2013. The EBM-DPSER conceptual model: integrating ecosystem services into the DPSIR framework. *Plos One*, 8.

Kershner, J., Samhouri, J.F., James, C.A., Levin, P.S., 2011. Selecting indicator portfolios for marine species and food webs: a Puget Sound case study. *Plos One*, 6.

Klais, R., Lehtiniemi, M., Rubene, G., Semenova, A., Margonski, P., Ikauniece, A., Simm, M., Põllumäe, A., Grinienė, E., Mäkinen, K., Ojaveer, H., 2016. Spatial and temporal variability of zooplankton in a temperate semi-enclosed sea: implications for monitoring design and long-term studies. *Journal of Plankton Research*, 38, 652-661.

Lee, R., Hagen, W., Kattner, G., 2006. Lipid storage in marine zooplankton. *Marine Ecology Progress Series*, 307, 273-306.

Leising, A.W., Schroeder, I.D., Bograd, S.J., Abell, J., Durazo, R., Gaxiola-Castro, G., Bjorkstedt, E.P., Field, J., Sakuma, K., Robertson, R.R., Goericke, R., Peterson, W.T., Brodeur, R., Barcelo, C., Auth, T.D., Daly, E.A., Suryan, R.M., Gladics, A.J., Porquez, J.M., McClatchie, S., Weber, E.D., Watson, W., Santora, J.A., Sydeman, W.J., Melin, S.R., Chavez, F.P., Golightly, R.T., Schneider, S.R., Fisher, J., Morgan, C., Bradley, R., Warybok, P., 2015. State of the California Current 2014-15: Impacts of the Warm-Water "Blob". *California Cooperative Oceanic Fisheries Investigations Reports*, 56, 31-68.

Leising, A.W., Schroeder, I.D., Bograd, S.J., Bjorkstedt, E.P., Field, J., Sakuma, K., Abell, J., Robertson, R.R., Tyburczy, J., Peterson, W.T., Brodeur, R., Barcelo, C., Auth, T.D., Daly, E.A., Campbell, G.S., Hildebrand, J.A., Suryan, R.M., Gladics, A.J., Horton, C.A., Kahru, M., Manzano-Sarabia, M., McClatchie, S., Weber, E.D., Watson, W., Santora, J.A., Sydeman, W.J., Melin, S.R., Delong, R.L., Largier, J., Kim, S.Y., Chavez, F.P., Golightly, R.T., Schneider, S.R., Warzybok, P., Bradley, R., Jahncke, J., Fisher, J., Peterson, J., 2014. State of the California Current 2013-14: El Nino Looming. *California Cooperative Oceanic Fisheries Investigations Reports*, 55, 51-87.

Levin, P.S., Fogarty, M.J., Murawski, S.A., Fluharty, D., 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. *Plos Biology*, 7, 23-28.

Levin, P.S., Wells, B.K., Sheer, M.B., (Eds.), 2013. *California Current Integrated Ecosystem Assessment: Phase II Report*. Available at https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-publications-reports/phaseIIIReport2013.

Lindenmayer, D., Likens, G., 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. *Trends in Ecology and Evolution*, 24, 482-486.

Lindenmayer, D.B., Likens, G.E., 2010. The science and application of ecological monitoring. *Biological Conservation*, 143, 1317-1328.

Link, J., Griffis, R., Busch, S., (Eds.), 2015. *NOAA Fisheries climate science strategy*: US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, NOAA Technical Memorandum NMFS-F/SPO-155.

Litzow, M.A., Hunsicker, M.E., 2016. Early warning signals, nonlinearity, and signs of hysteresis in real ecosystems. *Ecosphere*, 7.

Liu, H., Bi, H., Peterson, W., 2015. Large-scale forcing of environmental conditions on subarctic copepods in the northern California Current system. *Progress in Oceanography*, 134, 404-412.

Lovett, G., Burns, D., Driscoll, C., Jenkins, J., Mitchell, M., Rustad, L., Shanley, J., Likens, G., Haeuber, R., 2007. Who needs environmental monitoring? *Frontiers in Ecology and the Environment*, 5, 253-260.

Lynch, P., Methot, R.D., Link, J.S., (Eds.), 2018. *Implementing a next generation stock assessment enterprise: an update to the NOAA Fisheries Stock Assessment Improvement Plan*: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, NOAA Technical Memorandum NMFS-F/SPO-183.

Mackas, D., Peterson, W., Ohman, M., Lavaniegos, B., 2006. Zooplankton anomalies in the California Current system before and during the warm ocean conditions of 2005. *Geophysical Research Letters*, 33.

Mackas, D.L., Beaugrand, G., 2010. Comparisons of zooplankton time series. *Journal of Marine Systems*, 79, 286-304.

Mackas, D.L., Greve, W., Edwards, M., Chiba, S., Tadokoro, K., Eloire, D., Mazzocchi, M.G., Batten, S., Richardson, A.J., Johnson, C., Head, E., Conversi, A., Peluso, T., 2012. Changing zooplankton seasonality in a changing ocean: Comparing time series of zooplankton phenology. *Progress in Oceanography*, 97, 31-62.

Mackas, D.L., Peterson, W.T., Zamon, J.E., 2004. Comparisons of interannual biomass anomalies of zooplankton communities along the continental margins of British Columbia and Oregon. *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, 51, 875-896.

Mackas, D.L., Thomson, R.E., Galbraith, M., 2001. Changes in the zooplankton community of the British Columbia continental margin, 1985-1999, and their covariation with oceanographic conditions. *Canadian Journal of Fisheries and Aquatic Sciences*, 58, 685-702.

McCabe, R.M., Hickey, B.M., Kudela, R.M., Lefebvre, K.A., Adams, N.G., Bill, B.D., Gulland, F.M.D., Thomson, R.E., Cochlan, W.P., Trainer, V.L., 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, 43, 10366-10376.

McClatchie, S., 2014. *Regional fisheries oceanography of the California Current system and the CalCOFI program*. Dordrecht: Springer.

McClatchie, S., Duffy-Anderson, J., Field, J.C., Goericke, R., Griffith, D., Hanisko, D.S., Hare, J.A., Lyczkowski-Shultz, J., Peterson, W.T., Watson, W., Weber, E.D., Zapfe, G., 2014. Long time series in US fisheries oceanography. *Oceanography*, 27, 48-67.

McClatchie, S., Goericke, R., Leising, A., Auth, T., Bjorkstedt, E., Robertson, R.R., Brodeur, R., Du, X., Daly, E.A., Morgan, C., Chavez, F., Debich, A., Hildebrand, J., Field, J., Sakuma, K., Jacox, M., Kahru, M., Kudela, R., Anderson, C., Lavaniegos, B.E., Gomez-Valdes, J., Jimenez-Rosenberg, S., McCabe, R., Melin, S.R., Ohman, M.D., Sala, L., Peterson, B., Fisher, J., Schroeder, I., Bograd, S.J., Hazen, E., Schneider, S., Golightly, R.T., Suryan, R.M., Gladics, A.J., Loredo, S., Porquez, J.M., Thompson, A., Weber, E.D., Watson, W., Trainer, V., Warzybok, P., Bradley, R., Jahncke, J., 2016. State of the California Current 2015-16: comparisons with the 1997-98 El Nino. *CalCOFI Reports*, 57, 5-61.

McClenachan, L., Ferretti, F., Baum, J.K., 2012. From archives to conservation: why historical data are needed to set baselines for marine animals and ecosystems. *Conservation Letters*, 5, 349-359.

McQuatters-Gollop, A., Johns, D., Bresnan, E., Skinner, J., Rombouts, I., Stern, R., Aubert, A., Johansen, M., Bedford, J., Knights, A., 2017. From microscope to management: the critical value of plankton taxonomy to marine policy and biodiversity conservation. *Marine Policy*, 83, 1-10.

Miller, J., Peterson, W., Copeman, L., Du, X., Morgan, C., Litz, M., 2017. Temporal variation in the biochemical ecology of lower trophic levels in the Northern California Current. *Progress in Oceanography*, 155, 1-12.

Mirtl, M., Borer, E.T., Djukic, I., Forsius, M., Haubold, H., Hugo, W., Jourdan, J., Lindenmayer, D., McDowell, W.H., Muraoka, H., Orenstein, D.E., Pauw, J.C., Peterseil, J., Shibata, H., Wohner, C., Yu, X., Haase, P., 2018. Genesis, goals and achievements of Long-Term Ecological Research at the global scale: A critical review of ILTER and future directions. *Science of the Total Environment*, 626, 1439-1462.

NMFS, 2014. *Annual state of the California Current ecosystem report*: Report of the National Marine Fisheries Service to the Pacific Fishery Management Council. Available at https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-publications-reports.

NOAA, 2016. *NOAA Fisheries ecosystem-based fisheries management road map. NOAA Fisheries Procedure 01-120-01*: U.S. Department of Commerce, National Oceanic and Atmospheric Administration. Available at https://www.st.nmfs.noaa.gov/Assets/ecosystems/ebfm/EBFM_Road_Map_final.pdf.

NOAA, 2018. *Ecosystem-based fisheries management policy of the National Marine Fisheries Service. NOAA Fisheries Policy 01-120*: U.S. Department of Commerce, National Oceanic and Atmospheric Administration. Available at https://www.fisheries.noaa.gov/resource/document/ecosystem-based-fisheries-management-policy.

NOAA, 2019. 2018 West Coast whale entanglement summary. US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. Available at https://www.fisheries.noaa.gov/resource/document/2018-west-coast-whale-entanglement-summary.

Peterson, W., Keister, J., 2003. Interannual variability in copepod community composition at a coastal station in the northern California Current: a multivariate approach. *Deep-Sea Research II*, 50, 2499-2517.

Peterson, W., Morgan, C., Fisher, J., Casillas, E., 2010. Ocean distribution and habitat associations of yearling coho (*Oncorhynchus kisutch*) and Chinook (*O. tshawytscha*) salmon in the northern California Current. *Fisheries Oceanography*, 19, 508-525.

Peterson, W.T., 2009. Copepod species richness as an indicator of long-term changes in the coastal ecosystem of the Northern California Current. *California Cooperative Oceanic Fisheries Investigations Reports*, 50, 73-81.

Peterson, W.T., Fisher, J.L., Peterson, J.O., Morgan, C.A., Burke, B.J., Fresh, K.L., 2014. Applied fisheries oceanography ecosystem indicators of ocean condition inform fisheries management in the California Current. *Oceanography*, 27, 80-89.

Peterson, W.T., Fisher, J.L., Strub, P.T., Du, X.N., Risien, C., Peterson, J., Shaw, C.T., 2017. The pelagic ecosystem in the Northern California Current off Oregon during the 2014-2016 warm anomalies within the context of the past 20 years. *Journal of Geophysical Research-Oceans*, 122, 7267-7290.

Peterson, W.T., Schwing, F.B., 2003. A new climate regime in northeast Pacific ecosystems. *Geophysical Research Letters*, 30, 1896.

PFMC-CPSAS, 2016. *Pacific Fishery Management Council, Coastal Pelagic Species Advisory Subpanel report on Fishery Ecosystem Plan coordinated ecosystem indicator review initiative. Agenda Item D.1.a, September 2016*: Available at www.pcouncil.org/wp-content/uploads/2016/09/D1a_Sup_CPSAS_Rpt_SEPT2016BB.pdf.

PFMC-SAS, 2016. *Pacific Fishery Management Council, Salmon Advisory Subpanel report on ecosystem indicators. Agenda Item D.1.a, September 2016*: Available at www.pcouncil.org/wp-content/uploads/2016/08/D1a_SAS_Rpt_SEPT2016BB.pdf.

PFMC, 2012. *Draft annual state of the California Current ecosystem report*: Report of NMFS and the Ecosystem Plan Development Team to the Pacific Fishery Management Council. Available at https://www.pcouncil.org/wp-content/uploads/K3a_SUP_ATT1_DRAFT_CA_CURRENT_NOV2012BB.pdf.

PFMC, 2013. *Pacific Coast Fishery Ecosystem Plan for the U.S. portion of the California Current large marine ecosystem*: Pacific Fishery Management Council, Portland, OR.

Quaempts, E., Jones, K., O'Daniel, S., Beechie, T., Poole, G., 2018. Aligning environmental management with ecosystem resilience: a First Foods example from the Confederated Tribes of the Umatilla Indian Reservation, Oregon, USA. *Ecology and Society*, 23, 29.

Rice, J.C., Rochet, M.J., 2005. A framework for selecting a suite of indicators for fisheries management. *ICES Journal of Marine Science*, 62, 516-527.

Ruckelshaus, M., Levin, P., Johnson, J., Kareiva, P., 2002. The Pacific salmon wars: what science brings to the challenge of recovering species. *Annual Review of Ecology and Systematics*, 33, 665-706.

Russ, G.R., Miller, K., Rizzari, J., Alcala, A., 2015. Long-term no-take marine reserve and benthic habitat effects on coral reef fishes. *Marine Ecology Progress Series*, 529, 233-248.

Sainsbury, K., Gullestad, P., Rice, J., 2014. The use of national frameworks for sustainable development of marine fisheries and conservation, ecosystem-based management and integrated ocean management. In S. Garcia, J. Rice, A. Charles (Eds.), *Governance of Marine Fisheries and Biodiversity Conservation: Interaction and Coevolution* (pp. 301-316). Chichester, UK: John Wiley & Sons.

Samhouri, J.F., Andrews, K.S., Fay, G., Harvey, C.J., Hazen, E.L., Hennessey, S.M., Holsman, K., Hunsicker, M.E., Large, S.I., Marshall, K.N., Stier, A.C., Tam, J.C., Zador, S.G., 2017. Defining ecosystem thresholds for human activities and environmental pressures in the California Current. *Ecosphere*, 8, e01860.

Samhouri, J.F., Haupt, A.J., Levin, P.S., Link, J.S., Shuford, R., 2014. Lessons learned from developing integrated ecosystem assessments to inform marine ecosystem-based management in the USA. *ICES Journal of Marine Science*, 71, 1205-1215.

Seddon, A.W.R., Mackay, A.W., Baker, A.G., Birks, H.J.B., Breman, E., Buck, C.E., Ellis, E.C., Froyd, C.A., Gill, J.L., Gillson, L., Johnson, E.A., Jones, V.J., Juggins, S., Macias-Fauria, M., Mills, K., Morris, J.L., Nogues-Bravo, D., Punyasena, S.W., Roland, T.P., Tanentzap, A.J., Willis, K.J., Aberhan, M., van Asperen, E.N., Austin, W.E.N., Battarbee, R.W., Bhagwat, S., Belanger, C.L., Bennett, K.D., Birks, H.H., Ramsey, C.B., Brooks, S.J., de Bruyn, M., Butler, P.G., Chambers, F.M., Clarke, S.J., Davies, A.L., Dearing, J.A., Ezard, T.H.G., Feurdean, A., Flower, R.J., Gell, P., Hausmann, S., Hogan, E.J., Hopkins, M.J., Jeffers, E.S., Korhola, A.A., Marchant, R., Kiefer, T., Lamentowicz, M., Larocque-Tobler, I., Lopez-Merino, L., Liow, L.H., McGowan, S., Miller, J.H., Montoya, E., Morton, O., Nogue, S., Onoufriou, C., Boush, L.P., Rodriguez-Sanchez, F., Rose, N.L., Sayer, C.D., Shaw, H.E., Payne, R., Simpson, G., Sohar, K., Whitehouse, N.J., Williams, J.W., Witkowski, A., 2014. Looking forward through the past: identification of 50 priority research questions in palaeoecology. *Journal of Ecology*, 102, 256-267.

Shephard, S., Greenstreet, S.P.R., Piet, G.J., Rindorf, A., Dickey-Collas, M., 2015. Surveillance indicators and their use in implementation of the Marine Strategy Framework Directive. *ICES Journal of Marine Science*, 72, 2269-2277.

Singh, S., Haberl, H., Chertow, M., Mirtl, M., Schmid, M., (Eds.), 2013. *Long term socio-ecological research*. Dordrecht: Springer.

Slater, W., DePiper, G., Gove, J., Harvey, C., Hazen, E., Lucey, S., Karnauskas, M., Regan, S., Siddon, E., Yasumiishi, E., Zador, S., Brady, M., Ford, M., Griffis, R., Shuford, R., Townsend, H., O'Brien, T., Peterson, J., Osgood, K., Link, J., 2017. *Challenges, opportunities and future directions to advance NOAA Fisheries ecosystem status reports (ESRs): report of the National ESR Workshop*: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, NOAA Technical Memorandum NMFS-F/SPO-174.

Sydeman, W., Elliott, M., 2008. Developing the California Current integrated ecosystem assessment, Module I: select time-series of ecosystem state. Petaluma, CA.

Sydeman, W.J., Thompson, S.A., 2010. *The California Current integrated ecosystem assessment (IEA), Module II: trends and variability in climate-ecosystem state*. Petaluma, CA: Farallon Institute for Advanced Ecosystem Research.

Takahashi, M., Checkley, D.M., Litz, M.N.C., Brodeur, R.D., Peterson, W.T., 2012. Responses in growth rate of larval northern anchovy (*Engraulis mordax*) to anomalous upwelling in the northern California Current. *Fisheries Oceanography*, 21, 393-404.

Tolimieri, N., Haltuch, M.A., Lee, Q., Jacox, M.G., Bograd, S.J., 2018. Oceanographic drivers of sablefish recruitment in the California Current. *Fisheries Oceanography*, 27, 458-474.

Tucker, S., Thiess, M.E., Morris, J.F.T., Mackas, D., Peterson, W.T., Candy, J.R., Beacham, T.D., Iwamoto, E.M., Teel, D.J., Peterson, M., Trudel, M., 2015. Coastal distribution and consequent factors influencing production of endangered Snake River sockeye salmon. *Transactions of the American Fisheries Society*, 144, 107-123.

Ward, E., Anderson, S., Damiano, L., Hunsicker, M., Litzow, M., in press. Modeling regimes with extremes: the bayesdfa package for identifying and forecasting common trends and anomalies in multivariate time-series data. *R Journal*. DOI: 10.32614/RJ-2019-007.

Wells, B.K., Schroeder, I.D., Bograd, S.J., Hazen, E.L., Jacox, M.G., Leising, A., Mantua, N., Santora, J.A., Fisher, J., Peterson, W.T., Bjorkstedt, E., Robertson, R.R., Chavez, F.P., Goericke, R., Kudela, R., Anderson, C., Lavaniegos, B.E., Gomez-Valdes, J., Brodeur, R.D., Daly, E.A., Morgan, C.A., Auth, T.D., Field, J.C., Sakuma, K., McClatchie, S., Thompson, A.R., Weber, E.D., Watson, W., Suryan, R.M., Parrish, J., Dolliver, J., Loredo, S., Porquez, J.M., Zamon, J.E., Schneider, S.R., Golightly, R.T., Warzybok, P., Bradley, R., Jahncke, J., Sydeman, W., Melin, S.R., Hildebrand, J.A., Debich, A.J., Thayre, B., 2017. State of the California Current 2016-17: still anything but "normal" in the north. *California Cooperative Oceanic Fisheries Investigations Reports*, 58, 1-55.

Wells, B.K., Schroeder, I.D., Santora, J.A., Hazen, E.L., Bograd, S.J., Bjorkstedt, E.P., Loeb, V.J., Mcclatchie, S., Weber, E.D., Watson, W., Thompson, A.R., Peterson, W.T., Brodeur, R.D., Harding, J., Field, J., Sakuma, K., Hayes, S., Mantua, N., Sydeman, W.J., Losekoot, M., Thompson, S.A., Largier, J., Kim, S.Y., Chavez, F.P., Barcelo, C., Warzybok, P., Bradley, R., Jahncke, J., Goericke, R., Campbell, G.S., Hildebrand, J.A., Melin, S.R., Delong, R.L., Gomez-Valdes, J., Lavaniegos, B., Gaxiola-Castro, G., Golightly, R.T., Schneider, S.R., Lo, N., Suryan, R.M., Gladics, A.J., Horton, C.A., Fisher, J., Morgan, C., Peterson, J., Daly, E.A., Auth, T.D., Abell, J., 2013. State of the California Current 2012-13: no such thing as an "average" year. *California Cooperative Oceanic Fisheries Investigations Reports*, 54, 37-71.

Williams, G.D., Andrews, K.S., Tolimieri, N., Samhouri, J.F., Levin, P.S., Barcelo, C., Brodeur, R.D., 2013. Ecological integrity. In P.S. Levin, B.K. Wells, M.B. Sheer (Eds.), *California Current Integrated Ecosystem Assessment: Phase II Report*. Available at https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-publications-reports.

Wouters, N., Dakos, V., Edwards, M., Serafim, M.P., Valayer, P.J., Cabral, H.N., 2015. Evidencing a regime shift in the North Sea using early-warning signals as indicators of critical transitions. *Estuarine Coastal and Shelf Science*, 152, 65-72.