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To cite this article: Phillip S. Levin, Tessa B. Francis & Nathan G. Taylor (2016) Thirty-two essential questions for understanding the social–ecological system of forage fish: the case of pacific herring, *Ecosystem Health and Sustainability*, 2:4, e01213, DOI: [10.1002/ehs2.1213](https://doi.org/10.1002/ehs2.1213)

To link to this article: <https://doi.org/10.1002/ehs2.1213>



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Published online: 19 Jun 2017.



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Thirty-two essential questions for understanding the social–ecological system of forage fish: the case of Pacific Herring

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Abstract. Forage fishes are ecologically and economically important low trophic level species, and in recent years interest in their biology and management has intensified. Pacific Herring are emblematic of the management issues facing forage species—they are central components of the Northeast Pacific pelagic food web and support important commercial fisheries. In addition, the importance of Herring to indigenous peoples have made them cultural keystone species. We employed a participatory process to promote collaborative priority-setting for this critical forage species. Working with managers, the fisheries industry, indigenous peoples, and scientists, we co-constructed a conceptual model of the Pacific Herring social–ecological system (SES) in the Northeast Pacific. We then identified a set of questions, that, if answered, would significantly increase our ability to sustainably manage the Herring SES. Our objective was to generate a road map for scientists who wish to conduct useful forage fish research, for resource managers who wish to develop new research efforts that could fill critical gaps, and for public agencies and private foundations seeking to prioritize funding on forage fish issues in the Pacific. With this socio-cultural centrality comes complexity for fisheries management. Our participatory process highlighted the value of conceptualizing the full SES, overcame disciplinary differences in scientific approaches, research philosophy, and language, and charted a path forward for future research and management for forage species.

Key words: *fisheries; forage fish; interdisciplinary science; Pacific Herring; Pacific Ocean; social–ecological system.*

Citation: Levin, P. S., T. B. Francis, and N. G. Taylor. 2016. Thirty-two essential questions for understanding the social–ecological system of forage fish: the case of Pacific Herring. *Ecosystem Health and Sustainability* 2(4):e01213. doi:10.1002/ehs2.1213

Introduction

Small to medium-sized pelagic fishes, “forage fish,” have garnered increasing attention in recent years (Peck et al. 2014, Pikitch et al. 2014, Shelton et al. 2014a, Essington et al. 2015). Their abundance is highly variable, often driven by variability in climate and ocean conditions (Peck et al. 2014), and consequently their populations are vulnerable to overfishing (Essington et al. 2015). Forage fish provide a critical pathway from low trophic level primary producers and consumers (e.g., phytoplankton and zooplankton) to upper trophic level predators such as seabirds, marine mammals, and large fish (Smith et al. 2011). Additionally, forage fish support important commercial fisheries

(Alder et al. 2008), with current landings around 31.5 million tons (Pikitch et al. 2012); and, the value of forage fish to other marine fisheries can be quite large, perhaps as much as twice the value of fisheries directed at forage fish themselves (Pikitch et al. 2014). The total direct and indirect contribution of forage fish to global fisheries is some \$16.9 billion (Pikitch et al. 2012).

Pacific Herring (*Clupea pallasii*) of the Northeast Pacific Ocean are emblematic of the management issues facing forage species throughout the world. Pacific Herring are central components of the Northeast Pacific pelagic food web (Ainsworth et al. 2008, Harvey et al. 2012), and support large populations of predatory fish, marine mammals, and seabirds (Bishop et al. 2015, Surma and Pitcher 2015). In addition to their prominence in food webs and fisheries, Herring are considered a cultural keystone species (*sensu* Garibaldi and Turner 2004) for indigenous peoples throughout the Northeast Pacific (Thornton and

Manuscript received 5 November 2015; revised 29 January 2016; accepted 11 February 2016.

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Kitka 2015). Archeological evidence suggests that native people harvested Herring for millennia (McKechnie et al. 2014, Greene et al. 2015). Gathering of roe on kelp has long been an important traditional practice for native peoples, and Herring play a vital role in oral history, songs, dances, and place names (Haida Marine Traditional Knowledge Participants and Haida Oceans Technical Team 2011). Indeed, ethnographic and archeological evidence reveals that the presence of persistent human settlement was historically associated with existence of spawning Herring populations (Thornton et al. 2010).

Herring have also supported important commercial fisheries for at least a century. In the early 1900s Herring were dried and canned for human consumption (Lassuy 1989); however, throughout most of the 1900s most Herring landed in the Northeast Pacific were reduced to fish oil and fish meal (Trumble and Humphreys 1985). More recently, fisheries for sac-roe have dominated commercial fisheries. These fisheries target sexually mature fish and the roe are processed into a caviar-like product for export to Japan. Roe-on-kelp or roe-on-conifer branches has also been commercially harvested throughout the Northeast Pacific. Herring eggs harvested in this manner are eaten fresh, dried, or salted and command a high price (Haida Marine Traditional Knowledge Participants and Haida Oceans Technical Team 2011).

Despite their economic, cultural, and ecological importance, Herring populations have declined throughout the Northeast Pacific (e.g., Schweigert et al. 2010, Greene et al. 2015). Like other forage fish, the dynamics of Herring populations are highly influenced by climate conditions (Perry and Schweigert 2008, Ito et al. 2015), and poor ocean productivity in recent years has contributed to coast-wide declines (e.g., Schweigert et al. 2010). In addition, declines in California and Washington Herring appear associated with poor water quality, habitat degradation, and fisheries (Incardona et al. 2012, Shelton et al. 2014b, Greene et al. 2015). Farther north in British Columbia, overfishing in concert with poor ocean conditions appeared to cause declines in abundance in the 1930s and 1960s (Schweigert et al. 2010). Since the 1990s, increases in natural mortality in some regions of British Columbia (Martell et al. 2012) may be preventing rebuilding from recent overharvesting even though commercial fisheries have been closed in these regions since the early 2000s. Herring declines in the Gulf of Alaska in the 1990s appear to be related to poor ocean productivity and disease (Schweigert et al. 2010, Pearson et al. 2012).

Because of their ecological, economic, and cultural importance, Herring have become the center for management controversy throughout their range. In recent years this has led to petitions for listing Herring under the U.S. Endangered Species Act (Gustafson et al. 2006), legal action regarding indigenous use of Herring (e.g., *R. vs. Gladstone* [1996] 2 S.C.R. 723; *Ahousaht Indian Band*

and *Nation vs. Canada* (Attorney General), 2009 BCSC 1494), and even blockades and the occupation of government buildings to prevent Herring fishery openings (http://www.vancouver.sun.com/Heiltsuk+Nation+members+occupy+office+protest+Herring+fishery/10931646/story.html?__lsa=23bb-8f34). Productively confronting such controversy requires substantive communication between the producers and users of knowledge (Sarewitz and Pielke 2007).

Participatory processes that foster collaboration between researchers, resource managers, and other knowledge holders can catalyze the development of policy-relevant science that directly addresses blind spots and gaps in knowledge that may be at the root of conflicts (Sutherland et al. 2011). Following Sutherland et al. (2011), we employed a participatory process to promote collaborative priority-setting for Pacific Herring. Participants first co-constructed a conceptual model of the Pacific Herring social-ecological system (SES) in the Northeast Pacific. We then identified a set of questions, that if answered, would significantly increase our ability to sustainably manage the Herring SES. We also conducted “horizon scanning” (Sutherland and Woodroof 2009), in which individuals searched for potential threats and opportunities that are currently underappreciated. Our objective was to generate a road map for scientists who wish to conduct useful forage fish research, for resource managers who wish to develop new research efforts that could fill critical gaps, and for public agencies and private foundations seeking to prioritize funding on forage fish issues in the Pacific.

A Conceptual Model of the Herring Social-Ecological System

Building the conceptual model

Conceptual models can be useful tools for organizing diverse sets of stakeholder values and goals associated with conservation and natural resource management (Jones et al. 2011). They can be used to improve communication among stakeholders from diverse backgrounds (Abel et al. 1998) and increase understanding of complex system dynamics (Ozesmi and Ozesmi 2004). Creating a conceptual model helps guide and organize the complex, cross-disciplinary science and management of SESs (Dray et al. 2006), and helps to highlight the layers of interactions that mediate connections among SES components. Conceptual models are flexible to multiple types and sources of knowledge (Ozesmi and Ozesmi 2004), making them particularly useful for integrating standard scientific information with traditional and local ecological knowledge.

To identify the pressing issues related to the Pacific Herring SES, we convened a 3-d Pacific Herring Summit (the “Summit”)—a workshop bringing together individuals having technical, regulatory, economic, extractive,

social, and other connections to Pacific Herring on the west coast of North America. The aims of the Summit were to: (1) develop a conceptual model of the Herring SES and (2) identify major gaps in understanding about the dynamics within the Herring SES, using a participatory process.

The participatory approach we employed is rooted in decades of practice in participatory natural resource management and development (Chambers 1994). We opted for a participatory approach because it is pragmatic—broad and diverse perspectives are needed to fully conceptualize complex SESs (Fraser et al. 2006). Similarly, the participation of “nonscientific” experts can foster social learning, and provides insight into social, cultural, and political issues that would otherwise be missed (Middendorf and Busch 1997). In addition, participatory processes can result in increased community capacity to address ongoing and future problems (Stringer et al. 2006). Participatory processes can also empower previously marginalized groups and can afford legitimacy to the process (Stringer et al. 2006). Ultimately, that the absence of broad perspectives and detailed local knowledge may result in a failure of community support for policy changes (Eriksson et al. 2016) is persuasive motivation for bringing together all those that impact or are impacted by natural resource management.

Participants in the Herring Summit included representatives of Canadian First Nations and United States Native American tribes (including technical experts, hereditary leaders, and elected officials); nongovernmental organizations; universities; and local, regional, and national fisheries management agencies. The geographic coverage encompassed by the 118 participants included California, Washington, Alaska, and British Columbia. Participation was determined through a combination of direct recruitment, chain referrals, and self-nomination.

One of the major aims of the Summit was to co-create (*sensu* Bonney et al. 2009) a conceptual model of the Herring SES. To that end, the structure of the Summit was an intentional progression through the key themes related to the Herring SES, the foundation of which was expert presentations interspersed with small group discussion periods. The intention was that the final conceptual model would be informed by presentations and discussions of potential key components of the SES. The first day was comprised exclusively of presentations by representatives from British Columbia First Nations and United States Native American tribes who described historical changes in herring populations and the impacts of those changes on their communities. The second day included presentations on the role of Herring in the Northeast Pacific food web, oceanographic influences on Herring, Herring population structure, and cultural connections to Herring, both extant and historical. The final day included presentations on regional Herring fisheries

assessment and management practices by different agencies, and opportunities for traditional ecological knowledge (TEK) to be incorporated into management practices.

The conceptual model of the Pacific Herring SES (Fig. 1) was developed based on information collected during a series of four small group discussion sessions conducted on the second and third days of the Summit, which focused on both individual components of the SES and the SES as a whole. Participants were aggregated into 13 preassigned groups of 8–9 people, each with an appointed discussion facilitator and note taker, to jointly respond to a series of questions posed by the authors. The group membership and facilitation/recording personnel varied over the four discussion sessions, so that the knowledge shared was neither always the result of a shared belief system among individuals having a common background, nor limited by any restrictions felt in mixed-background groups. Groups shared the results from their discussions both orally and in written form after each discussion session.

Early on the second day, before the bulk of the presentations by subject matter experts, small groups were asked:

1. How are Pacific Herring connected to the SES, from California to Alaska?

Participants were asked to work within their groups to develop and sketch a conceptual model of the Herring SES, before being potentially influenced by the expert presentations.

Later on the second day, after the bulk of the expert presentations, participants were further asked to discuss in small groups two additional questions:

2. What are the major threats facing Pacific Herring?
3. What are the major uncertainties in the science and management of Pacific Herring?

These questions were selected and intentionally ordered as a logical progression toward a cohesive, co-produced conceptual model of the herring SES.

The conceptual models and notes provided by the groups from these first three discussion sessions were reviewed and synthesized to form a draft conceptual model of the herring SES. To synthesize all the conceptual models, major nodes of the Herring SES identified by groups were identified, and individual components of those nodes were listed within the nodes, with all redundancy removed (i.e., repeat nodes and components aggregated). Summit participants were then presented with this draft model, and for the fourth time organized into small discussion groups to review the model and identify missing information or components that did not reflect their view of the SES. The draft herring SES conceptual model was then updated based upon the input

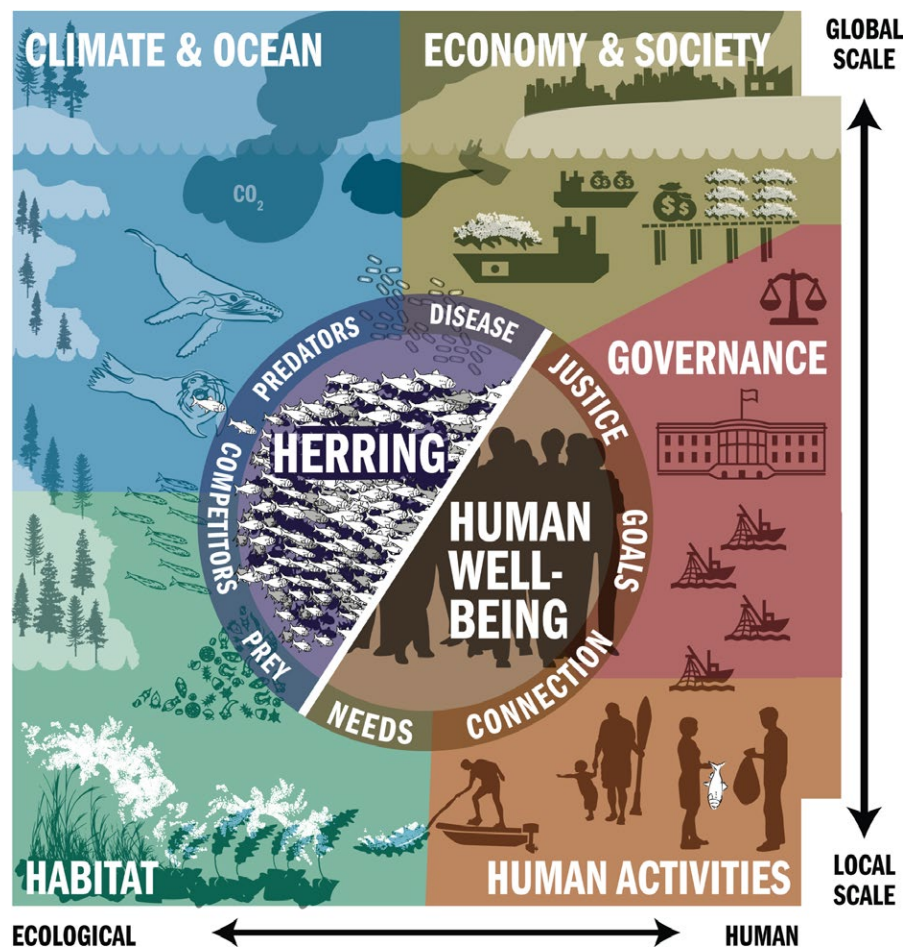


Fig. 1. Conceptual model of the Pacific Herring social–ecological system. Details of each of the section of the conceptualization are described in the text.

given by the small groups following their review to produce a final conceptual model.

The synthetic conceptual model

The final Herring conceptual model (Fig. 1) focuses on Herring and human wellbeing as key endpoints in the Herring SES (cf. Levin et al. in press). Herring populations and human wellbeing encompass the ecological, social, and economic outcomes—the “triple bottom line”—influenced by system dynamics and, potentially, management actions. The model will be most useful, therefore, in highlighting that management aimed at improving the sustainability of Pacific Herring fisheries must account for the full SES in which Herring sit. As such, management will be most successful when it includes a full reckoning of the influences of climate and ocean conditions, habitat, human activities, economics and societal forces, and governance processes, and institutions on both Herring and human wellbeing associated with Herring and their food web.

Human wellbeing is a state of being with others and the environment, where human needs are met, where indi-

viduals can enjoy a satisfactory quality of life and where individuals can act meaningfully to pursue their goals (McGregor et al. 2007). Human wellbeing encompasses a suite of benefits derived from ecosystem services, and framing fisheries assessments in terms of human wellbeing endpoints may offer insights on sustainable management practices (Coulthard et al. 2011). Increasingly diverse domains and attributes of human wellbeing have been linked to marine ecosystems, though the cultural dimensions of ecosystems remain relatively underappreciated (Chan et al. 2012, Poe et al. 2014). In our conceptual model, human wellbeing is tightly linked to Herring and the Herring food web and, following Breslow et al. (2013), is comprised of four domains: the ability to act meaningfully to pursue goals; conditions where human needs are met; connections with others and the environment; and equity and justice.

Herring and the Herring food web are at the center of this conceptualization. Herring and their eggs are consumed by a wide variety of predators, including marine mammals, birds, and other fish (Willson and Womble 2006, Brodeur et al. 2014, Bishop et al. 2015). Herring influence their prey, mainly zooplankton—which are

in turn strongly linked to the primary producers that form the base of the Pacific food web (Rose et al. 2008, Schweigert et al. 2010). Herring are connected to multiple competitors, such as other planktivores in the system (Schweigert et al. 2010); and disease and pathogens can negatively impact Herring populations (Hershberger et al. 1999). Herring populations have several dimensions or characteristics in this model—stock structure, abundance, condition—that are potentially influenced by their food web and the other nodes in the model.

The conceptual model describes Herring and human wellbeing as impacted by several components of the SES: (1) global and regional climate and oceanographic conditions; (2) global economic and social drivers, which include trade and economic policy; (3) institutions and governance structure, which dictate resource management practices, resource allocation policy, and access to the decision and knowledge processes; (4) human activities, which include industrial, commercial, recreational, and subsistence fisheries, impacts on the landscape, pollution; and (5) habitat structure and function, which impact Herring and their food web at multiple life stages and is itself also affected by the first three external drivers.

Institutions loom large in causing and confronting issues that directly or indirectly affect fisheries. Indeed, the “rules of the game” set by formal and informal institutional processes are the key determinants to the economic, social, and ecological success of fisheries (Acheson 2006, De Alessi et al. 2014). Local perceptions about the use or impact of fisheries will be affected by institutional and political memories, social, and political constraints and opportunities and linkages between governance and social–environmental contexts (Romero and Agrawal 2011). Institutions and governance mediate and structure decisions and the relationships between local and larger scale dynamics (Lemos and Agrawal 2006). Thus, achieving fisheries objectives requires attention to governance and associated institutions especially as they attend to fundamental issues of who has access to knowledge and decision making, who benefits from different outcomes, how different forms of knowledge are valued, and how participants are organized across power hierarchies (Armitage 2007). Understanding the effects of institutions and governance will greatly increase our ability to understand the broad consequences of specific policy options and potentially facilitate a more sustainable management arena.

Global and regional climate and ocean drivers—such as global changes in temperature, regional-scale climate cycles, predation regimes and local upwelling conditions— influence the entire SES, as do global economic and social drivers, which include trade and economic policy, broad social and political norms that influence fisheries, overseas demand for Herring products, and global economic conditions.

Pacific Herring is a pelagic species that migrates between inshore spawning and offshore feeding areas of the North Pacific. Consequently, during their life-history Herring occupy a wide range of *habitats*. Pacific Herring typically spawn in subtidal and high intertidal habitats, using seagrass, algae, gravel, and sand as spawning substrate. Herring spawnings are limited at least by water temperature, depth, and spawning substrate, among other factors (Hay et al. 1985). Because of the proximity of Herring spawning areas to the coast, in many populated regions Herring spawning habitat has been degraded by coastal development, nutrient input and sedimentation. Additionally, an influx of nonindigenous species has altered nearshore habitats (e.g., Shelton et al. 2014b), although the ultimate impact of these exotic species on Herring habitat remains uncertain. Thus, in some regions, the availability of spawning habitat may limit Herring population size and inhibit recovery of depleted populations.

Diverse *human activities* occur in, on and around the ocean. While these activities yield many benefits including jobs, livelihoods, food, energy and recreation, they also may negatively impact ecosystems. Loss or degradation of habitat, depletion of species, modification of food webs, loss of biodiversity, introduction of invasive species, and toxic contamination have all been associated with human activities (Andrews et al. 2015), and have the potential to positively or negatively affect Herring. Understanding the effects of human activities on Herring will increase the ability of managers to predict the positive or negative changes to Herring that would occur as a result of changes in human uses of coastal and marine ecosystems.

The final conceptual model benefited from the participatory process in that it evolved over the course of a 3-d discussion among a diverse group of stakeholders, which ultimately influenced perspectives on the Herring SES. The conceptual models constructed on day 2 were far narrower in scope and viewpoint than the final synthetic model. For example, several groups’ conceptual models were strictly biologically and physically oriented: Herring sat in the middle (often represented by a drawing of a generic “fish”), and around Herring were other biological components of the ecosystem in great detail: predators, nutrient flow, plankton, different life stages of Herring. Other conceptual models took a more human-centric view of the system, comprised exclusively of the human beneficiaries of Herring and Herring activities and/or Herring-associated benefits. These models were organized around services such as money, spiritual connection, storytelling, nutrition, family, and future opportunities. One such model contained neither a picture of nor the word “Herring” anywhere in the model. In contrast, the final conceptual model gives equal weight to social/cultural, ecological, and economic nodes in the Herring SES, representing the diversity of perspectives contributing to the model.

The Questions

At all stages of the participatory process described above, small groups reported back to the larger group highlighting unknowns and uncertainties in their understanding about the Herring SES. These were often written as questions or in lists in response to the question, “What are the major uncertainties in the science and management of Herring?” We collected all of these questions for synthesis. An initial effort at eliminating redundancy identified 60 unique questions. Further consolidation by the authors with feedback from participants returned 32 key questions about the herring SES.

We present these questions organized by the key nodes in our Herring SES conceptualization. By placing these questions within the framework of our conceptual model, we are not only classifying the nature of the questions, but we also wish to highlight that all questions must be placed in a broader context and are connected to each other. We do not attempt to prioritize these questions because the diverse participants approached these questions from very different perspectives and from disparate power and cultural orientations. Prioritization thus would be inherently political, and thus we opted to focus on identifying questions that were recognized as critical for all without prioritizing them.

Questions about broad social, political, and economic forces

1. How have global market forces influenced the commercial Herring fishery? How have the markets changed over time?
2. What are the social, cultural, and political motivations for Herring fisheries, and how have they changed over time?
3. What is the relationship between Herring fisheries and broader issues of indigenous rights?

Questions about human activities (and their effects on Herring)

4. What is the relative influence of fishing, other human activities and climate on Herring population dynamics, and how can the impacts be differentiated?
5. What are the cumulative effects of human activities (fishing, coastal development, toxins, etc.), predators and climate on Herring populations?
6. What are causes of historical disappearance of Herring, and is the current status of Herring a lingering consequence of historical impacts?
7. How does fishing affect spawn timing, and what impact does this have on population dynamics?
8. What are the ecological, economic, and cultural costs and benefits of alternative fisheries management strategies?

Climate questions

9. How does global-scale climate variability related to El Niño and the Pacific Decadal Oscillation influence Herring behavior and population dynamics?
10. How is changing climate affecting Herring populations?

Habitat questions

11. Does the quantity and/or quality of spawning habitat determine Herring productivity and population size?
12. Does the artificial supplementation of spawning habitat (i.e., by trees or boughs) result in increases in the long-term median Herring population size?
13. Are Herring using deeper spawning habitat? If so, why, and how does that affect their vulnerability to predation?

Institutional and governance questions

14. How do policies and management strategies that address the spatial distribution of fishing effort and the temporal order of fisheries better account for aboriginal rights as codified by court decisions and law?
15. What are the pros and cons of different temporal and spatial scales for adaptive Herring decision making?
16. How would different forms of knowledge alter definitions of overfishing thresholds and sustainable levels of fishing?
17. What role can institutional processes play in better facilitating the rebuilding of Herring populations?
18. How can we allocate harvest in such a way that supports ecological, economic, and cultural resilience?

Questions about Herring and the Herring food web

19. Are Herring vital rates (e.g., recruitment, mortality) or behavior positively or negatively density dependent? How has the nature of density dependence changed over time?
20. How do the processes that determine or limit Herring population size vary across spatial and temporal scales?
21. What factors affect survival of Herring eggs, larvae and young-of-the-year?
22. How has size structure changed over decadal to millennial time scales, and what are the causes and consequences of such changes?
23. What is the spatial structure of Herring populations, and what factors influence the degree of connectivity among sub-populations? Has this changed over time?

24. What factors influence interannual and interdecadal movement of spawning Herring stocks?
25. What is the role of genetic and life-history diversity in maintaining Herring populations? How has this changed over time?
26. What is the relative importance of bottom-up versus top-down processes for Herring behavior and population dynamics, and how has this varied over time?
27. What are the cross-ecosystem linkages that influence Herring, and how have they changed over time?
28. How have changes in ocean productivity, predator abundance or other factors affected the long-term median biomass of Herring?

Questions about human wellbeing

29. What thresholds of Herring abundance and distribution exist for meeting cultural objectives?
30. How do the economic and cultural benefits associated with the harvest of sac-roe, spawn-on-kelp, adult fish for bait, and adult fish for food propagate through local and regional social systems? What are the consequences of this for equity and food security?
31. What nonfishing human activities are supported by Herring, that is, what is the value of the supportive ecosystem services provided by Herring?
32. What is the trade-off between economics and human wellbeing if Herring remain in the ecosystem versus if they are harvested and removed from the system? How does this vary over the range of Pacific Herring?

This list of key questions highlights both the generality of knowledge gaps about Herring as well as the strength of a process that elicits such questions from diverse participants. For example, questions regarding ecological connectivity, life-history diversity and bottom-up vs. top-down forcing are common in many fisheries (e.g., Cowan et al. 2012); thus, it is not surprising that these questions emerged. However, two aspects of Herring biology stimulated questions that deviated from typical forage fish queries. First, Herring stocks may exhibit a finer degree of spatial structure than other forage fish (e.g., Small et al. 2005), but there is a great deal of uncertainty about the actual scale at which Herring are demographically isolated (e.g., Hay et al. 2001). This importance of this uncertainty is captured directly in questions 14, 15, 20, 23, and 24, and is implicit in many others (e.g., 4, 6, 9, 11, and 27). Secondly, Pacific Herring differ from most other forage fish in that they spawn in intertidal and shallow subtidal habitats (Hay et al. 1985). This has resulted in greater exposure of fish and eggs to human activities in coastal zones, particularly in urban areas. This potential for increased interaction with humans and their activi-

ties resulted in questions such as 4, 5, 12, and 27 that focus on potential nearshore impacts of humans.

Other questions moved well beyond those that conventional scientific subject matter experts would pose. For instance, question 2 addresses the motivations for herring fisheries. Understanding why people fish is central to successfully predicting the consequences of different management schemes, but the diverse motivations underlying fishing behavior are rarely considered by conventional fisheries scientists (Poe et al. 2015).

Importantly, the inclusion of Canadian First Nation members and representatives from U.S. Native American tribes clearly influenced the results of this process. For instance, questions 3 and 14 highlight that the Herring fishery, while important in its own right, is just one of a suite of issues confronting indigenous peoples in this region. Additionally, the strong link between Herring and the culture of native peoples resulted in the elevation of cultural outputs in several questions (e.g., 2, 29, 30). Finally, the presence of traditional knowledge holders resulted in several topics that emphasize that there are many ways of knowing about an ecosystem and that such alternative knowledge may provide a depth that is not available from conventional science (e.g., 6, 12, 13, 16, and 22).

Answering the Questions

Scientific information: surveys, empirical analyses, and modeling

Conventional scientific approaches have a fundamental role to play in addressing the questions above. For some of the above questions, continued or expanded ecological, economic, and social data collection will be critical. For example, disentangling the influence of fishing, other human activities and climate on Herring population dynamics (question 4) is a fundamental debate in fisheries management (Burkenroad 1946), and requires, at a minimum, time series of data that are temporally and spatially extensive (Vert-pre et al. 2013). While differentiating between the effects of fishing, climate, and other human activities in many fisheries is difficult because they typically occur simultaneously, Herring offer several advantages in resolving these questions. First, in the cases where low Herring abundances have resulted in long-term closures of Herring fisheries, these closures offer an opportunity to evaluate the ecological, economic, and social changes that occur in the absence of fishing. Additionally, the large geographic range of the species combined with relatively small-scale spatial structure of spawning stocks provide opportunities for comparative analysis (Murawski et al. 2009). For example, understanding the acute or chronic impacts of oil spills may be fruitfully tackled by comparison of some impacted stocks (e.g., in California or in the Gulf of Alaska) to other reference stocks.

Science has a key role conducting analyses that illustrate if particular management strategies (i.e., decisions about the collection of data, data analysis, harvest control rules) result in meeting particular economic, social, or ecological objectives or allocation decisions. One key tool has been closed-loop simulation employed in so-called Management Strategy Evaluation or MSE (Punt et al. 2014). MSE allows the rigorous examination of tradeoffs among objectives given a range of management and environmental scenarios and uncertain data and assessment methods. Importantly, MSE iterates through multiple possible management strategies that are simulated, modified, and re-evaluated (De La Mare 1998); thus, the process itself can be used to help refine objectives and to illustrate the challenges in weighing multiple or conflicting objectives (such as questions 14, 18, 32 listed above). MSE can also illustrate the value of additional data collection for meeting objectives and determine the cost-benefit ratio associated with those scientific endeavors. MSE can also examine the performance of management strategies across plausible broad forecasts of climate/environmental change (Punt et al. 2013), and has been employed this way for Herring specifically (Cleary et al. 2010).

Experimental management also provides a useful path forward for Herring and forage fish management. Once an MSE process has settled on a particular strategy and it has been implemented, actors in the socio-ecological system have the opportunity to observe the resulting behavior of the system and answer if it is behaving as was predicted in the modeling exercises. Moreover, a particular Management Strategy might be employed to deliberately probe the system to learn how it behaves in order to improve understanding (Walters 1986). Some of the above questions might be answered exclusively through empirical/experimental analyses: there is the opportunity for comparative and experimental studies to answer questions such as 11–13 or 12, respectively. But some of these experiments could be larger scale manipulations to deal with the effects of predators (5), the effects of fishing (7) or even experimental management regimes to address questions pertaining to the overall performance of the management system.

The role of traditional ecological knowledge

Traditional ecological knowledge is the “cumulative body of knowledge, practice, and belief evolving by adaptive processes and handed down through generations” (Berkes et al. 2000). Because indigenous peoples have depended on natural resources and have resided in particular locations for long periods of time, they are well situated to acquire knowledge of species, landscapes, and climate (Turner et al. 2000). Consequently, there have been increasing appeals to use TEK in conjunction with conventional scientific knowledge in resource management (Sutherland et al.

2014). TEK can help fill critical knowledge gaps and provide longer term perspectives on distribution and abundance (Thurstan et al. 2015). Equally as important, cross-fertilization of TEK with other knowledge sources (e.g., conventional scientific data, local ecological knowledge) can improve the capacity to interpret changes in ecosystems, understand the species or ecosystem responses to management actions, and improve the mechanistic understanding of a system (Tengö et al. 2014).

In searching to fill our knowledge gaps about the Pacific Herring SES, it will be important to respect, value, and use TEK (Turner et al. 2000). Although assimilating TEK into conventional management systems has proven challenging (Drew 2005, Sutherland et al. 2014), a number of new approaches are emerging that allow such integration (Plagányi et al. 2013, Tengö et al. 2014, Girondot and Rizzo 2015). As we seek to develop a more complete understanding of Herring and their ecosystem and search for innovative ways to recover depleted populations, TEK may provide a insights for a range of issues (Table 1). By applying TEK to these issues, we may not only find answers, but also realize a reduction in conflict and increased management effectiveness (Huntington 2000).

Conclusion

Forage fish provide a critical pathway for energy to flow from the bottom of the food web to higher trophic levels, and often support valuable fisheries across the globe (Pikitch et al. 2012). In this sense Herring are an archetypal forage fish. However, much more so than other forage fishes, Pacific Herring are at the foundation of cultural and social systems in the Northeastern Pacific. Perhaps because Pacific Herring spawn on nearshore habitats, the connections between people and Herring run deep. Guujaaw, past-president of the Haida Nation, an indigenous nation in British Columbia and Alaska, noted that for the Haida, “Herring are central to everything” (<http://news.nationalgeographic.com/news/2015/02/150211-Herring-decline-british-columbia-fishery-seabirds-environment>). With this centrality comes complexity for those wishing to manage for fisheries, their ecosystems and cultures.

Our participatory process highlighted the value of conceptualizing the full SES. Differences in scientific approaches, research philosophy and language challenge those engaged in interdisciplinary work. However, our participatory conceptual modeling helped individuals cross boundaries, and organize diverse values and goals. Perhaps, most importantly, this approach accommodated diverse types of information, from traditional knowledge, to qualitative information to quantitative data. Thus, the modeling facilitated the integration of information across knowledge holders and diverse scientific disciplines.

Table 1. Topics and issues potentially informed by traditional ecological knowledge, as identified by participants of the Pacific Herring summit.

General topic	Specific issue
Patterns of Herring distribution and abundance	<ul style="list-style-type: none"> • Long-term patterns of nearshore? Distribution and abundance of adults, juveniles, and eggs • Fine-scale stock spatial structure
Herring biology	<ul style="list-style-type: none"> • Long-term observations of the timing of spawning • Long-term observations of Herring size structure
Ecological interactions and habitat	<ul style="list-style-type: none"> • Long-term patterns in the abundance and distribution of Herring predators • Long-term patterns in the timing, distribution and magnitude of prey • Perspectives on spatial and temporal variability in Herring ecological interactions • Long-term patterns of Herring habitat quality, availability, and distribution
Management issues	<ul style="list-style-type: none"> • Long-term perspectives on the distribution and intensity of fishing • Viability of Herring transplantation as a restoration tool for depleted local stocks • Utility of habitat restoration/supplementation as a Herring restoration tool
Human wellbeing	<ul style="list-style-type: none"> • Vulnerability of local populations of Herring to fishing • Cultural and economic consequences of fishery closures

It is clear from the conceptual model and set of questions generated by participants that conventional disciplinary approaches are inadequate to address all facets of this “wicked” problem (*sensu* Rittel and Webber 1973). Moving forward, transdisciplinary approaches that draw from multiple sources of knowledge are the best hope for reaching targets that are sustainable for all.

Acknowledgments

We deeply appreciate the lively participation of the 118 participants in the Pacific Herring Summit (<http://oceanmodelingforum.org/wp-content/uploads/2015/07/Summit-Final-Attendee-List.pdf>). Their thoughtful comments and passion for Pacific Herring inspired this study. We thank the David and Lucille Packard Foundation, the Pew Charitable Trusts and The Canada Department of Fisheries and Oceans for sponsoring the Pacific Herring Summit. TF was supported by the David and Lucille Packard Foundation during the writing of this manuscript. The graphic of the Herring social-ecological system was illustrated by Sam Bradd. PSL thanks C. Sativus inspirational production.

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