Published in final edited form as:

Environ Monit Assess. 2015 March ; 187(3): 102. doi:10.1007/s10661-014-4233-4.

Complexity of bioindicator selection for ecological, human, and cultural health: Chinook salmon and red knot as case studies

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Abstract

There is considerable interest in developing bioindicators of ecological health that are also useful indicators for human health. Yet, human health assessment usually encompasses physical/chemical exposures and not cultural well-being. In this paper, we propose that bioindicators can be selected for all three purposes. We use Chinook or king salmon (*Oncorhynchus tshawytscha*) and red knot (*Calidris canutus rufa*, a sandpiper) as examples of indicators that can be used to assess human, ecological, and cultural health. Even so, selecting endpoints or metrics for each indicator species is complex and is explored in this paper. We suggest that there are several endpoint types to examine for a given species, including physical environment, environmental stressors, habitat, life history, demography, population counts, and cultural/societal aspects. Usually cultural endpoints are economic indicators (e.g., number of days fished, number of hunting licenses), rather than the importance of a fishing culture. Development of cultural/societal endpoints must include the perceptions of local communities, cultural groups, and tribal nations, as well as governmental and regulatory communities (although not usually so defined, the latter have cultures as well). Endpoint selection in this category is difficult because the underlying issues need to be identified and used to develop endpoints that tribes and stakeholders themselves see as reasonable surrogates of the qualities they value. We describe several endpoints for salmon and knots that can be used for ecological, human, and cultural/societal health.

Keywords

Indicators; Human health; Ecological health; Endpoints; Cultural health; Subsistence

Introduction

There is considerable concern about ecological health and the sustainability of natural ecosystems, especially as they affect human health and well-being. For many years, ecologists and environmentalists developed specific indicators to examine the health of different species, communities, and ecosystems (Baumann 1992; EPA 2000, 2008; Burger 2006a; Bartell 2006), while health professionals and others developed indicators of human health (Mendelsohn et al. 1998). A range of ecological indicators (e.g., number of species and productivity) were developed for natural ecosystems (Carignan and Villard 2001; Burger 2006b), for those ecosystems contaminated with pollutants (Fox 1994; Linthurst et al. 1995; Burger et al. 2004a; Burger 2007), and for recovering ecosystems (Cairns 1980; Harwell and Kelly 1990). This led to evaluating the goods and services that ecosystems provide (Bingham et al. 1995). Increasingly, governmental agencies, tribal nations, scientists, conservationists, managers, regulators, and the public have become interested in establishing indicators and biomarkers that assess aspects of both (NRC 1991; DiGuilio and Monosson 1996; Cole et al. 1998; Fox 2001; Burger and Gochfeld 2001, 2004).

It was a natural extension for scientists, social scientists, and economists to recognize the importance of sustainability of ecological systems so that both ecological and human systems could continue to produce goods and services (Costanza 1993; Beratan et al. 2004), that stakeholders should be involved in indicator selection (Burger 2009), and that indicators could be used to monitor global changes (Risebrough 1991). Although sustainability implies ensuring that ecosystems continue to provide these goods and services, the sustainability of

cultural well-being of different people is not always considered. Yet, preservation of diverse cultures is an important societal value, and we propose that indicators can be selected to provide information about ecological health, human health, and the health of diverse cultures (societal/cultural health). That is, preserving fish stocks to maintain fisheries is an important societal goal, with numerous measurement endpoints of fish population viability. However, preserving fish populations because they also have an important cultural and societal value independent of fisheries, is not always considered in indicator selection. Rather, it is assumed to include them much the same as historically indicators of human health were assumed to be protective of eco-receptors. Yet, we now know that this is not so; many species are more sensitive to some chemicals than are humans, and protecting humans does not necessarily protect eco-receptors (Hengstler et al. 1999; Kopf and Walker 2009).

In this paper, we demonstrate that if we carefully evaluate the factors that make for the health and well-being of species (for example, Chinook salmon [*Oncorhynchus tshawytscha*] and red knots [*Calidris canutus rufa*, a sandpiper]), these can be used to develop indicators that assess ecological, human, and cultural health of the broader environments of which they are a part. Salmon and knots were selected because they have complex life histories, varied habitat needs, are iconic species, and have economic and cultural importance to a wide range of people. We discuss each species separately, describing their cultural and societal importance, life history, potential endpoints, and complexities of end-point selection, and in the discussion, we discuss why those factors can simultaneously help us assess ecological, human, and cultural health. We also discuss the complexity of selecting endpoints to reflect conflicting societal/cultural viewpoints. It is at this stage that stake-holder involvement, from regulators and government officials, to tribal leaders, to natural resource trustees, to the general public should be involved. Their views should be taken into account for selecting indicator species, for developing measurement endpoints, and for devising management options.

Approach

Our approach was to (1) select species that are iconic and culturally important (e.g., salmon, red knot); (2) examine their physical environments, habitat needs, and life history traits from the literature; (3) describe the complexity of their life cycle and life history; and (4) identify traditional measurement endpoints or metrics for each category. For example, reproductive success can be measured by counting the number of young/hatched per nest and the number of young/born per female. This is a fundamental demographic variable. We then (1) define a final indicator category, called societal/cultural imperatives. We suggest that relevant aspects of species, communities, and ecosystem vitality combine with human dimensions to form cultural well-being, and (2) develop endpoints that might reflect cultural well-being. In this paper, bioindicator refers to the two species we are examining (e.g., salmon, knot), and measurement endpoint or biomarker refers to the characteristic that can be measured (e.g., reproductive success, levels of mercury or chromium in tissues) for the bioindicator species.

Although we have discussed life history traits with Native Americans and others living in the Northwest and Alaska for salmon, and with fishermen, bird-watchers, eco-tourists, and others for red knot in the eastern USA, we mainly relied here on the literature for

information. We adopted this approach because we wanted transparency in selecting measurement endpoints and to develop a method that was applicable to other species. The authors have extensive experience with both species in terms of biological aspects, ecological significance, and cultural importance (Burger et al. 2008, 2013a, b).

Chinook salmon

Salmon are anadromous fish that lay their eggs in fresh-water, most migrate to the sea as juveniles, and return up to 8 years later as mature adults to spawn in their natal streams. There are many species of salmon in the Pacific (Groot and Margolis 1991), and there is still controversy about their taxonomy and genetic lineages (Narum et al. 2010). Chinook or king salmon have a major fall run in many rivers of northwest North America (and are often called fall Chinook). The much smaller spring and summer runs are considered endangered (Chelan 2012), and many of these populations have declined (Groot and Margolis 1991; NRC 1996).

Cultural and societal importance

Salmon are iconic and important to Native American Tribes, to Pacific Northwesterners in general, to commercial fishermen, to recreational fishermen, and to ecosystem integrity in the northwestern USA and Canada (Landeen and Pinkham 1999; Butler and O'Connor 2004; CRITFC 2013). The Pacific Northwest is embroiled in major public policy debates about how to restore Pacific salmon. We consider that salmon are iconic for people of the northwestern USA and Canada because of their economic and recreational importance. Salmon fishing and conservation engender strong feelings and a desire for restoration of the populations. Salmon images are ubiquitous as befits an icon. Salmon, particularly Chinook, are important for people from Oregon to the Aleutian Islands, where salmon make up a significant part of the subsistence Aleut culture (Hamrick and Smith 2003; Burger et al. 2008), and by extension, people in the rest of the USA who depend upon salmon as a high-quality protein source that is usually low in contaminants because of its low trophic level (Burger et al. 2007a, b; Hardell et al. 2010).

Salmon are heavily fished recreationally, commercially, and by Native Americans (CRITFC 2013). For example, harvests of Chinook salmon have been as high as 19.5 million kilograms in 1889 from the Columbia River system alone, but by 1960, harvest had declined to less than five million kilograms (Fulton 1968; EPA 2009). Now, sometimes hatchery fish produce more offspring that reach adulthood than wild salmon produce in the same rivers (Hess et al. 2012). Declines in salmon result in cultural deprivation for some Native American tribes that have been using salmon from the Columbia River Basin for about 9000 years (Landeen and Pinkham 1999; Butler and O'Connor 2004; CRITFC 2013). The declines result in lower catches for commercial and recreational anglers as well; catches are regulated. However, declines in fisheries alone are not the only aspect of concern—rather it is the loss of cultural aspects of salmon that have been part of tribal society for about 9000 years and for other people who arrived since settlement. It is the social/cultural aspects of indicator selection that require additional thought to reflect the important aspects of salmon populations, salmon runs (timing and spatial extent), and timing relative to ancient tribal calendars (Bohnee et al. 2011), and other cultures of the northwest (Williams et al. 1999).

Life history

Several salmon populations or lineages are listed as threatened or endangered in the northwest by the US Fish and Wildlife Service (USFWS 2012). The Hanford Reach is one of the most significant spawning habitats for fall Chinook salmon (OHWB 2002), while the Snake River is the most significant for spring spawning Chinook. Historically, fall Chinook salmon spawned over a 900-km distance of the Columbia River, but because of dams (Hanrahan et al. 2004), they are now largely restricted to a 90-km section of the Hanford Reach (Dauble and Watson 1997) and the Snake River (Mueller and Ward 2010; Mueller et al. 2012). Habitat quality has also been affected by altering water level, currents, and flow characteristics. The biggest habitat difficulty is the inability of salmon to reach their traditional spawning grounds due to the construction of many dams built primarily for hydroelectric power during the twentieth century (Dauble et al. 2003a, b; Levin and Tolimieri 2001). Also, important are harvest limits (Hyun et al. 2012a, b), genetic stability, and supplementation of populations with hatchery fish (Holsman et al. 2012; Kostow 2012). One conclusion of salmon biologists and the public is that the Columbia River must be returned to normative conditions with natural water flows, habitats, and communities (Williams et al. 1999). There are literally hundreds of papers on salmon biology, fisheries, management, and conservation in northwestern North America (Williams 2006).

After population levels and landscape aspects (spatial extent of runs), life history information provides the most opportunities for endpoint selection. Salmon eggs are laid in freshwater in gravel nests (called redds). The vitality of the eggs depends upon water moving through redds to oxygenate the eggs. Important substrate characteristics are pebble count (the spaces between pebbles or stones that allow water to flow through nests), grain size in the nesting area, water depth, and water velocity. The spawning areas need downward flow of water through the part of the nest where the eggs are located (eggs are about 20 cm below the surface, Hanrahan et al. 2004). Salmon prefer nesting in areas with water velocities greater than 1 m/s and where stream flow fluctuations are reduced (Hatten et al. 2009). Fine sediment impairs egg survival because enough water does not flow through to provide sufficient oxygen for developing embryos (Honea et al. 2009).

Once the young hatch into the alevin stage, they spend some time in the nest, absorbing the remaining yolk sac for nutrients. Once the nutrients are exhausted, they emerge from the nest (called fry) and they are swept downriver or into calm water along the shore, by river currents. They feed on plankton. Young spend a variable part of their lives (months to years) in freshwater as smolt, and thereafter swim to the ocean, where they grow and mature over a period of years (up to 8 years, Johnson et al. 2012; Sharma and Quinn 2012). Salmon smolt face threats while floating or swimming downriver. For example, avian predators (e.g., terns and cormorants) can be severe (capturing up to 17 % of smolt) because the birds nest in dense colonies in the mouths of the estuaries where the smolt congregate (Collis et al. 2001; Schreck et al. 2006; Good et al. 2007).

Adult salmon come back to their natal river to spawn and then die. Once adults reach spawning grounds, they dig or excavate nests in gravel sediment. Those that spawn in major rivers (summer and fall runs) typically spend less than a year in freshwater before migrating to the sea. Spring run Chinook often go up rivers and spawn in smaller tributaries or streams

(Chelan 2012; Johnson et al. 2012). There are different life history strategies for Chinook salmon (Fig. 1). Males have several strategies so that there is a continuum of different strategies (Johnson et al. 2012). Males may mature a year earlier than females from the same cohort. Determining the maximum times in each stage and location (upstream, river, estuary, ocean), however, is difficult. As a further complication, for example, there are two life history strategies that occur in the Columbia River—one where salmon migrate to the ocean in their first year of life and the other where salmon spend a full year in freshwater (Sharma and Quinn 2012). In addition, some Chinook salmon spend their entire life in freshwater (i.e., see right side of Fig. 1; Connor et al. 2005; Johnson et al. 2012). These different life histories add complexity to developing endpoints because different people depend on each run.

Selection of nest sites within spawning areas is critical to reproductive success. Spawning habitat must be shallow enough to provide running water flow (for oxygen), yet have a low enough water velocity so nests do not wash away (Hanrahan et al. 2004). Dam operations and climate change could impact stream flow (Donley et al. 2012). Landscape scale habitat parameters, such as % urban land, proportion of stream length failing to meeting water quality standards, and index of ability of streams to recover from sediment flow events, are important in predicting recruitment of Chinook salmon (Dauble and Geist 2000; Regetz 2003). Agricultural runoff also must be considered. There is concern about contaminants from industry, agriculture, and urban areas (e.g., PCBs; EPA 2009) on salmon health and well-being. The Hanford Reach of the Columbia River is the stretch through the Department of Energy's Hanford nuclear weapons' production site. Nine nuclear reactors were built along the Hanford Bight (bend in the river), to take advantage of water for cooling the reactors. Hexavalent chromium was added to the cooling water to prevent corrosion to the reactor. There is concern about the potential impacts of hexavalent chromium on salmon eggs and young in the Columbia River (OHWB 2002), especially in the hyporheic zone of transition from groundwater to river water, where the eggs are deposited and the concentrations of hexavalent chromium are higher than in the river water. However, some studies have failed to find an effect of hexavalent chromium on egg viability (Farag et al. 2006a, b).

Potential endpoints

The assessment endpoints of concern are population levels of different salmon runs, different temporal patterns, and different spatial extent of runs. That is, the major rivers, tributaries, and streams in the Pacific Northwest provide a matrix of habitats than can be used by the several species of salmon. Assessing populations, runs, and temporal/spatial patterns is difficult, and usually, people turn to developing measurement endpoints, defined as endpoints, which can be measured in place of the desired assessment goal (stable salmon populations). Measurement endpoints can relate to physical features, saltwater or freshwater habitat, salmon life history traits, and counts at particular points in their life cycle (Table 1). Physical endpoints include presence of river/stream complexes, water flow and fluctuations, and oxygen levels. Habitat characteristics include overall exposure to water flow and depth, pebble size, bank slope, and dissolved oxygen. Salmon life history trait endpoints can include food availability, conspecific nesting density, and reproductive measures (Fig. 2).

Environmental endpoints include exposure to contaminants and abnormalities in different stages. Count indicators can include salmon landings, size and health of the landed salmon, fish ladder numbers, and monies derived from salmon fishing licenses. Many of these endpoints are routinely collected by states or agencies and are available in reports.

We also suggest that cultural measurement endpoints can be specifically designed to capture the value of salmon to different cultures (Table 1). Societal and cultural indicators really include a wide range of different types of indicators (Fig. 3), which assess the different economic (e.g., fishing and tourism businesses) and social/cultural values. In this sense, cultural endpoints include a range of other physical, environmental, and economic endpoints. This information is not routinely collected but can be estimated using well-established survey technique (Burger et al. 2013a, b)

Complexity of endpoint selection

As an indication of the complexity of endpoint selection, we examined the various points in the life cycle that lend themselves to indicator selection (Fig. 2). Differences in time to reach each stage, percent to reach each stage (survival), and condition (weight, size) can be used as endpoints in combination. Thus, the number of potential indicator endpoints for salmon is large, and the task is to select those that reflect the health of salmon (i.e., are biologically important) and populations of salmon, as well as being relevant to human health (from consumption exposure) and cultural health. For salmon, additional complexity comes from males having different life cycles: some mature in a few months, some in about a year, and others spend up to 8 years at sea before returning. These data in turn could be related to weather and other physical drivers, including climate change, sea level rise, sea temperature changes, and other habitat variables.

From a cultural standpoint, the most important endpoints are time to spawn from fry stage, percent survival from fry stage to spawning, condition at spawning, and size of the spawning population per area (stream, river, or riverine complex). Ultimately, it is the spawning adults that are caught for tribal, subsistence, recreational, and commercial fishing. However, to tribal nations and other people of the northwest, all life stages of salmon are valued. If the salmon are not healthy, then the people are not healthy (Bohnee et al. 2011). Thus, the complexity, while making indicator endpoint selection more difficult, must be captured by endpoint selection. Some of these endpoints are captured in Fig. 3. We suggest that social and cultural well-being (on the right side of Fig. 3) can be reflected at all levels of indicators. Any one aspect of salmon life history does not adequately represent the cultural importance, but rather a combination of complex biological, habitat, and cultural values must be combined.

Red knot

Red knots are medium-sized shorebirds (100–200 g) that breed in the Arctic and make long-distance migrations of up to 30,000 km to the southern hemisphere (Baker et al. 2004). In between, most stop for long periods in temperate marshes and along coastal shores. At least 21 % of the world's shorebird species (32 of 155 species) were listed as species of conservation concerns by Birdlife International (Piersma et al. 1997), and this number has

increased since then. Red knots have declined precipitously (Morrison et al. 2006) since the 1980s. The threats to shorebird populations include habitat loss, human disturbance, commercial harvesting of shorebird food, hunting and eggging, pollution, and long-term effects from climate change and sea level rise (Goss-Custard et al. 2000; Galbraith et al. 2014). While harvesting of birds may not be a problem in much of the developed world, large numbers of shorebirds are still harvested in some places, such as South America and Africa. Climate change and sea level rise pose a long-term threat to shorebirds because of the potential to render breeding, migration stopover sites, and overwintering habitats unsuitable (Galbraith et al. 2002, 2014). Red knots have become symbolic of the problems shorebirds face throughout the world and have been proposed for listing as a threatened species by the USFWS.

Cultural and societal importance

Red knots are iconic for eco-tourists, bird-watchers, and for conservationists bent on saving shorebirds and coastal ecosystems. They are a lightning rod for different opinions about both their importance ecologically and the need for their preservation and conservation. Although knots themselves are not harvested commercially, their survival is jeopardized by the commercial harvest of associated species. That is, the survival of the eastern North America subspecies is dependent upon an abundance of eggs of horseshoe crabs (*Limulus polyphemus*), on which the knots feed during their migratory stopover in the spring (Niles et al. 2008). The difficulty arises because horseshoe crabs lay their eggs in nests below ground, and shorebirds have sufficient eggs for consumption only when there are so many crabs breeding that they dig up the nests of other crabs, releasing the eggs to the surface where the shorebirds can find them. There is an active fishery for horseshoe crabs to use as bait to catch conch and eel and for their blood as a source for lysate for the medical industry. Declines in spawning horseshoe crabs due to overfishing have been implicated in the declines of knots and other shorebirds that depend on a superabundance of eggs (Baker et al. 2004; Niles et al. 2008, 2009). This controversy was addressed by development of a management plan for horseshoe crab fisheries that mandates consideration of knot and shorebird foraging requirements (ACMFC 2001); it is an ongoing adaptive management process. Thus, populations of horseshoe crabs are being managed above the level needed to sustain stable horseshoe crabs. Another factor affecting population levels of knots and other shorebirds is disturbance by people who use the same beaches as do foraging shorebirds (Burger et al. 2007a, b; Burger and Niles 2012).

As with salmon, the controversy involves different cultural factions. In addition to fishermen, there are bird-watchers who throng to Delaware Bay and other areas to see the massive concentrations of red knots, the hotels, restaurants, and businesses that cater to these eco-tourists, and conservationists who want to preserve biodiversity (Burger and Niles 2012). There are beachgoers, canoers, kayakers, and many others for whom birds are an integral part of their experience. They want to see large flocks of knots and other shorebirds. Along the east coast, where coastal tourism accounts for significant economic benefits to communities and states, the loss or decline in iconic shorebirds confers distinct disadvantages to the “beach experience” and is troubling.

Life history

There are several subspecies of red knot. The eastern North American subspecies (*Calidris c. rufa*), breeds in the Arctic, and winters along the Atlantic coast as far south as Tierra del Fuego in South America (Niles et al. 2010; Burger et al. 2012). Given this life history, any individual knot encounters a range of natural- and human-altered habitats. The most vulnerable period is during migration and on wintering grounds. During their stopover, knots must nearly double their weight to allow for a long migration north and to have sufficient fat resources to lay eggs once they arrive (Baker et al. 2004; Morrison et al. 2007). At some stopovers, they forage disproportionately in horseshoe crab nest depressions (Fraser et al. 2010), making such depressions an important indicator of optimal habitat. Knots arrive on the wet Arctic tundra just after snow melt, when food is still scarce, and females deplete their body fat to lay their clutch of four eggs. Since the breeding season is so short in the Arctic, breeding activities are shortened, and failure to breed upon arrival means no reproduction that year.

Like salmon, there are different life cycles in knots; there are both short-distance migrants and long-distance migrants, which results in very different habitat requirements (Fig. 4). Short-distance migrants normally migrate to the US coast or the Caribbean Islands (Burger et al. 2012). Long-distance migrants go to South America, often as far south as Tierra del Fuego (Niles et al. 2010). Some knots are scattered between the two. Unlike salmon, they regularly migrate thousands of kilometers and are exposed to very different conditions. Knots can make round-trip journeys of 26,700 km (Niles et al. 2010; Burger et al. 2012). The different life cycles can result in differences in travel distances of thousands of kilometers, instead of hundreds of kilometers as occurs in salmon. Thus, endpoints need to be developed for both populations, especially since the long-distance migrant populations are declining more rapidly than the others.

In the Arctic, knots encounter cold temperatures, snow, low prey availability, and high predator pressure (Fig. 5). They have a similar breeding cycle as salmon: egg laying, hatching, young chicks, fledging (achieving flight and independence), and ultimately, migration away from the breeding grounds. The habitat features that require assessment on the breeding ground include snow-free nesting areas with nearby water for foraging, high prey availability, and lack of predators. At stopover points farther south, they face difficulties foraging because of time and space constraints. That is, they mainly feed on a falling tide when food is just being uncovered by receding tides (Fig. 6). During low tide some continue to forage, but many roost or rest on high marshes, far from mammalian or avian predators. Along with tidal cycles, the shorebirds face human disturbance (e.g., people and dogs walking on beaches, Burger et al. 2007a, b; Burger and Niles 2012), which increases the importance of habitat endpoints.

Potential endpoints

Habitat features, including tidal beaches and mudflats for foraging at stopover and migration sites, sufficient and available prey during the winter, presence of spawning horseshoe crabs, and sufficient roosting sites safe from predators and human disturbance during their migration and wintering stages, can be used to develop measurement endpoints (Niles et al.

2008; Burger and Niles 2012; Burger et al. 2013a, Table 1). Physical measurement endpoints include: % snow cover on arrival and % available foraging pools in the Arctic, Arctic temperatures, and landscape features, such as snow, small hills, and intermix of water with land. Stopover habitat endpoints involve the presence of bays, estuaries, and mudflats for available foraging, as well as other species interaction. Life history endpoints include conspecific density, reproductive measures, and foraging needs (e.g., number of horseshoe crab eggs and density of invertebrate prey), as well as survival, longevity, and population levels at particular stopover or wintering sites (Fig. 7). Environmental monitoring involves examination of pollution, disease exposures (% flu virus on migration; they carry avian influenza; Maxted et al. 2012) and presence of people (Burger et al. 1997, 2004b, 2007a, b; Goss-Custard et al. 2006). Environmental counts include the number of birds at different places, under different conditions (Table 1).

Cultural endpoints are more difficult to develop than they were for salmon because most people in temperate regions are not directly harvesting red knots or their eggs, although some harvesting may occur on their breeding grounds and in South America. Even so, there are a number of recreational activities that rely on red knots and other shorebirds, including bird-watching, photography, and other eco-tourists or beachgoers. Local businesses often depend on eco-tourism. Further, knot presence and need for foraging space and horseshoe crab eggs during migration puts them in direct conflict with fishermen collecting the adult crabs for bait. Decreases in spawning crabs means there are fewer excess eggs on the beach for foraging shorebirds. Thus, red knots and other shorebirds are part of an ecosystem approach required for management. Several endpoints can serve as an indication of each of these components (Table 1).

Complexity of endpoint selection

For knots, the complexities of endpoint selection include maximizing the available information to address the ecological and life cycle needs of the knots themselves, their key prey (including horseshoe crab populations and crab egg production), fisheries interests (individual species and their associated food webs), recreational interests (e.g., bird-watching, eco-tourism, beachgoers, and joggers), associated business interests (local businesses that cater to fishing and recreational interests), and the medical industry that uses horseshoe crab blood. In addition, the mystique and existence values of red knots and other shorebirds go beyond any one of the interests alone, yet are relatively difficult to measure.

A view from the perspective of salmon or red knots

Another way to consider measurement endpoints is to consider their development and importance from the viewpoint of the indicator species (e.g., salmon and knots). In general, biologists try to develop measurement endpoints using biological characteristics, which should capture the well-being of populations they are considering. However, biologists and others normally make judgments about what the salmon (or knot) require or what level of salmon (or knot) populations is required for sustainability. However, the possibility exists that even higher populations would be beneficial for the species itself. Perhaps higher numbers would lead to more synchronous breeding through social facilitation or to heavier offspring through earlier breeding. Perhaps predation rates would be lower due to group

defense, swamping, or some other density-dependent mechanism. Perhaps having five to six males courting every female horseshoe crab might be beneficial for some reason (e.g., less time in amplexus, deeper nests, more sperm deposited). These aspects are unknowable, except perhaps by reading historic accounts of the breeding and migratory behavior of salmon and knots. Even so, it is important to keep an open mind about the effect of traditional or historical population levels on the behavior and well-being of species (whether they were higher or lower in the past).

Finally, from the perspective of the salmon and knots, their “managers” are made up of dozens upon dozens of organizational cultures or tribes. One could argue that just as there are several different Native American tribes in the northwest, there are several government agency “tribes” (EPA, NOAA, Department of Interior, federal, state), several conservation “tribes” (fishing clubs, bird clubs, Audubon Society, Nature Conservancy), and so on. The differences within these tribal groups may be greater than between them. Relevant differences and similarities have to be captured in endpoint selection if we are to preserve biodiversity for all cultures. For example, the different government agencies and different conservation groups must be considered when selecting endpoints. An endpoint that is important to NOAA may be less important to Audubon and not important to Native Americans.

A view from stakeholders

One key objective of our paper is to consider possible measurement endpoints for societal/cultural assessment: why do people and their cultures value these species; what do they value; and how can these values be measured? While individual physical, habitat, and life history traits can be used to develop measurement indicators, cultural and societal values often require a combination of different measurement endpoints, as well as frequent and important input from people in different cultures. This results in both complexity and controversy: complexity because several different levels of measurement endpoints must be combined, and controversy because the value of the species to each culture may differ and the desired outcome may differ. For example, in the case of salmon, tribal needs for abundant, healthy, and diverse salmon species and salmon runs may conflict with a business culture of harnessing hydropower and the commercial interests of salmon fishing. Enhancement of one “value” detracts from another. Similarly, for red knot, maintaining healthy populations with sufficient horseshoe crab eggs may seriously affect catch limits on horseshoe crabs. Selecting species and ecosystem traits or attributes to protect (e.g., a particular population level) results in trade-offs, and such tradeoffs often involve societal values. In the above example, maintaining sufficient salmon to satisfy the cultural needs of northwestern tribes may well mean removing dams that prevent salmon from reaching traditional spawning grounds. Or, on the contrary, keeping up hydroelectric production may result in keeping salmon populations below levels needed for cultural well-being by tribes or other people living in the northwest who value salmon populations highly. Such effects may be exacerbated, if, for example, additional dams are needed to produce hydropower for growing energy needs.

Perhaps one way to illustrate the complexity is to indicate the typical endpoints used by biologists, managers, and even economists (bottom of Fig. 8), compared to those cultural/societal indicators (or endpoints) of well-being (top of Fig. 8). Ecological and human health endpoints are often one-dimensional (e.g., no. of fish, no. of spawners, catch rate, and levels of mercury) and may include one or many such endpoints. In contrast, the cultural/society endpoints are multidimensional and cross disciplines (e.g., biological, economic, and spiritual). A fishing culture does not just value (and want measured) the number of fish but would include number of jobs, value of fish to their social life, and to their ceremonies and feasts. A shore culture does not just value the number of birds, but their density, the view of the beach, and interactions with the whole ecosystem. These cultural/societal endpoints will be hard to develop as they are, by nature, interdisciplinary and difficult to quantify. Numbers of salmon or knots can be counted, but how do you value having enough fish for a feast or ceremony, enough fish to give away to family and friends, and enough knots within shorebird flocks to know that the ecosystem is healthy and resilient?

Table 2 illustrates some of the cultural/societal views of the “salmon question” and “red knot question.” The statements are paraphrases and do not represent individual people, but rather represent a combination of views we have heard expressed over the years of our research with these species. As is clear, some of the statements involve simple monitoring over time and space, while others require determination of tribal, cultural, and stakeholder (which includes governments, regulators, conservationists, scientists, and the public) views of what they value about each resource, and how it affects their culture. As perceptions move from the simple (there aren’t enough fish, or birds) to the more complex (salmon affect my health and culture), it is both more difficult and more time-consuming to determine what these cultural values really represent, and how to measure or estimate them within a context of the species’ habitats, life histories, and populations. Our examples are not meant as final endpoint selection, but rather to generate a discussion of how to incorporate societal/cultural endpoints into our assessment of resources.

We suggest that examining cultural/societal values can only be accomplished with tribal and stakeholder involvement and participation, with involvement of other cultures (e.g., governmental and scientists) and with valuation by different interested groups. While economics can be used to develop and assess some endpoints, it fails to fully capture values, feelings, and emotions about culture. Cultural endpoints must encompass individual needs, community needs, and those of the associated environment.

Conclusions

In this paper, we suggest that environmental assessors should thoughtfully develop indicators and associated endpoints that can be used to measure (and thus assess) not only human and ecological health but also cultural/societal health as well. By the latter, we do not mean only economic health, but the well-being of cultures, such as subsistence, fishing, bird-watching, and even governmental cultures. We illustrate the complexities of doing so using salmon and red knots as they are iconic species with ecological, human, economic, and cultural attributes. Such assessments must involve assessing the perceptions and

attitudes of people, as well as traditional “health” measures of well-being for people and eco-receptors.

Acknowledgments

We thank the many people who we have discussed these topics with us or who have helped in the research, including L. Bliss, A. Bunn, E. DeVito, C. Duncan, C. Frank, M. Gilbertson, C. Jeitner, D. Jenkins, C. Minton, T. Pittfield, H. Sitters, and other field volunteers, as well as regulators and other governmental officials, tribal members associated with Hanford, and especially the Aleut people in Alaska who greatly influenced our views. We thank the many organizations and individuals who contributed throughout this research. This project was mainly funded by the Consortium for Risk Evaluation with Stakeholder Participation (Department of Energy, DE-FC01-86EW07053), with additional funding from NIEHS (P30ES005022), US Fish and Wildlife Foundation, NJ Department of Environmental Protection (Endangered and Nongame Program), Conserve Wildlife Foundation of New Jersey, Endangered and Nongame Species Program of the NJ Department of Environmental Protection, and Rutgers University. The views and opinions expressed in this paper are those of the authors and do not represent the funding agencies.

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Fig. 1. Life cycle of Chinook salmon, with the *darker arrows* indicating the predominant life cycle. Other life cycles are also illustrated, with temporal patterns

Fig. 2. Life cycle (as in Fig. 3), with some measurement endpoints shown for different life stages

Fig. 3. Complex interactions of salmon with their environment, food, and other nodes higher on the food chain. Cultural/social well-being is a combination of all of these endpoints

Fig. 4. Life cycle of red knot, from nesting in the Arctic to overwintering in temperate and South American habitats. Illustrates long-distance and short-distance migration patterns

Fig. 5. Diagram of nests of red knots in the Arctic, with nearby water to provide prey for adults and chicks

Fig. 6.

Diagram of foraging/wintering conditions for red knots, illustrating that they forage in sandy beach habitats where tides ebb and flow, exposing mudflats where they forage. They often prefer foraging on a falling tide, which exposes the most prey

Fig. 7.
Life cycle of red knot, with associated measurement endpoints

Fig. 8.

Types of endpoints for salmon, indicating traditional physical, biological, and economic endpoints (*bottom*), with cultural/societal endpoint indices on the top. The latter are complex and involve interconnections and existence values

Table 1

Possible measurement endpoints for Chinook salmon and red knot

Endpoint Type	Salmon	Red knot
Physical (physical features of the habitats used)	- Landscape features	- Landscape features
	- Presence of rivers, streams	- Presence of bays, estuaries, mudflats
	- Soil/gravel types	- Intermix of water and vegetation
	- Physical barriers (to movement)	- Snow cover on breeding grounds
Habitat (biological aspects of the environment surrounding the entire life cycle of the species)	- Water flow, water depth patterns	- Tidal regime
	- Intermix of gravel sizes	- Sea level rise at foraging stopover sites
	- Bank slope and vegetation protecting banks	- Presence of bays, estuaries and mudflats with prey available
	- Lack of vegetation in rivers/streams	- Extent of mudflats
	- Predator landscape	- Tundra vegetation above water
	- Food availability	- Predator landscape
Life history (behavioral, social, and physiological factors involved in survival and reproduction of a species)	- Conspecific nesting density	- Lack of competitors for food
	- Reproductive measures	- Food availability
	- % of river/stream km with redds	- Conspecific nest density
	- Average life span	- Reproductive measures
	- Average time to spawn	- % available breeding habitat with nests
	- Size at spawn	- % available foraging habitat with nests
	- Time of spawning	- Average age to breed
Environmental stressors (external physical, chemical, and biological exposures)	- Contaminant levels	- Average lifespan
	- Disease, tumors, growth abnormalities	- Weight when leaving stopover
	- Sea level rise	- Timing of migration, breeding
	- Sea temperature changes	
Environmental counts (systematic monitoring possible for each species)	- Commercial salmon landings	- Contaminant levels
	- Recreational landings	- Disease, tumors, growth abnormalities
	- Tribal landings	- Sea level rise
	- Size and health of the landed salmon	- Sea temperature changes
	- Fish ladder counts	- Number nesting/ha
	- Redd counts	- Number of stopover sites
	- 0 % of different size classes landed	- Number at migratory stopovers
Cultural/societal imperatives (aspect of the species or its role within the ecosystem that is valued)	- % of successful recreational, commercial, subsistence, or tribal fishing trips	- Weight of migrants at stopovers
	- Ability to obtain sufficient fish for traditional feasts, pow wows, festivals, or other events	- % of banded birds
		- Counts of prey (e.g., invertebrates and horseshoe crab eggs)

Endpoint Type	Salmon	Red knot
	- % of days able to fish compared to traditional activities (whether tribal, subsistence, or ceremonial)	- Ability to have sufficient birds visible to satisfy traditional birding weekends, banders, decoy carving, and eco-tourism interests
	- % of rivers/streams still with spawning salmon as indication of cultural access	- % of shoreline with birds compared to traditional viewing and casual viewing (e.g., beachgoers who expect birds) as indication of cultural access

After Burger et al. (2013a, b)

Table 2

Perception of social/cultural value

Bioindicator	Perception of social/cultural value	Possible measurement endpoint
Salmon	There seem to be fewer salmon.	Changes in abundance (measured yearly at fish ladders, or in spawning areas)
	There seem to be fewer salmon here where I fish.	Changes in abundance at these fishing places
	There seem to be fewer spawning salmon.	Changes in abundance at spawning sites (total no. of fish, fish/hour, fish/km)
	Salmon spawn in fewer streams.	Changes in spawning presence in key watershed segments
	Salmon aren't as big as they were when I was a "kid."	Regular monitoring of catch size of anglers for length and weight
	Fewer come and they don't spawn as long.	Monitoring length of spawning season at key spawning sites
	Salmon populations aren't healthy, and our people aren't healthy if salmon are not healthy.	Develop tribal and stakeholder-driven indicators of salmon health (i.e., numbers, size, spawning distribution in space and time); monitor over time. Try to identify and rate "unstated" values or endpoints.
	Salmon may be contaminated with chemicals and radionuclides, which affect their population, us, our children, and our culture.	Regular monitoring for contaminants and radionuclides, along with salmon population stability and extent (spatial, temporal) of salmon spawning.
	The government, businesses, and too many people have ruined the river, stopped salmon migration upriver, and destroyed our culture and health.	Identify, along with tribal members and stakeholders, the key aspects of a "salmon" culture, develop indicators for these, and monitor them, along with key salmon health indicators (many given above)
Red knot	They won't let me catch as many as my grandparents did, and it's the dams (chemicals, radionuclides, wardens) that are ruining it.	Examine catches historically, in different groups and cultures, compare to present day, develop fair catch limits and endpoints to demonstrate this. Try to identify the value they miss.
	I can't see (or photograph) big flocks like I once did.	Mean flock size at different points in the migratory or stopover locations
	There aren't as many as there used to be.	Abundance at key migratory and stopover areas
	I can't see them every day during migration.	Presence in key locations during appropriate tidal cycles
	There aren't as many, and that just goes to show the whole system is a mess.	Determine key nodes on the food web, and monitor numbers and relative relationship
	The d... shorebirds are messing up our right to fish for horseshoe crabs, and our way of life.	Monitor interaction between red knot numbers and number of spawning horseshoe crab eggs, determine by adaptive management the appropriate balance to allow catches of horseshoe crabs
	The d... fishermen are ruining the shorebirds, and our bay culture.	Identify, along with appropriate stakeholders, the key indicators of a "bay" culture, and then monitor them as well as the interaction between red knot numbers and number of spawning horseshoe crab eggs, determine by adaptive management the appropriate balance to allow catches of horseshoe crabs

Given are the phrases or ideas people with different cultural viewpoints express about these bioindicator species. Many of these endpoints require regular monitoring to determine trends. The complexity of the endpoints increase as the complexity of the cultural "feeling" does. These are only examples meant to illustrate possible endpoints and associated complexity