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Original Contribution

Top 10 Principles for Designing Healthy Coastal Ecosystems Like the Salish Sea

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Abstract: Like other coastal zones around the world, the inland sea ecosystem of Washington (USA) and British Columbia (Canada), an area known as the Salish Sea, is changing under pressure from a growing human population, conversion of native forest and shoreline habitat to urban development, toxic contamination of sediments and species, and overharvest of resources. While billions of dollars have been spent trying to restore other coastal ecosystems around the world, there still is no successful model for restoring estuarine or marine ecosystems like the Salish Sea. Despite the lack of a guiding model, major ecological principles do exist that should be applied as people work to design the Salish Sea and other large marine ecosystems for the future. We suggest that the following 10 ecological principles serve as a foundation for educating the public and for designing a healthy Salish Sea and other coastal ecosystems for future generations: (1) Think ecosystem: political boundaries are arbitrary; (2) Account for ecosystem connectivity; (3) Understand the food web; (4) Avoid fragmentation; (5) Respect ecosystem integrity; (6) Support nature's resilience; (7) Value nature: it's money in your pocket; (8) Watch wildlife health; (9) Plan for extremes; and (10) Share the knowledge.

Keywords: coastal ecosystem health, Georgia Basin, marine, Puget Sound, restoration, Salish Sea

INTRODUCTION

The inland sea of Washington State (USA) and British Columbia (Canada) is recognized as an international treasure (Fraser et al. 2006). Corresponding to the ancestral home of the Coast Salish people and often referred to as the Salish Sea (Fraser et al. 2006), the ecosystem stretches from Olympia in the south to Campbell River in the north and extends from the crest of the surrounding mountain ranges (Olympic, Cascade, Vancouver Island, and Coast Range) to the deepest part of the marine waters (Figure 1). The area south of the international border is called the Puget Sound Basin, and to the north, the Georgia Basin (Figure 1). Thousands of streams and rivers drain 7470 km of coastline into 16,925 square kilometers of marine water (1:250,000 scale World vector Shoreline and TEOPO2 topographic/ bathymetric GIS grid). In addition to nearly 7 million people, the region is home to over 200 species of marine

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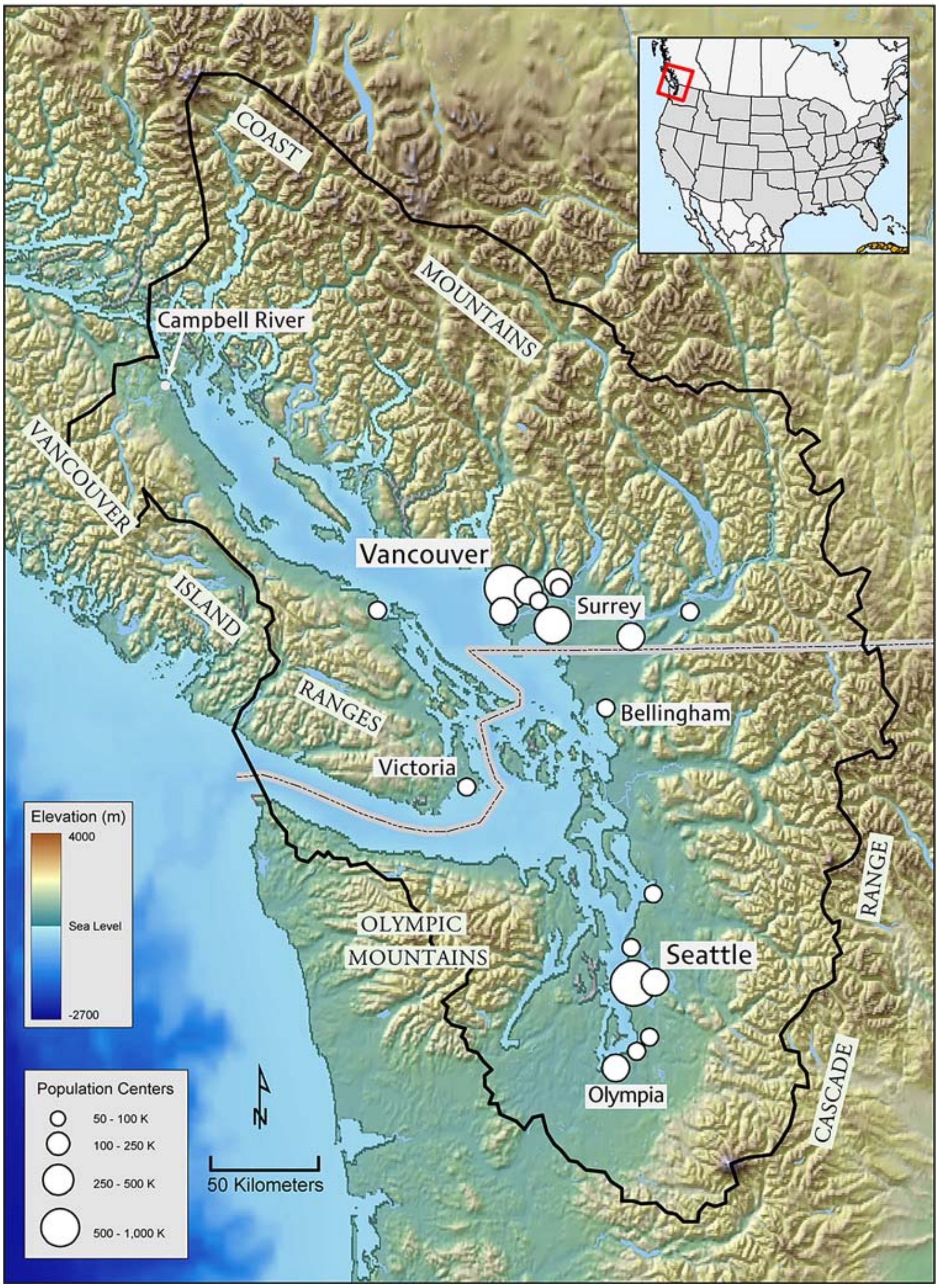

Figure 1. Map outlining the boundaries of the Salish Sea (*solid black line*), from the mountain tops to the marine water, showing terrestrial topography, marine bathymetry, and the "arbitrary" international border (*white-gray dotted line*) separating the Puget Sound Basin (United States) to the south and the Georgia Basin (Canada) to the north.

and anadromous fish, over 100 species of marine birds, 26 species of mammals, and thousands of invertebrate species (Puget Sound Partnership 2006; Brown and Gaydos 2007; Puget Sound Action Team 2007). Like other coastal zones around the world, the Salish Sea has been dramatically altered under pressure from a growing human population, conversion of native forest and shoreline habitat to urban development, toxic contamination of sediments and species, and overharvesting of resources (Thom and Levings 1994; Puget Sound Action Team 2007).

Washington State Governor Christine Gregoire recently initiated a statewide effort to restore the Puget Sound portion of this ecosystem by the year 2020 (Puget Sound Partnership 2006). Similar efforts have been undertaken in other estuarine and coastal regions of the United States and around the world. However, despite billions of dollars spent on ecosystems such as the Chesapeake Bay or Florida Everglades, their restoration remains a distant goal (Finkl and Charlier 2003; Powledge 2005).

Efforts at ecosystem restoration generally look backward in time, attempting to reconstruct complex, dynamic, self-organizing systems of living and non-living elements. The challenge is that conditions that existed prior to the present might never reoccur or could be impossible to recreate as species are extirpated, invasive species are introduced, and atmospheric and oceanic conditions change. We suggest that it is more appropriate to talk about designing future ecosystems that reflect current societal values and use what we know of ecological principles to guide the design process.

The concept of health provides a flexible, overarching framework for designing ecosystems. We agree with the definition proposed by the Puget Sound Partnership (2006) that defined a healthy ecosystem as a place where:

- Fish and shellfish are plentiful and safe to eat, air is healthy to breathe, and water and beaches are clean for swimming and fishing;
- People are able to use and enjoy the lands and waters of the region, tribal cultures are sustained, natural resource-dependent industries such as agriculture, tourism, and fisheries thrive, and the region is economically prosperous; and
- The rich diversity of species flourish and are supported by plentiful, productive habitat, as well as clean and abundant water.

Rebuilding a healthy Puget Sound and Salish Sea is an exercise in place-based ecosystem management. Place-based conservation strategies require that stewards know and understand the ecosystem, restore impaired resources, protect the ecosystem, and connect people wholeheartedly to the place (Davis 2005). Educating local citizens, scientists, businesses, and policymakers to “know, protect, and connect” to the Salish Sea will require a comprehensive strategy built on sound ecological principles that can serve as a foundation for the process. Using well-accepted ecological principles to educate society improves upon efforts of other ecosystem restoration educational efforts that provide citizens with lists of things to do without educating them on a guiding ecological rationale.

We propose 10 fundamental ecological principles to serve as a guiding framework for designing a healthy coastal ecosystem like the Salish Sea. These imperatives are designed to form a basis for educating and energizing policymakers and citizens in the concepts of place-based management. While this article is focused on the Salish Sea, the ecological principles are applicable to other ecosystem-based restoration efforts around the world.

THE 10 PRINCIPLES

Think Ecosystem: Political Boundaries Are Arbitrary

Although there is a major statewide effort to restore Puget Sound by the year 2020 (Puget Sound Partnership 2006), the Puget Sound basin is only one half of a large and unified ecosystem, the Salish Sea (Fraser et al. 2006). Efforts to restore Puget Sound will fail if they do not incorporate and integrate similar efforts on the Canadian side of the border. The international political boundary separating the Puget Sound and Georgia Basin is invisible to marine fish and wildlife; species listed as threatened or endangered under the US Endangered Species Act (ESA) or the Canadian Species at Risk Act, including Southern Resident killer whales (*Orcinus orca*), marbled murrelets (*Brachyramphus marmoratus*), and some ecologically significant units or species of Pacific salmon (*Onchorynchus* spp.), traverse the boundary daily (Brown and Gaydos 2007). Oceanographic processes such as freshwater inflows and wind-driven surface currents exchange biota, sediments, and nutrients throughout the larger ecosystem. For example, the less saline, more buoyant Fraser River plume can be observed by satellite imagery flowing across the international boundary throughout the year (Wilson et al. 1994), and tidal oscillations move huge volumes of water across the border four times daily (Thomson 1981).

International, state, provincial, or tribal, political boundaries impede ecosystem restoration. Management of the iconic Pacific salmon is a striking example of the unique challenges created when ecosystem and political boundaries do not align. The migration patterns of the five species of Pacific salmon in this ecosystem create transboundary fishery regimes containing mixed stocks from numerous river systems of origin (some from the USA and others from Canada). In 1945, the United States and Canada implemented the first bilateral Pacific salmon-sharing agreement, followed by the 1985 Pacific Salmon Treaty. However by 1997, as salmon stocks were declining, accusations from both sides about the interception and harvest of fish destined for the other country became so heated that the USA and Canada independently shifted their fishery regimes, foregoing all concerns about stock declines. These "salmon wars" ultimately culminated in a renewed salmon harvest agreement signed in 1999 (Ruckelshaus et al. 2002).

While the governments of Washington State and British Columbia signed an Environmental Cooperative Agreement in 1992 to work together on marine issues in the Salish Sea (British Columbia/Washington Marine Science Panel 1994) the agreement is hampered by internal constraints imposed by tribal and federal laws. For instance, a 1974 court decision reaffirmed the treaties between the U.S. Federal Government and 19 tribes in Washington signed in 1885, and ruled that 17 tribes with usual and accustom fishing areas in Puget Sound have the right to 50% of the harvestable fish and shellfish resources (Boldt decision 384 F. Supp. 312; 1974 U.S. Dist. LEXIS 12291). By contrast, in Canada, the Federal Government regulates all tribal harvest.

"Thinking ecosystem" requires focusing restoration efforts from the start on all sides of the political border and finding mutually agreeable solutions among all levels of government. The principle worked in the design of the Mount Elgon Regional Ecosystem Conservation Program, a transboundary natural resource management program involving the republics of Kenya and Uganda (Muhweezi et al. 2007), and will work for multi-national coastal ecosystems as well. Focus on the ecosystem as its own legitimate entity can help prevent the past experiences where agreements made when resources were abundant quickly unraveled as those resources declined.

Account for Ecosystem Connectivity

Ecosystems are more interconnected than most people appreciate. Citizens, scientists, managers, and policymakers filter out these connections in order to focus on specific areas or species of interest, using compartmentalization to simplify the daunting challenges of managing complex systems.

Understanding the connectivity and linkages between seemingly unrelated species and ecosystems is key to successful restoration. Like most ecosystems, the factors determining the fate of the Salish Sea extend hundreds of kilometers from the sea to the crest of the mountains that surround these waters (Figure 1). For example, the amount and configuration of impervious surfaces (e.g., concrete parking lots, roads) and harvested forests impact the biotic integrity of streams feeding into the Salish Sea (Alberti et al. 2007), which, in turn, affects the health of the entire ecosystem. Forest health impacts the abundance of the marbled murrelet, an endangered seabird that nests up to 50 miles inland in old growth forests, but spends the remaining 11.5 months of the year feeding at sea (Raphael 2006). Intricate food webs can connect species across ecosystems. For example, gray whale (*Eschrichtius robustus*) abundance is linked to productivity in the Bering Sea (Calambokidis et al. 2002); the abundance of migrating gray whales feeding in the Salish Sea could be important for the recovery of declining surf scoter (*Melanitta perspicillata)* populations (Anderson and Lovvorn 2008).

Commerce and transportation are powerful non-biological forces that link the biota of Puget Sound to other ecosystems. For instance, in 2006–2007 Washington State and tribal fishermen harvested over 225 metric tons of sea cucumbers (*Parastichopus californicus*), the majority of which were exported to Asian markets [M. Ulrich, Washington Department of Fish and Wildlife, personal communication]. Increasing non-local demand for fisheries can potentially drive unsustainable harvests and hinder restoration. The robust shipping industry that links the Salish Sea to most of the world also is a source of invasive species that can threaten the integrity of biological communities (Ruiz et al. 2000).

Connectivity contributes to ecosystem functions, and understanding these intricacies is important for designing healthy ecosystems. For example, recent modeling suggests that the mangrove-based ontogenetic migrations of parrotfish could, through a trophic cascade on macroalgae, enhance the recovery rate of midshelf Caribbean coral reefs from hurricanes (Mumby and Hastings 2008). Consequently, preserving or replanting mangroves will improve Caribbean coral resiliency in the face of predicted increased hurricane frequency and intensity (Knutson et al. 2001). While it is tempting to filter out the apparent "noise" from other species and ecosystems, acknowledging and identifying key cross-species and cross-habitat connections are essential to understanding changes in the system and measuring performance.

Understand the Food Web

Food webs represent complex trophic interactions among species; they can change seasonally and geographically (Paine 1980). Although often simplified for communication purposes, food web linkages are complex, subtle, and interactive; they play a major role in ecosystem connectivity, as well as in ecosystem resiliency and capacity for renewal.

A working food web model is a powerful tool for managing ecosystems. Around the world, traditional harvest management tools, such as maximum sustainable yield models, focus on how many individuals can be harvested sustainably by humans. However, the models fail to take into account the full range of trophic interactions and trophic needs (Struhsaker 1998; Walters et al. 2005). For example, an acceptable salmon harvest level is designed to ensure that sufficient individuals are left to spawn in order to maintain viability of the salmon run into the future. What it fails to account for are the needs of other species dependent on the same salmon run, i.e., those species that prey on salmon (e.g., whales) or those species that are salmon prey. Determining the impact of human-harvested salmon on killer whales, eagles, or any of the other 136 vertebrate species that rely on salmon or salmon carcasses (Cederholm et al. 2000) has proved elusive. Yet it has important biological and policy consequences. For instance, an important factor in listing Southern Resident killer whales as threatened under the ESA was the decline in its primary prey, salmon (Brosnan 2006).

Food webs can be used to identify priority or key species in biological communities. Measures taken to protect them and their habitats benefit the entire ecosystem. For instance, Pacific sand lance (*Ammodytes hexapterus*) and surf smelt (*Hypomesus pretiosus*) are key forage fish for some Puget Sound birds and mammals (Davoren and Burger 1999; Robards et al. 1999; Lance and Thompson 2005). Locating and protecting their intertidal gravel-sand spawning beaches and associated upland riparian habitats assures food supplies for many species. Human alteration of the shoreline can change environmental conditions of these beaches and halve egg survival (Rice 2006), resulting in “bottom up” impacts on the ecosystem through the food web.

Knowledge of food web dynamics allows managers to monitor movement of contaminants in the ecosystem (Ross et al. 2004) and the effects of the toxins on species composition, abundance, diversity, and ultimately, the food web itself. Bioaccumulation of toxins has been shown to impact multiple species in many ways, from the immunologic health of harbor seals (Ross et al. 1996) to the density and species richness of *Phoxocephalid* amphipods (Swartz et al. 1982).

Avoid Fragmentation

Human activities that break otherwise contiguous habitat (land and seascapes) into smaller pieces fragment ecosystems, reduce their ecological integrity, and threaten their capacity to renew themselves (Soulé and Lease 1995; Vitousek et al. 1997). Habitat is the place where species interact and form complex communities. Habitat size is directly linked to population size and the nature of species interactions. All species require a minimum number and density of individuals to persist (Shaffer 1981), thus they also require a minimum amount of suitable habitat. For most species, habitat configuration is also important (Hovel 2003). When habitats are fragmented, and shrink below the size required to support a minimum viable population or are significantly modified or disturbed, a sequence of events begins that can end with species extinction. At low densities (associated with small habitats), individuals may be unable to find mates (the Allee effect). For example, this is particularly critical for benthic animals with little mobility such as abalone and some rockfish species (Davis et al. 1998; Yoklavich 1998). Small populations are more susceptible to extinction by extreme natural events and are more likely to lack the genetic diversity needed to adapt to changing physical and biological conditions (Tilman and Downing 1994), such as climate change or competition from invasive species.

Unlike the terrestrial environment, where habitat size is visible and easily monitored, fragmentation in the marine environment is notoriously hard to study. Thus, it has received far less attention. Steneck et al. (2002) point to several ways in which people inadvertently fragment marine habitats. For instance, seafloor trawling can have devastating effects on the seafloor and result in isolated “islands” of unaltered submarine habitats too small to maintain viable populations. Pelagic species and large mammals can experience habitat fragmentation through fisheries and reserve policies. For instance, reserve areas may be too small to contain the necessary food resources to sustain populations of marine mammals.

Where the land meets the ocean, anthropogenic shoreline alterations can fragment the nearshore marine habitat and reduce productivity. For example, terrestrial insects falling into nearshore marine water are an important food source for migrating juvenile salmonids; the removal of overhanging shoreline vegetation reduces this important food source (Brennan and Culverwell 2004). Additionally, removal of overhanging shoreline vegetation can alter the microclimate of beaches and reduce their suitability for incubating eggs of intertidal spawning fish (Rice 2006).

Some tools used to address ecosystem fragmentation in terrestrial ecosystems also could be used to address ecosystem fragmentation in coastal ecosystems. Fragmentation through land subdivision and the loss of large-scale dynamic processes such as wildlife migrations and fire was identified as the major threat to the world's grassland ecosystems (Curtin and Western 2008). Cultural exchange between Masai pastoralists from Kenya and ranchers from the United States helped address these fragmentation threats by speeding up understanding and adaptation (Curtin and Western 2008).

Respect Ecosystem Integrity

Intact ecosystems are more than the sum of their parts. Processes and forces that bind the parts into a system produce synergies and properties that the individual parts do not possess when simply collected together. Ecological integrity, in which a system has all its parts and no "extra" ones, is a hallmark of environmental health (Leopold 1949). An intact ecosystem has a complete suite of species, and a full range of size and age classes of each component species.

Ignoring the ecological integrity and the power of biological interdependence in marine systems has been catastrophic. Historically, fishery practices targeted predators and preferentially removed old, large organisms (those with the greatest reproductive capacities; Berkeley et al. 2004), while relying on smaller, rapidly growing and barely reproducing younger animals for replenishment (Pauly et al. 1998). As a consequence, fishery collapses became widespread. But the ecosystem-wide impacts were just as disastrous. Because predators mediate competition among prey species (Paine 1969) and help assure that a few, fit individuals of all kinds survive to produce another generation, such single-species management strategies not only doomed targeted populations to death spirals, but also triggered trophic cascades with ecological effects that persisted for decades and involved hundreds of species (Dayton et al. 1995; Jackson et al. 2001).

Adding, or introducing, invasive species, toxic materials, and pathogens also reduces ecological integrity. In the Salish Sea, non-native species like the purple varnish clam (*Nuttallia obscurata*) likely were introduced in ballast water (Dudas 2005). Other species, like the Japanese seaweed *Sargassum muticum*, likely were introduced with the intentionally introduced Pacific oyster (*Crassostrea gigas*), and now compete with native kelp, impacting benthic subtidal communities (Britton-Simmons 2004). The ocean, a historical out-of-sight–out-of-mind dumping ground for industrial waste, now bears the burden of tonnes of organochlorines and other persistent organic pollutants that have bioaccumulated in the food chain and impacted the health of top predators (Moss et al. 2006). The Salish Sea's resident and transient killer whales are considered some of the most contaminated cetaceans in the world (Ross et al. 2000).

Support Nature's Resilience

A resilient ecosystem can rebound after a disturbance. Resilience is a measure of health and indicates how much stress a system can absorb before it permanently changes into an alternative state or collapses (Holling 1973, 1986; Gunderson 2000). While resilience is essential in a healthy ecosystem, it is frequently ignored in conservation planning. This is because it is hard to measure, and often only recognized once the system is on the verge of collapse.

Biological communities have several natural attributes that make them resilient in the face of change and disturbance. For example, the presence of a keystone species determines persistence and stability (Paine 1969; Estes et al. 1989; Walker 1995; Walker et al. 1999), and in the Salish Sea's rocky intertidal zone, the sea star *Pisaster ochraeus* is essential to maintaining a highly diverse and stable community. In their absence, a monoculture of mussels (*Mytilus* spp.) occurs (Paine 1969). Other communities lacking a keystone species rely on a suite of interacting organisms to build resilience (e.g., Tilman and Downing 1994; Walker 1995; Carpenter and Cottingham 1997; Walker et al. 1997, 1999; Gunderson 2000). Genetic diversity has also been shown to increase ecosystem resilience in seagrass (*Zostera marina*) communities stressed by elevated temperatures (Reusch et al. 2005).

Human actions can inadvertently disrupt the factors that allow ecosystems to respond and persist in the face of change. Removal of a keystone species can lead to ecosystem collapse (e.g., Estes et al. 1989). Overfishing can have a detrimental impact on resilience: 20 years of data from reserve versus fished sites showed that reserves maintained a greater complement of species, and were consistently able to withstand and rebound from extreme, but not unusual, environmental conditions such as El Niño years. Fished (non-reserve) sites had fewer species and communities and habitats within the fished sites (e.g., kelp forests) frequently collapsed during El Niño events (Lafferty and Behrens 2005).

The principle of building ecosystem resilience is gaining ground. Hughes et al. (2005) highlight the international emergence of a complex systems approach for sustaining and repairing marine ecosystems, linking ecological resilience to governance structures, economics, and society. Previously, several authors (e.g., Hughes et al. 2003) noted that corals in the Indo-Pacific and elsewhere are showing signs of resilience in their ability to adapt to climate change and called for international integration of management strategies that support reef resilience. Since then, toolkits on effective ways to build reef resilience as an integral part of designing healthy marine ecosystems have been developed and are being applied worldwide on reefs from India to Africa, the Caribbean, and the Americas (see http://www.reefresilience.org).

Value Nature: It's Money in Your Pocket

Economics is the allocation of limited resources among alternative, competing ends; it is about what people want, and what they are willing to give up in exchange (Daly and Farley 2004). Human well-being is derived from access to, and often the marketing of, essential ecological goods and services provided by ecosystems. These include fossil fuels, minerals, wood, fish, meat, edible plants, watchable wildlife, biofiltration of contaminants, and a multitude of other ecological "inputs." While higher values of waterfront properties are considered luxuries, most ecological goods and services are considered basic needs for human survival.

Despite the complexities of economic globalization, healthy ecosystems support economic prosperity and well-being (Srinivasana et al. 2008). The Salish Sea provides the people who live in the region with abundant natural capital which contributes substantially to the financial prosperity of the region. In Washington alone, marine fish and invertebrates support commercial fisheries worth $3.2 billion a year; the ports of Seattle and Tacoma enable over $70 billion in international trade; and water activities such as sailing, kayaking, whale-watching, and SCUBA diving generate 80% of all dollars spent on tourism and recreation in the state every year (Puget Sound Partnership, unpublished data).

Healthy ecosystems support economic prosperity. Unhealthy systems cost money to repair and in lost opportunity to benefit from the natural capital. Overharvesting, pollution, and loss of wild habitat reduce the quality and quantity of ecosystem services and, ultimately, the economic potential of a region (Clausen and York 2007). Fecal coliform contamination of nearshore waters closed a third of Washington's $97 million shellfish beds to harvest in 1 year alone (Puget Sound Action Team 2007; Pacific Coast Shellfish Growers Association 2008). In the Salish Sea, ecosystem services provided by higher trophic species like salmon and killer whales, which generally disappear before those provided by species lower in the food chain (Dobson et al. 2006), are decreasing. The cumulative economic and ecosystem services losses associated with the depletion of these higher trophic species is incalculable, but likely astronomical.

When appropriately balanced, ecosystem services can be used to simultaneously advance conservation and human needs, as has been shown with projects like Quito, Ecuador's Water Fund, China's Sloping Lands Program, Kenya's Il'Ngwesi Ecolodge, and Namibia's Conservancy Program (Tallis et al. 2008). A healthy Salish Sea that provides services such as plentiful and safe fish and shellfish, clean water, natural resource-dependent industries, is money in our pockets. Ecosystem services provide revenue from the marine-based industries that are the lifeblood of the region's economy, and mean less spent on major repairs to reverse ecological damage. Decision-makers and citizens working to restore ecosystems around the world need to grasp nature's economic benefits or they will grossly underestimate the full benefits of a restored ecosystem while overestimating the relative costs of restoring it.

Watch Wildlife Health

Disease in marine wildlife can serve as a sentinel for human health. Animals, particularly wildlife, are thought to be the source of over 70% of all emerging infections (Chomel et al. 2007). A burgeoning human population, increased travel opportunities, booming commerce, frequent animal relocations, and expanding aquaculture increase human exposure to zoonotic diseases from marine wildlife (Friend 2006).

Blooms of the phytoplankton *Pseudo-nitzschia* have caused closures of recreational, commercial, and tribal subsistence shellfish harvest in the Salish Sea (Trainer et al. 2006). These organisms produce domoic acid, a biotoxin known to cause seizures and death in marine mammals and amnesic shellfish disease in humans (Van Dolah et al. 2001). Marine mammals are exposed by eating fish that have consumed domoic acid (Lefebvre et al. 2002). Exposed animals often will strand on beaches and can serve as an early warning indicator for potential exposure of humans through shellfish consumption (Van Dolah et al. 2001), thereby allowing managers to close shellfish harvesting areas to protect human health.

Discovering that the feline parasite *Toxoplasma gondii* infected marine wildlife alerted people to the fact that raw shellfish consumption also could be a route of exposure for humans. If a pregnant woman becomes infected with this parasite, the parasite can infect the fetus, leading to mental retardation, seizures, blindness, and death in children (Alvarado-Esquivel et al. 2006). Interestingly, this cat parasite has been discovered to infect marine wildlife, such as sea otters (*Enhydra lutris;* Conrad et al. 2005), marine-foraging river otters (*Lontra canadensis;* Gaydos et al. 2007), and harbor seals (*Phoca vitulina;* Lambourn et al. 2001). It is believed that marine wildlife are exposed to *T. gondii* when cats shed the infective stage (oocyst) in feces, which is then transported by freshwater run-off into the marine ecosystem (Miller et al. 2002). Increased numbers of domestic and feral cats and their associated feces (Dabritz et al. 2006), as well as modifications in freshwater run-off (Miller et al. 2002), have probably increased marine mammal exposure to this parasite. Because shellfish can concentrate the infective *T. gondii* oocysts (Arkush et al. 2003), humans, like marine mammals, also are at risk for exposure by eating uncooked shellfish.

Human, wildlife, and ecosystem health are intimately connected. Understanding and monitoring diseases in both groups will help to identify where and when a stressed ecosystem is contributing to increased disease in people and wildlife, and how the ecosystem can be redesigned. In the Salish Sea region, high-quality public health programs exist, but efforts to monitor and understand marine wildlife health in both countries are limited and not well linked to human health networks. In many less-developed parts of the world, both human and wildlife health need to be better studied and incorporated into designing healthy ecosystems.

Plan for Extremes

Knowing that the daily average temperature is 71°F has little meaning if the daily temperature ranges from 115°F during the day and 27°F at night. We all know the perils of walking across a river with an "average depth of 4 feet." Planning for the extremes, and not just the average, is prudent.

High variation and diversity are key characteristics of living systems, and averages can mislead people seeking to understand and manage nature. For instance, fisheries management based on "average abundance" will fail to account for poor years, and is likely to drive the species extinct. Yet resource users often will prefer to manage for the average.

A major discovery of environmental science in the 20th Century was the ecological significance of "natural extreme events." Many people still view these kinds of events only as disasters that wreak havoc on society and cause humanitarian tragedies (Kumar et al. 2005). The emergence of disturbance ecology (e.g., Connell 1978; Paine and Levin 1981) illustrated the critical roles that rare extreme events like wildfires, hurricanes, droughts, floods, and El Niño Southern Oscillation events have played in sustaining biodiversity and ecological integrity in oceans (Dayton and Tegner 1984). As citizens, scientists, and decision-makers begin to envision a restored Salish Sea, that vision must include policies, laws, and management actions that account for extreme but natural events.

Share the Knowledge

Humans are integral parts of ecosystems. Citizens who understand that their own physical, mental, and economic well-being is intimately connected to the health of the ecosystem are more likely to support and engage in ecosystem restoration. While the people of the Salish Sea are believed to value their ecosystem, in reality there currently seems to be little support for restoring it. Despite overwhelming scientific evidence about declines in the health of Puget Sound, a 2006 poll found that only 8% of respondents felt the condition of the environment was the most important problem facing people in the Puget Sound region (Puget Sound Partnership, unpublished data). Widespread public education about the issues and what is at stake could build a connection to the ecosystem and rally support for its restoration.

But public support alone will not restore the Salish Sea. Political leadership and funding are equally essential. In the Florida Everglades, citizens have expressed their desire for ecosystem restoration to their political representatives, and the representatives themselves are charged with providing the long-term support and funding required for restoration (Kiker et al. 2001). Only an educated and dedicated political leadership, demonstrating vision and stamina, will keep a long-term focus on restoring ecosystems in the face of numerous short-term competing interests.

Marine resources of the Salish Sea are managed by multiple local, state, federal, tribal, and national governments. The common bonds among these myriad of governance agencies is the human community they serve and the ecosystem they seek to sustain as healthy and productive. Scientists play a unique role in linking citizens, politicians, and nature. By sharing knowledge, they can help inform citizens and decision-makers so that actions are science-based and take account of the key factors that will help ensure success.

MOVING FORWARD

The issues people face in designing a healthy Salish Sea are not unique. Human communities worldwide gather in ever increasing numbers at the coast, adding pressure on the ecosystem's goods and services. Human use threatens the sustainability of the natural, social, and economic values that attracted them to the coast in the first place (Martínez et al. 2007). Ocean and aquatic systems generate more than 60% of the world's ecosystem services (Costanza et al. 1997). Human communities ignore or degrade these services and their value at their own peril.

These 10 ecological principles can guide people in designing local actions that will have persistent global impacts on environmental quality and human health and well-being. These science-based principles will be most effective in informing political processes if they are communicated to citizens and policymakers in ways that are both tangible and memorable (Figure 2). Societies around the world that have cultural, religious, and economic differences are working to design healthy ecosystems. Expressing ecological principles in ways that might capture the attention and interest of local communities (e.g., Figure 2) will benefit place-based education and conservation efforts.

In summary, issues at political boundaries can be resolved with cooperation, while nature's boundaries are immutable, dynamic connections that cannot be negotiated or changed by policy; think ecosystem. Great thinkers and philosophers from Henry David Thoreau to Edward O. Wilson have espoused the global interdependence of people and other parts of nature that is inescapable in designing sustainable communities; account for ecosystem connectivity. Knowing how plants and animals are related to each other by their diets is a practical way to visualize connectivity, interdependence, and system integrity and helps predict how nature will respond to stresses; understand your food web. Habitats of adequate size and quality to support high levels of biodiversity are critical characteristics of healthy ecosystems; avoid fragmentation. Loss of integrity threatens nature's stability, beauty, and capacity for self-renewal, but integrity can be rebuilt and sustained by design; respect ecosystem integrity. While healthy ecosystems have tremendous capacity for self-renewal, resilience can be overwhelmed by collective human activities. Again, resilience can be restored by people, by design. Healthy ecosystems are money in your pocket because they save on

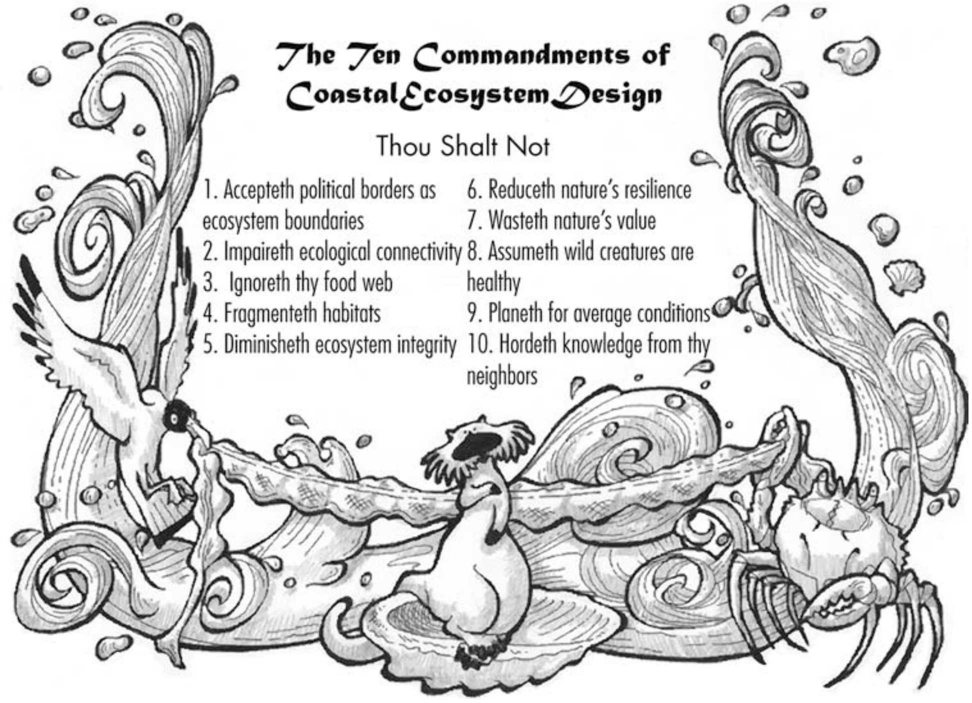

Figure 2. Top 10 ecological principles translated into a format intended to capture the attention of, and be meaningful to, people living in and around the Salish Sea.

repair costs and deliver essential goods and services; value nature. Diseases in marine animals are closely linked to human health and can provide early warnings as sentinels of ecosystem stress; watch wildlife health. Nature is variable and rarely average, and remember, extreme natural events test fitness, mediate competition, and assure diverse opportunities; plan for extremes. Finally, people matter from grassroots to government, and little will happen without educating and incorporating humans at every level into designing a healthy ecosystem for the future; share the knowledge.

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