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COMMENTARY

Urban seas as hotspots of stress in the Anthropocene ocean: The Salish Sea example

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Coastal seas and estuaries are among the most productive ecosystems on Earth and have long attracted human activity. Yet, urbanization pressures are intense and are compounded by accelerating climate stresses. Urban seas are now hotspots of stress in the Anthropocene ocean. The Salish Sea stands out as one of a few highly functioning urban seas in the world, boasting ecological riches and thriving coastal communities and industries, including tourism. For over 10,000 years the region has supported Indigenous peoples; now it is home to a growing population of almost nine million people, concentrated in and near the major cities of Seattle, Washington, and Vancouver, British Columbia. Increasing urbanization combined with intensifying climate stress is degrading the Salish Sea and acutely affecting communities already experiencing marginalization. Current environmental impacts include acidifying waters, hypoxia, and intense heat waves, all of which have had measurable impacts within the ecosystem. A recent synthesis of this system identified key domains for solutions, which we generalize here for invoking positive change in global urban seas: 1) innovation in data collection, curation, and integration using a systems approach in science and management; 2) sharing place-based knowledge to sustain community-based action; and 3) aligning science and policy with ecosystem boundaries. The differing governance and socio-political settings across two countries and numerous Indigenous nations creates a complex challenge in ecosystem management. Developing actionable solutions for people and the biota of the Salish Sea can create a global example of a sustainably managed urban sea with transferable insights to other urban seas in need of revitalization around the world.

Keywords: Urban seas, Urbanization, Climate change

Urban seas

Urban Seas are coastal estuaries and marginal seas with drainage basins that are extensively developed and populated by humans, creating unique human-environment conditions and exhibiting profound environmental change. Urban seas are a nexus of anthropogenic change, where global climate change intersects with urbanization, as well as being living laboratories for generating solutions for decelerating the Anthropocene.

1. Urban seas

Coastal ecosystems are highly productive as measured by primary productivity (Cloern et al., 2014), global biodiversity (Ray, 1991; Costanza et al., 1993; Worm et al., 2006), and ecosystem function (Barbier et al., 2011). Nutrient inputs from freshwater, upwelling, or a combination of both, support rich primary production in the form of phytoplankton, seagrasses, and benthic algae. Many coastal ecosystems today exist at the nexus of biological productivity and human productivity, the result of global urban and industrial expansion, concentrated at the intersections of rivers and coasts in estuaries (Lotze, 2010). Thus, *urban seas*—those estuaries and coastal embayments surrounded by dense human populations in one or more urban areas—are deeply impacted by intense human activities on land and the concomitant degradation of the seascape from myriad anthropogenic activities. These

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impacts have spanned generations, with legacy and continuing impacts, while emerging stressors add to the pressures that urban sea ecosystems face. Cumulative stress from urbanization and climate change puts urban seas at the center of anthropogenic change in the global oceans, and therefore also at the center of climate change solutions.

Urban seas, such as Chesapeake Bay and Baltic Sea, are among the most intensively studied ecosystems in the world (Chesapeake Bay: Officer et al., 1984; Baird and Ulanowicz, 1989; Hagy et al., 2004; Baltic Sea: Möllmann et al., 2009; Murray et al., 2019; Reckermann et al., 2022). There is opportunity to expand on the extensive science of these systems, as well as the many other urban seas that share similar environmental pressures resulting from urbanization (examples in **Table 1**), with the added impact of climate change bearing down with a diversity of local implications. While urban seas are each unique in their geographic, oceanographic, social, cultural, and economic features, and will require tailored solutions, a broadly framed approach could prove effective at mapping out viable solutions to address many challenging issues facing urban sea systems (National Academies of Sciences, Engineering, and Medicine [NASEM], 2022).

Here, using the Salish Sea as an example, we suggest that the existing level of understanding in these critical ecosystems must be combined with actionable solutions—both time-tested and novel—to improve conditions and mitigate future impacts. Furthermore, as harbingers of the cumulative impacts of anthropogenic change in its entirety, these systems can serve as priority testbeds for better understanding repercussions throughout the global

Table 1. Example urban seas and associated waterbody and watershed areas, major cities, population, and ecosystem impacts

Urban Sea	Waterbody Area (km^2)	Watershed Area (km^2)	Major Cities	Population (Millions)	Primary Ecosystem Impacts
Salish Sea[a]	17,800	320,000	Seattle, USA; Vancouver, Canada	8.9	Habitat loss, water and sediment contamination, overfishing, vessel traffic
Baltic Sea[b]	420,000	1,640,000	Copenhagen, Denmark; Helsinki, Finland; Riga, Latvia; Stockholm, Sweden; St. Petersburg, Russia	85	Eutrophication, overfishing, invasive species, water and sediment contamination
Bohai Sea[c]	77,0000	1,400,000	Dalian, Tangshan, Tianjin, and Weifang, China	208	Pollution, overfishing, land development and sedimentation, water quality
Chesapeake Bay[d]	11,600	165,700	Baltimore, Norfolk, and Washington, DC, USA	18.4	Nutrient enrichment, sedimentation, eutrophication, hypoxia, impaired water quality
Rio de la Plata Estuary[e]	38,000	3,100,000	Buenos Aires, Argentina; Montevideo, Uruguay	67	Water and sediment contamination from freshwater inflow, overfishing, vessel traffic
San Francisco Bay[f]	16,000	163,000	Oakland, San Francisco, and San Jose, USA	7.2	Invasive species, altered freshwater inflow and diversion, impaired water quality, habitat loss
Seto Inland Sea, Setonaikai[g]	21,800	47,000	Hiroshima, Kobe, and Takamatsu, Japan	35	Eutrophication, harmful algal blooms overfishing, hypoxia, land reclamation and habitat loss, dredging

[a]Sobocinski (2021); Flower (2022).

[b]HELCOM (2018); Reckermann et al. (2022).

[c]Bian et al. (2016); International Center for the Environmental Management of Enclosed Coastal Seas (2015).

[d]Kemp et al. (2005); Carey (2021); Chesapeake Bay Program (2022).

[e]Baigún et al. (2016); Organization of American States (2005).

[f]Cloern and Jassby (2012).

[g]Takeoka et al. (2002); Matsuda (2017).

ocean and as productive spaces for generating climate change solutions from local to global scales.

2. Salish Sea as urban sea

The Salish Sea is an inland sea bisected by the international border between Washington, USA, and British Columbia, Canada, and connected to the Pacific Ocean by the Strait of Juan de Fuca (**Figure 1**). It comprises the Strait of Georgia in the north and Puget Sound in the south, and includes numerous inlets, bays, and islands (**Figure 2**). The estuarine waters span 17,803 km^2 (Flower, 2020). The biophysical interactions within the Salish Sea defy geopolitical boundaries and jurisdictions as ocean water, nutrients, organisms, and pollutants circulate in the estuary with inflows of freshwater, sediments, and contaminants from the uplands.

An extensive network of rivers and large contributing watersheds, extending thousands of meters to prominent peaks in the Coast, Cascade, and Olympic mountain ranges, provide the freshwater input that makes the Salish Sea an estuary. The most prominent of these inputs is the Fraser River, which enters the Salish Sea in Canada, just north of the international border. The Fraser contributes approximately 50% of the freshwater and a significant amount of the sediment entering the Salish Sea (Khangaonkar et al., 2018), with discharge averaging 3,475 m^3 s^{-1}. This freshwater input drives much of the circulation in the Salish Sea (Geyer and Cannon, 1982; Sutherland et al., 2011).

Figure 1. Location and jurisdictions of the Salish Sea and its watersheds. The Salish Sea region is governed by numerous agencies and jurisdictions, including 12 counties in Washington (WA), 10 regional districts in British Columbia (BC), and over 80 First Nations and Tribal Governments with federally recognized land holdings. The Indigenous lands shown on this map are limited to the Indian Reserves and Reservations, Tribal Trust Lands, and First Nations Treaty Lands recognized by the US and Canadian federal governments as of 2021. This map does not show marine waters under Indigenous management, unceded Indigenous lands, land involved in ongoing treaty negotiations in British Columbia, usual and accustomed Indigenous fishing grounds, nor the numerous and often overlapping ancestral Indigenous territories that cover the entirety of the Salish Sea and its watersheds. Further details of land ownership and management can be found in the interactive maps in the Land Ownership chapter of the Salish Sea Atlas (Flower, 2022).

Figure 2. Watersheds and land cover of the Salish Sea bioregion. The three component estuarine water bodies (Strait of Juan de Fuca, Strait of Georgia, and Puget Sound) and the major cities are shown. The watershed extends into the upper Fraser River Basin, which has been omitted for clarity. Based on 30 × 30-m resolution satellite imagery from 2015; figure adapted from Sobocinski (2021). More detailed land cover data can be found in the Land Cover chapter of the Salish Sea Atlas (Flower, 2021).

The physical characteristics of the watersheds and estuarine subbasins shape the complex oceanography and biota within them (Geyer and Cannon, 1982; Sobocinski, 2021). The high productivity of biota in the Salish Sea is driven by abundant nutrients, specifically nitrogen, entering the sea from Pacific Ocean water (Mackas and Harrison, 1997; Davis et al., 2014). This nitrogen-rich water mixes with surface waters as it circulates from the entry in the Strait of Juan de Fuca throughout the Strait of Georgia and Puget Sound basins (Khangaonkar et al., 2017; MacCready et al., 2021). These nutrients, along with those from the rivers, are the raw material with which phytoplankton and microplankton build their cell walls, forming the base of an extensive food web that includes iconic species such as Pacific herring (*Clupea pallasii*), Pacific salmon (*Oncorhynchus* spp.), killer whales (*Orcinus orca*), bald eagles (*Haliaeetus leucocephalus*) and countless other interconnected species on which these icons depend.

The geological characteristics and complex oceanography within the Salish Sea contribute to variation in ecosystem response to anthropogenic change. The circulation and tidal processes that control the exchange and mixing of oceanic and freshwater are critical for biological production but also play a central role in the severity and local variation in environmental problems in the region, such as hypoxia, pollution, ocean acidification, and other climate change impacts (Sutherland et al., 2011; Khangaonkar et al., 2018). This oceanography along with the geomorphology of the Salish Sea as a deep, well-mixed, fjordal estuarine system have meant that it faces fewer of the system-scale impacts, like sedimentation and eutrophication, that other urban estuaries like Chesapeake Bay have faced (e.g., Kemp et al., 2005). Thus, generalizing both the problems and the solutions across the Salish Sea is challenging.

Urbanization induces primarily localized impacts, while climate change stemming from greenhouse gas emissions intensifies global impacts. Like other urban seas, the Salish Sea is already experiencing effects of global climate change, including changing precipitation regimes and freshwater delivery (Mauger et al., 2015), increasing sea water temperatures (Amos et al., 2015), declines in dissolved oxygen (Crawford and Pena, 2013), increasing ocean acidification (Bednaršek et al., 2020), and more frequent heat waves (Philip et al., 2021). Changes to the physical system are projected to intensify, even if CO_2 emissions were reduced drastically today. Physical models predict near-term effects of global climate change locally (Khangaonkar et al., 2019; MacCready et al., 2021), but the rapid pace of global climate change is altering local Salish Sea watershed hydrology and the global oceans in ways that may fundamentally alter circulation and mixing processes within the Salish Sea (Newton et al., 2003; Khangaonkar et al., 2019). This circulation and mixing have been key to mitigating many of the urbanization impacts in the Salish Sea (e.g., minimally treated sewage input, sedimentation from development; Johannessen et al., 2015).

Our understanding of organismal responses to oceanographic changes remains incomplete. Nonetheless, recent studies have shown that rising seawater temperature increases susceptibility of organisms to marine diseases (Harvell et al., 2019; Burge and Hershberger, 2020; Groner et al., 2021) and amplifies bioaccumulation of contaminants (Alava et al., 2018). Without a doubt, many effects are occurring simultaneously and, in some cases, synergistically (Cabral et al., 2019). How interactions among organisms and ecosystem processes are affected by the converging stressors from global climate change and urbanization into the future remains a key question locally and globally in urban seas, the answers to which will depend upon climate, topography, oceanography, and freshwater inputs (the physical system) further modified by unique histories of anthropogenic stressors within a given system.

Historically, the Salish Sea has been a productive estuary, but growing urbanization and increasing degradation threaten the persistence of many species and ecosystem processes. For over 10,000 years, Indigenous peoples on the Pacific Northwest coast have cultivated relationships of reciprocity with the sea and relied on its abundance of natural resources (Lindo et al., 2017; Toniello et al., 2019; Atlas et al., 2021). Between the 1770s and 1870s, settlers in search of the Northwest Passage, otter pelts, gold, timber, and salmon established what is currently British Columbia in Canada and Washington in the United States, displacing Indigenous peoples and dispossessing them of their lands and waters. In this same era, settlers drew the land and marine borders between the United States and Canada (**Figure 1**) and established the major cities of the region—Vancouver, Victoria, Seattle, Tacoma, and Olympia—transforming the Salish Sea into an urban sea. Today, these cities and the wider region are home to almost nine million people, and rapidly growing as the metropolitan areas of Seattle and Vancouver continue to prosper economically (Cappellano et al., 2021).

Like other urban seas, the Salish Sea is a multijurisdictional sea with connections across the world through major ports and other global industries. The sociopolitical and governmental configurations between 80+ sovereign Indigenous nations, Canada, and the United States and numerous smaller municipal jurisdictions contribute to differences in environmental policy across the border and across scales, as well as differences in Indigenous rights and co-management models (**Figure 1**). This complexity adds challenges but also creates unique opportunities for shaping a future urban sea that is more sustainable, just, and resilient.

The Salish Sea is notable among global urban seas for its relative health, with sustainable shellfish harvests, clear waters for boating and scuba diving, numerous species of fish and wildlife, and, thus far, resilience to urbanization and climate change stressors, due in part to its nature as a deep fjordal estuary with strong input of ocean water and high rates of mixing. Its more recent colonization and industrial urbanization make it a relatively young urban sea, with newer urban centers and much coastline remaining relatively undeveloped. Balanced against these positive signs is the drumbeat of warning signs: disappearing kelp beds (Berry et al., 2021), seagrass meadows threatened by disease (Groner et al., 2021), endangered resident orca whales (Wasser et al., 2017), changed flow in the Fraser River (Shrestha et al., 2012), habitat loss in its delta (Kehoe et al., 2020) and in the deltas of many other important rivers and streams (Brophy et al., 2019), and declining salmon runs (**Figure 3**; Losee et al., 2019; Pearsall et al., 2021), which exhibit lower marine survival in stocks from within the urban sea than from those outside. Salmon are an iconic species within this ecosystem and have been integral to Indigenous community identities for thousands of years; their decline is an important indicator of ecosystem change and one that integrates stressors across the urban estuarine landscape (Hodgson et al., 2020) and serves as an opportunity for innovative and time-tested management solutions (Atlas et al., 2021).

The industrial human footprint locally and globally brings with it stressors that threaten the resilience of the urban sea ecosystem through a complex array of legacy, continuing, and emerging impacts associated with industrialization, urbanization, and global trade (Izaguirre et al., 2021). These stressors collectively manifest as cumulative ecosystem impacts in the Salish Sea (**Figure 4**) as in other urban seas, with variable degrees of ecosystem degradation depending upon historical and current severity of impacts. There currently exists a gradient of impact in the Salish Sea, from the heavily urbanized waterways of the Duwamish River near Seattle to less-populated regions in the northern Strait of Georgia that have seen extensive logging but relatively little coastal development. This gradient can serve as a natural experiment in ecosystem response. Disentangling causes and specific solutions will only become more challenging as stressors continue to

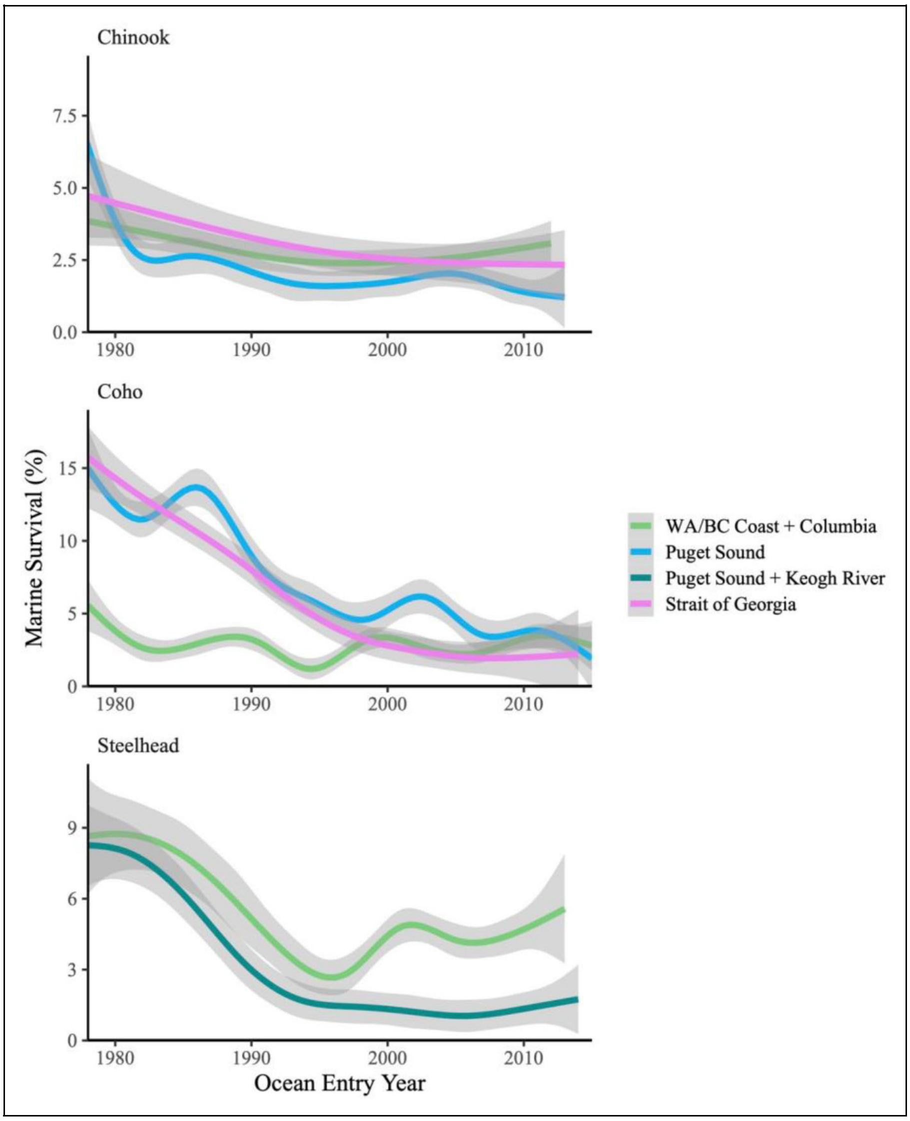

Figure 3. Salmon stocks in decline. In part due to declining marine survival, especially in the Salish Sea, salmon populations have declined in recent decades. Marine survival trends for Chinook salmon (*Oncorhynchus tshawytscha*, top panel) and Coho salmon (*O. kisutch*, middle panel) in Puget Sound (blue), Strait of Georgia (pink), and outside of the Salish Sea along the Washington (WA)/British Columbia (BC) Coast and the Columbia River (green) and for steelhead (*O. mykiss*, bottom panel) in Puget Sound and the Keough River of Vancouver Island (teal). A smoothing function (colored line and gray envelope showing confidence interval from a generalized additive model of survival as a function of ocean entry year) was applied to illustrate trends. All panels span ocean entry years 1978–2015. Underlying data as described in Zimmerman et al. (2015), Kendall et al. (2017), Ruff et al. (2017), and Sobocinski et al. (2021). Used with permission from Pearsall et al. (2021).

intensify. Compounding ecosystem dynamics are the parallels of socio-political complexity in management and governance. The Salish Sea shares both the ecosystem degradation and the complexity of solutions for repair and restoration with other urban seas; people who appreciate, study, and manage urban seas around the globe contend with similar issues like impaired water quality, contaminants, and overfishing, most of which are being exacerbated by global climate change.

3. Similarities across urban seas

Among urban seas worldwide, the Salish Sea remains a relatively robust and resilient ecosystem, supported by the dynamics of circulation and evidenced by standout features like extant resident orca whale populations. But there are relentless threats and pressures on the Sea, as there are on other urban seas (Kennish, 2002; Kemp et al., 2005; Cloern and Jassby, 2012; Freeman et al., 2019) and its future health is anything but certain, with most indicators of ecosystem condition failing to improve or declining (U.S. Environmental Protection Agency, 2021). If even a global exemplar like the Salish Sea is in peril, then clearly urban seas worldwide need significant attention, action, and transformation to survive, thrive, and support healthy coastal communities.

Many urban seas across the globe share common stressors threatening ecosystem function. These include loss of structured habitats like seagrasses, oyster reefs, and

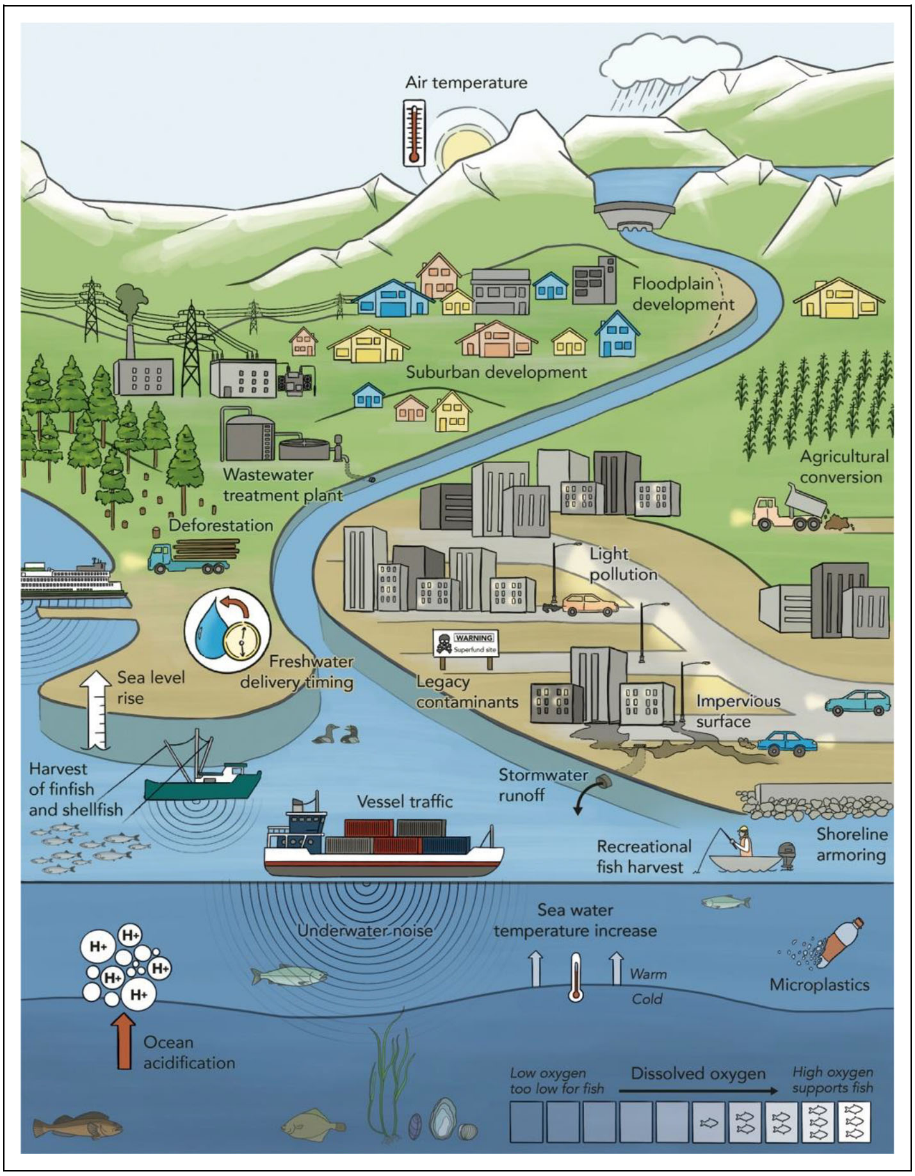

Figure 4. Cumulative impacts to the Salish Sea. Similar to other urban seas, a combination of local stressors caused by urbanization and global stressors from intensifying climate change bring cumulative impacts to the Salish Sea. Stressors in the Salish Sea are depicted here but all are generalizable to other urban seas (see **Table 1**). The cumulative impacts of multiple interacting stressors include histories of previous landscape and seascape uses as well as current impacts. Image: Emily M. Eng for the Salish Sea Institute, Western Washington University.

macroalgae; contamination from stormwater and wastewater run-off; loss of connectivity between uplands and the intertidal zone from development, dams, dikes, and dredging; overfishing; altered freshwater inflow; and light pollution, underwater noise, and other impacts resulting from the vibrant cities and their populations bordering these urban seas. These problems are worth highlighting in recognition that large scale solutions (beyond local and regional jurisdictions) may be needed to mitigate further degradation in the Salish Sea and other urban seas. Solutions will need to be reflective of and responsive to the unique ecological and political systems of their specific contexts, but the problems facing urban seas, and their solutions, are generalizable to some extent, and all must contend with global effects of climate change.

Global environmental stress is concentrated and compounded in urban seas—impacts from the landscape and seascape converge in coastal regions, the very regions that emerged as economic hubs because of their physical and biological characteristics that enabled ports, maritime industries, fishing to feed local and global populations, and commerce. At the same time, the solutions to these problems also lie within these very watersheds: science and academia, Indigenous nations and knowledge systems, industry, and government centers, all with skilled environmental professionals concentrated in and connected to urban sea city centers. By attending to the unique issues facing urban seas, possibilities can emerge for localized solutions as well as transferable and shared knowledge and approaches.

4. Boundary-spanning solutions

Our recent detailed synthesis of the Salish Sea (Sobocinski, 2021) recognized many existing efforts and recommended broad areas of focus to mitigate future losses and open opportunities toward revitalization and resilience. These solutions are applicable more broadly, and an intense focus on urban seas as a domain of study and experimentation may provide novel approaches in science, technology, human dimensions, governance, and socio-environmental-systems understanding that address the specific needs for urban sea recovery. Effective policies could benefit similar systems throughout the world. The growing intensification of change in urban seas necessitates urgency and large-scale investment. Here we offer three broad domains for solutions.

4.1. Data collection, curation, and integration using a systems approach in science and management

Collection, curation, and integration of data is essential for understanding the ecosystem services upon which we depend, from fisheries to climate buffering. Spatially and temporally detailed data are essential for detecting change, inferring significance, and planning and/or mitigating for future stressors. But these data sets require sustained investment and are currently not available for many key ecosystem indicators. Transboundary regions such as the Salish Sea present additional challenges related to organizing and harmonizing data collection and dissemination across multiple jurisdictions. Combining datasets from disparate sources is sometimes impossible due to spatial, temporal, and conceptual mismatches in how the data were collected, recorded, and distributed. Leveraging creative, collaborative partnerships and new technologies to collect data over longer time periods and across larger spatial scales, and to manage and disseminate those data, will allow better understanding of climate change and local human impacts (Pendleton et al., 2020; NASEM, 2022).

Ongoing modeling work throughout the Salish Sea, from the open ocean to the headwaters of our streams and rivers, is bringing together data, computing power, and technical expertise to better understand oceanographic processes and ecosystem responses. These models are the foundation of understanding human impacts like eutrophication, ocean acidification, and hypoxia (Khangaonkar et al., 2017; MacCready et al., 2021). But they must be informed by up-to-date data, with relevant temporal and spatial coverage. Investing in and maintaining sensors, cabled and autonomous, and systems and structures for data processing and dissemination is critical (Whitt et al., 2020).

As physical models continue to improve, modeling tools are needed to incorporate the multiple simultaneous, cumulative, and rapid impacts on the Salish Sea. To become truly powerful and integrative, models must incorporate the transboundary, social-ecological system at multiple levels of spatial and temporal complexity (Bograd et al., 2019). This integration is currently limited by methodology and computational power (Steenbeck et al., 2021), but these are not insurmountable obstacles. Innovation in model integration and application would be beneficial to urban seas around the world.

Systems approaches involve viewing ecosystems and human relationships as parts of an overall complex dynamic system, with history, nested connections, and a multitude of interactions and feedbacks (Levin, 1998). The challenges associated with environmental management are similar to those associated with any complex, large-scale, constantly evolving, difficult-to-define problem ("wicked" problems, *sensu* Rittel and Webber, 1973). These problems are rarely solved with simple solutions (Ostrom, 2007). Urban seas and the cumulative challenges they experience are prime examples of the need for a systems approach (Klinger and Newton, 2016).

To address the dynamic, non-linear, and cumulative effects of urbanization and climate change in urban seas, we must go beyond compartmentalized solutions. Addressing any single component in isolation is a failure to appreciate the compounding impacts in systems increasingly subjected to new stresses layered on top of compromised resiliency from previous eras (Levin et al., 2013). For example, in the Salish Sea, stormwater run-off laden with contaminants is interacting with foodwebs that are responding to both acute and protracted bottom-up changes in ocean physics and for which apex predators, like salmon and orcas, are changing. Integrating diverse, cross-disciplinary data streams and developing modeling techniques that cross knowledge domains will be necessary to assess and respond to cumulative stresses.

4.2. Place-based knowledge to sustain community-based action

As a result of development in urban seas, structured habitats have been lost throughout the landscape and seascape. Loss of habitats and their ecosystem services are an underlying cause of declines in valuable biota, once plentiful in many coastal ecosystems. In order to re-build and maintain resilience, especially at the land-sea ecotone where infrastructure exacerbates problems of rising sea level, we must understand, conserve, and recover valuable aspects of our ecosystems. Place-based research and knowledge systems, including historical ecology and Indigenous ways of knowing, can be utilized creatively and productively to inform conservation and restoration initiatives to target culturally relevant places (Poe et al., 2016) and to counteract shifting baseline syndrome (Pauly, 1995).

Climate change education and research is intensifying worldwide, preparing next generations of scholars and scientists to understand and intervene in global change processes and impacts. This work is essential and, we argue, must be paired with intentional place-based education and research to ensure that the specificities and contexts of local places, ecosystems, and sociopolitical configurations are reflected in climate change solutions at different scales.

For millennia in the Salish Sea, Coast Salish Indigenous peoples developed relationships and systems in place, nourished and sustained through ecocultural modification practices, cultural exchange, and knowledge systems.

Deep ecocultural ways of knowing are not universally shared by newcomers. Dedicated place-based educational initiatives for people moving to the Salish Sea because of global climate migration and/or economic pushes and pulls are critical. Otherwise increasing numbers will be unfamiliar with the values and sensitivities of the ecosystem, thereby limiting the future pool of inspiration and implementation of ecosystem-based solutions. Additionally, meaningful relationships are central to effective systems, and place-based and community-connected learning can facilitate relationship-building across disciplines, sectors, and organizations.

Investment in intentional Salish Sea-wide place-based education to tie the current community to its history and ecology is critical for building connectivity and familiarity with its cultural, political, and environmental complexities. These same approaches are relevant to urban seas around the world. Education initiatives from pre-K to graduate-level curricula to community approaches aimed at newcomers will increase ecosystem literacy and create stronger ties with the lands and waters around us. Building knowledge, relationships, and connections through place-based learning must happen in tandem with robust support for Indigenous communities to build capacity for ecocultural restoration as the region's original knowledge keepers and environmental stewards.

Place-based education initiatives will also build capacity to link next-generation data streams to regional feedbacks (e.g., "report cards" like Ocean Watch: Miller et al., 2020; and Vital Signs: Puget Sound Partnerships, 2022), which in turn can accelerate awareness, investment, and action. Experience within an ecosystem can generate awareness and mitigate environmental amnesia and the continued acceptance of progressive environmental degradation (Soga and Gaston, 2016). Opportunities for connecting people with urban seas outside of formal education settings can engage a variety of regional partners such as public aquaria, park systems, museums, and leisure and tourism ventures such as whale watching, cultural tours, and sportfishing. Supporting people to learn about the urban seas around them—not as backdrops to their lives but as dynamic, relational sites of ecocultural community—is a central element in transformative systems change through cultural shift.

4.3. Science and policy must align with ecosystem boundaries

Many urban seas span political boundaries. Differing jurisdictions and related governance, and thus science funding and focus, are barriers to cohesive science agendas and actionable policies. There is a need to prioritize cross-border ecosystem-scale work, engaging decision-makers at the highest levels in a shared effort to understand emerging and persistent concerns. To increase formal collaboration and provide a groundwork for shared methods and initiatives, in our system we recommend the formation of a Salish Sea Science Panel, with positions for scientists from bioregional universities, agencies, and communities from British Columbia, Washington State, and Indigenous Nations. The panel should identify and develop large-scale actionable science needs and priorities for the Salish Sea urban estuary. The scale of science and environmental policy must align with ecosystem boundaries.

Other urban seas already benefit from similar overarching, cross-jurisdictional efforts. The suggestion for the Salish Sea is modeled on an example from the Baltic Sea (Säre, 2020). There, the Helsinki Commission was formed to foster intergovernmental cooperation. Within this commission, representatives from governments and sectoral agencies of nine countries, the European Union, and researchers, experts and environmental organizations have been cooperating toward management within the Baltic Sea (Valman et al., 2015). Analysis of other examples from around the world can contribute to a repository of tools and knowledge to support ecosystem-based adaptive management and decision-making that can transcend political borders.

In addition to multiple ecosystem stresses, a primary contributor to the wicked problem of urban sea recovery is the multiplicity of actors (landowners, stakeholders) and levels of governance (from Indigenous nations to municipal to state/provincial to federal), many of them overlapping on the same parts of the seascape (Imperial et al., 2016; Parrot, 2017). But this challenge may also be a benefit, with numerous invested Indigenous groups, agencies, community organizations, and educational institutes already in place. Building a better future will require developing creative configurations and transformative solutions (Bennett, 2019), leveraging the ways societies, economies, and ecosystems are linked across scales—and in the Salish Sea and many other urban seas, across international borders. Ecosystem processes rarely exist along the same lines as political borders: aligning the scale of action is critical to system-scale, transformative change.

5. Conclusion

Urban seas are acute and tangible examples of human-induced changes taking place on the edges of our global ocean system—they are the nexus for human-ocean relationships. Climate change presents an intensifying challenge to planning for both protection and restoration. Mechanisms underlying resilience to global change that can be influenced by management-ready actions must be identified and tested (Kroecker et al., 2019). Existing functional habitats that have withstood pulse perturbations, like heat waves, should be prioritized for conservation, with attention paid to preventing further erosion of ecosystem structure and function. Spatial analyses can reveal habitats resilient to climate stress and culturally significant places (Cuerrier et al., 2015; Poe et al., 2016) to prioritize as sites to preserve. Moving forward, investments in mitigating climate impacts also present opportunities for restorative work. Positive, protective, restorative, and regenerative actions are increasingly necessary as stresses compound in urban sea ecosystems.

In recognizing the importance of functional urban seas, billions of dollars have been expended trying to repair these ecosystems, but it is not enough. In many cases, restorative change has been slow and incomplete, existing protections are outpaced by development, and decline continues, further jeopardizing both ecosystem function and potential actions that could right the course. At the same time, the climate change juggernaut is rapidly outpacing current protections and restorative actions. We must persevere and continue to invest in research and long-term monitoring to fully understand impacts, and also foster investment, decision-making, education, and policies that take real steps toward change.

Owing to the high concentration of anthropogenic activities, urban seas represent ideal natural laboratories to study the well-defined, intense chemical/biological gradients involved in the proximal impacts of high-density population in marginal sea marine ecosystems. Many urban seas have been the subject of rich research over the last century (Geyer and Cannon, 1982; Officer et al., 1984; Kennish, 2002; Lotze, 2010; Cloern and Jassby, 2012; Cabral et al., 2019; see also **Table 1** for sea-specific examples), and that understanding must be coupled with innovation in science and management, local ocean literacy, and bold policy actions at appropriate scales to reverse decline.

The Salish Sea stands as a preeminent global example of a system on the precipice: its future is in our hands. With more than 10,000 years of knowing from Indigenous peoples and a dedicated network of educators, scientists, policy makers, and communities, the Salish Sea represents a priority testbed for transdisciplinary solutions, integrating across socio-environmental domains, jurisdictional borders, science disciplines, and policy arenas to envision a systems approach to environmental sustainability in the most precarious area of our global ocean. Salish Sea scientists and managers can learn from examples of more degraded global urban seas to anticipate future declines and identify innovative solutions, reciprocating with transferable and adaptable approaches for urban sea management more broadly. An opportunity exists to demonstrate that salmon and orcas can persist in proximity to major metropolitan cities, but it will take more international cooperation, uplifting of Indigenous rights and sovereignty, and collaborative commitment to recovery. While there are strong signals of diminished ability to thrive today, with the investment of money, community knowledge, and bold action that questions the cost of doing business as usual and makes fundamental change at the land-sea interface now, this urban sea can be a leader in coastal solutions.

As a critical nexus of human-ocean systems, urban seas must be target areas for proactively managing the twin threats of urbanization and climate change. Fundamental to the toolkit of this work will be engaging a systems approach in science and management through data integration, implementing place-based education initiatives to sustain community-based action, and aligning science and policy with ecosystem boundaries. By prioritizing the hotspots of the Anthropocene ocean and making large-scale investments in urban sea renewal worldwide, we can decelerate decline and open different futures.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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