



## Review

# Advancing an integrated understanding of land–ocean connections in shaping the marine ecosystems of coastal temperate rainforest ecoregions

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### Abstract

Land and ocean ecosystems are strongly connected and mutually interactive. As climate changes and other anthropogenic stressors intensify, the complex pathways that link these systems will strengthen or weaken in ways that are currently beyond reliable prediction. In this review we offer a framework of land–ocean couplings and their role in shaping marine ecosystems in coastal temperate rainforest (CTR) ecoregions, where high freshwater and materials flux result in particularly strong land–ocean connections. Using the largest contiguous expanse of CTR on Earth—the Northeast Pacific CTR (NPCTR)—as a case study, we integrate current understanding of the spatial and temporal scales of interacting processes across the land–ocean continuum, and examine how these processes structure and are defining features of marine ecosystems from nearshore to offshore domains. We look ahead to the potential effects of climate and other anthropogenic changes on the

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**Author Contribution Statement:** Contributions follow CRediT designations: Funding acquisition: A.B., E.H., and B.P.V.H. Conceptualization: B.P.V.H., A.B., H.D., and C.T.E.K. Writing—original draft: B.P.V.H., S.A., A.B., H.D., J.M.J., C.T.E.K., P.K., K.A.St.P., A.H.-D., and C.A.V. Writing—Review & Editing: B.P.V.H., S.A., A.B., H.D., J.M.J., C.T.E.K., P.K., K.A.St.P., E.C., W.C.F., E.H., A.H.-D., C.L., and C.A.V. All authors contributed to the article and approved the submitted version.

coupled land–ocean meta-ecosystem. Finally, we review key data gaps and provide research recommendations for an integrated, transdisciplinary approach with the intent to guide future evaluations of and management recommendations for ongoing impacts to marine ecosystems of the NPCTR and other CTRs globally. In the light of extreme events including heatwaves, fire, and flooding, which are occurring almost annually, this integrative agenda is not only necessary but urgent.

Marine ecosystems are inextricably linked to the terrestrial environment through bi-directional land–ocean connectivity. This connectivity predominantly operates in a seaward direction through the delivery of freshwater and terrestrial materials to the marginal oceans found along coastlines globally. In addition, coastal bathymetry structures ocean circulation, affecting cross-and-along-shelf and upwelling or downwelling currents (Washburn and McPhee-Shaw 2013). Similarly, topographic relief on land influences near atmospheric circulation and moisture transport, for example, orographic effects (Albano et al. 2020). These factors interact to give marginal oceans distinct hydrodynamic and biogeochemical properties, and make them global hotspots for marine productivity, reflected in high primary producer biomass and fisheries yields (Ware and Thomson 2005). However, among marine environments, marginal oceans are uniquely vulnerable to human impacts, with approximately 40% of the human population living within 100 km of the coast (Martínez et al. 2007). Globally the land–ocean meta-ecosystem (Loreau et al. 2003) in marginal oceans is under threat from the cumulative effects of climate change and anthropogenic impacts associated with human settlement and development (Lotze et al. 2006), which change and disrupt critical land–ocean linkages, for example, the timing and volume of freshwater and material flux (Scavia et al. 2002; Ramesh et al. 2015; Fang et al. 2018). An integrated understanding of land–ocean connections and feedbacks is essential for predicting, managing and mitigating impacts on marginal oceans, and preserving their essential ecosystem functions (Ward et al. 2020; Bidlack et al. 2021).

Coastal temperate rainforest (CTR) regions of the world lie in the path of westerly wind storm tracks and are characterized by exceptionally high freshwater (Neal et al. 2010; Morrison et al. 2012; Hill et al. 2015) and material fluxes (Oliver et al. 2017; Edwards et al. 2021). These fluxes create particularly strong land–ocean connections (Cuevas et al. 2019; Marshall et al. 2021). Examples of CTR-influenced marginal oceans can be found on all continents except Antarctica (Fig. 1; Alaback 1991; DellaSala 2011). The coastal margins of many CTRs have complex, mountainous coastlines dominated by fjords and island archipelagos, high seasonality, high precipitation (often in the form of snow), high runoff, and large stores of above- and below-ground organic carbon. Together, these factors make for some of the highest watershed yields of sediment, carbon, nitrogen, phosphorus, and iron in the world (Oliver et al. 2017; Edwards et al. 2021; St. Pierre et al. 2021). As a general rule,

CTR coastal margins span wide latitudinal ranges which, together with their highly dissected and high-relief topography, promotes spatial variability of microclimates, glaciation, hydrology, plant communities, estuaries, and nearshore marine ecosystems (Callaway et al. 2012). Such variability is challenging to measure and averages over regional scales are unlikely to accurately represent most locations.

To date, most of the hydrological land–ocean interface research in CTR regions has focused on single, large river plumes (Hickey et al. 2010; Kastner et al. 2018) and large glacial watersheds and fjord systems (Vargas et al. 2011; Arimitsu et al. 2018), in part because of the local importance of these systems and their typically rapid response to climate change (Svendsen 1995; González et al. 2013; O’Neel et al. 2015; Bianchi et al. 2020). However, recent analyses have demonstrated that, collectively, small watersheds (mean watershed size of 118 km<sup>2</sup>) can contribute more than half of the freshwater volume transported from land-to-ocean in CTR regions despite comprising only a fifth of the watershed area (Morrison et al. 2012; Hill et al. 2015; O’Neel et al. 2015; McNicol et al. 2023). It is therefore likely that small watersheds have a significant influence on coastal hydrodynamics in these regions. Small CTR watersheds have also been shown to have high dissolved organic carbon loads (Oliver et al. 2017), in addition to high dissolved nitrogen and iron (St. Pierre et al. 2021), and they may therefore play a disproportionate role in regional land–ocean linkages. Importantly, the timing and duration of seasonal discharge events from small watersheds differ from large watersheds in CTR regions, and this requires adjustments to existing conceptual frameworks for marine ecosystem effects (Wheatcroft et al. 2010; Basdurak et al. 2020). The local and cumulative effects of discharge from small watersheds on CTR marine ecosystems remain important knowledge gaps. A multi-scale conceptual framework for CTR interface dynamics at the ecosystem level would be an important step toward understanding these land–ocean systems and how they respond to perturbations.

In this review we aim to advance the understanding of marine ecosystems in high-discharge CTR ecoregions by bridging traditional land–ocean disciplinary divides and building a common understanding of physical, biogeochemical, and ecological processes. Making sense of marine ecosystem dynamics in the presence of complex geographic and geochemical gradients along continental margins is challenging, yet important, because of the acceleration of long-term climatic trends and the expanding human footprint affecting these systems (Kunkel et al. 2013; Ramesh et al. 2015). Using the largest



**Fig. 1.** Global distribution of coastal temperate rainforest indicating latitudinal range and areal extent (km<sup>2</sup>) based on DellaSala (2011).

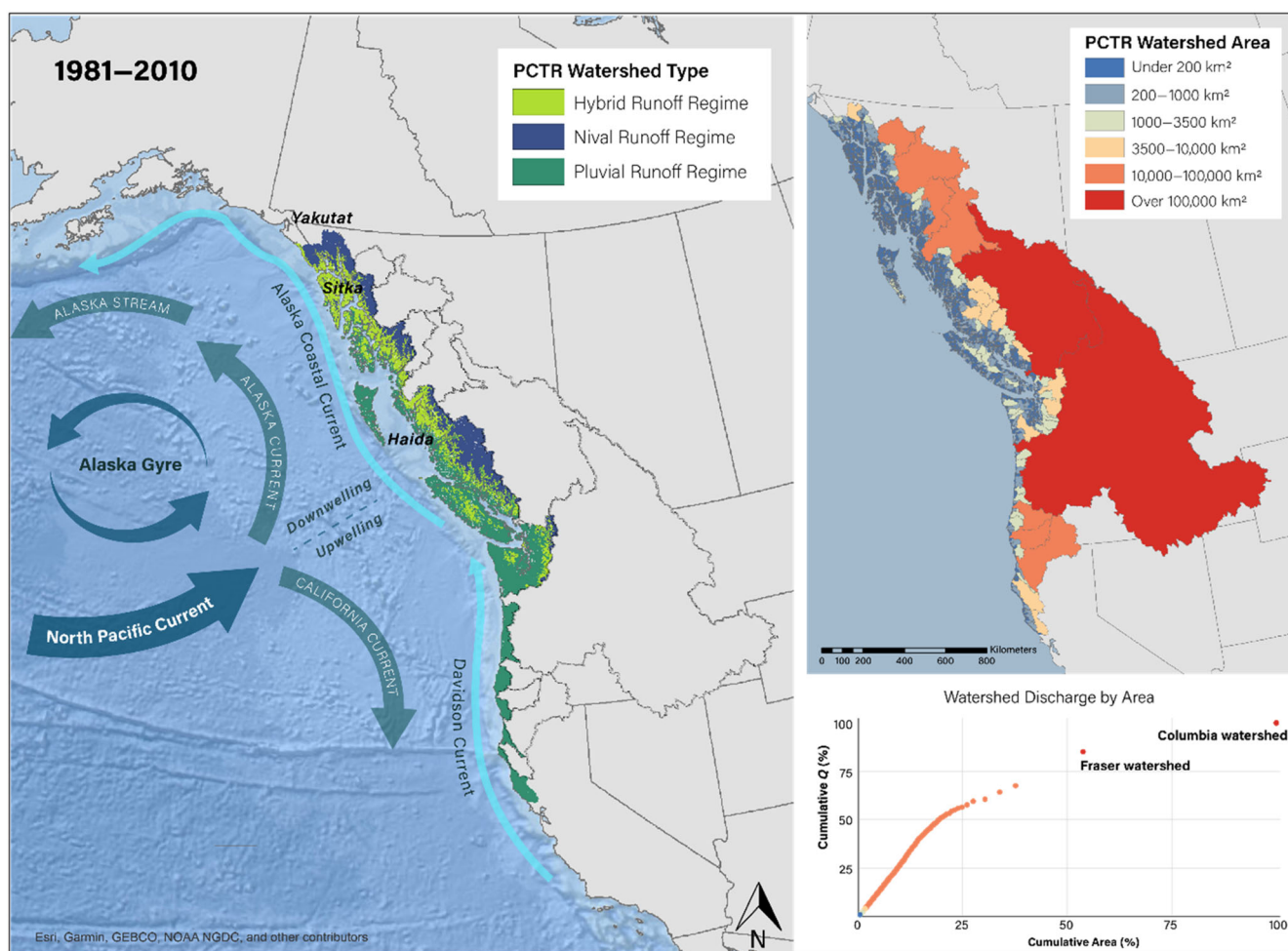
contiguous expanse of CTR on Earth—the Northeast Pacific CTR (NPCTR)—as a case study (Fig. 1), we integrate current understanding of the spatial and temporal scales of interacting processes across the land–ocean continuum, and examine how these processes structure marine ecosystems from near-shore to offshore domains. We do so through the lens of three interconnected aspects of marine ecosystems—circulation dynamics, biogeochemical cycling, and food webs—with emphasis on the fate and effects of freshwater discharge and its associated terrestrial materials. We first identify the key features of the terrestrial and marine ecosystems of the NPCTR; then summarize the major freshwater and material exports; and finally trace their fate and ecosystem effects as they are transported across marine habitats along gradients from the nearshore to the inner coast, continental shelf, and off-shelf open ocean regions. In doing so we advance a generalizable conceptual framework of CTR systems, and then look ahead to the potential effects of long-term environmental trends, climate and other anthropogenic changes in terrestrial systems on CTR marine environments. Finally, we review key data gaps and provide research recommendations that we hope will guide future evaluation of ongoing impacts in the NPCTR and other CTRs globally.

## ***The Northeast Pacific coastal temperate rainforest region***

### **Terrestrial environment**

An overview of the Northeast Pacific CTR (NPCTR) ecoregion was provided in Bidlack et al. (2021), and here for context we summarize key features relevant to the land–ocean interface. The perhumid and seasonal NPCTR stretches south from the Alsek River in Alaska to the Eel River in California, spanning a distance of more than 2000 km, a latitudinal extent of ~ 22°, and a gradient of climates from subpolar to temperate (Fig. 2). Historically, mean annual air temperature at sea level increased roughly 6°C from north to south, averaging 5.6°C at the northern end in Juneau, Alaska, and 11.6°C at the southern end of the region in Eureka, California.

The NPCTR has the highest annual precipitation of any ecoregion in North America (to > 5000 mm annually), largely driven by moisture transport across the Pacific and orographic effects (Bidlack et al. 2021). The presence of seasonally stored snow and ice generally increases northwards to create a latitudinal gradient in the relative runoff contribution of rain-dominated (pluvial, with peak discharge during winter), snow-dominated (nival, with peak discharge during spring and fall),



**Fig. 2.** (Left panel) Map of the Northeast Pacific showing the major ocean currents and circulation pathways, and primary hydrologic regime (pluvial, nival—includes glacial melt—and hybrid) types of coastal watersheds from 1981 to 2010 following Bidlack et al. (2021). (Top right panel) Distribution and areal extent (km<sup>2</sup>) of watersheds in the North Pacific Coastal Temperate Rainforest region. (Bottom right panel) Cumulative watershed area vs. cumulative discharge using a composite of measured and modeled discharge (figure derived using data from McNicol et al. 2023).

and glacial (peak discharge during late summer) coastal watersheds (Fig. 3). This gradient of watershed hydrology and climate imposes a seasonal outflow cycle that, in NPCTR watersheds, is largely coupled to winter rainfall in the south and increasingly coupled with spring/summer snow and ice melt toward the north (Morrison et al. 2012). The NPCTR watershed outflows merge with contributions from large continental watersheds that drain lands east of the NPCTR, characterized by snow and ice melt driven spring/summer “freshets.” In Alaska, tidewater glaciers directly connect the terrestrial cryosphere to marine ecosystems; however, the NPCTR is losing glacier mass at one of the highest rates globally (Gardner et al. 2013).

The coastal morphology of the NPCTR is diverse, and watersheds interface with the coastal ocean across an array of habitat types. The coastlines of California, Oregon, south and central Washington, and northern Gulf of Alaska are relatively

linear and watersheds discharge into exposed shelf environments. By contrast, the coastlines of southern Alaska, British Columbia, and the waters of Puget Sound, Washington, are complex, deeply incised by fjords, and intermeshed with channels and islands. Here the “inner coast” bathymetry can be substantially deeper (up to > 700 m) than the continental shelf (~ 150 m), and the deep fjords, sills, and channels complicate the hydrodynamic connection to the shelf. In such complex environments, local processes including estuarine circulation, tidal mixing, and local and regional winds play important roles in coastal circulation and water modification (Thomson 1981), and hence are important in mediating land–ocean connections.

Prior to European contact and colonization, the NPCTR had one of the highest densities of First Nations settlements in North America (Wolf et al. 1995). First Nations maintained and enhanced habitat diversity and ecosystem productivity

through management practices across the land–ocean system (Turner 2007; Lepofsky and Caldwell 2013). Since European colonization, the NPCTR has been modified through industrial resource extraction in forests and oceans. The impact of these activities has not been evenly distributed. Much of the southern to central NPCTR has been extensively logged and this is reflected by subsequently higher rates of watershed development (Wolf et al. 1995). Urbanization is also greatest in the south to central NPCTR resulting in higher human-driven degradation of estuarine environments in this region compared to more northern expanses of the NPCTR (Robb 2014). Associated with development in the southern NPCTR has been extensive growth of hydropower, impacting the connectivity of aquatic habitats (Sheer and Steel 2006).

### Oceanographic environment

The oceanographic environment of the NPCTR is complex. The large-scale circulation of the northeast Pacific is dominated by the eastward-flowing North Pacific Current (NPC) that bifurcates near the central latitude of the British Columbia coast into the southward-flowing California Current and the northward-flowing Alaska Current (Freeland 2006). The Davidson Current flows northward along the coast toward British Columbia, inside and counter to the California Current, intensifies and reaches the surface during winter, and weakens and becomes an undercurrent in summer (Thomson 1981). The Alaska Current follows the shelf break, turns westwards in the northern Gulf of Alaska along the Aleutian Shelf where it narrows ( $\sim 50$  km) and intensifies into the Alaska Stream. Shoreward of the Alaska Current is the Alaska Coastal Current (ACC), a northward-flowing coastal-trapped buoyancy boundary current with a low salinity core (Royer 1982; Stabeno et al. 1995; Weingartner et al. 2005; Stabeno et al. 2016), forming as far south as northern California, in response to high freshwater discharge (Mazzini et al. 2014). Offshore in the Gulf of Alaska, the NPC, Alaska Current, and Alaska Stream bound the cyclonic Alaskan Gyre which is itself an iron-limited, high-nutrient, low chlorophyll environment (Martin et al. 1989; Boyd et al. 1998). South of the NPC, the offshore waters are a low-nutrient, low-chlorophyll environment.

The NPC bifurcation marks the transition from a strongly upwelling-dominated shelf to the south to a strongly downwelling-dominated shelf to the north (Whitney et al. 2005). Upwelling occurs as far north as Vancouver Island in the summer months in response to a seasonal shift to predominantly northwesterly winds, bringing nutrient- and carbon dioxide-rich and oxygen-poor waters onto the shelf and occasionally to the surface in the southern part of the NPCTR (Feely et al. 2008). Summertime relaxation of downwelling from northern BC to Alaska allows deep nutrient-rich waters to be transported upward onto the continental shelf by upwelling-favorable winds. However, in this region, wind or tidal mixing is required to bring deep water to the

surface (Stabeno et al. 2004; Whitney et al. 2005). The resulting elevated on-shelf macro- and micronutrient availability make the NPCTR shelf highly productive (Ware and McFarlane 1989; Stabeno et al. 2004; Ware and Thomson 2005; Hickey and Banas 2008).

A feature of the Alaska Current-influenced coastal margin is the regular formation of large ( $\sim 200$  km diameter, 500 m deep), long-lived (2–5 yr), anti-cyclonic (upwelling) eddies at, from south to north, Haida Gwaii, Sitka, and Yakutat (Crawford et al. 2007; Ladd et al. 2009). These eddies form on the continental shelf and move slowly westwards ( $2\text{--}3\text{ cm s}^{-1}$ ) into the Gulf of Alaska. An additional eddy system forms westward of the Strait of Juan de Fuca, at the northern extent of the California Current region. This Juan de Fuca Eddy is strongly influenced by the Fraser River outflow, and drives Fraser River waters westward across the shelf (MacFadyen et al. 2008).

### Freshwater and material inputs to the NPCTR marine ecosystem

#### Freshwater inputs

Terrestrial inputs to the coastal ocean are constrained by freshwater discharge and its biogeochemical constituents (i.e., the dissolved and particulate materials that it transports), although atmospheric dust can be a significant source of nutrients (Young et al. 1991; Crusius et al. 2011). Three key parameters influence freshwater delivery to the coast: (1) watershed geomorphology, including relief, which affects river flow velocity and precipitation; (2) discharge volume, and (3) the timing of seasonal events and transitions. Watersheds of the NPCTR can be broadly divided into two categories: the vastly larger systems originating east of the coastal mountains and the small systems originating in the coastal mountains themselves (Fig. 2). Large drainage systems ( $> 9000\text{ km}^2$ ) crossing the Cascade Mountain Range, such as the Columbia ( $685,292\text{ km}^2$ ) and Fraser rivers ( $235,396\text{ km}^2$ ), have high annual discharge (e.g.,  $211\text{ km}^3\text{ yr}^{-1}$  for the Columbia and  $112\text{ km}^3\text{ yr}^{-1}$  for the Fraser) that peaks during spring–summer snowmelt (Morrison et al. 2012; Shanley and Albert 2014). In contrast, discharge from those watersheds constrained only to the coastal margin contributes 60% of the discharge entering the ocean, despite only occupying 22% of the contributing area (McNicol et al. 2023). The exclusively coastal margin watersheds have a mean watershed size of  $118\text{ km}^2$  among delineated watersheds  $> 20\text{ km}^2$  (McNicol et al. 2023) and are more numerous ( $> 4000$  reported for SE Alaska alone; Sergeant et al. 2020). These small watersheds are typically pluvial or nival, but some are also partially glacierized and have a characteristic late-summer discharge peak due to melt (Morrison et al. 2012; Sergeant et al. 2020; Giesbrecht et al. 2022). Due to the steep topography of the NPCTR, specific discharge from the thousands of small coastal watersheds is high. Collectively, these watersheds make a disproportionate contribution

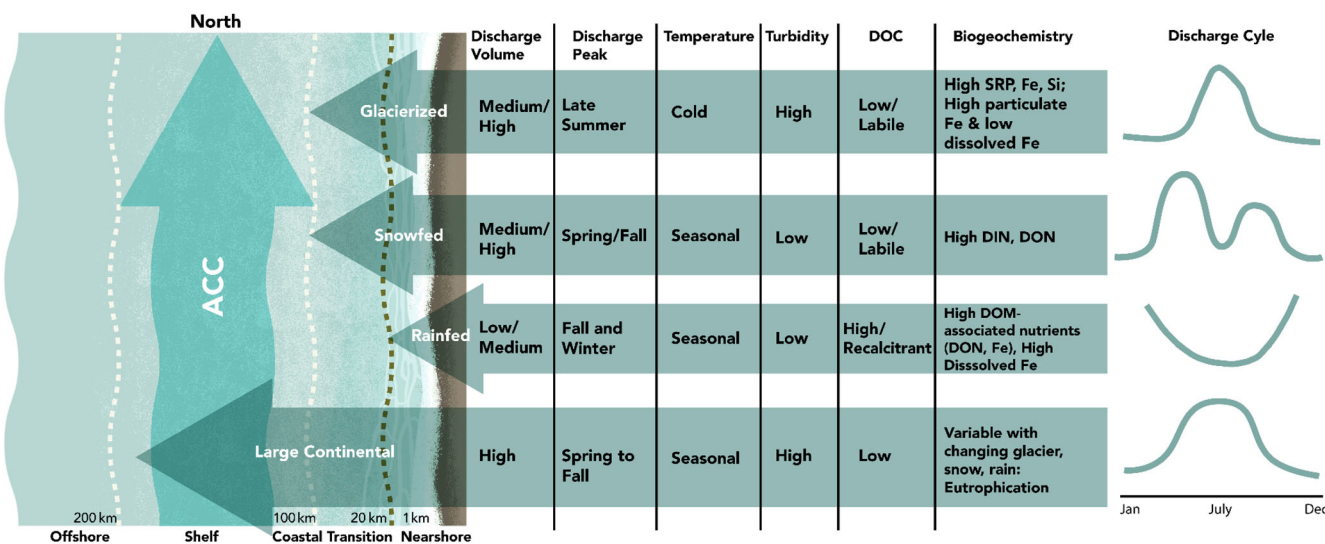
to freshwater in the ocean, approximating the annual runoff of the Mississippi River (Morrison et al. 2012; Hill et al. 2015).

### Material inputs

This review focuses on terrestrial inputs of dissolved inorganic carbon (DIC), organic carbon (OC), organic nitrogen (ON), macronutrients (nitrate—NO<sub>3</sub><sup>-</sup>, silicate—Si(OH)<sub>4</sub>, phosphate—PO<sub>4</sub><sup>3-</sup>), and dissolved and particulate iron (Fe). These material inputs, along with hydrological cycles and plume sizes are summarized in Fig. 3. NPCTR watersheds and estuaries have large stocks of above- and below-ground OC (Kauffman et al. 2020; Keith et al. 2009; McNicol et al. 2019), and the high rainfall contributes to high concentrations of dissolved organic carbon (DOC; <0.45 μm in diameter) relative to other ecoregions globally (D’Amore et al. 2015; Oliver et al. 2017; St. Pierre et al. 2020; Edwards et al. 2021). One modeling study suggests that the region is a global hotspot for watershed yield of particulate organic carbon (POC), as well as particulate organic nitrogen (PON) and phosphorus (Mayorga et al. 2010). Little attention has been given to other freshwater constituents. However, nitrogen and iron, which are potentially limiting in shelf and offshore waters, are closely associated with organic matter (OM) exported from small watersheds in the NPCTR (Sugai and Burrell 1984; Wetz et al. 2006; Hood et al. 2009; Fellman et al. 2021; St. Pierre et al. 2021).

The quantity and stoichiometry of inorganic nutrients and OM exported to marine ecosystems in the NPCTR are affected by watershed size and type, land cover (including vegetation), and configuration (Hood and Scott 2008; Fellman et al. 2014). For example, large watersheds, or watersheds with features such as lakes, dams, bogs or tidal

wetlands, have a higher potential than small watersheds for retention and biogeochemical transformation of terrestrial material prior to it reaching the coastal ocean (Gustavson 1975; Voss et al. 2015). Water and material residence time in the small, steep watersheds that cover much of the NPCTR is short and thus organic exports may include rapid pulses of untransformed, highly labile (bioavailable) OC and ON to the coastal ocean, particularly during storm events (Thom et al. 2018b; Fellman et al. 2021). The presence of land-terminating and tidewater glaciers strongly affects riverine biogeochemical exports. Glacierized watersheds can be intense physical and chemical weathering environments, typified by highly labile sediment loads, high inorganic nutrient exports (especially silica, phosphorus and iron), and low but labile exports of dissolved organic matter (DOM) derived from microbial activity (Anderson 2005; Whitney et al. 2005; Hood and Scott 2008; Schroth et al. 2011). Glacial discharge is also low in total alkalinity, which can simultaneously reduce calcium carbonate saturation states and either enhance or reduce the coastal uptake of atmospheric CO<sub>2</sub> depending on whether the glacier is land-terminating or tide-water (Evans et al. 2014; Reisdorph and Mathis 2014; Pilcher et al. 2018). One component of the land–ocean flux that we do not consider here is submarine groundwater discharge, which can represent a significant nutrient flux to the coastal ocean (Klinger and Erickson III 1997; Lu et al. 2015; Luijendijk et al. 2020; Santos et al. 2021). While surficial flows may have higher DOM concentrations, DOM in ground water discharge may be more labile (Inamdar et al. 2012). While subject to data gaps across much of the study area, recent research in the NPCTR suggests that submarine groundwater may contribute up to an order of magnitude



**Fig. 3.** Summary of the physical, hydrological and biogeochemical properties of watershed types (glacierized, snowfed [nival], rainfed [pluvial], and large continental), including the ocean extent of plumes across the nearshore, coastal transition, shelf and offshore zones. ACC, Alaska Coastal Current; SRP, soluble reactive phosphorus; Si, silicate; Fe, iron; DIN, dissolved inorganic nitrogen; DON, dissolved organic nitrogen; DOM, dissolved organic matter.

more nitrate than rivers (Lecher et al. 2016), primarily from the saline groundwater fraction driven by tidal action (Haag et al. 2023).

### ***Spatial and temporal scales of physical–ecological interactions at the marine–terrestrial interface***

The development of a conceptual framework for the role of freshwater and its biogeochemical constituents in marine ecosystem dynamics requires an approach that cuts across disciplinary (physical oceanography, geochemistry, biology) and domain (terrestrial, freshwater, estuarine, and marine) conventions. Freshwater discharge directly impacts coastal hydrodynamics and sediment processes through its effect on water column density structure and circulation, while the terrestrial materials transported by freshwater influences geomorphology, habitat complexity, biogeochemistry, productivity, and biotic diversity of coastal ecosystems. Below we discuss the individual and interactive effects of freshwater and material flux on marine ecosystem processes in the NPCTR across four generalized marine spatial scales from the continental coast to offshore. These terms have been variously defined in the literature for decades and here we select from among those definitions to constrain the geographic scope of this review:

1. *Nearshore Zone*: the area including the intertidal habitats alongshore and out to where water, moderated by turbidity, becomes too deep for light to penetrate and sustain photosynthesis. It is inclusive of marine and estuarine habitats, but stops at the furthest landward reach of saltwater into an estuary and upriver; tidal freshwater zones of rivers are very closely, aquatically connected to this zone (Borde et al. 2020; Leck et al. 2009);
2. *Coastal Transition Zone*: the area extending from the seawater boundary of the Nearshore Zone to roughly a maximum distance of 20 km from the outer exposed coast. The 20 km boundary is based on the approximate outer edge of the Riverine Coastal Domain, scaled annually to the Rossby Radius (Carmack et al. 2015);
3. *Shelf Zone*: the area of the continental shelf extending from the Coastal Transition Zone to where the continental shelf breaks (> 200 m deep) and slopes to the deep ocean;
4. *Offshore Zone*: the area on the ocean side of the continental shelf-break.

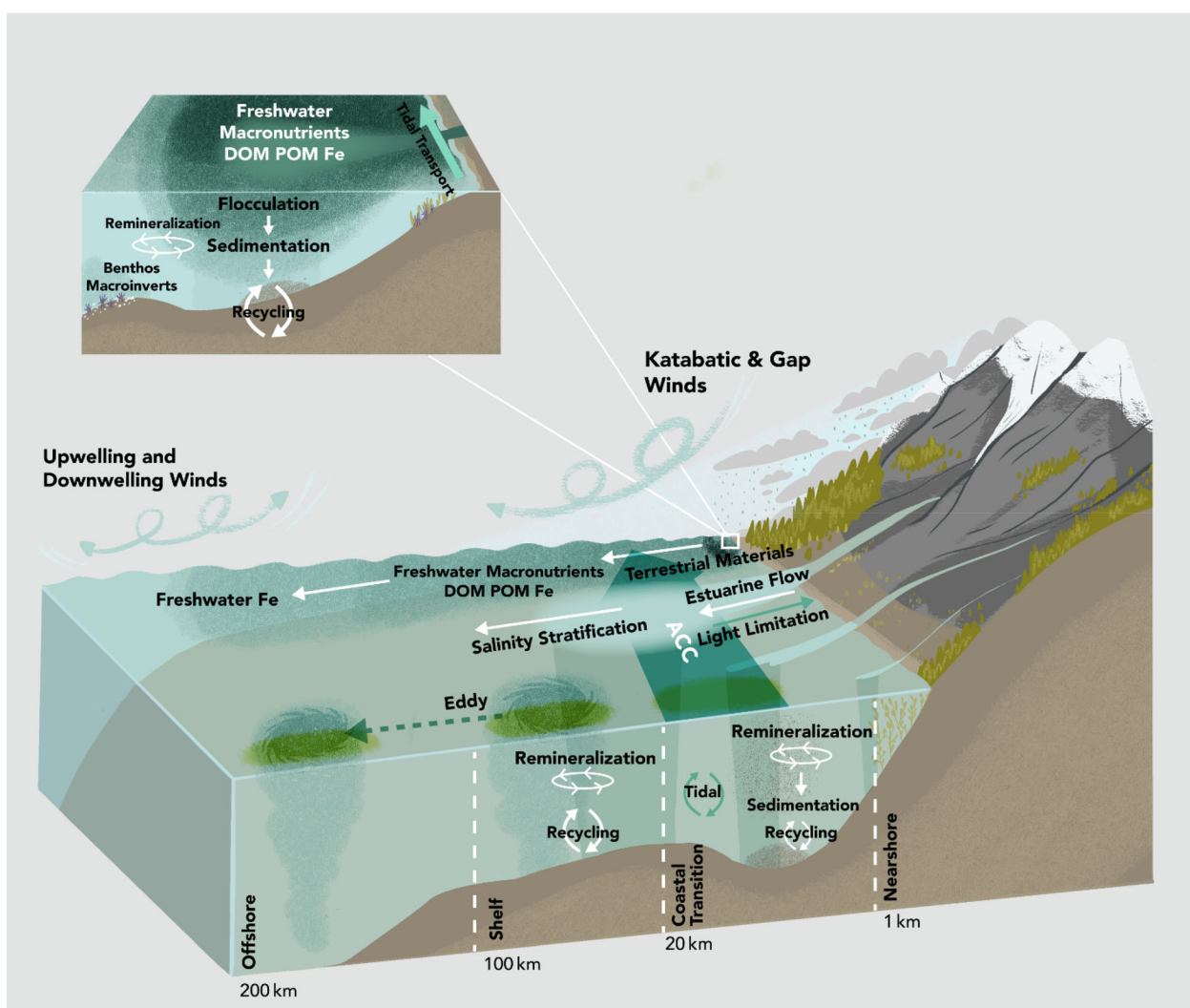
Land-derived contributions across these four zones are expected to scale to watershed size and the strength of freshwater influence, and the gradient of terrestrial material attenuation. The removal, retention, transformation, and transport of terrestrial materials through the Nearshore and Coastal Transition zones ultimately depends on the combination of (a) watershed type (Giesbrecht et al. 2022); (b) type and quality of terrestrial material (Bianchi 2011);

(c) biological, physical, and chemical attributes of the nearshore and coastal environment (Carstensen et al. 2020); and (d) discharge volume and timing (Wheatcroft et al. 2010).

### **The nearshore and coastal transition zones** ***Freshwater***

The Nearshore Zone (Fig. 4) is the zone that is the most directly influenced by freshwater and terrestrial materials flux and is a critical determinant of what terrestrial subsidies are received by downstream marine habitats. While the physical processes that govern the dynamics and mixing in large-scale river plumes have been studied extensively (Horner-Devine et al. 2015), less is known about plumes formed by freshwater discharge from creeks and small rivers. For instance, Basdurak et al. (2020) investigated the dynamics of very small plumes using an idealized numerical model in which freshwater initially enters coastal water as an inertial jet, decelerates and spreads due to its buoyancy, and is ultimately advected away by tidal currents. Their model results found that for discharges in the range from 0.1 to 30 m<sup>3</sup> s<sup>-1</sup>, the spatial scales of such plumes ranged from approximately 0.1–3 km from the discharge point, thickness limited to a few tens of cm, with temporal scales as short as 10–60 min. At their smallest discharge scale ( $\leq 1$  m<sup>3</sup> s<sup>-1</sup> and < 0.3 km plume diameter), plumes may be associated with little or no salt intrusion, meaning that there is no estuary. At medium scales ( $\sim 10$  m<sup>3</sup> s<sup>-1</sup> and 1 km plume diameter), plumes enter the marine environment as a jet and show very little attachment to the coast. Plumes of this size may therefore primarily act on surface waters. Along the open coast, the fate of such small plumes is largely dependent on wave forcing, which holds freshwater in the surf zone and determines the rate of mixing and alongshore transport (Wong et al. 2013; Kastner et al. 2018; Rodriguez et al. 2018). Coastlines in fjords and inland waterways of the NPCTR are protected from ocean swell, and the fate of freshwater discharge is determined primarily by the momentum and buoyancy of the outflow and ambient tidal currents.

At larger scales (> 30 m<sup>3</sup> s<sup>-1</sup> and 3 km plume diameter), plumes have longer durations of weeks to months and the sustained discharge drives larger scale estuarine circulation in the Coastal Transition Zone (Horner-Devine et al. 2015; Basdurak et al. 2020). Estuarine circulation, with outflowing freshwater in the upper layers driving inflowing saline water at depth, is a critical feature in most NPCTR fjords, contributing to seasonal deep-water renewal, replenishing oxygen and nutrients, and maintaining connection with the Shelf Zone (Etherington et al. 2007; Brandenberger et al. 2011; O'Neel et al. 2015; Jackson et al. 2022). Large plumes are directly influenced by the Coriolis Force and individually contribute to the northward flowing ACC. The cumulative discharge from small and large watersheds regionally affects seasonal stratification and drives the poleward buoyancy current of the ACC (Royer 1982; Carmack et al. 2015).



**Fig. 4.** Conceptual diagram of key processes occurring at the land–ocean interface in the North Pacific Coastal Temperate Rainforest across the near-shore, coastal transition, shelf, and offshore zones. ACC, Alaska Coastal Current.

### Biogeochemistry

The biogeochemical footprint of freshwater plumes and buoyancy currents in the marine environment will reflect the hydrodynamic processes outlined above, in addition to the influence of nearshore geomorphology, wind and tidal currents, and specific processes related to material types and biological demand.

**Macronutrients:** The terrestrial contribution of inorganic macronutrients ( $\text{NO}_3^-$ ,  $\text{Si}(\text{OH})_4$ ,  $\text{PO}_4^{3-}$ ) known to limit primary production is spatially and temporally variable in the NPCTR coastal ocean. Further, these contributions need to be considered in the context of a coastal system that has seasonally high background macronutrient concentrations due to summer upwelling and/or winter mixing of deep water to the surface. Freshwater inorganic macronutrient concentrations in the NPCTR are typically low ( $\text{NO}_3^- < 2 \mu\text{molL}^{-1}$ , though up to  $> 10 \mu\text{molL}^{-1}$  for the Fraser River (Voss et al. 2015);  $\text{PO}_4^{3-}$

$< 0.1 \mu\text{molL}^{-1}$ ), with the exception of silicate from the large continental and glacial rivers ( $\text{Si}(\text{OH})_4 > 40 \mu\text{molL}^{-1}$ ) which can exceed marine concentrations (Harrison et al. 1991; Whitney et al. 2005; Fellman et al. 2021; St. Pierre et al. 2021). This pattern in nutrient dynamics is a common feature of CTR regions (Lafon et al. 2014; Cuevas et al. 2019), though differences in the loading of macronutrients can result from contrasting lithology, vegetation cover, precipitation regimes, and temperature along watersheds (Conley et al. 2006; Voss et al. 2015). An example of vegetation effects is elevated nitrogen export ( $\text{NO}_3^-$  and dissolved organic nitrogen—DON) from Red Alder (*Alnus rubra*) stands in disturbed watersheds in the southern NPCTR (Compton et al. 2003), and in naturally alder dominated watersheds in Alaska (Shaftel et al. 2012). However, in general, freshwater discharge dilutes nitrate and phosphate in surface waters, though it can make a significant contribution to the marine silicate budget.

Freshwater discharge can also indirectly affect inorganic nutrient concentrations through its impact on local circulation. Estuarine circulation entrains nutrients into surface waters and can support elevated primary productivity (Harrison et al. 1991; Etherington et al. 2007). A dynamic unique to marine terminating glaciers, of which there are several dozen in the NPCTR, is that deep nutrient entrainment by buoyant subsurface meltwater during the summer months enhances the supply of nutrients to the sea surface (O'Neil et al. 2015). Fjords with marine-terminating glaciers have been demonstrated to have higher primary productivity than those with land-terminating glaciers, contributing to enhancements at higher trophic levels and increased fisheries catch rates in these systems (Meire et al. 2017).

**Iron:** Terrestrial-origin iron flux to the NPCTR ocean is high. While iron is typically not considered limiting in Nearshore and Coastal Transition zones (Strom et al. 2006), given the occurrence of deep waters with limited substrate connection, it is possible that some Coastal Transition Zone regions of the CTR are susceptible to seasonal iron limitation, which may be offset by inputs of terrestrial iron. The processes affecting the transport of iron to the Shelf and Offshore zones are important considerations in the productivity of those regions. Sedimentation removes particulate iron from the water column, and the processes governing sedimentation and the fate of this iron, as well as the dissolved fraction, are discussed further below.

**Inorganic carbon and ocean acidification:** Inorganic carbon transported from land to Nearshore and Coastal Transition zones by rivers, streams, and groundwater originates from respiration in forest, agricultural, and freshwater ecosystems, bedrock weathering, and cement dissolution or lime application in developed or agricultural landscapes (e.g., Regnier et al. 2013). The aqueous inorganic carbon system encompasses the partial pressure of  $\text{CO}_2$  ( $p\text{CO}_2$ ), dissolved inorganic carbon ( $\text{DIC} = [\text{CO}_2] + [\text{HCO}_3^-]$  (bicarbonate ion) +  $[\text{CO}_3^{2-}]$  (carbonate ion)), total alkalinity ( $\text{TA} = [\text{HCO}_3^-] + 2 \times [\text{CO}_3^{2-}] + \text{minor acid-neutralizing compounds}$ ), and hydrogen ions ( $\text{H}^+$ , measured as pH, referred to as “acidity”) (Dickson et al. 2007). Sources of  $\text{CO}_2$ , such as respiration, yield  $\text{H}^+$  and are thus acidifying, whereas  $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$  derived from chemical weathering processes provide buffering capacity. The influence of freshwater dilution on seawater biogeochemistry and acidification thus depends on the inorganic carbon composition of influent freshwater, particularly the ratio of acidifying to acid-neutralizing carbon species (Evans et al. 2014; Bianucci et al. 2018; Pilcher et al. 2018; Xue and Cai 2020).

NPCTR rivers show considerable variability in TA, with median values spanning  $\sim 500$ – $1950 \mu\text{mol L}^{-1}$  in the Columbia and Fraser rivers; median values of  $480$ – $1420 \mu\text{mol L}^{-1}$  in rivers flowing into the Salish Sea; and median values as low as  $200 \mu\text{mol L}^{-1}$  in small mountainous rivers on Vancouver Island (Evans et al. 2013; Voss et al. 2014; Bianucci

et al. 2018). TA inputs vary seasonally, depending on precipitation and runoff across watershed types (Voss et al. 2014). By way of comparison, in the Chilean CTR, low seawater TA ( $< 1800 \mu\text{mol L}^{-1}$ ) and DIC ( $< 200 \mu\text{mol L}^{-1}$ ) are associated with freshwater dilution near melting glaciers (Vargas et al. 2018), with similarly low TA observed in glacial meltwater in southeast Alaska (Evans et al. 2014). Despite this dilution effect, TA inputs across NPCTR rivers sum to represent a global temperate hotspot of chemical weathering flux to the ocean, including  $\sim 2.6 \text{ Tg yr}^{-1}$  from the Fraser and Columbia rivers and a similar flux from smaller NPCTR rivers (Hartmann et al. 2009; Mayorga et al. 2010).

Dynamic NPCTR carbonate chemistry is driven by freshwater DIC and TA inputs in combination with upwelling, seawater intrusion on tidal to seasonal timescales, local metabolism (photosynthesis: respiration), and the influence of global ocean acidification (OA), which is the oceanic uptake of anthropogenic  $\text{CO}_2$  that decreases calcium carbonate saturation states ( $\Omega$ ) and pH (increased acidity) (Feely et al. 2012; Duarte et al. 2013; Vargas et al. 2017; Lowe et al. 2019). Nearshore and coastal ecosystems in the NPCTR are particularly vulnerable to OA, because the northeastern Pacific Ocean has naturally high DIC levels and upwelling brings deep  $\text{CO}_2$ -rich water into coastal and estuarine environments (Feely et al. 2008; Ianson et al. 2016; Broullón et al. 2020). Large fluxes of low alkalinity freshwater and glacial meltwater in the northern NPCTR can combine with high remineralization rates of terrestrial and marine OM, which adds DIC, to decrease nearshore and coastal  $\Omega$  by increasing the DIC:TA of seawater and reducing seawater buffering capacity (Evans et al. 2014; Reisdorph and Mathis 2014; Siedlecki et al. 2017; Hare et al. 2020). However, glacial melt can decrease  $\Omega$  while retaining relatively high pH and low  $p\text{CO}_2$ , making the effects of glacial discharge on coastal buffering capacity and acidification complex and sometimes counterintuitive (Evans et al. 2014; Pilcher et al. 2018); these factors contribute to a variable carbonate chemistry, with a range of overall ( $\text{pH}_T$ ) of 7.17–8.56,  $\Omega_{\text{aragonite}}$  values of 0.25–4.0, and  $\Omega_{\text{calcite}}$  values of 0.39–5.08 (Feely et al. 2008; Evans et al. 2013; Evans et al. 2014; Reisdorph and Mathis 2014; Chan et al. 2017; Evans et al. 2022; Alin et al. 2024).

In fjords, bathymetry and circulation strongly influence bottom water oxygen and carbonate chemistry dynamics, with glacially formed sills limiting bottom water flushing and resulting in strong hypoxia and acidification in areas with restricted circulation (Feely et al. 2010; Ianson et al. 2016). South of the Salish Sea, fjords are absent, and corrosive events ( $\Omega < 1$ ) are associated with upwelling of deep low  $\text{CO}_2$  waters onto the shelf during boreal spring and summer (Feely et al. 2016). Where glacial sills or wider continental shelves retain water masses, remineralization hotspots result in the formation of corrosive conditions (Siedlecki et al. 2016; Hare et al. 2020). Observations of deep coastal and fjordal waters of the NPCTR show  $p\text{CO}_2$  values of  $180$ – $3460 \mu\text{atm}$ ,  $\text{pH}_T$  of 7.13–

8.30,  $\Omega_{\text{aragonite}}$  values of 0.23–2.69, and  $\Omega_{\text{calcite}}$  values of 0.37–4.28 (Feely et al. 2008; Feely et al. 2010; Feely et al. 2016; Hare et al. 2020; Evans et al. 2022). Other CTRs with fjords, seasonal upwelling and river runoff, or wide continental shelves, likely also experience respiration-enhanced subsurface acidification conditions (and possibly hypoxia) influenced by terrestrial inputs; however, the intensification of acidification and hypoxia in NPCTR and Chilean CTR subsurface environments is likely strongest due to the combination of upwelling and subsurface water masses in the eastern Pacific Ocean that are low in oxygen and high in DIC relative to other CTR regions and are the source of deep-water masses to these CTR coastal environments.

**Organic matter:** Significant modification of terrestrial materials can occur in tidal freshwater river floodplains and estuaries, particularly if retention of particulate organic matter (POM) occurs through sedimentation, decomposition, burial, and biotic assimilation (Morris et al. 2016; Crump et al. 2017; Diefenderfer et al. 2021). Sedimentation rates on tidal flats and nearshore wetland ecosystems (tidal forests, marshes, seagrass) within the NPCTR are high, and may be sufficient to keep pace with rising sea level during the Holocene to date (Peterson and Vanderburgh 2018; Borde et al. 2020; Poppe and Rybczyk 2022) though insufficient to counteract the sudden near-term effects of a subduction-zone earthquake on coastal land elevations (Atwater et al. 2001; Brand et al. 2023). Tidal wetlands in the southern NPCTR have been shown to store 217–1064 Mg C ha<sup>-1</sup>, depending on ecosystem type (Kauffman et al. 2020), and in submerged aquatic beds of eelgrass (*Zostera marina*) in British Columbia ~ 41% of the sediment OC is estimated to originate from terrestrial sources (Prentice et al. 2019). A substantial amount of terrestrial OM is therefore thought to be retained in nearshore sediments and tidal wetlands. While much of this terrestrial material is in the form of small particulates, tidal habitats also retain fallen trees (Hood 2023) which increase local habitat complexity, alter water and material flows, and likely affect the aquatic food web by providing substrate for invertebrate habitat (Simenstad et al. 2003; Diefenderfer and Montgomery 2009).

In contrast to depositional estuaries described above, much terrestrial material is transported by freshwater from the many small, steep watersheds of the NPCTR directly to the pelagic waters of the Nearshore Zone without being entrained in coastal wetlands. Data on the export of POM from small mountainous rivers in the southern NPCTR show that fluxes are episodic and occur predominantly during winter storms (Goñi et al. 2013; Thom et al. 2018b). In the northern NPCTR, watershed sediment fluxes are heavily influenced by glacial erosion, and sediment and particulate OC yields are positively correlated with watershed glacial coverage (Hood et al. 2020). Landslides can also mobilize significant amounts of OC to the ocean either directly or via freshwater transport (Vascik et al. 2021; Geertsema et al. 2022; Hage et al. 2022). Ultimately, and in consideration of many factors such as geology

governing the substrate and overall slope, the extent to which this material is transferred through the Coastal Transition Zone depends on watershed size, with larger watersheds transporting substantial amounts of material as far offshore as the Shelf Zone during the summer months (Prahl et al. 1994; Walsh et al. 2008; Wu et al. 2009).

Watershed yields of DOC and DON in the NPCTR can be exceptionally high, exceeding 30,000 kg km<sup>-2</sup> yr<sup>-1</sup> for DOC (Oliver et al. 2017) and 300 kg km<sup>-2</sup> yr<sup>-1</sup> for DON in some small, coastal watersheds (Fellman et al. 2021; St. Pierre et al. 2021). High protein-like DOM fluorescence has been associated with DOM contributions from glacial meltwaters in CTR nearshore ecosystems (Hood et al. 2009; Marshall et al. 2021). In the Chilean CTR of Patagonia, terrigenous humic- and protein-like substances comprise up to 60% of DOM in glacial fjords (González et al. 2019). Terrestrial- and freshwater-origin fatty acids are another important constituent of nearshore DOM, and their quantity scales with the terrestrial DOM contribution (Vargas et al. 2011). DOM may have greater cross-shelf transport potential than particulate POM, however, DOM rates of sedimentation through flocculation and remineralization through microbial heterotrophy may be high (Fellman et al. 2010; Wikner and Andersson 2012). Salinity-induced flocculation is an important removal mechanism of DOM and its associated metals (including Fe) and nutrients (N, P, SiO<sub>2</sub>) in nearshore waters (Sholkovitz 1976; Sholkovitz 1978). However, the characterization and fate of this DOM, in the Nearshore Zone and beyond, remain poorly resolved. This is particularly true for processes occurring in association with small plumes which are extremely difficult to study with typical oceanographic approaches.

The presence of deep fjords and deep incised channels in the coastal geomorphology adds an additional layer of complexity to the processing of terrestrial materials. Fjords are global hotspots of OC burial, a consequence of large material fluxes from land to sea due to glacial erosion and frequently low oxygen levels that slow remineralization (Smith et al. 2015; Ramirez et al. 2016; Bianchi et al. 2020). It is estimated that temperate fjords account for 11–12% of terrestrial OC burial in continental margin sediments globally (Nuwer and Keil 2005). In the NPCTR, terrestrial contributions account for between 95% of total OC in sediments at the head of fjords to less than 30% at the sill (Nuwer and Keil 2005; Walsh et al. 2008). Similarly, in the coastal temperate rainforest of Chilean Patagonia, terrestrial origin material can constitute 50–90% of OC content in sediments within continental fjords (Silva et al. 2011; Lafon et al. 2014).

Such high rates of OC deposition within fjords promote both biological and chemical oxidation at depth, especially in those systems separated from the shelf by a shallow sill. Shallow sills limit exchange with oceanic water and hypoxic or anoxic bottom waters are consequently a seasonal feature of many (though not all) fjords of the NPCTR (Feely et al. 2010; Brandenberger et al. 2011; Jackson et al. 2022) and other CTRs

in the southern hemisphere (Silva and Vargas 2014). Low oxygen conditions can create hotspots of the oxidoreductive processes required for the regeneration of limiting macro- ( $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ ) and micronutrients (Fe) to overlying and offshore waters (Smethie 1987), and limit OM remineralization, playing into the role of fjords as sinks for terrestrial (and marine) OC (Timothy and Soon 2001).

After initial sediment and OC deposition in the Nearshore Zone, remobilization can occur through dynamic and simultaneous forcing from land (seasonal and/or event-based flooding), the atmosphere (winds, precipitation), and the ocean (waves, currents, tides). The intense wave energies associated with storm events may discourage deposition and retention, and facilitate dispersal away from the Coastal Transition Zone (Wheatcroft et al. 1997; Hill et al. 2000). For instance, the wintertime peak in freshwater input and suspended sediment delivery into an evolving tidal flat in Willapa Bay, Washington (Borde et al. 2003), was one to two orders of magnitude greater than in summer, but wind and wave-generated shear stresses prevented sediment accumulation (Boldt et al. 2013). Local geomorphology and the presence of submerged vegetation and wood contribute to remobilization dynamics by determining the energy and direction of hydrological flows (Gambi et al. 1990; Boldt et al. 2013; Novak et al. 2020). In addition to tidal, seasonal, and interannual dynamics, episodically (at  $\sim 200$ – $800$  yr intervals) the tidal wetlands throughout the NPCTR are submerged by coseismic subsidence events, causing local mortality among plant communities and contributing rapid and substantial terrestrial subsidies to the nearshore ocean (Atwater et al. 2001; Peterson et al. 2020; Brand et al. 2023).

## Shelf and offshore zones

### Freshwater

The largest watershed discharging into the NPCTR is that of the Columbia River, and the associated freshwater plume significantly influences circulation and stratification across the Coastal Transition and Shelf zones (Hickey et al. 2010). The connection of other large continental and medium-sized watersheds to the shelf is dependent to a large extent on the coastal geomorphology and distance to shelf. The plumes of many of the large and medium watersheds discharging into the fjords and archipelagos of the inner coast mix into the surface ocean long before reaching the Shelf Zone (Hare et al. 2020). At larger scales, the cumulative freshwater discharge of small to large watersheds contributes to the coastal-trapped buoyancy boundary current, referred to as the ACC in Alaska, which is narrowest ( $\sim 10$  km) in winter when downwelling predominates, and widest ( $> 50$  km) in summer when downwelling relaxes or upwelling prevails (Weingartner et al. 2005).

Freshwater from the NPCTR is transported off the shelf and into the Offshore Zone by processes that include large anti-cyclonic Haida, Sitka, and Yakutat eddies (Fig. 3). These eddies

can travel  $> 1000$  km offshore and comprise up to 10% of the area of the Alaska Gyre (Crawford et al. 2007). Secondary pathways of freshwater transport to the offshore include entrainment of shelf water from the northern Gulf of Alaska by the returning circulation of the Alaska Gyre (Lam et al. 2006; Weingartner et al. 2009) and topographically steered cross-shelf jets (Peña et al. 2019). Gap winds, flowing through channels from the coast mountains, cause cooling and reoxygenation down to 100 m in some fjords (Jackson et al. 2023) and reach up to  $\sim 200$  km away from the coast, contributing to offshore transport (Ladd and Cheng 2016). In the Offshore Zone, freshwater plays a limited role in seasonal stratification, which is dominated by the balance between wind mixing and summer heating (Henson 2007). As discussed below, an important contribution of freshwater to the Offshore Zone is the delivery of iron to this iron-limited high-nutrient low chlorophyll region (Johnson et al. 2005).

### Biogeochemistry

**Macronutrients:** Despite typically low inorganic nutrient concentrations within freshwater in the NPCTR, with the exception of silicate, large river plumes indirectly influence macronutrient dynamics in the Shelf Zone. The strength of the estuarine outflow established by Fraser River discharge transports nutrient-rich deep water onto the continental shelf (MacFadyen et al. 2008). The nitrate from this outflow accounts for almost half of the primary productivity on the Vancouver Island shelf, a third of productivity on the Washington shelf, and a fifth of the productivity on the Oregon shelf during the upwelling season (Davis et al. 2014).

**Iron:** The high concentrations of dissolved and bioavailable particulate iron in the Coastal and Shelf zones are inversely related to salinity, reflecting their freshwater/terrestrial source (Wetz et al. 2006; Cullen et al. 2009; Wu et al. 2009; Lippiatt et al. 2010). Iron that is bound to particulate materials can contribute to significant repositories in shelf sediments (Roy et al. 2013). The proportion of iron in the dissolved fraction increases across the shelf as particulate material is lost, but the concentration decreases as it is taken up by phytoplankton (Strom et al. 2006) and bound to ligands (Kondo et al. 2021).

During winter, downwelling traps freshwater and associated iron in the Coastal Transition and Shelf zones and forces bottom water off the shelf and into the Offshore Zone (Lippiatt et al. 2010). Bottom water can be iron-enriched due to entrained sediments and the flux of reduced iron from sediment pore waters (Cullen et al. 2009). Sediment-derived iron may be reintroduced to the surface in the Coastal Transition and Shelf zones by storm-driven deep mixing events (Crusius et al. 2017). In the southern NPCTR, periodic relaxation of downwelling allows iron rich freshwater to move over the shelf where enhanced winter phytoplankton production can occur (Wetz et al. 2006).

In the upwelling regions of the NPCTR, surface freshwater-associated iron may be distributed more broadly across the

shelf toward the Offshore Zone during summer upwelling periods. On the shelf, iron from sediment pore waters can be reintroduced to the water column through sediment resuspension, and transported to the surface during strong upwelling periods (Johnson et al. 1999) or other deep mixing events (Crusius et al. 2017). Importantly, upwelled water from off the shelf has relatively low ( $< 1 \text{ nM L}^{-1}$ ) iron concentrations (Martin and Gordon 1988). Iron in the sediments is key to elevated shelf bottom-water iron concentrations, and iron concentrations in shelf waters are positively correlated with shelf width (Cullen et al. 2009). Terrestrial inputs may therefore be a significant source of iron to the Coastal and Shelf zones of the NPCTR (Chase et al. 2002).

The large anti-cyclonic eddies propagating from NPCTR shelves play an important role in delivering iron to the Offshore Zone. When first formed, Haida Eddies have iron concentrations two orders of magnitude higher than offshore waters (Johnson et al. 2005). As they age and decay, rising isopycnals at the center of the eddy continue to deliver deep iron to the surface and even after 16 months they can have iron concentrations 1.5–2 times higher than the surrounding waters (Whitney and Robert 2002; Johnson et al. 2005; Crawford et al. 2007). It is estimated that Haida eddies alone contribute 5–50% of the dissolved iron in the upper 1000 m of the southeastern Gulf of Alaska (Johnson et al. 2005).

Eddies are not the only means of terrestrial iron transport to the offshore zone. Southward recirculation of water from the northern Alaska shelf transports iron, macronutrients, and freshwater into the Gulf of Alaska, and these contributions have been related to increased production in the Offshore Zone (Lam et al. 2006). An additional source of iron to offshore waters is dust, particularly from fine glacial sediments from the NPCTR (Boyd et al. 1998). While this has received limited attention, it has been estimated that iron flux from glaciofluvial dust is comparable to the iron flux from coastal formed eddies (Cullen et al. 2009; Crusius et al. 2011).

**Inorganic carbon:** Shelf and Offshore Zones in the NPCTR generally have relatively low buffering capacities (high Revelle factors), low pH (high acidity), and low calcium carbonate saturation states ( $\Omega$ )—despite having relatively low anthropogenic  $\text{CO}_2$  inventories—although conditions may be less severe than those closer to shore as a result of diminished freshwater influence (Feely et al. 2004; Sabine et al. 2004; Jiang et al. 2015; Gruber et al. 2019; Jiang et al. 2019; Franco et al. 2021). However, in areas with broader continental shelves, retention zones can result in particularly acidified conditions forming at depth due to remineralization of OM (Feely et al. 2010; Bianucci et al. 2011; Siedlecki et al. 2015).

**Organic matter:** POM is rapidly lost from small plumes and not expected to leave the Nearshore Zone, but large continental river plumes can transport POM across the Coastal Transition Zone to the Shelf and Offshore zones (Prahl et al. 1994; Walsh et al. 2008; Wu et al. 2009). Estimates for the Washington continental margin are that terrestrial material

contributed  $\sim 60\%$  to shelf sediments,  $\sim 30\%$  to slope sediments, and  $\leq 15\%$  to basin sediments (Prahl et al. 1994; Walsh et al. 2008). Continental shelf canyons are known to be important conduits for terrestrial material from the continental shelf to the deep ocean (Puig et al. 2014). The significance of these terrestrial material inputs to pelagic and benthic food webs in the NPCTR is unknown, but evidence from other CTR regions indicates that terrestrial material can play an important role in structuring benthic communities (Leduc et al. 2020).

The dissolved fraction of terrestrial OM flux remains in the water column longer than particulates (Strom et al. 2006; Wu et al. 2009; Lu et al. 2015). DOM is depleted through a combination of microbial and photochemical degradation, losing the more labile components and becoming modified to the extent that the DOM source (terrigenous vs. autochthonous) can become difficult to identify (Lu et al. 2015). Modification of both particulate and dissolved terrigenous OM represents one of the important obstacles to identifying, tracing, and quantifying their contributions to marine ecosystems.

## How land–ocean discharge affects ecosystem dynamics in the NPCTR

### *Influence of freshwater on species distribution and ecosystem composition*

Freshwater exposure is a strong driver of marine community composition through its effect on osmotic stress experienced by biota, and therefore affects organism distributions in the NPCTR. For example, echinoderms, major grazers in NPCTR Nearshore Zone ecosystems, are particularly intolerant of low salinities, and freshwater outflows therefore play an important role in structuring local food webs (Held and Harley 2009; Iken et al. 2010). Eelgrass, which has several important roles in the Nearshore Zone throughout the NPCTR, is strongly influenced by freshwater outflows, with productivity declining with decreasing salinity (Kentula and DeWitt 2003). However, many biota at the marine-freshwater interface are euryhaline or highly mobile, and thus able to either tolerate or avoid large fluctuations in salinity. The interplay between the temporal dynamics of freshwater exposure (e.g., tidal cycles, flash floods, freshets) and organism tolerance and mobility leads to mutable communities in both pelagic (Breckenridge et al. 2020) and benthic habitats (Chapman and Brinkhurst 1981). Small creeks along the nearshore may have overlapping plumes, enabling estuarine species to move from one system to another via these bridging estuaries, for example, so-called “nomad” Coho salmon (Tschaplinski 1988; Koski 2009). Salinity is also an important driver of microbial community composition (Herlemann et al. 2011; Fortunato et al. 2012; Herlemann et al. 2016; Logares et al. 2018) and function, for example, methanogenesis (RoyChowdhury et al. 2018), though functional redundancy among taxa may also result in similar metabolic potential from river to ocean (Fortunato and Crump 2015). Freshwater, particularly from

glacierized watersheds, is often colder than seawater, seasonally influencing nearshore communities through temperature and turbidity. Invertebrate and fish communities may vary between estuaries influenced by cold, turbid, glacier-fed watersheds vs. warmer, clearwater systems without glaciers in their headwaters (Levings 2016; Whitney et al. 2017).

Freshwater discharge affects circulation and drives density stratification, both of which are important determinants of phytoplankton production and community composition in the NPCTR through their influence on nutrient and light availability. Nutrients entrained by estuarine circulation associated with larger watersheds promote primary production in the Coastal Transition and Shelf zones, though there is a tradeoff with turbidity driven light limitation (Hickey and Banas 2008; Masson and Peña 2009). In fjord ecosystems, freshwater discharge timing and strength determines bloom timing, production, and retention through effects on stratification, mixing layer depth, and advection (Wolfe et al. 2015). The freshwater content of the Coastal Transition and Shelf zones is an important factor in summer stratification in these regions. High freshwater content can lead to persistent summer stratification, macronutrient depletion in the euphotic zone, and decreased primary production (Thomson et al. 2012; McKinnell et al. 2014). This relates to the “Optimal stability window” proposed by Gargett (1997) for the north-eastern Pacific, where production is controlled by the tradeoff between light and nutrients associated with mixed layer depth. Overall, the influence of freshwater on production is substantial, but dependent on discharge volume and turbidity, setting, and season.

#### ***Influence of terrestrial material flux on marine food webs***

Strong cross-shelf gradients in freshwater influence and nutrient availability are reflected in gradients in phytoplankton community structure (cell size, species composition, biomass) and function (growth rate, nutrient utilization) (Bruland et al. 2001; Strom et al. 2006; Cuevas et al. 2019). In the Gulf of Alaska, nearshore phytoplankton communities are typically dominated by large ( $> 20 \mu\text{m}$ ) centric and pennate diatoms with high growth rates, while offshore communities are largely composed of small ( $< 5 \mu\text{m}$ ), slow-growing flagellate and *Syneccochocus* species (Strom et al. 2006). Differences in phytoplankton communities have been attributed to nutrient availability, fueled in part by terrestrial sources driving clear nearshore-offshore gradients in macro- ( $\text{NO}_3^-$ ,  $\text{PO}_4^3$ ,  $\text{Si}(\text{OH})_4$ ) and micronutrients, for example, Fe (Strom et al. 2006; Chase et al. 2007). Nitrate limitation may also control the standing stock of eelgrass and green algae (e.g., *Ulva fenestrata*) in the Nearshore Zone (Thom and Albright 1990).

Whereas phytoplankton of the Coastal Transition Zone and mid-shelf may be more likely to be limited by nitrogen (Strom et al. 2006), iron limitation predominates in the Offshore Zone of the NPCTR from the Gulf of Alaska (Martin et al. 1989) to the northern California Current (Till

et al. 2019). The flux of iron from terrigenous sources therefore has a significant bearing on offshore primary production (Chase et al. 2007). Although anti-cyclonic eddies comprise only 10% of the area of the Gulf of Alaska, they contain more than half of the region’s phytoplankton biomass and up to 80% in spring (Crawford et al. 2007). The smaller cells characteristic of offshore communities have a higher surface area-to-volume ratio, conferring a competitive advantage under chronic iron limitation.

Autotrophic production can be locally impacted by high particulate loads due to light limitation. In the highly turbid inner coast plumes associated with snow melt and glacially influenced systems, phytoplankton chlorophyll maxima are shallow and typically peak at intermediate turbidity levels (Harrison et al. 1991; Etherington et al. 2007; Murray et al. 2015). Reduced light can lead to increased cellular photopigment concentrations to sustain high levels of primary production in moderately terrestrially impacted waters (Paczkowska et al. 2019; Paczkowska et al. 2020). However, this physiological compensation cannot overcome reduced light availability in highly turbid waters, resulting in a change in community composition to more mixotrophic or heterotrophic protists. This community shift influences zooplankton food sources and can negatively impact mesozooplankton biomass. Light attenuation influences the vertical distributions of zooplankton, which tend to be more surface-orientated in low light conditions, and consequently the spatial distribution of higher trophic levels, for example, fish and avian predators (Arimitsu et al. 2012; Renner et al. 2012). At NPCTR latitudes, water clarity is also a critical factor in meeting annual light requirements for eelgrass growth and long-term survival (Thom et al. 2008; Thom et al. 2018a). Eelgrass provides an important nearshore habitat for juvenile Pacific salmon (*Oncorhynchus* spp.; Kennedy et al. 2018), juvenile Pacific cod (*Gadus macrocephalus*; Dean et al. 2000), spawning Pacific herring (*Clupea pallasii*; Shelton et al. 2014), and Dungeness crab (*Metacarcinus magister*), among many other species (Mumford 2007). Natural turbidity levels in the NPCTR can therefore shape the occurrence, composition, and production of primary producers, and the organisms dependent on them for food and habitat.

Terrestrial OM plays an important role in structuring marine microbial community composition and activity. While the ability to utilize low molecular weight OM is widespread among microbial heterotrophic taxa, the ability to degrade complex high molecular weight or highly aromatic OM is found in only a subset of taxa (Bianchi 2011; Logue et al. 2016). In the NPCTR, the composition of DOM entering streams and rivers from the land varies seasonally and depends on watershed characteristics (Fellman et al. 2009; Oliver et al. 2017; Fellman et al. 2020). In southeast Alaska streams, DOM is more labile in the spring than later in the summer (Fellman et al. 2009). In both the NPCTR (Fellman et al. 2010) and in the Chilean CTR (Marshall et al. 2021), the

higher proteinaceous component of glacierized DOM is generally thought to be more labile in marine waters than humic-rich DOM exported from coastal wetlands and forested watersheds; however, marine microbes have been shown to be adept at degrading humic DOM (Kisand et al. 2008). In coastal waters of the NPCTR, microbial cell counts across small, high DOM plumes increased with rainfall-heightened terrestrial DOM exports, suggesting microbial communities adapted to using terrestrial DOM (St. Pierre et al. 2020). In that study, streams consistently had lower cell counts than marine samples, so the observed increase could not be attributed purely to a flux of freshwater microbes into the nearshore environment. Contrary to expectations, marine microbial populations appear to utilize a larger fraction of the terrestrial DOM pool than freshwater microbial populations in the NPCTR (Fellman et al. 2010), in line with chemostat experiments in the Wadden Sea (Kisand et al. 2008). An important factor in the utilization of more recalcitrant (less bioavailable) terrestrial materials may be priming by labile marine DOM (Bianchi 2011; Seidel et al. 2015).

In the Baltic Sea, high terrestrial DOM input has been linked to an increased ratio of bacterial to phytoplankton production (Wikner and Andersson 2012; Andersson et al. 2018; Degerman et al. 2018). Given the substantial terrestrial DOM input to the NPCTR, it is highly likely that bacterial production is similarly amplified in this environment (Finke et al. 2017). Microzooplankton are necessary trophic intermediaries between bacteria and higher trophic levels, conferring a potentially significant role of this functional group in CTR marine food webs (Sommer et al. 2002; Paczkowska et al. 2020). These heterotrophic food web pathways may be strongest during the winter, when autochthonous primary production is limited and rainfed watershed runoff is highest.

POM, part of which is derived from flocculating DOM, is accessible to direct consumption by filter feeders, such as zooplankton and bivalve mollusks, and deposit feeders, and also contributes indirectly to food webs via breakdown and recycling through the microbial loop (Moore et al. 2004). POM in the estuarine turbidity maxima of the Columbia River Estuary have been shown to be hotspots of microbial production (Crump and Baross 1996; Herfort et al. 2017), contributing to the role of estuaries as “bioreactors” (Crump et al. 2017) and coastal filters (Bouwman et al. 2013; Carstensen et al. 2020). This POM sustains unique microbial communities compared to particle-free water samples in the estuary, as observed in other aquatic systems, which are likely adapted to complex OM degradation (Bell and Albright 1981; Luef et al. 2007; Ochs et al. 2010).

Although the relative importance of direct vs. indirect trophic pathways, including the microbial loop, has not been established, dietary tracers have been used to estimate the contribution of terrestrial material to marine ecosystems. Stable isotopes and fatty acid analyses have shown that terrestrial carbon can contribute 20–50% of the body carbon in

zooplankton (copepods) along the CTR of Chilean Patagonia (Vargas et al. 2011), with up to 61% of zooplankton fatty acids being derived from vascular plants (Lafon et al. 2014). Although highly variable, terrestrial material dietary quality is typically considered to be low due to low nitrogen content and lack of essential fatty acids (Moore et al. 2004; Harfmann et al. 2019) required for organism physiological health. However, Harfmann et al. (2019) found that a mixed phytoplankton/terrestrial material diet (1:3 carbon ratio) enhanced the survival of the copepod *Eurytemora affinis* relative to a diet of only phytoplankton. Terrestrial material can therefore represent an important supplementary food source for zooplankton.

Relatively few studies have attempted to measure terrestrial material contributions to higher trophic level marine consumers in CTR regions, with stable isotope analysis of bulk tissues being the most common approach. Estimates of terrestrial material contributions to consumer biomass range from 2% to 44%, including oysters, fish and seabirds (Romanuk and Levings 2005; Conway-Cranos et al. 2015; Arimitsu et al. 2018). This variation between studies likely reflects local environmental conditions such as landform (e.g., deep fjord vs. shallow estuary) which can affect sedimentation and habitat for alternative OM sources (e.g., saltmarsh, eelgrass); hydrology which can affect sedimentation rates and substrate types; and species examined (Hyndes et al. 2014). It is important to note that stable isotope analysis of bulk tissues can be confounded by a variety of factors (e.g., organism physiological state, body size, trophic level, species specific trophic enrichment factors). Increasingly, food web ecologists are using compound-specific (e.g., amino and fatty acid) stable isotope analyses, providing much greater resolution of feeding relationships (Whiteman et al. 2019). Other new tools include metagenomics, recently used to estimate substantial terrestrial material uptake by the estuarine copepod *Eurytemora affinis* (Harfmann et al. 2019). Application of such approaches will further advance understanding of terrestrial material trophic pathways.

### Ocean acidification

Acidified (and hypoxic) conditions naturally occur in the NPCTR, but are worsening due to climate change and will likely be exacerbated as a result of changing hydrological and biogeochemical dynamics in the NPCTR (Barth et al. 2024; Feely et al. 2024). This has direct and indirect implications for marine and anadromous species. For example, pink and coho salmon exposure to acidified conditions that are currently found in some NPCTR environments may impair appropriate predator-avoidance behavior during freshwater and early ocean life phases (Ou et al. 2015; Williams et al. 2019). Economically important Dungeness, Tanner, and red king crab experience survival, growth, calcification, and dissolution impacts as a result of larval–juvenile life stage exposure to current or near-future OA conditions in the NPCTR (Long et al. 2013;

Bednaršek et al. 2020). Shellfish, including Pacific oysters (*Crassostrea gigas*) and mussels (*Mytilus galloprovincialis*), manifest larval shell development defects in response to  $\Omega_{\text{aragonite}}$  levels currently present in the Salish Sea and experience more energetically expensive calcification under acidifying conditions (Waldbusser et al. 2015a; Waldbusser et al. 2015b). Indirect food web effects of OA include impaired larval development and survival of euphausiids (krill), an important food source for fish and seabirds in the region, and severe dissolution effects on pteropods (pelagic snails) under current conditions in the Salish Sea (McLaskey et al. 2016; Bednaršek et al. 2021). Acidified conditions can also disrupt acid–base balance in fish and favor the growth of harmful algal taxa (Haigh et al. 2015). Further, many species, such as Dungeness crab and pteropods, experience particularly strong physiological impacts of exposure to combinations of stressors including increased temperature, hypoxia, and OA, with impacts varying across life stages (Bednaršek et al. 2021; Berger et al. 2021). However, while freshwater influence on coastal carbonate chemistry in the NPCTR may exacerbate ongoing OA, some marine organisms inhabiting river-influenced areas appear to have evolved to compensate for the metabolic costs of low pH, high  $p\text{CO}_2$  conditions through phenotypic plasticity and processes of “local adaptation,” (e.g., Aguilera et al. 2016; Vargas et al. 2017; Saavedra et al. 2018; Osmá et al. 2020).

### **Climate change and other anthropogenic impacts on land–ocean connections in the NPCTR marginal ocean**

Moving stepwise through the spatial and temporal scales of land–ocean interactions in the NPCTR reveals that freshwater and its associated materials are the defining feature of this marine domain. Freshwater flux impacts coastal circulation and horizontal connectivity among habitats, is a key parameter in stratification and hence vertical connectivity, affects sedimentary processes including wetland deposition and accretion, and controls the distribution of biota based on salinity and temperature tolerance. Terrestrial inorganic and organic material fluxes are essential ingredients in ocean primary production and heterotrophic microbial production, which support pelagic and benthic food webs and drive the biogeochemical processes that control nutrient recycling, oxygen levels, and carbonate chemistry. The effects of freshwater and terrestrial materials on the marine ecosystem are evident across the Nearshore, Coastal Transition, Shelf, and Offshore zones. The dominant effects shift between zones, reflecting the transformation, retention, and removal of materials, and scaled impacts of freshwater on hydrodynamics, from plumes to coast-wide circulation. Freshwater and material inputs are similarly important to ecosystem structure and function in the oceans of other CTR regions (Fig. 1), including the role of freshwater in circulation (Stanton 1976; MacKenzie et al. 1988; Simpson et al. 1993; Atkinson et al. 2002), and

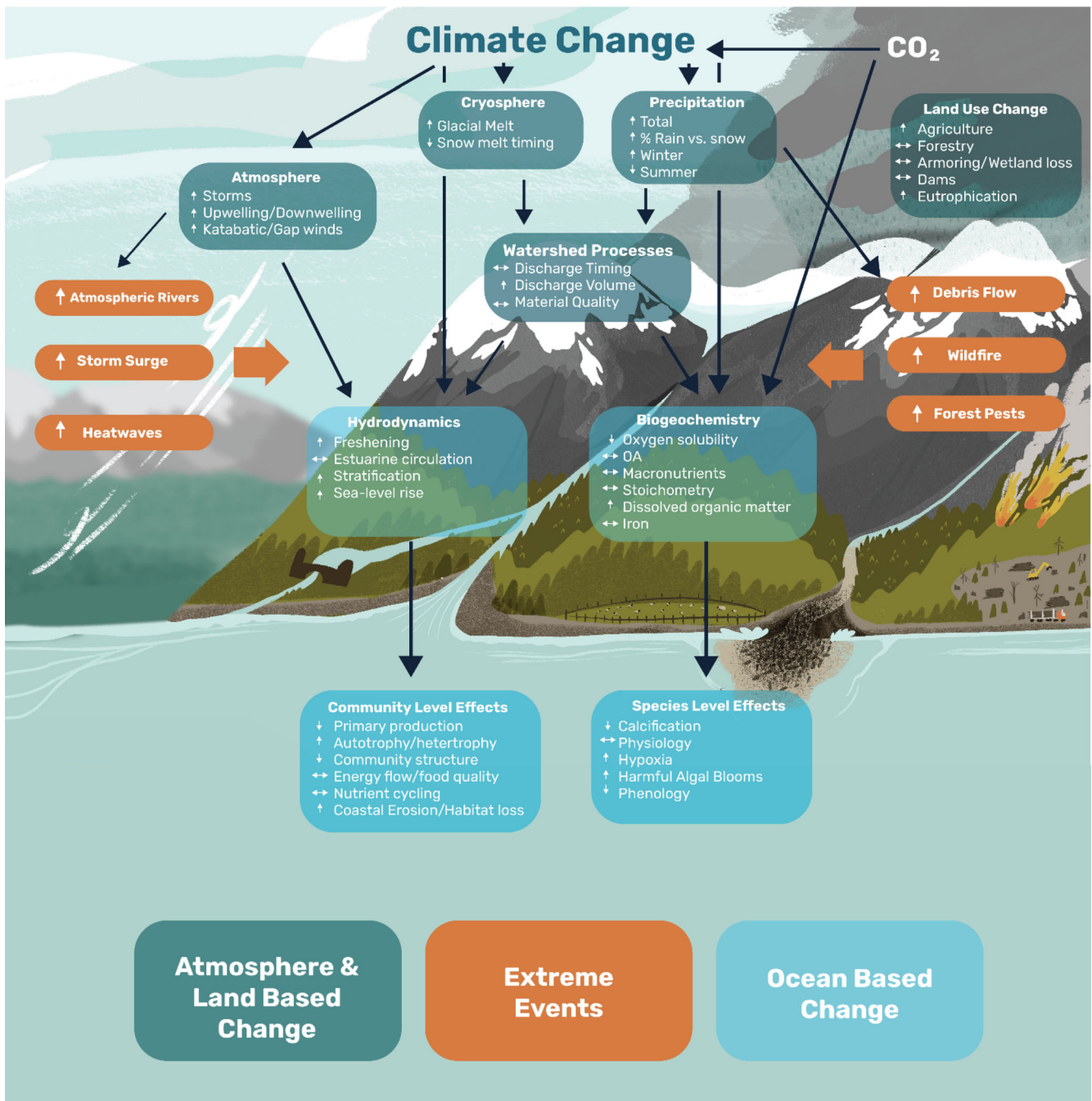
terrestrial materials in ocean biogeochemistry (MacKenzie et al. 1988; Frigstad et al. 2013; Vargas et al. 2016), primary productivity, plankton community composition (González et al. 2010; Vargas et al. 2012; Cuevas et al. 2019), and subsidies to marine food webs (McLeod and Wing 2009; Vargas et al. 2011). This makes marginal oceans in CTR regions uniquely vulnerable to stressors acting on the adjacent terrestrial environment. Figure 5 identifies important land–ocean pathways susceptible to change in CTR systems and below we discuss change driven by climate and other anthropogenic stressors with respect to the key elements related to watershed processes and coastal hydrodynamics–biogeochemistry. In addition, we underscore the significance of extreme events in amplifying changes in land–ocean connections. It is important to note that many of these changes are already underway (Beamer et al. 2017; Hood et al. 2020; Jackson et al. 2023).

### **Watershed processes—Freshwater delivery and quality**

Climate change is forecast to continue to dramatically change the quality of freshwater and its delivery to the NPCTR ocean (Fig. 5). In the Cascade Mountains region of the Columbia River basin, air temperatures have increased by 1.2 to 1.4°C since 1895, and under RCP 4.5 and 8.5 will increase by about 2–4.5°C more over current temperatures by 2100 (Halofsky et al. 2022) and the annually averaged water temperature of the Columbia River basin has increased by ~2.2°C since the 1850s (Scott et al. 2023). The Columbia’s largest tidal tributary has warmed at ~1.1°C per century over the same period, has stopped freezing, and cold water days (< 2°C) now only occur rarely (Talke et al. 2022). Winter warming is promoting a shift to rain-dominated precipitation, contributing to a seasonal shift of discharge to increased winter flow (Morrison et al. 2002; McAfee et al. 2014; Riche et al. 2014). In British Columbia, in the next 20–50 yr overall discharge is predicted to increase by ~10% in all months except June to August when discharge is projected to decrease by up to 10% (Morrison et al. 2014). Similarly, in southeast Alaska winter discharge is forecast to increase 1–3-fold by 2080 (Shanley and Albert 2014). Decreased snowpack and high rates of ice loss (Rounce et al. 2023) are resulting in a decline of snowmelt runoff, with a similar decline in glacial runoff expected (Moore et al. 2009; Bliss et al. 2014; Huss and Hock 2018). In combination with earlier snow melt timing (Musselman et al. 2021), shortening of the high flow season (Morrison et al. 2002), and drier summer months, summer drought is increasing throughout the NPCTR (Mote and Salathé 2010; Lader et al. 2020). This intensification of the seasonal hydrological cycle affects the volume, timing, and duration of freshwater and associated materials delivery to the coast.

### **Hydrodynamics and biogeochemistry of the NPCTR ocean**

Changes in the hydrological cycle are directly linked to coupled hydrodynamic–biogeochemical processes in the



**Fig. 5.** Overview of climate change and other anthropogenic impacts on the land–ocean system in the North Pacific Coastal Temperate Rainforest region. Arrows within text bubbles indicate direction of change (see Table for supporting literature).

NPCTR ocean (Fig. 5). The increase in total freshwater discharge, and intensification of seasonality, is enhancing density stratification in the ocean, favoring earlier spring phytoplankton blooms but weakening vertical nutrient exchange through the summer which can reduce total annual phytoplankton production (Yin et al. 1997; Weingartner et al. 2005; Thomson et al. 2012). Observations already show a decline in the salinity of coastal surface waters in British

Columbia since records began in the 1940s (Chandler 2021). Changes in spring phytoplankton bloom timing can create a mismatch with zooplankton life cycles, impacting zooplankton recruitment (Tommasi et al. 2013) and dependent consumers (Schweigert et al. 2013). Intensification of summer stratification, in addition to reducing production, favors smaller phytoplankton species and flagellates, and mixotrophic and heterotrophic communities (Harrison

et al. 1983; Sommer et al. 2002; Vargas et al. 2012), altering food web structure and nutritional dynamics (Finkel 2007; Winder et al. 2017; Lerner et al. 2022; McLaskey et al. 2022). Stratified conditions are also conducive to blooms of some harmful algal taxa (Esenkulova et al. 2021); however, harmful taxa are diverse both taxonomically and in response to physical and chemical conditions (Paerl and Otten 2013; Dodrill et al. 2023), and further research is required to understand their response to change in CTR regions. The cumulative effect of increased freshwater discharge should strengthen the Alaska Coastal Current (ACC) and along-shelf connectivity in the NPCTR coastal ocean, while the cross-shelf extent of the ACC may become more dynamic due to the predicted intensification of upwelling and downwelling (Foreman et al. 2011). Intensification of winter downwelling will promote the formation of eddies, which increase the transport of freshwater and associated materials such as iron into the Offshore Zone, strengthening cross-shelf connectivity and offshore primary production.

In the short-term, enhanced glacier melting will increase the supply of labile DOC to fjords (Milner et al. 2017). Higher OC exports are likely to lead to increased heterotrophic production and intensification of microbial food web pathways (Wikner and Andersson 2012). Oxygen in British Columbia deep fjord water has decreased by 20% over the past 70 yr (Jackson et al. 2021), possibly leading to increased frequency of die-offs of deep-water fauna (including some species that are tolerant of low oxygen) behind sills, as seen in Howe Sound and Saanich Inlet in British Columbia (Levings 1980; Chu and Tunnicliffe 2015). While some of this decline is related to oceanic processes—for example rising temperatures decreasing oxygen solubility and increasing remineralization rates (Jackson et al. 2021), long water residence time in fjords (Farmer and Freeland 1983), and bathymetry (Thomson et al. 2017)—increased material inputs from the land may have also been a factor through enhancement of remineralization in deep waters. The projected increase in inputs from land-terminating glacier melt is expected to increase future alkalinity input from glacial discharges and may somewhat compensate other drivers of coastal acidification (Siedlecki et al. 2017; Pilcher et al. 2018). In the long term (> 10 yr), reduced glacial runoff will decrease overall sediment and nutrient yields to the coastal ocean, though OC contributions are likely to increase (Fellman et al. 2014).

Drier summers are associated with an increase in the occurrence and intensity of wildfires (Halofsky et al. 2020) and occurrence of forest pests (Davis et al. 2013). Wildfires can significantly increase watershed flux of metals (Magliozzi et al. 2024) and OC, ON, and inorganic nutrients (Spencer et al. 2003; Stephan et al. 2012; Aguilera and Melack 2018; Granath et al. 2021; Barron et al. 2022), with the potential to impact coastal water quality. Macro and micronutrient additions to the ocean also occur through ash deposition (Coward et al. 2022; Hamilton et al. 2022), and this can enhance

microbial production (Ladd et al. 2023). Smoke from fires can have a substantial environmental footprint. The extensive wildfires in Australia in 2019 and 2020 yielded a smoke plume that moved eastwards across the Tasman Sea to New Zealand, causing a widespread phytoplankton bloom due to iron addition (Li et al. 2021; Tang et al. 2021). Snow darkening in New Zealand increased snowmelt by  $\sim 0.41 \pm 0.2$  cm day<sup>-1</sup> during the southern summer, equivalent to the effect of a  $\sim 1.8^\circ\text{C}$  increase in air temperature (Pu et al. 2021). In the NPCTR, enhanced deposition of black carbon from wildfires would increase melt rates on the icefields that mantle coastal mountain ranges (Kaspari et al. 2015; Nagorski et al. 2019). Similar to wildfires, tree mortality due to forest pests changes soil hydrology and biogeochemistry, increasing nutrient loading in impacted watersheds (Clow et al. 2011), and may synergistically increase the frequency and size of wildfires (Woo et al. 2024). The projected increase in wildfire and forest pest prevalence can therefore be expected to have strong and varied effects on the land–ocean system in the NPCTR.

Anthropogenic land-use change also modifies the magnitude and composition of material exported from watersheds (Aufdenkampe et al. 2011). Forested watersheds have higher DOC and lower DIC yields than agricultural or grassland watersheds, while agricultural land exports more DIN (Barnes and Raymond 2009; Kindler et al. 2011; Pérez et al. 2015; Curra-Sánchez et al. 2022). Within forested watersheds, logging activity can increase the flux of DOC, DIN, and DON to receiving watersheds (Kreutzweiser et al. 2008). Urbanization and industrialization significantly impact freshwater and materials flux. Impervious surfaces alter freshwater flow regimes (Levin et al. 2020), and stormwater and wastewater have significantly increased freshwater material loads, including DIC and DIN concentrations, compared to forested and agricultural watersheds, contributing to coastal eutrophication (Brandenberger et al. 2008; Barnes and Raymond 2009; Savage et al. 2010; Curra-Sánchez et al. 2022). Furthermore, high alkalinity ( $\sim 2000$   $\mu\text{mol L}^{-1}$ ) of point sources (wastewater treatment plants and industrial outfalls) associated with increasing urbanization are predicted to alter net landscape fluxes of buffering vs. acidifying inorganic carbon to coastal waters with implications for calcifying organisms (Bianucci et al. 2018; Moore-Maley et al. 2018).

Critical to the response of CTR oceans to land-use and associated changes to freshwater and material inputs is the health of the estuaries and wetlands that are the engine of the coastal filter, where retention and transformation of terrestrial materials occurs (Carstensen et al. 2020; Ward et al. 2020). Conversion of these habitats allows more terrestrial material to reach the Coastal Transition Zone. This promotes increased heterotrophy in the pelagic environment and sediments, reducing oxygen and shifting the balance of nutrient cycling away from the coastal interface habitats, and increasing nearshore turbidity with associated reduction in light penetration and primary productivity of phytoplankton and submerged aquatic

vascular plants and algae (Thom et al. 2008; Blain et al. 2021). Furthermore, loss of the estuary and wetland filters exacerbates eutrophication and changes nutrient stoichiometry. This can enhance phytoplankton production and shift phytoplankton species composition, respectively, with an array of ecosystem implications, including hypoxia, altered food web pathways and nutrition (Howarth and Marino 2006; Peñuelas et al. 2013; Winder et al. 2017), and harmful algal blooms (Paerl and Otten 2013).

Although anthropogenic impacts on NPCTR estuaries and wetlands are diverse and widespread (Emmett et al. 2000; Kehoe et al. 2021), robust estuarine restoration programs can reverse declines in the key services provided by these interface habitats (Christie et al. 2018; Woo et al. 2021; Littles et al. 2022; Hall et al. 2023). However, restoration programs and coastal planning need to take into account sea level rise as an important hydrodynamic factor in coastal change. The magnitude of relative sea level rise in the NPCTR is highly spatially variable due to tectonics, water withdrawals, glacial isostatic rebound (Miller et al. 2018), and atmospheric cycles affecting ocean temperature (Han et al. 2015; Wang et al. 2019). Rates of sea level rise in the NPCTR were very low between 1990 and 2010, but are projected to increase (Han et al. 2015; Oppenheimer et al. 2019), threatening estuarine and coastal wetland habitat, particularly in the southern portion of the NPCTR. This is exacerbated by shoreline armoring that limits scope for inland habitat migration (Dethier et al. 2016), dams that settle sediment and limit the buffering capacity of estuaries against erosion (Templeton and Jay 2013), habitat loss through land reclamation, and erosion associated with increasing storm surge (Kennish 2001; Soontiens et al. 2016).

### Extreme events

Against the background of long-term climate change and pervasive anthropogenic impacts, the NPCTR is becoming increasingly affected by extreme events, intensifying the changes outlined above and leading to more dynamic land–ocean connections (Fig. 5). Climate change is driving an increase in the intensity and frequency of droughts and extreme precipitation events, such as those associated with atmospheric rivers and synoptic weather patterns that transport moisture from low to high latitudes (Radić et al. 2015; Payne et al. 2020; Sharma and Déry 2020). For example, a November 2021 atmospheric river event in British Columbia led to an unseasonably extreme discharge event of the Fraser River equivalent to the summer freshet (Gillett et al. 2022). An increase in the occurrence of rain-on-snow events will further contribute to an increase in short duration extreme discharge events (Trubilowicz and Moore 2017; Musselman et al. 2018). Extreme precipitation events enhance the mobilization and delivery of terrestrial materials to the ocean (Fellman et al. 2009; Johannessen et al. 2017; Johannessen et al. 2019), including through landslides and debris flows (Jakob and

Lambert 2009; Gariano and Guzzetti 2016; Vascik et al. 2021; Geertsema et al. 2022), and especially in drought, fire- and forest pest-affected landscapes (Smith et al. 2011; Harris et al. 2015). Altered timing and magnitude of terrestrial inputs due to extreme events can also affect primary production levels and in turn influence the severity and duration of hypoxia and acidification events in coastal and estuarine ecosystems (Alin et al. 2024; Barth et al. 2024).

Similarly, heatwaves are expected to increase in frequency and intensity (Oliver et al. 2018), which can amplify change in NPCTR land–ocean interaction dynamics, for example, via increased and earlier snow melt, and increased freshwater and particle flux events (Johannessen et al. 2019; Gillett et al. 2022). In addition, heat waves impose direct physiological stress on NPCTR organisms in both terrestrial and aquatic ecosystems, leading to changes in communities that reflect the winners and losers in the face of extreme conditions (Raymond et al. 2022). The June 2021 heatwave experienced in the northeast Pacific region (Philip et al. 2021) had far-reaching effects, including increased rates of glacial melt, wildfires, massive die-off of intertidal biota, and destabilized soils causing fatal debris flows and flooding in parts of the region with the extreme autumnal atmospheric river event that followed (Gillett et al. 2022). Marine heatwaves can amplify the response of the marine ecosystem to long-term warming-driven changes, speeding up biogeographic range shifts and biomass declines that will change the functional ecology of the NPCTR, potentially impacting essential ecosystem services at the land–ocean interface (Cheung et al. 2015; Cheung and Frölicher 2020).

### Recommendations for future research

We have outlined key internal processes (Fig. 4) and attendant external stressors acting on the land–ocean interface system (Fig. 5). Most of these stressors are already occurring and increasing, and are projected to be amplified under future climate scenarios. While the current state of knowledge allows stressors to be identified, several key gaps limit our understanding of potential consequences for marine ecosystems (Table 1). Filling these knowledge gaps in the NPCTR and other CTR regions requires new approaches that emphasize land–ocean connections and encourage integration across disciplines. Below, we highlight four directions intended to support these aims.

#### Fill the nearshore and coastal transition zone knowledge gap

Nearshore processes related to the fate of freshwater and terrestrial material inputs are still poorly constrained in CTR environments, in large part due to lack of observations in these spatially heterogeneous zones. The Nearshore Zone, and to a lesser extent the Coastal Transition Zone, are habitats that typically fall outside of the sampling remit of the

**Table 1.** Knowledge gaps and associated key questions in coastal temperate rainforest (CTR) land–ocean systems.

| Knowledge gap   | Key questions   |
|---|---|
| Role of small watersheds in CTR marine ecosystems               | How do watershed characteristics predict the composition of material contributed to the coastal ocean?<br>What are the marine biogeochemical processes that determine that fate of materials emanating from small watersheds?<br>How do marine biogeochemical processes scale, spatially and temporally, with watershed and plume size?<br>What are the cumulative effects of small watersheds on coastal ecosystems?<br>How do changing inputs of terrestrial material alter coastal biogeochemistry (e.g., hypoxia, acidification)? |
| Freshwater carbonate system                                     | How does the freshwater carbonate system vary across the full range of CTR watershed types?<br>How do contrasting land uses and geological characteristics of river basins determine the timing and composition of river runoff and influence coastal ocean carbonate chemistry?<br>How does the interplay between river discharges and coastal upwelling influence the spatial/temporal variability regime in carbonate chemistry?   |
| Role of terrestrial micronutrients in CTR marine ecosystems     | Are deep nearshore, coastal transition, and shelf zone habitats in CTR regions seasonally iron-limited?<br>What is the role of terrestrially derived iron in nearshore, coastal transition, and shelf zone primary production?  |
| Role of terrestrial macronutrients in CTR marine ecosystems     | What are the spatial and temporal patterns of marine macronutrient(s) limitation in CTR regions, and in nearshore and coastal transition zones in particular?   |
| Balance of autotrophy vs. heterotrophy in CTR marine ecosystems | How does freshwater macronutrient delivery contribute to limitation/replenishment in the marine environment?<br>How does the composition of terrestrial material effect autotrophy/heterotrophy ratios?<br>What are the spatial and temporal scales of autotrophy/heterotrophy ratios associated with terrestrial material flux?<br>What are the nutritional implications of autotrophy/heterotrophy ratios for marine food webs, for example, essential fatty acid production, energy transfer efficiency, food chain length?        |
| Transport and food web uptake of terrestrial organic matter     | What approaches can be used to trace and quantify terrestrial material contributions to marine food webs despite its transformation during trophic transfer?<br>What is the spatial and temporal variability of terrestrial subsidies to the marine ecosystem?<br>What are the nutritional implications of terrestrial materials for marine biota, for example, provision of essential fatty acids and micronutrients?  |
| Evolutionary consequences of land–ocean connections             | What are organism dependencies across life stages and life history events on freshwater and terrestrial materials flux in CTR regions?<br>How will organisms adapted to CTR land–ocean connections be affected by change?   |
| The effects of extreme events                                   | What are the individual and synergistic effects of extreme events such as wildfire, landslides, and flooding on the quantity, quality, and timing of terrestrial material exported to the marine environment?<br>What are the short- and long-term effects of extreme land–ocean connection events on marine biogeochemistry and ecosystems in CTR regions?   |
| Effects of anthropogenic stressors on the land–ocean system     | What are the individual and synergistic effects of intensive human activities including forestry, agriculture, aquaculture, hydropower, dredging, industrialization, urbanization and associated shoreline development on land–ocean connections?   |
| Hidden land–ocean connections                                   | What is the contribution of saline and fresh submarine groundwater discharge to micro and macronutrients in the CTR coastal ocean?<br>What is the role of shelf canyons in transporting terrestrial materials to the deep ocean in CTR regions?   |

oceanographic surveys that are the basis of coastal water characterization and observation. The inclusion of Nearshore and Coastal Transition zone biogeochemical processes into research about cross-shelf coastal dynamics is needed to develop a more complete and integrated understanding of land–ocean interactions in CTR regions. One of the challenges with doing so is the higher-resolution spatial and temporal features that must be sampled to resolve the processes and interactions occurring in these zones. For example, small

plumes exist at scales of centimeters (vertically), not typically measured by standard oceanographic methods. Yet, locally and collectively at regional scales, small-scale processes that are temporally variable may be critical to the fate of materials transported by these small watershed outflows, and their role in coastal ecosystems. The development and application of new methods is required to resolve small plume dynamics, for example, moorings, drones (aerial and underwater), high-resolution satellite imagery, autonomous surface vessels,

surface-mounted multi-probe data loggers (e.g., temperature, salinity, macronutrients, chl-*a*), and hydrodynamic modeling, as well as new approaches that link information collected across different spatial scales, from point source to coast-wide, such as nested models. Resolving the biogeochemical processes and signatures in small watersheds and their associated plumes is needed to understand their role in CTR ecosystems and guide responsible management and land-use planning for these features that contribute more than half of the freshwater reaching the coastal ocean in the NPCTR.

### Biogeochemical processes at the land–ocean interface

Expanded research is needed to better understand the processes that govern the transport, transformation, retention and removal of freshwater and terrestrial material in Near-shore, Coastal Transition, Shelf and Offshore zones, and their effects on the marine ecosystem. There is a particular need for research on unconstrained inputs to CTR marine ecosystems, foremost among which are submarine groundwater discharge and its controlling factors in watershed geology and hydrology, and wildfire effects through modification of freshwater biogeochemistry, material flux, and ash deposition. Microcosm and mesocosm experiments are one approach to testing hypotheses in a controlled environment to better understand terrestrial material processing and its effect on the marine ecosystem (e.g., uptake of terrestrial DOC/DON by marine bacteria). Experimental systems, real or modeled, can also be used to explore how predicted changes in CTR ecosystems (e.g., increased freshwater flows, acidification, increased turbidity) are likely to impact biota, from individuals (e.g., physiology, behavior, growth) to communities (e.g., food web pathways, competitive interactions, functional properties). Opportunities exist for natural experiments through engagement with restoration efforts, for example, dam removal (Morley et al. 2020) and wetland restoration (Littles et al. 2022), that build understanding of essential land–ocean linkages and their roles at the habitat and community level. Experimental case studies need to be complemented by observational programs that can resolve the effects of short- to long-term change on the land–ocean system (Alin et al. 2024).

One area of particular importance is the balance of autotrophy vs. heterotrophy in CTR marine ecosystems. The large input of terrestrial OM to CTR marginal oceans favors heterotrophic bacterial production over autotrophic production (Dagg et al. 2004; Wikner and Andersson 2012), and this is expected to increase under ongoing climate change and other human impacts. This has consequences for the marine food web, including shifting energy flow toward potentially less efficient microbial pathways and reducing production of essential fatty acids necessary for the health of higher trophic level organisms. However, the relative contributions of autotrophy and heterotrophy associated with terrestrial inputs to the marine ecosystem, and how these contributions scale across the shelf, remain poorly understood and could be

addressed through the incorporation of more omics- and natural or experimental stable-isotope-based approaches.

### Harmonize measurements across domains and disciplines

Comparable measurements of terrestrial, freshwater, and marine ecosystem properties are a necessary step toward an integrative understanding of land–ocean interactions. From a biogeochemical perspective, oceanographers often focus on macronutrients. Doing so can bias understanding of coastal food webs toward inputs affecting autotrophic production, while ignoring significant microelement and OM contributions. Basic surveys at the land–ocean interface should include measurements of turbidity, water temperature, dissolved oxygen, total dissolved nitrogen, ammonium, DOC, POC, and iron (Fe), in addition to the major macronutrients and fatty acids. Though it is acknowledged that some of these measurements may be more challenging to make in marine waters due to lower concentration and analytical salinity effects, they are necessary to fully resolve ecosystem processes in coastal waters (Ward et al. 2020). Harmonization of measurements also requires standardization of methods used. Establishing a common suite of measurements across marine and freshwater, and method standardization, would benefit from workshops and working groups that connect researchers across domains and disciplines. Importantly, data suitable to answer some of the research questions highlighted in Table 1 may already exist in unpublished datasets, and collaborative initiatives would provide a forum to discuss and share these data. Adoption of FAIR data principals—Findability, Accessibility, Interoperability, and Reusability—across land–ocean research domains would support integrated knowledge development in future initiatives (Wilkinson et al. 2016).

### Conduct integrated land-to-ocean field surveys that draw on diverse knowledge types

Transdisciplinary collaborative surveys have the potential to link scientists in terrestrial freshwater, coastal, and marine research disciplines (e.g., geomorphology, hydrology, biogeochemistry, ecology) through simultaneous integrative watershed-to-shelf surveys. With careful sampling design and timing, such surveys could vastly increase understanding of the land–ocean continuum, including key environmental factors describing stepping stone regions or “control points” (Bernhardt et al. 2017) where heightened transport, transformation, retention, and removal of materials occurs. Such a meta-ecosystem approach acknowledges the strength of the connections between land and ocean in CTR regions. Data collected in integrated surveys could feed back into marine ecosystem models that are explicitly developed to incorporate terrestrial inputs. Taking steps in this direction will foster positive feedback between models, experiments, and field surveys, and support crossing the land–ocean disciplinary divide. Such integration could be further enhanced through the inclusion

of traditional ecological knowledge and indigenous world views that already embody an understanding of interconnectedness across the land–ocean continuum (Wolf et al. 1995; Thornton 2017; Enyew et al. 2021; Tulloch et al. 2024).

## Conclusions

In writing this review, our intention was to advance a conceptual understanding of the unique physical, chemical, and biological processes occurring at the land–ocean interface in CTR regions, and their roles in structuring marine ecosystem dynamics. Although we specifically use the NPCTR as a model system, the defining characteristics, processes, and future challenges are applicable and relevant to CTR systems globally. To date, global research around land–ocean interactions and emerging conceptual frameworks have focused on the largest watersheds draining into low-latitude subtropical and tropical oceans (30° S to 30° N). However, CTR regions differ from low-latitude regions in many fundamental aspects, both terrestrial and marine. Seasonality is intense and this governs discharge and material transport cycles, incident light, and productivity in both terrestrial and aquatic environments. Watersheds are diverse, varying in their contributions of rain, snow, and ice to discharge volume, timing, gradients, and energy. Furthermore, small coastal watersheds contribute disproportionately to total discharge volume. Importantly, the temperate and subarctic oceans that CTR regions empty into differ from the oligotrophic low-latitude oceans of tropical and subtropical rivers in being largely eutrophic. This has often been cited as a reason for terrestrial inputs being more important in low-latitude marine ecosystems; however, it is clear from the evidence presented in this review that freshwater and terrestrial materials are a critical ingredient in the structure and function of marine ecosystems in CTR regions. The spatial and temporal scales of land–ocean interactions in CTR regions vary from those of tiny freshwater plumes to the cumulative effects of freshwater and material fluxes across the Nearshore to Offshore zones. While the importance of terrestrial inputs to CTR marine ecosystems is apparent, critical knowledge gaps remain, which must be filled so as to advance an integrated understanding of the CTR meta-ecosystem. An integrated, transdisciplinary approach is necessary to understand and predict CTR marine ecosystem responses to climate change combined with other anthropogenic stressors. Such research efforts will provide critical and urgent information to better inform adaptation to climate change, land-use practices that support functionality of the land–ocean meta-ecosystem, and management responses to the extreme events—including heatwaves, fire, and flooding and their downstream impacts—that are occurring almost annually and impacting valued benefits from recreation to fisheries.

## Data availability statement

There are no new data associated with this publication. It is based on assessment of the literature or previously published data sources.

## References

- Aguilera, R., and J. M. Melack. 2018. Relationships among nutrient and sediment fluxes, hydrological variability, fire, and land cover in coastal California catchments. *J. Geophys. Res. Biogeophys.* **123**: 2568–2589. doi:10.1029/2017JG004119
- Aguilera, V. M., C. A. Vargas, M. A. Lardies, and M. J. Poupin. 2016. Adaptive variability to low-pH river discharges in *Acartia tonsa* and stress responses to high PCO<sub>2</sub> conditions. *Mar. Ecol.* **37**: 215–226. doi:10.1111/maec.12282
- Alaback, P. B. 1991. Comparative ecology of temperate rainforests of the Americas along analogous climatic gradients. *Rev. Chil. Hist. Nat.* **64**: 399–412.
- Albano, C. M., M. D. Dettinger, and A. A. Harpold. 2020. Patterns and drivers of atmospheric river precipitation and hydrologic impacts across the Western United States. *J. Hydrometeorol.* **21**: 143–159. doi:10.1175/JHM-D-19-0119.1
- Alin, S. R., J. A. Newton, R. A. Feely, S. Siedlecki, and D. Greeley. 2024. Seasonality and response of ocean acidification and hypoxia to major environmental anomalies in the southern Salish Sea, North America (2014–2018). *Biogeosciences* **21**: 1639–1673. doi:10.5194/bg-21-1639-2024
- Anderson, S. P. 2005. Glaciers show direct linkage between erosion rate and chemical weathering fluxes. *Geomorphology* **67**: 147–157. doi:10.1016/j.geomorph.2004.07.010
- Andersson, A., and others. 2018. Influence of allochthonous dissolved organic matter on pelagic basal production in a northerly estuary. *Estuar. Coast. Shelf Sci.* **204**: 225–235. doi:10.1016/j.ecss.2018.02.032
- Arimitsu, M. L., J. F. Piatt, E. N. Madison, J. S. Conaway, and N. Hillgruber. 2012. Oceanographic gradients and seabird prey community dynamics in glacial fjords. *Fish. Oceanogr.* **21**: 148–169. doi:10.1111/j.1365-2419.2012.00616.x
- Arimitsu, M. L., K. A. Hobson, D. A. N. Webber, J. F. Piatt, E. W. Hood, and J. B. Fellman. 2018. Tracing biogeochemical subsidies from glacier runoff into Alaska's coastal marine food webs. *Glob. Chang. Biol.* **24**: 387–398. doi:10.1111/gcb.13875
- Atkinson, L. P., and others. 2002. Oceanographic observations in Chilean coastal waters between Valdivia and Concepción. *J. Geophys. Res. Oceans* **107**: 18-11–18-13. doi:10.1029/2001JC000991
- Atwater, B. F., and others. 2001. Rapid resetting of an estuarine recorder of the 1964 Alaska earthquake. *GSA Bull.* **113**: 1193–1204. doi:10.1130/0016-7606(2001)113<1193:RROER>2.0.CO;2
- Aufdenkampe, A. K., and others. 2011. Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Front. Ecol. Environ.* **9**: 53–60. doi:10.1890/100014

- Barnes, R. T., and P. A. Raymond. 2009. The contribution of agricultural and urban activities to inorganic carbon fluxes within temperate watersheds. *Chem. Geol.* **266**: 318–327. doi:10.1016/j.chemgeo.2009.06.018
- Barron, S. M., N. Mladenov, K. E. Sant, and A. M. Kinoshita. 2022. Surface water quality after the Woolsey fire in Southern California. *Water Air Soil Pollut.* **233**: 377. doi:10.1007/s11270-022-05844-x
- Barth, J. A., and others. 2024. Widespread and increasing near-bottom hypoxia in the coastal ocean off the United States Pacific northwest. *Sci. Rep.* **14**: 3798. doi:10.1038/s41598-024-54476-0
- Basdurak, N. B., J. L. Largier, and N. J. Nidziko. 2020. Modeling the dynamics of small-scale river and creek plumes in tidal waters. *J. Geophys. Res. Oceans* **125**: e2019JC015737. doi:10.1029/2019JC015737
- Beamer, J. P., D. F. Hill, D. McGrath, A. Arendt, and C. Kienholz. 2017. Hydrologic impacts of changes in climate and glacier extent in the Gulf of Alaska watershed. *Water Resour. Res.* **53**: 7502–7520. doi:10.1002/2016WR020033
- Bednaršek, N., G. Pelletier, A. Ahmed, and R. A. Feely. 2020. Chemical exposure due to anthropogenic ocean acidification increases risks for estuarine calcifiers in the Salish Sea: Biogeochemical model scenarios. *Front. Mar. Sci.* **7**: 580. doi:10.3389/fmars.2020.00580
- Bednaršek, N., and others. 2021. Integrated assessment of ocean acidification risks to pteropods in the northern high latitudes: Regional comparison of exposure, sensitivity and adaptive capacity. *Front. Mar. Sci.* **8**: 671497. doi:10.3389/fmars.2021.671497
- Bell, C. R., and L. J. Albright. 1981. Attached and free-floating bacteria in the Fraser River estuary, British Columbia, Canada. *Mar. Ecol. Prog. Ser.* **6**: 317–327. doi:10.3354/meps006317
- Berger, H. M., and others. 2021. Seasonality and life history complexity determine vulnerability of Dungeness crab to multiple climate stressors. *AGU Adv.* **2**: e2021AV000456. doi:10.1029/2021AV000456
- Bernhardt, E. S., J. R. Blaszczak, C. D. Ficken, M. L. Fork, K. E. Kaiser, and E. C. Seybold. 2017. Control points in ecosystems: Moving beyond the hot spot hot moment concept. *Ecosystems* **20**: 665–682. doi:10.1007/s10021-016-0103-y
- Bianchi, T. S. 2011. The role of terrestrially derived organic carbon in the coastal ocean: A changing paradigm and the priming effect. *Proc. Natl. Acad. Sci.* **108**: 19473–19481. doi:10.1073/pnas.1017982108
- Bianchi, T. S., and others. 2020. Fjords as aquatic critical zones (ACZs). *Earth Sci. Rev.* **203**: 103145. doi:10.1016/j.earscirev.2020.103145
- Bianucci, L., K. L. Denman, and D. Ianson. 2011. Low oxygen and high inorganic carbon on the Vancouver Island shelf. *J. Geophys. Res. Oceans* **116**: C07011. doi:10.1029/2010JC006720
- Bianucci, L., and others. 2018. Sensitivity of the regional ocean acidification and carbonate system in Puget Sound to ocean and freshwater inputs. *Elementa* **6**: 22. doi:10.1525/elementa.151
- Bidlack, A. L., and others. 2021. Climate-mediated changes to linked terrestrial and marine ecosystems across the Northeast Pacific coastal temperate rainforest margin. *Bioscience* **71**: 581–595. doi:10.1093/biosci/biaa171
- Blain, C. O., S. C. Hansen, and N. T. Shears. 2021. Coastal darkening substantially limits the contribution of kelp to coastal carbon cycles. *Glob. Chang. Biol.* **27**: 5547–5563. doi:10.1111/gcb.15837
- Bliss, A., R. Hock, and V. Radić. 2014. Global response of glacier runoff to twenty-first century climate change. *J. Geophys. Res. Earth* **119**: 717–730. doi:10.1002/2013JF002931
- Boldt, K. V., C. A. Nittrouer, and A. S. Ogston. 2013. Seasonal transfer and net accumulation of fine sediment on a muddy tidal flat: Willapa Bay, Washington. *Cont. Shelf Res.* **60**: S157–S172. doi:10.1016/j.csr.2012.08.012
- Borde, A. B., H. L. Diefenderfer, V. I. Cullinan, S. A. Zimmerman, and R. M. Thom. 2020. Ecohydrology of wetland plant communities along an estuarine to tidal river gradient. *Ecosphere* **11**: e03185. doi:10.1002/ecs2.3185
- Borde, A. B., R. M. Thom, S. Rumrill, and L. M. Miller. 2003. Geospatial habitat change analysis in Pacific northwest coastal estuaries. *Estuaries* **26**: 1104–1116. doi:10.1007/BF02803367
- Bouwman, A. F., and others. 2013. Nutrient dynamics, transfer and retention along the aquatic continuum from land to ocean: Towards integration of ecological and biogeochemical models. *Biogeosciences* **10**: 1–22. doi:10.5194/bg-10-1-2013
- Boyd, P. W., and others. 1998. Atmospheric iron supply and enhanced vertical carbon flux in the NE subarctic Pacific: Is there a connection? *Global Biogeochem. Cycles* **12**: 429–441. doi:10.1029/98GB00745
- Brand, M. W., and others. 2023. Impacts of a Cascadia subduction zone earthquake on water levels and wetlands of the lower Columbia River and estuary. *Geophys. Res. Lett.* **50**: e2023GL103017. doi:10.1029/2023GL103017
- Brandenberger, J. M., E. A. Crecelius, and P. Louchouart. 2008. Historical inputs and natural recovery rates for heavy metals and organic biomarkers in Puget Sound during the 20th century. *Environ. Sci. Technol.* **42**: 6786–6790. doi:10.1021/es703099c
- Brandenberger, J. M., P. Louchouart, and E. A. Crecelius. 2011. Natural and post-urbanization signatures of hypoxia in two basins of Puget Sound: Historical reconstruction of redox sensitive metals and organic matter inputs. *Aquat. Geochem.* **17**: 645–670. doi:10.1007/s10498-011-9129-0
- Breckenridge, J., E. Pakhomov, S. Emry, and N. Mahara. 2020. Copepod assemblage dynamics in a snowmelt-dominated

- estuary. *Estuaries Coasts* **43**: 1502–1518. doi:10.1007/s12237-020-00722-3
- Broullón, D., and others. 2020. A global monthly climatology of oceanic total dissolved inorganic carbon: A neural network approach. *Earth Syst. Sci. Data* **12**: 1725–1743. doi:10.5194/essd-12-1725-2020
- Bruland, K. W., E. L. Rue, and G. J. Smith. 2001. Iron and macronutrients in California coastal upwelling regimes: Implications for diatom blooms. *Limnol. Oceanogr.* **46**: 1661–1674. doi:10.4319/lo.2001.46.7.1661
- Callaway, J. C., A. B. Borde, H. L. Diefenderfer, V. T. Parker, J. M. Rybczyk, and R. M. Thom. 2012. Pacific coast tidal wetlands, p. 103–116. *In* D. P. Batzer and A. H. Baldwin [eds.], *Wetland habitats of North America: Ecology and conservation concerns*. Univ. of California Press. doi:10.1525/9780520951419-010
- Carmack, E., P. Winsor, and W. Williams. 2015. The contiguous panarctic riverine coastal domain: A unifying concept. *Prog. Oceanogr.* **139**: 13–23. doi:10.1016/j.pocean.2015.07.014
- Carstensen, J., and others. 2020. Factors regulating the coastal nutrient filter in the Baltic Sea. *Ambio* **49**: 1194–1210. doi:10.1007/s13280-019-01282-y
- Chan, F., and others. 2017. Persistent spatial structuring of coastal ocean acidification in the California current system. *Sci. Rep.* **7**: 2526. doi:10.1038/s41598-017-02777-y
- Chandler, P. C. 2021. Sea surface temperature and salinity observed at shore stations and weather buoys along the B.C. coast in 2020, p. 40–43. *In* J. L. Boldt, A. Javorski, and P. C. Chandler [eds.], *State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2020*. Canadian technical reports in fisheries and aquatic science. <https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/41067113.pdf>
- Chapman, P. M., and R. O. Brinkhurst. 1981. Seasonal changes in interstitial salinities and seasonal movements of subtidal benthic invertebrates in the Fraser River estuary, B. C. *Estuar. Coast. Shelf Sci.* **12**: 49–66. doi:10.1016/S0302-3524(81)80117-X
- Chase, Z., A. van Geen, P. M. Kosro, J. Marra, and P. A. Wheeler. 2002. Iron, nutrient, and phytoplankton distributions in Oregon coastal waters. *J. Geophys. Res. Oceans* **107**: 38-1–38-17. doi:10.1029/2001JC000987
- Chase, Z., P. G. Stratton, and B. Hales. 2007. Iron links river runoff and shelf width to phytoplankton biomass along the U.S. west coast. *Geophys. Res. Lett.* **34**: L04607. doi:10.1029/2006GL028069
- Cheung, W. W. L., R. D. Brodeur, T. A. Okey, and D. Pauly. 2015. Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. *Prog. Oceanogr.* **130**: 19–31. doi:10.1016/j.pocean.2014.09.003
- Cheung, W. W. L., and T. L. Frölicher. 2020. Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific. *Sci. Rep.* **10**: 6678. doi:10.1038/s41598-020-63650-z
- Christie, P., D. Fluharty, H. Kennard, R. Pollnac, B. Warren, and T. Williams. 2018. Policy pivot in Puget Sound: Lessons learned from marine protected areas and tribally-led estuarine restoration. *Ocean Coast. Manag.* **163**: 72–81. doi:10.1016/j.ocecoaman.2018.05.020
- Chu, J. W. F., and V. Tunnicliffe. 2015. Oxygen limitations on marine animal distributions and the collapse of epibenthic community structure during shoaling hypoxia. *Glob. Chang. Biol.* **21**: 2989–3004. doi:10.1111/gcb.12898
- Clow, D. W., C. Rhoades, J. Briggs, M. Caldwell, and W. M. Lewis. 2011. Responses of soil and water chemistry to mountain pine beetle induced tree mortality in Grand County, Colorado, USA. *Appl. Geochem.* **26**: S174–S178. doi:10.1016/j.apgeochem.2011.03.096
- Compton, J. E., M. R. Church, S. T. Larned, and W. E. Hogsett. 2003. Nitrogen export from forested watersheds in the Oregon coast range: The role of N<sub>2</sub>-fixing red Alder. *Ecosystems* **6**: 773–785. doi:10.1007/s10021-002-0207-4
- Conley, D., M. Sommer, J. D. Meunier, D. Kaczorek, and L. Saccone. 2006. Silicon in the terrestrial biogeochemistry, p. 13–28. *In* V. Ittekkot, D. Unger, C. Humborg, and N. Tac An [eds.], *The silicon cycle: Human perturbations and impacts on aquatic systems*. Island Press.
- Conway-Cranos, L., and others. 2015. Stable isotopes and oceanographic modeling reveal spatial and trophic connectivity among terrestrial, estuarine, and marine environments. *Mar. Ecol. Prog. Ser.* **533**: 15–28. doi:10.3354/meps11318
- Coward, E. K., K. Seech, M. L. Carter, R. E. Flick, and V. H. Grassian. 2022. Of sea and smoke: Evidence of marine dissolved organic matter deposition from 2020 Western United States wildfires. *Environ. Sci. Technol. Lett.* **9**: 869–876. doi:10.1021/acs.estlett.2c00383
- Crawford, W. R., P. J. Brickley, and A. C. Thomas. 2007. Mesoscale eddies dominate surface phytoplankton in northern Gulf of Alaska. *Prog. Oceanogr.* **75**: 287–303. doi:10.1016/j.pocean.2007.08.016
- Crump, B. C., and J. A. Baross. 1996. Particle-attached bacteria and heterotrophic plankton associated with the Columbia River estuarine turbidity maxima. *Mar. Ecol. Prog. Ser.* **138**: 265–273. doi:10.3354/meps138265
- Crump, B. C., and others. 2017. Quantity and quality of particulate organic matter controls bacterial production in the Columbia River estuary. *Limnol. Oceanogr.* **62**: 2713–2731. doi:10.1002/lno.10601
- Crusius, J., A. W. Schroth, J. A. Resing, J. Cullen, and R. W. Campbell. 2017. Seasonal and spatial variabilities in northern Gulf of Alaska surface water iron concentrations driven by shelf sediment resuspension, glacial meltwater, a Yakutat eddy, and dust. *Global Biogeochem. Cycles* **31**: 942–960. doi:10.1002/2016GB005493

- Crusius, J., A. W. Schroth, S. Gassó, C. M. Moy, R. C. Levy, and M. Gatica. 2011. Glacial flour dust storms in the Gulf of Alaska: Hydrologic and meteorological controls and their importance as a source of bioavailable iron. *Geophys. Res. Lett.* **38**: L06602. doi:[10.1029/2010GL046573](https://doi.org/10.1029/2010GL046573)
- Cuevas, L. A., F. J. Tapia, J. L. Iriarte, H. E. González, N. Silva, and C. A. Vargas. 2019. Interplay between freshwater discharge and oceanic waters modulates phytoplankton size-structure in fjords and channel systems of the Chilean Patagonia. *Prog. Oceanogr.* **173**: 103–113. doi:[10.1016/j.pcean.2019.02.012](https://doi.org/10.1016/j.pcean.2019.02.012)
- Cullen, J. T., M. Chong, and D. Ianson. 2009. British Columbian continental shelf as a source of dissolved iron to the subarctic northeast Pacific Ocean. *Global Biogeochem. Cycles* **23**: GB4012. doi:[10.1029/2008GB003326](https://doi.org/10.1029/2008GB003326)
- Curra-Sánchez, E. D., and others. 2022. Contrasting land-uses in two small river basins impact the colored dissolved organic matter concentration and carbonate system along a river-coastal ocean continuum. *Sci. Total Environ.* **806**: 150435. doi:[10.1016/j.scitotenv.2021.150435](https://doi.org/10.1016/j.scitotenv.2021.150435)
- D'Amore, D. V., C.-L. Ping, and P. A. Herendeen. 2015. Hydro-morphic soil development in the coastal temperate rainforest of Alaska. *Soil Sci. Soc. Am. J.* **79**: 698–709. doi:[10.2136/sssaj2014.08.0322](https://doi.org/10.2136/sssaj2014.08.0322)
- Dagg, M., R. Benner, S. Lohrenz, and D. Lawrence. 2004. Transformation of dissolved and particulate materials on continental shelves influenced by large rivers: Plume processes. *Cont. Shelf Res.* **24**: 833–858. doi:[10.1016/j.csr.2004.02.003](https://doi.org/10.1016/j.csr.2004.02.003)
- Davis, J. M., C. V. Baxter, E. J. Rosi-Marshall, J. L. Pierce, and B. T. Crosby. 2013. Anticipating stream ecosystem responses to climate change: Toward predictions that incorporate effects via land–Water linkages. *Ecosystems* **16**: 909–922. doi:[10.1007/s10021-013-9653-4](https://doi.org/10.1007/s10021-013-9653-4)
- Davis, K. A., and others. 2014. Estuary-enhanced upwelling of marine nutrients fuels coastal productivity in the U.S. Pacific northwest. *J. Geophys. Res. Oceans* **119**: 8778–8799. doi:[10.1002/2014JC010248](https://doi.org/10.1002/2014JC010248)
- Dean, T. A., L. Halderson, D. R. Laur, S. C. Jewett, and A. Blanchard. 2000. The distribution of nearshore fishes in kelp and eelgrass communities in Prince William sound, Alaska: Associations with vegetation and physical habitat characteristics. *Environ. Biol. Fishes* **57**: 271–287. doi:[10.1023/A:1007652730085](https://doi.org/10.1023/A:1007652730085)
- Degerman, R., R. Lefébure, P. Byström, U. Båmstedt, S. Larsson, and A. Andersson. 2018. Food web interactions determine energy transfer efficiency and top consumer responses to inputs of dissolved organic carbon. *Hydrobiologia* **805**: 131–146. doi:[10.1007/s10750-017-3298-9](https://doi.org/10.1007/s10750-017-3298-9)
- DellaSala, D. A. 2011. *Temperate and boreal rainforests of the world: Ecology and conservation*. Island Press.
- Dethier, M. N., and others. 2016. Multiscale impacts of armoring on Salish Sea shorelines: Evidence for cumulative and threshold effects. *Estuar. Coast. Shelf Sci.* **175**: 106–117. doi:[10.1016/j.ecss.2016.03.033](https://doi.org/10.1016/j.ecss.2016.03.033)
- Dickson, A. G., C. L. Sabine, and J. R. Christian. 2007. *Guide to best practices for ocean CO<sub>2</sub> measurements*. PICES Special Publication 3, 191 pp.
- Diefenderfer, H. L., A. B. Borde, and V. I. Cullinan. 2021. Floodplain wetland channel planform, cross-sectional morphology, and sediment characteristics along an estuarine to tidal river gradient. *J. Geophys. Res. Earth* **126**: e2019JF005391. doi:[10.1029/2019JF005391](https://doi.org/10.1029/2019JF005391)
- Diefenderfer, H. L., and D. R. Montgomery. 2009. Pool spacing, channel morphology, and the restoration of tidal forested wetlands of the Columbia River, U.S.A. *Restor. Ecol.* **17**: 158–168. doi:[10.1111/j.1526-100X.2008.00449.x](https://doi.org/10.1111/j.1526-100X.2008.00449.x)
- Dodrill, T. N., Y. Pan, and T. D. Peterson. 2023. River discharge mediates extent of phytoplankton and harmful algal bloom habitat in the Columbia River estuary (USA) during North Pacific marine heat waves. *Estuaries Coasts* **46**: 166–181. doi:[10.1007/s12237-022-01129-y](https://doi.org/10.1007/s12237-022-01129-y)
- Duarte, C. M., and others. 2013. Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. *Estuaries Coasts* **36**: 221–236. doi:[10.1007/s12237-013-9594-3](https://doi.org/10.1007/s12237-013-9594-3)
- Edwards, R. T., and others. 2021. Riverine dissolved organic carbon and freshwater export in the eastern Gulf of Alaska. *J. Geophys. Res. Biogeo.* **126**: e2020JG005725. doi:[10.1029/2020JG005725](https://doi.org/10.1029/2020JG005725)
- Emmett, R., and others. 2000. Geographic signatures of north American west coast estuaries. *Estuaries* **23**: 765–792. doi:[10.2307/1352998](https://doi.org/10.2307/1352998)
- Enyew, E. L., M. P. Poto, and A. Tsiouvalas. 2021. Beyond borders and states: Modelling ocean connectivity according to indigenous cosmovisions. *Arctic Rev.* **12**: 207–221. doi:[10.23865/arctic.v12.3290](https://doi.org/10.23865/arctic.v12.3290)
- Esenkulova, S., K. D. Suchy, R. Pawlowicz, M. Costa, and I. A. Pearsall. 2021. Harmful algae and oceanographic conditions in the Strait of Georgia, Canada based on citizen science monitoring. *Front. Mar. Sci.* **8**: 725092. doi:[10.3389/fmars.2021.725092](https://doi.org/10.3389/fmars.2021.725092)
- Etherington, L., P. Hooge, E. Hooge, and D. Hill. 2007. Oceanography of Glacier Bay, Alaska: Implications for biological patterns in a glacial fjord estuary. *Estuaries Coasts* **30**: 927–944. doi:[10.1007/BF02841386](https://doi.org/10.1007/BF02841386)
- Evans, W., B. Hales, and P. G. Stratton. 2013. pCO<sub>2</sub> distributions and air–water CO<sub>2</sub> fluxes in the Columbia River estuary. *Estuar. Coast. Shelf Sci.* **117**: 260–272. doi:[10.1016/j.ecss.2012.12.003](https://doi.org/10.1016/j.ecss.2012.12.003)
- Evans, W., G. T. Lebon, C. D. Harrington, Y. Takeshita, and A. Bidlack. 2022. Marine CO<sub>2</sub> system variability along the north-east Pacific inside passage determined from an Alaskan ferry. *Biogeosciences* **19**: 1277–1301. doi:[10.5194/bg-19-1277-2022](https://doi.org/10.5194/bg-19-1277-2022)
- Evans, W., J. T. Mathis, and J. N. Cross. 2014. Calcium carbonate corrosivity in an Alaskan inland sea. *Biogeosciences* **11**: 365–379. doi:[10.5194/bg-11-365-2014](https://doi.org/10.5194/bg-11-365-2014)

- Fang, X., X. Hou, X. Li, W. Hou, M. Nakaoka, and X. Yu. 2018. Ecological connectivity between land and sea: A review. *Ecol. Res.* **33**: 51–61. doi:10.1007/s11284-017-1549-x
- Farmer, D. M., and H. J. Freeland. 1983. The physical oceanography of fjords. *Prog. Oceanogr.* **12**: 147–219. doi:10.1016/0079-6611(83)90004-6
- Feely, R. A., B. R. Carter, S. R. Alin, N. Bednaršek, and D. Greeley. 2024. How anthropogenic carbon dioxide uptake and respiration reduce habitat suitability for marine calcifiers along the west coast of North America. *J. Geophys. Res. Oceans* **129**: 2023JC019892R. doi:10.1029/2023JC019892
- Feely, R. A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales. 2008. Evidence for upwelling of corrosive “acidified” water onto the continental shelf. *Science* **320**: 1490–1492. doi:10.1126/science.1155676
- Feely, R. A., and others. 2004. Impact of anthropogenic CO<sub>2</sub> on the CaCO<sub>3</sub> system in the oceans. *Science* **305**: 362–366. doi:10.1126/science.1097329
- Feely, R. A., and others. 2010. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuar. Coast. Shelf Sci.* **88**: 442–449. doi:10.1016/j.ecss.2010.05.004
- Feely, R. A., and others. 2012. Decadal changes in the aragonite and calcite saturation state of the Pacific Ocean. *Global Biogeochem. Cycles* **26**: GB3001. doi:10.1029/2011GB004157
- Feely, R. A., and others. 2016. Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuar. Coast. Shelf Sci.* **183**: 260–270. doi:10.1016/j.ecss.2016.08.043
- Fellman, J. B., E. Hood, D. V. D’Amore, and R. T. Edwards. 2021. Streamflow variability controls N and P export and speciation from Alaskan coastal temperate rainforest watersheds. *Biogeochemistry* **152**: 253–270. doi:10.1007/s10533-020-00752-w
- Fellman, J. B., E. Hood, M. I. Behnke, J. M. Welker, and R. G. M. Spencer. 2020. Stormflows drive stream carbon concentration, speciation, and dissolved organic matter composition in coastal temperate rainforest watersheds. *J. Geophys. Res. Biogeo.* **125**: e2020JG005804. doi:10.1029/2020JG005804
- Fellman, J. B., E. Hood, R. G. M. Spencer, A. Stubbins, and P. A. Raymond. 2014. Watershed glacier coverage influences dissolved organic matter biogeochemistry in coastal watersheds of Southeast Alaska. *Ecosystems* **17**: 1014–1025. doi:10.1007/s10021-014-9777-1
- Fellman, J. B., E. Hood, R. T. Edwards, and D. V. D’Amore. 2009. Changes in the concentration, biodegradability, and fluorescent properties of dissolved organic matter during stormflows in coastal temperate watersheds. *J. Geophys. Res. Biogeo.* **114**: G01021. doi:10.1029/2008JG000790
- Fellman, J. B., R. G. M. Spencer, P. J. Hernes, R. T. Edwards, D. V. D’Amore, and E. Hood. 2010. The impact of glacier runoff on the biodegradability and biochemical composition of terrigenous dissolved organic matter in near-shore marine ecosystems. *Mar. Chem.* **121**: 112–122. doi:10.1016/j.marchem.2010.03.009
- Finke, J. F., B. P. V. Hunt, C. Winter, E. C. Carmack, and C. A. Suttle. 2017. Nutrients and other environmental factors influence virus abundances across oxic and hypoxic marine environments. *Viruses* **9**: 152. doi:10.3390/v9060152
- Finkel, Z. V. 2007. Does phytoplankton cell size matter? The evolution of modern marine food webs, p. 333–350. *In* P. G. Falkowski and A. H. Knoll [eds.], *Evolution of primary producers in the sea*. Academic Press.
- Foreman, M. G. G., B. Pal, and W. J. Merryfield. 2011. Trends in upwelling and downwelling winds along the British Columbia shelf. *J. Geophys. Res. Oceans* **116**: C10023. doi:10.1029/2011JC006995
- Fortunato, C. S., L. Herfort, P. Zuber, A. M. Baptista, and B. C. Crump. 2012. Spatial variability overwhelms seasonal patterns in bacterioplankton communities across a river to ocean gradient. *ISME J.* **6**: 554–563. doi:10.1038/ismej.2011.135
- Fortunato, C. S., and B. C. Crump. 2015. Microbial gene abundance and expression patterns across a river to ocean salinity gradient. *PLoS One* **10**: e0140578. doi:10.1371/journal.pone.0140578
- Franco, A. C., and others. 2021. Anthropogenic and climatic contributions to observed carbon system trends in the northeast Pacific. *Global Biogeochem. Cycles* **35**: e2020GB006829. doi:10.1029/2020GB006829
- Freeland, H. J. 2006. What proportion of the north Pacific current finds its way into the Gulf of Alaska? *Atmos. Ocean* **44**: 321–330. doi:10.3137/ao.440401
- Frigstad, H., and others. 2013. Long-term trends in carbon, nutrients and stoichiometry in Norwegian coastal waters: Evidence of a regime shift. *Prog. Oceanogr.* **111**: 113–124. doi:10.1016/j.pocean.2013.01.006
- Gambi, M. C., A. R. Nowell, and P. A. Jumars. 1990. Flume observations on flow dynamics in *Zostera marina* (eelgrass) beds. *Mar. Ecol. Prog. Ser.* **61**: 159–169. doi:10.3354/meps061159
- Gardner, A. S., and others. 2013. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science* **340**: 852–857. doi:10.1126/science.1234532
- Gargett, A. E. 1997. The optimal stability ‘window’: A mechanism underlying decadal fluctuations in North Pacific salmon stocks? *Fish. Oceanogr.* **6**: 109–117. doi:10.1046/j.1365-2419.1997.00033.x
- Gariano, S. L., and F. Guzzetti. 2016. Landslides in a changing climate. *Earth Sci. Rev.* **162**: 227–252. doi:10.1016/j.earscirev.2016.08.011

- Geertsema, M., and others. 2022. The 28 November 2020 landslide, tsunami, and outburst flood—A hazard cascade associated with rapid deglaciation at Elliot Creek, British Columbia, Canada. *Geophys. Res. Lett.* **49**: e2021GL096716. doi:10.1029/2021GL096716
- Giesbrecht, I. J. W., and others. 2022. Watershed classification predicts streamflow regime and organic carbon dynamics in the northeast Pacific coastal temperate rainforest. *Global Biogeochem. Cycles* **36**: e2021GB007047. doi:10.1029/2021GB007047
- Gillett, N. P., and others. 2022. Human influence on the 2021 British Columbia floods. *Weather Clim. Extrem.* **36**: 100441. doi:10.1016/j.wace.2022.100441
- Goñi, M. A., J. A. Hatten, R. A. Wheatcroft, and J. C. Borgeld. 2013. Particulate organic matter export by two contrasting small mountainous rivers from the Pacific northwest, U.S. *A. J. Geophys. Res. Biogeo.* **118**: 112–134. doi:10.1002/jgrg.20024
- González, C. E., R. Escribano, A. Bode, and W. Schneider. 2019. Zooplankton taxonomic and trophic community structure across biogeochemical regions in the eastern south Pacific. *Front. Mar. Sci.* **5**: 498. doi:10.3389/fmars.2018.00498
- González, H. E., and others. 2010. Primary production and plankton dynamics in the Reloncaví Fjord and the Interior Sea of Chiloé, Northern Patagonia, Chile. *Mar. Ecol. Prog. Ser.* **402**: 13–30. doi:10.3354/meps08360
- González, H. E., and others. 2013. Land–ocean gradient in haline stratification and its effects on plankton dynamics and trophic carbon fluxes in Chilean Patagonian fjords (47–50° S). *Prog. Oceanogr.* **119**: 32–47. doi:10.1016/j.pocean.2013.06.003
- Granath, G., and others. 2021. The impact of wildfire on biogeochemical fluxes and water quality in boreal catchments. *Biogeosciences* **18**: 3243–3261. doi:10.5194/bg-18-3243-2021
- Gruber, N., and others. 2019. The oceanic sink for anthropogenic CO<sub>2</sub> from 1994 to 2007. *Science* **363**: 1193–1199. doi:10.1126/science.aau5153
- Gustavson, T. C. 1975. Sedimentation and physical limnology in proglacial Malaspina Lake, southeastern Alaska, p. 249–263. *In* A. V. Jopling & B. C. McDonald [eds.], *Glaciofluvial and Glaciolacustrine Sedimentation*. Society of Economic Paleontologists and Mineralogists, Special Publication 23. Society of Economic Paleontologists and Mineralogists.
- Haag, J., H. Dulai, and W. Burt. 2023. The role of submarine groundwater discharge to the input of macronutrients within a macrotidal subpolar estuary. *Estuaries Coasts* **46**: 1740–1755. doi:10.1007/s12237-023-01231-9
- Hage, S., and others. 2022. Turbidity currents can dictate organic carbon fluxes across river-fed fjords: An example from Bute inlet (BC, Canada). *J. Geophys. Res. Biogeo.* **127**: e2022JG006824. doi:10.1029/2022JG006824
- Haigh, R., D. Ianson, C. A. Holt, H. E. Neate, and A. M. Edwards. 2015. Effects of ocean acidification on temperate coastal marine ecosystems and fisheries in the Northeast Pacific. *PLoS One* **10**: e0117533. doi:10.1371/journal.pone.0117533
- Hall, J., P. Roni, K. Ross, M. J. Camp, J. Nuckols, and C. Ruffing. 2023. Estimating juvenile Salmon estuarine carrying capacities to support restoration planning and evaluation. *Estuaries Coasts* **46**: 1046–1066. doi:10.1007/s12237-023-01185-y
- Halofsky, J. E., D. L. Peterson, and B. J. Harvey. 2020. Changing wildfire, changing forests: The effects of climate change on fire regimes and vegetation in the Pacific northwest, USA. *Fire Ecol.* **16**: 4. doi:10.1186/s42408-019-0062-8
- Halofsky, J. E., D. L. Peterson, and R. A. Gravenmier [eds.]. 2022. *Climate change vulnerability and adaptation in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest*. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. doi:10.2737/PNW-GTR-1001
- Hamilton, D. S., and others. 2022. Earth, wind, fire, and pollution: Aerosol nutrient sources and impacts on ocean biogeochemistry. *Ann. Rev. Mar. Sci.* **14**: 303–330. doi:10.1146/annurev-marine-031921-013612
- Han, G., Z. Ma, N. Chen, R. Thomson, and A. Slangen. 2015. Changes in mean relative sea level around Canada in the twentieth and twenty-first centuries. *Atmos. Ocean* **53**: 452–463. doi:10.1080/07055900.2015.1057100
- Hare, A., W. Evans, K. Pocock, C. Weekes, and I. Gimenez. 2020. Contrasting marine carbonate systems in two fjords in British Columbia, Canada: Seawater buffering capacity and the response to anthropogenic CO<sub>2</sub> invasion. *PLoS One* **15**: e0238432. doi:10.1371/journal.pone.0238432
- Harfmann, J., T. Kurobe, B. Bergamaschi, S. Teh, and P. Hernes. 2019. Plant detritus is selectively consumed by estuarine copepods and can augment their survival. *Sci. Rep.* **9**: 9076. doi:10.1038/s41598-019-45503-6
- Harris, H. E., C. V. Baxter, and J. M. Davis. 2015. Debris flows amplify effects of wildfire on magnitude and composition of tributary subsidies to mainstem habitats. *Freshw. Sci.* **34**: 1457–1467. doi:10.1086/684015
- Harrison, P. J., J. D. Fulton, F. J. R. Taylor, and T. R. Parsons. 1983. Review of the biological oceanography of the Strait of Georgia: Pelagic environment. *Can. J. Fish. Aquat. Sci.* **40**: 1064–1094. doi:10.1139/f83-129
- Harrison, P. J., and others. 1991. Nutrient and plankton dynamics in the Fraser River plume, Strait of Georgia, British Columbia. *Mar. Ecol. Prog. Ser.* **70**: 291–304. doi:10.3354/meps070291
- Hartmann, J., N. Jansen, H. H. Dürr, S. Kempe, and P. Köhler. 2009. Global CO<sub>2</sub>-consumption by chemical weathering: What is the contribution of highly active weathering regions? *Global Planet. Change* **69**: 185–194. doi:10.1016/j.gloplacha.2009.07.007

- Held, M. B. E., and C. D. G. Harley. 2009. Responses to low salinity by the sea star *Pisaster ochraceus* from high- and low-salinity populations. *Invertebr. Biol.* **128**: 381–390. doi:10.1111/j.1744-7410.2009.00175.x
- Henson, S. A. 2007. Water column stability and spring bloom dynamics in the Gulf of Alaska. *J. Mar. Res.* **65**: 715–736. doi:10.1357/00224007784219002
- Herfort, L., and others. 2017. Factors affecting the bacterial community composition and heterotrophic production of Columbia River estuarine turbidity maxima. *MicrobiologyOpen* **6**: e00522. doi:10.1002/mbo3.522
- Herlemann, D. P. R., D. Lundin, A. F. Andersson, M. Labrenz, and K. Jürgens. 2016. Phylogenetic signals of salinity and season in bacterial community composition across the salinity gradient of the Baltic Sea. *Front. Microbiol.* **7**: 1883. doi:10.3389/fmicb.2016.01883
- Herlemann, D. P. R., M. Labrenz, K. Jürgens, S. Bertilsson, J. J. Waniek, and A. F. Andersson. 2011. Transitions in bacterial communities along the 2000 km salinity gradient of the Baltic Sea. *ISME J.* **5**: 1571–1579. doi:10.1038/ismej.2011.41
- Hickey, B., and N. Banas. 2008. Why is the northern end of the California current system so productive? *Oceanography* **21**: 90–107. doi:10.5670/oceanog.2008.07
- Hickey, B. M., and others. 2010. River influences on shelf ecosystems: Introduction and synthesis. *J. Geophys. Res. Oceans* **115**: C00B17. doi:10.1029/2009JC005452
- Hill, D. F., N. Bruhis, S. E. Calos, A. Arendt, and J. Beamer. 2015. Spatial and temporal variability of freshwater discharge into the Gulf of Alaska. *J. Geophys. Res. Oceans* **120**: 634–646. doi:10.1002/2014JC010395
- Hill, P. S., T. G. Milligan, and W. R. Geyer. 2000. Controls on effective settling velocity of suspended sediment in the Eel River flood plume. *Cont. Shelf Res.* **20**: 2095–2111. doi:10.1016/S0278-4343(00)00064-9
- Hood, E., J. B. Fellman, and R. G. M. Spencer. 2020. Glacier loss impacts riverine organic carbon transport to the ocean. *Geophys. Res. Lett.* **47**: e2020GL089804. doi:10.1029/2020GL089804
- Hood, E., and D. Scott. 2008. Riverine organic matter and nutrients in southeast Alaska affected by glacial coverage. *Nat. Geosci.* **1**: 583–587. doi:10.1038/ngeo280
- Hood, E., and others. 2009. Glaciers as a source of ancient and labile organic matter to the marine environment. *Nature* **462**: 1044–1047. doi:10.1038/nature08580
- Hood, W. G. 2023. Distribution of large wood in river delta tidal marshes: Implications for habitat restoration. *Estuaries Coasts* **46**: 109–127. doi:10.1007/s12237-022-01122-5
- Horner-Devine, A. R., R. D. Hetland, and D. G. MacDonald. 2015. Mixing and transport in coastal river plumes. *Annu. Rev. Fluid Mech.* **47**: 569–594. doi:10.1146/annurev-fluid-010313-141408
- Howarth, R. W., and R. Marino. 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnol. Oceanogr.* **51**: 364–376. doi:10.4319/lo.2006.51.1\_part\_2.0364
- Huss, M., and R. Hock. 2018. Global-scale hydrological response to future glacier mass loss. *Nat. Clim. Chang.* **8**: 135–140. doi:10.1038/s41558-017-0049-x
- Hyndes, G. A., I. Nagelkerken, R. J. McLeod, R. M. Connolly, P. S. Lavery, and M. A. Vanderklift. 2014. Mechanisms and ecological role of carbon transfer within coastal seascapes. *Biol. Rev.* **89**: 232–254. doi:10.1111/brv.12055
- Ianson, D., S. E. Allen, B. L. Moore-Maley, S. C. Johannessen, and R. W. Macdonald. 2016. Vulnerability of a semi-enclosed estuarine sea to ocean acidification in contrast with hypoxia. *Geophys. Res. Lett.* **43**: 5793–5801. doi:10.1002/2016GL068996
- Iken, K., and others. 2010. Large-scale spatial distribution patterns of echinoderms in nearshore rocky habitats. *PLoS One* **5**: e13845. doi:10.1371/journal.pone.0013845
- Inamdar, S., and others. 2012. Dissolved organic matter (DOM) concentration and quality in a forested mid-Atlantic watershed, USA. *Biogeochemistry* **108**: 55–76. doi:10.1007/s10533-011-9572-4
- Jackson, J. M., S. Johannessen, J. Del Bel Belluz, B. P. V. Hunt, and C. G. Hannah. 2022. Identification of a seasonal subsurface oxygen minimum in Rivers Inlet, British Columbia. *Estuaries and Coasts* **45**: 754–771. doi:10.1007/s12237-021-00999-y
- Jackson, J. M., L. Bianucci, C. G. Hannah, E. C. Carmack, and J. Barrette. 2021. Deep waters in British Columbia mainland fjords show rapid warming and deoxygenation from 1951 to 2020. *Geophys. Res. Lett.* **48**: e2020GL091094. doi:10.1029/2020GL091094
- Jackson, J. M., and others. 2023. Winter Arctic outflow winds cause upper ocean cooling and reoxygenation in a temperate Canadian fjord. *Geophys. Res. Lett.* **50**: e2023GL104549. doi:10.1029/2023GL104549
- Jakob, M., and S. Lambert. 2009. Climate change effects on landslides along the southwest coast of British Columbia. *Geomorphology* **107**: 275–284. doi:10.1016/j.geomorph.2008.12.009
- Jiang, L.-Q., B. R. Carter, R. A. Feely, S. K. Lauvset, and A. Olsen. 2019. Surface ocean pH and buffer capacity: Past, present and future. *Sci. Rep.* **9**: 18624. doi:10.1038/s41598-019-55039-4
- Jiang, L.-Q., R. A. Feely, B. R. Carter, D. J. Greeley, D. K. Gledhill, and K. M. Arzayus. 2015. Climatological distribution of aragonite saturation state in the global oceans. *Global Biogeochem. Cycles* **29**: 1656–1673. doi:10.1002/2015GB005198
- Johannessen, S. C., R. W. Macdonald, C. A. Wright, and D. J. Spear. 2017. Short-term variability in particle flux: Storms, blooms and river discharge in a coastal sea. *Cont. Shelf Res.* **143**: 29–42. doi:10.1016/j.csr.2017.05.016
- Johannessen, S. C., R. W. Macdonald, and C. A. Wright. 2019. Rain, runoff, and diatoms: The effects of the North Pacific

- 2014–2015 warm anomaly on particle flux in a Canadian west coast fjord. *Estuaries Coasts* **42**: 1052–1065. doi:10.1007/s12237-018-00510-0
- Johnson, K. S., F. P. Chavez, and G. E. Friederich. 1999. Continental-shelf sediment as a primary source of iron for coastal phytoplankton. *Nature* **398**: 697–700. doi:10.1038/19511
- Johnson, K. W., L. A. Miller, N. E. Sutherland, and C. S. Wong. 2005. Iron transport by mesoscale Haida eddies in the Gulf of Alaska. *Deep-Sea Res. II Top. Stud. Oceanogr.* **52**: 933–953. doi:10.1016/j.dsr2.2004.08.017
- Kaspari, S., S. McKenzie Skiles, I. Delaney, D. Dixon, and T. H. Painter. 2015. Accelerated glacier melt on Snow Dome, Mount Olympus, Washington, USA, due to deposition of black carbon and mineral dust from wildfire. *J. Geophys. Res. Atmos.* **120**: 2793–2807. doi:10.1002/2014JD022676
- Kastner, S. E., A. R. Horner-Devine, and J. Thomson. 2018. The influence of wind and waves on spreading and mixing in the Fraser River plume. *J. Geophys. Res. Oceans* **123**: 6818–6840. doi:10.1029/2018JC013765
- Kauffman, J. B., and others. 2020. Total ecosystem carbon stocks at the marine–terrestrial interface: Blue carbon of the Pacific northwest coast, United States. *Global Chang. Biol.* **26**: 5679–5692. doi:10.1111/gcb.15248
- Kehoe, L. J., and others. 2021. Conservation in heavily urbanized biodiverse regions requires urgent management action and attention to governance. *Conserv. Sci. Pract.* **3**: e310. doi:10.1111/csp2.310
- Keith, H., B. G. Mackey, and D. B. Lindenmayer. 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world’s most carbon-dense forests. *Proc. Natl. Acad. Sci.* **106**: 11635–11640. doi:10.1073/pnas.0901970106
- Kennedy, L. A., F. Juanes, and R. El-Sabaawi. 2018. Eelgrass as valuable nearshore foraging habitat for juvenile Pacific Salmon in the early marine period. *Mar. Coast. Fish.* **10**: 190–203. doi:10.1002/mcf2.10018
- Kennish, M. J. 2001. Coastal salt marsh systems in the U.S.: A review of anthropogenic impacts. *J. Coast. Res.* **17**: 731–748.
- Kentula, M. E., and T. H. DeWitt. 2003. Abundance of seagrass (*Zostera marina* L.) and macroalgae in relation to the salinity-temperature gradient in Yaquina Bay, Oregon, USA. *Estuaries* **26**: 1130–1141. doi:10.1007/BF02803369
- Kindler, R., and others. 2011. Dissolved carbon leaching from soil is a crucial component of the net ecosystem carbon balance. *Glob. Chang. Biol.* **17**: 1167–1185. doi:10.1111/j.1365-2486.2010.02282.x
- Kisand, V., D. Rucker, and M. Simon. 2008. Significant decomposition of riverine humic-rich DOC by marine but not estuarine bacteria assessed in sequential chemostat experiments. *Aquat. Microb. Ecol.* **53**: 151–160. doi:10.3354/ame01240
- Klinger, L. F., and D. J. Erickson III. 1997. Geophysiological coupling of marine and terrestrial ecosystems. *J. Geophys. Res. Atmos.* **102**: 25359–25370. doi:10.1029/97JD01620
- Kondo, Y., R. Bamba, H. Obata, J. Nishioka, and S. Takeda. 2021. Distinct profiles of size-fractionated iron-binding ligands between the eastern and western subarctic Pacific. *Sci. Rep.* **11**: 2053. doi:10.1038/s41598-021-81536-6
- Koski, K. V. 2009. The fate of coho salmon nomads: The story of an estuarine-rearing strategy promoting resilience. *Ecol. Soc.* **14**: 4. doi:10.5751/ES-02625-140104
- Kreutzweiser, D. P., P. W. Hazlett, and J. M. Gunn. 2008. Logging impacts on the biogeochemistry of boreal forest soils and nutrient export to aquatic systems: A review. *Environ. Rev.* **16**: 157–179. doi:10.1139/A08-006
- Kunkel, K. E., and others. 2013. Regional climate trends and scenarios for the U.S. National Climate Assessment Part 9. Climate of the Contiguous United States. NOAA Technical Report.
- Ladd, C., and W. Cheng. 2016. Gap winds and their effects on regional oceanography part I: Cross sound, Alaska. *Deep-Sea Res. II Top. Stud. Oceanogr.* **132**: 41–53. doi:10.1016/j.dsr2.2015.08.006
- Ladd, C., and others. 2009. A synoptic survey of young mesoscale eddies in the eastern Gulf of Alaska. *Deep-Sea Res. II Top. Stud. Oceanogr.* **56**: 2460–2473. doi:10.1016/j.dsr2.2009.02.007
- Ladd, T. M., and others. 2023. Food for all? Wildfire ash fuels growth of diverse eukaryotic plankton. *Proc. R. Soc. B: Biol. Sci.* **290**: 20231817. doi:10.1098/rspb.2023.1817
- Lader, R., A. Bidlack, J. E. Walsh, U. S. Bhatt, and P. A. Bieniek. 2020. Dynamical downscaling for southeast Alaska: Historical climate and future projections. *J. Appl. Meteorol. Climatol.* **59**: 1607–1623. doi:10.1175/JAMC-D-20-0076.1
- Lafon, A., N. Silva, and C. A. Vargas. 2014. Contribution of allochthonous organic carbon across the Serrano River basin and the adjacent fjord system in Southern Chilean Patagonia: Insights from the combined use of stable isotope and fatty acid biomarkers. *Prog. Oceanogr.* **129**: 98–113. doi:10.1016/j.pocean.2014.03.004
- Lam, P. J., J. K. B. Bishop, C. C. Henning, M. A. Marcus, G. A. Waychunas, and I. Y. Fung. 2006. Wintertime phytoplankton bloom in the subarctic Pacific supported by continental margin iron. *Global Biogeochem. Cycles* **20**: GB1006. doi:10.1029/2005GB002557
- Lecher, A. L., C.-T. Chien, and A. Paytan. 2016. Submarine groundwater discharge as a source of nutrients to the North Pacific and Arctic coastal ocean. *Mar. Chem.* **186**: 167–177. doi:10.1016/j.marchem.2016.09.008
- Leck, M. A., A. H. Baldwin, V. T. Parker, S. Lisa, and D. F. Whigham. 2009. Plant communities of tidal freshwater wetlands of the continental USA and Canada, p. 41–58. *In* A. Barendregt, D. F. Whigham, and A. H. Baldwin [eds.], *Tidal freshwater wetlands*. Backhuys Publishers.
- Leduc, D., and others. 2020. Structure of infaunal communities in New Zealand submarine canyons is linked to origins of sediment organic matter. *Limnol. Oceanogr.* **65**: 2303–2327. doi:10.1002/lno.11454

- Lepofsky, D., and M. Caldwell. 2013. Indigenous marine resource management on the northwest coast of North America. *Ecol. Process.* **2**: 12. doi:[10.1186/2192-1709-2-12](https://doi.org/10.1186/2192-1709-2-12)
- Lerner, J. E., C. Marchese, and B. P. V. Hunt. 2022. Stable isotopes reveal that bottom-up omnivory drives food chain length and trophic position in eutrophic coastal ecosystems. *ICES J. Mar. Sci.* **79**: 2311–2323. doi:[10.1093/icesjms/fsac171](https://doi.org/10.1093/icesjms/fsac171)
- Levin, P. S., E. R. Howe, and J. C. Robertson. 2020. Impacts of stormwater on coastal ecosystems: The need to match the scales of management objectives and solutions. *Philos. Trans. R. Soc. B: Biol. Sci.* **375**: 20190460. doi:[10.1098/rstb.2019.0460](https://doi.org/10.1098/rstb.2019.0460)
- Levings, C. D. 1980. Benthic biology of a dissolved oxygen deficiency event in Howe sound, B.C, p. 515–522. In H. J. Freeland, D. M. Farmer, and C. D. Levings [eds.], *Fjord oceanography*. NATO Conference Series, vol 4. Springer, Boston, MA. doi:[10.1007/978-1-4613-3105-6\\_46](https://doi.org/10.1007/978-1-4613-3105-6_46)
- Levings, C. D. 2016. A gammarid amphipod as a potential indicator of deglaciation and estuarine change. Annual meeting of the Pacific Estuarine Research Society.
- Li, M., F. Shen, and X. Sun. 2021. 2019–2020 Australian bush-fire air particulate pollution and impact on the South Pacific Ocean. *Sci. Rep.* **11**: 12288. doi:[10.1038/s41598-021-91547-y](https://doi.org/10.1038/s41598-021-91547-y)
- Lippiatt, S. M., M. C. Lohan, and K. W. Bruland. 2010. The distribution of reactive iron in northern Gulf of Alaska coastal waters. *Mar. Chem.* **121**: 187–199. doi:[10.1016/j.marchem.2010.04.007](https://doi.org/10.1016/j.marchem.2010.04.007)
- Littles, C., and others. 2022. Adaptive management of large-scale ecosystem restoration: Increasing certainty of habitat outcomes in the Columbia River Estuary, U.S.A. *Restor. Ecol.* **30**: e13634. doi:[10.1111/rec.13634](https://doi.org/10.1111/rec.13634)
- Logares, R., S. V. M. Tesson, B. Canbäck, M. Pontarp, K. Hedlund, and K. Rengefors. 2018. Contrasting prevalence of selection and drift in the community structuring of bacteria and microbial eukaryotes. *Environ. Microbiol.* **20**: 2231–2240. doi:[10.1111/1462-2920.14265](https://doi.org/10.1111/1462-2920.14265)
- Logue, J. B., and others. 2016. Experimental insights into the importance of aquatic bacterial community composition to the degradation of dissolved organic matter. *ISME J.* **10**: 533–545. doi:[10.1038/ismej.2015.131](https://doi.org/10.1038/ismej.2015.131)
- Long, W. C., K. M. Swiney, C. Harris, H. N. Page, and R. J. Foy. 2013. Effects of ocean acidification on juvenile red king crab (*Paralithodes camtschaticus*) and tanner crab (*Chionoecetes bairdi*) growth, condition, calcification, and survival. *PLoS One* **8**: e60959. doi:[10.1371/journal.pone.0060959](https://doi.org/10.1371/journal.pone.0060959)
- Loreau, M., N. Mouquet, and R. D. Holt. 2003. Meta-ecosystems: A theoretical framework for a spatial ecosystem ecology. *Ecol. Lett.* **6**: 673–679. doi:[10.1046/j.1461-0248.2003.00483.x](https://doi.org/10.1046/j.1461-0248.2003.00483.x)
- Lotze, H. K., and others. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science* **312**: 1806–1809. doi:[10.1126/science.1128035](https://doi.org/10.1126/science.1128035)
- Lowe, A. T., J. Bos, and J. Ruesink. 2019. Ecosystem metabolism drives pH variability and modulates long-term ocean acidification in the Northeast Pacific coastal ocean. *Sci. Rep.* **9**: 963. doi:[10.1038/s41598-018-37764-4](https://doi.org/10.1038/s41598-018-37764-4)
- Lu, Y., J. W. Edmonds, Y. Yamashita, B. Zhou, A. Jaegge, and M. Baxley. 2015. Spatial variation in the origin and reactivity of dissolved organic matter in Oregon–Washington coastal waters. *Ocean Dynam.* **65**: 17–32. doi:[10.1007/s10236-014-0793-7](https://doi.org/10.1007/s10236-014-0793-7)
- Luef, B., F. Aspetsberger, T. Hein, F. Huber, and P. Peduzzi. 2007. Impact of hydrology on free-living and particle-associated microorganisms in a river floodplain system (Danube, Austria). *Freshw. Biol.* **52**: 1043–1057. doi:[10.1111/j.1365-2427.2007.01752.x](https://doi.org/10.1111/j.1365-2427.2007.01752.x)
- Luijendijk, E., T. Gleeson, and N. Moosdorf. 2020. Fresh groundwater discharge insignificant for the world's oceans but important for coastal ecosystems. *Nat. Commun.* **11**: 1260. doi:[10.1038/s41467-020-15064-8](https://doi.org/10.1038/s41467-020-15064-8)
- MacFadyen, A., B. M. Hickey, and W. P. Cochlan. 2008. Influences of the Juan de Fuca Eddy on circulation, nutrients, and phytoplankton production in the northern California current system. *J. Geophys. Res. Oceans* **113**: C08008. doi:[10.1029/2007JC004412](https://doi.org/10.1029/2007JC004412)
- MacKenzie, A. L., H. F. Kaspar, and P. A. Gillespie. 1988. Nutrients, and microplankton biomass off the New Zealand South Island north-west coast, January 1982. *N. Z. J. Mar. Freshw. Res.* **22**: 551–564. doi:[10.1080/00288330.1988.9516325](https://doi.org/10.1080/00288330.1988.9516325)
- Magliozzi, L. J., and others. 2024. Wildland–urban interface wildfire increases metal contributions to stormwater runoff in paradise, California. *Environ. Sci.: Processes Impacts* **26**: 667–685. doi:[10.1039/d3em00298e](https://doi.org/10.1039/d3em00298e)
- Marshall, M. G., and others. 2021. Seasonal changes in dissolved organic matter composition in a patagonian fjord affected by glacier melt inputs. *Front. Mar. Sci.* **8**: 612386. doi:[10.3389/fmars.2021.612386](https://doi.org/10.3389/fmars.2021.612386)
- Martínez, M. L., A. Intralawan, G. Vázquez, O. Pérez-Maqueo, P. Sutton, and R. Landgrave. 2007. The coasts of our world: Ecological, economic and social importance. *Ecol. Econ.* **63**: 254–272. doi:[10.1016/j.ecolecon.2006.10.022](https://doi.org/10.1016/j.ecolecon.2006.10.022)
- Martin, J. H., R. M. Gordon, S. Fitzwater, and W. W. Broenkow. 1989. Vertex: Phytoplankton/iron studies in the Gulf of Alaska. *Deep-Sea Res. A: Oceanogr. Res. Pap.* **36**: 649–680. doi:[10.1016/0198-0149\(89\)90144-1](https://doi.org/10.1016/0198-0149(89)90144-1)
- Martin, J. H., and M. R. Gordon. 1988. Northeast Pacific iron distributions in relation to phytoplankton productivity. *Deep-Sea Res. A: Oceanogr. Res. Pap.* **35**: 177–196. doi:[10.1016/0198-0149\(88\)90035-0](https://doi.org/10.1016/0198-0149(88)90035-0)
- Masson, D., and A. Peña. 2009. Chlorophyll distribution in a temperate estuary: The Strait of Georgia and Juan de Fuca Strait. *Estuar. Coast. Shelf Sci.* **82**: 19–28. doi:[10.1016/j.ecss.2008.12.022](https://doi.org/10.1016/j.ecss.2008.12.022)
- Mayorga, E., and others. 2010. Global nutrient export from WaterSheds 2 (NEWS 2): Model development and

- implementation. *Environ. Model. Software* **25**: 837–853. doi:10.1016/j.envsoft.2010.01.007
- Mazzini, P. L. F., J. A. Barth, R. K. Shearman, and A. Erofeev. 2014. Buoyancy-driven coastal currents off Oregon during fall and Winter. *J. Phys. Oceanogr.* **44**: 2854–2876. doi:10.1175/JPO-D-14-0012.1
- McAfee, S. A., J. Walsh, and T. S. Rupp. 2014. Statistically downscaled projections of snow/rain partitioning for Alaska. *Hydrol. Process.* **28**: 3930–3946. doi:10.1002/hyp.9934
- McKinnell, S., E. Curchitser, K. Groot, M. Kaeriyama, and M. Trudel. 2014. Oceanic and atmospheric extremes motivate a new hypothesis for variable marine survival of Fraser River sockeye salmon. *Fish. Oceanogr.* **23**: 322–341. doi:10.1111/fog.12063
- McLaskey, A. K., I. Forster, J. Del Bel Belluz, and B. P. V. Hunt. 2022. A high-resolution time series of particulate matter fatty acids reveals temporal dynamics of the composition and quality available to zooplankton in a temperate coastal ocean. *Prog. Oceanogr.* **206**: 102843. doi:10.1016/j.pocean.2022.102843
- McLaskey, A. K., and others. 2016. Development of *Euphausia pacifica* (krill) larvae is impaired under pCO<sub>2</sub> levels currently observed in the Northeast Pacific. *Mar. Ecol. Prog. Ser.* **555**: 65–78. doi:10.3354/meps11839
- McLeod, R. J., and S. R. Wing. 2009. Strong pathways for incorporation of terrestrially derived organic matter into benthic communities. *Estuar. Coast. Shelf Sci.* **82**: 645–653. doi:10.1016/j.ecss.2009.02.025
- McNicol, G., and others. 2019. Large, climate-sensitive soil carbon stocks mapped with pedology-informed machine learning in the North Pacific coastal temperate rainforest. *Environ. Res. Lett.* **14**: 014004. doi:10.1088/1748-9326/aaed52
- McNicol, G., and others. 2023. Small, coastal temperate rainforest watersheds dominate dissolved organic carbon transport to the Northeast Pacific Ocean. *Geophys. Res. Lett.* **50**: e2023GL103024. doi:10.1029/2023GL103024
- Meire, L., and others. 2017. Marine-terminating glaciers sustain high productivity in Greenland fjords. *Glob. Chang. Biol.* **23**: 5344–5357. doi:10.1111/gcb.13801
- Miller, I., and others. 2018. Projected sea level rise for Washington State—A 2018 assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, Oregon State University, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project.
- Milner, A. M., and others. 2017. Glacier shrinkage driving global changes in downstream systems. *Proc. Natl. Acad. Sci.* **114**: 9770–9778. doi:10.1073/pnas.1619807114
- Moore-Maley, B. L., D. Ianson, and S. E. Allen. 2018. The sensitivity of estuarine aragonite saturation state and pH to the carbonate chemistry of a freshet-dominated river. *Biogeosciences* **15**: 3743–3760. doi:10.5194/bg-15-3743-2018
- Moore, J. C., and others. 2004. Detritus, trophic dynamics and biodiversity. *Ecol. Lett.* **7**: 584–600. doi:10.1111/j.1461-0248.2004.00606.x
- Moore, R. D., and others. 2009. Glacier change in western North America: Influences on hydrology, geomorphic hazards and water quality. *Hydrol. Process.* **23**: 42–61. doi:10.1002/hyp.7162
- Morley, S. A. and others 2020. Shifting food web structure during dam removal—Disturbance and recovery during a major restoration action. *PLOS ONE* **15**: e0239198. doi:10.1371/journal.pone.0239198
- Morris, J. T., and others. 2016. Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. *Earth's Future* **4**: 110–121. doi:10.1002/2015EF000334
- Morrison, J., M. C. Quick, and M. G. G. Foreman. 2002. Climate change in the Fraser River watershed: Flow and temperature projections. *J. Hydrol.* **263**: 230–244. doi:10.1016/S0022-1694(02)00065-3
- Morrison, J., M. G. G. Foreman, and D. Masson. 2012. A method for estimating monthly freshwater discharge affecting British Columbia coastal waters. *Atmos. Ocean* **50**: 1–8. doi:10.1080/07055900.2011.637667
- Morrison, J., W. Callendar, M. G. G. Foreman, D. Masson, and I. Fine. 2014. A model simulation of future oceanic conditions along the British Columbia continental shelf. Part I: Forcing fields and initial conditions. *Atmos. Ocean* **52**: 1–19. doi:10.1080/07055900.2013.868340
- Mote, P. W., and E. P. Salathé. 2010. Future climate in the Pacific northwest. *Clim. Change* **102**: 29–50. doi:10.1007/s10584-010-9848-z
- Mumford, T. F. 2007. Kelp and eelgrass in Puget Sound. Puget Sound Nearshore Partnership Report. Report No. 2007-05. Published by Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.
- Murray, C., S. Markager, C. A. Stedmon, T. Juul-Pedersen, M. K. Sejr, and A. Bruhn. 2015. The influence of glacial melt water on bio-optical properties in two contrasting Greenlandic fjords. *Estuar. Coast. Shelf Sci.* **163**: 72–83. doi:10.1016/j.ecss.2015.05.041
- Musselman, K. N., N. Addor, J. A. Vano, and N. P. Molotch. 2021. Winter melt trends portend widespread declines in snow water resources. *Nat. Clim. Chang.* **11**: 418–424. doi:10.1038/s41558-021-01014-9
- Musselman, K. N., and others. 2018. Projected increases and shifts in rain-on-snow flood risk over western North America. *Nat. Clim. Chang.* **8**: 808–812. doi:10.1038/s41558-018-0236-4
- Nagorski, S. A., S. D. Kaspari, E. Hood, J. B. Fellman, and S. M. Skiles. 2019. Radiative forcing by dust and black carbon on the Juneau Icefield, Alaska. *J. Geophys. Res. Atmos.* **124**: 3943–3959. doi:10.1029/2018JD029411
- Neal, E. G., E. Hood, and K. Smikrud. 2010. Contribution of glacier runoff to freshwater discharge into the Gulf

- of Alaska. *Geophys. Res. Lett.* **37**: L06404. doi:[10.1029/2010GL042385](https://doi.org/10.1029/2010GL042385)
- Novak, A. B., and others. 2020. Factors influencing carbon stocks and accumulation rates in eelgrass meadows across New England, USA. *Estuaries Coasts* **43**: 2076–2091. doi:[10.1007/s12237-020-00754-9](https://doi.org/10.1007/s12237-020-00754-9)
- Nuwer, J. M., and R. G. Keil. 2005. Sedimentary organic matter geochemistry of Clayoquot Sound, Vancouver Island, British Columbia. *Limnol. Oceanogr.* **50**: 1119–1128. doi:[10.4319/lo.2005.50.4.1119](https://doi.org/10.4319/lo.2005.50.4.1119)
- O’Neel, S., and others. 2015. Icefield-to-ocean linkages across the northern Pacific coastal temperate rainforest ecosystem. *Bioscience* **65**: 499–512. doi:[10.1093/biosci/biv027](https://doi.org/10.1093/biosci/biv027)
- Ochs, C. A., H. E. Capello, and O. Pongruktham. 2010. Bacterial production in the Lower Mississippi River: Importance of suspended sediment and phytoplankton biomass. *Hydrobiologia* **637**: 19–31. doi:[10.1007/s10750-009-9981-8](https://doi.org/10.1007/s10750-009-9981-8)
- Oliver, A. A., and others. 2017. A global hotspot for dissolved organic carbon in hypermaritime watersheds of coastal British Columbia. *Biogeosciences* **14**: 3743–3762. doi:[10.5194/bg-14-3743-2017](https://doi.org/10.5194/bg-14-3743-2017)
- Oliver, E. C. J., and others. 2018. Longer and more frequent marine heatwaves over the past century. *Nat. Commun.* **9**: 1324. doi:[10.1038/s41467-018-03732-9](https://doi.org/10.1038/s41467-018-03732-9)
- Oppenheimer, M., and others. 2019. Sea level rise and implications for low-lying islands, coasts and communities, p. 321–445. *In* H.-O. Pörtner and others [eds.], *IPCC special report on the ocean and cryosphere in a changing climate*. Cambridge University Press. doi:[10.1017/9781009157964.006](https://doi.org/10.1017/9781009157964.006)
- Osma, N., L. Latorre-Melín, B. Jacob, P. Y. Contreras, P. von Dassow, and C. A. Vargas. 2020. Response of phytoplankton assemblages from naturally acidic coastal ecosystems to elevated pCO<sub>2</sub>. *Front. Mar. Sci.* **7**: 511962. doi:[10.3389/fmars.2020.00323](https://doi.org/10.3389/fmars.2020.00323)
- Ou, M., and others. 2015. Responses of pink salmon to CO<sub>2</sub>-induced aquatic acidification. *Nat. Clim. Chang.* **5**: 950–955. doi:[10.1038/nclimate2694](https://doi.org/10.1038/nclimate2694)
- Pérez, C. A., M. D. DeGrandpre, N. A. Lagos, G. S. Saldías, E.-K. Cascales, and C. A. Vargas. 2015. Influence of climate and land use in carbon biogeochemistry in lower reaches of rivers in central southern Chile: Implications for the carbonate system in river-influenced rocky shore environments. *J. Geophys. Res. Biogeo.* **120**: 673–692. doi:[10.1002/2014JG002699](https://doi.org/10.1002/2014JG002699)
- Paczkowska, J., O. F. Rowe, D. Figueroa, and A. Andersson. 2019. Drivers of phytoplankton production and community structure in nutrient-poor estuaries receiving terrestrial organic inflow. *Mar. Environ. Res.* **151**: 104778. doi:[10.1016/j.marenvres.2019.104778](https://doi.org/10.1016/j.marenvres.2019.104778)
- Paczkowska, J., S. Brugel, O. Rowe, R. Lefébure, A. Brutemark, and A. Andersson. 2020. Response of coastal phytoplankton to high inflows of terrestrial matter. *Front. Mar. Sci.* **7**: 80. doi:[10.3389/fmars.2020.00080](https://doi.org/10.3389/fmars.2020.00080)
- Paerl, H. W., and T. G. Otten. 2013. Harmful cyanobacterial blooms: Causes, consequences, and controls. *Microb. Ecol.* **65**: 995–1010. doi:[10.1007/s00248-012-0159-y](https://doi.org/10.1007/s00248-012-0159-y)
- Payne, A. E., and others. 2020. Responses and impacts of atmospheric rivers to climate change. *Nat. Rev. Earth Environ.* **1**: 143–157. doi:[10.1038/s43017-020-0030-5](https://doi.org/10.1038/s43017-020-0030-5)
- Peña, M. A., I. Fine, and W. Callendar. 2019. Interannual variability in primary production and shelf-offshore transport of nutrients along the northeast Pacific Ocean margin. *Deep-Sea Res. II Top. Stud. Oceanogr.* **169–170**: 104637. doi:[10.1016/j.dsr2.2019.104637](https://doi.org/10.1016/j.dsr2.2019.104637)
- Peñuelas, J., and others. 2013. Human-induced nitrogen-phosphorus imbalances alter natural and managed ecosystems across the globe. *Nat. Commun.* **4**: 2934. doi:[10.1038/ncomms3934](https://doi.org/10.1038/ncomms3934)
- Peterson, C., and S. Vanderburgh. 2018. Tidal flat depositional response to neotectonic cyclic uplift and subsidence (1–2 m) as superimposed on latest-holocene net sea level rise (1.0 m/ka) in a large shallow mesotidal wave-dominated estuary, Willapa Bay, Washington, USA. *J. Geogr. Geol.* **10**: 109. doi:[10.5539/jgg.v10n1p109](https://doi.org/10.5539/jgg.v10n1p109)
- Peterson, C. D., T. C. Linde, and S. Vanderburgh. 2020. Late-Holocene shoreline responses to competing shelf, bay, and beach accommodation spaces under conditions of relative sea level change, and the potential for future catastrophic beach retreat in the Columbia River Littoral cell, Washington and Oregon, USA. *Mar. Geol.* **427**: 106272. doi:[10.1016/j.margeo.2020.106272](https://doi.org/10.1016/j.margeo.2020.106272)
- Philip, S. Y., and others. 2021. Rapid attribution analysis of the extraordinary heatwave on the Pacific coast of the US and Canada June 2021. *Earth Syst. Dynam. Discuss.* **13**: 1689–1713. doi:[10.5194/esd-13-1689-2022](https://doi.org/10.5194/esd-13-1689-2022)
- Pilcher, D. J., S. A. Siedlecki, A. J. Hermann, K. O. Coyle, J. T. Mathis, and W. Evans. 2018. Simulated impact of glacial runoff on CO<sub>2</sub> uptake in the Gulf of Alaska. *Geophys. Res. Lett.* **45**: 880–890. doi:[10.1002/2017GL075910](https://doi.org/10.1002/2017GL075910)
- Poppe, K. L., and J. M. Rybczyk. 2022. Assessing the future of an intertidal seagrass meadow in response to sea level rise with a hybrid ecogeomorphic model of elevation change. *Ecol. Modell.* **469**: 109975. doi:[10.1016/j.ecolmodel.2022.109975](https://doi.org/10.1016/j.ecolmodel.2022.109975)
- Prahl, F. G., J. R. Ertel, M. A. Goni, M. A. Sparrow, and B. Eversmeyer. 1994. Terrestrial organic carbon contributions to sediments on the Washington margin. *Geochim. Cosmochim. Acta* **58**: 3035–3048. doi:[10.1016/0016-7037\(94\)90177-5](https://doi.org/10.1016/0016-7037(94)90177-5)
- Prentice, C., M. Helsing-Lewis, R. Sanders-Smith, and A. K. Salomon. 2019. Reduced water motion enhances organic carbon stocks in temperate eelgrass meadows. *Limnol. Oceanogr.* **64**: 2389–2404. doi:[10.1002/lno.11191](https://doi.org/10.1002/lno.11191)
- Pu, W., and others. 2021. Unprecedented snow darkening and melting in New Zealand due to 2019–2020 Australian wildfires. *Fundam. Res.* **1**: 224–231. doi:[10.1016/j.fmre.2021.04.001](https://doi.org/10.1016/j.fmre.2021.04.001)

- Puig, P., A. Palanques, and J. Martín. 2014. Contemporary sediment-transport processes in submarine canyons. *Ann. Rev. Mar. Sci.* **6**: 53–77. doi:10.1146/annurev-marine-010213-135037
- Radić, V., A. J. Cannon, B. Menounos, and N. Gi. 2015. Future changes in autumn atmospheric river events in British Columbia, Canada, as projected by CMIP5 global climate models. *J. Geophys. Res. Atmos.* **120**: 9279–9302. doi:10.1002/2015JD023279
- Ramesh, R., and others. 2015. Land–Ocean interactions in the coastal zone: Past, present & future. *Anthropocene* **12**: 85–98. doi:10.1016/j.ancene.2016.01.005
- Ramirez, M. T., and others. 2016. Modern deposition rates and patterns of organic carbon burial in Fiordland, New Zealand. *Geophys. Res. Lett.* **43**: 11768–11776. doi:10.1002/2016GL070021
- Raymond, W. W., and others. 2022. Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. *Ecology* **103**: e3798. doi:10.1002/ecy.3798
- Regnier, P., and others. 2013. Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nat. Geosci.* **6**: 597–607. doi:10.1038/ngeo1830
- Reisdorph, S. C., and J. T. Mathis. 2014. The dynamic controls on carbonate mineral saturation states and ocean acidification in a glacially dominated estuary. *Estuar. Coast. Shelf Sci.* **144**: 8–18. doi:10.1016/j.ecss.2014.03.018
- Renner, M., M. L. Arimitsu, and J. F. Piatt. 2012. Structure of marine predator and prey communities along environmental gradients in a glaciated fjord. *Can. J. Fish. Aquat. Sci.* **69**: 2029–2045. doi:10.1139/f2012-117
- Riche, O., S. C. Johannessen, and R. W. Macdonald. 2014. Why timing matters in a coastal sea: Trends, variability and tipping points in the Strait of Georgia, Canada. *J. Mar. Syst.* **131**: 36–53. doi:10.1016/j.jmarsys.2013.11.003
- Robb, C. K. 2014. Assessing the impact of human activities on British Columbia's estuaries. *PLoS One* **9**: e99578. doi:10.1371/journal.pone.0099578
- Rodriguez, A. R., S. N. Giddings, and N. Kumar. 2018. Impacts of nearshore wave-current interaction on transport and mixing of small-scale buoyant plumes. *Geophys. Res. Lett.* **45**: 8379–8389. doi:10.1029/2018GL078328
- Romanuk, T. N., and C. D. Levings. 2005. Stable isotope analysis of trophic position and terrestrial vs. marine carbon sources for juvenile Pacific salmonids in nearshore marine habitats. *Fish. Manag. Ecol.* **12**: 113–121. doi:10.1111/j.1365-2400.2004.00432.x
- Rounce, D. R., and others. 2023. Global glacier change in the 21st century: Every increase in temperature matters. *Science* **379**: 78–83. doi:10.1126/science.abo1324
- Roy, S., S. Sathyendranath, H. Bouman, and T. Platt. 2013. The global distribution of phytoplankton size spectrum and size classes from their light-absorption spectra derived from satellite data. *Remote Sens. Environ.* **139**: 185–197. doi:10.1016/j.rse.2013.08.004
- RoyChowdhury, T., and others. 2018. Temporal dynamics of CO<sub>2</sub> and CH<sub>4</sub> loss potentials in response to rapid hydrological shifts in tidal freshwater wetland soils. *Ecol. Eng.* **114**: 104–114. doi:10.1016/j.ecoleng.2017.06.041
- Royer, T. C. 1982. Coastal fresh water discharge in the northeast Pacific. *J. Geophys. Res. Oceans* **87**: 2017–2021. doi:10.1029/JC087iC03p02017
- Saavedra, L. M., D. Parra, V. S. Martin, N. A. Lagos, and C. A. Vargas. 2018. Local habitat influences on feeding and respiration of the intertidal mussels *Perumytilus purpuratus* exposed to increased pCO<sub>2</sub> levels. *Estuaries Coasts* **41**: 1118–1129. doi:10.1007/s12237-017-0333-z
- Sabine, C. L., and others. 2004. The oceanic sink for anthropogenic CO<sub>2</sub>. *Science* **305**: 367–371. doi:10.1126/science.1097403
- Santos, I. R., and others. 2021. Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. *Nat. Rev. Earth Environ.* **2**: 307–323. doi:10.1038/s43017-021-00152-0
- Savage, C., P. R. Leavitt, and R. Elmgren. 2010. Effects of land use, urbanization, and climate variability on coastal eutrophication in the Baltic Sea. *Limnol. Oceanogr.* **55**: 1033–1046. doi:10.4319/lo.2010.55.3.1033
- Scavia, D., and others. 2002. Climate change impacts on U.S. coastal marine ecosystems. *Estuaries* **25**: 149–164. doi:10.1007/BF02691304
- Schroth, A. W., J. Crusius, F. Chever, B. C. Bostick, and O. J. Rouxel. 2011. Glacial influence on the geochemistry of riverine iron fluxes to the Gulf of Alaska and effects of deglaciation. *Geophys. Res. Lett.* **38**: L16605. doi:10.1029/2011GL048367
- Schweigert, J. F., M. Thompson, C. Fort, D. E. Hay, T. W. Therriault, and L. N. Brown. 2013. Factors linking Pacific herring (*Clupea pallasii*) productivity and the spring plankton bloom in the Strait of Georgia, British Columbia, Canada. *Prog. Oceanogr.* **115**: 103–110. doi:10.1016/j.pocean.2013.05.017
- Scott, M. H., S. A. Talke, D. A. Jay, and H. L. Diefenderfer. 2023. Warming of the lower Columbia River, 1853 to 2018. *River Res. Appl.* **39**: 1828–1845. doi:10.1002/rra.4177
- Seidel, M., and others. 2015. Molecular-level changes of dissolved organic matter along the Amazon River-to-ocean continuum. *Mar. Chem.* **177**: 218–231. doi:10.1016/j.marchem.2015.06.019
- Sergeant, C. J., J. A. Falke, R. A. Bellmore, J. R. Bellmore, and R. L. Crumley. 2020. A classification of streamflow patterns across the coastal Gulf of Alaska. *Water Resour. Res.* **56**: e2019WR026127. doi:10.1029/2019WR026127
- Shafteel, R. S., R. S. King, and J. A. Back. 2012. Alder cover drives nitrogen availability in Kenai lowland headwater streams, Alaska. *Biogeochemistry* **107**: 135–148. doi:10.1007/s10533-010-9541-3

- Shanley, C. S., and D. M. Albert. 2014. Climate change sensitivity index for Pacific Salmon habitat in Southeast Alaska. *PLoS One* **9**: e104799. doi:10.1371/journal.pone.0104799
- Sharma, A. R., and S. J. Déry. 2020. Variability and trends of landfalling atmospheric rivers along the Pacific coast of northwestern North America. *Int. J. Climatol.* **40**: 544–558. doi:10.1002/joc.6227
- Sheer, M. B., and E. A. Steel. 2006. Lost watersheds: Barriers, aquatic habitat connectivity, and salmon persistence in the willamette and lower columbia River Basins. *Trans. Am. Fish. Soc.* **135**: 1654–1669. doi:10.1577/T05-221.1
- Shelton, A. O., T. B. Francis, G. D. Williams, B. Feist, K. Stick, and P. S. Levin. 2014. Habitat limitation and spatial variation in Pacific herring egg survival. *Mar. Ecol. Prog. Ser.* **514**: 231–245. doi:10.3354/meps10941
- Sholkovitz, E. R. 1976. Flocculation of dissolved organic and inorganic matter during the mixing of river water and seawater. *Geochim. Cosmochim. Acta* **40**: 831–845. doi:10.1016/0016-7037(76)90035-1
- Sholkovitz, E. R. 1978. The flocculation of dissolved Fe, Mn, Al, Cu, Ni, Co and Cd during estuarine mixing. *Earth Planet. Sci. Lett.* **41**: 77–86. doi:10.1016/0012-821X(78)90043-2
- Siedlecki, S. A., D. J. Pilcher, A. J. Hermann, K. Coyle, and J. Mathis. 2017. The importance of freshwater to spatial variability of aragonite saturation state in the Gulf of Alaska. *J. Geophys. Res. Oceans* **122**: 8482–8502. doi:10.1002/2017JC012791
- Siedlecki, S. A., and others. 2015. Seasonal and interannual oxygen variability on the Washington and Oregon continental shelves. *J. Geophys. Res. Oceans* **120**: 608–633. doi:10.1002/2014JC010254
- Siedlecki, S. A., and others. 2016. Experiments with seasonal forecasts of ocean conditions for the northern region of the California current upwelling system. *Sci. Rep.* **6**: 27203. doi:10.1038/srep27203
- Silva, N., C. A. Vargas, and R. Prego. 2011. Land–ocean distribution of allochthonous organic matter in surface sediments of the Chiloé and Aysén interior seas (Chilean Northern Patagonia). *Cont. Shelf Res.* **31**: 330–339. doi:10.1016/j.csr.2010.09.009
- Silva, N., and C. A. Vargas. 2014. Hypoxia in Chilean patagonian fjords. *Prog. Oceanogr.* **129**: 62–74. doi:10.1016/j.pcean.2014.05.016
- Simenstad, C., A. Wick, S. van de Wetering, and D. Bottom. 2003. Dynamics and ecological functions of wood in estuarine and coastal marine ecosystems. *In* S. V., Gregory, K. Boyer, A. Gurnell [eds.], *The Ecology and Management of Wood in World Rivers* American Fisheries Society Symposium **37**: 265–277. Bethesda.
- Simpson, J., and others. 1993. Periodic stratification in the Rhine ROFI in the North Sea. *Oceanol. Acta* **16**: 23–32.
- Smethie, W. M. 1987. Nutrient regeneration and denitrification in low oxygen fjords. *Deep-Sea Res. A: Oceanogr. Res. Pap.* **34**: 983–1006. doi:10.1016/0198-0149(87)90049-5
- Smith, H. G., G. J. Sheridan, P. N. J. Lane, P. Nyman, and S. Haydon. 2011. Wildfire effects on water quality in forest catchments: A review with implications for water supply. *J. Hydrol.* **396**: 170–192. doi:10.1016/j.jhydrol.2010.10.043
- Smith, R. W., T. S. Bianchi, M. Allison, C. Savage, and V. Galy. 2015. High rates of organic carbon burial in fjord sediments globally. *Nat. Geosci.* **8**: 450–453. doi:10.1038/ngeo2421
- Sommer, U., H. Stibor, A. Katechakis, F. Sommer, and T. Hansen. 2002. Pelagic food web configurations at different levels of nutrient richness and their implications for the ratio fish production: Primary production. *Hydrobiologia* **484**: 11–20. doi:10.1023/A:1021340601986
- Soontiens, N., and others. 2016. Storm surges in the Strait of Georgia simulated with a regional model. *Atmos. Ocean* **54**: 1–21. doi:10.1080/07055900.2015.1108899
- Spencer, C., K. Gabel, and F. Hauer. 2003. Wildfire effects on stream food webs and nutrient dynamics in Glacier National Park, USA. *For. Ecol. Manage.* **178**: 141–153. doi:10.1016/S0378-1127(03)00058-6
- St. Pierre, K. A., and others. 2020. Terrestrial exports of dissolved and particulate organic carbon affect nearshore ecosystems of the Pacific coastal temperate rainforest. *Limnol. Oceanogr.* **65**: 2657–2675. doi:10.1002/lno.11538
- St. Pierre, K. A., and others. 2021. Rain-fed streams dilute inorganic nutrients but subsidise organic-matter-associated nutrients in coastal waters of the northeast Pacific Ocean. *Biogeosciences* **18**: 3029–3052. doi:10.5194/bg-18-3029-2021
- Stabeno, P., R. Reed, and J. Schumacher. 1995. The Alaska Coastal Current: Continuity of transport and forcing. *J. Geophys. Res. Oceans* **100**: 2477–2485. doi:10.1029/94JC02842
- Stabeno, P. J., N. A. Bond, A. J. Hermann, N. B. Kachel, C. W. Mordy, and J. E. Overland. 2004. Meteorology and oceanography of the northern Gulf of Alaska. *Cont. Shelf Res.* **24**: 859–897. doi:10.1016/j.csr.2004.02.007
- Stabeno, P. J., S. Bell, W. Cheng, S. Danielson, N. B. Kachel, and C. W. Mordy. 2016. Long-term observations of Alaska Coastal Current in the northern Gulf of Alaska. *Deep-Sea Res. II Top. Stud. Oceanogr.* **132**: 24–40. doi:10.1016/j.dsr2.2015.12.016
- Stanton, B. R. 1976. Circulation and hydrology off the west coast of the South Island, New Zealand. *N. Z. J. Mar. Freshw. Res.* **10**: 445–467. doi:10.1080/00288330.1976.9515629
- Stephan, K., K. L. Kavanagh, and A. Koyama. 2012. Effects of spring prescribed burning and wildfires on watershed nitrogen dynamics of central Idaho headwater areas. *For. Ecol. Manage.* **263**: 240–252. doi:10.1016/j.foreco.2011.09.013
- Strom, S. L., M. B. Olson, E. L. Macri, and C. W. Mordy. 2006. Cross-shelf gradients in phytoplankton community structure, nutrient utilization, and growth rate in the coastal

- Gulf of Alaska. *Mar. Ecol. Prog. Ser.* **328**: 75–92. doi:10.3354/meps328075
- Sugai, S. F., and D. C. Burrell. 1984. Transport of dissolved organic carbon, nutrients, and trace metals from the Willson and Blossom Rivers to Smeaton Bay, Southeast Alaska. *Can. J. Fish. Aquat. Sci.* **41**: 180–190. doi:10.1139/f84-019
- Svendsen, H. 1995. Physical oceanography of coupled fjord-coast systems in northern Norway with special focus on frontal dynamics and tides, p. 149–164. *In* H. R. Skjoldal, C. Hopkins, K. E. Erikstad, and H. P. Leinaas [eds.], *Ecology of fjords and coastal waters*. Proceedings of the Mare nor symposium on the ecology of fjords and coastal waters, 5–9 December 1994, Elsevier, Amsterdam.
- Talke, S. A., D. A. Jay, and H. L. Diefenderfer. 2022. Warming of the Willamette River, 1850–present: The effects of climate change and direct human interventions. *EGU sphere* **2022**: 1–40. doi:10.5194/egusphere-2022-793
- Tang, W., and others. 2021. Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires. *Nature* **597**: 370–375. doi:10.1038/s41586-021-03805-8
- Templeton, W. J., and D. A. Jay. 2013. Lower Columbia River sand supply and removal: Estimates of two sand budget components. *J. Waterw. Port Coast. Ocean Eng.* **139**: 383–392. doi:10.1061/(ASCE)WW.1943-5460.0000188
- Thom, R., and others. 2018a. Eelgrass (*Zostera marina* L.) restoration in Puget Sound: Development of a site suitability assessment process. *Restoration Ecology* **26**: 1066–1074. doi:10.1111/rec.12702
- Thom, R. M., S. L. Southard, A. B. Borde, and P. Stoltz. 2008. Light requirements for growth and survival of eelgrass (*Zostera marina* L.) in Pacific northwest (USA) estuaries. *Estuaries Coasts* **31**: 969–980. doi:10.1007/s12237-008-9082-3
- Thom, R. M., and R. G. Albright. 1990. Dynamics of benthic vegetation standing-stock, irradiance, and water properties in central Puget Sound. *Mar. Biol.* **104**: 129–141. doi:10.1007/BF01313166
- Thom, R. M., and others. 2018b. Storm-driven particulate organic matter flux connects a tidal tributary floodplain wetland, mainstem river, and estuary. *Ecol. Appl.* **28**: 1420–1434. doi:10.1002/eap.1759
- Thomson, R. E. 1981. *Oceanography of the British Columbia coast*. Thorn Press.
- Thomson, R. E., D. J. Spear, M. V. Krassovski, R. A. S. Hourston, T. A. Juhász, and S. F. Mihály. 2017. Buoyancy-driven coastal current blocks ventilation of an anoxic fjord on the Pacific coast of Canada. *J. Geophys. Res. Oceans* **122**: 2976–2998. doi:10.1002/2016JC012512
- Thomson, R. E., R. J. Beamish, T. D. Beacham, M. Trudel, P. H. Whitfield, and R. A. S. Hourston. 2012. Anomalous ocean conditions may explain the recent extreme variability in Fraser River sockeye salmon production. *Mar. Coast. Fish.* **4**: 415–437. doi:10.1080/19425120.2012.675985
- Thornton, T. F. 2017. Coastal lakes and lagoons as dynamic sites of exchange among the Tlingit of Alaska. *Marit. Stud.* **16**: 4. doi:10.1186/s40152-017-0059-3
- Till, C. P., and others. 2019. The iron limitation mosaic in the California current system: Factors governing Fe availability in the shelf/near-shelf region. *Limnol. Oceanogr.* **64**: 109–123. doi:10.1002/lno.11022
- Timothy, D. A., and M. Y. S. Soon. 2001. Primary production and deep-water oxygen content of two British Columbian fjords. *Mar. Chem.* **73**: 37–51. doi:10.1016/S0304-4203(00)00071-2
- Tommasi, D. A., R. D. Routledge, B. P. Hunt, and E. A. Pakhomov. 2013. The seasonal development of the zooplankton community in a British Columbia (Canada) fjord during two years with different spring bloom timing. *Mar. Biol. Res.* **9**: 129–144. doi:10.1080/17451000.2012.708044
- Trubilowicz, J. W., and R. D. Moore. 2017. Quantifying the role of the snowpack in generating water available for run-off during rain-on-snow events from snow pillow records. *Hydrol. Process.* **31**: 4136–4150. doi:10.1002/hyp.11310
- Tschaplinski, P. J. 1988. The use of estuaries as rearing habitats by juvenile coho salmon, p. 123–142. *In* Chamberlin, T. W. [Eds.], *Applying 15 years of Carnation Creek results*. Nanaimo, British Columbia: Pacific Biological Station.
- Tulloch, V. J. D., and others. 2024. Predicting regional cumulative effects of future development on coastal ecosystems to support indigenous governance. *J. Appl. Ecol.* **61**: 1728–1742. doi:10.1111/1365-2664.14659
- Turner, N. J. 2007. Importance of biodiversity for first peoples of British Columbia. For the Biodiversity BC Technical Subcommittee for the report on the status of biodiversity in BC.
- Vargas, C. A., L. A. Cuevas, N. Silva, H. E. González, R. De Pol-Holz, and D. A. Narváez. 2018. Influence of glacier melting and river discharges on the nutrient distribution and DIC recycling in the southern Chilean Patagonia. *J. Geophys. Res. Biogeo.* **123**: 256–270. doi:10.1002/2017JG003907
- Vargas, C. A., P. Y. Contreras, C. A. Pérez, M. Sobarzo, G. S. Saldías, and J. Salisbury. 2016. Influences of riverine and upwelling waters on the coastal carbonate system off Central Chile and their ocean acidification implications. *J. Geophys. Res. Biogeo.* **121**: 1468–1483. doi:10.1002/2015JG003213
- Vargas, C. A., P. Y. Contreras, and J. L. Iriarte. 2012. Relative importance of phototrophic, heterotrophic, and mixotrophic nanoflagellates in the microbial food web of a river-influenced coastal upwelling area. *Aquat. Microb. Ecol.* **65**: 233–248. doi:10.3354/ame01551
- Vargas, C. A., R. A. Martinez, V. San Martin, M. Aguayo, N. Silva, and R. Torres. 2011. Allochthonous subsidies of organic matter across a lake–river–fjord landscape in the Chilean Patagonia: Implications for marine zooplankton in

- inner fjord areas. *Cont. Shelf Res.* **31**: 187–201. doi:10.1016/j.csr.2010.06.016
- Vargas, C. A., and others. 2017. Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. *Nat. Ecol. Evol.* **1**: 0084. doi:10.1038/s41559-017-0084
- Vascik, B. A., A. M. Booth, B. Buma, and M. Berti. 2021. Estimated amounts and rates of carbon mobilized by landsliding in old-growth temperate forests of SE Alaska. *J. Geophys. Res. Biogeophys.* **126**: e2021JG006321. doi:10.1029/2021JG006321
- Voss, B. M., and others. 2014. Tracing river chemistry in space and time: Dissolved inorganic constituents of the Fraser River, Canada. *Geochim. Cosmochim. Acta* **124**: 283–308. doi:10.1016/j.gca.2013.09.006
- Voss, B. M., and others. 2015. Seasonal hydrology drives rapid shifts in the flux and composition of dissolved and particulate organic carbon and major and trace ions in the Fraser River, Canada. *Biogeosciences* **12**: 5597–5618. doi:10.5194/bg-12-5597-2015
- Waldbusser, G. G., and others. 2015a. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nat. Clim. Chang.* **5**: 273–280. doi:10.1038/nclimate2479
- Waldbusser, G. G., and others. 2015b. Ocean acidification has multiple modes of action on bivalve larvae. *PLoS One* **10**: e0128376. doi:10.1371/journal.pone.0128376
- Walsh, E. M., A. E. Ingalls, and R. G. Keil. 2008. Sources and transport of terrestrial organic matter in Vancouver Island fjords and the Vancouver–Washington margin: A multiproxy approach using d13Corg, lignin phenols, and the ether lipid BIT index. *Limnol. Oceanogr.* **53**: 1054–1063. doi:10.4319/lo.2008.53.3.1054
- Wang, Y., H. Liu, P. Lin, and J. Yin. 2019. Record-low coastal sea levels in the Northeast Pacific during the winter of 2013–2014. *Sci. Rep.* **9**: 3774. doi:10.1038/s41598-019-40397-w
- Ward, N. D., and others. 2020. Representing the function and sensitivity of coastal interfaces in Earth system models. *Nat. Commun.* **11**: 2458. doi:10.1038/s41467-020-16236-2
- Ware, D., and G. McFarlane. 1989. Fisheries production domains in the Northeast Pacific Ocean. Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. *Can. Spec. Publ. Fish. Aquat. Sci.* **108**: 359–379.
- Ware, D. M., and R. E. Thomson. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the Northeast Pacific. *Science* **308**: 1280–1284. doi:10.1126/science.1109049
- Washburn, L., and E. McPhee-Shaw. 2013. Coastal transport processes affecting inner-shelf ecosystems in the California current system. *Oceanography* **26**: 34–43. doi:10.5670/oceanog.2013.43
- Weingartner, T., L. Eisner, G. L. Eckert, and S. Danielson. 2009. Southeast Alaska: Oceanographic habitats and linkages. *J. Biogeogr.* **36**: 387–400. doi:10.1111/j.1365-2699.2008.01994.x
- Weingartner, T. J., S. L. Danielson, and T. C. Royer. 2005. Freshwater variability and predictability in the Alaska Coastal Current. *Deep-Sea Res. II Top. Stud. Oceanogr.* **52**: 169–191. doi:10.1016/j.dsr2.2004.09.030
- Wetz, M. S., B. Hales, Z. Chase, P. A. Wheeler, and M. M. Whitney. 2006. Riverine input of macronutrients, iron, and organic matter to the coastal ocean off Oregon, U.S.A., during the winter. *Limnol. Oceanogr.* **51**: 2221–2231. doi:10.4319/lo.2006.51.5.2221
- Wheatcroft, R. A., C. K. Sommerfield, D. E. Drake, J. C. Borgeld, and C. A. Nittrouer. 1997. Rapid and widespread dispersal of flood sediment on the northern California margin. *Geology* **25**: 163–166. doi:10.1130/0091-7613(1997)025<0163:RAWDOF>2.3.CO;2
- Wheatcroft, R. A., M. A. Goñi, J. A. Hatten, G. B. Pasternack, and J. A. Warrick. 2010. The role of effective discharge in the ocean delivery of particulate organic carbon by small, mountainous river systems. *Limnol. Oceanogr.* **55**: 161–171. doi:10.4319/lo.2010.55.1.0161
- Whiteman, J. P., E. A. Elliott Smith, A. C. Besser, and S. D. Newsome. 2019. A guide to using compound-specific stable isotope analysis to study the fates of molecules in organisms and ecosystems. *Diversity* **11**: 8. doi:10.3390/d11010008
- Whitney, E. J., A. H. Beaudreau, and D. H. Duncan. 2017. Spatial and temporal variation in the diets of pacific staghorn sculpins related to hydrological factors in a glacially influenced estuary. *Trans. Am. Fish. Soc.* **146**: 1156–1167. doi:10.1080/00028487.2017.1341852
- Whitney, F., and M. Robert. 2002. Structure of Haida eddies and their transport of nutrient from coastal margins into the NE Pacific Ocean. *J. Oceanogr.* **58**: 715–723. doi:10.1023/A:1022850508403
- Whitney, F. A., W. R. Crawford, and P. J. Harrison. 2005. Physical processes that enhance nutrient transport and primary productivity in the coastal and open ocean of the subarctic NE Pacific. *Deep-Sea Res. II Top. Stud. Oceanogr.* **52**: 681–706. doi:10.1016/j.dsr2.2004.12.023
- Wikner, J., and A. Andersson. 2012. Increased freshwater discharge shifts the trophic balance in the coastal zone of the northern Baltic Sea. *Glob. Chang. Biol.* **18**: 2509–2519. doi:10.1111/j.1365-2486.2012.02718.x
- Wilkinson, M. D., and others. 2016. The FAIR Guiding Principles for scientific data management and stewardship. *Sci. Data* **3**: 160018. doi:10.1038/sdata.2016.18
- Williams, C. R., and others. 2019. Elevated CO<sub>2</sub> impairs olfactory-mediated neural and behavioral responses and gene expression in ocean-phase coho salmon (*Oncorhynchus kisutch*). *Glob. Chang. Biol.* **25**: 963–977. doi:10.1111/gcb.14532
- Winder, M., J. Carstensen, A. W. E. Galloway, H. H. Jakobsen, and J. E. Cloern. 2017. The land–sea interface: A source of

- high-quality phytoplankton to support secondary production. *Limnol. Oceanogr.* **62**: S258–S271. doi:[10.1002/lno.10650](https://doi.org/10.1002/lno.10650)
- Wolf, E. C., A. P. Mitchell, and P. K. Schoonmaker. 1995. The rain forests of home: An atlas of people and place. Ecotrust. p. 31.
- Wolfe, A. M., S. E. Allen, M. Hodal, R. Pawlowicz, B. P. V. Hunt, and D. Tommasi. 2015. Impact of advection loss due to wind and estuarine circulation on the timing of the spring phytoplankton bloom in a fjord. *ICES J. Mar. Sci.* **73**: 1589–1609. doi:[10.1093/icesjms/fsv151](https://doi.org/10.1093/icesjms/fsv151)
- Wong, S. H. C., S. G. Monismith, and A. B. Boehm. 2013. Simple estimate of entrainment rate of pollutants from a coastal discharge into the surf zone. *Environ. Sci. Technol.* **47**: 11554–11561. doi:[10.1021/es402492f](https://doi.org/10.1021/es402492f)
- Woo, I., and others. 2021. Carbon flux, storage, and wildlife Co-Benefits in a restoring estuary. In K.W. Krauss, Z. Zhu and C.L. Stagg [eds.], *Wetland carbon and environmental management*. doi:[10.1002/9781119639305.ch5](https://doi.org/10.1002/9781119639305.ch5)
- Woo, H., C. Bone, K. Nadeem, and S. W. Taylor. 2024. Influence of mountain pine beetle outbreaks on large fires in British Columbia. *Ecosphere* **15**: e4722. doi:[10.1002/ecs2.4722](https://doi.org/10.1002/ecs2.4722)
- Wu, J., A. Aguilar-Islas, R. Rember, T. Weingartner, S. Danielson, and T. Whitledge. 2009. Size-fractionated iron distribution on the northern Gulf of Alaska. *Geophys. Res. Lett.* **36**: L11606. doi:[10.1029/2009GL038304](https://doi.org/10.1029/2009GL038304)
- Xue, L., and W.-J. Cai. 2020. Total alkalinity minus dissolved inorganic carbon as a proxy for deciphering ocean acidification mechanisms. *Mar. Chem.* **222**: 103791. doi:[10.1016/j.marchem.2020.103791](https://doi.org/10.1016/j.marchem.2020.103791)
- Yin, K., R. H. Goldblatt, P. J. Harrison, M. A. S. John, P. J. Clifford, and R. J. Beamish. 1997. Importance of wind and river discharge in influencing nutrient dynamics and phytoplankton production in summer in the central Strait of Georgia. *Mar. Ecol. Prog. Ser.* **161**: 173–183. doi:[10.3354/meps161173](https://doi.org/10.3354/meps161173)
- Young, R. W., and others. 1991. Atmospheric iron inputs and primary productivity: Phytoplankton responses in the North Pacific. *Global Biogeochem. Cycles* **5**: 119–134. doi:[10.1029/91GB00927](https://doi.org/10.1029/91GB00927)

### Acknowledgments

This paper arose out of a workshop entitled “Marine–terrestrial interactions in the Pacific Temperate Coastal Rainforest domain” from 31 January to 2 February, 2018, in Vancouver, British Columbia. The workshop was organized by the Coastal Rainforest Margins Research Network ([coastalmarginsnetwork.org](https://coastalmarginsnetwork.org)) and supported by the National Science Foundation under Grant No. 1557186. B.P.V.H. was supported by NSERC Discovery Grant RGPIN-2017-04499; K.A.St.P. was supported by a Hakai Coastal Initiative and Banting postdoctoral fellowship. We thank Mercedes Minck and Molly Tankersley for assistance with figures. This is PMEL contribution number 5405. C.A.V. was supported by the Millennium Science Initiative Program—Millennium Institute of Oceanography (IMO) ICN12\_019, and the Coastal Socio-Ecological Millennium Institute (SECOS) ICN2019\_015.

### Conflict of Interest

None declared.

Submitted 03 February 2024

Revised 29 July 2024

Accepted 05 October 2024

Associate Editor: Anna R. Armitage