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Key Points:

- The Northeast Pacific Coastal Temperate Rainforest drainage basin exports 3.5 Tg-C yr^{-1} of dissolved organic carbon (DOC) to the ocean
- More than 50% of the land-to-ocean DOC flux is derived from small (median = 44 km^2), coastal watersheds
- Modeled watershed DOC yields peak in coastal British Columbia where climate and landcover combine to maximize terrestrial-aquatic DOC fluxes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Small, Coastal Temperate Rainforest Watersheds Dominate Dissolved Organic Carbon Transport to the Northeast Pacific Ocean

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Abstract The northeast Pacific Coastal Temperate Rainforest (NPCTR) extending from southeast Alaska to northern California is characterized by high precipitation and large stores of recently fixed biological carbon. We show that 3.5 Tg-C yr^{-1} as dissolved organic carbon (DOC) is exported from the NPCTR drainage basin to the coastal ocean. More than 56% of this riverine DOC flux originates from thousands of small (mean = 118 km^2), coastal watersheds comprising 22% of the NPCTR drainage basin. The average DOC yield from NPCTR coastal watersheds (6.20 g-C m^{-2} yr^{-1}) exceeds that from Earth's tropical regions by roughly a factor of three. The highest yields occur in small, coastal watersheds in the central NPCTR due to the balance of moderate temperature, high precipitation, and high soil organic carbon stocks. These findings indicate DOC export from NPCTR watersheds may play an important role in regional-scale heterotrophy within near-shore marine ecosystems in the northeast Pacific.

Plain Language Summary Carbon and water are dominant features within coastal temperate rainforests, which ring the Pacific coast of northeast America and Asia, the southern coast of Chile, and western New Zealand. The environmental conditions that support large stores of above ground forest biomass also facilitate the movement of organic carbon through soils and streams to coastal zones. Here we present the results of a large data synthesis to estimate the flux of dissolved organic carbon from the land to sea along the Northeast Pacific Coastal Temperate Rainforest region that extends from northern California through Southeast Alaska. We highlight that, although large rivers like the Fraser River in Canada and the Columbia River in the United States drain the majority of the region, the majority of the dissolved organic carbon entering coastal ecosystems originates from small, coastal watersheds, highlighting the direct connection in the carbon cycle between terrestrial and estuarine ecosystems within this region.

1. Introduction

The northeast Pacific Coastal Temperate Rainforest (NPCTR) is a region of dramatic elevation gradients including steep and subdued terrain and the largest remaining icefields in North America (Bidlack et al., 2021; O'Neel et al., 2015). Ecosystems within the NPCTR are characterized by slow and incomplete decomposition of organic carbon (OC), resulting in one of the densest soil carbon stocks on Earth (228 ± 111 Mg ha^{-1}; McNicol et al., 2019). The regional proximity to frontal storms from the Gulf of Alaska leads to extreme rates of precipitation (>6 m yr^{-1} at high elevations) and an annual land-to-ocean freshwater flux of roughly 1,300 km^3 (runoff = 0.9 m yr^{-1}; Hill et al., 2015; Morrison et al., 2012). This freshwater discharge from the 1.4 M km^2 NPCTR drainage basin is 60% greater than that from the 3.4 M km^2 Mississippi River (Dai & Trenberth, 2002), and it provides an important vector for lateral transport of dissolved organic carbon (DOC) across the terrestrial-marine interface.

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Quantifying the linked flows of water and DOC across coastal margins is crucial for understanding the flow of energy between terrestrial and estuarine ecosystems (Bauer et al., 2013; Hopkinson et al., 1998; Tank et al., 2012). Globally, small (<10,000 km^2) mountainous watersheds are disproportionately important sources of terrestrial materials to the ocean (Milliman & Syvitski, 1992). In the NPCTR, the combination of large soil organic carbon (OC) stocks and high runoff rates facilitates rapid transfer of DOC to the coastal zone and mixing within the dominant currents that drive water flow in the Northeast Pacific Ocean. This organic matter provides metabolic support for coastal environments along the Riverine Coastal Domain, a narrow strip of buoyancy-driven boundary currents along western North America (Carmack et al., 2015).

Many small coastal watersheds in the northern and central NPCTR have extremely high yields of dissolved organic carbon (10–40 g-C m^2 yr^{-1}; D'Amore et al., 2015; Oliver et al., 2017). However, there are few regional scale, data-driven estimates for riverine DOC fluxes from temperate rainforest ecosystems to coastal environments. The southeast Alaska drainage basin, which includes the northern portion of the NPCTR, has been estimated to export ~1 Tg-C yr^{-1} as DOC (Edwards et al., 2021; Stackpoole, Stets, et al., 2017). In contrast, the Amazon River exports about 27 Tg-C yr^{-1} as DOC from an area ~50 times greater than the southeast Alaska drainage basin (Moreira-Turcq et al., 2003), illustrating that DOC yields from coastal temperate rainforest (CTR) ecosystems may be larger than those from some tropical rainforests. However, runoff and DOC concentrations vary dramatically among the diverse watersheds of the NPCTR drainage basin (Giesbrecht et al., 2022), hindering efforts to scale DOC fluxes across this region.

Here we present the first comprehensive estimate for the flux of DOC entering the northeast Pacific across the perhumid and seasonal domains of the NPCTR coastal margin. We compile a continuous transboundary riverine DOC data set to model long-term mean annual fluxes of DOC by watershed, explore the relative contributions of small coastal watersheds and larger continental river systems to the land-to-ocean flux of DOC within this C-rich ecoregion, and consider implications of this flow of DOC to downstream marine ecosystems.

2. Data and Methods

2.1. Watershed Characterization and DOC Data Compilation

Our study region extends from the Eel River watershed in northern California to the coastal watersheds of Glacier Bay National Park in southeast Alaska (Figure 1a). This region encompasses the perhumid NPCTR north of Vancouver Island, which receives substantial precipitation in every month of the year, as well as the seasonal NPCTR from Vancouver Island southward, which is characterized by an annual summer dry season. We used the watershed boundary data set produced by Gonzalez Arriola et al. (2018), which merges existing government data products including the USGS National Hydrography Data set, the U.S. Watershed Boundary Data set, and British Columbia Freshwater Atlas into seamless outlines with a consistent resolution (>~20 km^2) across international (AK–BC–WA) and state (WA–OR–CA) boundaries. We omitted (~63,000) very small drainage polygons (<10 km^2), which were mostly tiny islets, together representing only 0.27% of the region. For each watershed, we used existing geospatial datasets to describe 17 watershed characteristics expected to control the watershed DOC yield (Table S1 in Supporting Information S1) in this region, including climate normals calculated from 1981 to 2010 (see Giesbrecht et al., 2022 for details).

Streamwater DOC concentration data were compiled from federal, provincial, and state databases, unpublished data, and previously published estimates, resulting in an initial data set of 10,632 DOC measurements across 560 sites. This data set was filtered to ensure that measurement location(s) closest to (but not within) the estuary were used when multiple sites were present in a watershed, and that minimum criteria for watershed DOC sample size ($n \geq 3$) and seasonal distribution were met (see Text S1 in Supporting Information S1). Filtering resulted in a final data set of 3,706 DOC measurements across 116 watersheds, with 2,758 observations from 108 small coastal watersheds and 948 observations from eight continental watersheds (Data Set S1, Butman et al., 2023).

2.2. Estimates of Carbon Flux and Yield

Continental watersheds: The 10 continental watersheds in the study domain (Figure 1a) are gauged for discharge by federal agencies with DOC data available at the gauge site for 8 of 10 of the watersheds. In gauged watersheds, we used LOADEST (Runkel et al., 2004) to fit regression models for estimating annual fluxes (Tg yr^{-1})

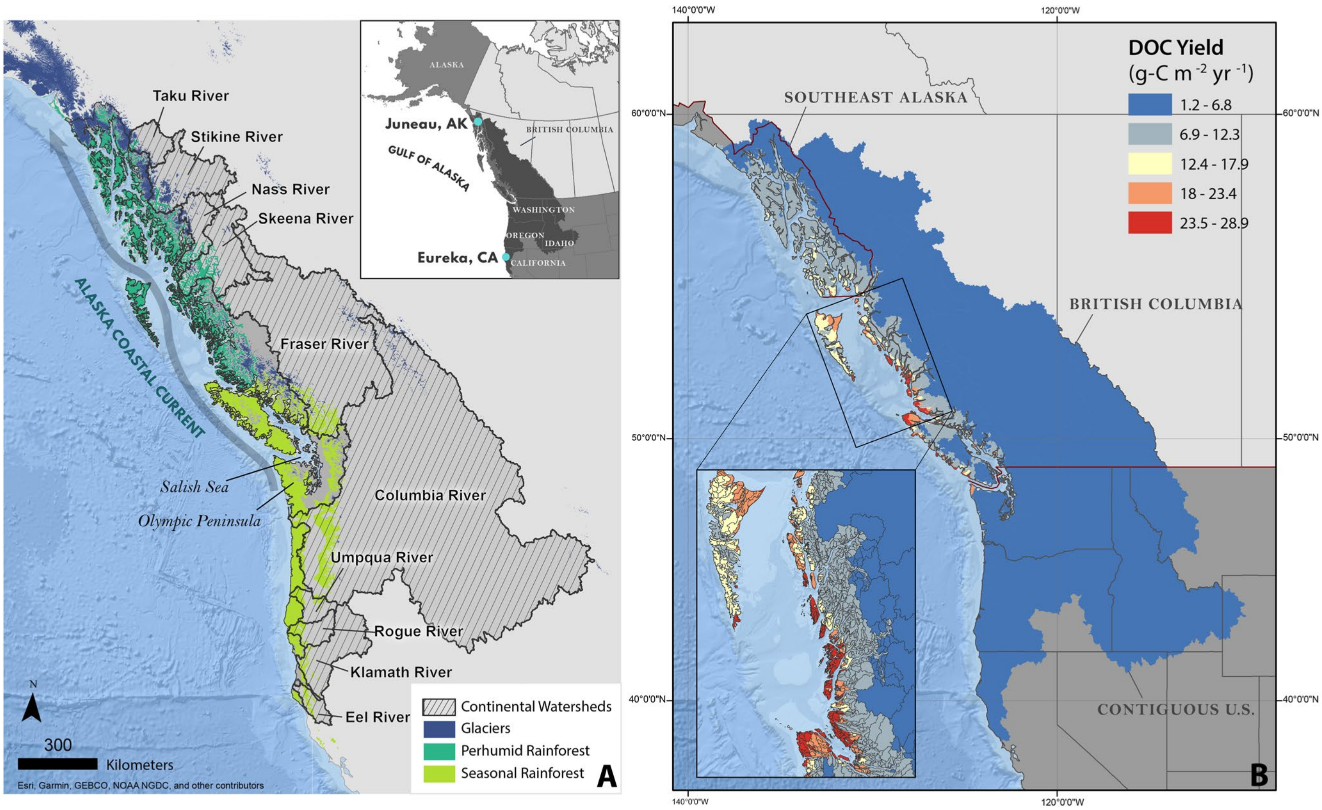

Figure 1. Location and extent of the Northeast Pacific Coastal Temperate Rainforest (colored zones) in the context of the larger NPCTR drainage basin, which includes small coastal watersheds (thin black lines) and ten large continental watersheds (heavy black lines) used in this analysis (a). Range of modeled watershed carbon yields across the study region, which includes the S.E. Alaska, British Columbia, and Contiguous U.S. sub-regions (b).

at the most downstream gauge in each continental watershed ($n = 3$; Table S3 in Supporting Information S1). Gauged fluxes were extrapolated to the watershed outlet using proportional discharge (see below for description and Table S3 in Supporting Information S1 for calculations). Fluxes previously calculated for U.S.-terminating watersheds ($n = 5$; Edwards et al., 2021; Stets & Striegl, 2012) were used for extrapolation from gauge to outlet. For watersheds without DOC data (the Eel and Nass), fluxes were interpolated using the area-weighted flux from nearby watersheds (Table S3 in Supporting Information S1). Annual yields (g-C m^{-2} yr^{-1}) were then calculated by dividing watershed outlet DOC fluxes by the total watershed area.

Coastal watersheds: Because most small, coastal watersheds in the NPCTR are not gauged, fluxes and yields were calculated for all coastal watersheds with screened DOC concentration data from the closest measurement site to the coast ($n = 108$, see above). For watersheds that did not have enough DOC and/or discharge data to use LOADEST (85 of 108 watersheds), DOC yields were calculated using mean monthly runoff (1981–2010) estimates generated from a modification of the distributed climate water balance model (DCWBM) (Moore et al., 2012; see Text S1 in Supporting Information S1). Mean monthly runoff at the coastal watershed outlet was generated for each NPCTR watershed as a composite of modeled and gauged discharge. Mean monthly DOC yields were calculated as the product of mean monthly DOC concentration data and modeled monthly runoff. In cases where DOC data were not available for all months, monthly yields were scaled to annual yields by multiplying by the ratio of annual discharge to the sum of discharge during months for which DOC yields were computed. For the subset of coastal watersheds that met minimum LOADEST requirements (i.e., availability of gauged discharge data and a minimum of 12 DOC values; 23 of the 108 watersheds) and the 8 continental watersheds with DOC data, fluxes and yields were modeled via LOADEST as described above. A comparison of the two approaches confirmed similar results (Figure S3 in Supporting Information S1).

To extrapolate DOC yields to NPCTR coastal watersheds, we developed a model training data set comprised of LOADEST yields and calculated watershed yields, using LOADEST yields where both were available. We used

Table 1
Watershed Information and DOC Fluxes and Yields by Watershed Type (Small Coastal Versus Large Continental; Rows 1–4) and Sub-Region (Rows 4–7)

Sub-region	Watershed count	Watershed area (km^2)	Annual DOC flux (Tg-C yr^{-1})	DOC yield (range; g-C m^{-2} yr^{-1})
Small Coastal	2,695	317,768	1.97 ± 0.85	6.2 (1.3–28.9)
Perhumid	*1,913*	*171,509*	*1.26*	*7.3 (2.1–28.8)*
Seasonal	*782*	*146,258*	*0.71*	*4.9 (1.3–28.9)*
Large Continental	10	1,125,294	1.57 ± 0.07	1.4 (0.9–3.0)
S.E. Alaska	1,172	154,365	0.76	4.9 (1.1–26.5)
British Columbia	1,243	455,592	1.74	3.8 (1.4–28.9)
Contiguous U.S.	290	833,105	1.04	1.2 (1.0–28.0)
NPCTR drainage basin total	2,705	1,443,062	3.5 ± 0.92	2.4 (1.0–28.9)

Note. Small coastal watersheds are further subdivided into the perhumid and seasonal CTR ecoregions. The S.E. Alaska and Contiguous U.S. sub-regions include significant areas of British Columbia due to transboundary watersheds.

forward feature selection (FFS; Meyer et al., 2018) to identify the predictor subset that minimized the model mean absolute error (MAE) during leave-one-out cross validation after stepwise training of a Random Forest algorithm on all 17 watershed attribute predictors. An initial pair of, then single, predictors were added when they resulted in the lowest MAE, resulting in a final predictor set of two variables (Hargreaves reference evapotranspiration and percent of MAP as snow; Table S1 in Supporting Information S1) that was used to train a Random Forest model using all DOC yields calculated for coastal watersheds via the LOADEST and DCWBM methods described above. Final model predictions were corrected for regression-to-the-mean effects common to decision tree algorithms using a linear spline function between observed and predicted DOC (Zhang & Lu, 2012), and yields were calculated for all NPCTR coastal watersheds using the final corrected model. Overall error in the modeled flux was computed by scaling the model mean absolute error estimated during cross validation to the model domain (Warner et al., 2019). The methods used to calculate watershed DOC yields across the full study domain are shown in Figure S4 in Supporting Information S1, and further methodological details are in Text S1 in Supporting Information S1.

3. Results and Discussion

3.1. DOC Export From the NPCTR Drainage Basin

We estimate that the total riverine DOC flux from the NPCTR drainage basin is 3.5 ± 0.92 Tg-C yr^{-1} (Table 1). This constitutes about 1.6% of the annual DOC flux from global rivers to the ocean and roughly 10% of the total DOC flux to the Pacific Ocean (Dai et al., 2012; Li et al., 2017). In the context of North America, the flux of DOC from the NPCTR drainage basin exceeds the DOC fluxes from the three largest watersheds on the continent: the Mississippi (1.7–2.8 Tg-C yr^{-1}; Cai et al., 2015; Ren et al., 2016; Stackpoole, Stets, et al., 2017), Mackenzie (1.38 Tg-C yr^{-1}, Holmes et al., 2012), and Yukon (1.47 Tg-C yr^{-1}; Holmes et al., 2012) river basins. Moreover, land-to-ocean DOC loss from the NPCTR drainage basin equates to more than half of annual DOC export from the conterminous United States (6.3 Tg-C yr^{-1}; Stets & Striegl, 2012) and more than 8% of the DOC flux from the entire North American continent (42.5 Tg-C yr^{-1}; Li et al., 2019). Within North America, the NPCTR drainage basin serves as a hotspot of DOC production, the export of which is closely connected to the coastal ocean. Our findings further suggest that the role of coastal temperate rainforest ecosystems in continental scale land-to-ocean DOC fluxes warrants further examination in other CTR regions such as southern South America, New Zealand, and Japan.

Within the NPCTR drainage basin, the annual DOC flux is derived largely from coastal watersheds, with 1.97 ± 0.85 Tg (56%) of the DOC flux coming from roughly 2,700 small (median = 44 km^2) coastal watersheds that account for 22% of the NPCTR drainage basin area (Figure 2, Table 1). In contrast, only 1.57 ± 0.07 Tg (44%) of the DOC flux originates from the large continental watersheds that cross the Coast Mountains and account for the majority (78%) of the land area draining to the NPCTR coastal margin. The CTR zone within the NPCTR drainage basin, which includes abundant runoff from glaciers and icefields, thus serves as the primary driver of the land-to-ocean DOC flux in this region. Within the small watersheds of the CTR zone, the perhumid ecoregion, which is characterized by higher annual precipitation distributed evenly across the year, had a higher annual DOC flux (1.26 Tg) compared to the seasonal ecoregion (0.71 Tg), which experiences an extended summer (June–September) dry season (Waring & Franklin, 1979).

The spatial distribution of the riverine DOC flux from the NPCTR drainage basin is important because the Alaska Coastal Current originates close to the Columbia River mouth and transports freshwater and solutes northward to the productive near-shore marine ecosystems of the Gulf of Alaska (Figure 1; Stabeno et al., 1995). On a regional basis, British Columbia in the geographic center of the NPCTR had the largest annual DOC flux (1.74 Tg C; Table 1), followed by the contiguous U.S. (1.04 Tg C; 62% from the Columbia River Basin), and the watersheds draining into coastal southeast Alaska (0.76 Tg C). Our annual DOC flux estimate

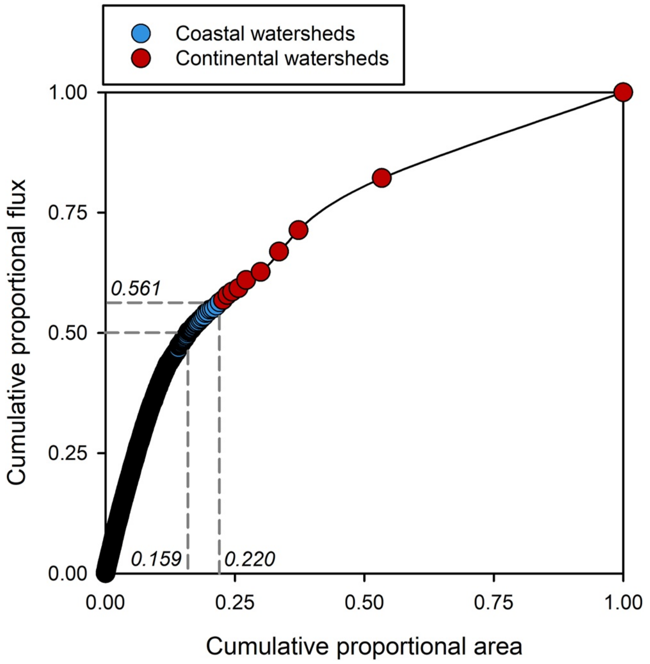

Figure 2. Cumulative proportion of the regional DOC flux versus cumulative proportional watershed area. Blue dots represent small coastal watersheds (n = 2,695), and red dots represent the 10 continental watersheds.

for southeast Alaska and transboundary watersheds of the British Columbia/Alaska panhandle is notably smaller than a recent estimate of 1.12 Tg yr^{-1} by Edwards et al. (2021), who modeled DOC concentration and streamflow at the watershed scale. Our more conservative estimate of NPCTR DOC flux may arise from our model underestimating the exceptionally high DOC yields from small, outer coast watersheds in the center of our study domain (e.g., Oliver et al., 2017; Figure S4 in Supporting Information S1) due to a paucity of training data within this region (Figure S5 in Supporting Information S1).

3.2. Regional DOC Yields

The range of magnitudes for our modeled watershed DOC yields (1–29 g-C m^{-2} yr^{-1}; Table 1) agrees with measured DOC yields from our study region including the central coast of British Columbia (24–38 g-C m^{-2} yr^{-1}; Oliver et al., 2017) and southeast Alaska (11–30 g-C m^{-2} yr^{-1}; D'Amore et al., 2015), as well as similar coastal temperate rainforest watersheds in Chile (Pérez-Rodríguez & Biester, 2022; 1–44 g-C m^{-2} yr^{-1}). Moreover, our yield estimate for southeast Alaska is consistent with recent modeled yields of DOC (6.2 g-C m^{-2} yr^{-1}; Edwards et al., 2021) and total organic carbon (dissolved + particulate OC; 12.7 g-C m^{-2} yr^{-1}; Stackpoole, Stets, et al., 2017) for this region, given that particulate organic carbon (POC) can constitute more than 50% of the total riverine OC flux in the glacier-dominated watersheds found in the region (Bhatia et al., 2013; Hood et al., 2020).

The average DOC yield from the entire NPCTR drainage basin (2.4 g-C m^{-2} yr^{-1}; Table 1) is higher than the average DOC yield from Earth's tropical latitudes (30°N–30°S) of 2.13 g-C m^{-2} yr^{-1} (Huang et al., 2012). The importance of small watersheds to this regional DOC flux is exemplified by the DOC yield from the NPCTR coastal watersheds (6.20 g-C m^{-2} yr^{-1}), and particularly the perhumid CTR (7.30 g-C m^{-2} yr^{-1}), exceeding that for the large continental river basins (1.23 g-C m^{-2} yr^{-1}) by a factor of 5–6x. The DOC yield from the NPCTR coastal watersheds exceeds that for the boreal forest dominated landscapes of Finland (4.5 g-C m^{-2} yr^{-1}; Räike et al., 2015) and Norway (3.0 g-C m^{-2} yr^{-1}; de Wit et al., 2015) as well as the peatland-rich landscape of Great Britain (5.0 g-C m^{-2} yr^{-1}; Williamson et al., 2021). Moreover, the highest DOC yields from outer-coast watersheds of the NPCTR (20–30 g-C m^{-2} yr^{-1}; Figure 2) are within the lower end of the range of DOC yields from peat-dominated, high-standing tropical islands in southeast Asia (26–96 g-C m^{-2} yr^{-1}; Baum et al., 2007; Moore et al., 2013; Wit et al., 2015), which have among the highest watershed DOC yields yet reported.

Within North America, the DOC yields we report for the NPCTR coastal watersheds are generally higher than those documented for watersheds in other ecoregions including agricultural (0.3–2.3 g-C m^{-2} yr^{-1}; Royer & David, 2005), blackwater swamp (3.3–6.2 g-C m^{-2} yr^{-1}; Avery et al., 2003; Leech et al., 2016), temperate forest (2–10 g-C m^{-2} yr^{-1}; Campbell et al., 2000; Huntington & Aiken, 2013). Overall, our findings indicate that CTR ecosystems are a regional and global hotspot of DOC export to the ocean (Edwards et al., 2021; Oliver et al., 2017; Stackpoole, Butman, et al., 2017). Further, our findings underscore the importance of small coastal watersheds as drivers of riverine material fluxes to the ocean (Destouni et al., 2008; Milliman & Syvitski, 1992; Warrick et al., 2015).

3.3. Drivers of DOC Export From NPCTR Ecosystems

Our final Random Forest model for watershed DOC yields included two features: the percent of precipitation received as snow (PAS) and reference evapotranspiration (Eref; Table S1 in Supporting Information S1), with the highest yields of DOC occurring in watersheds with low PAS and Eref. (Figure S6 in Supporting Information S1). In the coastal mountains of the NPCTR, PAS acts as a proxy for topographic effects such as slope and elevation (Giesbrecht et al., 2022), both of which are negatively correlated wetland coverage and soil organic carbon stocks at the watershed scale (D'Amore et al., 2016; Sobek et al., 2007). This is consistent with the idea that low elevation and low relief watersheds within the NPCTR harbor abundant peatlands and forested wetlands that have tight hydrological connections to stream networks play an outsized role in the transfer of DOC between terrestrial and aquatic ecosystems (D'Amore et al., 2010; Fellman et al., 2009) similar to other temperate ecosystems (Creed et al., 2003; Inamdar & Mitchell, 2006; Laudon et al., 2004; Wei et al., 2021).

The inclusion of Eref in the DOC yield model highlights the role of excess moisture as a driver of watershed DOC export. Reference evapotranspiration decreases with latitude across the NPCTR, while mean annual precipitation (MAP) increases across the same gradient (Giesbrecht et al., 2022; Shanley et al., 2015) meaning that excess moisture (MAP-Eref) increases moving northward in the NPCTR. Regionally, this northward increase in excess moisture leads to lower temperatures, slower decomposition, and the buildup of SOM (McNicol et al., 2019). Excess moisture also increases specific discharge, which ranges from ∼1 to 7 m yr^{-1} in the perhumid NPCTR (Giesbrecht et al., 2022). This elevated freshwater flux amplifies the positive relationship between soil C stocks and riverine DOC export (Aitkenhead & McDowell, 2000; Tank et al., 2018) within the NPCTR. Volume loss from the more than 20,000 km^2 of glacier ice in the northern portion of the NPCTR also contributes substantially to streamflow (Neal et al., 2010), and glacier runoff in this region is projected to increase in coming decades (Bliss et al., 2014). Thus heavily glacierized watersheds will continue to contribute substantially to regional DOC fluxes despite having small terrestrial C stocks and correspondingly low riverine DOC concentrations (Hood et al., 2009).

Within the NPCTR, the highest watershed DOC yields occur along the outer coast between northern Vancouver Island in Canada and the southern Alexander Archipelago in southeast Alaska (Figure 1b). The latitudinal temperature gradient across our study region appears to play an important role in the storage and release of soil C to streams. The most dense stores of soil OC (>500 Mg C ha^{-1}) occur in the Alexander Archipelago of southeast Alaska (McNicol et al., 2019). However, the largest watershed DOC yields occur further south consistent with the idea that temperature is an important control on DOC production within the soil profile (Christ & David, 1996; D'Amore et al., 2010; Ziegler et al., 2017). In addition, the transition from the perhumid rainforest to the seasonal rainforest north of Vancouver Island occurs coincident with the peak in watershed DOC yields suggesting that episodic drying and rewetting of soils may also facilitate DOC production and increase lateral DOC export at the watershed scale (Tiwari et al., 2022; Tunaley et al., 2016). In the southern NPCTR, south of Vancouver Island, watershed DOC yields are limited by relatively lower soil C stocks (Sun et al., 2004) and catchment water yields compared to the northern and central NPCTR. In this context, the central NPCTR is a "sweet spot" for land-to-ocean DOC transport as a result of positive interactions between key environmental variables such as temperature, evapotranspiration, precipitation, and soil OC that control riverine DOC export.

The highest DOC yields we modeled occurred in the smallest watersheds in our study domain (largely <50 km^2). This is consistent with the idea the large OC stocks in upland and particularly wetland soils within small watersheds in the NPCTR have a larger proportional influence (compared to larger watersheds) on streamwater DOC concentrations due to their consistent hydrological connectivity to the stream network (Covino, 2017) and short water residence times, particularly during storm events, which minimize instream processing and uptake of DOC (Raymond et al., 2016). The magnitude of watershed DOC fluxes from NPCTR modeled here and documented previously (D'Amore et al., 2015; Edwards et al., 2021; Oliver et al., 2017) further highlights the importance of accounting for small, wetland-rich, near-coastal watersheds in regional riverine DOC flux calculations (Williamson et al., 2021).

Projected future increases in precipitation and temperature across the central and northern NPCTR (Lader et al., 2020; Shanley et al., 2015) can be expected to increase rates of soil carbon export as DOC from coastal watersheds. Within individual watersheds, streamwater DOC concentrations across the region increase sharply with discharge (D'Amore et al., 2010; Fellman et al., 2020; Hood et al., 2020) indicating that watershed DOC export is broadly transport (water) limited and will increase with precipitation. The frequency of landfalling atmospheric river precipitation events is projected to increase substantially (50%–600%) in the NPCTR in coming decades (Gao et al., 2015), and these extreme high flow events can be expected to strongly enhance DOC export from NPCTR watersheds (Raymond & Saiers, 2010; Yoon & Raymond, 2012).

3.4. Fate of Riverine DOC in NPCTR Marine Ecosystems

The land-to-ocean DOC fluxes we document may serve as an important source of C and energy for near-shore ecosystems. Along the coastline of the perhumid NPCTR, the small coastal watersheds with high DOC yields drain largely into sheltered inside waters and fjords. As a result, the residence time and potential for biological processing of DOC in estuarine ecosystems adjacent to the NPCTR is substantially higher compared to coastlines where runoff from rivers enters the open ocean and is rapidly transported offshore (Edwards et al., 2021). Riverine DOC in the NPCTR has been shown to readily metabolized by marine microbes (Fellman et al., 2010) and serves as a primary source of organic matter in near-shore ecosystems (St. Pierre et al., 2022). Moreover, at upper trophic levels terrestrial OC has been shown to account for a substantial proportion (12%–50%) of the biomass C of copepods, birds, and fish in CTR fjord ecosystems in Chile and Alaska (Arimitsu et al., 2018; Vargas et al., 2011), however it is unclear what proportion of this C enters marine food webs as DOC compared to POC.

Climate change may alter the flow of OC across the land-ocean interface in the NPCTR. Glacier lake outburst floods (Harrison et al., 2018) and landslides associated with both atmospheric rivers (Darrow et al., 2022) and glacier recession are projected to increase in frequency (Holm et al., 2004). These events deliver large volumes of sediment via rivers to the coast, where freshwater plumes can extend more than 50 km down fjord ecosystems and impact coastal C cycling and marine food webs (Geertsema et al., 2022; Meerhoff et al., 2019). Perturbations to riverine sediment transport driven by extreme events will also affect the form of riverine OC. Currently, DOC is the dominant vector of land-to-ocean OC transport in the NPCTR, accounting for more than 80% of OC export in forested watersheds and up to 50% of OC export in heavily glacierized watersheds (Hood et al., 2020). However, during extreme high flow events, fluxes of POC increase far more rapidly than those for DOC due to the mobilization of sediment from terrestrial and aquatic ecosystems (Dhillon & Inamdar, 2014). Thus, an increase in the incidence of glacier lake outburst floods, extreme precipitation events, and landslides within the NPCTR will amplify the role of POC as a vector for the transfer of OC to near-shore marine ecosystems.

4. Conclusions

We present the first unified estimate for the flux of riverine DOC to the NE Pacific and show that the NPCTR drainage basin is a global hotspot of land-to-ocean OC transport, representing ∼10% of the total DOC exported to the Pacific Ocean. Our model results suggest that majority of this DOC flux originates from small, coastal watersheds, with the highest watershed yields occurring on the outer coast in central British Columbia. Watershed fluxes of POC and inorganic C remain unquantified, however, they may contribute an additional 50% to the regional riverine carbon flux (Stackpoole, Stets, et al., 2017). The large land-to-ocean OC fluxes we quantify will facilitate efforts to model heterotrophic production in near-shore marine ecosystems in the Gulf of Alaska as well as contribute to our understanding of whether terrestrial ecosystems within the NPCTR function as a C sink or source at regional scales.

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Data Availability Statement

Site locations, DOC data, discharge data, and modeled DOC yields used in this paper are available through the Environmental Data Initiative (https://doi.org/10.6073/pasta/288f23f208bd0188ed69649624d0553c).

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